US Army Corps of Engineers

AC 150/5370-14A
Appendix 1

Hot-Mix Asphalt Paving

American Association of State Highway and Transportation Officials
Federal Aviation Administration
Federal Highway Administration
National Asphalt Pavement Association
U.S. Army Corps of Engineers
American Public Works Association
National Association of County Engineers

HANDBOOK 2000

U.S. Department
of Transportation

Federal Aviation
Administration

Advisory Circular

Subject: HOT MIX ASPHALT PAVING HANDBOOK

Date: July 24, 2001
Initiated by: AAS-200

AC No: 150/5370-14A
Change:

1. PURPOSE. This advisory circular (AC) provides updated guidance on asphalt paving operations including project organization, mix design, quality control, plant operations, laydown, and compaction.

2. CANCELLATION. AC 150/5370-14, Hot Mix Asphalt Paving Handbook, dated October 15, 1991, is cancelled

3. BACKGROUND. Agencies and contractors share common concerns about the problems of properly constructing hot mix pavements. Training is a major problem in the decentralized industry such as asphalt paving, where many contractors operate on too small a scale to make long-term investments in personnel development. As a result, the knowledge and experience of field personnel are often not up to date, and pavement quality frequently may not meet modern performance demands. This handbook concentrates on state of the art field practices for asphalt paving, including plant operations, transportation of materials, surface preparation, laydown, compaction, and quality control processes. The handbook is included in this AC as Appendix 1.

DAVID L. BENNETT
Director, Office of Airport Safety and Standards

Hot-Mix Asphalt Paving Handbook 2000

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PREFACE

In the year 2000, more than $20 billion will be spent in the United States to construct asphalt pavements for highways and airports. In a period in which pavement performance demands are increasing dramatically, asphalt paving contractors, public agencies, and the pavement research community share the opinion that the utmost care must be taken to construct these pavements properly. It is also important that improvements resulting from significant research findings and technological advances be incorporated into hot-mix asphalt paving practice in a timely fashion. Pavement experts agree, however, that highway and airport agencies and their pavement contractors have difficulty not only in incorporating new technology and research findings into field practice, but also in consistently applying proven procedures from earlier research experience.

Training is also a problem in this decentralized industry, where many producers and contractors operate on too small a scale to make long-term investments in personnel development. As a result, the knowledge and experience of field personnel are often not up to date, and pavement quality frequently may not meet modern performance demands.

Responding to recommendations from industry, government, and academic officials, the first edition of the *Hot-Mix Asphalt Paving Handbook* was prepared by the Transportation Research Board (TRB) in 1991 with financial support from the American Association of State Highway and Transportation Officials, the Federal Aviation Administration, the Federal Highway Administration, the National Asphalt Pavement Association, and the U.S. Army Corps of Engineers. Although field manuals and handbooks were then available from many sources, none had been adopted by all major industry segments. Since its appearance, the *Hot-Mix Asphalt Paving Handbook* has been widely accepted as a standard training aid throughout the major segments of the paving industry. As a result, a great deal of confusion among personnel from contractors and specifying agencies regarding paving practices has been alleviated.

In the 1990s, asphalt paving practices evolved rapidly, and TRB has updated the handbook at the request of its sponsors to address this evolution. This second edition of the handbook addresses recent research findings including those of the Strategic Highway Research Program, new paving equipment, the growth in recycling, changes in quality control practices, and the introduction of new techniques from Europe and elsewhere. This edition also uses both the American customary and International System (metric) units of measurement.

As with the first edition, this handbook is being technically approved and distributed as a general guide for asphalt paving construction by its financial sponsors. It is also being made available through the American Public Works Association and the National Association of County Engineers.

This handbook covers the state of the art of asphalt paving, including plant operations, transportation of materials, surface preparation, laydown, compaction, and quality control processes. It is aimed at the field personnel who are responsible for these operations—both contractor personnel who do the work and agency personnel who oversee and inspect the work. It is hoped that the handbook will continue to promote a common understanding of the processes involved and thereby result in improved asphalt pavement construction.

The handbook is not intended to cover administration, contracting procedures, site investigation, geometric design, structural design, or mix design, although some general information is included concerning contract administration and mix design. Therefore, existing agency policies and procedures will have precedence in these areas.

To undertake this update, the National Research Council (NRC) appointed a study committee chaired by E. Ray Brown, Director of the National Center for Asphalt Technology, Auburn University. The committee, with members knowledgeable in the various aspects of asphalt pavement construction practices and representing agencies, producers, and contractors, has prepared this update with the assistance of James A. Scherocman and Ronald J. Cominsky. Mr. Scherocman also participated in the preparation of the first edition of the handbook. The final version of this second edition incorporates changes made in response to comments received from members of the committee, approving organizations, and members of the panel appointed to review the draft in accordance with NRC's report review guidelines.

This handbook has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. Appreciation is expressed to the following individuals for their participation in the review of this report: Timothy B. Aschenbrener, Colorado Department of Transportation; Lester A. Hoel, University of Virginia; Gerald Huber, Heritage Research Group; Byron E. Ruth, University of Florida; and Randy C. West, APAC, Inc. While these individuals have provided constructive comments and suggestions, it must be emphasized that responsibility for the final content of this handbook rests entirely with the authoring committee and the institution.

The Transportation Research Board is a unit of the National Research Council, which is the principal operating agency of the National Academy of Sciences and the National Academy of Engineering. The National Research Council provides independent advice on scientific and technical matters under a congressional charter granted to the National Academy of Sciences, a private, nonprofit institution dedicated to the advancement of science and technology and to their use for the general welfare.

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PART III Hot-Mix Asphalt Laydown and Compaction

PART I

Project Organization, Mix Design, and Quality Control

Introduction

PURPOSE AND ORGANIZATION OF HANDBOOK

The purpose of this *Hot-Mix Asphalt Paving Handbook* is to describe the production and placement of asphalt mixtures from a practical point of view. The handbook has been prepared for those actively involved in the construction of asphalt pavements. The intended audience comprises two different groups that share a common interest in quality construction of hot-mix asphalt (HMA) pavements. The first consists of agency personnel, including those who hold such titles as resident engineer, county engineer, municipal engineer, project engineer, and plant or paving inspector. Throughout this volume, the term "agency" denotes the governmental or other owner of the work. The second group consists of contractor employees, including those who hold such titles as project superintendent, plant or paving superintendent, and plant or paving foreman. This handbook focuses on field practices—at the asphalt plant during mix production and at the paving site during mix laydown and compaction operations.

Following this introduction, **Part I** begins by providing a brief review of project organization (Section 2). The role of mix design relative to mixture behavior during manufacture, placement, and compaction is then addressed (Section 3); included is a discussion of Superpave® binder and mix specifications and requirements. The importance of quality control on the part of the contractor and quality assurance on the part of the governmental or other agency responsible for project control is then considered, together with the differences between method-type specifications and end-result-type specifications (Section 4).

Part II is organized roughly in the order of HMA plant operations. First, an overview of types of asphalt plants is given (Section 5). Aggregate storage and handling (Section 6) and the asphalt cement supply system (Section 7) are then reviewed. Next is a discussion of mixing operations in the three types of plants—batch, parallel-flow drum-mix, and counter-flow drum-mix (Sections 8, 9, and 10, respectively). Finally, surge and storage silos (Section 11) and emission control (Section 12) are addressed. Each section in Part II ends with a listing of the key operating factors to be monitored for the respective operations.

Part III reviews the various operations involved in placing the HMA at the laydown site. Delivery of the mix to the paver is described first (Section 13). The following sections address in turn surface preparation (Section 14), mix placement (Section 15), automatic screed control (Section 16), joint construction (Section 17), compaction (Section 18), and mat problems (Section 19). As in Part II, each section ends with a summary of key operating factors that should be monitored in each of these areas.

HOT-MIX ASPHALT DEFINED

The term "hot-mix asphalt" is used generically to include many different types of mixtures of aggregate and asphalt cement that are produced at an elevated temperature in an asphalt plant. Most commonly HMA is divided into three different types of mix—dense-graded, open-graded, and gap-graded—primarily according to the gradation of the aggregate used in the mix (see Table 1-1). The dense-graded type is further subdivided into continuously graded or conventional HMA, large-stone mix, and sand asphalt mix. The open-graded type includes the subtypes open-graded friction course and asphalt-treated permeable base. The gap-graded type encompasses both gap-graded asphalt concrete mixes and stone-matrix asphalt mixes. Representative gradations are shown in Figure 1-1. Pavement designers specify different mixture types to satisfy different pavement performance demands and to accommodate variability in the nature and cost of available aggregates and asphalt cement supplies.

Dense-Graded Hot-Mix Asphalt

Dense-graded HMA is composed of an asphalt cement binder and a well or continuously graded aggregate.

Conventional HMA consists of mixes with a nominal maximum aggregate size in the range of 12.5 mm (0.5 in.) to 19 mm (0.75 in.). This material makes up the bulk of HMA used in the United States.

TABLE 1-1 Types of Hot-Mix Asphalt

Dense-Graded	Open-Graded	Gap-Graded
Conventional Nominal maximum aggregate size usually 12.5 to 19 mm (0.5 to 0.75 in.)	Porous friction course	Conventional gap-graded
Large-stone Nominal maximum aggregate size usually between 25 and 37.5 mm (1 and 1.5 in.)	Asphalt-treated permeable base	Stone-matrix asphalt (SMA)
Sand asphalt Nominal maximum aggregate size less than 9.5 mm (0.375 in.)		

Large-stone mixes contain coarse aggregate with a nominal maximum size larger than 25 mm (1 in.). As seen in Figure 1-1a, these mixes have a higher percentage of coarse aggregate than the conventional mixes [larger than the 4.75-mm (No. 4) sieve]. During plant production of large-stone mixes, as compared with conventional HMA, some additional equipment wear may occur in the batch plant dryer and the counter-flow and parallel-flow mixing drums because of the use of the larger aggregate. Additional wear may also be experienced on the slat conveyor and the augers of the paver. Because of the large size of the aggregate, the compactive effort applied to the mix must be monitored to prevent excessive fracture of the larger aggregate pieces during the compaction process.

Sand asphalt (sometimes called sheet asphalt) is composed of aggregate that passes the 9.5-mm (0.375-in.) sieve (see Figure 1-1a). The binder content of the mix is higher than that of conventional HMA because of the increased voids in the mineral aggregate in the mixture. Unless manufactured sand or a rough-textured natural sand is used in the mix, the rut resistance of this type of mix is typically very low. Sand mix can be produced in a batch plant or drum-mix plant with no significant changes in the plant operation. Transport and placement of the mix are also standard. Under the compaction equipment, however, sand mix may tend to shove and check under steel wheel rollers, especially when constructed in relatively thick layers [greater than 50 mm (2 in.)].

Open-Graded Mixes

Open-graded mixes consist of an aggregate with relatively uniform grading and an asphalt cement or modified binder (see Figure 1-1b). The primary purpose of these mixes is to serve as a drainage layer, either at the pavement surface or within the structural pavement section.

As noted, there are two types of open-graded mixes. The first comprises mixes used as a surface course to provide a free-draining surface in order to prevent hydroplaning, reduce tire splash, and reduce tire noise; this type of mix is frequently termed an *open-graded friction course*. The second type, termed *asphalt-treated permeable base*, comprises a uniformly graded aggregate of larger nominal maximum size than that used for open-graded friction course—19 mm (0.75 in.) to 25 mm (1.0 in.)—and is used to drain water that enters the structural pavement section from either the surface or subsurface.

The production of open-graded mixes is similar to that of dense-graded mixes, the major difference being the mix temperature. Lower mixing temperatures are used for the open-graded materials to prevent draindown during temporary storage in a surge silo and during delivery to the paver by a haul vehicle. More recently, polymers and fibers have been used in open-graded friction courses to reduce draindown and improve the durability of mixtures. The placement of an open-graded mix is usually conventional. Less compactive effort is generally needed with this type of mix than with dense-graded mixtures.

Gap-Graded Mixes

Gap-graded mixes are similar in function to dense-graded mixes in that they provide dense impervious layers when properly compacted. *Conventional gap-graded mixes* have been in use for many years. Their aggregates range in size from coarse to fine, with some intermediate sizes missing or present in small amounts; an illustrative grading for this type of mix is shown in Figure 1-1c.

The second type of gap-graded mix is *stone-matrix asphalt* (SMA) mix; a representative grading for this type of mix is also shown in Figure 1-1c. The production

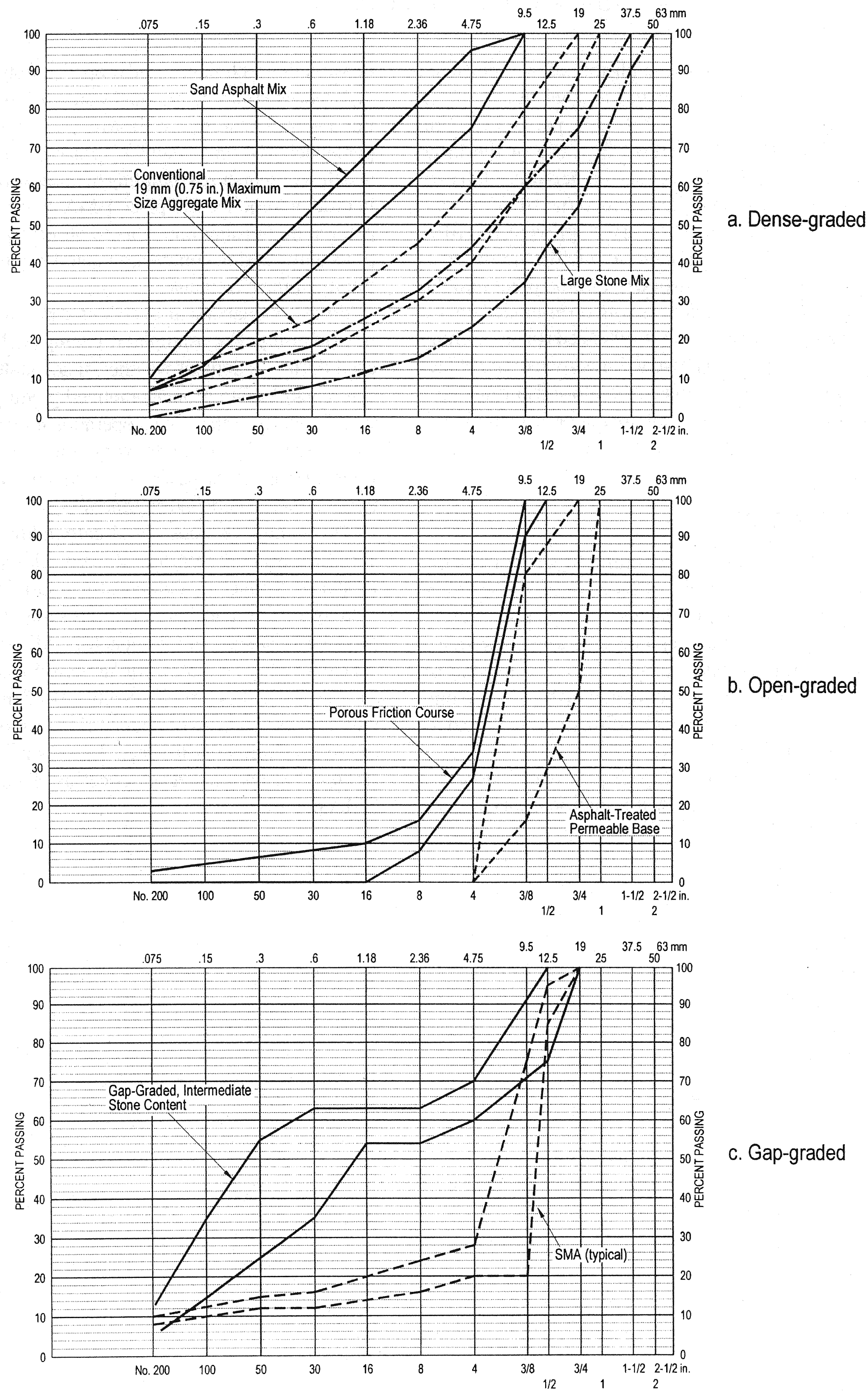


FIGURE 1-1 Representative aggregate gradations.

of SMA mix requires the addition of a significant amount of mineral filler to the normal aggregate in order to achieve the required 8 to 10 percent passing the 0.075-mm (No. 200) sieve. Because of the large amount of mineral filler needed, a separate delivery system is normally necessary to feed the filler into the plant. In addition, it is necessary to prevent the filler material from becoming airborne inside the dryer or mixing drum and being carried out of the plant into the emission-control equipment. As with open-graded mixes, the discharge temperature of the mix needs to be carefully controlled at the plant to prevent draindown of the binder during temporary mix storage in the silo and during transport to the job site. Fibers or polymer or both are normally used with SMA to prevent draindown.

WORKMANSHIP

Several major construction factors directly affect the ultimate performance of an HMA pavement: the structural design of the pavement layers; the asphalt-aggregate mix design; the construction procedures used to produce, place, and compact the mix; and the workmanship or quality of construction. Poor workmanship can be one of the most significant factors leading to premature distress of an asphalt pavement.

Causes of poor workmanship frequently include ignorance of or failure to comply with specifications, proper construction techniques, and proper equipment operation. Appropriate training of construction personnel is key to good workmanship as well. Mix plant and paving train personnel must understand the processes and procedures and the consequences of failing to observe proper practice in order to produce and place HMA properly. For example, failure of roller operators to observe proper spacing procedures during compaction could result in premature rutting of the pavement.

Project management decisions can also lead to poor workmanship. For example, if paving is allowed to proceed during inclement weather, inadequate compaction can result despite proper practice by equipment operators. Similarly, if the paving operation moves too quickly, it can exceed the rate of delivery of material; the result is frequent stops of the paving train, which in turn can cause unnecessary pavement roughness.

This handbook does not directly address workmanship, but it is inherent in all discussions that follow. Proper performance of all construction-related tasks, including testing and inspection, ensures that the HMA produced, placed, and compacted will perform as expected. Quality control and quality assurance procedures, such as those described in Section 4 of this handbook, will identify instances of poor workmanship, but not their causes and only after the fact. There is no substitute for careful adherence to best practices by all concerned with HMA paving.

2 Project Organization

The most essential part of project planning and organization is communication. Effective communication is vital to all elements of project organization reviewed in this section:

- The project documents are written instructions that must describe the requirements clearly and in detail.
- The preconstruction conference initiates verbal communication between the representatives of the agency and contractor personnel; it sets the tone for both the working relationship and direct communications during project execution.
- Ongoing communication between the contractor and the agency is essential to performing high-quality work.
- Project records make it possible to track events should doing so become necessary.
- Safety on the job cannot be maintained if communication among all parties is inadequate.

PROJECT DOCUMENTS

Project documents illustrate and describe work to be done under the contract. Specific definitions of these documents and other terms that apply directly to a project are normally included in the first section of the governing standard specifications. Project documents include the following:

- *Plans*—Drawings that show the location, character, dimensions, and details of the work to be done.
- *Standard specifications*—Directions, provisions, and requirements for performing the work illustrated and described in the plans. The items in the standard specifications relate to or illustrate the method and manner of performing the work or describe the qualities and quantities of materials and labor to be furnished under the contract.
- *Special or supplemental specifications*—Approved additions and revisions to the standard specifications.
- *Special provisions*—Additions or revisions to the standard or supplemental specifications that are applicable only to an individual project.

A number of other documents are often incorporated by reference into the standard specifications, supplemental specifications, and special provisions. Material specifications and test procedures from the American Association of State Highway and Transportation Officials (AASHTO) and ASTM are often listed in the specifications and become part of the contract documents, just as though the whole text were included. Additional documents, such as the *Manual on Uniform Traffic Control Devices* and Occupational Safety and Health Administration (OSHA) regulations, are treated in the same manner when referenced in the specifications.

Many of the material specifications and test methods written by AASHTO or ASTM for national use are modified for use under local conditions. Governmental agencies often publish their own material specifications and test methods. These publications typically are referenced in the contract documents and become part of those documents. Inspection manuals or guidelines normally are intended for use by the agency's representatives and are not part of the contract documents.

If there is a discrepancy between the instructions and specifications in any of the contract documents, a definite hierarchy exists among the above major types of documents. The order of priority, from highest to lowest, is usually special provisions, plans, special or supplemental specifications, and standard specifications. This order of priority corresponds to the documents' specific applicability to a project or contract.

Plans and specifications need to be accurate and complete, and they should leave little room for assumptions or later reinterpretation. In addition, plans and specifications need to define the responsibilities of both agency and contractor. If method specifications are used, the type and frequency of the inspection and testing procedures must be given explicitly. If quality control/quality assurance (QC/QA) specifications are used, the requirements for the contractor to monitor its own work and for agency personnel to do the necessary acceptance testing must be provided in detail. Accurate and complete contract documents save many hours of later discussion between agency and contractor representatives. When warranty specifications are used, the agency allows the contractor to conduct all testing necessary to control the product. The agency allows the contractor to design and control the product within general guidelines.

PRECONSTRUCTION CONFERENCE

A preconstruction conference is often held before work on a project begins. During this meeting, the overall tone—preferably one of cooperation—is set for the job. The agency's representatives are generally responsible for outlining the scope of the project and discussing the information provided in the contract documents. The agency representatives are also responsible for discussing any unusual aspects of the job—items that are not routine construction practices. A list of agency personnel who will be assigned to the project should be provided to the contractor.

The individuals representing the contractor should be familiar with all aspects of the job and be able to speak with authority about what is to be accomplished. A progress schedule for the job should be presented and discussed with the agency representatives. Any questions about the data and information in the contract documents should be raised and clarification requested, if necessary. A listing of key contractor personnel who will be assigned to the project should be provided, with clear lines of authority delineated. This list should include alternates for key personnel who may not always be available when needed.

Those attending the preconstruction conference should not assume that all others present understand fully and are in complete agreement with the proposed schedule. Agreement is needed on the methods to be used to complete the project on schedule with a minimum of delays and change orders. Because continuity of asphalt paving operations is critical to providing quality pavement, the discussion between agency and contractor personnel should include such items as material sources, plant production rates, haul distances and routes, paving widths and speed, and type and operation of compaction equipment. If known at this time, a list of the equipment to be used on the project should be supplied to the agency by the contractor.

The role of each person associated with the project, from both the agency and the contractor, should be discussed and clarified. To this end, supervisory personnel must define the tasks, authority, and responsibility of each of the key individuals to be involved in the work.

Sampling methods and frequencies should be discussed. Test methods to be used should be reviewed to ensure that all involved understand the purpose of each test, its location and the personnel who are to conduct it, the time frame for the return and communication of the test results, and the procedures to be used if failing test results are obtained. If not adequately covered in the specifications, the use of duplicate or split samples (one for testing by the contractor and one for testing by the agency) needs to be considered, as well as procedures for retesting of inadequate materials or for referee testing by a third party. The details of the quality control program as they relate to both the contractor and the agency should be discussed so that everyone is aware of "who, what, why, when, and how."

One of the most important items to be addressed at the preconstruction conference is job safety (as discussed further below). Safety is a legal and financial responsibility of all involved with the project, and a moral responsibility as well. Discussion of this topic should include not only the safety of those working on the job (both contractor and agency personnel), but also the safety of the traveling public. Clear responsibility for maintenance of all traffic control devices, such as signs, pavement markings, and flagging, should be delineated. The name of the contractor representative responsible for safety should be provided to the agency so that rapid and clear communications can be accomplished should safety problems occur. All personnel involved in the project must be required to comply with all safety standards applicable to the type of construction and asphalt paving work to be carried out.

ONGOING COMMUNICATION

Communication cannot stop once the preconstruction conference has concluded. The quality of the work completed and the safety of those performing and inspecting the construction are directly related to the quality of the communication between the agency and the contractor. It is important that the individuals in daily charge of the project for both the agency and the contractor meet periodically, on both a formal and an informal basis, to discuss the progress and quality of the work done to date and the schedule for future work.

Formal Meetings

The frequency of formal meetings depends on the scope and the size of the paving job. On a major project, update meetings should occur at least twice a week. Key personnel from both the agency and the contractor should be present at these meetings. The discussion should include such items as the quantity of work completed and test results obtained. The meeting should also focus on what has yet to be accomplished and the schedule for the coming weeks. Changes to be made as the work progresses, such as changes in personnel, equipment and construction methods used, and mix design, should all be discussed. Problems that have arisen and those that are anticipated should be communicated to both parties, and solutions explored.

If formal meetings are needed, they should be held on a regularly scheduled basis, such as every Monday morning at 8:00 a.m. at the project office. The meeting should be conducted jointly by the agency and the contractor and should be used as a forum for positive input to the job. A list of all individuals in attendance should be prepared, along with written minutes of the meeting. These minutes should be completed and distributed to all involved as quickly as possible.

Informal Meetings

Informal meetings should be held on a daily basis between the individuals in charge of the job for the agency and the contractor. Ideally, these meetings should occur at a regularly scheduled time, and they can be held on the job site—at the asphalt plant or at the paver. The purpose of these informal meetings is twofold. First, occurrences the day before, such as work completed, test results, and any problem areas, should be discussed and resolved. Second, the discussion should address what is expected to happen during the next several days—an update on the information exchanged at the last formal meeting.

Asphalt paving projects, like many construction projects, are not always conducted as originally scheduled. Changes occur because of problems with material supply, equipment breakdown, contractor and subcontractor schedules, and weather conditions. When such changes occur, it is important that they be communicated between the contractor and the agency. Communication is a two-way process. Daily informal meetings provide a forum for the exchange of such information.

Forms of Communication

Communications should be both oral and written. Much information can be communicated in oral form, but discussion of important information should be followed up in written form. In some cases, particularly when conditions on the project change substantially, formal letters should be written by the contractor and the agency. Often, however, an informal note can be written to confirm information already communicated orally. In addition, personnel for both the agency and the contractor should keep daily diaries of events that occur. If an occurrence is important enough to be remembered later on, it is important enough to be written down immediately after it happens so the information will be accurate and complete.

PROJECT RECORDS

Accurate and complete records are needed for all construction projects. This is true both for the project engineer and staff and for the contractor's general superintendent, plant and paving superintendents, and all foremen. Trying to reconstruct events at a later time without written notes and complete test data is usually frustrating and often results in conflicting opinions about what happened. One procedure should be followed at all times: if in doubt about whether the information is important or beneficial, write it down.

Plant Reports

The results of all daily and periodic tests conducted at the asphalt plant should be recorded. Although different forms may be used for this purpose, both project inspection personnel and contractor employees should collect essentially the same type of information. Further, contractor personnel should complete and keep their own records, even if not required to do so by the agency.

Regardless of which form is used, the following data should be shown: (*a*) project number and location information, (*b*) weather conditions, (*c*) source of materials used on the project, (*d*) job-mix formula information, (*e*) aggregate gradation and asphalt content test data, (*f*) mix test results, (*g*) amount of each material (aggregate, asphalt cement, and additives) used, (*h*) number of tonnes (tons) of asphalt mix produced, and (*i*) location on pavement where daily production was placed (see Figure 2-1). Any additional information required by agency specifications, such as the moisture content of the individual aggregate stockpiles, should also be reported on the form.

It is important to record on the form the date, time, and location of all samples taken and the name of the individual who took them. If, for example, aggregate gradation is determined from samples taken at two different locations (e.g., from the cold-feed belt and from the extracted mix), those locations must be marked on the report. Similarly, if asphalt content is normally deter-

HMA Plant QC Report

Date: ________ Test Report No: ________ Project: ____________ Time:________ Lot No: ________
Sublot No: ________ Location Mix Placed: ________ Sample Location (truck, paver, in-place): ________

Asphalt Cement

Grade ________ Source ________ Design Content ________ Measured Content ________

Test Method ________

Aggregate

Source of Aggregate (stockpiles, cold feed, extraction, ignition): ________

Washed or dry gradation? ________

Sieve Size	JMF Percent Passing	Measured Percent Passing
37.5 mm	______	______
25 mm	______	______
19 mm	______	______
12.5 mm	______	______
9.5 mm	______	______
4.75 mm	______	______
2.36 mm	______	______
1.18 mm	______	______
0.6 mm	______	______
0.3 mm	______	______
0.15 mm	______	______
0.075 mm	______	______

Aggregate	Source	% Used
1	______	______
2	______	______
3	______	______
4	______	______
5	______	______

Fine Aggregate Angularity: ________

Coarse Aggregate Angularity: ________

Percent Flat & Elongated (5 to 1): ________

Mix Testing

No. of gyrations @ Nd: ________ Laboratory Compaction Temp: ________ Bulk Specific Gravity: ________

Voids @Nd: ________ Voids filled @ Nd: ________ VMA @ Nd: ________

% Gmm @ Ni: ________ % Gmm @ Nd: ________ % Gmm @ Nmax: ________

Maximum Theoretical Specific Gravity: ________ Retained Tensile Strength (percent): ________

Sample obtained and tested by: ____________________

FIGURE 2-1 Example plant report.

mined by nuclear gauge and occasionally checked by extraction, the procedure used to measure this mix property should be recorded. Failing test results should be highlighted on the form.

Most forms should have a "Remarks" area. This portion of the form should be used to indicate any unusual occurrences or test results that took place during the day. Additional comments about the possible cause of any failing test results should be provided. Any corrective actions or changes to the mix materials, plant operating parameters, or test procedures should be indicated, as should the results of those actions or changes.

Field Compaction Report

Information on what occurred at the paving site during mix placement and compaction operations must be recorded. Again, the form of this information may differ between the paving inspector and the contractor's superintendent, but essentially the same information should be reported by both. This consistency will allow for more meaningful discussions later on if deficiencies should develop in the test results or in the performance of the mix under traffic.

The data shown on the field compaction report generally include the following: (*a*) project number and location; (*b*) type and number of tonnes (tons) of each mix placed and its exact location—layer number, thickness, lane, and station number; (*c*) the location (both transversely and longitudinally—station number) of any tests taken; and (*d*) density results obtained. An example of a field compaction report for the core method is provided in Figure 2-2. Other project information that should be recorded includes (*a*) weather conditions; (*b*) type and make of compaction equipment used by the contractor; (*c*) type, amount, and location of any tack coat material placed; (*d*) a running total of the tonnes (tons) of each mix placed on the project; and (*e*) smoothness results obtained.

All samples taken must also be clearly identified on the form to reflect the location from which the material was gathered, the time and date of the sampling, the reason the sample was taken, what quantity of material the sample represents, and the name of the person who took the sample. If a nuclear gauge was used to determine the relative density of the mix, any calibration procedures used to check the reliability of the gauge should be referenced. Any failing test results should be highlighted.

The "Remarks" area on the pavement report form should be used to report any unusual conditions or test results that occurred during the day. An explanation for any failing test results should be provided, if possible,

MARYLAND
STATE HIGHWAY ADMINISTRATION
OFFICE OF MATERIALS & RESEARCH

HMA FIELD COMPACTION REPORT - CORE METHOD

QC:___
Acceptance:___
I.A.S.T.:___
Other:___

Date Sampled:___ Contract No:___ F.A.P. No:___ Plant Location:___

Mix Design No:___ Depth:___ Laid Over:___ Cut By:___

Lot Size:___ Lot No:___ Mix Lot No:___ Mix Sublot No:___

Witnessed By:___ Tested By:___

CORE SAMPLE NUMBER	DATE & TIME TONNAGE LAID	LOCATION (Indicate Station Number per MSMT 418)	THICKNESS	MAXIMUM GRAVITY WEIGHT - GRAMS in Air	in Water	SSD in Air	VOLUME in cc	BULK SPECIFIC GRAVITY	% DENSITY	SUBLOT AVERAGE % DENSITY	PWSL =
											PAY FACTOR =
											REMARKS:

PROJECT ENGINEER: Send first 3 copies to Plant with cores.

PLANT CONTROL TECHNICIAN: Original to QA folder
First carbon to Project
Second carbon for Plant records

CORE LOT AVERAGE

STANDARD DEVIATION

Sheet ___ of ___

FIGURE 2-2 Example field compaction report.

and the steps taken to correct the problem should be noted, along with their results.

Daily Diary

All project supervisors, both agency and contractor, should be required to keep a detailed daily diary for possible later reference. This document should be used to record any changes that are made in the mode of operation of the asphalt plant or the laydown and compaction equipment. It should also document any nonroutine events that occur on the job. The daily diary can be used to document other information as well, such as a listing of visitors to the project. It should also be used to record the reasons for any delays in paving (e.g., an equipment breakdown or poor weather conditions).

For the information in a diary to be accurate and meaningful, it must be recorded shortly after the events occur. The diary should be updated at least twice a day—once around midday and again at the end of the day. If job conditions and schedules preclude making the midday entry, the events of the day should always be written down upon completion of each day's activities.

The information contained in the diary must be as detailed and complete as possible. If a conversation concerning project activity is held with other project personnel, whether agency inspection personnel or contractor employees, the date and location of the conversation should be recorded. The names and titles of any people involved in the discussion should be noted, as well as the topics addressed. If a discussion affects the progress of the project or the results obtained from the mix manufacturing and placement operations, its outcome must be stated: Who told whom to do what, and what was the reply?

The importance of the information contained in the daily diary cannot be overemphasized. Many claims and lawsuits have been settled on the basis of such information. If one party to a dispute can present information written in a timely fashion in a diary, whereas another can only rely on memory to reconstruct the events, the writer will usually have an advantage in the settlement of the disagreement. The information in the diary may also be useful for conducting follow-up research and for determining the reasons for premature failures.

SAFETY

Working around an asphalt plant can be hazardous. Operating machinery, high temperatures, noise, and moving delivery and haul trucks all add to the possibility of an accident occurring. If an individual is not trained to perform a particular function or is not paying attention to what is happening, he or she can be burned by hot asphalt mix, sprayed with hot asphalt cement, catch a hand in a piece of machinery, or be struck by a moving vehicle. Working around an asphalt paving site can also be hazardous. Those working on the pavement around the paver (e.g., the ticket taker, truck dump person, screed operator, and rakers) are susceptible to being hit by passing traffic or hurt by equipment being used in the paving operation. People can be injured by the haul trucks backing into or pulling away from the paver, as well as by compaction equipment.

The saying that "safety is everyone's business" is certainly true on an HMA paving project. From the contractor's superintendent, to the operator of the front-end loader at the asphalt plant, to the truck driver, to the raker behind the paver—every individual who works for the contractor must be continuously aware of the need to apply safe work habits. Likewise, every person who works as a representative of the agency—from the project engineer, to the inspector at the plant, to the ticket taker at the paver—must be aware of and practice safe work habits. OSHA regulations must be known, understood, and followed by each person involved in the project.

As noted earlier, communication is one of the keys to a safe work environment. Every individual involved in the project should know what is expected and how to perform the assigned tasks. Proper training in the operation of a piece of equipment is essential for its operators, for example. Retraining is necessary at frequent intervals because the longer a person continues to perform the same task, day after day, the more likely he or she is to do things by habit and ignore surrounding events.

Safety talks are a good way to start the day for both contractor and agency personnel. Several different organizations publish short, concise safety presentations that can be completed in 2 or 3 minutes. People need to be reminded that they are operating in a potentially dangerous environment at both the plant and the laydown site, and daily talks are one way of meeting this need. Further, if an unsafe work practice is noticed, corrective action should be taken immediately, even if the paving operation must be shut down until the unsafe practice has changed.

Individuals most likely to be hurt on an asphalt paving project are those who are new to this type of work. Without adequate advance training, these people do not fully understand the difference between following safe work practices and taking foolish chances. Often new employees, working for either the agency or the contractor, want to show that they are capable and can perform the tasks assigned to them. At times their enthusiasm to excel and to please others can overshadow their awareness of proper safety practices.

Needless injuries are also suffered by those who have been around the plant and the paving operations for many years and are therefore comfortable with the equipment. Sometimes these people perform their duties by habit. They typically take shortcuts because they have survived without injury for many years. Safety should be as much a part of these individuals' day as it is for those new to the job.

Constant care and vigilance are needed to prevent accidents and injuries associated with HMA. OSHA, the National Asphalt Pavement Association, state departments of transportation, and other organizations have published manuals that deal with safety at the asphalt production plant and around a paving operation. These manuals should be made available to all agency and contractor plant and paving personnel, and should be required reading. Safety is everyone's business on a construction project.

SECTION

3 Mix Design and the Job-Mix Formula

HMA has two primary ingredients: binder and aggregate. The asphalt binder is usually asphalt cement, which is obtained from the refining of crude oil. Asphalt cements are graded by one of three methods. The two methods that have been widely used are the penetration grading system and the viscosity grading system. Recently, many states and other agencies have adopted a performance grading (PG) system developed under the Strategic Highway Research Program (SHRP). The aggregate used is typically a combination of coarse and fine materials, with mineral filler added as needed. The aggregates are often available locally, from either a pit or a quarry. The mix design system determines the correct proportion of asphalt cement and aggregate required to produce an asphalt mix with the properties and characteristics needed to withstand the effects of traffic and the environment for many years.

Mix design is performed in the laboratory, generally using one of three methods. Until the late 1990s, the most common mix design method was the Marshall method, used by about 75 percent of state highway departments, as well as by the U.S. Department of Defense and the Federal Aviation Administration. A second method, used by many public agencies in the western United States, is the Hveem method. By the mid-1990s state departments of transportation began to implement the Superpave® (Superior Performing Asphalt Pavement) method of mix design, also developed under SHRP. In this method, samples are compacted with a Superpave gyratory compactor and tested for volumetric properties. Improved test and analysis procedures are under development to help predict the performance of the HMA under traffic. Test results will be analyzed to estimate the resistance of the HMA mix to fatigue failure, permanent deformation (rutting), moisture susceptibility, and thermal (low-temperature) cracking.

For an asphalt paving project, the mix design is developed by either the government agency, the contractor, or a consultant, depending on the requirements of the project specifications. Regardless of who completes the laboratory mix design phase of the job, the result of the mix design process is a job-mix formula. The job-mix formula is the starting point for the contractor in producing the asphalt mix for the project.

The properties of the asphalt cement and the aggregates used to produce an asphalt mix, as well as the above three methods of mix design, are briefly reviewed in this section. Also discussed are some of the differences that can exist between laboratory and plant-produced mixes, and differences between the job-mix formula values and the plant test results.

ASPHALT CEMENT: GRADING SYSTEMS AND PROPERTIES

Penetration and Viscosity Grading Systems

The penetration of an asphalt cement (indentation measured by a standard needle in units of 0.1 mm or 1.0 dmm) is determined at 25°C (77°F). The stiffer the asphalt (i.e., the lower its penetration), the stiffer will be the mix containing the material at a given temperature. For example, at a given temperature, a mix containing 60–70 penetration grade asphalt cement typically will be stiffer and may require somewhat more compactive effort by the rollers to achieve the desired density than will a mix made using a 120–150 penetration grade asphalt cement.

Grading of asphalt cements by viscosity is defined by a viscosity measurement at 60°C (140°F) on the material in its original (as received from the refinery) condition (termed AC) or on a binder considered to be comparable to the binder after it has passed through the hot-mix process (termed AR). In the AC grading system, a mix containing an AC-20 will be stiffer than a mix containing an AC-10 at the same temperature. Similarly in the AR grading system, a mix containing an AR-4000 will be stiffer than one containing an AR-2000 at the same temperature.

Superpave Performance Grading System

While grading systems based on penetration and viscosity have worked satisfactorily for many years, requirements have been based on tests performed at prescribed loading times and at standard temperatures not necessarily representative of in-service conditions. Limits for the tests have been based on agency experience. To provide an improved set of asphalt specifications, SHRP developed the PG system. Included in this new set of specifications are tests used to measure physical properties that can be related directly to field performance by engineering principles. Moreover, the tests are performed at loading times, temperatures, and aging conditions that represent more realistically those encountered by in-service pavements. The PG specifications help in selecting a binder grade that will limit the contribution of the binder to low-temperature cracking, permanent deformation (rutting), and fatigue cracking of the asphalt pavement within the range of climate and traffic loading found at the project site.

An important difference between the PG specifications and those based on penetration or viscosity is the overall format of the requirements. For the PG binders, the physical properties remain constant; however, the temperatures at which those properties must be achieved vary depending on the climate in which the binder is expected to serve. An example of the binder designation in this system is PG64-22. This binder is designed to resist environmental conditions in which the average 7-day maximum pavement design temperature is 64°C (147°F) or lower, and the minimum pavement design temperature is –22°C (–8°F) or higher. Details on this new grading system are well described in the Asphalt Institute publication *Superpave Series No. 1 (SP-1), Performance Graded Asphalt Binder Specification and Testing.*

Temperature–Viscosity Characteristics

Knowledge of the temperature versus viscosity characteristics of the asphalt binder is important in the production and placement of HMA pavements. At the high temperatures associated with mixing of the binder and aggregate in the hot-mix facility, the flow characteristics of the binder (as measured by viscosity) must be known to provide assurance that the binder can be pumped and handled in the facility. Similarly, in mix placement, compaction of the hot mix is influenced by the stiffness of the binder. As the binder becomes stiffer or more viscous, a greater compactive effort is required to achieve a given prescribed density. Thus in the temperature range 85°C (185°F) to about 163°C (325°F), knowledge of the relationship between temperature and viscosity is useful.

The change in viscosity with change in the temperature of a binder is referred to as the binder's temperature susceptibility. A material that is highly temperature susceptible is one that exhibits a large change in viscosity for a small change in temperature. Asphalts that have the same penetration at 25°C (77°F) may not necessarily have the same viscosity at 135°C (275°F) since their temperature susceptibility characteristics may vary. Accordingly, in the production and placement of HMA it is desirable for the contractor to have the temperature versus viscosity relationship of the binder available. It should also be noted that this relationship is required for some mix design procedures since the mix compaction temperature in the laboratory is based on a prescribed viscosity level.

As noted above, the temperature susceptibility characteristics of the binder can also influence the compaction process. A mix containing a binder with a high temperature susceptibility will stiffen more quickly with a drop in temperature than one containing a binder of lower temperature susceptibility. Thus if the temperature susceptibility characteristics of the binder in the mix change during production—for example, if a different binder source is used for the same grade—it will likely be necessary to change the compaction procedures to achieve the prescribed level of density.

AGGREGATE CHARACTERISTICS AND PROPERTIES

The characteristics of aggregates influence their properties and, in turn, affect the performance of HMA. These characteristics influence the amount of binder required for satisfactory performance and can have an effect on construction, particularly placement of HMA. The aggregate characteristics discussed in this section include surface texture and shape, gradation, absorption, clay content, and durability.

For Superpave, coarse aggregate angularity, fine aggregate angularity, clay content, and flat and elongated particles are considered consensus properties, and the criteria for these properties are set nationally. Criteria for all other aggregate properties are set by the user agency on the basis of availability of materials and experience.

Surface Texture and Shape

The aggregate's surface texture is the most important factor contributing to its frictional resistance. This characteristic also strongly influences the resistance of a mix to rutting. The rougher the texture of the aggregate, the better will be the rutting resistance of the mix. During construction, however, an HMA containing an aggregate with a rough texture will necessitate a greater compactive effort to achieve the required density than an HMA containing a smooth-textured aggregate.

The shape of the aggregate also influences the rutting resistance of a mix, with angular aggregate producing greater resistance than more rounded material. The improved resistance to rutting of angular aggregates likely results from increased surface roughness produced by crushing and to some extent from aggregate interlock. As with surface texture, the more angular the aggregate, the greater will be the compaction effort required to produce a mix with a specified degree of density.

Two tests for objectively defining the above characteristics have been selected as a part of the Superpave system—the *coarse aggregate angularity* test and the *fine aggregate angularity* test. Generally, the acceptance criteria used for these parameters are higher as the amount of traffic increases and as the mix is placed closer to the pavement surface.

Another parameter associated with shape is related to the ratio of the maximum to minimum particle dimensions; a particle is considered flat and elongated if the ratio is greater than 5. Flat and elongated particles tend to break during mixing and handling, changing the properties of the aggregate skeleton. By placing a limit on the proportion of particles with these characteristics, the potential for aggregate fracture during construction is limited.

Particle Size Distribution (Gradation)

One of the important properties of aggregates for use in pavements is the distribution of particle sizes, or gradation. Aggregates having different maximum particle sizes can have different degrees of workability. Typically, the larger the maximum size of aggregate in a given mix type in relation to the layer thickness and the greater the amount of large aggregate in the mix, the more difficult it is to compact the mix. Further, if the nominal maximum aggregate size exceeds one-third of the compacted thickness of the pavement layer, the surface texture of the mix can be affected, and the degree of density of the mix obtained by compaction may be reduced. To improve the resistance of HMA to rutting, both the proportion of coarse aggregate [retained on the 4.75-mm (No. 4) sieve] and the maximum particle size may be increased.

Although a relatively minor factor for most mixes in comparison with the other aggregate characteristics, the maximum particle size can be a significant factor in the properties of the HMA when large-stone [greater than 25 mm (1 in.) nominal maximum size] mix is being produced. This is particularly true with regard to density, and a field compaction test strip may be necessary to determine the degree of density that can be achieved in the large-stone mix.

Gradation is generally controlled by specifications that define the distribution of particle sizes; examples were shown earlier in Figure 1-1. The grading charts of Figure 1-1 represent the conventional way of displaying aggregate gradations—the 0.45 power plot. The abscissa is particle size plotted to a 0.45 power scale, while the ordinate is usually the percent by weight passing a given size on an arithmetic scale.

A grading chart of this type, developed by the former Bureau of Public Roads (BPR) [now the Federal Highway Administration (FHWA)] in the early 1960s is shown in Figure 3-1. This chart is based on work by Nijboer (*1*) and confirmed by BPR staff (*2*). Nijboer experimented with aggregate gradations represented by an equation in which the percent passing a given size is equal to a constant times that size raised to the power n. For maximum density, the value of n was determined experimentally to be 0.45. Thus the grading chart shown in Figure 3-1 is a plot of the sieve opening raised to the 0.45 power, and the ordinate is the percent passing plotted to an arithmetic scale. On this chart, the maximum density grading for a particular maximum size corresponds to a straight line drawn from the origin to the selected maximum particle size. The line shown in Figure 3-1 represents the maximum density gradation for an aggregate with a 25.0-mm (1.0-in.) maximum size. This form of representing the gradation of an aggregate has been incorporated into the Superpave mix design method. It must be noted that this maximum density line is approximate but can serve as a useful reference in proportioning aggregates.

To avoid confusion, the Superpave method uses the following aggregate size definitions:

- *Maximum size*—one sieve size larger than the nominal maximum size.
- *Nominal maximum size*—one sieve size larger than the first sieve to retain more than 10 percent by weight.

In the Superpave method, aggregate gradation is specified by adding two features to the chart of Figure 3-1: control points and a restricted zone. The control points function similarly to specification limits (i.e., limits within which gradations must pass). The restricted zone occurs along the maximum density gradation. Figure 3-2 illustrates these features for a 19.0-mm (0.75-in.) nominal maximum size gradation.

Figure 3-3 shows the Superpave gradation requirements for a 25.0-mm (1.0-in.) maximum size aggregate, and illustrates an aggregate grading meeting the Superpave requirements and passing below the restricted zone.

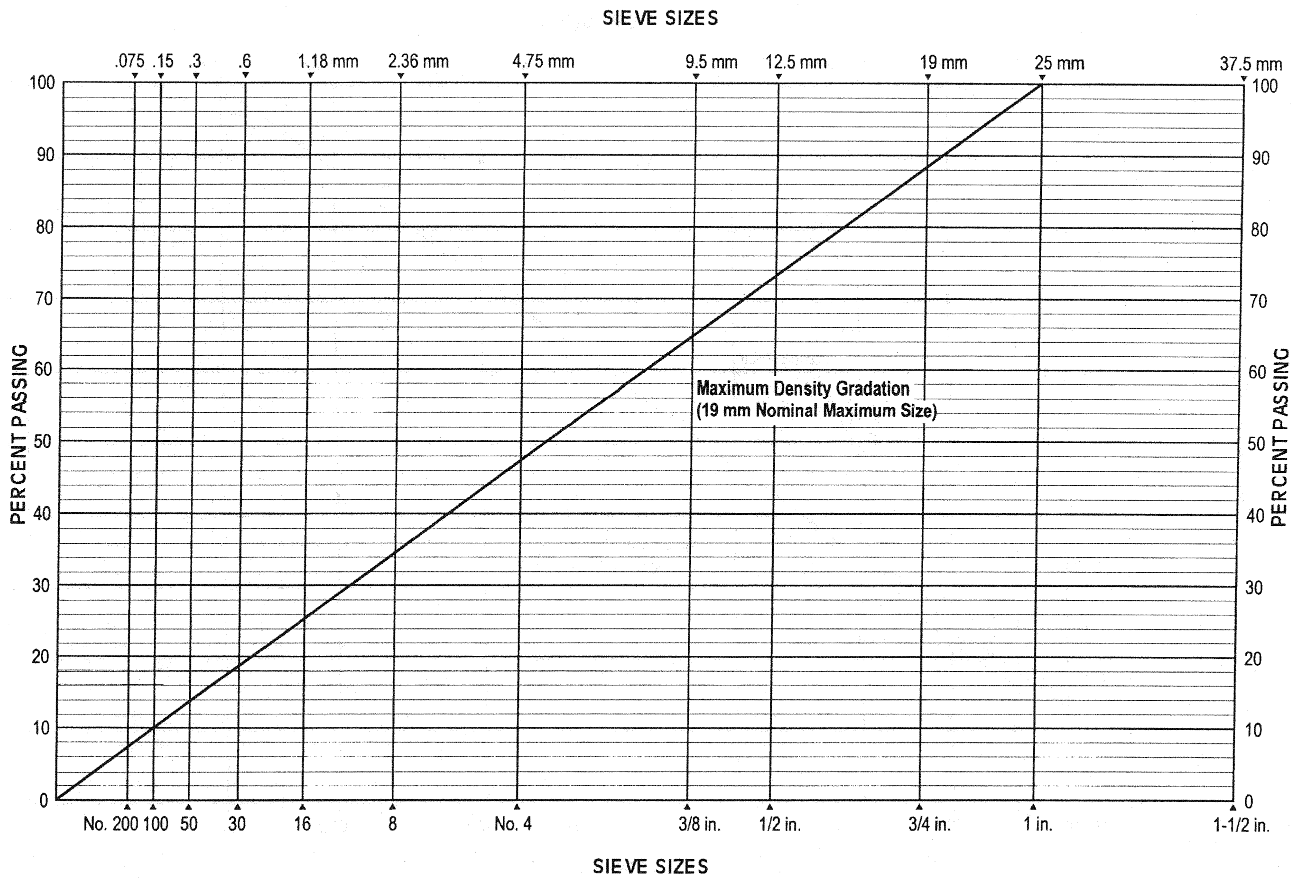


FIGURE 3-1 Gradation chart, exponential scale (n = 0.45).

The restricted zone was introduced as a guide to ensure that mixes would have sufficient voids in the mineral aggregate (VMA) to allow enough asphalt for adequate durability, since it was observed that gradations that follow the maximum density line may have, at times, lower-than-desirable VMA. Low VMA results in very little void space within which to develop sufficiently thick asphalt films for a durable mix. Another purpose of the restricted zone was to restrict the amount of natural sand in the mix. Aggregates with excessive amounts of natural sand produce HMA mixes that are tender. Some aggregate gradations that pass through the restricted zone provide mixes that perform very well in service; nonetheless, it is strongly recommended that gradations of the type illustrated in Figure 3-4—with steep slopes through the restricted zone—be avoided so as not to produce mixes that are tender and difficult to compact (*3*).

Figure 3-5 shows a schematic of the components of HMA and illustrates what is meant by the term VMA. Mixes that follow the maximum density line may have lower-than-desirable VMA according to some specification requirements. With a lower VMA, the mix may be more critical with respect to asphalt content; that is, a small increase in asphalt content above the design value may lead to a significant reduction in resistance to rutting. When such mixes are used, control of the binder content during construction is extremely important.

The amount and size distribution of the material passing the 0.075-mm (No. 200) sieve, sometimes referred to as "fines content," influence the compactibility of an asphalt–aggregate mix. Mix with a low fines content may be difficult to compact. Increasing the fines content will cause the stiffness of the mix to increase, enabling the mix to become dense under the roller rather than "shove around." However, too much material in this size range may also affect the compactibility of the mix. Accordingly, the Superpave method places a limit on the dust proportion, or the computed ratio of the percent passing the 0.075-mm (No. 200) sieve to the effective asphalt content (expressed as a percentage of the weight of the total mix). [Effective asphalt content is the total asphalt content less the pro-

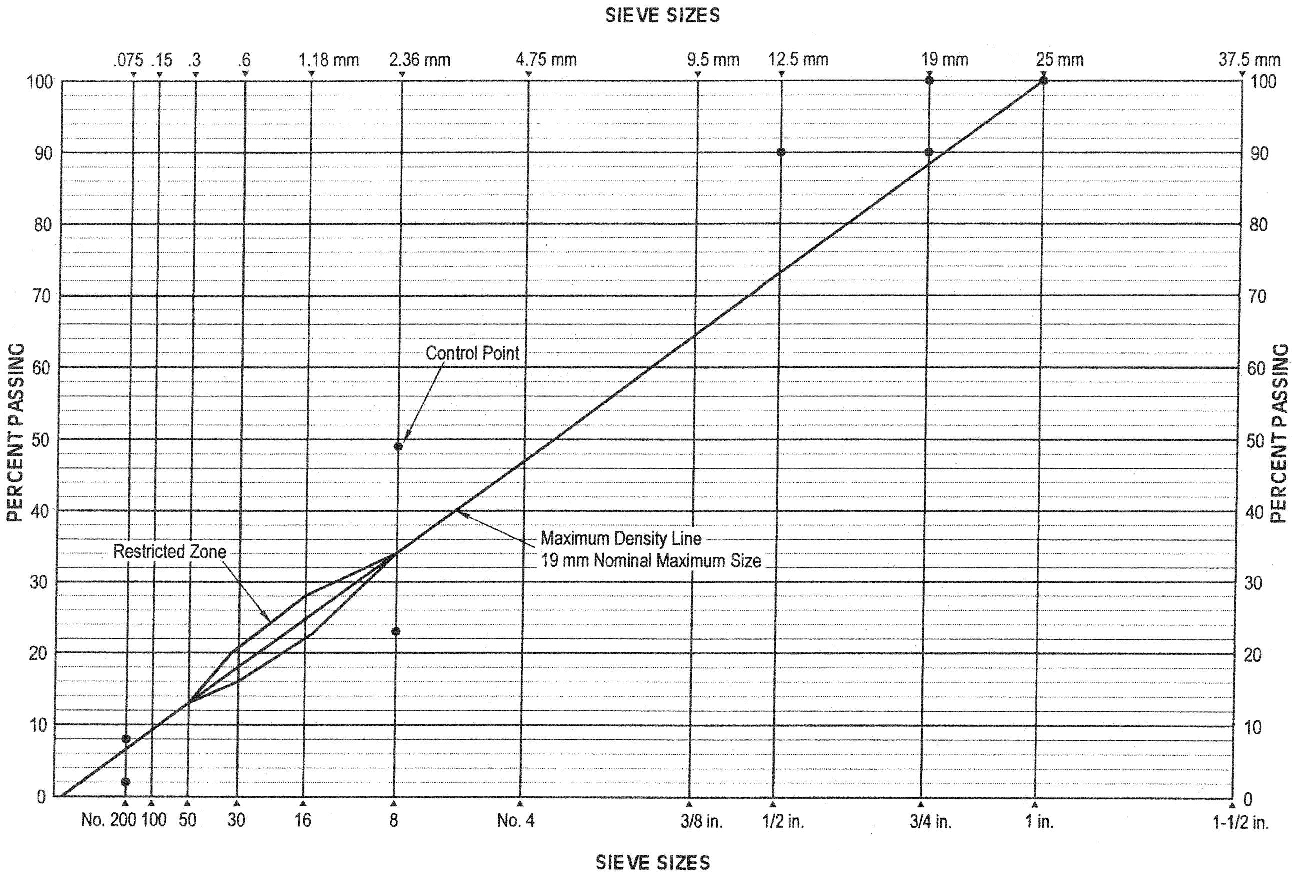


FIGURE 3-2 Control points and restricted zone for aggregate gradation with 19-mm nominal maximum size.

portion (percentage) of asphalt absorbed by the aggregate.]

The size distribution of the material passing the 0.075-mm sieve influences the stiffness of the binder dust mixture as well and therefore may also affect the compactibility of the mix. For the same asphalt, if the majority of the fines are smaller than 0.020 mm (20 microns), the stiffness of the binder will be greater than if the majority of the fines are in the range of 0.075 to 0.020 mm. Gradation of the material smaller than 0.075 mm (No. 200 sieve) alone may not indicate the stiffening effect of fines.

Absorption

The amount of asphalt cement that is absorbed by the aggregate can significantly affect the properties of the asphalt mixture. If the aggregate particles have high asphalt absorption, the asphalt content in the mix must be increased to compensate for binder material that is drawn into the pores of the aggregate and is unavailable as part of the film thickness around those particles. If that asphalt content adjustment is not made, the mix can be dry and stiff, the amount of compactive effort needed to achieve density in the mix will need to be increased, and the mix will have a tendency to ravel under traffic. If absorptive aggregates that have a high water content are used, extra time will be required in the production of HMA to ensure that the moisture in the pores can evaporate. Otherwise, the asphalt may not be properly absorbed, leading to compaction difficulties.

Clay Content

The presence of clay in the fine aggregate [material passing the 4.75-mm (No. 4) sieve] can have a detrimental effect on the water sensitivity of an asphalt concrete mix. For example, clay minerals coating ag-

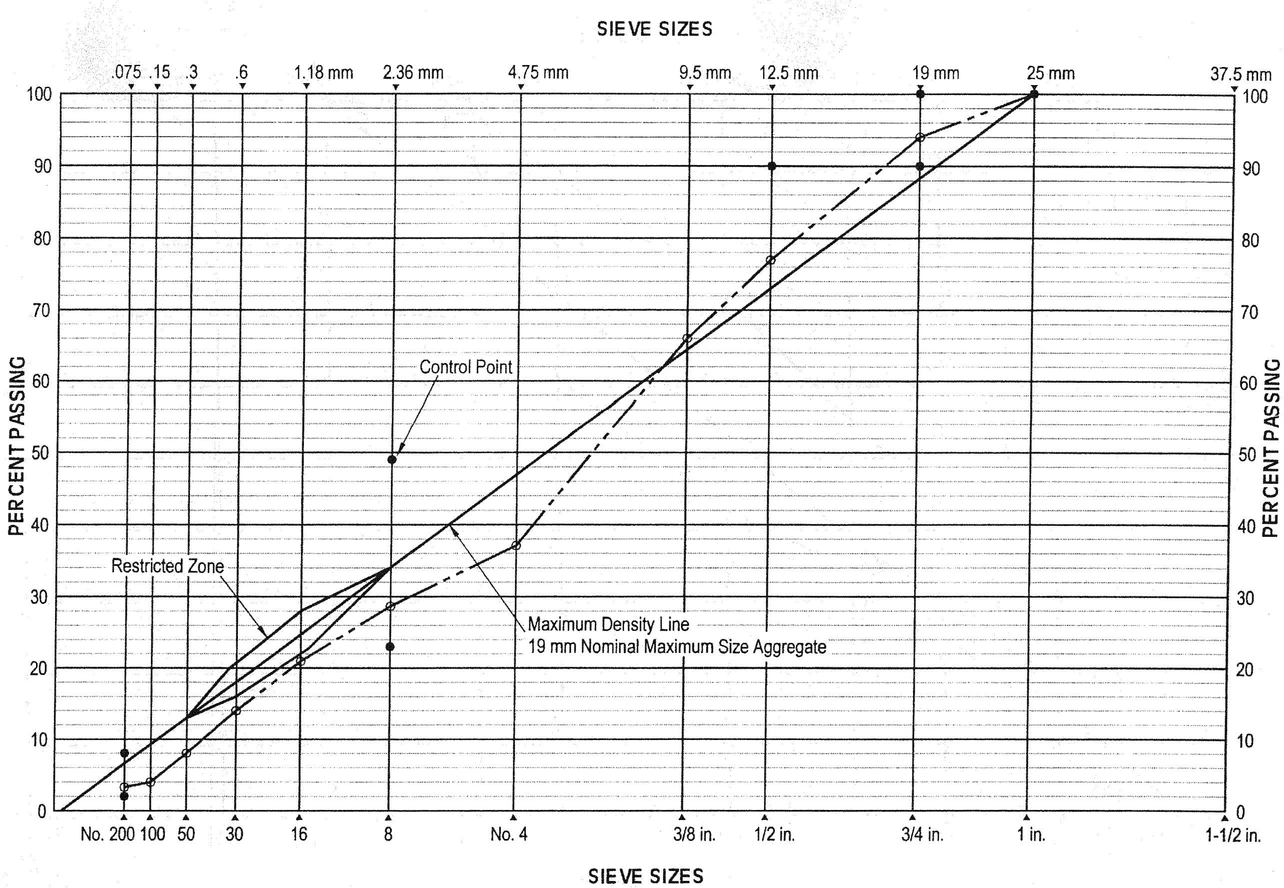


FIGURE 3-3 Aggregate grading meeting Superpave criteria and passing below restricted zone.

gregates can prevent asphalt binders from thoroughly bonding to the surface of aggregate particles, increasing the potential for water damage to the paving mixture. The sand equivalent test is used to limit the presence of clay material in the aggregate.

Additional Factors Affecting Durability

To mitigate the degradation (production of fines) of aggregate during the production and placement of HMA, the Los Angeles abrasion test is used. By setting a maximum abrasion loss in this test, aggregate degradation is presumed to be limited.

In areas where freezing and thawing occur, the sodium or magnesium soundness test is used. By setting a maximum value in terms of aggregate degradation, the resistance of aggregate breakdown from freeze–thaw cycles is improved. In this regard, it should be noted that limits placed on the water absorption of aggregates also assist in reducing freeze–thaw damage.

Limits are also placed on the amount of deleterious materials in the aggregate—defined as the percent by weight of undesirable contaminants, such as clay lumps, soft shale, coal, wood, or mica.

MIX DESIGN PROCEDURES

To produce an asphalt mix design, asphalt binder and aggregate are blended together in different proportions in the laboratory. The resulting mixes are evaluated using a standard set of criteria to permit selection of an appropriate binder content. The type and grading of the aggregate and the stiffness and amount of the asphalt binder influence the physical properties of the mix. The design (or optimum) binder content is selected to ensure a balance between the long-term durability of the mix and its resistance to rutting (stability), as illustrated in Figure 3-6 (*4*). This section provides a brief introduction to each of the three mix design procedures.

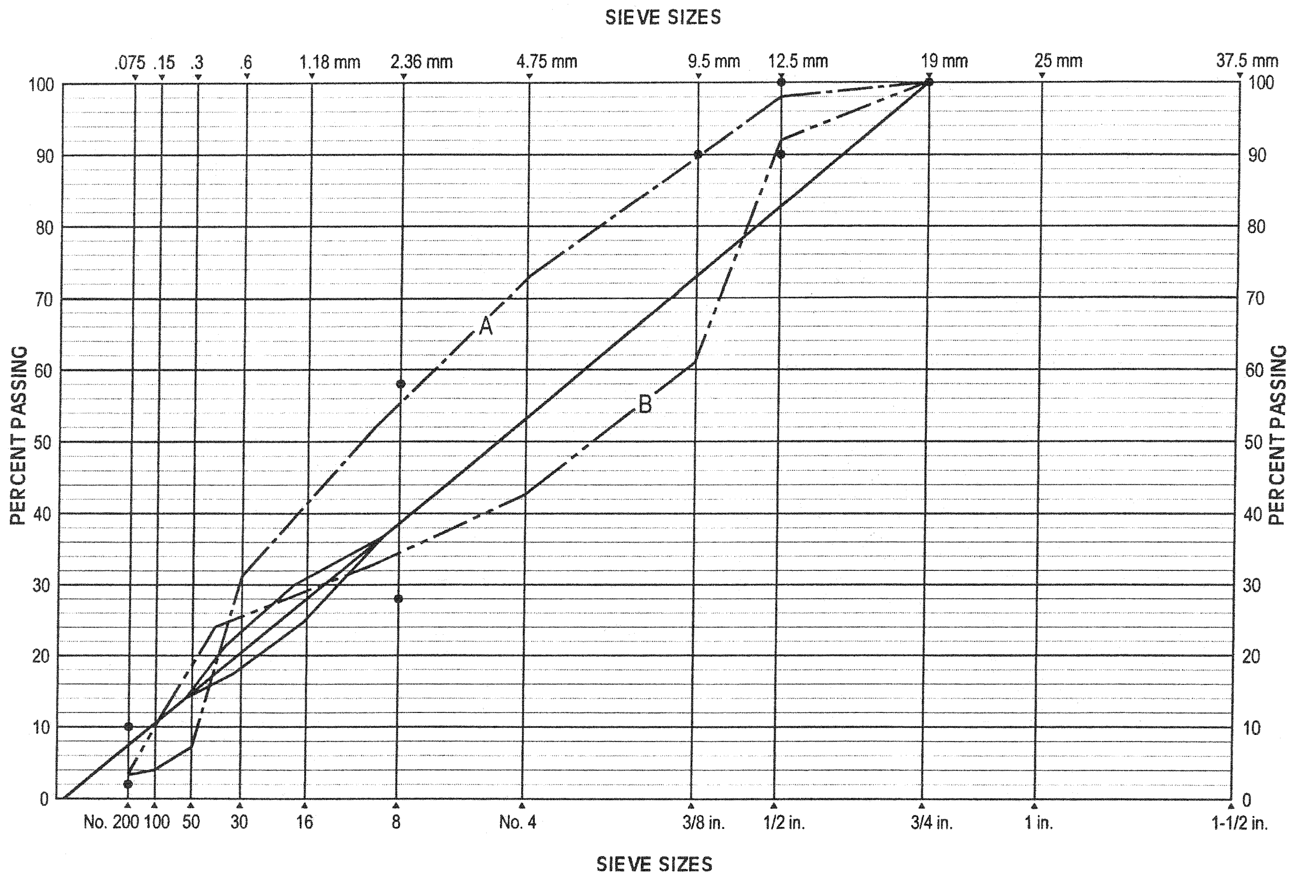


FIGURE 3-4 Examples of aggregate grading that is likely to produce tender mixes.

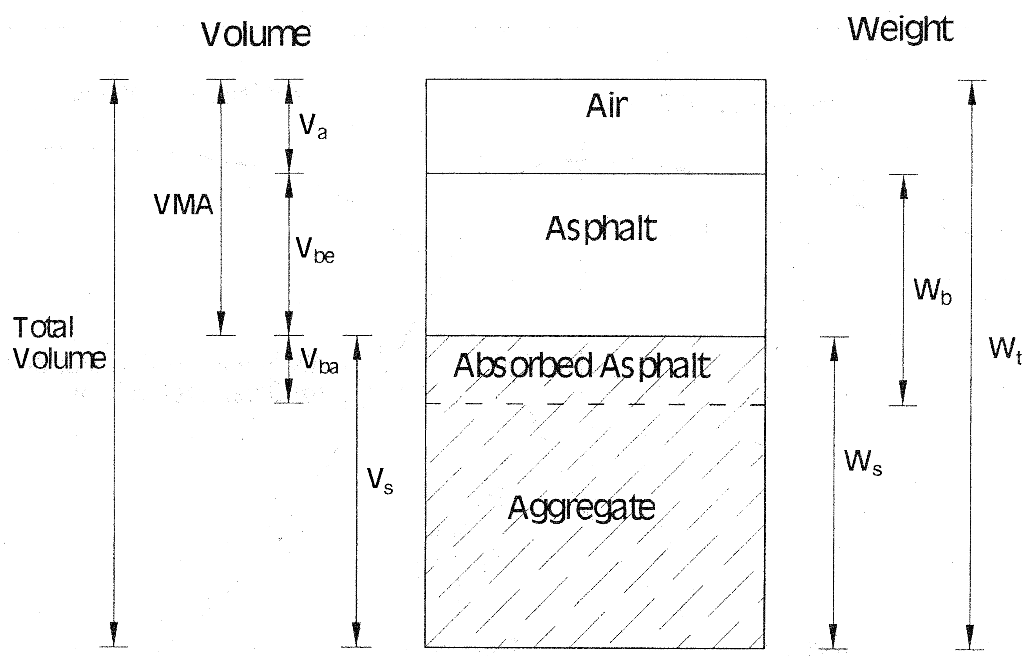
Marshall Method

The Marshall method resulted from developments by the U.S. Army Corps of Engineers (USACE) for a mix design procedure for airfield pavements during World War II and subsequent modifications (*5,6*). At the time of publication the method was being used by USACE for military airfield pavements and by the Federal Aviation Administration for both commercial and general aviation airfield pavements. The procedure was adapted, in modified form, by the Asphalt Institute for the design of mixes for highway pavements (*7*), and through the 1990s was used by many highway organizations, both in the United States and abroad. Many organizations have made minor changes to the method and have developed their own criteria.

For airfield pavements, mixes are prepared over a range of binder contents using impact compaction (ASTM D1559). The compactive effort is dependent on the tire pressure(s) of the aircraft using the facility. For commercial airfields subjected to aircraft with tire pressures on the order of 1400 kPa (200 psi), 75 blows of the compaction hammer per side are used to compact the laboratory test specimens. This compactive effort has been selected to produce densities representative of those resulting from repeated traffic loads.

The design procedure includes a density-voids analysis of the compacted specimens to determine the percent air voids and percent voids filled with asphalt (VFA). After these determinations, the specimens are tested at 60°C (140°F), and the Marshall stability (maximum load observed in the test) and flow value (deformation corresponding to the maximum load) are obtained.

Data resulting from these mix evaluations are plotted as a series of curves and include (*a*) density versus asphalt content, (*b*) percent air voids versus asphalt content, (*c*) percent VFA versus asphalt content, (*d*) Marshall stability versus asphalt content, and (*e*) flow value versus asphalt content. The design asphalt content is determined as the average of the four contents selected corresponding to the peak density, 4 percent air voids, 75 percent VFA, and maximum Marshall stability. This asphalt content is then checked to ensure that the resulting air void content and percent VFA fall within prescribed limits, that the Marshall stability exceeds a



V_a = volume of air
V_{be} = volume of effective binder
VMA = voids in mineral aggregate
V_{ba} = volume of absorbed binder
V_s = volume of mineral aggregate

W_t = total weight of mix
W_b = weight of binder in mix
W_s = weight of mineral aggregate in mix

FIGURE 3-5 Components of hot-mix asphalt.

specified minimum level, and that the flow value does not exceed a prescribed maximum value. Selection criteria established for this methodology were the result of controlled loads on test tracks and observations of the in-service performance of mixes for a range of aircraft loads and environmental conditions.

For highway pavements, variations on the methodology developed by USACE are used. For example, in the Asphalt Institute procedure (*7*), the binder content corresponding to 4 percent air voids is selected (on the basis of a compactive effort representative of the traffic to be applied). Compactive efforts range from 35 to 75 blows per side for traffic ranging from light to heavy. Other mix properties, including the Marshall stability, flow value, and VMA, are then checked to determine whether specified criteria have been satisfied.

Hveem Method

This method, developed by F. N. Hveem of the California Division of Highways (now Caltrans), has been used by that organization since the early 1940s (*8,9*). Other highway agencies, particularly in the western United States, have adapted this procedure to their own requirements. As is the case with the Marshall method, actual design criteria vary among organizations using this method, although the equipment for mix evaluation is essentially the same. The design philosophy embodied in this procedure is as follows: (*a*) stability is a function primarily of the surface texture of the aggregate; (*b*) optimum asphalt content is dependent on the surface area, surface texture and porosity of the aggregate, and asphalt stiffness; and (*c*) if required, the design asphalt content is adjusted to leave a minimum of 4 percent calculated air voids to avoid bleeding or possible loss of stability.

Kneading compaction (ASTM D1561) is used to prepare specimens for laboratory testing over a range of asphalt contents. The compactive effort was established to produce densities considered representative of those obtained under traffic soon after construction.

The Hveem stabilometer, a closed-system triaxial compression test, provides the key performance measure in this method. Mix specimens are tested in this device at 60°C (140°F) over a range of binder contents,

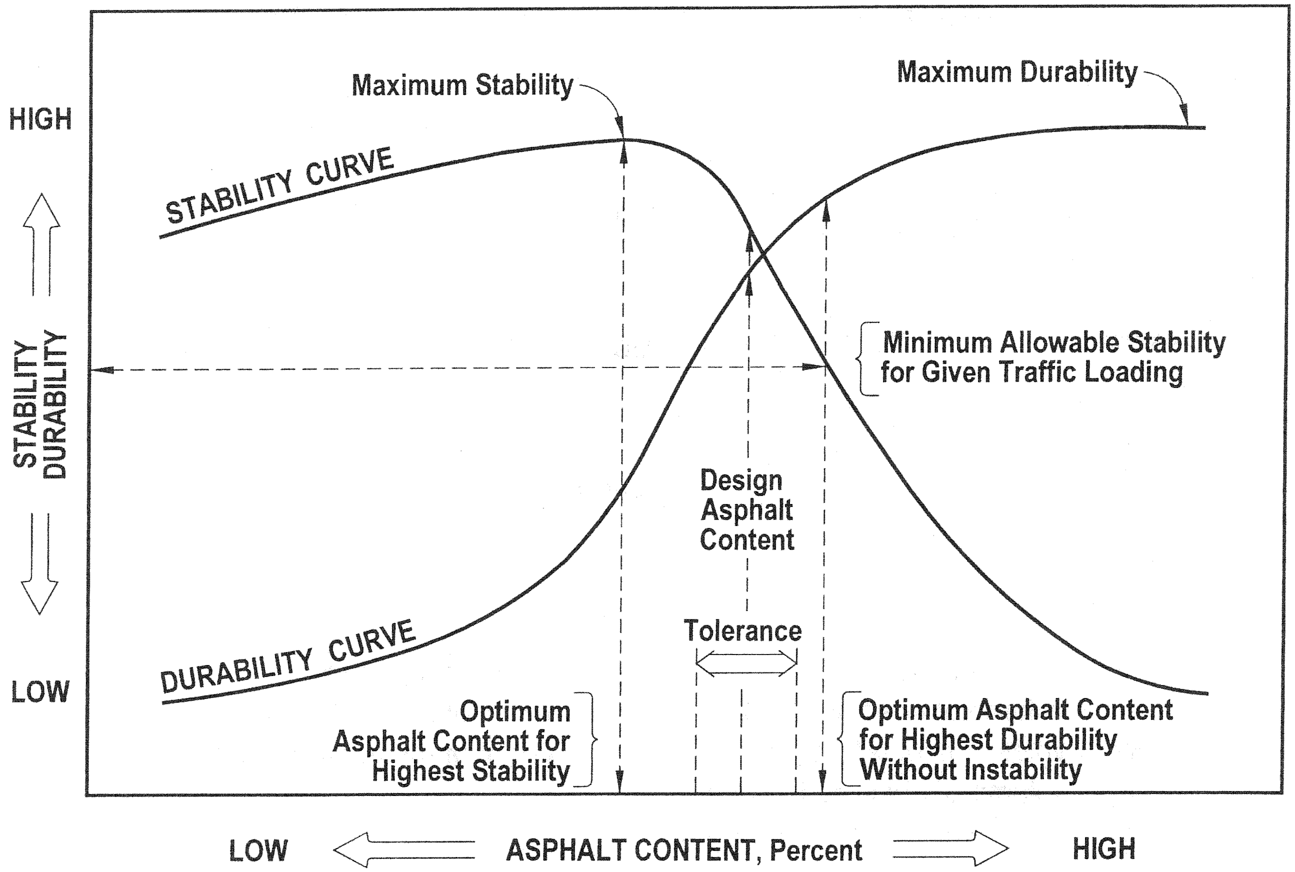


FIGURE 3-6 Schematic of stability–durability relationship of hot-mix asphalt, illustrating philosophy of selecting design asphalt content.

and a stability curve as a function of asphalt content similar to that shown in Figure 3-6 is produced. By setting a minimum level of stability consistent with the applied traffic, the design asphalt content is selected in a way similar to that illustrated in Figure 3-6. For the same aggregate and asphalt cement, design binder contents selected with this procedure generally tend to be slightly lower than those obtained using the USACE 75-blow Marshall procedure.

Superpave Method

The Asphalt Institute publication *Superpave Mix Design (10)* is an excellent source of information on the Superpave procedure, as is *The Superpave Mix Design Manual for New Construction and Overlays* (*11*). As originally conceived, the method included both a volumetric design procedure and performance tests on the resulting mix or mixes obtained from the volumetric design. As of this writing, only the volumetric procedure was being used since the performance tests and their use for predicting in situ performance were undergoing further evaluation.

The volumetric mix design is accomplished in four steps: (*a*) selection of component materials, (*b*) selection of design aggregate structure, (*c*) selection of design asphalt content, and (*d*) evaluation of moisture susceptibility. Selection of the component materials includes selection of the appropriate binder performance grade and aggregate with requisite characteristics for the traffic applied. As noted earlier, both the high temperature and low temperature at the pavement site establish the binder grade to be used. Aggregate characteristics include coarse aggregate angularity, fine aggregate angularity, flat and elongated particles, and clay content. Design requirements for the aggregate increase as the traffic, expressed in equivalent 80-kN (18,000-lbf) single-axle loads (ESALs), increases.

The aggregate gradation is specified using the 0.45 power gradation chart; an example of a grading meeting Superpave criteria was shown earlier in Figure 3-3.

Three trial blends are normally evaluated. In locations with limited previous experience, more than three trial blends may be needed. In locations with a long and uniform history, only one trial blend may be needed. Selection of the design aggregate structure, the second step in the mix design procedure, is made on the basis of the properties of specimens compacted with the Superpave gyratory compactor.

For each of the blends, a trial asphalt content is used that is either calculated to produce 4 percent air voids at a design number of gyrations in the Superpave gyratory compactor or selected based on experience. The design number of gyrations, $N_{design,}$ is established as a function of traffic (design ESALs) and climate (air temperature). Heavily trafficked pavements require a relatively high N_{design}, while low-volume pavements require low N_{design}. Because the asphalt content used during this step is merely a trial value, 4 percent air voids is rarely achieved at $N_{design.}$ Accordingly, the compacted properties of each trial blend are evaluated to estimate an asphalt content that would produce 4 percent air voids. The following parameters are then estimated for each of the trial blends:

- VMA at N_{design},
- VFA at N_{design},
- Percentage of maximum theoretical density at $N_{initial}$,
- Percentage of maximum theoretical density at $N_{maximum}$, and
- Dust proportion.

The parameter $N_{initial}$ is calculated from N_{design}. $N_{initial}$ represents mix response during initial compaction, as in breakdown rolling. A high density at $N_{initial}$ is generally considered undesirable since it is likely that the mix would compact very easily, and thus could be susceptible to rutting. Although some data indicate this, it is not always true. A high density at $N_{maximum}$ is also considered undesirable since $N_{maximum}$ represents a traffic level much higher than that for which the project is designed. By limiting the density at $N_{maximum}$, it is expected that the mix will not densify to extremely low air voids with unexpectedly high traffic.

The trial blends are compared with established criteria, and a blend estimated to meet the criteria is selected. This blend is termed the design aggregate structure. To determine the design asphalt content, trial specimens are compacted at $N_{design,}$ with the design aggregate structure at four different asphalt contents bracketing the estimated asphalt content (usually duplicates at each asphalt content).

Volumetric properties of the compacted mix (e.g., air voids, VMA) are determined for the four asphalt contents. The design asphalt binder content is selected to achieve 4 percent air voids at N_{design}. Usually, the design asphalt binder content is within 0.1 to 0.2 percent of the estimated binder content from the previous step. After the design aggregate structure and design asphalt binder content have been established, the moisture susceptibility of the design mix is evaluated using AASHTO T283.

In the original Superpave method for high traffic loads, the intent was to subject the design mix (or mixes) to performance tests, including the simple shear test and the indirect tensile test. As noted earlier, this portion of the methodology is under review, and any guidelines must await the results of this evaluation.

LABORATORY AND PLANT-PRODUCED MIXES

As noted earlier, differences may exist between the properties of an asphalt mix designed in the laboratory and the "same" job-mix formula produced in a batch or drum-mix plant. It is important to examine those differences and understand how and why the test properties or characteristics of a mix produced in a plant may vary significantly from the results predicted by tests conducted on laboratory-produced material.

Asphalt Cement Binder

In an asphalt cement storage tank, the binder is held in bulk and usually is circulated continuously by a pump. Minimal aging and hardening occur during storage. In the laboratory, the asphalt cement can be heated in an oven for various periods of time. Laboratory samples may undergo more aging because they are usually handled in small quantities in open containers. Sometimes modifiers are added in the field and are not evaluated during the mix design phase. In these cases, the laboratory- and plant-produced mix properties may vary. Therefore, it is recommended that all the materials used in the field also be used in the laboratory mix design.

Laboratory mixing of asphalt and aggregate is done either by hand or by means of a mechanical mixer, and mixing times may vary. After mixing, the loose mix is aged to allow for asphalt absorption and, presumably, some additional stiffening. The Superpave method incorporates an aging time (termed short-term oven aging) to produce a mix stiffness comparable to that which will exist early in the pavement life, usually less than 1 year.

Aggregate

The Superpave method requires washed sieve analysis of all fractions, including filler. As the aggregate passes through a batch plant dryer or drum mixer, its gradation is usually changed to some degree. The amount of the change (an increase in the amount of fines in the mix) is a function of many variables, but is related primarily to the hardness of the aggregate. As the abrasion resistance of the aggregate decreases, the amount of fines generated inside the dryer or the drum normally increases. For a hard, durable aggregate, the amount passing the 0.075-mm (No. 200) sieve may increase no more than 0.2 percent when processed. If a soft aggregate is used, the amount of the aggregate passing the 0.075-mm (No. 200) sieve may increase by as much as 1 or 2 percent.

All materials will vary in gradation from the average value for the percent passing each sieve. This variation is recognized by assigning allowable tolerance values to each sieve size. Thus the aggregate in the cold-feed bins can be expected to fall within a range of gradations instead of conforming to an exact gradation. In the laboratory, however, the aggregate is sieved into many different fractions and then recombined to an exact gradation curve. The degree of precision in the laboratory is significantly greater than that in an asphalt batch or drum-mix plant.

The aggregate used to make laboratory samples is completely dry—there is essentially no moisture in the material. For aggregate heated in a batch plant dryer or in the dryer on a counter-flow drum-mix plant, it is possible to reduce the moisture content to about 0.1 percent by weight of the aggregate, but in most cases the moisture content in the aggregate will range up to 0.5 percent, depending on the amount of moisture in the incoming aggregate, the production rate of the dryer, and the aggregate discharge temperature. Rarely will the aggregate discharged from a typical dryer have no retained moisture. For aggregate processed through a parallel-flow drum-mix plant, the moisture content in the mix at discharge typically is less than 0.2 percent but can be higher, depending on the same variables as for the batch plant. Although there should be no more than 0.5 percent moisture retained in the plant-produced mix, there will be differences in the amount of moisture between the laboratory- and plant-produced mixes. The amount of moisture retained in the plant-produced mix can have a significant effect on the tenderness of the mix and the ability to densify the HMA under the compaction equipment.

In the laboratory, oven heating usually results in uniform heating of both the coarse and fine portions of the aggregate. In the plant dryer or drum mixer, the coarse aggregate usually is heated to a lower temperature than is the fine aggregate, and there is often a distinct temperature differential between the two fractions of aggregate. In a batch plant, the temperature is generally equalized during pugmill mixing. In a parallel-flow or counter-flow drum-mix plant, however, a heat balance is not always obtained unless the material is held in the surge silo for a period of time.

If a wet scrubber is used on either a batch or drum-mix plant, any fines captured are carried out of the dryer or drum mixer and wasted. These fines are no longer part of the aggregate gradation. If a baghouse is used as the emission-control device on either type of plant, some or all of the collected fines can be returned to the mix. If the fines from the baghouse are wasted, a slightly different aggregate gradation will exist in the mix, similar to that which occurs when the plant is equipped with a wet scrubber system. If all of the baghouse fines are returned to the mix, the gradation of the aggregate still may be different from that tested in the laboratory because of aggregate breakdown in the plant. Thus the type of emission-control equipment used on the batch or drum plant can significantly affect the properties of the asphalt mixture. The amount of fines can change the dust-to-asphalt ratio, and thus the stiffness of the resulting asphalt mix. The change in the type and amount of fines normally is not taken into account in the laboratory mix design procedure. However, some mix designers add baghouse fines to the mix during the mix design process to simulate the mix gradation after breakdown of material in the plant.

Baghouses operate at different efficiencies, depending on the pressure drop between the dirty and clean sides of the filter bags. If the bags are clean and the pressure drop is small, the fines-laden exhaust gases pass through the fabric filter, and some of the very fine particles pass through the plant stack. As the bags become more heavily coated with material and the pressure drop increases, more of the fines are captured on the coating already on the bags. Thus as the loading on the bags is increased, the baghouse actually becomes more efficient, and a greater volume of fines, as well as a finer gradation of material, is returned to the mix in either a batch or drum-mix plant. The change in the amount of fines captured and sent back to the plant can be substantial.

If the plant is equipped with only a dry collector (knockout box or cyclone), most of the fines returned to the mix will be larger than the 0.300-mm (No. 50) sieve. With the use of a fabric filter, particles as small as 5 microns (smaller than the asphalt cement film thickness on the aggregate) can be reincorporated into the mix. These ultra-fine particles can have an influence on mix response during the construction process. Further, the baghouse fines must be returned consistently and uniformly to the plant for incorporation into the mix.

If reclaimed asphalt pavement (RAP) is incorporated into the mix, it is normally mixed in the laboratory until thoroughly heated and blended with the new aggregate. In the plant, however, the degree of mixing and the transfer of heat from the new aggregate to the reclaimed material are functions of many variables, such as the amount of RAP in the mix, the point of introduction of the RAP, the temperature of the new aggregate, and the amount of mixing time available. Blending of RAP with the new aggregate differs for a batch plant, a parallel-flow drum-mix plant, and a counter-flow drum-mix plant. Blending of the RAP with the new aggregate in the laboratory, however, is always the same, regardless of the type of plant that will be used to manufacture the HMA mix.

In the laboratory, the RAP used in the mix design process may be a representative sample of the materials to be recovered from the paving project. In most instances, however, the aggregate gradation and asphalt content of the RAP actually incorporated into the mix may vary from the values obtained from the representative sample. The milling and processing to reclaim material may add a significant amount of fines [percent passing the 0.075-mm (No. 200) sieve] to the mix. The extent of this expected variability needs to be considered during the laboratory mix design process.

Mixing Process

As the mix time increases in a batch plant pugmill, the degree of aging of the asphalt binder also increases. For relatively short wet-mix times (28 to 35 seconds), the average asphalt cement will decrease 30 to 45 percent in penetration and increase roughly the same percentage in viscosity. For longer wet-mix times (up to 45 seconds), the penetration of the asphalt cement may be up to 60 percent below the original value, while the viscosity of the binder material may increase up to 4 times its original value. Higher mixing temperatures may substantially increase the degree of hardening of the asphalt cement. Thus the mix produced in a batch plant pugmill can be much stiffer than the same material produced in the laboratory with essentially unaged asphalt. For the Superpave mix design method, the degree of plant hardening is simulated by subjecting the mix to short-term aging prior to compaction.

The amount of hardening of the asphalt cement that occurs in a drum-mix plant may be less, more, or the same as that in the pugmill of a batch plant. The degree of hardening is quite variable and is a function of the composition and thickness of the asphalt cement film around the aggregate particles, as well as many other factors. Less hardening generally occurs during the coating process as the moisture content of the incoming new and reclaimed aggregate increases, as the volume of aggregate in the drum increases, as the mix discharge temperature decreases, and as the production rate of the plant increases. Further, much less hardening of the binder material will occur in a counter-flow drum-mix plant than in a parallel-flow drum-mix plant. Even with the aging procedure used in the Superpave mix design method, the correlation between the degree of aging of the binder processed in a drum-mix plant, particularly a parallel-flow drum mixer, and the aging of the binder during the short-term aging procedure is only approximate.

The laboratory mixing process is accomplished by hand or by machine, with the time necessary to blend the asphalt cement and aggregate depending on the efficiency of the mixing process. Usually several minutes is required to obtain complete coating of the aggregate. During this period, the asphalt cement is exposed to the air, and some hardening takes place. The degree of hardening is a function of the aggregate temperature and the mixing time. The change in asphalt cement properties will differ from that which will occur during mix production in a batch or drum-mix plant.

Asphalt mix samples obtained from the plant or from the pavement before compaction may be sent in loose condition to a laboratory for future testing. The amount of hardening that occurs in the binder material depends on the time between manufacture and testing, as well as on the storage conditions (temperature and availability of oxygen). The process of reheating the sample, including the time and temperature of heating and any remixing of the sample, also can have a significant effect on the measured properties of the mix. Thus the laboratory handling process can affect the differences found between plant- and laboratory-prepared samples.

Compaction

Several methods, including impact compaction (Marshall hammer), kneading compaction, and Superpave gyratory compaction, are used to compact HMA specimens in the laboratory. The purpose of any laboratory compaction process is to approximate, as closely as possible, the particle orientation produced in the field by the rollers and some amount of traffic loading. Intra- and interlaboratory test results have indicated that the degree of compaction obtained in the laboratory can be highly variable, depending on the method used.

The compaction process in the laboratory is very quick, usually completed in a comparatively short time (less than 5 minutes). This contrasts with roller operations in the field, which use many different roller combinations, roller passes, and roller patterns, and in which final density levels may not be attained until 30 minutes or longer after the mix has been placed by the paver. Also, during the laboratory compaction process, the temperature of the mixture is relatively constant. In the pavement, the temperature of the material continually decreases with time. In the laboratory, the compaction effort is usually applied before the mix temperature drops to 115°C (240°F) for the Marshall and Superpave methods (depending on the viscosity characteristics of the binder material) or 105°C (220°F) for the Hveem method. In the field, the mix may cool to 80°C (175°F) before the compaction process has been completed.

In the laboratory, the asphalt mix is compacted against a solid foundation, whereas in the field a wide variety of base types and stiffnesses is encountered. An asphalt mix can be placed as part of a newly constructed pavement, as the first layer on top of a soft subgrade soil, or as the surface course on a full-depth asphalt pavement structure. The material can be used as an overlay on distressed asphalt or PC pavement. The ability to obtain a particular level of density in an asphalt mixture depends in part on the rigidity of the base being overlaid and on the type of compaction equipment used. The differences between some pavement and laboratory base conditions can be significant. A test section is necessary to establish the compactive effort and rolling pattern required to obtain a specified density in the asphalt mix.

SUMMARY

The objective of testing plant-produced asphalt mixtures is to compare the test results with the laboratory job-mix formula. An attempt is made to have the plant-produced mix equal to the laboratory job-mix formula. This is often difficult to accomplish because of all the variables that exist at the plant—from the type of plant used to the particular plant operating conditions. There are often major differences between laboratory and plant mixes—in the gradation of the aggregates, the rounding of the aggregates as they pass through the plant, the degree of hardening of the asphalt cement, and the wasting of any fines through the emission-control system. The primary causes of these differences include mixing method, moisture content, and increased fine content. In addition, compaction conditions are considerably different between the laboratory and the actual mix compaction under various rollers in the field.

The job-mix formula produced in the laboratory, therefore, should serve as an initial mix design. As discussed in the following section on quality control/quality assurance, the desired properties of the mix should be checked and verified on the plant-produced, laboratory-compacted asphalt mixture. Daily tests should be run to determine the characteristics of the mix actually being manufactured (mix verification). All of the mix values should be within the range required by the mix design process. If the test results on the plant-produced mix indicate compliance with the job-mix formula requirements, the plant should continue to operate. If one or more of the mix properties are outside the desired range, an investigation should quickly be conducted to determine the cause and extent of the deficiency. In most cases, however, the plant should not be shut down or drastic changes made in the mix design on the basis of only one set of test results. In addition, if major differences in gradation exist between the aggregate used in the laboratory mix design process and the aggregate used in the plant, the job-mix formula should be adjusted or a new mix design developed.

Problems that develop in the batch or drum-mix plant and on the pavement during the laydown and compaction process are discussed in Section 19. Some of these problems, such as checking and shoving, can be related to deficiencies in the mix design used to create the job-mix formula and to differences between the properties of the job-mix formula and the properties of the mix actually produced in the plant.

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SECTION

4 Quality Control/ Quality Assurance

Highway construction specifications are a means to an end. Their objective is to provide the traveling public with an adequate and economical pavement on which vehicles can move easily and safely from point to point. A practical specification is one that is designed to ensure adequate performance at minimum cost; a realistic specification takes account of variations in materials and construction that are inevitable and characteristic of the best construction possible today.

Transportation agencies have traditionally used method specifications for specifying and accepting HMA pavement materials and construction. With this type of specification, the methods to be used in constructing a section of pavement are stated by the agency. If the contractor adheres to the methods prescribed and adherence is verified by the inspector, 100 percent payment to the contractor is ensured. A major deficiency of method specifications is that price adjustments for contractor nonconformance are often arbitrary and based solely on the judgment of the agency inspector or engineer. Statistical concepts are seldom employed with a typical method specification, making acceptance on this basis somewhat subjective.

In the past 20 years, many agencies have moved toward specifications in which the contractor is responsible for QC and is free to choose the construction methods to be used. The desired end result is stated, and the contractor or producer is allowed the fullest possible latitude in obtaining that result. However, certain restrictions are generally included to ensure at least a minimum acceptable level of quality and to prevent extensive construction or production before defects are discovered. Thus the increased use of QC/QA specifications signifies a shift in the burden of choosing the proper construction methods and in the responsibility for QC from the agency to the contractor.

The focus in this chapter is on QC/QA under both types of specifications. First, QC and QA are defined. Method specifications and QC/QA specifications are then reviewed in turn. It should be noted that within these two broad classes of specifications there are many detailed variations, depending on the owner, and that most actual specifications combine features of both types. Note also that guidance on QC/QA for production and laydown of Superpave is provided in *NCHRP Report 409: Quality Control and Acceptance of Superpave-Designed Hot-Mix Asphalt* (*1*).

DEFINITIONS

Quality Control

The *quality* of HMA can be defined in terms of the characteristics (e.g., asphalt content, air voids, density) required to achieve a specific level of excellence (see Section 3). In the case of highway HMA materials or construction, excellence is measured according to a certain level of performance, expressed in terms of such features as durability, ride quality, and safety. *Quality control*, or *process control*, of HMA denotes mixing and placing the HMA ingredients (aggregates and asphalt) in a prescribed manner, so that it is reasonable to expect the pavement to perform properly.

The distinction between process control and *acceptance testing* is important. Acceptance testing is based on the principle of estimating the parameters of a characteristic of the lot by limited random sampling. A lot is a quantity of material (e.g., day's production run, 1,000 linear meters, 1,500 metric tons) produced under essentially the same conditions. Random sampling is a procedure whereby every portion of the lot has an equal chance of being selected as the sample. Normally the parameters estimated are the acceptable quality level and a measure of variability or spread. It is the agency's responsibility to accept the lot at full payment, incentive payment, or reduced payment, or to reject the lot entirely.

Process control, on the other hand, is the means of providing adequate checks during production (or construction) to minimize the contractor's or producer's risk of having the lot rejected. A process is said to be in control when all removable variations have been brought into tolerance. In fact, a primary purpose of process control is to eliminate assignable causes of variance so that the overall variability of the finished lot will approximate the variation used to design the sampling plan for lot acceptance. It may be said, then, that process control is an effort to maintain a given level of production with respect to both the acceptable level and the degree of uniformity, whereas acceptance testing is a check on the finished product to determine the degree to which these goals have been attained.

Many agencies currently require the HMA producer or contractor to be solely responsible for all QC activities, including performance of those tests and adjustments necessary to produce an HMA pavement that will meet all aspects of expected performance. QC includes testing and observing the quality of the aggregates purchased at the pits and quarries so that uniformity is maintained; setting the proportions at the cold feed or setting the hot-bin weights (when required), adding the correct amount of asphalt, and determining the mixing times and techniques; and determining correct laydown and proper rolling techniques. Most important, QC involves constant testing and evaluation of test results to determine whether production is in control. QC also includes the actions of plant personnel in making necessary changes and adjustments in day-to-day operations.

FHWA has adopted the following definition for QC: "all contractor/vendor operational techniques and activities that are performed or conducted to fulfill the contract requirements." AASHTO defines QC as follows: "the sum total of activities performed by the seller (producer manufacturer, and/or Contractor) to make sure that a product meets contract specification requirements. Within the context of highway construction this includes materials handling and construction procedures, calibration and maintenance of equipment, production process control, and any sampling, testing, and inspection that is done for these purposes."

Quality Assurance

A general definition for QA is those activities necessary to ensure that the quality of a product is as it should be. The phrase "to ensure the quality of a product" relates to those decisions necessary to determine conformity with specifications; the phrase "as it should be" refers to the basic engineering properties of the material or construction process.

AASHTO and FHWA define QA as "all those planned and systematic actions necessary to provide confidence that a product or service will satisfy given requirements for quality." This definition represents a view of QA as an all-encompassing concept that includes QC, acceptance, and independent assurance.

Acceptance is defined as "all the factors that comprise the owner's determination of the quality of the product as specified in the contract requirements." These factors include verification sampling, testing, and inspection, and may include results of QC sampling and testing. *Independent assurance* encompasses those activities that combine to produce an unbiased and independent evaluation of all the sampling and testing procedures used in the acceptance program. QA may be viewed as a three-legged stool, as shown in Figure 4-1. Note that QC, acceptance, and independent assurance all support the QA operation.

METHOD SPECIFICATIONS

Method specifications were probably the most widely used type of specification in highway construction until the mid-1980s. As noted earlier, with this type of specification, the agency directs the contractor to use specific methods, including materials, proportions, and equipment. The placement process is also explicitly defined, with each step being either controlled or directed, and in some cases actually performed by a representative of the agency.

Relative to HMA production, method specifications require that the component materials—asphalt cement, aggregates, and additives—be pretested and approved. The proportions of the materials and the way they are mixed are specified. Quite often the agency performs the mix design and designates the job-mix formula. The mixture must also meet other specific requirements related, for example, to air voids, stability, and flow. In the extreme case, the specification can be considered an equipment and labor rental specification. To illustrate, for HMA compaction, the agency might tell the contractor what equipment to use, when to roll, and how many passes to make with each roller.

Method specifications have evolved with experience and reflect a lack of quick acceptance tests for assessing the quality of materials and construction. In most instances, the QC and acceptance decisions are based on individual test results. Terminology such as "substan-

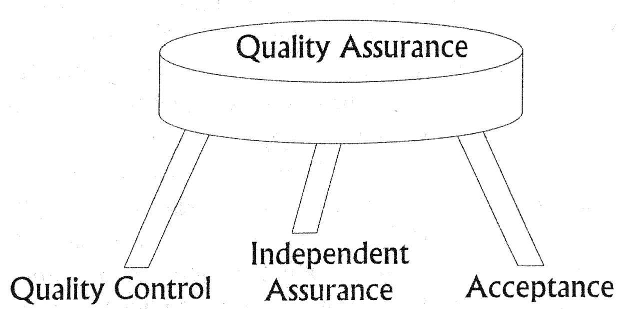

FIGURE 4-1 Elements of quality assurance.

tial compliance" and "reasonably close conformity" is associated with method specifications. For example, one agency's HMA specification states:

> If at anytime during the course of the work any of the asphalt determinations, gradations and Marshall criteria are not being met as specified herein, or in the case of persistent or recurrent deviations for any one of these characteristics, the contractor shall, when so directed, make any necessary changes in the [job-mix formula], in materials, or equipment to be within reasonably close conformity with these requirements.

Advantages and Disadvantages of Method Specifications

Method specifications offer an advantage when a measure of quality is particularly difficult to define. Asphalt-mix segregation is one such case. Segregation is an undesirable feature, but the allowable degree of segregation is difficult to measure or to specify. Thus, method specifications can be used to specify what a contractor must do to prevent segregation.

Method specifications have a number of disadvantages, however:

- Contractors may not be allowed to use the most economical or innovative procedures to produce the product.
- Inspection is labor-intensive.
- If the quality of the product is measured and found to be less than desirable, the contractor has no legal responsibility to improve it.
- The agency assumes the bulk of the specification risk.
- The quality attained is difficult to relate to the performance of the finished product.

The major weakness of this type of specification is that there is no assurance it will produce the desired quality of construction. Most important, by explicitly specifying the material and procedures, the owner or agency obligates itself to a large degree to accept the end product. Such a specification is also very difficult to enforce uniformly. The terms "reasonably close conformity" and "substantial compliance" cannot be precisely defined. In the absence of a clearly established quality level and a uniform means of measuring compliance, decisions become arbitrary, and acceptance procedures become inconsistent in their application. Limits are usually based solely on subjective judgment or experience and are often difficult to meet because of the lack of definition of the capabilities of the production process and the desired product.

Contractor Quality Control Activities

Many paving projects have been carried out successfully with method specifications. Every successful HMA contractor controls the quality of the hot mix throughout the production process. Testing to ensure quality begins with raw aggregates and ends with finished pavement. Each test has a place in the overall control system, from designing the job mix through proportioning, mixing, and placing the HMA.

Plant Control of Aggregate

Design qualities are the main consideration when selecting aggregates for a job-mix formula. The decision concerning which aggregate to use is based solely on test data originating at the source pits or quarries, long before the material reaches the mix production plant. The general characteristics and physical properties of aggregates for HMA surface and base courses are defined in AASHTO's Standard Specifications for Transportation Materials. In addition, agencies typically have their own standards. The raw aggregates should come from sources approved by the agency and should be tested for compliance with designated quality standards.

Plant Control of Asphalt

Asphalt is generally purchased from a source tested and accepted by the agency or accepted on the basis of the supplier's certification. Cost and local preference may affect the selection of a supplier. In many areas the purchase agreement with the asphalt supplier requires certification of the test results from a production run of material or an identifiable lot of material. Strict QC procedures may also require that the hauler supplying material to the plant furnish a "prior load certificate," which protects the supplier of the load from disputes resulting from contamination during transport. These requirements should be specified when executing a purchase agreement.

Very few control tests for asphalt are performed by the plant QC personnel. Penetration tests are sometimes performed in the plant laboratory to detect contamination during transport. It is good practice to randomly sample incoming loads of asphalt cement for future testing if necessary. The agency may also sample asphalt at the plant and run tests in the agency laboratory. In this case, samples stored on site are useful should any question arise about the quality of the asphalt.

Variations in the properties of asphalt are often missed because these properties are not frequently tested. This is a potential problem because if asphalt properties change from lot to lot, the mix properties and laydown characteristics of the hot mix may also change. These variations can be monitored if the plant QC technician reads and maintains a file of the certificates of tests submitted by the asphalt supplier.

The temperature of the incoming asphalt must be closely monitored. Specifications set limits on the allowable temperature in the asphalt storage tanks. Overheating by the supplier or hauler is cause for rejection of the asphalt cement.

Plant Control of Mixtures

Plant control of mixtures includes a series of elements so closely interrelated that they are difficult to separate. One test may perform a variety of functions, satisfying a number of these QC needs. The basic elements pertaining to mixtures that require QC testing are as follows:

- Mix design
  - Selection of an asphalt cement
  - Selection of aggregates
  - Development of the job-mix formula
  - Selection of a mixing temperature
- Day-to-day plant control and tests
  - Stockpile or cold-feed gradations
  - Hot-bin gradations (for batch plants)
  - Cold-feed adjustments
  - Hot-bin weight adjustments (for batch plants)
  - Asphalt content tests
  - Gradation of aggregate in mix
  - Adjustments of mixing time and temperature
  - Preparation of Marshall, Hveem, or Superpave specimens for applicable testing of
    - Voids
    - VMA
    - VFA
    - Density
    - Flow (Marshall only)
    - Stability (Marshall and Hveem only)

Field Control of Placement

QC must be exercised during placement and monitored by individual tests and measurements. The success of QC during placement depends on making corrections while the mix is hot and when a problem can be actively corrected. One step in producing a quality product is to construct a test strip at the start of the project. The following listing of placement controls should be closely monitored by the contractor:

- Application of tack coat
- Rate of HMA delivery
- Paver speed
- Paver adjustments
- Grade control
- Thickness control
- Density control
  - Temperature of air and mixture
  - Roller type
  - Rolling pattern and coverage
  - Roller speed
- Control of yield thickness
- Control of smoothness

Quality Control Documentation

The contractor should maintain adequate records of all QC inspections and tests. These records should indicate the nature and number of observations/tests performed, courses of action when required, and quantities approved and rejected. In most instances, tabular data are documented as illustrated in Table 4-1. In this example for asphalt content, individual test results are compared as recorded, and comparisons are made with the job-mix formula and the allowable tolerances.

Some contractors will plot these tabular data on a simple QC chart, commonly referred to as a "straight-line" or "trend" chart. Figure 4-2 illustrates such a chart. In this case, the vertical axis represents the asphalt content, and the data points (which are connected with straight lines) consist of individual test results in the order (dates) in which they were obtained. Included on this chart are the job-mix formula and the associated allowable agency tolerances. These tolerances are shown as horizontal straight lines intersecting the vertical axis (percent asphalt) at the appropriate points. The plotted data now depict the condition or trend of the HMA production process with regard to asphalt content in relation to the allowable tolerances for the job-mix formula. Similar tabular data or the fundamental QC chart should be documented for all measurable test data (e.g., gradation, density, thickness, Marshall stability). Such QC documentation, although not as efficient as that produced with QC/QA specifications, provides the contractor with decision information needed to make necessary adjustments or changes in day-to-day operations.

Agency Acceptance Testing

Acceptance testing associated with method specifications is performed under agency authority to ensure that the product meets the specifications. The process usually includes the evaluation of tests and observations of the hot mix and the completed pavement.

Acceptance testing may be performed by technicians employed by the agency or consultants hired by the agency, or it may involve monitoring and observing QC tests performed by the contractor. If an agency's inspector is observing the tests, the contractor may be required to perform certain tests at stated frequencies.

Acceptance tests may include

- Asphalt content tests,
- Gradation (usually specific sieve sizes),
- Marshall/Hveem stability tests,
- Density of laboratory compacted specimens (bulk specific gravity),
- Volumetric tests (air voids, VMA, VFA),
- Pavement density tests (cores, nuclear gauge), and
- Smoothness.

Most agency specifications require daily sampling and testing for acceptance. As discussed earlier, acceptance is usually based on "substantial compliance," "reasonably close conformity," or "satisfaction of the engineer" in relation to the agency specifications.

QUALITY CONTROL/QUALITY ASSURANCE SPECIFICATIONS

Advantages and Disadvantages of QC/QA Specifications

The greatest advantage of QC/QA specifications to agencies is that they place responsibility for quality of materials and construction on the contractor or producer. Other advantages include more complete, as-built records; statistically defensible acceptance decisions; and savings in labor costs for agency technical personnel when features of the QC/QA specifications are fully implemented.

Advantages of QC/QA specifications to contractors and producers stem from greater latitude in the choice of materials and equipment and in the design of the most economical mixtures that meet the specified requirements. Perhaps the greatest benefit is derived from the lot-by-lot acceptance procedures that are incorporated in most QC/QA specifications. When lots are immediately accepted, conditionally accepted with a reduction in payment, or rejected, contractors or producers understand their position. An enforced reduction in price is almost certain to attract the attention of management at higher levels. Management then has the opportunity to take corrective action before large quantities of out-of-specification material or construction are produced and to avoid

TABLE 4-1 Quality Control Data for Asphalt Content

Date	Percent Asphalt	JMF	Tolerance	Allowable Range
June 4	6.1	6.0	±0.4	5.6–6.4
June 4	6.4	6.0	±0.4	5.6–6.4
June 5	5.8	6.0	±0.4	5.6–6.4
June 5	5.8	6.0	±0.4	5.6–6.4
June 6	6.0	6.0	±0.4	5.6–6.4
June 7	6.2	6.0	±0.4	5.6–6.4
June 8	5.8	6.0	±0.4	5.6–6.4
June 10	5.6	6.0	±0.4	5.6–6.4
June 10	6.0	6.0	±0.4	5.6–6.4
June 11	6.2	6.0	±0.4	5.6–6.4
June 11	5.9	6.0	±0.4	5.6–6.4
June 12	5.8	6.0	±0.4	5.6–6.4
June 12	5.9	6.0	±0.4	5.6–6.4
June 13	5.9	6.0	±0.4	5.6–6.4
June 14	6.0	6.0	±0.4	5.6–6.4
June 14	6.2	6.0	±0.4	5.6–6.4
June 15	6.3	6.0	±0.4	5.6–6.4
June 17	6.0	6.0	±0.4	5.6–6.4
June 17	6.0	6.0	±0.4	5.6–6.4
June 18	6.3	6.0	±0.4	5.6–6.4

Note: JMF = job-mix formula.

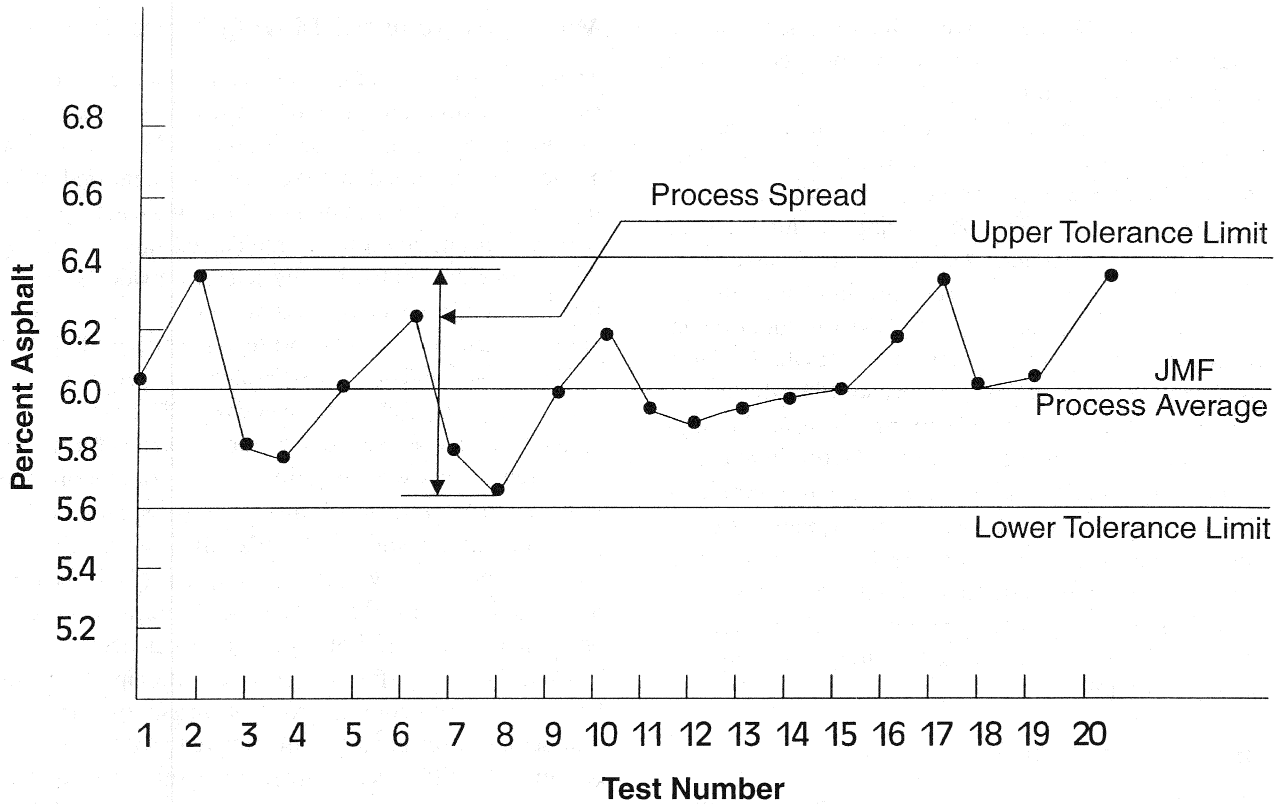

FIGURE 4-2 Asphalt content of paving mixture.

the tie-up of capital when payment is delayed because of failing test results.

The primary advantage to both the agency and the contractor is that the risks to both parties can be quantified and balanced.

Both contractors and agencies must face some issues under QC/QA specifications. When first utilizing these specifications, agencies may encounter resistance from contractors due to the unknown impact on contractor costs and profits. Initially, bid prices may increase. Small contractors may believe they cannot afford to maintain QC technicians on a full-time basis when the prospect of successfully bidding for contracts is uncertain. These organizations may have to arrange with a testing laboratory to do the QC work. If agencies want to monitor some of the QC properties as well as their own QA sampling and testing, they should plan for an increase in workload because of the greater number of tests required. Spot checking of the contractor's QC systems may require more highly qualified personnel than those employed by the agency solely for inspection duties.

Quality Control Activities

Most QC/QA specifications call for the contractor to be responsible for QC. Associated with this requirement is the submission of a process quality control plan (QC plan). Each agency differs in its QC plan requirements, but essentially the plan outlines the minimum requirements for the number of tests to be run, the frequency of the testing, and the plotting of test results (control charts), as well as criteria for when action will be taken to put an out-of-control process back in control. Other factors that might be addressed in a QC plan include the number and frequency of plant inspections, verification of calibrations, and type and amount of documentation to be maintained.

The earlier discussion of QC activities for plant control of aggregate, asphalt, mixtures, and placement under method specifications is applicable to QC/QA specifications as well. These QC activities are the basis for construction of quality HMA pavements. The major difference with QC/QA specifications is that variation is recognized by the agency when the tolerance limits are established. It is this variation that the contractor attempts to identify and control.

The measured quality of a manufactured product such as HMA is always subject to a certain amount of variation attributable to such factors as the asphalt type, aggregate type, plant type, stockpiling procedures, testing, operator, and equipment. *Chance causes* are part of every HMA process and can be reduced but generally not eliminated. In a stable system of HMA production and inspection, acceptable variation is inevitable. However, reasons for excess variation should be discovered and corrected. This type of variation is termed *assignable causes* and is associated with factors that can be eliminated, thereby making it possible to identify the process trend and reduce variability. Examples of assignable causes of variation are improper cold-feed gate settings, malfunctioning asphalt pump, tests conducted improperly, stockpile gradation changes resulting in shifting of the job-mix formula, and equipment out of calibration.

Quality Control Charts

Most QC plans indicate the use of QC charts for evaluating trends in the data, establishing assignable causes, or verifying that the HMA production process is in control. It is important to stress that control charts do not serve to place or keep an HMA process under control; the contractor must control the HMA process. Control charts simply provide a visual warning that the contractor should investigate for possible problems with the HMA production or placement process.

In addition to facilitating early detection of trouble, the use of control charts with QC/QA specifications provides a number of benefits. The charts can be used to

- Decrease variability,
- Establish process capability,
- Reduce price adjustment costs,
- Decrease inspection frequency,
- Provide a basis for altering specification tolerances,
- Serve as a permanent record of quality,
- Provide a basis for acceptance, and
- Instill quality awareness.

A more detailed description of the use of control charts can be found in the National Asphalt Pavement Association's Publication QIP 97, *Quality Control for Hot-Mix Plant and Paving Operations* (2).

Moving Average and Moving Range Charts

There are many different ways to chart data (e.g., test results). The simplest methods are moving average and moving range charts. These charts plot the data in time sequence so that trends in the data can be identified. With regard to construction materials, the charts can be plotted with the specification limits indicated, thus facilitating the identification of test results that are outside the specification requirements. Several agencies and contractors have adopted this type of charting quite successfully.

Figures 4-3 and 4-4 are examples of moving average and moving range charts, respectively. The moving average chart can be used to monitor properties for which price reductions will be assessed for noncompliance with specifications or job-mix tolerances, such as asphalt content, air voids, and gradation. Since the drift of an HMA process away from the target (job-mix formula) is detected early in the process, corrections can be made before undesirable consequences occur.

Range is the difference between the smallest and largest measurement in a group of measurements. The easiest range to calculate is a moving range of two, which is simply the difference between a measurement and the one that follows. The range is a measure of variability and can be used to estimate that part of the total spread attributable to batch-to-batch variation and to variations due to sampling and testing. A chart of the plotted values of a moving range of two measurements is often used in connection with a chart of the moving average of the measurements. The moving average shows whether the HMA process average is close to the target or job-mix formula value, while the moving range chart shows whether the HMA process spread is below the tolerance limits when the HMA process average is constant and close to the proper value.

Statistical Quality Control Charts

Simple moving average and moving range charts do not allow a complete evaluation of the HMA data from a statistical viewpoint. A more powerful approach is use of a statistical control chart. The main purpose of statistical control charts is to identify assignable causes of variation that increase the spread of the measurements. As noted earlier, an assignable cause is one that can be located and eliminated. The presence of assignable causes may be due to improper functioning or operation of one or more items of equipment, improper sampling and testing, or mistakes in the calculation of test results.

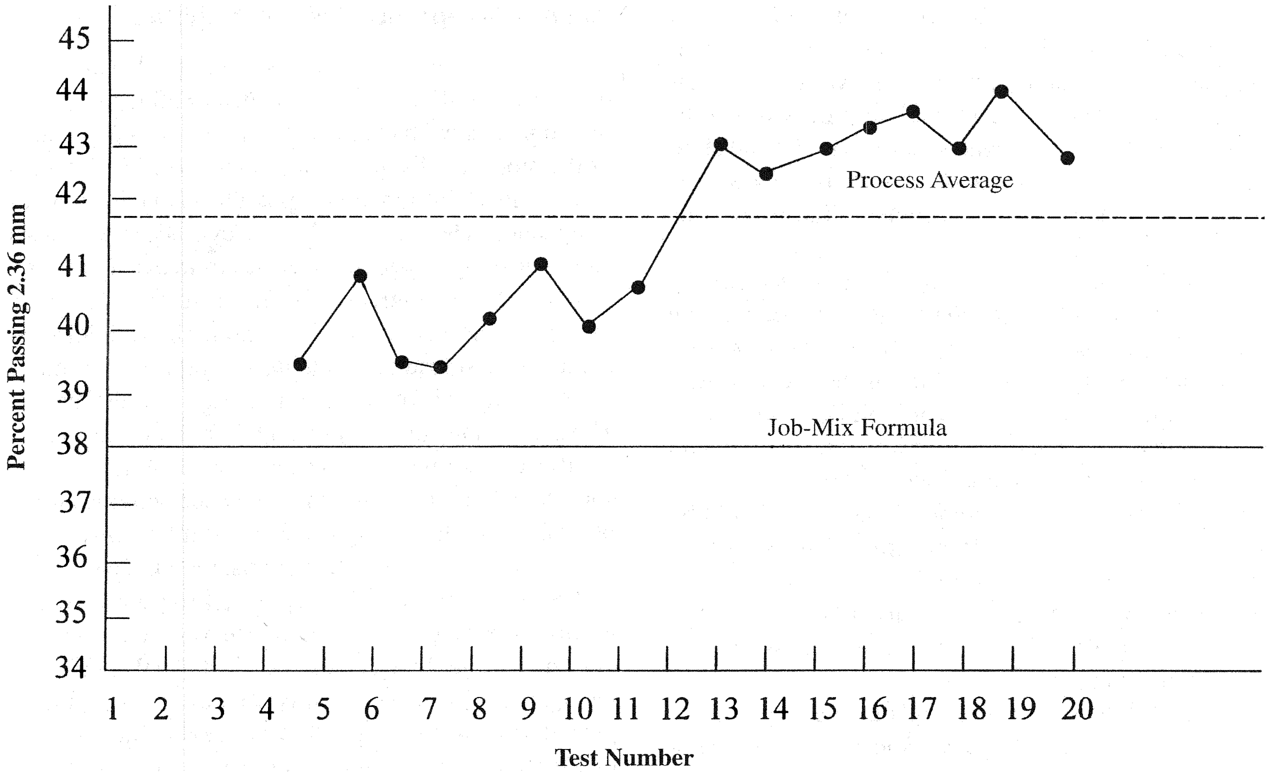

FIGURE 4-3 Moving average of five measurements, percent passing 2.36-mm (No. 8) sieve extraction gradation.

If the measurements made on samples from a process have a constant average and a constant standard deviation (measure of variation), the limits that include most extreme values will remain at fixed distances from the average. The process is then said to be in "statistical control." This is the basis for simple statistical control charts. Such a chart is drawn with a center line representing the average value of the measurements. Limit lines representing the expected spread of measurements due to chance causes are equally spaced above and below the average line. Measurements plotted on this chart are expected to be normally distributed, with most of the plotted points near the center line and nearly all points within the limit lines. The presence of too many points

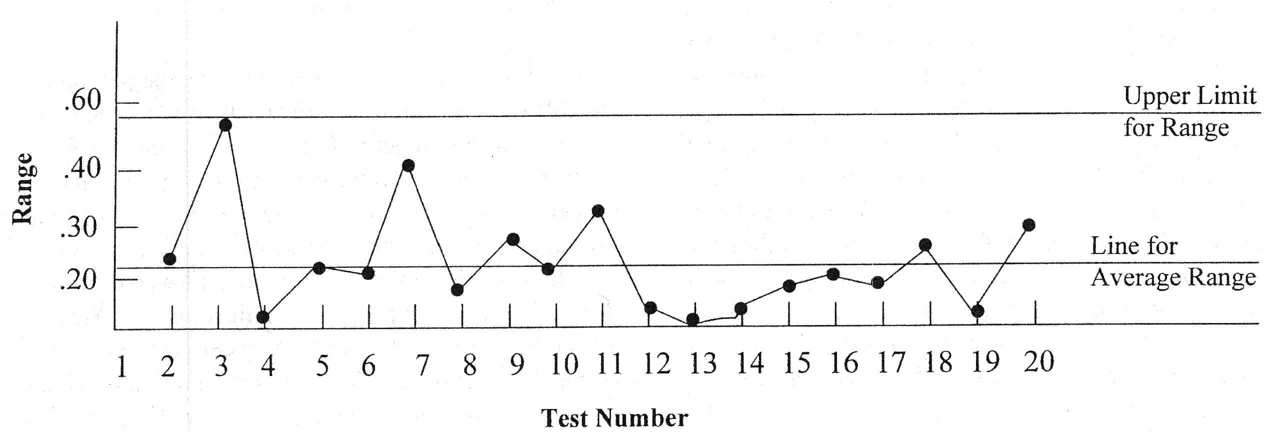

FIGURE 4-4 Moving ranges of two measurements, asphalt content in paving mixtures.

outside the limit lines or too many points on one side of the center line indicates the possible existence of an assignable cause that is increasing the variability of the measurements and suggests that the process could be out of control. If the assignable cause is found and eliminated, the spread of the measurements is reduced, and there is less chance of measurements falling outside specified limits.

It should be noted that the limit lines, called *control limits* on statistical control charts, are not specification limits. The purpose of the charts is to assist QC personnel in maintaining the uniformity of the process. Any point falling outside of a control limit line should be a danger signal, and the reason for its occurrence should be investigated. The circumstances at the time any very large or very small measurements occurred should be noted for future reference. If all points on the statistical control chart fall within the limit lines, these lines can be extended with the expectation that all points will fall within the extended lines in the future unless there is some change in the process.

As with the moving average and moving range charts, two charts are used with the statistical control charting process—*chart for averages* and *chart for ranges*. Figure 4-5 provides examples of these two charts. Plotting of points near or beyond the warning limits alerts the contractor that an assignable cause may be acting on the HMA process. Plotting of points beyond the action limits indicates that an assignable cause is definitely present.

The chart for averages in Figure 4-5 shows lack of control during the period between Samples 28 and 40. It is evident that some assignable cause resulted in an increase in the air voids during this period, probably as a result of some change in materials or proportioning. In actual practice, immediate action should have been taken as soon as the result for Test 28 was recorded. Results of Samples 44 and 76 should have been checked for errors in testing or recording. The range chart shows fairly satisfactory control of variation due to sampling and testing.

Statistical control charts are of limited value on small jobs in which relatively few measurements are made on samples from a particular process. These charts are most useful on jobs that use a large tonnage of the same paving mixture, produced over a long enough period of time to make it practical to identify assignable causes and to take steps to remove these causes. It should also be noted that statistical control charts indicate when to look for possible trouble, but not where to look or what the assignable cause is. These determinations must be made by the contractor.

Agency Acceptance Testing Activities

An acceptance program defines a set of rational procedures to be used by the agency in determining the degree of compliance with contract requirements and the value of the product delivered by the contractor. The intent is to use as much information as possible in making this determination. The results of the agency's acceptance tests and its ongoing inspection activities form the heart of the program. Valid contractor QC test results can be used to augment the agency's information. The validation of contractor test results should be accomplished through a statistically valid comparison with agency test results. The agency may also rely on supplier/vendor testing or certification for the acceptance of some items. All persons directly participating in acceptance activities must be qualified for their assigned responsibilities. Only qualified laboratories should perform the required tests.

The objective of any acceptance program is to determine the degree of compliance with contract requirements and the value of a product. To this end, the QC/QA specifications usually contain an acceptance plan that identifies a method of taking and making measurements on a sample for the purpose of determining the acceptability of a lot of HMA production and construction. The acceptance plan usually contains the following:

- Method of test and point of sampling,
- Lot size,
- Sample size,
- Acceptance limits,
- Method of evaluation,
- Risks associated with specification,
- Operating characteristics curve, and
- Bonus/price adjustment system.

A *lot* is the amount of product that is to be judged acceptable or unacceptable on the basis of a sample comprising a stated number of test results. Since the number of specimens in the sample usually remains constant for a lot of a particular product, the determination of the most appropriate lot size is basically an economic decision. If the lot is very large (e.g., an entire project), the cost of rejecting the product or adjusting the payment can have severe negative consequences for the contractor. On the other hand, if the lot is very small (e.g., a load of material), the cost of testing may exceed the benefits provided. Generally, a lot is defined in terms of time, production, or area.

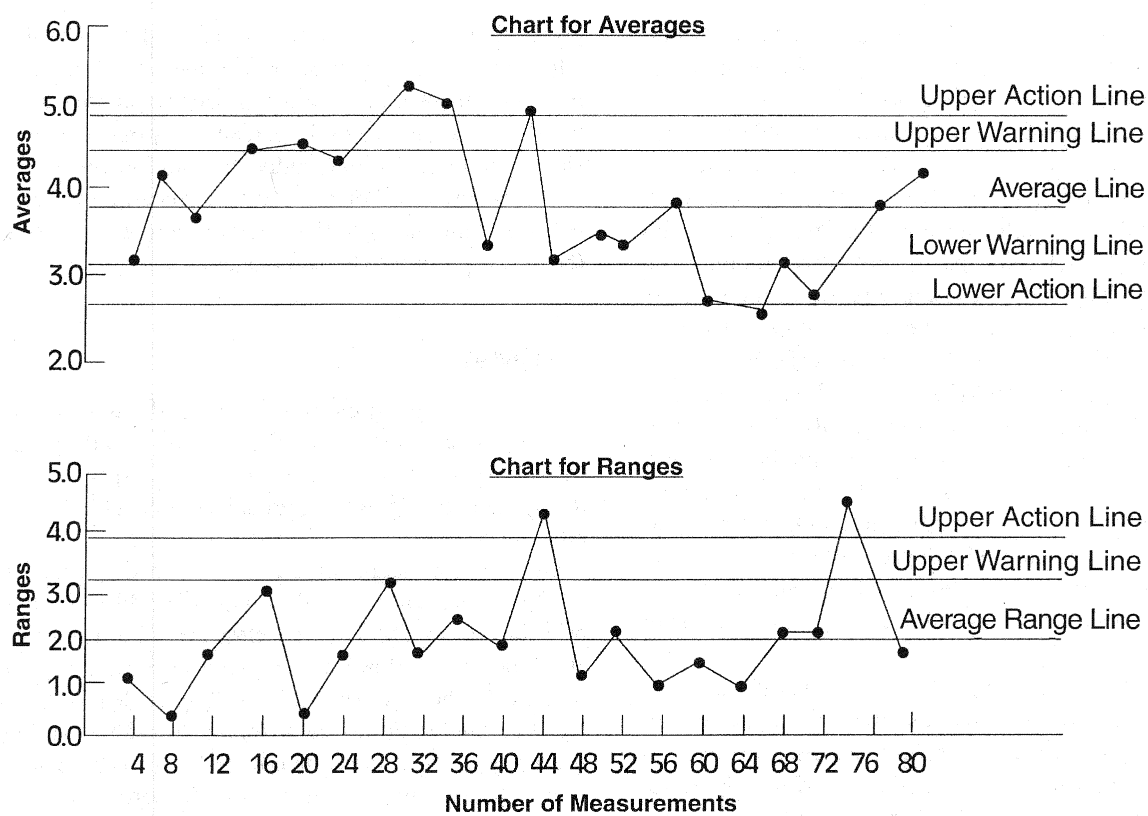

FIGURE 4-5 Average and range statistical control charts for air voids (four measurements).

The *method of test* for judging compliance and the *point of sampling* must be stated in the specification. The method of test must be stated because different methods have differing within-test variabilities that affect the overall variability and thus the specification limits. While there are often many choices for the point of sampling, a single point must be specified. Again, the variability is often influenced by the point of sampling. Both of these elements should be the same as those used when establishing the acceptance limits of the specification.

The number of specimens making up the sample taken to judge the compliance of a lot is often termed the *sample size*. This is not to be confused with the amount of material (size of sample) for testing. The proper sample size is associated with the risk used by the specification writer in developing the specification. In most QA specifications, the sample size ranges from 3 to 5.

Acceptance limits, which are an important part of an acceptance plan, are established in several ways. Establishing limits requires defining acceptable and unacceptable material, both of which are engineering decisions. The definition of acceptable material should address the material that will provide satisfactory service when used for the intended purpose. What constitutes acceptable material is often determined on the basis of what has performed well in the past. The level at which the material is just considered acceptable is known as the *acceptable quality level*. Once acceptable material has been defined, unacceptable material is defined. Unacceptable material is that which is unlikely to provide satisfactory performance. It should have a low probability of being accepted or will be accepted only under the conditions of a reduced payment schedule. The level at which the material is considered unacceptable and requires removal and replacement is known as the *rejectable quality level*.

The method of evaluation for acceptance, acceptance at reduced payment, or rejection of HMA material is generally based on the *percent of material within specification limits* (PWL) or the *percent defective* (PD). Figure 4-6 illustrates the relationship between PWL and PD. With a PWL specification, the percent defective and percent within limits are complementary; in other words, the percent defective plus the percent within limits equals 100 percent. Both are based on the area under the bell-shaped curve. For example, the acceptance quality level may be set at 90 PWL, while the rejectable quality level may be set at 70 PWL, and a reduction in pay is applied between 70 and 90 PWL.

Two types of *risks* are associated with QC/QA specifications: the contractor's and the agency's. The contractor's risk is the probability of rejection of a lot of material when the lot is acceptable. The agency's risk is the probability of accepting a lot when the lot is unacceptable. These risks exist as a result of the location of the specification limits. The power of QC/QA specifications is that the two risks are quantifiable.

Operating characteristics curves illustrate the risks associated with various levels of quality. These curves for a specification are extremely important because they indicate how the risks are related to each other and to various sample sizes and populations. Operating characteristics curves should be developed for all specifications before they are implemented and should be updated to reflect any changes in the acceptance limits or procedures.

One last requirement with QC/QA specifications is the decision on how to address material that does not meet the specifications. Material correction or removal and plant shutdown are two methods traditionally used. Such methods are costly and do not provide positive incentives to keep the process in control. Alternative approaches using price adjustment schedules have therefore been developed. Both negative and positive price adjustments have been employed. The state-of-the-art price adjustment philosophy is that the price should be adjusted to be commensurate with the estimated performance of the product. If the performance is estimated to be adversely affected by 10 percent, the price adjustment should stipulate that the product be paid for at 90 percent of the bid price. Likewise, if the estimated performance is better than that specified, a positive price adjustment (bonus) is permitted by some agencies.

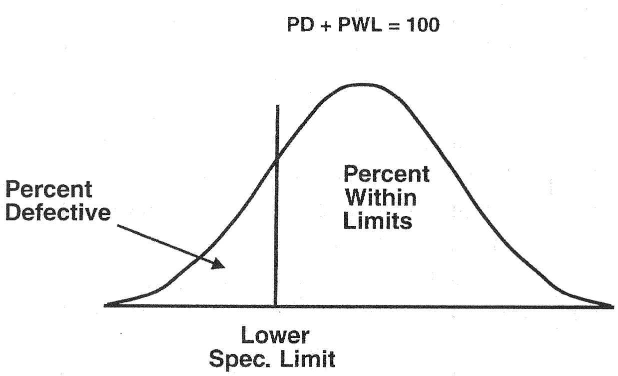

FIGURE 4-6 Relationship between percent within limits and percent defective.

SUMMARY

Two types of specifications are typically used for controlling the production of HMA: method and QC/QA. Method specifications have served the industry well in the past, but the QC/QA approach results in better overall control.

Statistical concepts are now being used widely with QC/QA specifications in the control of HMA. Such approaches allow for a much better evaluation of all the HMA produced. Random samples must be taken for the statistical concepts to be valid. Sliding-scale pay factors are often used with statistical approaches. These sliding-scale pay factors allow the contractor to receive an incentive for very high-quality work, 100 percent payment for acceptable work, and a disincentive for work that is less than desirable but still marginally acceptable.

With QC/QA specifications, the contractor is required to perform the QC testing, and the owner agency is responsible for QA. At times many of the tests conducted for QC are also used for QA. More and more states are beginning to use QC/QA specifications based on statistical concepts with sliding-scale pay factors.

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PART II

Hot-Mix Asphalt Plant Operations

SECTION

5 Types of Asphalt Plants: Overview

The purpose of an HMA plant is to blend aggregate and asphalt cement together at an elevated temperature to produce a homogeneous asphalt paving mixture. The aggregate used can be a single material, such as a crusher run aggregate or a pit run material, or it can be a combination of coarse and fine aggregates, with or without mineral filler. The binder material used is normally asphalt cement but may be an asphalt emulsion or one of a variety of modified materials. Various additives, including liquid and powdered materials, can also be incorporated into the mixture. Indeed, with Superpave the use of additives is becoming more common. Use of additives can result in a need for more binder storage tanks, as well as silos for adding mineral materials.

There are three basic types of HMA plants currently in use in the United States: batch, parallel-flow drum-mix, and counter-flow drum-mix. All three types serve the same ultimate purpose, and the asphalt mixture should be essentially similar regardless of the type of plant used to manufacture it. The three types of plants differ, however, in operation and flow of materials, as described in the following sections.

BATCH PLANTS

The major components of a batch plant are the cold-feed system, asphalt cement supply system, aggregate dryer, mixing tower, and emission-control system. A typical batch plant is depicted in Figure 5-1; the major plant components are shown in Figure 5-2. The batch plant tower consists of a hot elevator, a screen deck, hot bins, a weigh hopper, an asphalt cement weigh bucket, and a pugmill. The flow of materials in a batch tower is illustrated in Figure 5-3.

The aggregate used in the mix is removed from stockpiles and placed in individual cold-feed bins. Aggregates of different sizes are proportioned out of their bins by a combination of the size of the opening of the gate at the bottom of each bin and the speed of the conveyor belt under the bin. Generally, a feeder belt beneath each bin deposits the aggregate on a gathering conveyor located under all of the cold-feed bins. The aggregate is transported by the gathering conveyor and transferred to a charging conveyor. The material on the charging conveyor is then carried up to the aggregate dryer.

The dryer operates on a counter-flow basis. The aggregate is introduced into the dryer at the upper end and is moved down the drum by both the drum rotation (gravity flow) and the flight configuration inside the rotating dryer. The burner is located at the lower end of the dryer, and the exhaust gases from the combustion and drying process move toward the upper end of the dryer, against (counter to) the flow of the aggregate. As the aggregate is tumbled through the exhaust gases, the material is heated and dried. Moisture is removed and carried out of the dryer as part of the exhaust gas stream. The hot, dry aggregate is then discharged from the dryer at the lower end.

The hot aggregate is usually transported to the top of the plant mixing tower by a bucket elevator. Upon discharge from the elevator, the aggregate normally passes through a set of vibrating screens into, typically, one of four hot storage bins. The finest aggregate material goes directly through all the screens into the No. 1 hot bin; the coarser aggregate particles are separated by the different-sized screens and deposited into one of the other hot bins. The separation of aggregate into the hot bins depends on the size of the openings in the screen that is used in the screen deck and the gradation of the aggregate in the cold-feed bins.

The heated, dried, and resized aggregate is held in the hot bins until being discharged from a gate at the bottom of each bin into a weigh hopper. The correct proportion of each aggregate is determined by weight.

At the same time that the aggregate is being proportioned and weighed, the asphalt cement is being pumped from its storage tank to a separate heated weigh bucket located on the tower just above the pugmill. The proper amount of material is weighed into the bucket and held until being emptied into the pugmill.

The aggregate in the weigh hopper is emptied into a twin-shaft pugmill, and the different aggregate fractions are mixed together for a very short period of time—usually less than 5 seconds. After this brief dry-mix time, the asphalt cement from the weigh bucket is discharged

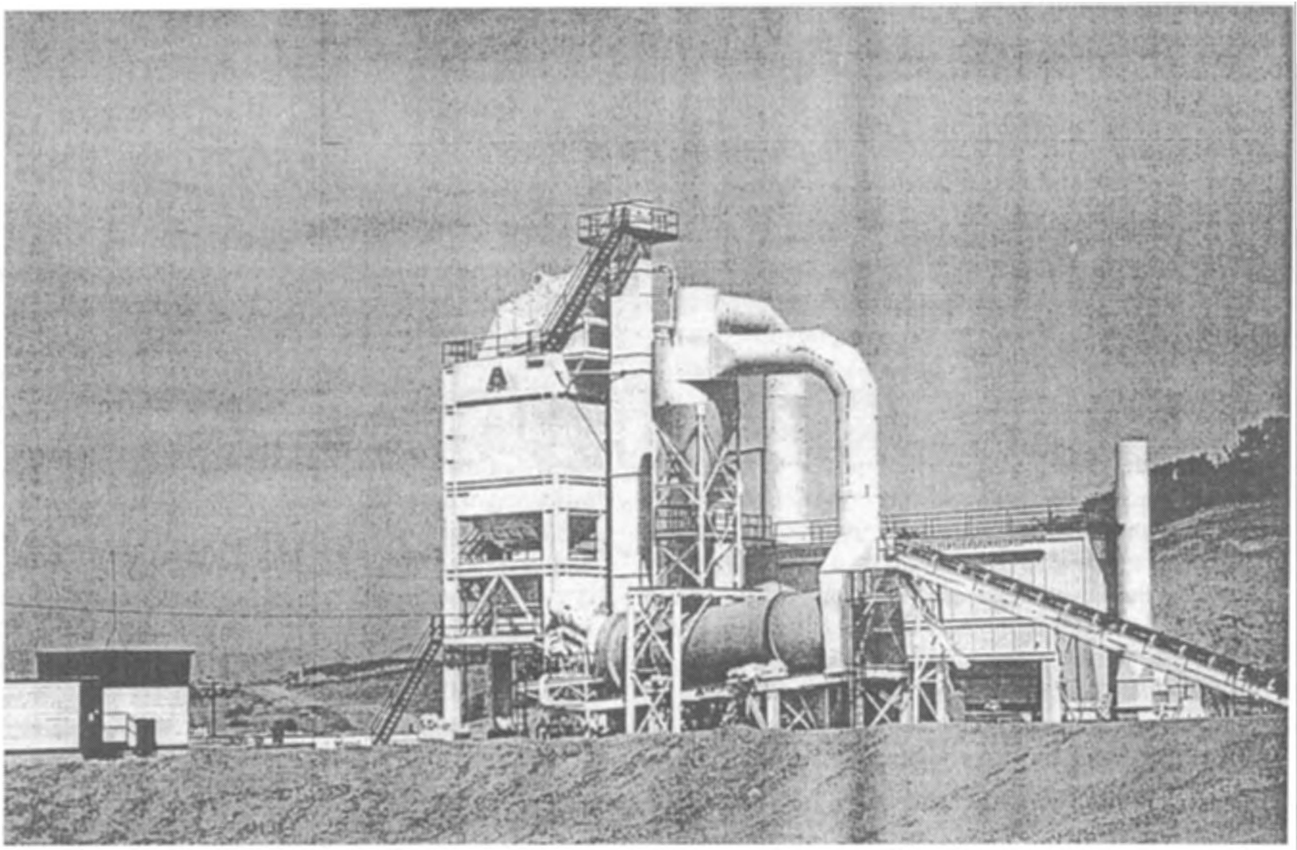

FIGURE 5-1 Typical HMA batch plant.

into the pugmill, and the wet-mix time begins. The mixing time for blending of the asphalt cement with the aggregate should be no more than that needed to completely coat the aggregate particles with a thin film of the asphalt cement material—usually in the range of 25 to 35 seconds, with the lower end of this range being for a pugmill that is in good condition. The size of the batch mixed in the pugmill can be in the range of 1.81 to 5.44 tonnes (2 to 6 tons).

When mixing has been completed, the gates on the bottom of the pugmill are opened, and the mix is discharged into the haul vehicle or into a conveying device that carries the mix to a silo from which trucks will be loaded in batch fashion. For most batch plants, the time needed to open the pugmill gates and discharge the mix is approximately 5 to 7 seconds. The total mixing time (dry-mix time + wet-mix time + mix discharge time) for a batch can be as short as about 30 seconds, but typically, the total mixing time is about 35 seconds.

The plant is equipped with emission-control devices, comprising both primary and secondary collection systems (see Section 12). A dry collector or knockout box is normally used as the primary collector. Either a wet scrubber system or, more often, a dry fabric filter system (baghouse) can be used as the secondary collection system to remove particulate matter from the exhaust gases that flow out of the dryer and send clean air to the atmosphere through the stack.

If RAP is incorporated into the mix, it is placed in a separate cold-feed bin from which it is delivered to the plant. The RAP can be added to the new aggregate in one of three locations: the bottom of the hot elevator; the hot bins; or, most commonly, the weigh hopper. Heat transfer between the superheated new aggregate and the reclaimed material begins as soon as the two materials come in contact and continues during the mixing process in the pugmill.

PARALLEL-FLOW DRUM-MIX PLANTS

The parallel-flow drum-mix plant is a variation of the old-style continuous-mix plant. It consists of five major components: the cold-feed system, asphalt cement sup-

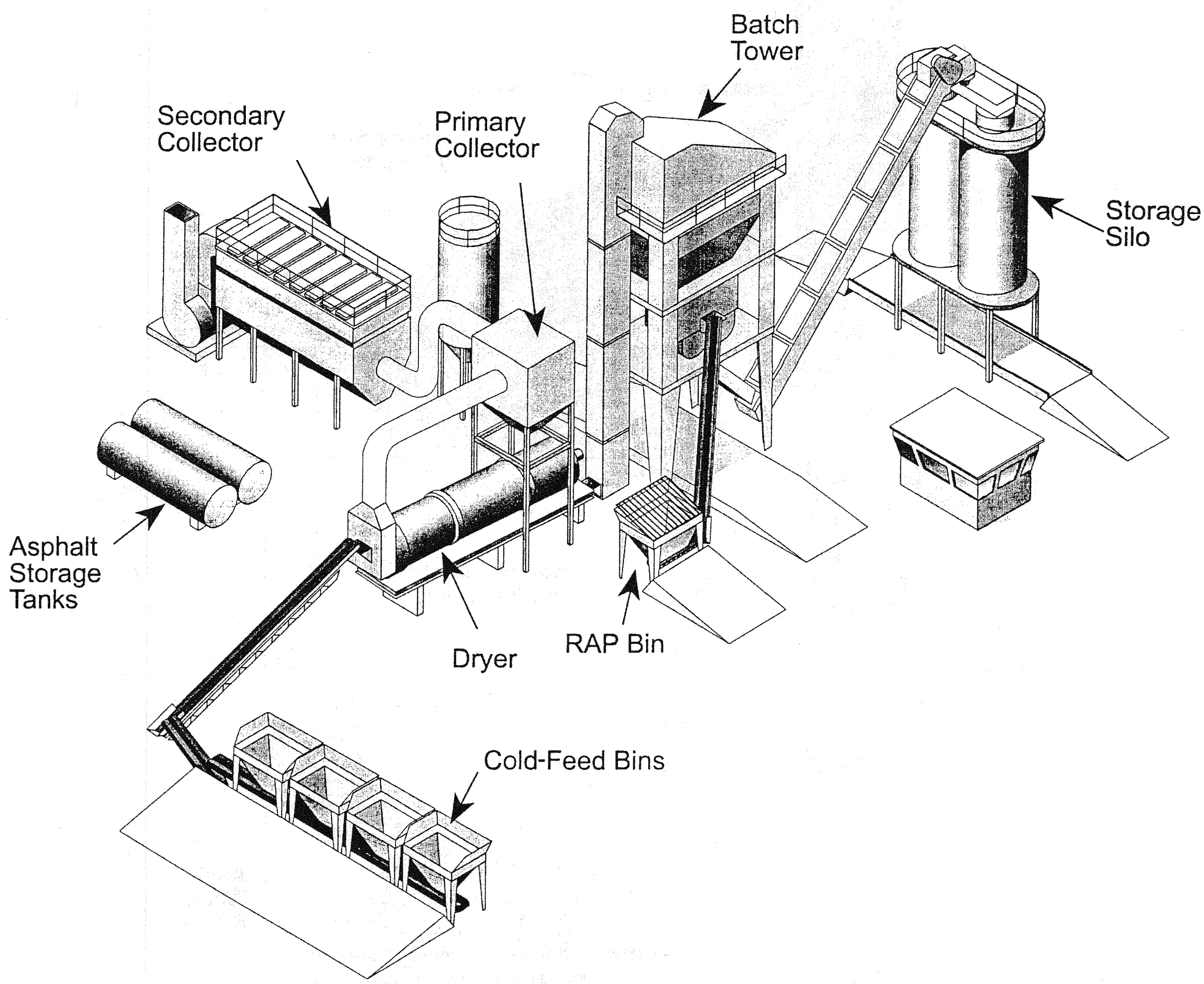

FIGURE 5-2 Major components of a batch plant.

ply system, drum mixer, surge or storage silos (see Section 11 for definitions of these silo types), and emission-control equipment. A typical parallel-flow drum-mix plant is depicted in Figure 5-4; the major plant components are shown in Figure 5-5.

The cold-feed bins are used to proportion the material to the plant. A variable-speed feeder belt is used under each bin. The amount of aggregate drawn from each bin can thus be controlled by both the size of the gate opening and the speed of the feeder belt to provide accurate delivery of the different-sized materials. The aggregate on each feeder belt is deposited onto a gathering conveyor that runs beneath all of the cold-feed bins. The combined material is normally passed through a scalping screen and then transferred to a charging conveyor for transport to the drum mixer.

The charging conveyor is equipped with two devices that are used to determine the amount of aggregate being delivered to the plant: a weigh bridge under the conveyor belt measures the weight of the aggregate passing over it, and a sensor determines the speed of the belt. These two values are used to compute the wet weight of aggregate, in tonnes (tons) per hour, entering the drum mixer. The plant computer, with the amount of moisture in the aggregate provided as an input value, converts the wet weight to dry weight in order to determine the correct amount of asphalt cement needed in the mix.

The conventional drum mixer is a parallel-flow system—the exhaust gases and the aggregate move in the same direction. The burner is located at the upper end (aggregate inlet end) of the drum. The aggregate enters the drum either from an inclined chute above

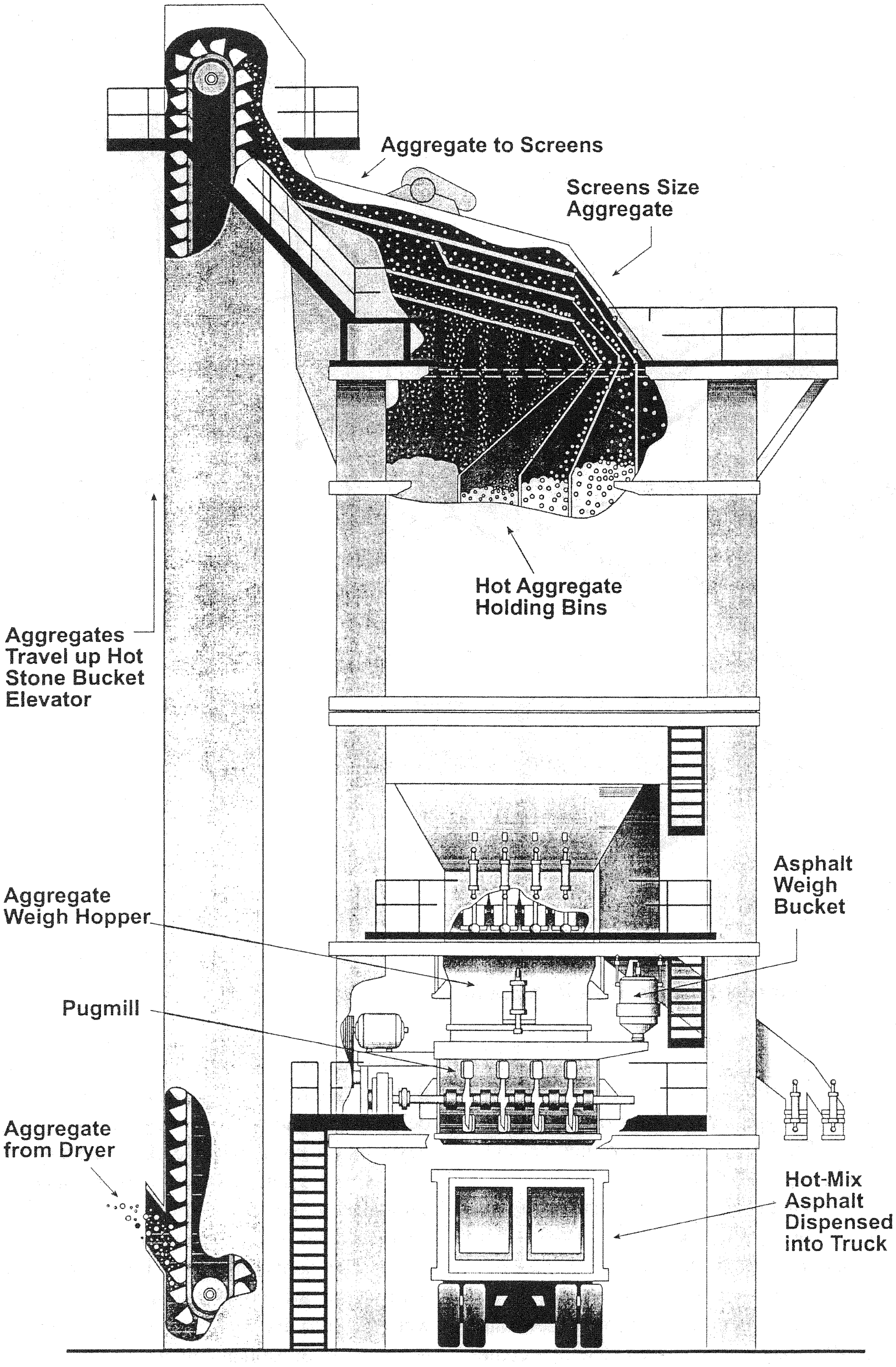

FIGURE 5-3 Flow of materials in batch tower.

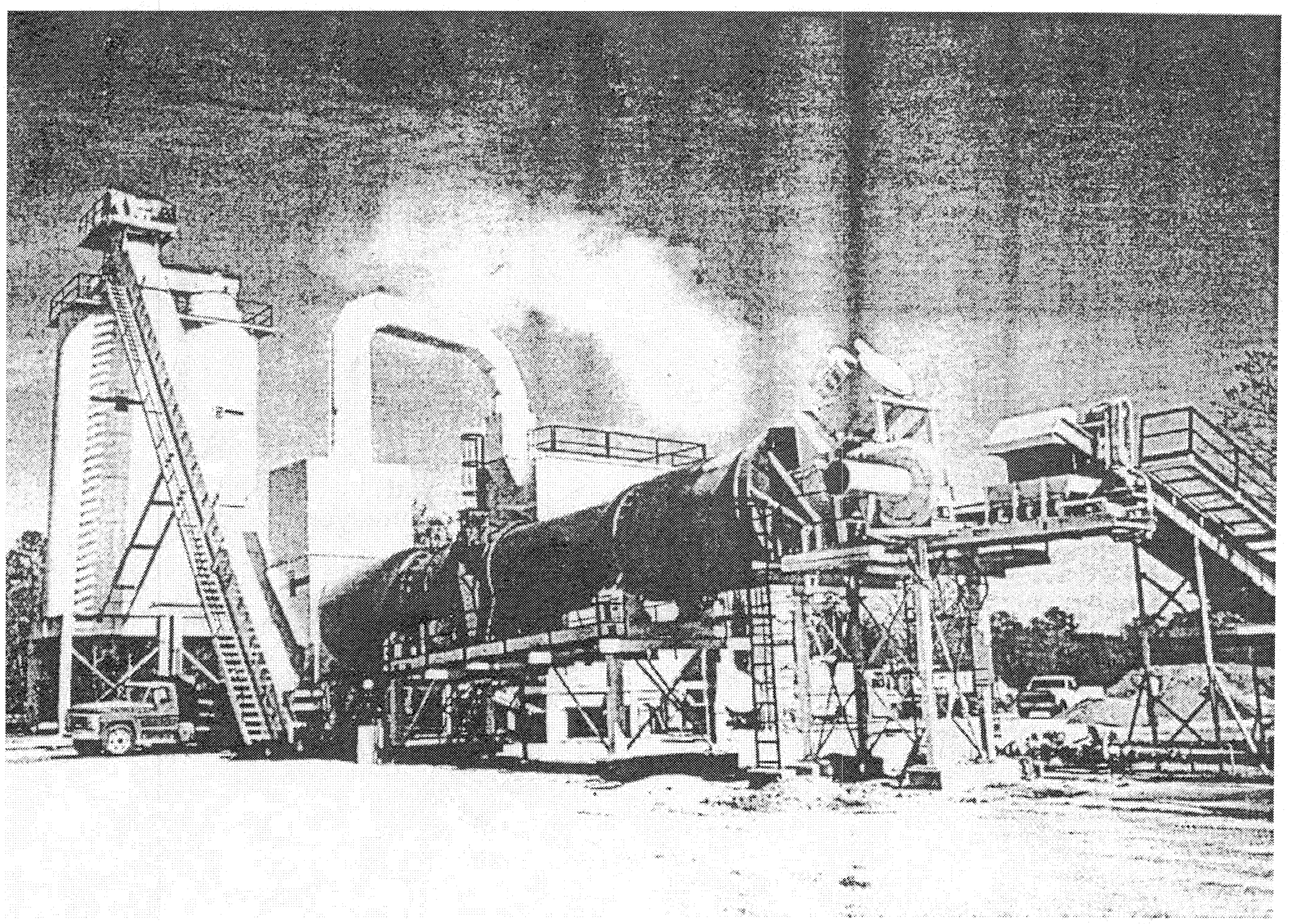

FIGURE 5-4 Typical HMA parallel-flow drum-mix plant.

the burner or on a Slinger conveyor under the burner. The aggregate is moved down the drum by a combination of gravity and the configuration of the flights located inside the drum. As it travels, the aggregate is heated and the moisture removed. A dense veil of aggregate is built up near the midpoint of the drum length to assist in the heat-transfer process.

If RAP is added to the new aggregate, it is deposited from its own cold-feed bin and gathering/charging conveyor system into an inlet located near the center of the drum length (split-feed system). In this process, the reclaimed material is protected from the high-temperature exhaust gases by the veil of new aggregate upstream of the RAP entry point. When mixes with high RAP content are used, it is more likely that the RAP will be overheated in the process. This may result in smoke being emitted from the drum or damage to the RAP.

The new aggregate and reclaimed material, if used, move together into the rear portion of the drum. The asphalt cement is pulled from the storage tank by a pump and fed through a meter, where the proper volume of asphalt cement is determined. The binder material is then delivered through a pipe into the rear of the mixing drum, where the asphalt cement is injected onto the aggregate. Coating of the aggregate occurs as the materials are tumbled together and moved to the discharge end of the drum. Mineral filler or baghouse fines, or both, are also added into the back of the drum, either just before or in conjunction with the addition of the asphalt cement.

The asphalt mix is deposited into a conveying device (a drag slat conveyor, belt conveyor, or bucket elevator) for transport to a storage silo. The silo converts the continuous flow of mix into a batch flow for discharge into the haul vehicle.

In general, the same type of emission-control equipment is used on the drum-mix plant as on the batch plant. A primary dry collector and either a wet scrubber system or a baghouse secondary collector can be used. If a wet scrubber system is used, the collected fines cannot be recycled back into the mix and are wasted; if a baghouse is

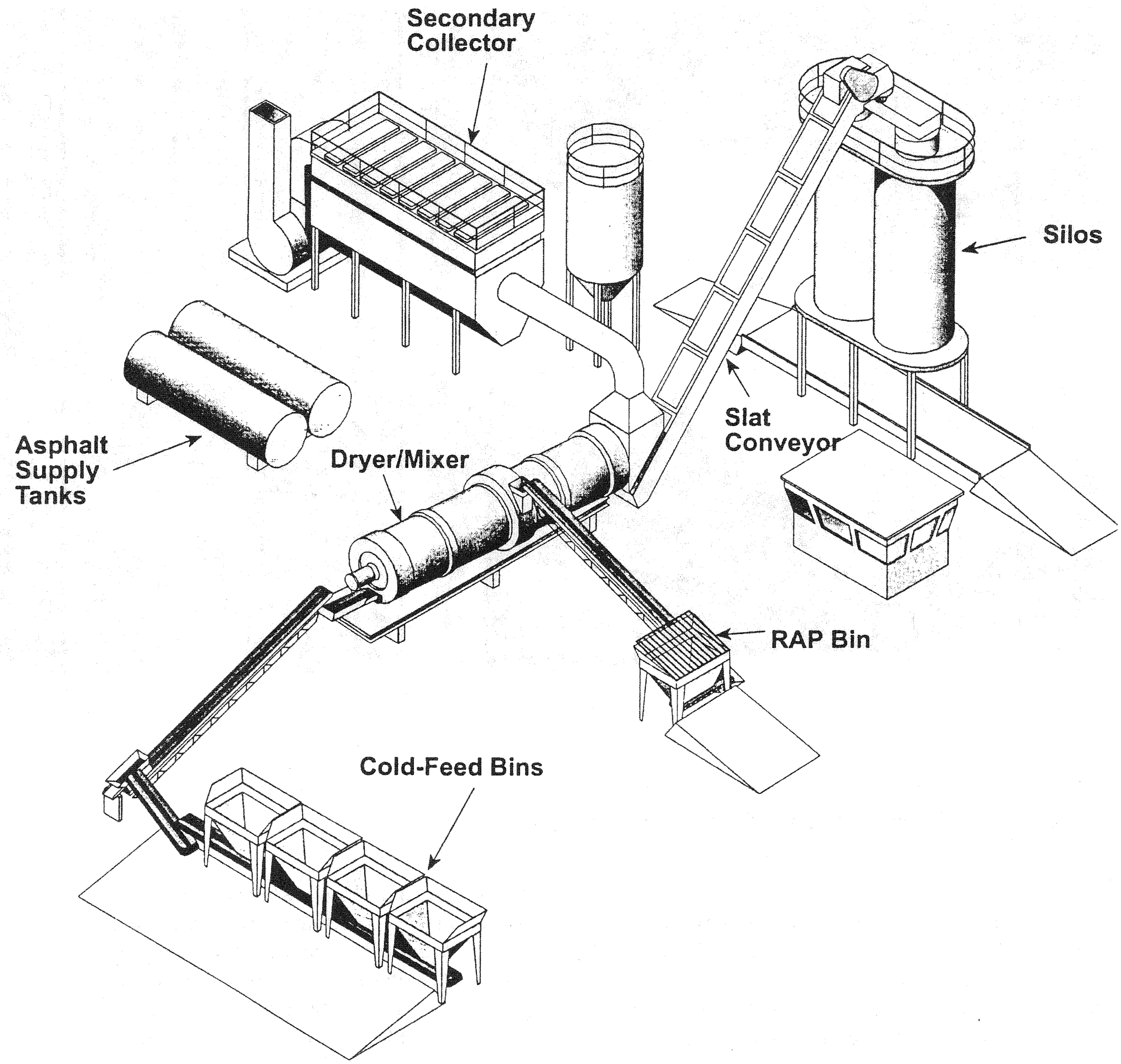

FIGURE 5-5 Major components of a parallel-flow drum-mix plant.

used, the collected fines can be returned in whole or in part to the mixing drum, or they can be wasted.

In the late 1980s, a number of variations on the conventional parallel-flow drum-mix plant were introduced to the HMA industry. One of these is the coater plant. For this type of drum mixer, the asphalt cement injection pipe is removed from the drum. This modification eliminates exposure of the asphalt cement to the high-temperature exhaust gases and reduces both hydrocarbon and visible emissions from the plant. The uncoated aggregate, which is heated and dried inside the parallel-flow drum, is discharged into a single- or dual-shaft mixing chamber, where it is sprayed with asphalt cement. The blending of the asphalt cement and the aggregate takes place as the materials move from one end of the mixing unit to the other. When mixing has been completed, the material is delivered to the conveying device used to transport it to the silo. Figure 5-6 depicts the coater type of drum-mix plant. Because the number of coater parallel-flow drum-mix plants in use is currently limited, this type of plant is not discussed further in this manual.

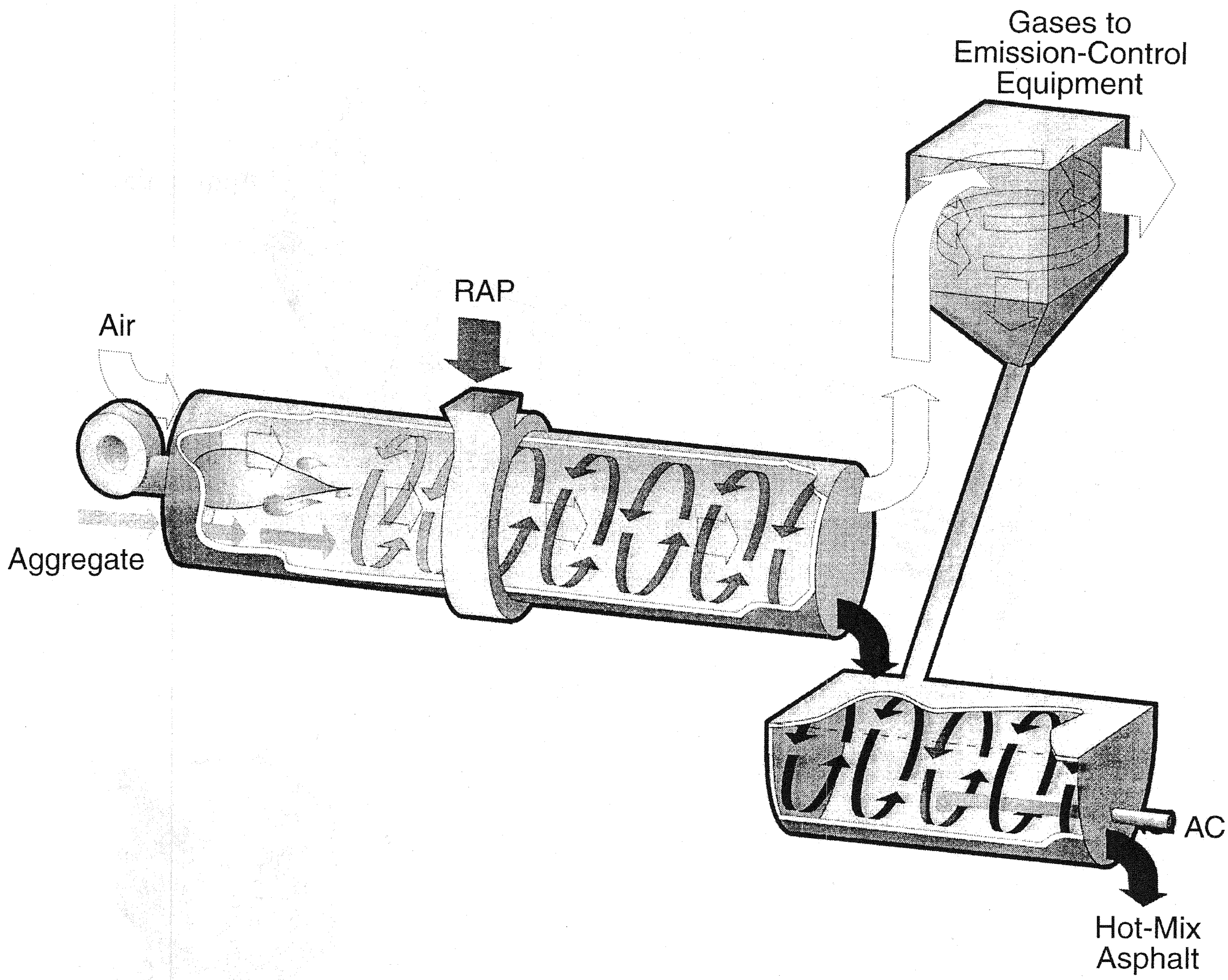

FIGURE 5-6 Drum-mix plant with coater.

COUNTER-FLOW DRUM-MIX PLANTS

A more recent development in drum-mix plant design is the counter-flow drum-mix plant. Its design represents an effort to improve the heat transfer process inside the drum and to reduce plant emissions. In the counter-flow drum-mix plant, the heating and drying of the aggregate are accomplished in a manner similar to that of a conventional batch plant dryer.

Two basic types of counter-flow drum-mix plants are in use. The first, shown in Figure 5-7, has the mixing unit extended on the end of the aggregate dryer portion of the drum. The second, shown in Figure 5-8, has the mixing unit folded back around the aggregate dryer portion of the drum. With both designs, the aggregate enters the drum from the upper end. The burner, however, is located near the lower end of the drum, similar to its position on a batch plant dryer. The aggregate moves down the drum against the flow of the exhaust gases in a counter-flow direction. No asphalt cement is introduced into the aggregate within the main (drying) portion of the drum. The mixing of the binder material with the heated and dried aggregate is accomplished completely outside of the exhaust gas stream—behind or underneath the burner.

In the counter-flow drum-mix plant design shown in Figure 5-7, the hot aggregate passes the burner into a mixing zone. At the upper end of the mixing zone, the baghouse fines or mineral filler (or both) are added to the aggregate. A short distance later, the binder material is introduced into the drum. The mixing of the aggregate and asphalt cement thus takes place behind (downstream of) the dryer in a separate mixing zone, out of contact with the exhaust gases from the burner. If RAP is used in the asphalt mix, it is introduced into the drum

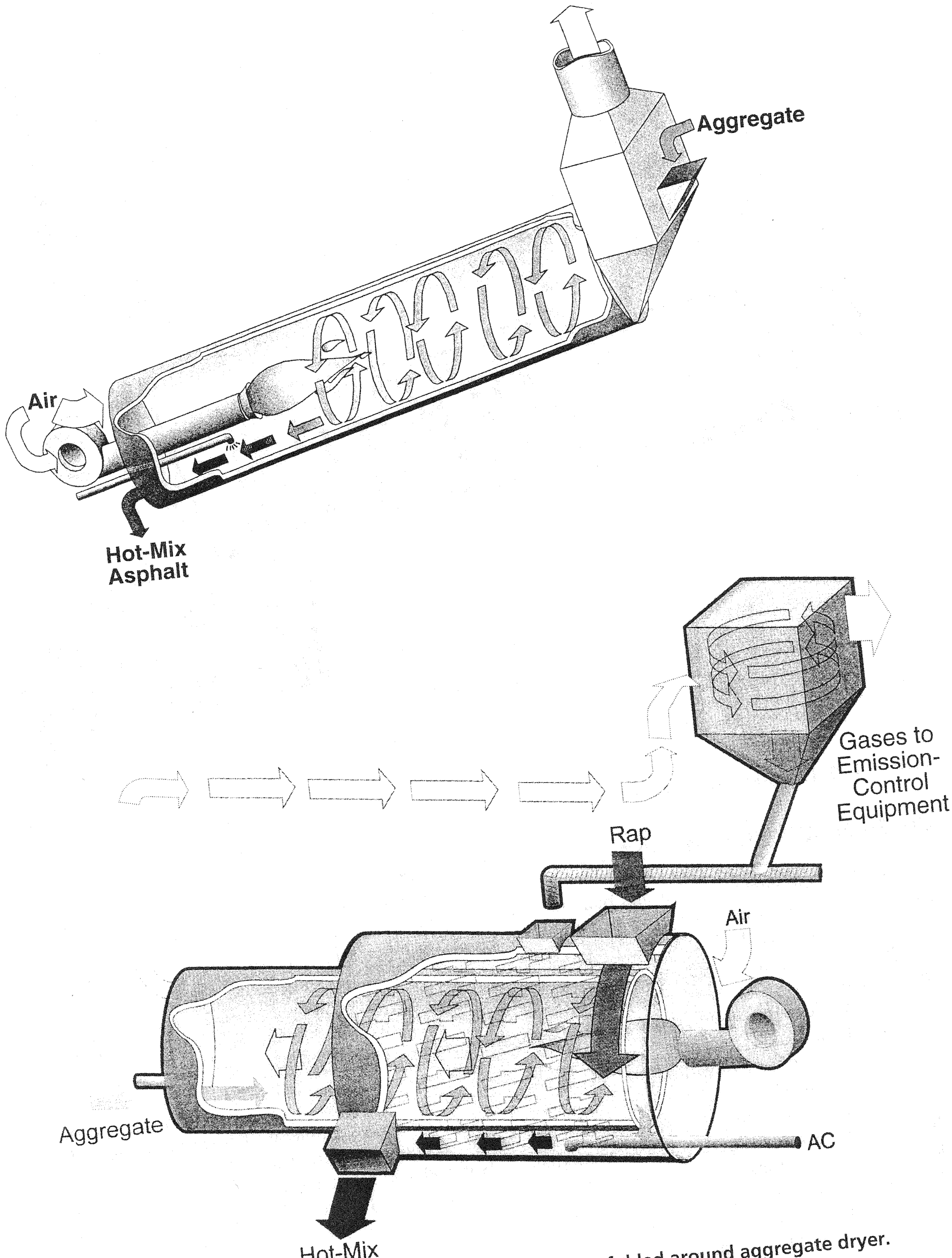

FIGURE 5-8 Counter-flow drum mixer with mixing unit folded around aggregate dryer.

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downstream of (behind) the burner. Thus the RAP also does not come in contact with the high-temperature exhaust gases from the burner, and visible hydrocarbon emissions are reduced. The reclaimed material is heated by overheating the new aggregate in the upper end of the counter-flow dryer and blending the two materials together in the lower portion of the drum, between the burner and the discharge end of the mixing unit.

In the counter-flow drum-mix plant design shown Figure 5-8, the inner drum acts as an aggregate dryer, and the outer drum serves as the mixing unit. The asphalt cement is introduced into the aggregate after the aggregate has been discharged from the inner into the outer drum. The blending of the two materials occurs as the aggregate and asphalt cement are conveyed back uphill in the outer drum by a set of mixing paddles attached to the inner drum. The inner drum rotates, whereas the outer drum is stationary. This type of counter-flow drum-mix plant is known commercially as a double-barrel plant because of the double-drum setup. Any mineral filler or baghouse fines, as well as RAP material, enters the drum in the double-barrel process between the inside and outside drums. Thus, as with the design shown in Figure 5-7, the material is kept away from the exhaust gases from the burner. In particular, this protects the RAP from contact with the high-temperature exhaust gases and thus reduces the possibility that visible emissions will be generated during the recycling process.

SECTION

6 Aggregate Storage and Handling

The storage and handling of both new aggregate and RAP material for use in any type of asphalt plant are addressed in this section. Proper stockpiling techniques, both for placement of the aggregate in the stockpile and for removal of the aggregate from the stockpile, are first discussed. Next is a review of the discharge of the aggregate from the cold-feed bins onto the individual feeder belts; the passage of the aggregate onto the gathering conveyor; and the delivery of the aggregate, sometimes through a scalping screen, to the charging conveyor and finally to the batch plant dryer or drum-mixer. The use of a weigh bridge system on the charging conveyor on a drum-mix plant to determine the amount of aggregate being fed into the drum is also addressed. A discussion of the delivery of RAP from its cold-feed bin to the batch or drum-mix plant is then presented. A brief review of the addition of hydrated lime to reduce moisture damage in the HMA mix is followed by a discussion of calibration of the cold-feed system, including the proper means of checking the rate of aggregate delivery from the individual cold-feed bins and over the weigh bridge system. The final subsection provides a summary of the key operating factors to be considered when monitoring the storage and handling of new aggregates and RAP.

AGGREGATE STOCKPILES

Quality control of HMA, regardless of whether a batch or drum-mix plant is used to manufacture the mix, begins with the stockpiles of aggregate that are to be processed through the plant and incorporated into the mix. The aggregate should be stored on a sloped, clean, stable surface, with the different sizes of coarse and fine aggregate kept separated. Care should be exercised during both the stockpiling and removal processes to minimize segregation of the aggregate in each pile. (Segregation is the undesirable separation of blended aggregate into zones with improper gradation.) If segregation of a particular size of coarse or fine aggregate does occur, an effort should be made to blend the segregated materials together before the aggregate is delivered into the cold-feed bins. This is difficult to do, however, and care must be taken with this operation to keep from aggravating the segregation problem.

Building Stockpiles

Aggregate should be stockpiled on a clean, dry, stable surface and should not be allowed to become contaminated with foreign materials such as dust, mud, or grass. Fugitive dust in the aggregate stockpile area should be controlled so that the dust does not coat the surface of the aggregates and thus does not alter the gradation of the material in each stockpile. The stockpiles should be constructed to be free draining to ensure that the moisture content of the aggregate is as low as possible. Paved stockpile pads should be used to facilitate drainage and provide a solid working platform. Excess moisture, particularly in the fine aggregates (sand), increases the cost of drying the aggregates and reduces the production capacity of the plant. When using a drum-mix plant, the moisture content of each aggregate size should be determined at least twice a day and the average moisture content of the combined aggregates entered into the plant computer system.

To reduce the amount of moisture that accumulates in the aggregate, especially from rain, it is often cost-effective to cover the aggregate stockpiles. The cover typically is in the form of a roof or a shed, as seen in Figure 6-1. A tarp placed directly on top of the aggregate should generally not be used since moisture will typically collect under the tarp instead of evaporating. If only one roof is used, it should be placed on top of the fine aggregate pile since this material will typically have a higher moisture content than that of the coarser aggregate. If a second roof is used, it should be placed on top of the RAP since the moisture content of this material will directly affect the temperature of the recycled mix. If multiple roofs are available, they should then be placed over the various coarse aggregate stockpiles.

As noted, the stockpiles of the various aggregate sizes should be kept separated—by physical barriers, if necessary—at all times. The cold-feed bins and feeders are calibrated to provide a specific amount of each size of aggregate from each bin. If the various materials are

FIGURE 6-1 Covered aggregate stockpiles.

blended in the stockpiles, a combination of sizes will occur in each cold-feed bin. This blending of the aggregate will cause variations in the gradation of the HMA produced by a drum-mix plant and may cause problems with unbalanced hot bins in a batch plant.

Segregation is a major concern with stockpiled aggregate. Many aggregate problems are caused by mishandling of the aggregate during stockpiling and load-out operations. Whenever possible, aggregate should be stockpiled by individual size fractions. A well-graded or continuously graded material should not be contained in one stockpile. Aggregate of larger sizes, particularly when combined with that of smaller sizes, has a tendency to roll down the face of a stockpile and collect at the bottom, leading to segregation.

Prevention of segregation begins with the construction of the stockpile. If possible, stockpiles should be constructed in horizontal or gently sloping layers. If trucks are used to carry the incoming aggregate to the plant site, each load should be dumped in a single pile, as seen in Figure 6-2. Any construction procedure that results in the aggregate being pushed or dumped over the side of the stockpile should be avoided because these practices may result in segregation. Trucks and loaders should be kept off the stockpiles since they can cause aggregate breakage, fines generation, and contamination of the stockpile.

Aggregate coming off the end of a stacking conveyor or radial stacker can be segregated in one of three ways. First, if the particle sizes are small and if the wind is strong, the coarser particles can fall straight down, and the finer particles will be carried to one side of the pile by the wind. Second, and more commonly, even if there is no wind and aggregate is dropped straight down, it will still segregate. Sand particles have less energy, and they do not roll far when they land. Larger pieces have more energy and will roll to the outside edge of the pile. Third, if the speed of the conveyor belt is high, the coarser particles will be thrown farther from the top of the conveyor, and the finer particles will drop more directly into the stockpile. An example of the use of a conveyor to create a RAP stockpile is shown in Figure 6-3.

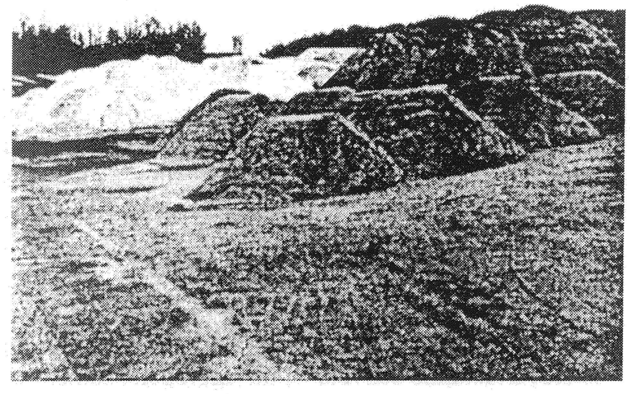


FIGURE 6-2 Horizontal stockpiles.

Removing Aggregate from Stockpiles

Proper operation of the front-end loader used to load haul trucks or charge the cold-feed bins of the asphalt plant will help in avoiding problems with aggregate segregation and gradation variation. The outside edge of the stockpile will generally be coarser than the interior because, as noted, the larger aggregate particles have a tendency to roll down the side of the pile. Significant changes in gradation may result from the way the stockpile was produced. The loader operator

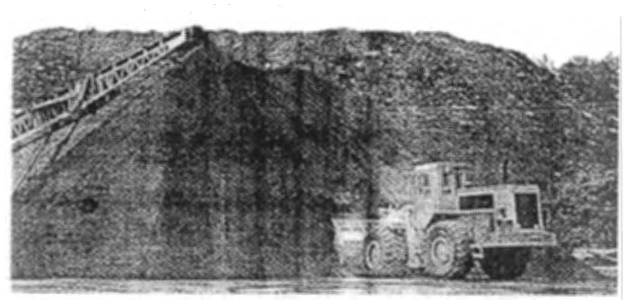


FIGURE 6-3 RAP stockpile using radial stack.

should remove the aggregate in a direction perpendicular to the aggregate flow into the pile and should work the entire face of the stockpile. This practice will minimize aggregate gradation changes and variation in the moisture content of the mix produced by the asphalt plant.

When cleaning the edges of the stockpile, the loader operator should be careful not to push or dump yard material that would contaminate the stockpile. When loading out of a stockpile, the loader operator should ensure that the loader bucket is up high enough to be in the stockpile and not in the yardstone.

When loading from a stockpile built in layers, the loader operator should try to obtain each bucket load by entering the lower layer at the approximate midpoint of the height of that layer and scooping up through the overlying layer. This practice results in half the aggregate being from each layer; it also reblends the aggregate, which in turn reduces segregation. Removal of aggregate from a stockpile should be planned so that a minimum amount of aggregate is disturbed with each bucket load. Removal of aggregate from the bottom of a large stockpile will often result in the above-noted problem of coarser aggregate particles rolling down the face of the pile and gathering at the bottom, increasing possible segregation problems.

Besides working the face of the stockpile, the loader operator should use sound stockpile management techniques. A good practice is to rotate stockpiles so that the first material put into the stockpile is removed first. Areas of the stockpile that are segregated should be reblended by the loader operator at the stockpile. The operator should not feed one or two loads of coarse aggregate and then one or two loads of fine aggregate into the cold-feed bins in an attempt to blend the aggregate. Doing so will cause significant problems in achieving the required aggregate gradation in the mix, regardless of what type of plant is used to produce the mix. It should be noted that the best approach to minimizing segregation is always to use proper stockpiling techniques in the first place, as discussed above, and not to rely on the loader operator to reblend segregated materials adequately.

Generally, RAP should be stockpiled using the same techniques described for aggregate. If the RAP is delivered to the stockpile in large pieces or slabs, it must be crushed before it is used in the plant. If the RAP has been produced by cold milling, this finer material will have a tendency to retain more moisture from rainfall while stockpiled than will RAP maintained in larger pieces.

Segregation of RAP into larger particles and smaller pieces will generally occur more readily than with aggregate because the reclaimed material will usually contain a greater variety of particle sizes than is typical of aggregate stockpiles. Normally this is not a problem because the RAP pieces will usually break down inside the drum mixer or in the batch plant pugmill during the heating, drying, and mixing processes. If a significant amount of large chunks of RAP [pieces greater than 50 mm (2 in.) in size] is fed into the plant at one time, however, those chunks may not be properly heated and mixed with the new aggregate and asphalt binder material. Thus care should be taken to ensure that the RAP material fed into the plant is as consistent in gradation as possible. It is often necessary to screen out and then crush the largest pieces of RAP to ensure proper heat transfer and mixing of the RAP and new aggregate inside the drum mixer.

COLD-FEED SYSTEMS FOR NEW AGGREGATE

Typically the cold-feed systems on HMA batch and drum-mix plants are similar. Each consists of cold-feed bins, feeder conveyors, a gathering conveyor, and a charging conveyor. On most drum-mix plants and on some batch plants, a scalping screen is included in the system at some point. If RAP is also being fed into the plant to produce a recycled mix, an additional cold-feed bin or bins, feeder belt and/or gathering conveyor, scalping screen, and charging conveyor are necessary to handle the extra material.

Cold-Feed Bins and Feeder Conveyors

The flow of aggregates through a plant begins at the cold-feed bins, as seen in Figure 6-4. The plant is equipped with multiple bins to handle the different sizes of new aggregate used in the mix. Most cold-feed bins are rectangular in shape, have sloping sides, and have a rectangular or trapezoidal opening at the bottom. A bulkhead or divider should be used between each cold-feed bin to prevent overflow of the aggregate from one bin into another. The resulting commingling of aggregate sizes can significantly alter the gradation of the mix being produced, particularly in a drum-mix plant, where no screens are used to resize the aggregate after it is dried. If bulkheads are not in place between the cold-feed bins and mixing of the different-sized aggregates is a problem, these devices should be installed.

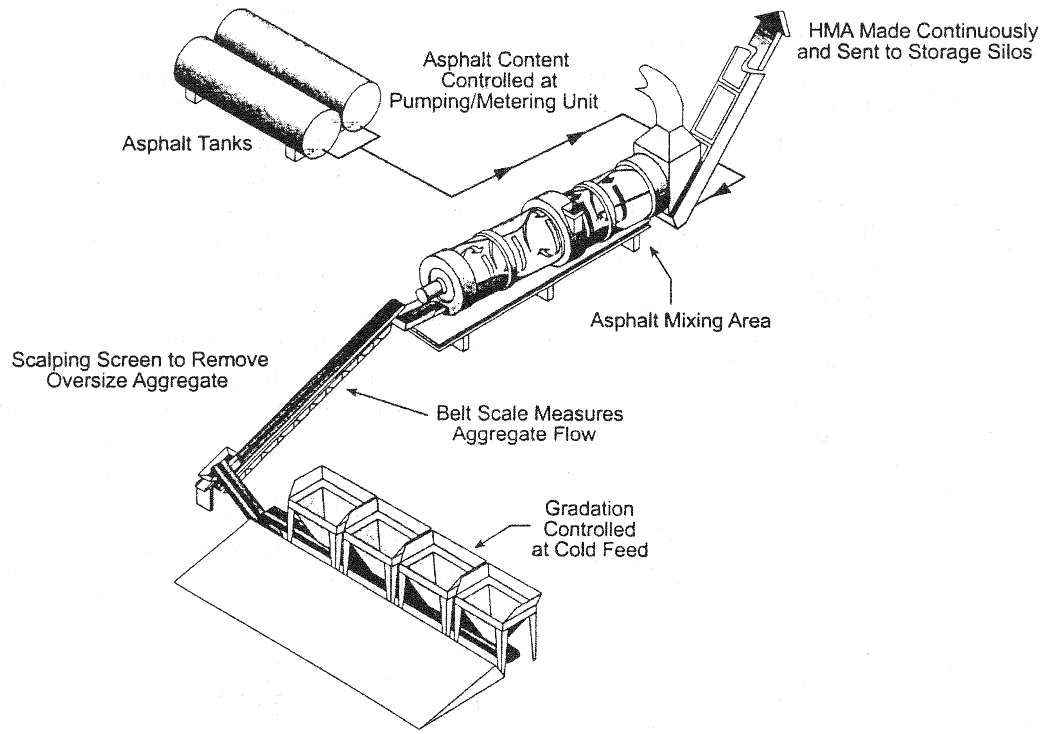


FIGURE 6-4 Flow of material through a drum-mix plant (continuous-flow facility).

Care should be taken not to pile aggregate higher than the top of the bulkheads, again to prevent aggregate in one bin from spilling over into the adjacent bin. If bins overflow, the resulting contamination of aggregate materials will lead to a difference in the gradation of the produced HMA mix.

Each cold-feed bin is equipped with a gate to control the size of the discharge opening on the bin and a feeder belt to draw aggregate out of each bin at a controlled rate. On some plants, the speed of the feeder belt under the bin is not variable; the amount of aggregate that is withdrawn from the bin is determined by the setting of the gate opening. The degree of control exercised over the amount of aggregate withdrawn from each bin is thus governed by the number of possible gate settings on each feeder gate. The size of the gate opening is set by raising or lowering the gate using a manual or electric-powered crank or wheel, or by unbolting, moving, and rebolting a sliding plate on one end of the bin.

Most cold-feed bins are equipped with variable-speed feeder belts under each bin, as shown in Figure 6-5. The gate opening and the feeder belt speed for each bin are set to deliver an amount corresponding to the desired proportion of that aggregate needed in the mix. The more a particular aggregate is required, the larger is the opening of the bin discharge gate. The speed of each belt is then set in accordance with the exact amount of material withdrawn from the bin. If a small change is needed in the amount of material to be delivered from a bin, the speed of the feeder belt can be increased or decreased to accommodate that change. Theoretically, it is possible to withdraw aggregate from a bin using the full range of the belt speed, from 1 to 100 percent of the maximum speed. In practice, only 20 to 80 percent of the maximum belt speed (ideally closer to 50 percent) should be used when adjusting the rate of aggregate feed. This practice allows the plant operator some leeway to vary the production rate of each feeder for changes in operating conditions without having to change the settings of the gate openings.

If a large change is needed in the feed rate for a particular size of aggregate, however, the gate opening at the discharge end of the bin will need to be adjusted. The speed setting of each feeder belt is displayed on the operator's console in the plant control trailer and is typically shown as a percentage of the maximum belt speed. If the feeder belt under a given cold-feed bin is operating at less than 20 percent or more than 80 percent of maximum speed, the gate setting may need to be changed so that the belt can operate closer to the middle of its speed range for the selected production rate.

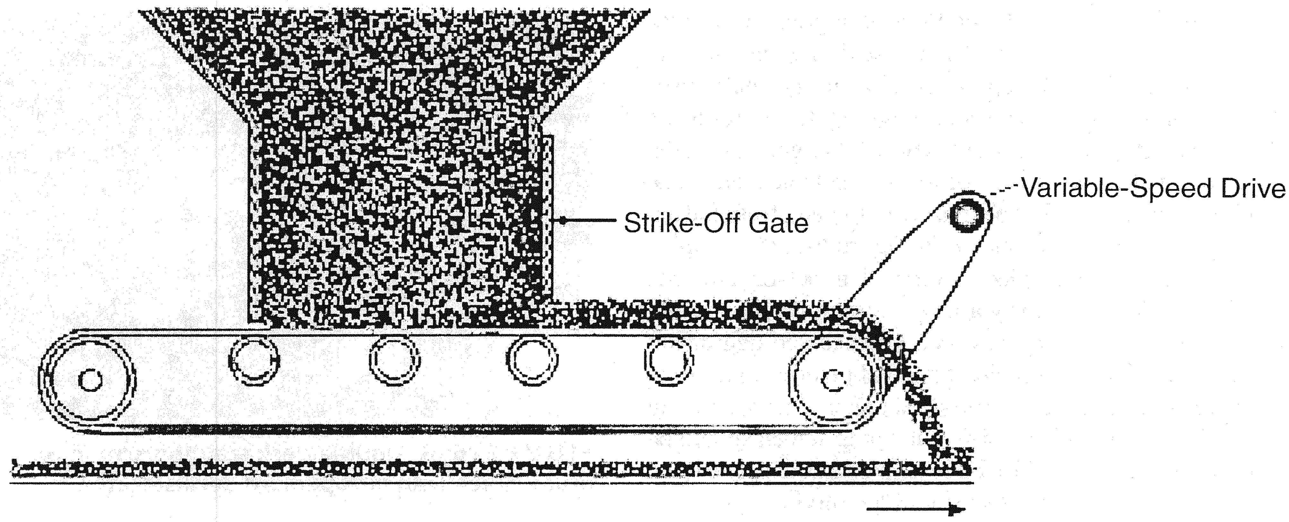


FIGURE 6-5 Continuous feeder belt.

The speed setting for each feeder belt is adjusted independently to allow the proper amount of aggregate to be pulled from each bin. Once determined, the speed of all the feeder belts is synchronized so that a change in the speed of one is proportional to the change in the speed of all the others. Thus if the production of the plant is increased from 225 to 320 tonnes (250 to 350 tons) per hour, a change in the master control setting causes a corresponding change in the speed of all the feeder belts.

Each cold-feed bin and its companion feeder belt should be equipped with a no-flow sensor (typically a limit switch) that will alert the operator when no aggregate is coming out of the cold-feed bin. If the bin is empty or the aggregate has bridged over the discharge opening in the bin, and no material is being discharged onto the collecting conveyor, the no-flow sensor will indicate the condition by sounding an audible alarm or automatically shutting down the plant after a preset time.

Collecting Conveyor

As shown in Figure 6-6, aggregate deposited from each feeder belt is dropped onto a collecting conveyor, located beneath all of the individual feeder conveyors, that collects the aggregate discharged from each of the bins. The speed of the conveyor is constant. The amount of aggregate deposited on this conveyor is thus a function of the size of the gate opening and the speed of the feeder conveyor under each cold-feed bin.

To reduce the amount of buildup that may occur on this conveyor, particularly when the various aggregates are wet, the coarser aggregates should be placed on the belt first. The sand, which typically has the higher moisture content, may stick to the conveyor belt if placed on the belt first and may need to be continually removed. This may, in turn, affect the gradation of the aggregate in the mix.

Scalping Screens and Devices

On drum-mix plants it is desirable to insert a scalping screen into the cold-feed system to prevent oversized material from entering the mixer. Scalping can sometimes be accomplished by placing a screen over the top of the cold-feed bins. In many cases, however, this screen is only a grizzly type of device with relatively large openings. Because of the large volume of aggregate that is delivered at one time from the front-end loader to a cold-feed bin, a screen with small openings

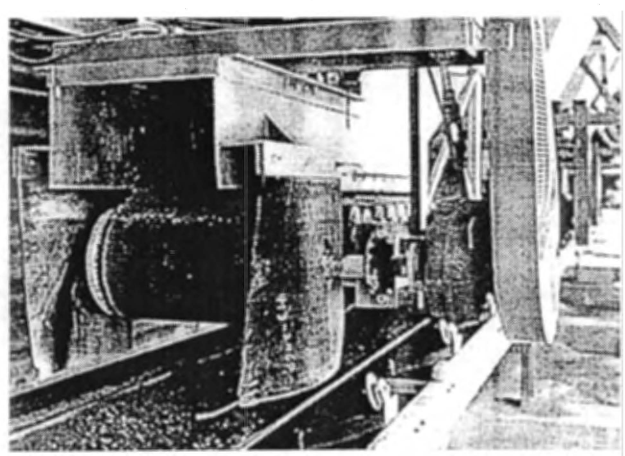


FIGURE 6-6 Collecting conveyor under cold-feed bins.

cannot properly handle the flow of aggregate from the loader bucket to the bin. Thus, scalping screens employed on top of the cold-feed bins are normally used only for the larger-sized coarse aggregate and for RAP.

A scalping screen is used to remove larger-sized deleterious materials such as tree roots, vegetable matter, and clay lumps, as well as oversized aggregate, from the aggregate material. As shown in Figure 6-7, the scalping screen is most often placed somewhere between the end of the collecting conveyor and the drum. While it is not always necessary to pass quarry-processed aggregates through a scalping screen, it is good practice to do so to prevent any extraneous oversized material from entering the drum and thus the mix. A scalping screen should be used as part of the cold-feed system on a batch plant if the screens have been removed from the mixing tower or if the screens are bypassed. The openings in the scalping screen (the bottom screen if a double-deck screen is being used) are typically slightly larger than the maximum-sized aggregate used in the mix.

Scalping devices can be tailored to the needs of the individual plant. Typically only a single-deck scalping screen is used. Some plants, however, employ a double-deck scalping screen, which controls two different top-size aggregates without requiring changing of the screen (see Figure 6-8). If both screens are being used, a flop gate at the lower end of the second screen is employed to redirect the aggregate caught on the bottom screen to the charging conveyor. The flop gate can be operated either manually or automatically. The openings in the screen can be either square or slotted. The advantage of the slotted screen is that a smaller screen area can be used to handle a given volume of material.

Some scalping screens are equipped with a bypass chute. This device allows the aggregate on the collecting conveyor to be deposited directly on the charging conveyor without passing through the screen. This procedure is sometimes used when quarry-processed aggregate or aggregate known to be free of deleterious material is fed to the plant.

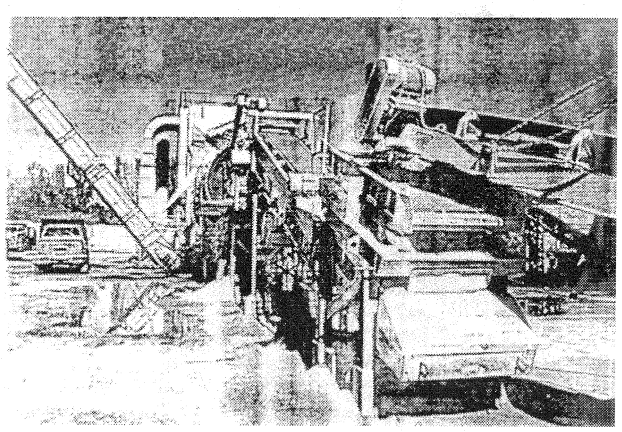


FIGURE 6-7 Single-deck scalping screen on drum-mix plant.

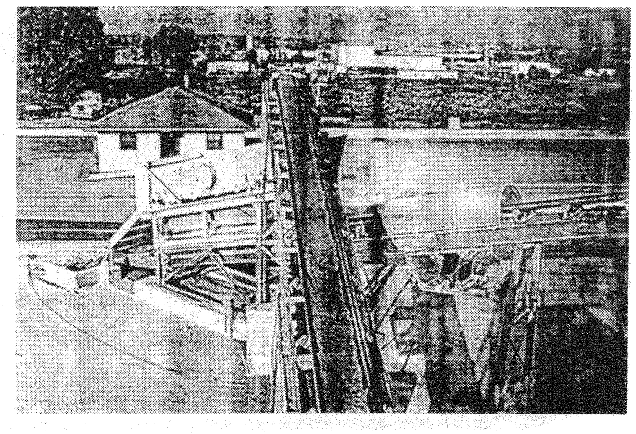


FIGURE 6-8 Double-deck scalping screen on drum mixer with air-operated deck selector.

One make of cold-feed bins includes a small scalping screen under each cold-feed bin instead of a scalping screen at the end of the collecting conveyor. The aggregate from a particular bin falls off the feeder belt and onto the scalping screen. Material of the proper size passes through the screen and onto the collecting conveyor. Oversized pieces are rolled down the screen into a reject chute that deposits this aggregate in a pile beside each bin for subsequent disposal. Because these individual bin scalping screens are very small, the proper amount of aggregate will not pass through the screen onto the charging conveyor if they become blinded or clogged. Thus the operation of such scalping screens should be monitored on a regular basis.

Charging Conveyor

Batch Plants

The combined coarse and fine aggregates are discharged from the gathering conveyor onto the charging conveyor for transport to the drum. For a batch plant, this conveyor delivers the aggregate to the inclined chute at the upper end of the dryer. The charging conveyor is a simple belt that operates at a constant speed but carries a variable amount of aggregate, depending on the volume of aggregate delivered from the cold-feed bins. The conveyor should normally be equipped with a device such as a scraper blade or brush, located on the underside of the belt, to clean off the belt as it revolves. This device will prevent any buildup of aggregate on the belt. If a significant amount of fine aggregate (sand) continually builds up on the belt and must be removed, the order of aggregate placed on the gathering conveyor from the cold-feed bins should be changed, if necessary, so that the coarser aggregates are placed on that belt first.

Drum-Mix Plants

For a parallel-flow drum-mix plant, the charging conveyor carries the aggregate to a charging chute above the burner on the drum or to a Slinger conveyor under the burner. From one of these two entry points, the aggregates are introduced into the mixing drum. For a counter-flow drum-mix plant, the charging conveyor carries the aggregate to an inclined chute at the upper end of the drum. For both types of plant, the charging conveyor contains a weigh bridge system (shown in Figure 6-9) that measures the amount of aggregate, in tonnes (tons) per hour, being fed to the drum mixer. The weigh bridge, or belt scale, determines the weight of aggregate passing over the weigh idler. The charging conveyor operates at a constant speed that is independent of the speed of the other conveyors. The weigh bridge itself is located near the midpoint of the length of the charging conveyor.

A weigh idler, as shown in Figure 6-10, is the heart of the weigh bridge system. This idler is different from the fixed idlers on the conveyor frame. It is free to move and is attached to a load cell. As the aggregates pass over the weigh idler, the weight of the material is recorded as an electrical signal in the computer control system. The weight value by itself is meaningless, however, because it covers only an instant of time. Thus the charging conveyor is also equipped with a belt speed sensor, as shown in the figure. This device, usually located on the belt takeup pulley, is a tachometer, which, coupled with the diameter of the pulley, is used to measure the actual speed of the conveyor belt.

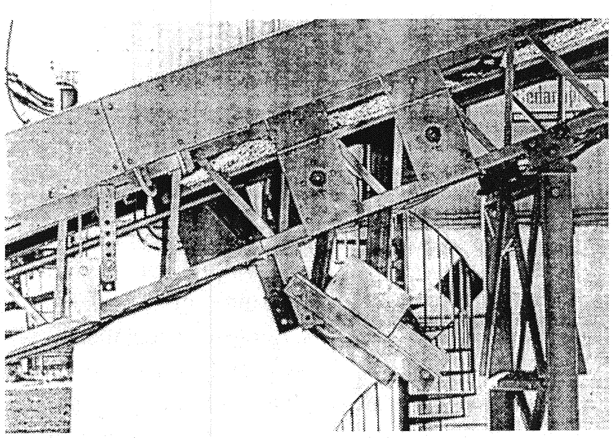


FIGURE 6-9 Weigh bridge.

To obtain an accurate belt speed reading, it is essential that the charging conveyor belt be tight around the gravity takeup pulley, as shown in Figure 6-10. Any slippage of the belt over the speed sensor will result in an erroneous reading and an incorrect wet aggregate weight input to the drum mixer. Some conveyors are equipped with an air-actuated takeup system, located on the tail shaft pulley, that operates in a manner similar to that of the gravity takeup system. The purpose of this system is to keep the belt tight and eliminate the potential problem of inaccurate belt speed sensor readings.

The information from the weigh idler on the belt scale and from the belt speed sensor is combined to determine the actual weight of the aggregate in tonnes (tons) per hour. This value is the wet weight and includes the moisture in the aggregate. The wet weight is converted to dry weight by the plant computer so that the proper amount of asphalt cement will be added to the mix. The average moisture content in the combined coarse and fine aggregates is input manually.

The moisture content of each of the aggregates being fed into the plant should be checked regularly and the average amount of moisture in the incoming aggregate determined. This determination should be made whenever the moisture content of the aggregate stockpiles has changed, such as after it has rained, or a minimum of twice a day. This frequency can be reduced to a minimum of once a day during periods of consistent dry weather conditions. An erroneous moisture content input into the computer system will result in an inaccurate amount of binder material being added to the mix. If the actual moisture content of the incoming aggregate is higher than the value input to the computer, slightly less aggregate dry weight is actually being introduced into the drum, and a higher-than-desired amount of asphalt cement is being added to the aggregate. Conversely, if the actual moisture content of the incoming aggregate is lower than the value input to the computer, more aggregate is being introduced into the mixing drum, and a slightly lower binder content will result. The difference in the asphalt content, of course, will depend on the difference between the actual and input moisture values.

If the aggregates being carried on the belt are relatively dry, all the aggregates that pass over the weigh bridge will enter the drum. As discussed earlier, however, if the moisture content of the aggregates is high, some of the fine aggregate may stick to the charging

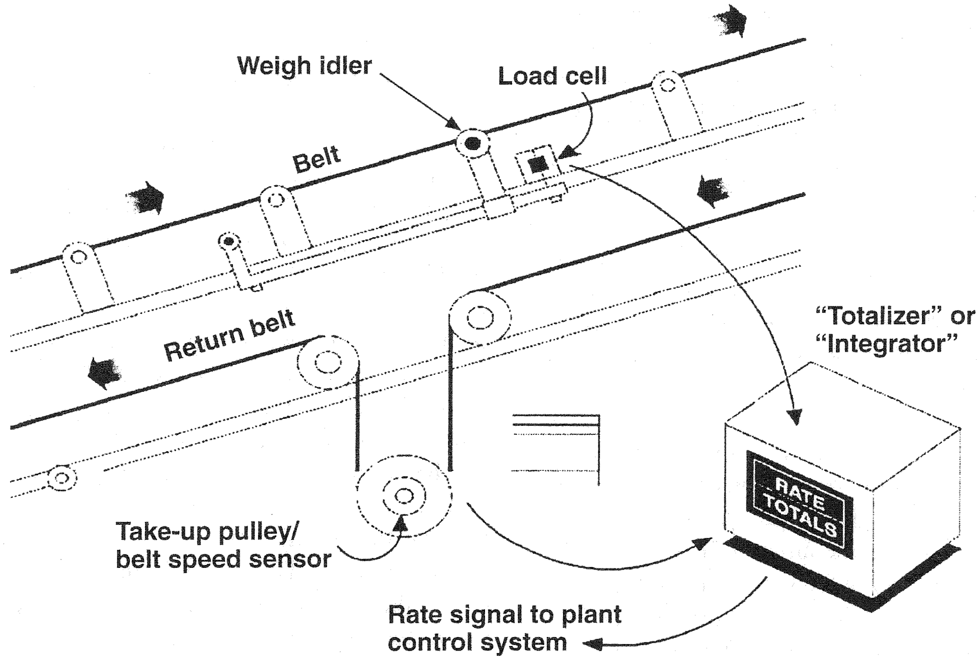


FIGURE 6-10 How a weigh bridge works.

conveyor belt. This "extra" material will not be fed into the drum but will remain on the belt. If not removed by a scraper or brush, this material will continually be detected by the weigh bridge, and the plant computer will calculate a greater weight of aggregate entering the drum than is actually occurring. The computer will in turn signal the asphalt pump to deliver more asphalt cement to the plant to allow for the additional aggregate. Thus the belt scraper or brush should be in place, continually cleaning the charging conveyor belt as it carries aggregate to the mixing drum. As discussed previously, the amount and gradation of the fine aggregate removed by the scraper will change the gradation of HMA mix produced by the plant.

Individual Bin Weigh Bridges

On a few plants, the individual cold-feed bins may be equipped with weigh bridge systems located on the individual feeder belts. In this arrangement, the belt under each individual cold-feed bin must be longer than feeder belts without a weigh bridge. Usually a plant with individual cold-feed weigh bridges will not have a weigh bridge installed on the last feeder belt, closest to the drum mixer. Another standard weigh bridge is installed, however, on the charging conveyor. This latter system provides data on the combined weight of all the aggregates, as does the weigh bridge system on most drum-mix plants.

The plant computer and controls are able to display the amount of aggregate pulled from each cold-feed bin. The amount of material delivered from the bins equipped with individual weigh bridges is read directly, after the amount of moisture in each aggregate fraction has been deducted. The weight of aggregate discharged from the last bin is determined by subtracting (using the computer) the amount of aggregate weighed by the individual feeders from the total aggregate weight measured by the weigh bridge located on the charging conveyor, adjusted for moisture content.

COLD-FEED SYSTEMS FOR RECLAIMED ASPHALT PAVEMENT

The cold-feed system for handling RAP is essentially the same as the conventional cold-feed system for new aggregate. On most plants, as shown in Figure 6-11, a separate cold-feed bin is used. The bin (or bins) is similar to the cold-feed bins used for aggregate except that all four sides of the RAP feed bins are usually much steeper. The steeper sides allow the asphalt-coated aggregate to be discharged from the bins more easily. This is particularly important in hot or wet weather, when the RAP can

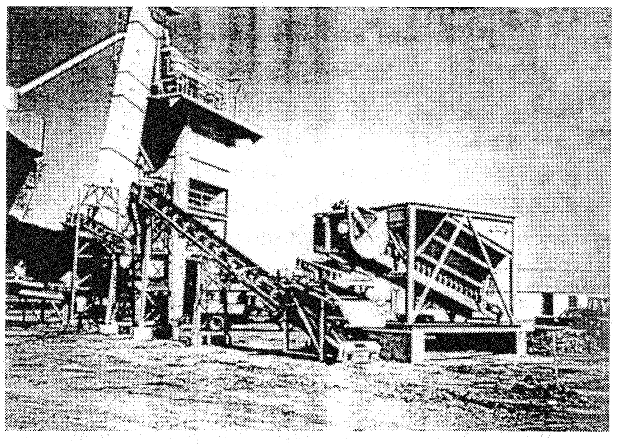


FIGURE 6-11 Inclined RAP feeder.

become sticky. The steeper sides reduce the tendency of the reclaimed material to bridge the opening at the bottom of the bin.

If a separate cold-feed bin arrangement is used for the reclaimed material, there is normally a variable-speed feeder belt under each bin. The bins also have a gate that can be set at various openings. The RAP, typically delivered to the bin by front-end loader, is discharged onto the feeder belt. If only one cold-feed bin is used, the RAP on the feeder belt is transferred to a charging conveyor. If more than one cold-feed bin is employed, the feeder belt under each bin delivers the RAP to a gathering conveyor and then to the charging conveyor.

The RAP should then be passed through a scalping screen to remove any oversized pieces of asphalt mixture or deleterious material. An alternative arrangement is to place a scalping screen or fixed-bar grizzly over the cold-feed bin and thereby remove any oversized and foreign material before it enters the bin. Still another alternative is to place a small crusher in the system between the cold-feed bin and the charging conveyor to reduce the size of any oversized RAP pieces.

After exiting the scalping screen, the RAP is dropped onto the inclined conveyor for transport to the plant. If it is being carried to a batch plant, the material can be delivered to the boot (bottom) of the hot elevator, to one of the hot bins at the top of the plant, or to the weigh hopper. If the RAP is being transported to a drum-mix plant, the charging conveyor will be equipped with a weigh bridge system that measures the weight of the material passing over it, as well as the speed of the belt. This weight, in tonnes (tons) per hour, includes the moisture in the RAP. The average moisture content value is input manually to the plant controls, and the dry weight of the RAP is calculated by the plant computer. The information determined from the weigh bridge system on the RAP charging conveyor is combined with the data from the weigh bridge system for the aggregate to determine the plant input tonnage.

For most parallel-flow drum-mix plants, the charging conveyor delivers the RAP into the center rotary inlet located on the mixing drum, as discussed below and in Section 9. For some counter-flow drum-mix plants, the charging conveyor delivers the RAP into the upper portion of the mixing chamber or drum, just ahead of the asphalt cement injection point, as discussed below and in Section 10. For other counter-flow drum-mix plants, the RAP is delivered to an outer drum where the aggregate, RAP, and new asphalt cement are blended.

Single-Feed Drum-Mix Plants

A very limited number of drum-mix plants have only one set of cold-feed bins. Some of the bins are used to hold the new aggregate, and the others are used to handle the RAP. For one type of plant still in use but no longer manufactured, the new and reclaimed aggregates are fed into the burner end of the drum-mix plant at the same time. In this case, the RAP is handled in the same way as aggregate. It can be deposited underneath or on top of the aggregate, depending on which cold-feed bins are selected to hold the asphalt-coated aggregates. The reclaimed material is often deposited on top of the aggregate so that it can be exposed to a water spray (used to reduce potential emission problems) when traveling up the charging conveyor.

Split-Feed Drum-Mix Plants

Most parallel-flow and counter-flow drum-mix plants are equipped with a split-feed system to handle the RAP. Typically, a separate cold-feed bin and conveyor system is used to feed this material into the drum mixer through a rotary center inlet.

On some older plants, however, a separate cold-feed bin is not used for the RAP. Rather, the material is placed in one or more of the conventional cold-feed bins. The gathering conveyor under the bin or bins is modified, however, by being divided into two different belts, moving in different directions. The gathering conveyor under the feeder belts for the new aggregate carries this material to a charging conveyor moving to the burner end of the drum-mix plant. The gathering conveyor under the feeder belts for the RAP transports the RAP to a separate charging conveyor that carries it to an inlet location near the midpoint of the length of the mixing drum on a parallel-flow drum-mix plant and to the upper end of the mixing unit or to the outer drum on a counter-flow drum-mix plant.

Regardless of which cold-feed bin system is used for the RAP, a weigh bridge and speed sensor are employed to measure the amount of reclaimed material moving up the charging conveyor and into the drum. Although using the same cold-feed bin system to handle both new and reclaimed material saves the cost of a separate cold-feed bin or bins for the RAP, there is a greater chance of bridging the opening at the bottom of the bin because of the shallower angle of the sides of the conventional cold-feed bins.

ADDITION OF HYDRATED LIME

To reduce the occurrence of moisture damage in the HMA mix, hydrated lime is sometimes added to the mix at a rate of 1 to 2 percent by weight of aggregate. This material may be added in one of two different forms—as a dry powder or as a slurry. If a slurry is used, it is typically proportioned as one part hydrated lime to three parts water. The lime can be added by being mixed with the aggregate on the cold-feed belt or by being introduced into the rear of the drum, similar to what is done with a conventional mineral filler. The addition of lime as a mineral filler is discussed in Sections 9 and 10.

The dry lime or slurry is often added to the aggregate as it moves along the gathering conveyor or up the charging conveyor. The lime is normally placed on top of the aggregate and is then mixed with the aggregate either when the aggregate passes through the scalping screen, when it passes through a set of plows or mixing paddles on the belt, or in an in-line pugmill placed in the cold-feed system between the gathering conveyor and the charging conveyor. The amount of mixing of the lime that occurs as aggregate passes through the scalping screen, however, is normally not enough to ensure that all of the aggregate particles are adequately coated with lime. Therefore, this method should generally not be used. If the lime is to be mixed with the aggregate on the gathering or charging conveyor, a set of plow blades should be used to move the aggregate and the lime back and forth as the material moves up the belt. An even better way to ensure that the hydrated lime is properly mixed with the coarse and fine aggregate is to place a twin-shaft pugmill in the cold-feed system. This latter method distributes the lime more uniformly throughout the aggregate particles.

CALIBRATION

The rate of aggregate flow from each cold-feed bin should be determined to ensure that the proper proportion of each aggregate is being delivered from the bin to the plant, so that the mix will have the proper gradation. The method used to calibrate the cold-feed bins depends on the type of plant being used and on the type of feeder belt under each bin.

Each cold-feed bin should be calibrated at a flow volume that will be within the range of material to be delivered from the bin during mix production. Ideally, the bin should be checked at rates that are approximately equal to 20, 50, and 80 percent of the estimated operational flow rate.

If a cold-feed bin is equipped with a constant-speed feeder belt, the only way to change the amount of aggregate delivered from the bin is to vary the size of the gate opening. In this case, the size of the gate opening at which the calibration procedure is conducted depends on the proportion of aggregate to be drawn out of the bin. If, according to the mix design information, 25 percent of the total amount of aggregate in the asphalt mix should come out of a given bin, that bin should be calibrated at the gate opening size that will typically provide this rate of flow. In addition, the calibration procedure should be completed at both the next-largest and next-smallest gate settings to allow for small changes in production rate. If significant changes in production rate are anticipated, the cold-feed bins should be calibrated at whatever gate openings are needed to provide the proper amount of that size of aggregate to the plant.

Many cold-feed bins on batch plants and the vast majority of the cold-feed bins on both parallel-flow and counter-flow drum-mix plants are equipped with a variable-speed feeder belt in addition to a means of changing the size of the gate opening under the bin. The gate opening on the cold-feed bin should be set at that level which will deliver the proper amount of aggregate for the desired plant production rate. In addition, the bin should be calibrated at three different feeder belt speeds: 20, 50, and 80 percent of the range of speed of the feeder belt. The optimum operating condition is for the cold-feed bin to provide the proper amount of aggregate from the preset gate opening with the feeder belt operating at approximately 50 percent of its maximum speed. Doing so allows the plant operator some latitude to increase or decrease the production rate of the plant without having to change the setting of the gate opening at the bottom of the cold-feed bins.

The calibration of each cold-feed bin is accomplished by drawing aggregate out of a bin for a specific period of time and determining the weight of the aggregate delivered during that time. In most cases, a truck's empty (tare) weight is determined. Aggregate is withdrawn from the cold-feed bin and delivered, usually by means of a diverter chute on the charging conveyor, into the truck. After a set period of time, the flow of the aggregate is stopped, and the truck is weighed to determine the amount of aggregate delivered. For cold-feed bins equipped with only a constant-speed feeder belt, the weighing process is accomplished for a variety of gate opening settings. For cold-feed bins that are equipped with variable-speed feeder belts, the calibration process may be repeated at different gate opening settings, with at least three different belt speeds per gate opening.

On a drum-mix plant, the weigh bridge must also be calibrated. This is accomplished by running aggregate over the charging conveyor and thus the weigh idler for a given period of time. Instead of being delivered to the drum mixer, the aggregate is diverted into an empty (tared) truck. After the selected time period has passed, the aggregate flow is terminated, and the truck is weighed to determine the amount of aggregate delivered. The weight thus determined is compared with the weight of aggregate calculated by the plant computer system. The two weights should be within the tolerance band set by the agency and typically within 1.0 percent of each other (assuming that the weigh bridge and the truck scale are both accurate to 0.5 percent). It must be noted that both methods used to weigh the material—the conveyor weigh bridge and the truck scale—must usually meet a tolerance of 0.5 percent of the true weight. Since one weight is being compared against the other and each has a tolerance of 0.5 percent, the two weights should be within 1.0 percent of each other.

For many drum-mix plants, the weigh bridge should be calibrated at a production rate that is near the estimated normal production rate for the plant. If the drum mixer is going to run at 90 percent of capacity, the calibration of the weigh bridge should be completed at three production rates: 70, 85, and 100 percent of capacity. This calibration, however, will probably not be correct if the plant is run at a much lower capacity, such as 60 percent. In this case, the calibration procedure should be repeated at the lower production rate (bracketing the estimated rate with one rate above and one rate below the most probable production level).

Because of the differences in the operating procedures of different makes and models of cold-feed bins and asphalt plants, it is difficult to generalize the exact calibration procedure to use. The calibration instructions provided with the plant should be followed.

SUMMARY

Several key factors should be considered in the storage and handling of aggregate and RAP, both when in the stockpile and when being fed into a batch or drum-mix plant:

- The stockpiles should be built on a clean, dry, and stable foundation. Positive drainage for each pile should be provided. Aggregate of different sizes should be separated.
- The moisture content of each aggregate should be determined at least twice a day and more often if moisture conditions change, such as after rainfall. The average moisture content of the aggregate coming into the plant dryer or drum mixer should be input to the plant control system to permit proper setting of the burner controls, calculation of the dry weight of the incoming aggregate, and determination of the plant production rate.
- Covering the aggregate piles—particularly those of fine aggregate—with a roof should be considered to reduce the moisture content of the stockpiled aggregate.
- Stockpiles should be built in horizontal or gently sloping layers. Any stockpiling procedure that results in aggregate being pushed or dumped over the side of a stockpile should be avoided to prevent segregation. Travel on stockpiles by trucks and front-end loaders should be minimized to prevent aggregate breakage and the generation of fines.
- The front-end loader should work the full face of the stockpile, removing the aggregate in a direction perpendicular to the flow of the aggregate into the stockpile. The operator of the front-end loader should go straight into the stockpile, roll the bucket up, and then back out instead of scooping up through the stockpile. Doing so will minimize segregation caused by the larger-sized aggregate rolling down the face of the stockpile. The operator is the key to providing a consistent gradation of material to the plant and minimizing segregation.
- If the coarser-aggregate stockpiles are segregated, the loader operator should not place a bucketful of coarse material and then a bucketful of finer material into the cold-feed bins. The segregated materials should be preblended by the loader (or by other means) before the material is introduced into the cold-feed bins.

- Cold-feed bins that are kept relatively full of aggregate should be separated by bulkheads between bins, located at the top of the bins, so aggregate that is supposed to be in one bin cannot overflow into another.
- The discharge end of the feeder belt should be equipped with a "no-flow" device to indicate to the plant operator when an inadequate amount of aggregate is being delivered from a cold-feed bin.
- If the plant is equipped with variable-speed feeder belts, they should be run at a speed that is between 20 and 80 percent of their maximum speed. Ideally, the speed of the feeder belts should be in the middle of their speed range to allow for small increases and decreases in plant production capacity without the need to change the settings of the cold-feed bin gate openings. The feeder belts should be calibrated at the speed at which they will typically run.
- A scalping screen should be placed in the cold-feed charging system of a drum-mix plant or a batch plant operated without screens to remove any oversized and deleterious material from the aggregate.
- For drum-mix plants, the weigh bridge should be checked to see whether the weigh idler is free to move and the conveyor belt is tight around the gravity takeup pulley to ensure an accurate belt speed sensor reading.
- The cold-feed bin(s) used for RAP should have steep sides to prevent the material from bridging the gate opening at the bottom of the bin.
- The RAP feed system on both a batch and a drum-mix plant should include a scalping screen over the cold-feed bin or at some other point in the material flow.
- Cold-feed bins should be calibrated. For bins equipped with constant-speed feeder belts, the flow of aggregate from the bins should be determined at three different gate opening settings: one at the estimated plant production rate, one above that rate, and one below that rate.
- For cold-feed bins equipped with variable-speed feeder belts, the bins may be calibrated at up to three different gate openings, as well as at three different belt speeds—approximately 20, 50, and 80 percent of the range of belt speeds.
- The weigh bridge on the charging conveyor of a drum-mix plant must also be calibrated. This should be accomplished by collecting and weighing the amount of aggregate that passes over the weigh bridge in a set amount of time and comparing that weight with the weight determined by the plant computer system. For the weigh bridge to be calibrated properly, the two weights should be within 1.0 percent of each other.

7 Asphalt Cement Supply System

The asphalt cement supply system consists of two major components. The first comprises one or more tanks used to store the asphalt cement until it is needed by the mixing plant. The second is a pump and meter system used to draw asphalt cement from the storage tank in proportion to the amount of aggregate being delivered to the batch plant pugmill or drum mixer. In this section these two components, as well as the use of liquid antistrip materials and calibration of the pump and meter system, are reviewed. The section ends with a summary of key operating factors to be considered when monitoring the operation of the asphalt cement supply system.

STORAGE TANKS

Figure 7-1 shows a typical arrangement of multiple horizontal asphalt cement storage tanks. All asphalt cement storage tanks must be heated to maintain the correct temperature of the asphalt cement so its viscosity will be low enough that it can be pumped and mixed with the heated and dried aggregate. Most asphalt cement storage tanks are heated by a hot-oil system and are equipped with a small heater to heat and maintain the temperature of the oil. The hot oil is circulated through a series of coils inside the storage tank, as shown in Figure 7-2, and the heat is then transferred from the oil, through the coils, to the asphalt cement. This heat transfer process reduces the viscosity of the asphalt cement, causing it to flow upward and circulate or roll, and causing new, lower-temperature asphalt cement to come in contact with the heating oils. Thus the hot-oil system, through a set of thermocouples and solenoid valves, maintains the proper temperature of the asphalt cement, generally in the range of 150°C (300°F) to 180°C (350°F), depending on the grade and type of asphalt cement being used.

Another common approach is to use electric heating elements to heat the asphalt tanks directly. Heating elements that can be removed for servicing are submerged directly into the tank. Scavenger coils may be installed in the asphalt tank to heat oil for asphalt lines and other parts of the plant requiring heat.

A less commonly used, much older style of asphalt cement storage tank is the direct-fired tank. In this system, the asphalt cement is heated by direct heat exchange from the combustion source, through a series of heat tubes, to the asphalt cement. Care needs to be used with this type of tank to prevent overheating of the asphalt cement immediately adjacent to the heat tubes.

All storage tanks should be completely insulated and heated, and all the lines for both asphalt cement and heating oil should be insulated to prevent loss of heat. Both the line used to fill the tank from the asphalt cement transport truck or railcar and the discharge line from the tank to the plant should be located near the bottom of the tank. The return line from the pump should be located so that the asphalt cement enters the tank at a level beneath the surface of the asphalt cement stored in the tank and does not fall through the air. This practice reduces the oxidation of the asphalt cement during the circulation process.

On most asphalt storage tanks, the discharge line to the batch or drum-mix plant is located at a point closest to the plant to minimize the amount of pipe required. The return line for the asphalt cement not used by the plant (depending on the particular plant pump and meter setup, as discussed below) is typically located on the same end of the storage tank. If it is desired to circulate the contents of the tank in order to keep the material blended, the return line should be relocated to the opposite end of the tank. Otherwise, only the material located at the end of the tank that contains the discharge and return lines will be circulated.

If the HMA plant is equipped with more than one asphalt cement storage tank, the capability should exist to pump material from one tank to another. It is important that the plant operator know from which tank material is being pulled, especially if different grades or types of asphalt cement are being stored in different tanks.

All asphalt cement storage tanks contain a "heel" of material at the bottom of the tank. This material, located beneath the heating coils, usually does not circulate efficiently. The volume of material in the heel depends on the type and style of the storage tank, the location of the heating coils, and the amount of time since the tank was

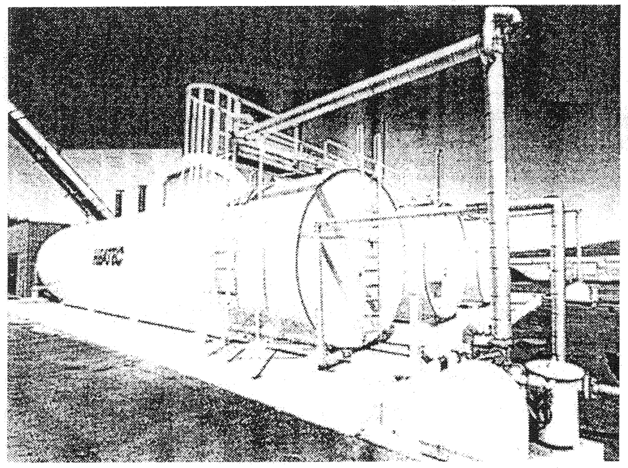


FIGURE 7-1 Typical horizontal asphalt cement storage tanks.

last cleaned. It is recognized, however, that some asphalt cement will typically remain in the bottom of an "empty" tank. Therefore, placing asphalt cement of one type or grade into a tank that previously contained a different type or grade can cause an alteration of the properties of the asphalt cement to the point that it no longer meets specifications.

The capacity of an asphalt cement storage tank is a function of its diameter and length. The amount of material in the tank can be determined using a tank "stick." The stick measures the distance from the top of the dome or the top of the tank down to the level of the asphalt cement in the tank (the point at which the tank stick just touches the top of the material). This distance is noted, and the amount of asphalt cement in the tank below this level is determined from the tank manufacturer's calibration chart.

When asphalt cement is delivered from a transport vehicle into a storage tank, it is important to ensure either that the tank is clean or that it already contains the same type of material as that being pumped into the tank. If it is empty at the time the new material is being added, the tank should be checked to ensure that no water has accumulated in the bottom. If asphalt cement is loaded on top of an asphalt emulsion or on top of a layer of water in the tank, violent foaming of the asphalt cement may occur, creating a serious safety problem. Care should be taken to ensure that all valves are in the proper position to prevent pressure from building up in the lines and causing an explosion.

Most asphalt storage tanks are horizontal, as in Figure 7-1. Increasingly, however, vertical tanks are being used. Vertical tanks minimize separation of modifier in asphalt cement and result in less overall area needed for storage.

PUMP AND METER SYSTEM

Batch Plants

Batch plants typically employ one of two systems to transfer asphalt cement from the storage tank to the weigh bucket near the pugmill. The type of system used depends on the location of the return line—whether one or two asphalt cement lines are present from the pump to the weigh bucket.

In the single-line process, two lines extend from the storage tank to the pump, but only one line extends from the pump to the weigh bucket. The pump is a constant-volume, constant-speed unit that runs continuously. Asphalt cement is always being pulled from the storage tank through the pump and circulated back to the tank. When asphalt cement is needed in the weigh bucket, a valve on the end of the line at the top of the weigh bucket opens, and material is discharged into that bucket. When the proper amount of asphalt cement is in the bucket, as determined by weight, not volume, that valve is shut, and a pressure relief valve at the pump is opened. The asphalt

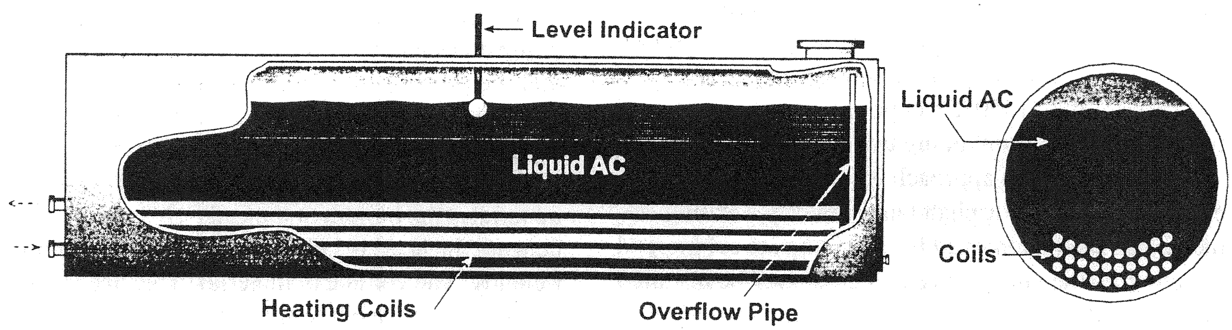


FIGURE 7-2 Heating of horizontal storage tank.

cement then passes through the pump, but is recirculated back to the storage tank, in the second line, instead of being sent to the plant. A variation on this system allows the asphalt cement to circulate through the pump itself instead of being returned back to the storage tank. In the dual-line process, one line is used to deliver asphalt cement to the weigh bucket, and the second line is used to return the "excess" asphalt cement back to the storage tank. The asphalt cement passes through the pump to a three-way valve at the weigh bucket. When asphalt cement is needed in the weigh bucket, the valve opens, and the material is discharged into the bucket. When the preselected weight is reached, the valve closes, and the asphalt cement is recirculated in the second line back to the storage tank.

Because the amount of asphalt cement used in almost all batch plants is measured by weight, no correction is needed for the temperature of the asphalt cement. On a few older batch plants, however, the amount of asphalt cement delivered is determined by volume. In this case, the amount of asphalt cement delivered to the pugmill must be corrected in accordance with both the temperature and the specific gravity of the asphalt cement. This can be accomplished using the procedure given in ASTM Specification D4311.

Drum-Mix Plants

Asphalt Cement Delivery

Most drum-mix plants employ one of three systems to pull the asphalt cement from the storage tank, meter it, and pump it to the plant: (*a*) a variable-volume pump with a constant-speed motor, (*b*) a constant-volume pump with a variable-speed motor, or (*c*) a constant-volume pump with a constant-speed motor with a metering valve. The use of a particular pump and meter system is dependent on the make, model, and date of manufacture of the plant and the choice of the plant owner.

With a system that uses a variable-volume pump driven by a constant-speed motor, the amount of asphalt cement pulled from the storage tank is controlled by changing the volume of asphalt cement being pumped. The volume needed at the pump is determined by the plant computer in proportion to the amount of aggregate being fed into the plant. As the amount of aggregate entering the drum mixer increases, the volume of asphalt cement pulled through the pump also increases. When the plant is not using asphalt cement, the material continually passes through the pump and meter and through a three-way valve that is set to circulate the asphalt cement back to the storage tank instead of to the plant.

A second system incorporates a fixed-displacement (constant-volume) pump driven by a variable-speed motor. The quantity of asphalt cement delivered to the meter is varied by changing the speed of the motor. The amount of material sent to the plant is also dependent on the aggregate feed rate. A three-way valve in the system downstream of the meter allows the asphalt cement to be recirculated back to the tank when not needed by the plant.

The third system consists of a constant-volume pump driven by a constant-speed motor. In this arrangement, the same volume of asphalt cement is pulled from the storage tank at all times. A proportioning valve is placed in the line between the pump and the asphalt cement meter. The position of the valve determines the volume of material sent through the meter. The proportioning valve sends some of the asphalt cement through the meter and the rest back through the recirculating line to the storage tank. The system also has a valve downstream of the meter that allows the asphalt cement sent through the meter to be recirculated to the tank. This valve is used during the warm-up period for the meter and during the calibration process. Again, the position of the proportioning valve is determined by the rate of aggregate feed into the drum mixer, both of which are controlled by the plant computer. A constant-volume, constant-speed system is shown in Figure 7-3.

With parallel-flow drum-mix plants, the asphalt cement line typically enters the drum from the rear, and the binder material is discharged into the drum at a point normally one-quarter to one-third the length of the drum, from the discharge end of the drum. With one type of counterflow drum-mix plant, the asphalt cement pipe is placed in the mixing unit portion of the drum, behind or below the burner, and the binder material is added shortly after the aggregate passes out of the exhaust gas stream. In another type of counter-flow drum-mix plant, the asphalt cement is added to the heated aggregate in the outer drum away from the burner.

Temperature Compensation

Most asphalt meters measure the flow of asphalt by volume and convert this volume to weight using the specific gravity and temperature of the asphalt. Asphalt cement expands when heated. Thus the volume of asphalt cement at 180°C (350°F) will be somewhat greater than its volume at 150°C (300°F). This latter volume will be more than the volume at 15°C (60°F), which is the standard temperature for determining the volume of asphalt cement using conversion charts based on the specific gravity of the asphalt cement. If the specific gravity of the as-

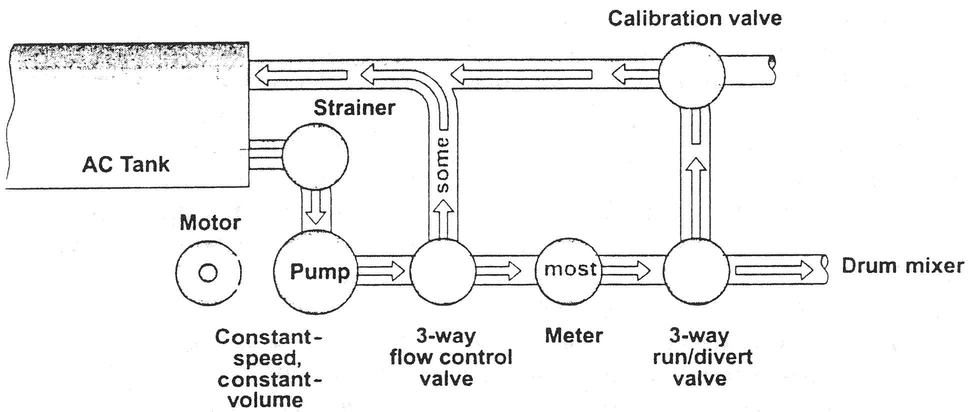


FIGURE 7-3 Asphalt metering system for drum-mix plants with constant-volume, constant-speed pump and flow control valve.

phalt cement and its temperature are known, however, the volume measured at the elevated temperature can easily be converted to the standard volume at 15°C (60°F) using the procedure given in ASTM Specification D4311.

The volume of asphalt cement moving through the meter likewise changes with temperature. Some meters are set to measure the temperature of the asphalt cement moving through the system and send that information, together with the volume data, to the plant computer. The specific gravity of the asphalt cement is set manually on the controls. The computer then calculates the volume of asphalt cement being fed into the plant at the standard temperature of 15°C (60°F) and converts that amount to a weight that is displayed on the plant console.

On some meters, a temperature-compensating device is installed directly on the meter stand itself. As the temperature of the asphalt cement changes, the meter senses the change and, on the basis of the specific gravity of the asphalt cement, calculates the volume, at 15°C (60°F), passing through the meter. This corrected volume (and corresponding weight) is then sent to the plant console for display.

Regardless of the particular arrangement employed, the asphalt pump system must be capable of changing the volume of asphalt cement passed through the meter in direct response to the demand of the aggregate supply. The response of the pump system must be directly related to the change in the amount of material measured by the aggregate weigh bridge system. In addition, the volume of asphalt cement measured at any given temperature must be converted to the volume at 15°C (60°F). At this standard reference temperature, the weight of the asphalt cement can be determined in terms of tonnes (tons) of material per hour, as with the aggregate feed rate. The total of the aggregate input (new aggregates plus RAP) and the weight of the asphalt cement provides the production rate for the drum mixer, in tonnes (tons) of HMA per hour. As production rates are adjusted, the asphalt pump system is timed so that the increase or decrease in asphalt cement reaches the drum at the same time that the increased or decreased material flow reaches that point in the drum.

Another type of asphalt meter, called a "mass-flow meter," measures the flow of asphalt by weight and, therefore, does not require temperature corrections.

CALIBRATION

The pump and meter system on a batch or drum-mix plant must be calibrated to ensure that the proper amount of asphalt cement is being delivered to the mix. For a batch plant operation, the amount of asphalt cement needed is measured by weight (although a few older batch plants measure the asphalt cement by volume), with the asphalt cement being placed in the plant weigh bucket. For a drum-mix plant, the amount of asphalt cement is measured by volume as it is pumped through a meter into the rear of the drum.

For a drum mixer, the amount of asphalt cement is calibrated by pumping the material into an empty container, the tare weight of which is known. Most often, an asphalt distributor truck is used for this purpose. The actual weight of the material delivered to the container is determined. The weight of the material indicated by the metering system as having been delivered is then determined by multiplying the corrected volume delivered from the meter totalizer by the specific gravity of the asphalt cement. With some systems, this calculation is done automatically. The actual weight is compared

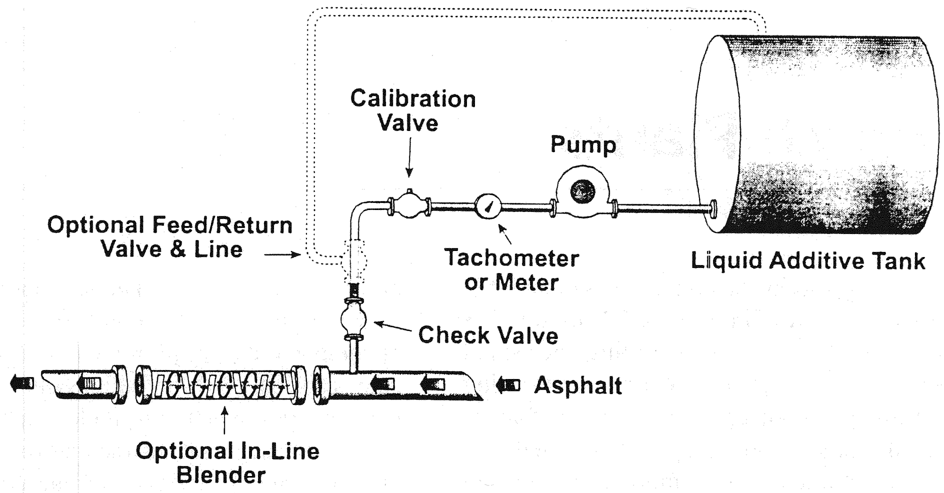


FIGURE 7-4 Typical asphalt additive tank system.

with that calculated by the metering system. To be in proper calibration, the values should be within the required tolerance band (typically 1.0 percent) for the asphalt cement supply system.

ADDITION OF LIQUID ANTISTRIP MATERIALS

Liquid antistrip additives are typically added to the asphalt cement to improve the adhesion of the binder material to the surface of the aggregate and increase resistance to moisture damage. The additive can be blended with the asphalt cement at several different locations. It can be in-line mixed with the asphalt cement as that material is pumped out of the tank truck or tank car and into the tank. It can also be added to the asphalt cement in the tank, with the two different materials being circulated together before the treated asphalt cement is sent to the drum mixer. The most common method, however is to add the liquid antistrip material to the asphalt cement, using an in-line blender, as the binder material is pumped from the storage tank to the rear of the drum-mix plant. A typical liquid antistrip additive tank system is illustrated in Figure 7-4.

SUMMARY

The following factors should be considered when monitoring the operation of the asphalt cement supply system, composed of the storage tank and the pump and meter system:

- The asphalt cement in the storage tank should be kept at a constant temperature, normally between 150°C (300°F) and 180°C (350°F). The tank should be properly insulated. All hot-oil lines should be insulated and the asphalt cement lines jacketed and insulated.
- The asphalt cement fill, discharge, and recirculation lines should enter the tank so that all charging and discharging of asphalt cement occurs below the surface of the material in the tank. Ideally, the binder return line should be located at the opposite end of the tank from the discharge line.
- The volume of asphalt cement in the tank must be converted to a standard volume at 15°C (60°F) when a tank stick is used to check the amount of material in the tank.
- The amount of asphalt cement used in a batch plant is measured by weight, so that no volume correction for temperature is needed.
- A correction for temperature must be made when calculating the volume of asphalt cement binder passing through a volumetric meter on a drum-mix plant if the meter is not equipped with an automatic temperature-compensating device. This correction is based on both the actual temperature of the asphalt cement and its specific gravity at 15°C (60°F).
- The asphalt cement supply system should be calibrated by weighing the amount of material delivered in a known amount of time. The corrected amount is determined in conjunction with knowledge of both the temperature and the specific gravity of the asphalt cement.

SECTION

8 Batch Plants

In this section the operation and components of an HMA batch plant (depicted earlier in Figures 5-1 through 5-3) are described in detail. Aggregate handling, the asphalt cement supply system, aggregate heating and drying, screening and storage of hot aggregate, mixing of aggregate and asphalt cement, production of recycled mix, loading of the mix in truck or silo, emission control, and, finally, calibration are reviewed in turn. The section ends with a summary of key operating factors to be considered when monitoring the operation of a batch plant.

AGGREGATE HANDLING

Aggregate Stockpiles

The stockpiling techniques used for handling aggregate in a batch plant mixing operation are no different from those in a parallel-flow or counter-flow drum-mix plant (see Sections 9 and 10, respectively; see also the discussion of aggregate storage and handling in Section 6). Proper stockpiling techniques are as important for batch plant operations as they are for drum-mix plant operations. In particular, care needs to be taken to keep the various aggregate sizes separate and to prevent segregation of each size of aggregate in the stockpile.

It is sometimes assumed that the screens in the batch plant tower will overcome any problems with variation in the gradation of the incoming new aggregate. If the proper proportion of each size of aggregate is not delivered from the cold-feed bins, however, the amount of aggregate in the hot bins will be out of balance. As a result of lack of separation of the aggregate stockpiles or segregation of the aggregate in one or more stockpiles, one or more of the hot bins may be either starved or overflowing with material.

Cold-Feed Systems for New Aggregates

Some older batch plant cold-feed bins are equipped with a constant-speed feeder belt under each bin (see also Section 6). The amount of aggregate withdrawn from each bin is thus controlled by the size of the gate opening at the bottom of the bin. Most plants, however, have cold-feed bins that are equipped with a variable-speed feeder belt beneath each bin. The amount of aggregate withdrawn from each bin is regulated by the size of the gate opening and the speed of the conveyor belt. The aggregate is discharged from each feeder belt onto the collecting conveyor, which runs underneath all of the bins and delivers the aggregate to a scalping screen, if one is used. After the aggregate passes through the scalping screen, it is deposited onto the charging conveyor for delivery to the dryer. If no scalping screen is included in the system (which is normally the case because the screens at the top of the plant tower are used to remove any oversized material), the aggregate is transferred directly from the collecting conveyor to the charging conveyor.

Cold-Feed Systems for Reclaimed Asphalt Pavement

RAP is usually held in a separate, steep-sided cold-feed bin that is equipped with either a variable-speed or constant-speed feeder belt. The material from the bin is deposited on the feeder belt or onto a collecting conveyor for transport to a scalping screen. After passing through the scalping screen, the RAP is deposited on a charging conveyor for delivery to the plant. An alternative method is to use a scalping screen at the transfer point between the collecting conveyor and the charging conveyor so that the RAP passes through the screen as it is being placed in the cold-feed bin.

The RAP cannot be heated in the dryer because it will generate visible hydrocarbon emissions (blue smoke) when exposed to the high-temperature exhaust gases from the burner. Thus the feed of the RAP must be separated from the feed of the new aggregate. The RAP can enter the plant at one of three primary locations downstream of the dryer: the bottom of the hot elevator; one of the hot bins at the top of the tower; or the weigh hopper, which is the preferred location for most batch plant operations.

Addition of Hydrated Lime

Hydrated lime can be added to the aggregate in a batch plant mixing operation in one of two ways: it can be placed on the aggregate, in either dry or slurry form, similar to the method of addition for a drum-mix plant (see Sections 9 and 10), or it can be added in dry form to the aggregate, similar to a mineral filler. If the hydrated lime is added to the aggregate in slurry form, the water in the slurry will have to be removed during the drying process inside the aggregate dryer. This will both increase the cost of drying the aggregate and reduce the production rate of the plant.

ASPHALT CEMENT SUPPLY SYSTEM

Storage Tanks

The storage tank used for the asphalt cement for a batch plant operation is the same as that used for a drum-mix plant. The material is generally stored at temperatures between 149°C and 177°C (300°F and 350°F), depending on the grade or viscosity (or both) of the asphalt cement. The binder material must be fluid enough to mix properly with the aggregate in the pugmill.

Pump System

The asphalt content of the mix is determined by weight, not volume (except for a very few old batch plants). Thus no meter is used to proportion the amount of asphalt cement needed in the mix. The pump, which runs continuously, pulls the asphalt cement from the storage tank and either delivers it to the weigh bucket or recirculates it to the tank, depending on the opening of the control valve at the weigh bucket. When the valve is open to the weigh bucket, the binder material is pumped into the bucket until the correct weight is reached. At that time, the valve is closed, and the asphalt cement is recirculated back to the storage tank.

Addition of Liquid Antistrip Additives

Liquid antistrip additives are added to the asphalt cement in the batch plant in a manner similar to that for a drum-mix plant. The additive can be blended with the asphalt cement as that material is pumped out of the delivery vehicle or as it is pumped from the storage tank to the weigh bucket. Alternatively, it can be blended with the asphalt cement in the storage tank by circulating the two materials together for a period of time before the treated material is pumped to the asphalt cement weigh bucket.

AGGREGATE HEATING AND DRYING

The dryer on a conventional batch plant operates on a counter-flow principle. Its operation is similar to that of a counter-flow drum-mix plant (although, since the aggregate dryer was in use before the modern counter-flow drum-mix plant, it is more correct to say that the counter-flow drum-mix plant operates similarly to a conventional aggregate dryer). The aggregate is charged into the dryer at the upper end of the drum and flows through the dryer by the action of the rotating flights and gravity. The burner is located at the lower or discharge end of the dryer. The exhaust gases move toward the upper end of the dryer, counter to the direction of the flow of the aggregate. This process is shown in Figure 8-1.

The dryer is a rotating drum that is generally 1.5 to 3.0 m (5 to 10 ft) in diameter and 6 to 12 m (20 to 40 ft) in length. The length of the drum is normally propor-

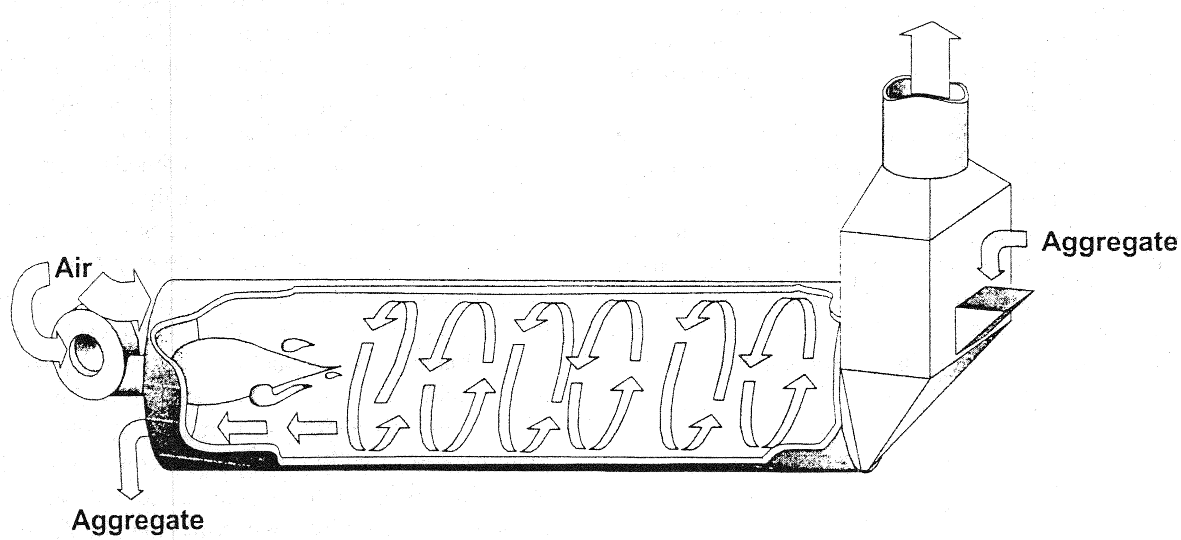


FIGURE 8-1 Typical counter-flow dryer.

tional to the diameter at a ratio of 4 : 1. Thus a dryer with a diameter of 2.4 m (8 ft) would typically be 9.7 m (32 ft) in length. The function of the dryer is to remove the moisture from the aggregate and to heat the material to the desired discharge temperature, generally in the range of 138°C to 163°C (290°F to 325°F). The moisture content of the aggregate upon exiting the dryer should be less than 0.5 percent and ideally less than 0.2 percent.

The aggregate is fed into the dryer from the charging conveyor by means of either a charging chute at the top of the dryer or, occasionally, a Slinger conveyor at the bottom of the dryer. The flights inside the dryer, shown in Figure 8-2, are used to lift and tumble the material in a veil across the diameter of the dryer. As the aggregate flows down the dryer, it is heated by the exhaust gases from the burner, and the moisture is driven off. The burner flame, which generally has a much longer, thinner shape than the short, bushy flame of the burner on a parallel-flow drum-mix plant, extends into the dryer to penetrate the aggregate veil. The aggregate is heated and dried by the exhaust gases from the burner by means of conduction, convection, and radiation. Because of the higher efficiency of the counter-flow system, a batch plant dryer typically uses less fuel to heat and dry a given amount of aggregate than does the mixing drum on a parallel-flow drum-mix plant.

The dwell or residence time of the aggregate inside the dryer is a function of the length of the drum, the design and number of flights, the speed of rotation, and the slope of the dryer [typically 2.5 to 6.0 deg, or 26 to 63 mm/m ($\frac{5}{16}$ to $\frac{3}{4}$ in./ft)]. If more than 0.5 percent remains in the aggregate upon discharge from the dryer, the density of the veil of aggregate inside the drum must be increased, typically by lowering the slope of the dryer or by changing the number or type of flights used in the dryer. Both of these procedures will increase the dwell time of the aggregate inside the dryer, and both may be difficult and costly to perform.

Because the aggregate typically makes up between 92 and 96 percent of the weight of the asphalt mix, it governs the temperature of the mix produced in the pugmill. Excessive heating of the aggregate may cause excessive hardening of the asphalt cement in the mixing process. If a recycled mix is to be produced, however (as discussed in a later section), the new aggregate must be superheated in the dryer to accomplish the necessary heat exchange in the pugmill. In this case, the required temperature of the new aggregate is dependent on the amount of RAP and its moisture content.

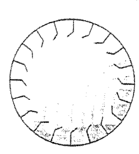


FIGURE 8-2 Proper veiling.

SCREENING AND STORAGE OF HOT AGGREGATE

Hot Elevator

New Aggregate

The heated and dried aggregate is discharged from the dryer through a chute into the bottom of the bucket elevator. The hot material is transported by the continuously moving buckets up to the top of the batch plant tower, as illustrated earlier in Figure 5-1. From the hot elevator, the aggregate is delivered to the screen deck at the top of the tower.

RAP

It is not generally advisable to add the RAP into the plant at the bottom of the hot elevator, particularly when the amount of RAP exceeds approximately 10 percent of the mix. The RAP should be fed, if possible, into the new-aggregate discharge chute from the dryer so that it is on top of the hot new aggregate and is directed into the center of the buckets. If that is not feasible, the reclaimed material should be deposited into a separate steep-sided chute located above the new-aggregate entry at the bottom of the hot elevator. The RAP must be placed in the buckets after the new aggregate to prevent the asphalt-coated material from sticking to the buckets as it is heated by contact with the superheated new aggregate.

There is a limit to the amount of RAP that can be fed into the bottom of the hot elevator, and this limit is related to the heating process as the material travels to the top of the tower. Depending on the percentage of RAP used in the mix, the moisture content of the RAP, and environmental conditions, the reclaimed material can be sufficiently heated while traveling up the hot bucket elevator with the new aggregate to stick to the screens instead of passing through them. The result may be clogging (blinding) of the screens and a consequent change in the gradation of the new aggregate in each of the hot bins as material that should be in a given bin passes over that bin and ends up in another, coarser-gradation bin. If the screens become clogged enough, shutdown of the plant may eventually result. It is recommended that if more than 10 percent RAP is to be added to the mix and if the RAP is to be introduced into the plant at the bottom of the hot elevator, the screens at the top of the tower be either removed or bypassed. If this is done, all of the new and reclaimed aggregate will be delivered into the No. 1 hot bin.

Screen Deck

The aggregate is discharged from the hot elevator buckets onto a set of vibrating screens that are used to separate the material into different sizes. Four screen decks typically are used, arranged as shown in Figure 8-3. The top screen is generally a scalping screen used to remove any oversized material from the aggregate flow and reject it to a bypass or overflow chute. The remaining three screen decks divide the aggregate into four different fractions. The amount of material in each fraction is dependent on the size and shape of the openings in the screens. Each screen deck may have several different screen sizes in order to improve screening efficiency and protect the smaller screens from oversized aggregate.

The screens can have square (most common), rectangular, or slotted openings. For example, in a typical batch plant used to manufacture base, binder, and surface course mixes, the openings in a square screen might be 32 mm ($1\frac{1}{4}$ in.) for the top deck, 14 mm ($\frac{9}{16}$ in.) for the second deck, 8 mm ($\frac{5}{16}$ in.) for the third deck, and 4 mm ($\frac{5}{32}$ in.) for the bottom deck. The sand-sized aggregate, smaller than 4 mm ($\frac{5}{32}$ in.) in diameter, would pass directly through all of the screens and be deposited into the No. 1 hot bin. Aggregate that was larger than 4 mm ($\frac{5}{32}$ in.) but no larger than 8 mm ($\frac{5}{16}$ in.) would be carried over the first screen and then dropped into the No. 2 hot bin. For any particular mix, the proper screens need to be used in the screen deck to produce the required gradation in the asphalt mix. If mix gradations change significantly, it may be necessary to change the screen sizes used at the top of the mixing tower. Different-sized screens than those in the above example may be used for various combinations of aggregate to meet particular agency specifications.

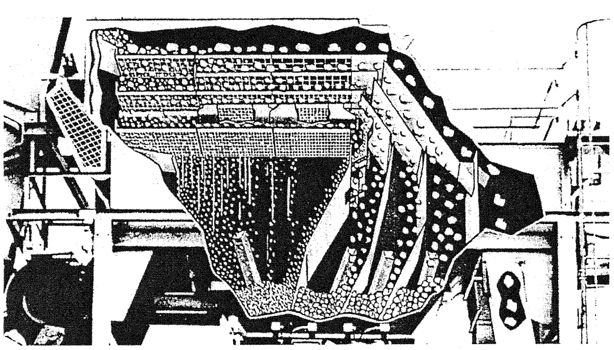


FIGURE 8-3 Cutaway illustration of screening process.

Many screen decks use a split-screen setup in which screens with two different-sized openings are placed at the same level (in the same deck). For example, the top deck might employ a screen with an opening of 8 mm ($\frac{5}{16}$ in.) for the half of the deck nearest to the hot elevator and a screen with an opening of 32 mm ($1\frac{1}{4}$ in.) for the half of the deck over the No. 3 and 4 hot bins. This arrangement will improve the efficiency of the screening operation.

Not all of the material that should be in a particular bin always ends up in that bin. The term "carryover" refers to finer aggregate that fails to pass through the larger screens and is deposited in bins intended for larger-sized material. A small amount of carryover, generally less than 10 percent, from one bin to the adjacent bin is often found. The carryover is caused by the flow of aggregate moving across instead of through the screens. The amount of carryover is increased as the openings in the screens become clogged or blinded with aggregate and as the amount of aggregate being delivered by the hot elevator is increased. The primary problem occurs when the amount of carryover is variable over time, causing the gradation of the aggregate found in each of the hot bins to change. This situation is often due to continued variation in the rate of feed of the aggregate from the cold-feed bins.

Moreover, if a screen develops tears or holes, some of the aggregate that should be deposited in another bin will pass through the screen and end up in a bin with smaller-sized material. Thus screens at the top of the tower should be checked regularly to ensure that there are no holes and that the screens are not clogged or blinded with aggregate. Analysis of hot-bin gradations will help identify where tears or holes exist.

In some locations, batch plants are routinely operated without screens; the screen deck is removed, or a screen bypass chute is used. All of the aggregate that is transported up the hot elevator is deposited directly into the No. 1 bin. Without screens, the batch plant is operated in much the same manner as a counter-flow drum-mix plant, and the final gradation of the mix is determined by the consistency of the gradation of the aggregate in the cold-feed bins. Because no screening is done to separate the aggregate into different sizes, the various gradations that are proportioned out of the cold-feed bins (unless only one aggregate blend is used to make the mix) are deposited directly into the No. 1 hot bin upon discharge from the hot elevator. All of the aggregate used in the mix is drawn from this one hot bin into the weigh hopper and then into the pugmill.

Hot Bins

New Aggregate

The total capacity of the hot bins is usually proportional to the size of the pugmill. The capacity of each of the hot bins, however, is not the same. The No. 1 (sand) bin has the greatest capacity. Generally about 40 to 50 percent by weight of the aggregate delivered by the hot elevator passes through the screens and into this bin. The typical capacity (percentage of total hot-bin capacity) of each of the remaining three bins is 25 to 30 percent for bin No. 2, 15 to 20 percent for bin No. 3, and 10 percent for bin No. 4.

Some segregation of the aggregate occurs in each hot bin, particularly in the No. 1 (sand) bin. This segregation is caused by the finer material in each size fraction passing through the screens more directly than the coarser material of the same fraction. Thus the aggregate on the side of each hot bin that is closest to the hot elevator will generally be finer in gradation than the aggregate on the opposite side of the same hot bin.

The partitions between the hot bins should be checked regularly to ensure that no holes have developed and that aggregate in one bin is not flowing into another. The overflow pipes at the top of each bin should be open. Fines sometimes build up in the corners of the No. 1 bin. When the level of aggregate in the bin is low, the collected fines can break loose, and a slug of that material can enter the weigh hopper. If this is a continuing problem with a particular plant, fillets can be welded in the corners of the No. 1 bin to reduce the buildup of the fine material, or a plate can be used at the top of the No. 1 bin to deflect the fines and direct that material into the center of the bin.

Even though the screens on the batch plant are used to regrade the aggregate that is fed into the plant from the cold-feed bins, the proportion of material delivered from each cold-feed bin must be correct, or one of the hot bins will either run out of material or overflow. Because all the aggregate that is discharged from the cold-feed bins will end up in the mix, it is very important that the aggregate placed in the cold-feed bins be graded consistently. The screens should not be used to attempt to overcome a problem with a variable incoming aggregate gradation, as discussed below.

RAP

Although the practice is not recommended, in the operation of some batch plants RAP is deposited directly into one of the hot bins on the plant. A separate charging conveyor or bucket elevator is used to carry the reclaimed material to the top of the plant. The RAP is deposited through a screen bypass directly into the No. 1 hot bin with the sand, or into the No. 4 hot bin if no other aggregate is in that bin (when a surface course mix is being produced, and no large aggregate is needed). Further, if the RAP is placed in the No. 1 hot bin, the heat transfer process between the superheated sand and the ambient-temperature RAP can begin while both are together in that hot bin. If the asphalt-coated material is placed in the No. 4 bin, no such heat advantage is realized because of a lack of heated new aggregate in the bin.

The disadvantage of placing the RAP in either the No. 1 or the No. 4 bin is that some of the asphalt-coated particles will stick to the walls of the bin. This can be a major problem, particularly if the amount of reclaimed material used in the mix and the moisture content of that material are both high. If superheated new aggregate is in the bin adjacent to the RAP, a significant amount of the RAP will stick to the partition between the two bins.

Weigh Hopper

New Aggregate

If a base course mix is being produced, all four of the hot bins may be filled with aggregate. If a binder or surface course mix is manufactured, only two or three of the hot bins will normally be needed. The aggregate in the hot bins can be discharged into the weigh hopper in any order; however, a coarse aggregate is typically discharged into the weigh hopper before the fine aggregate is deposited. This is done to prevent the finest aggregate particles from leaking out through the gates at the bottom of the weigh hopper if the sand (No. 1 bin material) is emptied into the weigh hopper first.

Normally the gate at the bottom of the No. 3 hot bin is opened, and the aggregate is discharged into the weigh hopper until the correct weight is reached. The gate on the No. 3 bin is then shut, and the gate on the No. 2 hot bin is opened and the weigh hopper filled with that material until the correct cumulative weight (combined weight of the No. 3 and No. 2 bin material) is reached. The aggregate in each of the last two hot bins (No. 1 and No. 4) is added to the weigh hopper in the same manner. The weighing of each aggregate is accomplished in about 5 seconds. It is important that the aggregate delivered from each hot bin be deposited as near the center of the weigh hopper as possible so that the hopper is not unbalanced on the scale and spillage of the aggregate does not occur.

If mineral filler is needed in the mix, it is normally added to the aggregate already in the weigh hopper. The filler is delivered pneumatically or mechanically from a storage silo to a small holding hopper typically located on the plant tower just above the weigh hopper. It is then added to the weigh hopper by means of a horizontal screw conveyor. On some batch plants, the filler is weighed separately from the other aggregate and then augered into the main aggregate weigh hopper after the aggregate from the hot bins has been weighed. On other plants, the filler is weighed as a fifth aggregate as it is added to the material already in the hopper.

Most batch plants are operated in automatic or semi-automatic mode. The different aggregate materials temporarily held in the hot bins are weighted out one at a time. If there is not enough aggregate in a particular hot bin to attain the required weight in the weigh hopper, the weighing system waits until enough of that size aggregate is available before the aggregate from the next hot bin is weighed. Thus if the plant is to be kept running efficiently and not continually waiting for aggregate to weigh, it is important that the proper aggregate gradations be delivered consistently to the plant from the cold-feed bins. Even though the batch plant is normally equipped with screens, control of the aggregate gradation must be achieved at the cold-feed bins.

If the material delivery from the cold-feed bins is not consistent, one or more of the hot bins at the top of the batch plant tower will eventually run out of aggregate or another hot bin will contain too much material and overflow, or both. In such cases, there might be a tendency for the plant operator to switch the plant to the manual processing mode and to rebalance the aggregate flow by adding or subtracting certain aggregate sizes from the aggregate blend for a short period of time. This procedure, of course, changes the aggregate gradation in the HMA mix. To eliminate the need for such procedures, the plant operator must control the amount of each size of aggregate being delivered from the cold-feed bins, just as control is needed at the cold-feed bins to achieve a consistent aggregate gradation for a drum-mix plant, whether parallel-flow or counter-flow.

RAP

The most common location for adding RAP to a batch plant is in the weigh hopper. Once the aggregate from the hot bins has been deposited in the hopper and weighed, the reclaimed material is usually fed into the hopper as a fifth aggregate (or a sixth aggregate, if mineral filler is used in the mix), although it can actually be added to the weigh hopper in any order except first. The charging conveyor used to deliver the RAP to the weigh hopper, shown earlier in Figure 5-2, must be oversized in this case because it does not run continuously. The RAP must be deposited into the weigh hopper in approximately 5 seconds.

The RAP must be discharged from the charging conveyor into a steeply angled chute and thence into the center of the weigh hopper. The steep angle prevents the RAP from collecting in the chute. If this material is deposited on one side of the weigh hopper so that the hopper is unbalanced, an accurate weight will not be determined. The charging chute should be equipped with a flop gate to prevent the escape of fugitive dust from the weigh hopper area when the aggregate is emptied into the pugmill.

MIXING OF AGGREGATE AND ASPHALT CEMENT

The aggregate and the asphalt cement binder are blended together in a twin-shaft pugmill. Mixing paddles, shown in Figure 8-4, are attached to two horizontal shafts that rotate in opposite directions. The aggregate is first discharged from the weigh hopper into the pugmill and is mixed for a very brief time (dry-mix time) before the asphalt cement is introduced into the pugmill and the wet-mix time begins. When the mixing has been completed, the asphalt mix is discharged from the pugmill directly into a haul truck or into the conveying device for transport to the silo.

Pugmill Capacity

The size of the batch produced depends on the size of the pugmill. Some batch plants have a pugmill capacity as little as 0.9 tonne (1 ton). The pugmill of most batch plants, however, has a capacity of 1.8 to 4.5 tonnes (2 to

FIGURE 8-4 Interior of pugmill.

5 tons). One of the largest batch-plant pugmills made can mix 10.4 tonnes or 10 400 kg (11.5 tons or 23,000 lb) of mix in a single batch. The total mixing time for the various batch sizes is the same—typically as short as 35 seconds per batch. The only difference is the size of each batch, not the time needed to produce it.

Nominal pugmill capacity is determined by the dimensions of the live zone. If too much aggregate is placed in the pugmill, the material above the paddle tips will tend to stay on top and not be mixed with the other aggregate. If too little aggregate is deposited into the pugmill, the material will be thrown around and up into the air by the paddles instead of getting mixed. These two conditions are illustrated in Figure 8-5.

Batch size should not be varied from batch to batch; consistent batch size is one of the keys to a consistent mix. The optimum approach is to select a batch size at or slightly below the nominal capacity of the pugmill and produce all batches at that tonnage. If the plant is equipped with a 2.7-tonne (3-ton) pugmill and the average haul truck being used can hold 12.5 tonnes (14 tons) of mix, the batch size selected should be 2.5 tonnes (2.8 tons) [12.5 tonnes (14 tons) per truck, divided by five batches]. The plant operator should not attempt to produce four batches of 2.7 tonnes (3 tons) each and a fifth batch of only 1.8 tonnes (2 tons).

RAP

Pugmill recycling is gaining in popularity. By adding an additional weigh hopper to the batch facility, the RAP is conveyed into and weighed in its own hopper while the asphalt and virgin aggregates are being weighed. The same heat-transfer, steam-release, and practical limits apply to this approach as apply to the weigh-box method of batch plant recycling, as shown in Figure 8-6. The advantages of this method include the following:

- During long production runs of recycled pavement, an increase in the production rate per hour can be achieved with the slightly shorter batch cycle time.
- There is less wear and tear on the equipment from abrupt starting and stopping.
- The weighing process can be done more slowly and accurately with a separate weigh hopper that is undisturbed by instant steam release.

Typically, a high-speed Slinger conveyor is used to convey the RAP from the RAP weigh hopper to the pugmill. A chute or high-speed screw conveyor can also be used.

Mixing Time

Dry-Mix Time

Dry-mix time starts when charging of the aggregate into the pugmill begins and ends when asphalt injection begins. Dry-mix time should be minimal—normally no more than 1 or 2 seconds. Although the aggregate in the weigh hopper is layered, the different-sized aggregates can be blended adequately during the wet-mix cycle and do not need to be premixed during the dry-mix cycle. The main purpose of the dry-mix time is to allow some aggregate to enter the pugmill before the asphalt cement is discharged so that the liquid cement does not run out of the gates at the bottom of the pugmill.

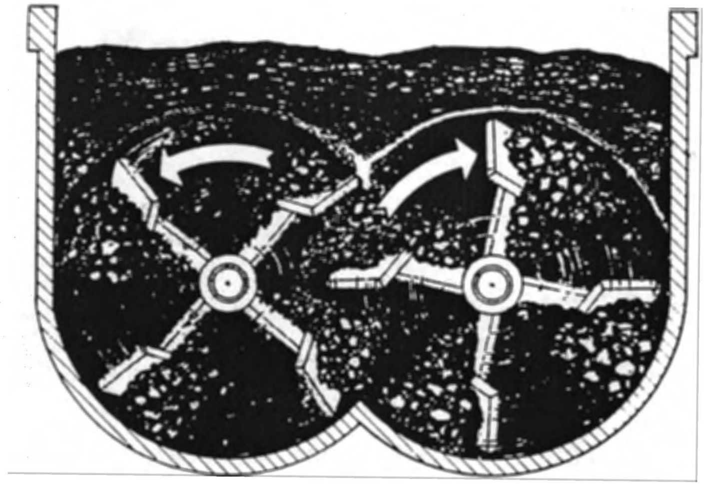
Increasing dry-mix time decreases the plant production rate without benefiting the mix and causes unnecessary wear on the pugmill paddles and liners. In addition, any increase in the dry-mix time raises the cost of producing the mix. The dry-mix time should thus be kept as short as possible; 1 second is normally adequate.

Wet-Mix Time

While the aggregate is still being discharged from the weigh hopper into the pugmill, the addition of the asphalt cement commences. This material is fed into the pugmill by gravity flow or pressure spray and is added either through one pipe in the center of the pugmill or through two pipes, one over each of the two mixing shafts. The wet-mix time starts when the asphalt enters the pugmill. Typically 5 to 10 seconds is required for all the asphalt cement to be discharged from the weigh bucket. Pressure injection systems can be used to reduce this time.

Wet-mix time should be no longer than is necessary to coat the aggregate completely with asphalt cement. If the paddle tips and pugmill liners are in good condition and if the pugmill is full, the wet-mix time can be as short as 27 seconds. If the paddle tips are worn, the wet-mix time will be extended somewhat, but typically should not be more than 33 seconds. Because the condition of the paddle tips affects the amount of wet-mix time, it should be checked regularly and the tips changed when necessary. As a general rule, a 30-second wet-mix time is more than adequate to uniformly distribute the asphalt cement and coat the aggregate.

The mixing time should be as short as possible to avoid excessive hardening of the asphalt cement in a thin film around the aggregate particles as a result of exposure to high temperatures. The required wet-mix time can be established using the Ross count procedure to



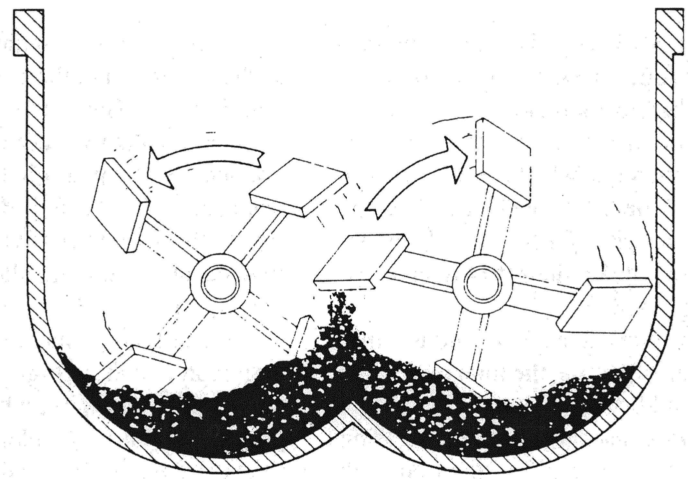


FIGURE 8-5 Overfilled and underfilled pugmills.

determine the degree of particle coating of the coarse aggregate in the mix, as given in ASTM D2489. Once the asphalt cement has been properly distributed, additional wet-mix time does not improve the degree of coating but only oxidizes (hardens) the asphalt cement by continuing to expose the binder material to air.

Coating of the aggregate in a pugmill occurs first with the smallest-sized aggregate particles. If wet mixing is done for only 10 seconds and the material is discharged from the pugmill at the end of that time, only the smaller fine aggregate [the material finer than the 0.600-mm or 0.425-mm (No. 30 or No. 40) sieve] will typically be coated with the asphalt cement; the coarser aggregate particles will be only partially coated with asphalt. If wet-mixing time is extended to 20 seconds and the material is discharged from the pugmill at the end of that time, only the aggregate of 4.75-mm (No. 4) sieve size and smaller will typically be coated with asphalt cement; the coarser aggregate particles will remain uncoated. Complete coating of all the coarse aggregate in the mix usually takes about 26 to 28 seconds of wet-mixing time in a pugmill with paddle tips and lining in good condition. Thus the Ross count procedure, which looks only at the degree of asphalt coating on the coarse aggregate particles [larger than the 4.75-mm (No. 4) sieve], is an effective way of determining the minimum amount of wet-mix time needed to distribute the asphalt cement properly throughout the aggregate.

Total Mix Time

Mixing time has a direct effect on the production capacity of a plant. If a 1-second dry-mix time and a 27-second wet-mix time are used, proper mixing of the two materi-

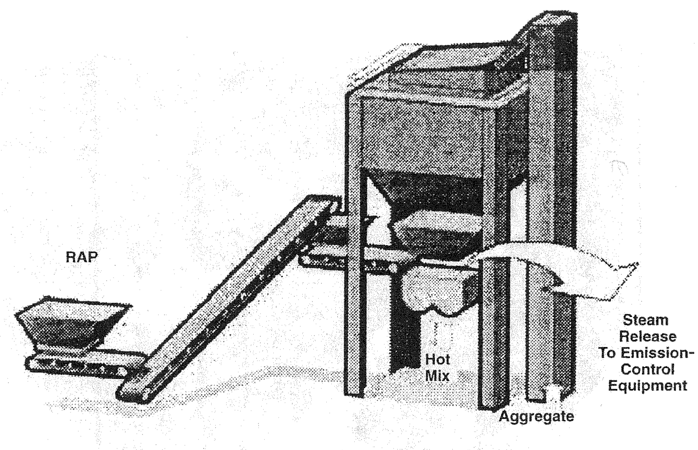


FIGURE 8-6 Weigh-box method of batch plant recycling.

als can be accomplished in 28 seconds. Given approximately 7 seconds more to open the gates at the bottom of the pugmill, discharge the mix, and close the gates, the total cycle time required to produce a batch of HMA is 35 seconds. This time is the same whether the batch size is 1.8 tonnes (2 tons) or 4.5 tonnes (5 tons). Theoretically, if a plant with a pugmill capacity of 4.5 tonnes (5 tons) is run continuously for 1 hour, 465 tonnes (514 tons) of asphalt mix can be manufactured.

If a 5-second dry-mix time and a 35-second wet mix time were required by specification, the total cycle time to produce the mix would be 47 seconds (assuming a 7-second gate-opening, mix-discharge, and gate-closing time). This increased cycle time (47 compared with 35 seconds) would decrease the amount of mix produced in a pugmill with a capacity of 4.5 tonnes (5 tons) from 465 tonnes (514 tons) to 348 tonnes (383 tons) per hour. If a 60-second total cycle time were used, the production rate for the same plant would be reduced to only 270 tonnes (300 tons) per hour. Thus the dry- and wet-mix times have a significant effect on the amount of mix produced by a given plant and the cost of producing that mix.

If the plant is not equipped with a silo, there will be times when the plant production may have to be interrupted because of a lack of available haul trucks. This problem must be monitored by the plant operator. In no case should the plant mixing time be extended during the wet-mix cycle. If the asphalt cement has been added to the aggregate and the wet-mix time is extended to 40 or 50 seconds or longer, excessive hardening of the asphalt cement will occur. This extended wet-mix time can be highly detrimental to the long-term performance of the mix on the roadway.

If trucks are not available, the plant should be idled with no material in the pugmill—the paddles should be "mixing air." The second, much less desirable, choice is to let the plant wait during the dry-mix time; the aggregate is in the pugmill, but the asphalt cement has not been added. This can be done only for a short period of time; otherwise excessive breakdown of the aggregate may occur. Again, the plant should not be idled during the wet-mix time.

Several factors may reduce the supply of incoming aggregate, such as high moisture content or insufficient screen capacity, which extend drying time. The production rate of the plant will be reduced (total cycle time increased) while waiting for dry aggregate. If this problem occurs, the plant operator must not increase the total cycle time by arbitrarily increasing the wet-mix time. Rather, the total cycle time should be increased by delaying the discharge of the aggregate from the weigh hopper into the pugmill and thus "mixing air" instead of aggregate (increased dry-mix time) or asphalt mix (increased wet-mix time).

PRODUCTION OF RECYCLED MIX

Recycling Variables

The temperature of the new aggregate and the moisture content of the RAP govern the amount of reclaimed material that can be introduced into a recycled mix produced in a batch plant. For the heat transfer to take place from the heated new aggregate to the ambient-temperature RAP, the new aggregate must be superheated—heated to a temperature above that needed to produce a conventional HMA. This heat transfer can take place in the hot elevator, in the hot bins, in the weigh hopper, or in the pugmill, depending on where the RAP is introduced into the plant. For most dryers, the maximum new-aggregate temperature upon discharge from the dryer should be about 260°C (500°F) in order not to reduce the life of the dryer and to keep from driving off internal moisture in the aggregate.

The three primary variables that determine the temperature to which the new aggregate must be heated to accomplish the necessary heat transfer are the moisture content of the reclaimed material, the discharge temperature of the final recycled mix, and the amount of reclaimed material used. Depending on the values for these variables, up to 50 percent RAP may be blended with new aggregate to manufacture a recycled HMA. Very rarely, however, is it feasible to use that amount of RAP in an HMA mix produced in a batch plant.

Moisture Content

As the moisture content of the reclaimed material increases, the required new-aggregate temperature increases significantly. This is illustrated in Table 8-1. If 20 percent RAP is used in the mix, if the moisture content of that material is 1 percent, and if the required mix discharge temperature is 127°C (260°F), the temperature to which the new aggregate must be heated is 177°C (350°F), as seen in Section B of the table. If the same RAP has a moisture content of 4 percent, however, the temperature of the new aggregate must be increased to 199°C (390°F) for the same amount of reclaimed material and the same mix discharge temperature.

Mix Discharge Temperature

Using Section C of Table 8-1 as an illustration, the amount of RAP incorporated into the mix is 30 percent. If the moisture content of this material is 3 percent as it is delivered to the plant, the new-aggregate temperature must be at least 196°C (385°F) when the mix discharge temperature is only 104°C (220°F). If the discharge temperature is 138°C (280°F), however, the temperature of the new aggregate must be increased to 246°C (475°F). Thus a higher mix discharge temperature for the recycled mix from the pugmill requires an increase in the new-aggregate temperature from the dryer.

Amount of RAP

As the amount of RAP in the recycled mix increases, the new-aggregate temperature must also increase. If only 20 percent RAP is used and if the moisture content of that material is 4 percent for a mix discharge temperature of 138°C (280°F), the new-aggregate discharge temperature must be 213°C (415°F), as determined from Section B of Table 8-1. Increasing the mount of RAP to 50 percent, using Section E of the table and for the same value of moisture content (4 percent) and mix discharge temperature [138°C (280°F)], the new-aggregate temperature must be raised to 405°C (760°F) to accomplish the heat-transfer process. This latter temperature significantly exceeds the recommended maximum new-aggregate temperature of 260°C (500°F).

Dryer Operation

If the temperature of the new aggregate exiting the dryer exceeds approximately 260°C (500°F), the cost of operating and maintaining the dryer can increase significantly. Because of extremely high aggregate temperatures and the reduced volume of aggregate in the dryer when a large percentage of RAP is used in the recycled mix as compared with a normal mix, the veil of aggregate inside the dryer will typically not be adequate. This lack of veil will increase the temperature of the dryer shell and may necessitate increased maintenance on the inside of the dryer, especially on the discharge flights.

If the mix production is stopped for a long period of time because of a lack of haul trucks or mechanical problems, the superheated new aggregate will lie in the bottom portion of the dryer. If the temperature of this material is greater than about 260°C (500°F), warping of the drum shell can occur, and the dryer will be out of round. Further, at the end of each production cycle, the dryer should be allowed to run empty with the exhaust fan operating for a reasonable cooling-down period after aggregate feed shutdown. This cooling procedure will protect against possible warping of the dryer shell and the flights.

Visible Emissions

When the RAP is deposited on top of the superheated new aggregate in the weigh hopper and when the two materials are mixed together in the pugmill, emissions of both moisture and dust can occur. These emissions are caused by escape of the moisture, in the form of steam, from the RAP. The amount of moisture vapor, as well as blue smoke, released can be quite large. For a mix containing 50 percent reclaimed material in a 2.7-tonne (3-ton) batch of recycled mix, with a moisture content of 3 percent, 40 kg (90 lb) of water, which will convert to approximately 422 m^3 (14,900 ft^3) of water vapor, will be released in about 5 seconds. This release of vapor usually

TABLE 8-1 Required Aggregate Temperature

Reclaimed Material Moisture Content (%)	Recycled Mix Discharge Temperature, °F			
	220°F	240°F	260°F	280°F
A. Ratio: 10% RAP/90% Aggregate				
0	250	280	305	325
1	260	290	310	335
2	270	295	315	340
3	280	300	325	345
4	285	305	330	350
5	290	315	335	360
B. Ratio: 20% RAP/80% Aggregate				
0	280	310	335	360
1	295	320	350	375
2	310	335	360	385
3	325	350	375	400
4	340	365	390	415
5	355	380	405	430
C. Ratio: 30% RAP/70% Aggregate				
0	315	345	375	405
1	335	365	395	425
2	360	390	420	450
3	385	415	445	475
4	410	440	470	500
5	435	465	495	525
D. Ratio: 40% RAP/60% Aggregate				
0	355	390	425	460
1	390	425	460	495
2	425	460	495	530
3	470	500	535	570
4	500	535	570	610
5	545	575	610	645
E. Ratio: 50% RAP/50% Aggregate				
0	410	455	495	540
1	465	515	550	590
2	520	580	605	650
3	575	620	660	705
4	640	680	715	760
5	690	735	775	820

NOTE: 20°F loss between dryer and pugmill assumed in these calculations.
°C = (°F – 32)/1.8.
SOURCE: National Asphalt Pavement Association, *Hot Recycling in Hot Mix Batch Plants* (IS-71), page 2.

causes carryout of dust particles from the weigh hopper and the pugmill areas.

One way to control the particulate emissions is to reduce the amount of moisture or reduce the amount of RAP used in the recycled mix, or both. The moisture content of the reclaimed material can be kept low by not crushing this material until just before it is needed and by keeping the RAP under a roof to prevent rain from falling on it. Another common approach is to adequately vent the weigh hopper and pugmill into the emission-control system on the plant. (See also the discussion of emission control in Section 12.)

LOADING IN TRUCK OR SILO

If the mix discharged from the pugmill is loaded directly into the haul truck, each batch should be deposited into a different location on the truck. The first batch should be placed in the front portion of the bed. The driver should then move the truck forward so that the second batch is placed into the rear section of the truck bed, adjacent to the tailgate. The remaining batches should be discharged into the center of the bed, with the position of the truck under the pugmill changing for each batch. This procedure will minimize the distance the coarse aggregate particles can roll in the bed, thereby reducing the possibility of segregation of the mix.

If the mix is to be stored in a silo temporarily, it should be discharged from the pugmill into the center of a hopper and then into a conveying device, which can be a drag-slat conveyor, a belt conveyor, or a bucket elevator. The silo should be operated in a manner similar to the silo used with a drum-mix plant (see Sections 9 and 10; see also the discussion of silos and truck loading techniques in Section 11).

EMISSION CONTROL

Because the asphalt cement is not added to the aggregate inside the dryer, the amount of dust carryout from a batch plant dryer is generally greater than that from a parallel-flow drum mixer. The operation of the emission-control equipment—wet-scrubber system or baghouse (fabric filter)—is the same, however, regardless of the type of plant used.

If the baghouse fines are fed back into the mix, they should be fed into a filler metering system before being introduced into the weigh hopper on the tower. This procedure will ensure that the baghouse fines are delivered uniformly into the mix. On some plants, the fines are transported to the bottom of the hot elevator and deposited on top of the new aggregate that is discharged from the dryer. As long as the fines are delivered consistently, this method of fines return is acceptable, particularly if the aggregate will pass through the screen deck. If screens are not used, however, small lumps of fines can be deposited into the No. 1 hot bin and possibly end up in the mix without being broken up. Thus returning the baghouse fines to the hot elevator is probably not as good a practice as placing them directly into the weigh hopper.

If the plant is equipped with a baghouse and a recycled asphalt mix with a high percentage of RAP is being produced, the temperature of the exhaust gases from the dryer to the baghouse should be monitored continuously to ensure that the bags in the fabric filter are not damaged by excessive heat. The higher the temperature to which the new aggregates must be heated, the greater is the chance for problems with the baghouse operation. (See Section 12 for a full discussion of emission control.)

CALIBRATION

The calibration procedure for a batch plant involves checking the accuracy of the scales, both for the aggregate weigh hopper and for the asphalt cement weigh bucket. This is usually accomplished by adding a known amount of weight to each scale and reading the weight shown on the scale dial. For this purpose, a set of ten 22.6-kg (50-lb) weights is normally used.

The aggregate scale is unloaded and set to a zero reading. The ten 22.6-kg (50-lb) weights are hung from the scale, and the reading on the dial is recorded. The weights are removed, and 226 kg (500 lb) of aggregate is then added to the weigh hopper. The ten weights are again hung from the scale, and the next reading on the dial [452 kg (1,000 lb)] is recorded. The weights are removed once again, and an additional 226 kg (500 lb) of material is added. The weights are placed on the scale, and the next dial reading is recorded [678 kg (1,500 lb)]. This process continues [adding the weights, recording the dial reading, removing the weights, adding 226 kg (500 lb) of aggregate to the weigh hopper, and then repeating the sequence] until the capacity of the aggregate scale has been reached.

The same process is used for the asphalt cement weigh bucket, except that only one 22.6-kg (50-lb) weight is typically used. First the weigh bucket is unloaded and the scale set to a zero reading. Next, one 22.6-kg (50-lb) weight is hung from the scale, and the dial reading is recorded. Asphalt cement to a weight of 22.6 kg (50 lb) is then introduced into the weigh bucket. The 22.6-kg (50-lb) weight is placed back on the scale again, and the dial reading is recorded. An additional 22.6 kg (50 lb) of asphalt cement is added to the weigh bucket [for a total of 45.2 kg (100 lb)]. The procedure continues [adding the weight, recording the dial reading, removing the weight, adding 22.4 kg (50 lb) of asphalt cement, and then repeating the sequence] until the capacity of the asphalt cement weigh bucket scale has been reached.

For both scales, the actual dial reading after each set of weights has been added to the scale and the "theoretical" scale reading are compared. If the two readings are the same (within 0.5 percent), the scale is in calibration. If the two readings differ by more than that amount, the scale must be adjusted. Adjustments are made using the procedures provided by the scale manufacturer.

SUMMARY

The following factors should be considered when monitoring the operation of a batch plant:

- The moisture content of the aggregate when discharged from the dryer should be less than 0.5 percent and ideally less than 0.2 percent.
- The amount of carryover of the aggregate from one hot bin to the next should be relatively constant and generally less than 10 percent. Significant changes in the amount of carryover from one bin to the adjacent bin may result in a major change in the aggregate gradation in the HMA being produced.
- The screens should be checked regularly for holes and blinding.
- The pugmill should be operated at nominal capacity. Both overloading and underloading of the pugmill with aggregate will decrease the efficiency of the mixing process significantly. Batch size should be consistent from batch to batch. The paddle tips and the pugmill lining should be checked periodically to ensure that they are in good condition.
- The dry-mix time for the aggregate in the pugmill should be minimal—usually no more than 1 or 2 seconds.
- The wet-mix time for blending the asphalt cement and the aggregate should be no longer than needed to coat the aggregate properly and completely. For most batch plants, the wet-mix time can be as short as 27 seconds.
- Increasing the wet-mix time over the minimum needed to completely coat the coarse aggregate particles in the HMA increases the aging (oxidation or hardening) of the binder material, increases the wear on the pugmill components, reduces the production rate of the plant, and increases the cost of producing the mix.
- The plant operator must not idle the plant during the wet-mix cycle and should not do so during the dry-mix time. When the plant is waiting for trucks, there should be no material in the pugmill; the pugmill should "mix air."
- The total mix cycle time to produce and discharge a batch of mix, regardless of the size of the pugmill, may (and generally should) be as short as 35 seconds.
- If RAP is introduced into the plant at the bottom of the hot elevator, it should be placed on top of the superheated new material and not in the bottom of the buckets.
- If reclaimed material is charged into the weigh hopper, it should be placed in the center of the weigh hopper so that the hopper is balanced and an accurate weight can be determined.
- The temperature to which the new aggregate must be heated to obtain adequate heat transfer to the reclaimed material is a function of the amount of RAP used in the recycled mix, the amount of moisture in the RAP, and the mix discharge temperature. To prevent potential damage to the dryer, the new aggregate generally should not be heated to a temperature greater than 260°C (500°F). If the temperature of the new aggregate (as found in Table 8-1) is greater than this value for the amount and moisture content of the RAP, it will be necessary to reduce the percentage of RAP added to the recycled mix.

9 Parallel-Flow Drum-Mix Plants

This section is concerned with the processing of aggregate and asphalt cement in a parallel-flow drum-mix plant. The methods used to introduce the aggregate into the drum are first reviewed, followed by the operation of the burner system and the three-step heating, drying, and mixing process that occurs as the aggregate moves down the drum. The importance of the veil of aggregate across the whole cross section of the drum is stressed. Next, methods for introducing the asphalt cement into the drum and onto the aggregate are considered, as well as the systems used to deliver both mineral filler and baghouse fines into the drum. The addition of RAP into the drum, primarily by use of a split-feed system for the new aggregate and the RAP, is then discussed, followed by information on the factors that affect the production rate of the plant. Finally, the relationship between the mix discharge temperature and the exhaust gas temperature as it exits the drum is analyzed, as this information is used to determine the efficiency of the heat transfer process inside the drum mixer. The section ends with a summary of key factors to be considered in monitoring the operation of a parallel-flow drum-mix plant.

AGGREGATE ENTRY

There are two ways to introduce new aggregate from the charging conveyor. The first is by means of a charging chute located above the burner. The aggregate is delivered into a sloped chute and slides by gravity into the drum. The chute is angled to push the aggregate away from direct contact with the burner flame and toward the rear of the drum. The aggregate can also be deposited on a Slinger conveyor belt located beneath the burner. On some plants, the speed of this conveyor can be changed so that the aggregate can be deposited farther down the drum, away from the burner flame. Figures 9-1 and 9-2 show a rotating feed and a Slinger conveyor, respectively, for a counter-flow drum.

BURNER SYSTEM

The burner heats and dries the aggregate. Burners are rated by a Uniform Burner Rating Method that is based on eight criteria: (*a*) percent excess air, (*b*) percent leakage air, (*c*) percent casing (shell) loss, (*d*) fan gas temperature, (*e*) percent moisture removed from the aggregate, (*f*) mix discharge temperature, (*g*) use of No. 2 fuel oil, and (*h*) specific heat of the aggregate. The maximum output for the burner under these conditions can be found on the rating plate attached to each burner, although the actual operating conditions for the burner may differ from those used to rate the burner.

Fuel

Most burners are designed to burn more than one type of fuel with only minor changes in the burner settings. Three types of fuel are used: gaseous, liquid, and solid. Gaseous fuels include both natural gas and liquid petroleum gas. Liquid fuels include propane, butane, No. 2 fuel oil, heavy fuel oil (Nos. 4 through 6), and reclaimed oil. Pulverized coal and pelletized biomass are examples of solid fuels.

The fuel selected should be at the proper consistency for complete atomization at the time of combustion. No. 2 fuel oil will burn at ambient temperatures, without preheating, because it has a viscosity below 100 saybolt seconds universal (SSU). For proper atomization, heavy fuel oil, such as Nos. 5 or 6, must be preheated before burning to reduce the viscosity below 100 SSU and thereby atomize the fuel properly for its complete combustion. Some reclaimed oil, which has been filtered and dewatered, burns well. Other reclaimed fuel, contaminated with heavy metals, hazardous waste, or water, burns erratically and incompletely and generally should not be used in an HMA plant burner. Incomplete combustion is not normally a problem when gaseous fuels are used.

Unburnt fuel can cause difficulty with the burner, the plant, and the mix, and is a waste of money as well. It can cause clogging of the burner nozzle, difficulties in lighting the burner, and increased maintenance costs. Incomplete combustion can result in unburnt fuel entering the emission-control equipment—coating and blinding the filter bags in a baghouse (increasing the opportunity for a baghouse fire) or covering the wastewater pond surface with fuel if a wet scrubber system is used. In-

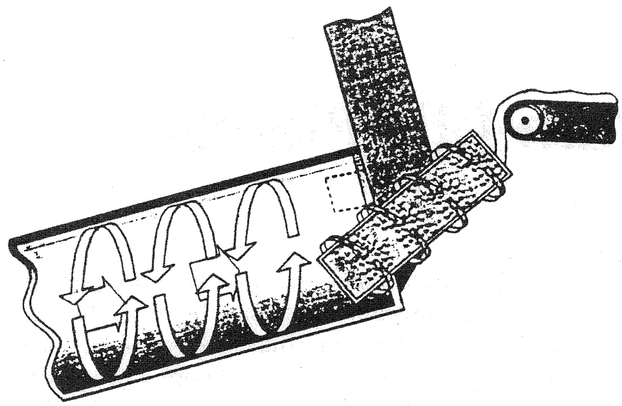


FIGURE 9-1 Typical rotating charging chute for delivery of new aggregate.

complete combustion also reduces the amount of heat available to dry the aggregate and thus increases fuel consumption and operating costs. Further, it can lower the temperature of the exhaust gases, which can result in condensation of the moisture (steam) in the baghouse.

Moreover, unburnt fuel can change the properties of the HMA. First, the fuel can decrease the viscosity of the asphalt cement binder material and reduce the amount of hardening the binder undergoes during the mixing process. The unburnt fuel can also impinge directly on the surface of the coarser aggregate particles, resulting in formation of a brown stain on the aggregate and softening of the film thickness of the asphalt cement on those surfaces. These two problems can affect the stiffness, stability, and strength of the asphalt mix produced.

Unburnt fuel problems can be recognized in several ways. A flame eye, which is an electronic device used to sense the color of the burner flame, can be employed to monitor the hue of the burner flame and shut the burner down if the color does not indicate complete combustion. A uniform, constant roar from the burner is usually a good sign (although it is possible to have a problem with unburnt fuel even when the noise of the burner is constant). In contrast, a coughing, sputtering, or spitting burner indicates possible incomplete combustion. If fuel is condensing on the filter bags, the pressure drop across the baghouse will increase, and the bags will be stained with fuel. When a wet scrubber system is used, the water in the wastewater pond surface will be covered with an oil sheen.

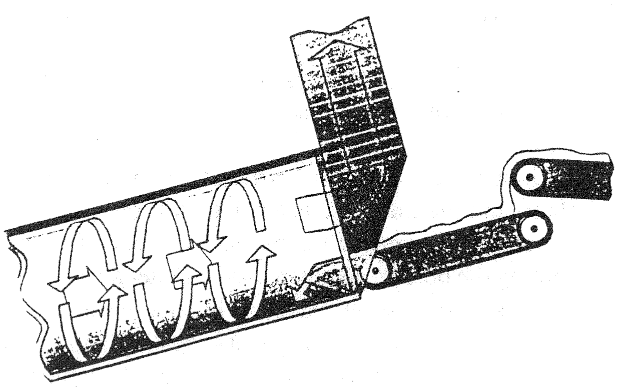


FIGURE 9-2 Typical Slinger conveyors for aggregate delivery.

Burners

The primary function of the burner is to blend the proper amounts of air and fuel to obtain complete combustion of the fuel. Two primary types of burners are used on aggregate dryers and drum mixers, either counter- or parallel-flow. First, many plants are equipped with a burner that requires from 30 to 45 percent of the air needed for combustion to be forced through the burner by a blower on the burner itself. The remaining 70 to 55 percent of the combustion air is pulled by the exhaust fan on the plant into the combustion zone around the burner. This type of equipment—a combined induced- and forced-draft burner—is shown in Figure 9-3. Some burners operate with all of the air needed for combustion being forced through the burner by a blower. This second type of burner, shown in Figure 9-4, is known as a forced-draft, total-air, or 100 percent air burner. These latter burners are generally much quieter than the first type and more fuel-efficient as well.

Some burners must be adjusted by the plant operator (*a*) as the amount of aggregate inside the dryer or drum mixer changes, (*b*) as the amount of moisture in the aggregate increases or decreases, and (*c*) as the aggregate discharge temperature is changed to control the drying and heating of the material. Most burners are equipped with an automatic device that controls the fuel input to maintain a relatively constant discharge temperature for the aggregate (or for the mix in a drum mixer).

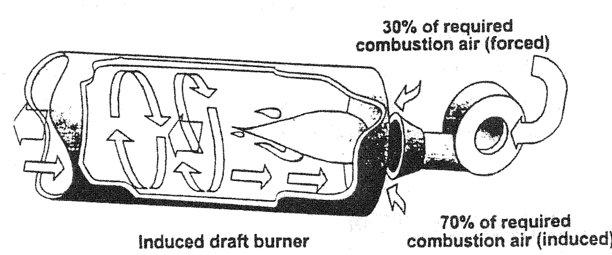


FIGURE 9-3 Combined induced- and forced-draft burner.

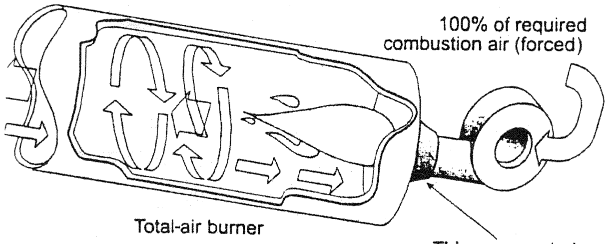


FIGURE 9-4 Forced-draft, total-air, or 100 percent burner.

A lack of either air or fuel will reduce the efficiency of the burner. Usually the availability of air is the limiting factor. The exhaust fan, besides providing the induced air, must also pull the moisture vapor (steam) created in the drying process and the products of combustion through the dryer or drum mixer. The capacity of this fan is a controlling factor in the heating and drying of the aggregate. The volume of the exhaust gases (air, moisture vapor, and combustion products) pulled by the fan is constant, depending on the setting of the damper in the system.

The efficiency of the system is also affected by air leaks. Because the fan pulls a constant volume of exhaust gases, at a constant damper setting, through the system from the burner and through the fan, any air that enters the system downstream of the burner reduces the amount of secondary air that can be pulled by the fan. Air leaks should be eliminated to provide the volume of air at the burner required to achieve complete combustion of the fuel. A damper, operated manually or automatically, should also be placed in the ductwork to control the amount of air entering the system.

HEAT TRANSFER PROCESS

Temperatures Inside the Drum

The temperature of the burner flame exceeds 1400°C (2,500°F). Exit gas temperatures for parallel-flow drum mixers are typically as much as 30°C (54°F) higher than exit mix temperatures. Exit gas temperatures higher than this could indicate improper flighting, and corrective actions should be taken. Typical temperature profiles for the exhaust gases and the aggregate along the length of the drum for parallel- and counter-flow drums are shown in Figures 9-5 and 9-6. The difference between the exhaust gas and mix discharge temperatures represents the efficiency of the heat transfer process and the amount of heat that is available to dry and heat the aggregate. Perfect heat transfer in a parallel-flow drum would require that the mix discharge and exhaust gas temperatures be equal at the point at which the mix is discharged from the plant.

Although a measure of the efficiency of the heat transfer process is obtained by comparing the mix discharge and exhaust gas temperatures at the time the gases exit the drum, it is often difficult to determine the temperature of the exhaust gases accurately at this location. The temperature differential is normally measured in the ductwork at a point between the end of the drum mixer and the entry of the exhaust gases into the emission-control equipment. This latter procedure is done by means of a thermocouple attached to the ductwork upstream of the point where the exhaust gases are drawn into the wet scrubber or baghouse system. For efficient operation of the drum mixer, the temperature of the exhaust gas before entry into the emission-control system should be within 10°C (20°F) of the mix discharge temperature.

It is generally not possible to compare the mix discharge temperature and the temperature of the exhaust gases at the point at which they exit the plant stack. If a wet scrubber is employed on the plant, the water used to impinge on the dust particles in the exhaust gases will naturally cool the gases. Moreover, for both wet scrubber and baghouse emission-control systems, any leakage air that is drawn into the ductwork and emission-control equipment between the end of the drum and the stack will reduce the temperature of the exhaust gases before they leave the stack. Thus the mix discharge and exhaust gas temperatures must be compared in the ductwork before the gases enter the emission-control equipment.

If the exhaust gas temperature in the ductwork is, say, 180°C (360°F) and the mix discharge temperature is 140°C (280°F), the veil of aggregate inside the drum is probably incomplete, and the drum is being operated inefficiently. Several problems result, including increased fuel use, possible separation of some of the very fine aggregate particles from the rest of the aggregate in the drum, and increased deterioration of the filter bags if a baghouse is used.

The temperature of the exhaust gases must also be controlled at the location where the asphalt cement is injected. Certain asphalt cements, depending on the source of the crude oil and the refining process used to produce the material, may contain small amounts of volatile material or "light ends" that can be driven off at temperatures as low as 330°C (600°F) and even much lower when moisture is present. Visible emissions can

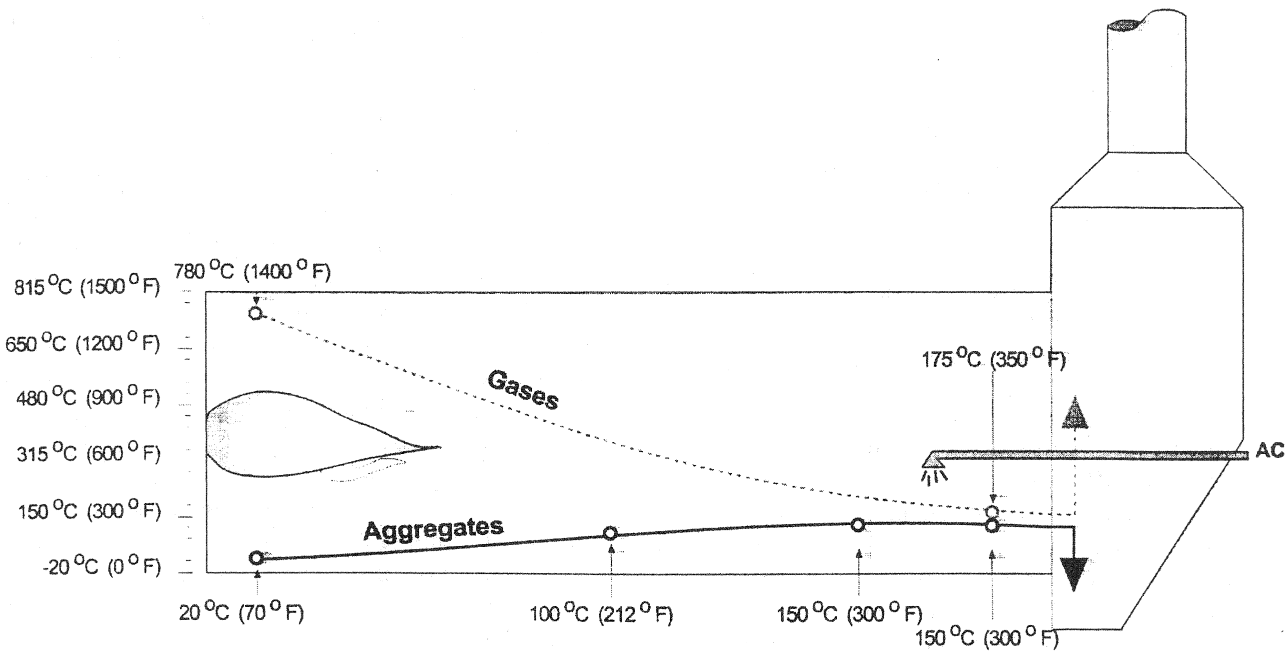


FIGURE 9-5 Temperature profile for parallel-flow drum drying aggregate.

be avoided if the temperature of the exhaust gases is below this value at the location where the asphalt cement enters the drum.

Exhaust gas temperatures will normally be higher when a recycled mix is being produced. These higher temperatures are related to the reduction in the density of the veil of aggregate upstream of the RAP entry point at the center rotary inlet and the resultant less-efficient heat transfer. The greater the amount of RAP used in the recycled mix, the less will be the amount of new aggregate, and the less complete the veil of material will be ahead of the RAP entry point. To prevent the production of visible emissions (blue smoke) during recycling, the temperature of the exhaust gases should be below

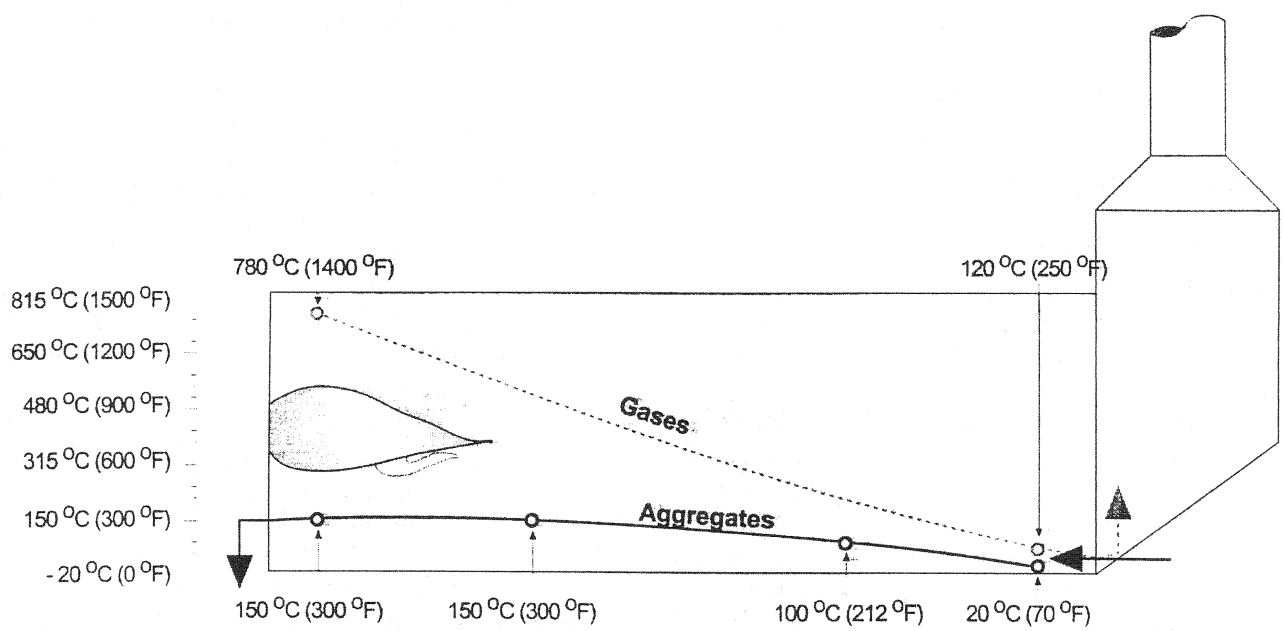


FIGURE 9-6 Temperature profile of counter-flow drum drying aggregate.

about 200°C (400°F) at the point at which the RAP enters the drum.

Flight Design

The aggregate fed into the burner end of the drum mixer moves down the length of the unit by a combination of gravity flow and the lifting flights as the drum rotates. Factors that affect the length of time required for an individual aggregate particle to pass through the drum include the length and diameter of the drum, the slope of the drum, the number and type of flights inside the drum, the speed of rotation of the drum, and the size of the aggregate particles. In general, it takes about 4 to 8 minutes for an incoming aggregate particle to reach the discharge end of the drum.

Each drum plant manufacturer uses a different pattern, shape, number, and location for the flights inside the drum. Although named differently by different manufacturers, the flights used in the various sections of the drum generally serve the same purposes: to expose the aggregate to the heat from the burner gases without dropping it through the flame, to remove the moisture from the aggregate, to coat the aggregate with asphalt cement, and to heat the coated material to the proper discharge temperature.

When a parallel-flow drum mixer is used, the burner flame should be short and bushy and not extend very far into the drum to protect the asphalt cement from high temperatures. The burner flame must have enough room, however, to expand and combust the fuel completely. The incoming aggregate cannot be deposited directly into the fire, or it will quench the flame. Thus the first flights at the upper end of the drum are used to direct the aggregate into the drum beyond the tip of the flame.

The next flights are used to lift some of the aggregate from the bottom of the drum and begin tumbling the material through the exhaust gases from the burner. As the aggregate moves down the drum, an ever greater amount of aggregate is lifted and tumbled. Near the midpoint of the length of the drum, a veil of aggregate is developed across the whole cross-sectional area. This veil is essential to accomplish the heat transfer from the exhaust gases so that the drying and heating of the aggregate can take place. The more complete the veil, the more efficient and effective the heat transfer process will be, the less fuel will be consumed, and the lower will be the particulate emissions from the plant.

Some drum mixers are equipped with devices, located near the drum midpoint, designed to retard the flow of aggregate down the drum. A ring inserted inside the drum reduces the diameter at that point. A buildup of aggregate occurs in front of the ring, creating a heavier veil of material. Some drum manufacturers install "kicker" or reverse-angle flights at this same location to intercept the aggregate and turn it back upstream, thus concentrating the aggregate in one location, increasing the density of the veil, and improving the heat transfer. Although restricting the diameter of the drum in some fashion is beneficial to increase the density of the veil of aggregate inside the drum, the reduced cross-sectional area also causes the velocity of the exhaust gases to rise, thereby potentially increasing the amount of fines carryout from the drum mixer.

Farther down the drum length, asphalt cement is injected into the drum, and mixing flights are used to combine the aggregate with the asphalt cement. These flights also allow the asphalt cement–coated particles to continue to be heated by the exhaust gases, complete the heat transfer process, and raise the mix temperature to the desired level for discharge. At the rear of the drum, discharge flights are employed to deposit the material into the discharge chute for transport to the surge silo.

As the flights wear from the abrasive action of the aggregate moving through the drum, the efficiency of the heating and drying process can be reduced. (The amount of wear on the flights depends on the operating conditions of the plant and the type of aggregate being processed.) Thus, the condition of the flights should be checked on a regular basis. Worn and missing flights should be replaced as necessary. In addition, if proper heat transfer is not being accomplished, the type and location of the flights inside the drum can be altered to improve the veil of aggregate moving across the cross section of the drum at its midpoint.

Early drum-mix plants were constructed with a 4:1 length-to-diameter ratio that was used for batch plant dryers; thus a dryer 2.45 m (8 ft) in diameter was 9.75 m (32 ft) in length. The recent trend is to use longer drums to obtain more complete heat transfer from the exhaust gases to the aggregate and reduce emission problems, particularly when a recycled mix is being produced. Some current drum mixers have length-to-diameter ratios of 5:1 and 6:1. Thus a drum mixer 2.45 m (8 ft) in diameter might be 12.19 to 14.63 m (40 to 48 ft) in length.

Increasing the Veil of Aggregate

Kicker flights, dams, donuts, or retention rings can be used to retard the flow of material down the drum and increase the density of the veil of aggregate. Another method for achieving the same effect is to lower the slope of the drum. The reduction in slope (from a maximum of 6.0 percent to a minimum of 2.5 percent) increases the dwell or residence time of the aggregate in the drum and thus provides more time to complete the heat transfer process. The additional aggregate retained in the drum because of the lower slope also causes a denser veil of material across the drum cross section, further improving the degree of heat transfer.

Lowering the slope of the drum does not normally cause a change in the plant production rate. An individual aggregate particle takes longer to travel through the drum when the slope is decreased, but the actual production rate is unchanged in terms of tonnes (tons) per hour. Power requirements for the electric motors used to turn the drum are increased because of the extra weight of aggregate in the drum. The net result, however, is a better veil of aggregate, more complete heat transfer, and a reduction in the temperature of the exhaust gases at all locations in the drum.

Several manufacturers have developed drum mixers that change in diameter along their length: the drum is one diameter at one or both ends and a smaller diameter in the center. The change in diameter allows more room for combustion of the burner fuel and provides for development of a denser veil of aggregate in the drum by squeezing the same volume of material that was tumbling in a drum 2.60 m (8.2 ft) in diameter, for example, into a section 2.13 m (7 ft) in diameter, significantly increasing the density of the aggregate veil. In this case, the reduced diameter works in the same manner as the installation of a ring inside the drum. The heavier veil improves the efficiency of the heat transfer process. The velocity of the exhaust gases, however, also rises because of the smaller diameter, potentially increasing the amount of particulates carried out into the emission-control equipment and possibly reducing production levels as well.

Heat Transfer

While the exhaust gas temperature is being reduced as the gases move down the drum, the temperature of the aggregate is increasing as it travels in a parallel direction. The heat transfer process takes place in three ways: radiant, conductive, and convective. Radiant heat comes from the burner flame as aggregates pass under or over the flame. Conductive heat comes from contact with heated aggregate and the hot shell. Convective heat is transferred by the hot exhaust gases. The primary method of heat transfer is convective.

The aggregate enters the drum at ambient temperature, and radiant heat from the flame strikes the aggregate, which immediately begins to dry and heat. As the material moves down the drum, its temperature is increased until it reaches a point upstream of the drum midpoint, where its temperature remains relatively constant because the heat from the exhaust gases is being used to evaporate the moisture in the aggregate. The amount of time the aggregate temperature remains constant depends in part on the amount of moisture in the incoming material. The porosity of the aggregate is also a factor. Moisture in porous material takes longer to be removed from the internal pores. Fine aggregate (sand) is typically heated more quickly and gets hotter than coarse aggregate because of its greater surface area per kilogram (pound).

Once most of the moisture has been removed, the aggregate temperature begins to rise again. After the asphalt cement is injected, mixing flights are used in most drum-mix plants to tumble the mix, partially exposing the material to the exhaust gases. The mix reaches the required discharge temperature as it approaches the end of the drum. In summary, the aggregate increases in temperature until drying begins, the temperature remains relatively constant until the aggregate is dried, and then the temperature increases again as the aggregate proceeds down the drum.

The moisture content of the aggregate decreases gradually in the front portion of the drum and then more rapidly as the aggregate reaches the temperature required to vaporize water. If the dwell time in the central portion of the drum is long enough, the moisture content of the mix at discharge can be reduced to less than 0.1 percent. The moisture content of the mix at discharge should almost always be less than 0.5 percent, and ideally less than 0.2 percent.

ASPHALT CEMENT INJECTION

On a very few old parallel-flow drum-mix plants, the asphalt cement supply line enters from the front of the drum, at the burner end. The diameter of the pipe used depends on the capacity of the plant, with a diameter of 50 to 100 mm (2 to 4 in.) being typical. The asphalt cement is not normally sprayed through a nozzle, but injected into the drum merely by flowing out of the end of the pipe. The actual point of discharge varies but tends to be between the midpoint and about two-thirds of the way down the drum length from the burner.

One advantage of early asphalt cement introduction is quick capture of the dust particles in the aggregate by the binder material. This action reduces the amount of particulate carryout by encapsulating the fines in the asphalt cement. There are, however, three disadvantages: (*a*) the asphalt cement may be hardened more by exposure to the higher-temperature exhaust gases, (*b*) the production of blue smoke (visible stack emissions) from volatilization of the light ends from certain asphalt cements can be increased because of these higher exhaust gas temperatures, and (*c*) an increase in the moisture content of the mix at discharge may occur because the asphalt cement coats the aggregate particles before all the water in the material has been removed. These disadvantages of the system outweigh its advantages. Thus it is not good practice to inject the binder material near the burner end of the mixing drum.

On most parallel-flow drum-mix plants, the asphalt cement is injected through a pipe 100 mm (4 in.) in diameter, entering from the rear of the drum (see Figure 9-7). In many cases, the location of the asphalt cement entry is at a point approximately 40 to 30 percent of the length of the drum from the mix discharge end (60 to 70 percent of the length of the drum from the burner end). At this location, the small amount of moisture remaining in the aggregate causes the volume of the binder to expand by foaming and helps coat the aggregate. In a drum-mix plant, coating rather than mixing may be the more appropriate term for the blending of the asphalt cement with the aggregate. If the moisture content of the aggregate is still high at the point where the asphalt cement is injected, the coating of the aggregate particles may be delayed until more moisture is removed.

If the asphalt cement being used contains volatile material, resulting in excessive blue-smoke emissions, it may be necessary to move the asphalt cement supply pipe toward the mix discharge end of the drum. This change will reduce the exposure of the asphalt cement to the higher-temperature exhaust gases and decrease the generation of visible hydrocarbon emissions. If the veil of aggregate at the midpoint of the length of the drum is adequate, however, it should not be necessary to move the asphalt cement line back. Moving the supply line can decrease the uniformity of the coating of the binder on the aggregate if the line is placed too close to the discharge end of the drum.

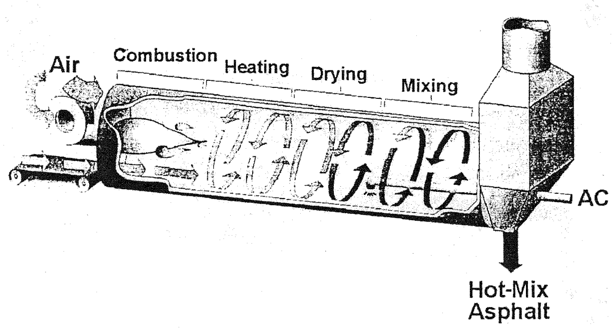


FIGURE 9-7 Parallel-flow drum-mixer zones.

In some drum-mix plants, however, the asphalt cement injection line is completely removed from the drum. The aggregate is heated and dried in the drum but exits uncoated. The aggregate is discharged into a single- or twin-shaft coater unit (screw conveyor), where the asphalt cement is injected (see Figure 5-6 in Section 5). The mixing of the materials occurs as the aggregate and asphalt cement move along the screw conveyor. The blended material is then deposited into a transfer device for transport to the surge silo. The drum-mix coater unit is basically a means to keep the asphalt cement out of the high-temperature exhaust gas stream and thus prevent the generation of visible emissions.

Because of problems in completely coating the coarse and fine aggregates during the very short time they are in the screw conveyor coater unit (not enough mixing time and mixing action), many plants with these units have been modified by the contractor to place the asphalt cement injection pipe back up inside the drum a short distance. This practice results in a longer mixing time for the binder material and the aggregate and thus more complete aggregate coating.

MINERAL FILLER AND BAGHOUSE FINES FEED SYSTEM

Two types of aggregate fines—commercial mineral filler and baghouse fines—can be fed into a drum-mix plant, either individually or in combination. The basic equipment needed to handle each type of material is essentially the same. The primary difference among the various systems relates to the degree of sophistication in the controls used to meter the materials.

Mineral Filler

Mineral filler, such as hydrated lime, portland cement, fly ash, or limestone dust, is stored in a silo or other appropriate container and delivered to the plant through a vane feeder system or small weigh hopper located at the bottom of the silo. The speed of the feeder is related to the amount of new and reclaimed aggregate being delivered to the drum. The silo is normally equipped with an aerating system to keep the mineral filler from packing into a tight mass and bridging the opening to the feeder. If the flow of filler is restricted, the vane feeder will still rotate, but no material will be sent to the plant.

The mineral filler can be delivered to the charging conveyor on the cold-feed system and delivered into the drum as part of the aggregate. This practice is not recommended, however. First, there is a problem of dusting of the filler material when it is deposited on the incoming aggregate. Second, the very fine filler has a tendency to become airborne easily inside the drum (picked up in the exhaust gas stream) and carried either to the discharge chute on the drum or into the emission-control equipment. Thus, some of the filler can be carried out of the drum mixer instead of being incorporated into the mix.

It is also possible to blend the mineral filler with the asphalt cement in the storage tank before the combined materials are fed into the plant. This is rarely done, however, because of problems of separation and settlement of the heavier mineral filler (higher specific gravity) from the lighter asphalt cement whenever plant production is interrupted.

The mineral filler from the vane feeder thus typically enters the delivery pipe and is conveyed pneumatically through the line and into the rear of the drum. The filler is discharged in one of two ways. It can be deposited from the line onto the aggregate at the bottom of the drum or fed into a mixing device, where the mineral filler and asphalt cement are mixed before being dropped into the drum.

If the mineral filler is discharged directly into the drum mixer, this can be done either upstream or downstream of the asphalt cement injection point. If the filler is discharged into the drum upstream of the asphalt cement entry point, it is usually dropped directly on the aggregate in the bottom of the drum because the filler is dry and of very small particle size. If lifted into the exhaust gas stream, a major portion of the material, depending on drum operating conditions, may be carried out of the drum and into the emission-control equipment.

If the mineral filler is discharged from its feed pipe into the drum after the asphalt cement has been injected into the drum mixer, a greater portion of the filler is usually captured by the asphalt cement. The mineral filler has less chance of becoming airborne and being carried out of the drum. If the mineral filler and asphalt cement are blended in some form of mixing device as the asphalt cement is being introduced into the drum, minimal carryout of the filler material normally occurs.

Baghouse Fines

If a baghouse (fabric filter) is used as the emission-control equipment on the plant, either all or a portion of the material captured can be fed back into the drum mixer. The fines captured in the baghouse are carried, usually by a screw conveyor, through an air lock and then fed pneumatically through a pipe into the rear end of the drum, as seen in Figure 9-8.

The baghouse fines typically are not metered, but are returned on a continuous basis and discharged into the drum in a fashion similar to that of mineral filler. Occasionally a surge of fine material may be carried back to the drum mixer. If plant operating characteristics cause such surges of baghouse fines to occur regularly, the fines should be collected in a small surge silo and then metered back into the plant using a vane feeder system. If the baghouse fines are not needed to satisfy mix design requirements, they can be wasted instead of being returned to the mix.

The returned fines must be incorporated into the asphalt mixture and not allowed to recirculate back to the

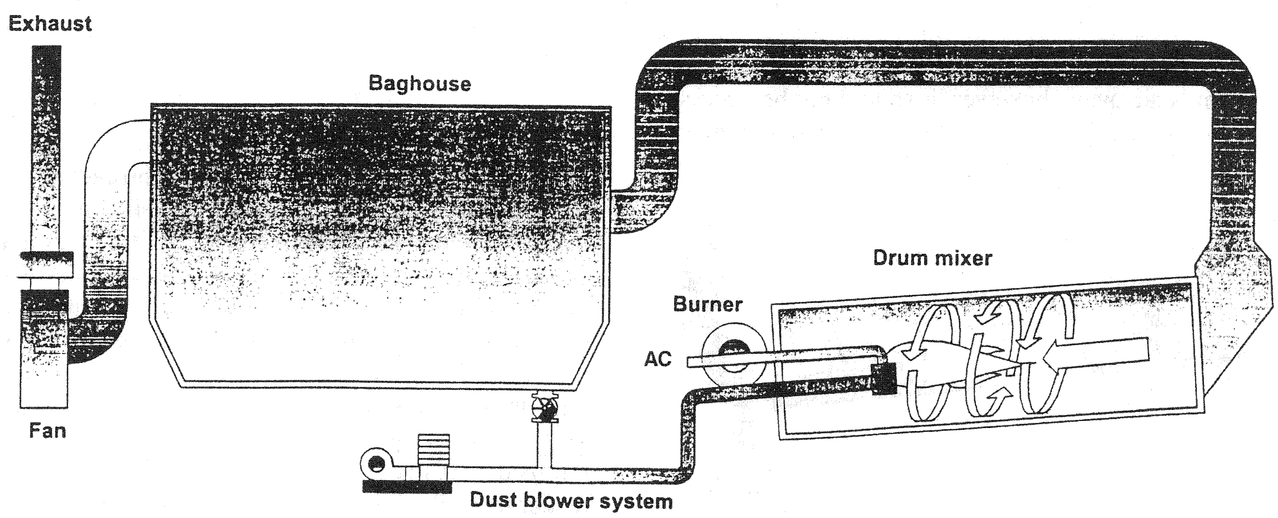


FIGURE 9-8 Pneumatic transfer to mixing area of drum.

baghouse. This is accomplished by ensuring that the fines are kept out of direct contact with the high-velocity exhaust gases and are quickly coated with asphalt cement. If the fines are carried back to the baghouse, they will be caught and again returned to the drum mixer. Soon the baghouse will be overloaded with fines, because new fines are continually being generated inside the plant. The baghouse will become plugged and will not operate properly. It is therefore essential that, as with mineral filler, baghouse fines be coated with asphalt cement before being picked up by the exhaust gases and carried out of the mixer.

The amount and gradation of the baghouse fines returned to the asphalt mix inside the drum can have a significant effect on the properties of the mixture produced.

RECLAIMED ASPHALT PAVEMENT RECYCLING SYSTEMS

Single-Feed Systems

Because of inherent emission-control problems involved in using single-feed systems, split-feed systems, in which the RAP is fed to the drum mixer separately from the new aggregate, are used most commonly to produce recycled asphalt mixes. On the few remaining plants that use a single-feed system to deliver both the new aggregate and the RAP to the burner end of the drum mixer, several methods are used, alone or in combination, to protect the asphalt-coated material from direct contact with the flame and to reduce the generation of visible hydrocarbon emissions.

One method is to spray water on the combined aggregate on the charging conveyor before it enters the drum. The degree of protection offered by the additional water on the surface of the aggregate depends on the amount of moisture already in and on the reclaimed material, the amount of water applied (typically between 1 and 4 percent by weight of reclaimed aggregate), and the position of the reclaimed material on the charging conveyor—underneath or on top of the new aggregate.

Another method involves use of a heat shield to reduce the contact of the combined aggregate with the flame. This device spreads the flame out around the circumference of the drum and decreases the concentration of heat at any one point near the flame. The performance of the heat shield is dependent on its location inside the drum, the amount of RAP in the mix, the moisture content of new and reclaimed aggregate, and the required mix discharge temperature. The efficiency of the heat shield can be determined by the amount of blue smoke that is generated during the recycling operation.

Split-Feed Systems

With a split-feed system, the new aggregate is delivered to the burner end of the drum-mix plant in a conventional manner. The RAP is delivered into a separate entry point near the midpoint of the drum length, as shown earlier in Figure 5-6.

A variety of designs are employed for the intake system used to introduce the RAP into the drum. Typically, the drum has a series of ports or entry chutes cut into the shell to allow the RAP to be introduced from the charging conveyor as the drum turns. At the point at which the RAP enters the shell, a short length of the flighting is often removed or configured so that the asphalt-coated material can easily be added to the new aggregate. The RAP begins heating as soon as it enters the port. The combined aggregate is picked up by the flights, and the heating and drying of the new material and the RAP continue.

When RAP is charged into the drum at its midpoint, less new aggregate is placed into the drum at the burner end, reducing the density of the veil of aggregate upstream of the RAP entry and decreasing the amount of heat transferred from the exhaust gases to the new aggregate. Thus the temperature of the gases at the point at which they come in contact with the RAP is higher, and there is a greater chance of burning off the asphalt coating on the RAP. This problem increases in severity as the amount of RAP used in the recycled mix increases and the amount of new aggregate decreases accordingly. Methods for reducing the exhaust gas temperature involve increasing the density of the veil of new aggregate upstream of the RAP entry location, as well as raising the temperature of the RAP before it comes into contact with the heated new aggregate.

Normally, if 20 percent or less RAP is being incorporated into a recycled mix and a split-feed system is used, minimal hydrocarbon emissions are produced, depending on the adequacy of the veil of new aggregate inside the drum and the discharge temperature of the mix. As the percentage of RAP rises and the moisture content of the RAP increases, there is a greater potential for emission problems. When the amount of RAP used exceeds 50 percent by weight of mix, the emission of blue smoke during the recycling process can become significant. A combination of procedures, outlined above, is needed to ensure adequate heat transfer from the exhaust gases to the new aggregate before those gases come in contact with the RAP.

Only under ideal and carefully controlled production conditions may it be possible to incorporate over 50 percent RAP in a recycled mix without a major problem with visible emissions. Because of the reduced production rates and emission-control problems that occur when high percentages of RAP are used in a recycled asphalt mix, it is normally good practice to limit the amount of reclaimed material processed through a split-feed drum-mix plant to approximately 50 percent of the total aggregate weight. In most cases, the amount of RAP actually used is much less than 50 percent of the total mix weight.

PRODUCTION RATES

HMA drum-mix plants are rated by the number of tonnes (tons) of mix that can be produced per hour. The production capacity is usually related to the incoming aggregate temperature, the mix discharge temperature, the specific heat of the aggregate, and an average aggregate moisture content removal of 5 percent for a plant operated at sea level. Plant capacities are also affected by a number of other variables, including drum diameter, fuel type, exhaust gas velocity, capacity of the exhaust fan, amount of excess air at the burner, estimated air leakage into the system, and atmospheric conditions. Aggregate gradation may be a factor with mixes containing a large percentage of coarse aggregate because such mixes are more difficult to heat uniformly than mixes incorporating a balance of coarse and fine aggregate particles.

One of the variables that has the greatest effect on the plant production rate is the average moisture content of the coarse and fine aggregates. The moisture content of the fine aggregate is usually higher than that of the coarse aggregate. The average moisture content is thus a function of the amount of moisture in the coarse aggregate and its percentage in the mix, plus the amount of moisture in the fine aggregate and its percentage in the mix.

If, for example, 60 percent of the mix consists of coarse aggregate with 3.0 percent moisture and 40 percent of the mix is fine aggregate (with 8.0 percent moisture), the moisture content of the combined aggregate is 5.0 percent. If the fine aggregate moisture is reduced to 6.0 percent, the moisture in the cold feed entering the drum is reduced to 4.2 percent. As the average percentage of moisture in the aggregate increases, the production capacity of a drum mixer of a given diameter decreases. At a constant average incoming moisture content, the production rate increases as the drum diameter becomes larger. The theoretical relationship among average moisture content, drum diameter and length, and calculated drum-mix plant production rate [at a mix discharge temperature of 132°C (270°F)] is shown in Table 9-1 for different models of one particular make of plant, at a given volume of exhaust gas flow and set of operating conditions for each size of plant. Similar charts are available from manufacturers of other makes of drum mixers.

Table 9-1 indicates that at an average moisture content of 5 percent, a drum-mix plant having a diameter of 1.8 m (6 ft) has a theoretical production capacity of 143 tonnes (158 tons) of mix per hour. If a drum 2.44 m (8 ft) in diameter is used, the manufacturing rate increases to 276 tonnes (305 tons) of mix per hour. For a drum mixer 3.0 m (10 ft) in diameter, the capacity increases to 492 tonnes (541 tons) of mix per hour at 5 percent moisture removal.

As the moisture content in the aggregate decreases from 5 to 3 percent, the production rate for a drum mixer

TABLE 9-1 Nominal Drum-Mix Capacities

Drum Diam. & Length (ft)	Capacity (Tons per Hour) for Surface Moisture Removed (%)								
	2	3	4	5	6	7	8	9	10
5 × 22	178	140	116	100	84	79	74	63	58
6 × 24	278	220	178	158	137	121	116	100	89
7 × 30	420	336	273	236	205	184	163	147	137
8 × 32	541	430	352	305	263	236	210	194	173
9 × 36	719	578	478	410	357	315	284	257	236
10 × 40	956	761	630	541	473	430	378	341	315

NOTE: Figures for each size of dryer are for asphalt concrete mix capacities. Examples of the effects of moisture content on plant production rates are for one manufacturer's drum-mix plants. 1 ft = 0.305 m; 1 ton = 0.907 tonne.
SOURCE: Barber-Greene.

that is 2.4 m (8 ft) in diameter increases from 276 tonnes (305 tons) per hour to 391 tonnes (430 tons) of mix per hour. If the aggregates have a higher moisture content (for example, 8 percent), a drum mixer of the same 2.4-m (8-ft) diameter can produce only 191 tonnes (210 tons) of asphalt mix per hour. Thus the average moisture content of the aggregate directly affects the capacity of a drum-mix plant.

The mix discharge temperature, held constant at 132°C (270°F) in the example above, also affects the production rate of the plant: as the mix discharge temperature decreases for a given aggregate moisture content and drum size, the volume of mix that can be manufactured in a given period of time increases. Figure 9-9 shows that for a drum-mix plant from one manufacturer that is 2.2 m (7.3 ft) in diameter and 8.5 m (28 ft) in length, with 5 percent moisture removal, the production rate increases from 232 tonnes (255 tons) per hour at a mix discharge temperature of 149°C (300°F) to 273 tonnes (300 tons) per hour at a temperature of 121°C (250°F). When the moisture content of the incoming aggregate is relatively high, the production rate changes are not as great when the mix discharge temperature is decreased. At 8 percent average moisture content, the production capacity of the same plant increases from 159 to 182 tonnes (175 to 200 tons) per hour as the mix discharge temperature decreases from 149°C (300°F) to 121°C (250°F).

The production rate of a drum-mix plant is also affected by the volume and velocity of the exhaust gases being pulled through the system by the exhaust fan. As the volume and velocity of the gases decrease, the production capacity of the drum mixer is reduced.

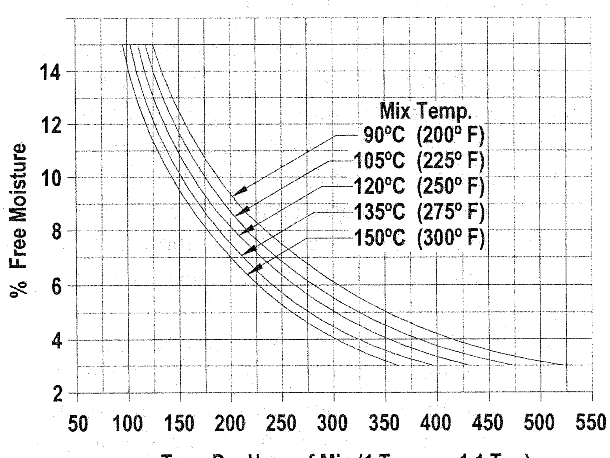


FIGURE 9-9 Effect of moisture content and mix discharge temperature on drum-mix plant production rate.

For those plants that operate with a split-feed system, the production rate of recycled mixtures is also a function of the volume of RAP being fed into the drum mixer. As the amount of RAP delivered to the drum surpasses 50 percent of the total aggregate feed, the capacity of the plant is decreased, as shown in Figure 9-10 for one particular make of drum-mix plant. This decrease is caused by the lack of an adequate amount of new aggregate in the upper end of the drum mixer to provide for proper heat transfer from the burner exhaust gases to the new aggregate. This, in turn, reduces the heat transferred from the new aggregate to the RAP.

Figure 9-10 shows that a recycled mix made up of 60 percent RAP and 40 percent new aggregate, with a weighted moisture content in the combined materials of 5 percent, has an index number of approximately 0.70. The index number means that this plant can produce only 70 percent as much mix per hour, at a 60/40 blend of RAP and new aggregate, as could be produced if the same plant used all new aggregate. Thus, if the plant could manufacture 280 tonnes (308 tons) per hour with 100 percent new material at 5 percent moisture removal, it would theoretically have a capacity of only $280 \times 0.70 = 196$ tonnes ($308 \times 0.70 = 216$ tons) per hour if 60 percent RAP were incorporated into the mix. As the amount of RAP used in the recycled mix increases above 50 percent, the amount of mix that can be produced in a drum-mix plant is reduced proportionately.

The index number provides a means of estimating the effect of the introduction of RAP into the drum mixer on the production rate of the plant. The actual production rate of a drum-mix plant will depend on a variety of factors, including the volume of gases being pulled through the system and the temperature of those gases. In addition, several of the newer types of continuous-mix plants,

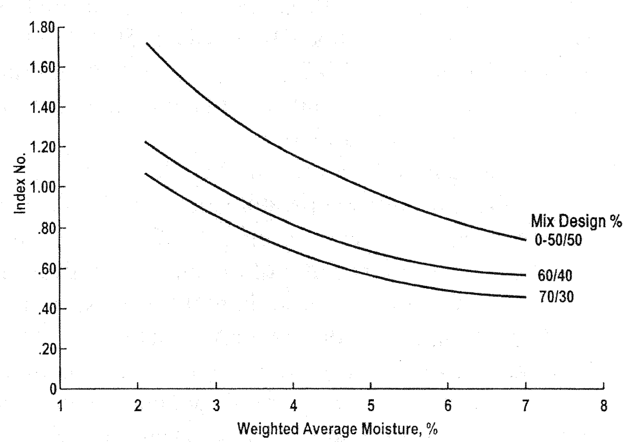


FIGURE 9-10 Effect of amount of RAP on drum-mix plant production.

such as the counter-flow drum mixers (see Section 10), are generally more efficient in heat transfer and thus can process amounts of RAP above 50 percent with less effect on the plant production rate.

PLANT EFFICIENCY

A plant should be operated at the most efficient production rate, irrespective of demand; it should be shut down when the silos are full and restarted when mix is needed once again. There are two methods of judging the efficiency of operation of a parallel-flow drum-mix plant: (*a*) determining the differential between the temperature of the mix upon discharge and that of the exhaust gases at the same point, and (*b*) observing the asphalt mixture as it is discharged.

Mix and Stack Temperatures

If perfect heat transfer could take place inside the drum, the temperature of the mix upon discharge from the parallel-flow drum-mix plant would be equal to the temperature of the exhaust gases at the same point (see also the earlier discussion of the heat transfer process). This equilibrium point would mean that the heat transfer was in balance and the drum mixer was running at maximum possible heat transfer efficiency. Under normal operating conditions, if the veil of aggregate inside the drum is complete, the exhaust gas temperature measured at the drum exit or before the gases enter the emission-control system should be within 10°C (18°F) of the temperature of the mix (assuming that no leakage occurs and no cooling air is added in the ductwork between the end of the drum and the point at which the gas temperatures are measured in the ductwork). Thus, if the mixture discharge temperature is 140°C (285°F), the measured exhaust gas temperature should be less than 150°C (300°F). This small temperature differential implies that the drum mixer is operating efficiently and that minimum fuel per tonne (ton) is being burned.

Exhaust gas temperature higher than about 10°C (18°F) above the mix temperature indicates that the heat transfer process inside the drum is not as efficient as it could be, primarily because of the lack of a uniformly dense veil of aggregate throughout the cross section of the drum. Temperature differentials of up to 55°C (98°F) between the mix and the exhaust gases are sometimes found, indicating that the plant is not being maintained or operated properly and that emission control might be a problem. The degree of operating inefficiency is related to the difference between the two temperatures (mix discharge and exhaust gas) before entry into the emission-control system.

During production of a recycled asphalt mixture in a single-feed drum mixer, the heat transfer between the exhaust gases and the new and reclaimed aggregates should be similar to that for a mixture using all new material. Thus for this process, the exhaust gas temperature should be within the 10°C (18°F) temperature differential if the plant is operating correctly. If a split-feed system is being employed, the difference between the two temperatures may be greater than 10°C (18°F), depending on the proportion of RAP introduced at the center inlet point. As a higher percentage of RAP is incorporated in the recycled mix, the temperature differential increases. When 50 percent of the recycled mix consists of RAP, the temperature of the exhaust gases may be more than 40°C (72°F) above the mix discharge temperature.

The efficiency of the heating and drying operation, therefore, can be judged in part by observing the temperature differential between the mix leaving the drum and the exhaust gases measured in the ductwork. Because both temperatures are usually recorded continuously and displayed on the plant control console, this method of monitoring the plant production process is easy to implement.

High exhaust gas temperatures can also lead to significant, premature corrosion on one side of the ductwork between the discharge end of the drum mixer and the primary collector. This corrosion is another reason why the efficiency of the plant operation needs to be monitored, and the temperature of the exhaust gases at the time they exit the drum mixer must be controlled.

Mix Discharge Monitoring

A second way to judge the efficiency of the drum-mix plant operation is to observe the asphalt mixture as it is discharged from the drum. The appearance of the mix, whether it consists of all new aggregate or a blend of new and reclaimed aggregate, should be uniform across the width of the discharge chute. The color of the aggregate particles should be consistent, and the finer aggregate particles should be evenly distributed throughout the mixture.

If the fuel used by the burner is not being completely combusted, the coarser aggregate particles in the mix may appear to be covered with a dark brown stain instead of with the proper film thickness of asphalt cement. In addition, the adhesion of the asphalt cement binder to the aggregate may be reduced, and the mix will have an increased tendency to strip when tested for potential moisture damage.

If the veil of aggregate inside the drum is not complete, the exhaust gases will travel down one side of the drum, depending on which direction the drum is turning, at a higher velocity than on the other side of the drum. Fine dust-sized particles will be picked up in the exhaust gas stream and carried to the rear of the drum. As the exhaust gases change direction to enter the ductwork, the larger dust particles will drop out of the gas stream. These uncoated particles will be discharged on one side of the mixture as it exits the drum. A steady stream of light-brown, uncoated, fine aggregate particles on one side of the HMA discharge chute thus indicates that the veil of aggregate inside the drum is incomplete.

If a dry, powdered additive such as hydrated lime is being added to the incoming cold aggregate at the burner end of the mixer, it is possible for very fine material to be picked up in the exhaust gases shortly after it is charged into the plant. When the aggregate veil is proper, the fine material will be trapped in the tumbling mass of aggregate and incorporated into the mix. If the aggregate veil is incomplete, however, the powdered material may be carried down one side of the drum and then dropped into the bottom of the drum at the mix discharge point, depending on the size of the particles relative to the exhaust gas velocity. The powdered lime will then be visible on one side of the asphalt mixture as it is discharged from the drum. Thus this method of adding mineral filler should not be used unless that filler is well blended with the incoming aggregate before the two materials are charged into the drum mixer.

Typically, a high stack temperature relative to the mix discharge temperature will be accompanied by a stream of light-colored fines on one side of the mix discharge chute. Both of these phenomena are indications that the drum mixer is not operating efficiently. The plant operator should alter the production process to achieve a denser veil of aggregate in the drum.

SUMMARY

The following key factors should be considered when monitoring the operation of a parallel-flow drum-mix plant:

- The sound of the burner should be monitored. A uniform, constant roar is desirable. A coughing, sputtering, or spitting sound may mean that the burner is not able to properly and completely combust the fuel it is trying to burn. Brown stains or a reduced asphalt cement film thickness on the coarser aggregate particles at the discharge end of the drum mixer also indicates problems with unburnt fuel.
- The density of the veil of aggregate inside the drum near the midpoint of its length is the key to efficient operation of the drum mixer and economical fuel usage. The completeness of the veil can be determined from a comparison of the discharge temperature of the mix with that of the exhaust gases at the stack. The stack temperature should be no more than 10°C (18°F) higher than the mix discharge temperature if the veil of aggregate inside the drum is complete across the cross-sectional area of the drum (assuming that no cooling air is added in the emission-control system). Greater temperature differentials indicate that the plant is not being operated efficiently.
- The presence of light-brown, uncoated fine aggregate on one side of the mix in the discharge chute is also an indication that the veil of aggregate is incomplete across the drum circumference.
- The generation of visible hydrocarbon emissions from the stack further indicates that the temperature of the exhaust gases inside the drum is too high at the point where the asphalt cement is injected into the drum.
- The density of the veil of aggregate inside the drum can be increased through the use of kicker flights, dams, donuts, or retention rings near the midpoint of the drum length. The density can also be increased by lowering the slope of the drum to increase the dwell or residence time of the aggregate in the drum.
- Mineral filler or baghouse fines should be added through the mix discharge end of the drum. These materials should be coated with asphalt cement or captured in the mix before they are exposed to the exhaust gases moving down the drum.
- If RAP is added to the drum through a split-feed system, the difference between the mix discharge temperature and the exhaust gas temperature measured at the stack will typically be greater than 10°C (18°F) and will usually increase roughly in proportion to the amount of RAP added to the mix.
- The plant production rate is determined at a given mix discharge temperature and an average moisture content in the aggregate, usually 5 percent, at a given elevation (sea level). An increase in the moisture content or an increase in the mix discharge temperature will decrease the capacity of the drum mixer in terms of tonnes (tons) of mix produced per hour.
- Production rates for recycled HMA, up to a RAP content of 50 percent, will normally be similar to the production rates for mixes containing all new aggregate. Above that amount of reclaimed material per ton of mix, the production rate of the parallel-flow drum mixer will decrease as the amount of reclaimed material increases.

SECTION

10 Counter-Flow Drum-Mix Plants

In this section the processing of aggregate and asphalt cement inside a counter-flow drum-mix plant is addressed. This type of plant, developed in the early 1930s, has replaced the parallel-flow drum-mix plant in recent years as the primary type of plant purchased by contractors to manufacture HMA. The counter-flow drum-mix plant is essentially a counter-flow aggregate dryer similar to that used to heat and dry aggregate for a batch plant operation, with a mixing unit attached in one of two primary ways to the end of the dryer. The methods used to introduce the aggregate into the drum, the operation of the burner, and the heating and drying of the aggregate as it moves through the drum against the direction of the exhaust gases from the burner are reviewed first. The operation of the mixing unit is then described, including the introduction of the hot aggregate, the RAP, and the asphalt cement binder. The blending of the mix components is also reviewed. The section ends with a summary of the key factors that should be considered in monitoring the operation of a counter-flow drum-mix plant.

Two different types of counter-flow drum-mix plants are commonly marketed. The first, more conventional plant, shown earlier in Figure 5-7, has the mixing unit extended on the end of the aggregate dryer portion of the drum. The second type, a double-barrel plant shown in Figure 5-8, has the mixing unit folded back around the aggregate dryer portion of the drum. Both styles of plant accomplish the same processes—heating and drying the aggregate; adding mineral filler, baghouse fines, and RAP, as needed; adding the asphalt cement binder material; and mixing all of the components together to produce a high-quality HMA product.

AGGREGATE ENTRY, HEATING, AND DRYING

The aggregate enters the counter-flow drum-mix plant from the upper end of the drum, similar to the entry used for a batch plant dryer as discussed in Section 8. The aggregate normally is delivered into a sloped chute by the charging conveyor and slides by gravity into the drum. A Slinger conveyor system may be used to feed the aggregate into the drum. On some plants, a rotating chute is employed to ensure that the aggregate does not hang up during introduction into the drum.

On the conventional counter-flow drum-mix plant with the mixing unit extended behind the aggregate dryer portion of the drum (Figure 5-7), the burner head is embedded into the rotating drum. Although the burner itself is located outside the drum, the burner fuel does not ignite and burn until it reaches the burner head. All the air needed to combust the fuel is delivered through the burner. Additional air is drawn into the drum by the exhaust fan through a tube that surrounds the burner assembly and protects the burner from damage by the aggregate. Figure 5-7 shows the burner head as the aggregate moves downstream toward the burner, with the exhaust gases moving in the opposite direction.

On the double-barrel type of counter-flow drum mixer, the burner location is similar to that on a normal counter-flow aggregate dryer. The burner is a total-air burner, as discussed in Section 9 and shown in Figure 9-4. The position of the burner on this type of plant is seen in Figure 5-8.

The heating and drying of the aggregate are accomplished as the combined coarse and fine aggregate material moves through the dryer by the action of the rotating flights and gravity. The burner is located at the lower or discharge end of the drying unit, and the aggregate moves toward the burner as it travels through the drum. The exhaust gases from the burner move upstream, in the opposite direction to the flow of the aggregate. As the aggregate moves toward the burner and continues to heat, the moisture is removed from the surface of the aggregate particles. The internal moisture in the aggregate pieces is driven out, and the heating of the aggregate continues until the required aggregate discharge temperature is obtained.

If RAP is to be added to the new aggregate, the temperature of the new aggregate is increased to the level necessary to permit adequate heat transfer between the superheated new aggregate and the ambient-temperature reclaimed material. This practice is similar to the additional heating of the new aggregate when RAP is to be used in a batch plant mixing process (see Section 8).

In contrast with a parallel-flow drum-mix plant, no asphalt cement binder material is added inside the drying portion of the counter-flow drum mixer. The initial section of the drum is a dryer only. No material—mineral filler, baghouse fines, or RAP—is added upstream of the burner.

MIXING UNIT

Conventional Counter-Flow Drum

For the counter-flow unit in which the burner is embedded into the drum and the mixing occurs as an extension of the operation of the drying drum, the heated and dried aggregate passes over a dam or retention ring located just behind (downstream of) the burner head. A series of openings or ports is typically used to permit the aggregate to pass into the mixing unit.

Once the heated aggregate has entered the mixing chamber of the drum, the RAP, if used, is added to the new aggregate. Because the RAP is introduced into the drum behind the burner, it is not exposed to the burner flame. For this reason, hydrocarbon emissions are not a problem, as they can be with a parallel-flow drum mixer. Heat transfer from the new aggregate begins as soon as the two materials come together at the upper end of the mixing unit. Moisture contained in the RAP is pulled out of the mixing unit and around the burner by the exhaust fan. Any hydrocarbon emissions released from the RAP are also pulled out of the mixing unit by the exhaust fan, but these fumes are incinerated as they pass through the burner area. Thus with a counter-flow drum mixer, the generation of blue smoke is minimized.

Shortly after the RAP has been introduced into the mixing portion of the drum, any other additives needed in the HMA, including baghouse dust and mineral filler, are also introduced. Because the air flow in the mixing unit is minimal, there is no chance for any relatively heavy powdered additive, such as the returned fines or filler, to become airborne and be drawn into the drying portion of the drum by the exhaust fan. Mixing of the RAP, filler and baghouse fines, and new aggregate begins as soon as the materials are introduced into the mixing chamber.

Very soon after all of the aggregate materials have been initially blended together, the binder is added to produce the HMA. The coating of the aggregate takes place as the combined materials are tumbled together and move toward the discharge end of the unit. Depending on the angle of the drum, as well as the number and type of flights in the mixing chamber, the mixing time in this type of counter-flow drum is typically in the range of 45 to 60 seconds. On completion of the mixing process, the HMA material is delivered into a discharge chute and transported to a silo.

Double-Barrel Counter-Flow Drum

With a double-barrel system, the mixing chamber is folded back around the aggregate drying drum. This mixing unit is unusual because it does not rotate. As seen in Figure 5-8, the heated and dried aggregate is discharged from underneath the burner downward into the nonrotating outer shell or drum. This occurs at the lower end of the mixing unit.

Shortly after the new aggregate enters the mixing chamber, RAP, if used, is added to the external drum. This material falls into the shell and quickly blends with the superheated new aggregate. Heat transfer from the hot new aggregate to the ambient-temperature RAP begins immediately. As with the conventional counter-flow drum mixer, any moisture in the RAP and any hydrocarbon emissions that develop during the heating process are drawn back into the dryer unit by the exhaust fan. The moisture is carried into the emission-control equipment, similar to what happens with the moisture released by the new aggregate during the heating and drying process. The hydrocarbon emissions from the RAP, if any, are incinerated by the burner.

Once the RAP has entered the outer shell, any additives, such as mineral filler, needed in the mix are deposited into the mixing area. The baghouse fines are also introduced into the outer shell at the same location. Because the flow of air in the area between the inner drum and the outer shell is minimal, there is no tendency for the added materials to be pulled out of the mixing chamber and into the aggregate dryer section of the drum-mix plant.

When all of the aggregate materials are in the outer shell, the asphalt cement is added to the mix. On most double-barrel plants, the binder materials can be added in one of two different locations. If RAP is not added to the mix, the asphalt cement is most often introduced as quickly as possible—shortly after the new aggregate, baghouse fines, and mineral filler, if any, have been charged into the exterior drum. If RAP is used in the mix, the addition of the binder material is delayed so some heat transfer can take place between the superheated new aggregate and the reclaimed material. The new binder material enters the outer shell slightly farther downstream (but uphill).

Mixing takes place by a series of paddles attached to the outside of the inner drum—the aggregate dryer (see

Figure 5-8). The paddles are set at the proper angle to push the combination of new aggregate, baghouse fines and mineral filler, RAP, and asphalt cement uphill, blending these materials together as they travel in the narrow space between the outside of the rotating inner drum and the inside of the nonrotating outer drum. Mixing occurs only in a lower quarter-portion of the circumference of the outer shell; the mix is not carried over the top of the inner drum. In addition to the heat transfer that takes place by direct contact between the new aggregate and the other mix components, further heating occurs as all the materials come in contact with the inner drum and by radiation of heat from the inner drum into the outer shell.

To achieve efficient mixing, the appropriate distance between the ends of the paddles and the inside of the outer shell must be maintained. The paddle tips and liner plate of the outer shell must be checked for wear periodically to ensure that material is not building up on the outer shell and that adequate mixing is occurring. Depending on the size and production capacity of the double-barrel plant, blending of all of the mix components typically occurs in less than 60 seconds. Upon completion of the mixing process, the HMA material is delivered into a discharge chute for transport to a silo.

SUMMARY

The following key factors should be considered when monitoring the operation of a counter-flow drum-mix plant:

- The new aggregate should be introduced into the upper end of the counter-flow dryer without obstruction. An inclined or rotating chute can be used for this purpose.
- The RAP is introduced into the mixing unit behind the burner for a conventional counter-flow drum-mix plant and under the burner into the outer shell for a double-barrel plant.
- In general, the RAP should enter the mixing unit before the mineral filler and baghouse fines are introduced into the mixing chamber.
- The asphalt cement should be charged into the mixing unit after some heat transfer has taken place between the superheated new aggregate and the RAP. If mineral filler or baghouse fines are also being added to the mix, the binder material should be injected into the mixing area after the additives have entered.
- The HMA mix being discharged from the mixing unit should be sampled to ensure that the mix components are completely mixed and adequately coated with asphalt cement.

SECTION

Surge and Storage Silos and Truck-Loading Techniques

The primary purpose of a silo on a batch plant is to allow the plant to continue to produce material when trucks are not available to accept mix directly from the pugmill. For a drum-mix plant (either parallel-flow or counter-flow) operation, the main purpose of the silo is to convert a continuous mixing operation into a discontinuous or batch-type truck-loading process and to hold the mix temporarily until the next transport vehicle is available. In this section the types of silos and silo designs, as well as mix loading and unloading operations, are described. The emphasis throughout is on measures taken to prevent segregation, defined as the separation of the coarsest aggregate particles in the mix from the rest of the mix. The section ends with a summary of key factors that should be considered in monitoring silo and truck-loading operations.

TYPES OF SILOS AND SILO DESIGNS

Surge Versus Storage Silos

During the normal daily operation of an HMA plant, a silo can be used to store asphalt mix between the arrivals of trucks at the plant. In this case, the silo is typically termed a surge silo. If the silo is to be used to hold the mix for longer periods of time (several hours or more), it may be termed a storage silo. A storage silo can easily be used as a surge silo, but a surge silo may not be suitable for use as a storage silo.

There are several differences between the two types of silos. First, the capacity of a storage silo is typically greater than that of a surge silo. Second, a surge silo is usually insulated but not heated, whereas a silo used for mix storage is always well insulated and usually heated, either completely or partially. Third, the gates at the bottom of a storage silo are heated and sealed when mix is to be held for a long period of time; this is done to reduce the amount of air that can pass up into the mix through the gates. The bottom of a surge silo, on the other hand, is not normally heated or sealed.

The primary operation of both types of silos, however, is similar. Only the ability to store quantities of mix for longer time periods without significant changes in the mix properties differentiates the two types. Regardless of the type of silo used, the mix that is held in the silo and then delivered to the haul truck should meet the same specifications and requirements as that discharged directly from the pugmill on a batch plant or from the discharge end of the drum mixer before passage into and out of the silo.

Insulation and Heat

As noted, most surge silos are insulated; this is done to reduce the loss of heat from the mix as it resides temporarily in the silo. The type of insulating material used and its thickness vary among silo manufacturers.

The cone at the base of a surge silo is usually heated to prevent the mix from sticking to the wall of the cone and building up. The heat can be provided by an electrical or hot-oil system. In some cases, the vertical walls of the silo are also heated so that the mix can retain its desired temperature for an extended period of time. If the silo is to be used strictly as a surge silo and is emptied of mix at the end of each production day, heating of the silo walls is usually unnecessary.

Storage

If an asphalt mixture must be retained in the silo overnight or over a weekend, this can usually be accomplished quite successfully without undue hardening or temperature loss in the mix. A well-insulated silo is required, but heating of the vertical silo walls is generally unnecessary. Mixes stored for several days in silos equipped with heated cones have shown only minimal oxidation and temperature loss. The amount of hardening that occurs is related to the amount of mix in the silo. The large mass of mix in a full silo will age less than will a small volume of mix in a nearly empty silo. The amount of temperature loss in the stored mix will depend on a number of other factors as well, including the initial mix temperature, the gradation of the material, and environmental conditions.

Asphalt mix (except mixtures with high coarse aggregate content, including friction course, stone-matrix asphalt, and coarse-graded Superpave mixes) may be stored for as long as a week when kept in a heated, air-tight silo. An inert gas system can be used to purge the silo of oxygen, but this is rarely done. The gates at the bottom of the silo, as well as any openings at the top of the silo, must be well sealed, however, to prevent the movement of air into and through the mix. The silo must also be completely heated and very well insulated. Mixes with high coarse aggregate content may tend to experience draindown if stored for an extended period of time.

If mix is to be stored in a silo for more than 2 or 3 days, such as over a long weekend or because of inclement weather conditions, it is advisable to remove a small amount of mix [at least 2 to 3 tonnes (2 to 3 tons) of material] from the silo every day or every other day during the storage period to ensure that the mix at the bottom of the cone does not set up and become impossible to discharge. If the mix is left undisturbed for a number of days, a plug of cold mix may form. When the discharge gates are finally opened, nothing happens—the mix has set up and will not flow out of the silo. The small amount of mix that is removed from the silo can be placed on the RAP pile for later recycling.

Although mix can be stored for relatively long periods of time, it is rarely necessary to do so with a continuously operating plant. Most silos, therefore, are used either as surge silos or periodically for overnight storage of the asphalt material. Mix held for more than 2 or 3 days in a silo should be tested to ensure that it meets all the same specifications and requirements as mix delivered directly to the paving site. This testing should include measurement of the mix temperature upon discharge from the silo and the properties of the asphalt cement recovered from the mix. As long as the mixture meets specifications, the length of time for which material is held in the silo should not be restricted. Such restriction increases the cost of the mix and reduces the efficiency of the mix production.

If an open-graded mixture is being stored temporarily, however, care must be taken to keep the mix storage temperature low enough so that the asphalt cement does not flow off of the aggregate (drain down) and collect at the bottom of the silo at the discharge gates. In general, it is not advisable to store an open-graded HMA mix overnight.

Conveying Devices

A variety of conveying devices are used to carry the HMA from the discharge chute on the drum mixer or the hopper under the pugmill of a batch plant to the silo. The equipment most commonly used is the drag slat conveyor, shown in Figures 11-1 and 11-2. In this system, a continuous set of flights connected by a drag chain pulls the mix up an inclined metal chute. The amount of mix that can be carried by the drag slats depends on the spacing between the slats, the depth of the individual flights, the width of the flights, and the slope of the conveyor, as well as the size and speed of the drag chain and the power of the drive motor. On some drag slat conveyors, the speed of the conveyor can be altered to change the capacity of the device to better match the output of the plant.

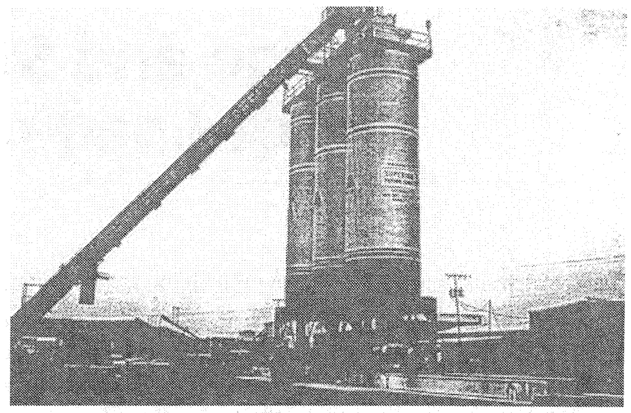


FIGURE 11-1 Slat conveyor feeding silos at an HMA plant.

A belt conveyor can also be used to deliver the mix to the silo. This belt is essentially the same as those that carry the incoming aggregate into the drum mixer or dryer, except that it is able to withstand the increased temperature of the hot-mix material. A conveyor belt cannot operate at an angle as steep as a slat conveyor. As shown in Figure 11-3, a bucket elevator is also used on some plants. This device is similar to the equipment used

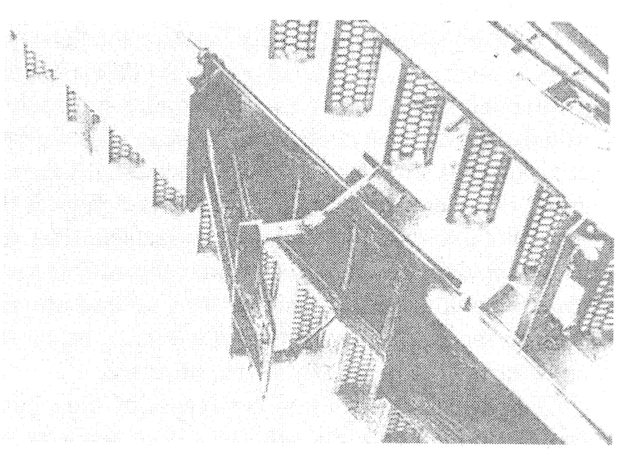


FIGURE 11-2 Drop-out chute in slat conveyor.

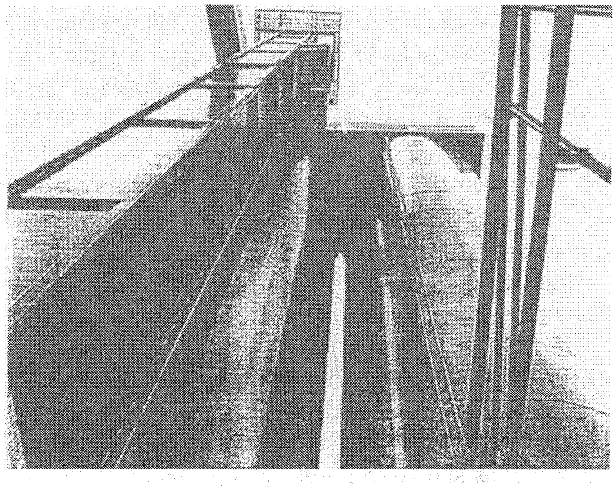


FIGURE 11-3 Bucket elevator feeding silos.

on batch plants to carry the hot aggregate from the discharge end of the dryer to the top of the mixing tower.

The type of conveying equipment employed is seldom a major factor in the uniformity of the mix delivered to the silo. The important factor is the manner in which the mix exits from the conveying device and is delivered into the top of the silo, as discussed later in this section.

Bin Geometry

Silos come in a variety of shapes. The vast majority of silos currently in use are circular, but silos can also be oval, elliptical, rectangular, or square. The shape of the silo can affect the amount of segregation that occurs upon both loading and unloading of the silo. Less segregation of a given mix is generally found with circular silos than with those of other shapes. For circular silos, the probability of segregation problems with mixes containing larger-sized coarse aggregate increases as the diameter of the silo increases. In general, however, the silo geometry is not a major factor in segregation; the manner in which the silo is operated (loaded and unloaded) has a greater effect on the uniformity of the mix and the amount of segregation.

Silo Cone

The bottom of the surge silo is shaped like a funnel or cone. Sometimes the cone is visible, and sometimes it is covered with sheet metal, as a downward extension of the side walls of the silo. The angle of the cone varies among manufacturers, but is usually between 55^0 and 70^0. This slope ensures that the mix is deposited as a mass into the truck. The angle needs to be steep enough and the gate opening(s) large enough to ensure that the larger aggregate particles do not roll into the center of the cone (rathole) as the mix is drawn down, causing segregation.

The vast majority of surge silos have low bin indicator systems that warn the plant operator when the level of mix in the silo has decreased to a point near the top of the cone. Keeping the volume of mix in the silo above this minimum level will reduce random segregation. As very coarse or gap-graded mixes are pulled below the top of the cone, there can be a tendency for the largest aggregate particles to roll into the center of the crater. These larger aggregate particles may then appear in the mix behind the paver as random pockets of segregation.

MIX DELIVERY

Segregation most typically occurs in mixes that contain a significant proportion of large aggregate or are gap-graded. The actual separation of the large and small particles occurs when the asphalt mix is placed in a conical pile inside the silo and the bigger particles run down the side of the pile, collecting around the bottom edge. Segregation can also occur when all the mix being discharged from the conveying device is thrown to one side of the silo, allowing the coarser pieces to run back across the silo to the opposite wall.

Recently, differential cooling of the mix as a result of materials segregation has been identified as a problem. The issue is addressed in the discussion of segregation in Section 13.

Top-of-Silo Segregation

Segregation on the roadway is often the result of operation at the top of the silo. Mix delivered to the top of the silo by a slat conveyor, belt conveyor, or bucket elevator will be discharged to the sides of the silo, as illustrated in Figure 11-4, unless some means is employed to redirect the flow into the center of the silo. On some silos, a series of baffles is used to contain and change the direction of the material. Other silos are equipped with a splitter system to divide the mix as it is delivered, causing a portion of the mix to be placed in each part of the silo. In general, use of a baffle or splitter system can reduce the tendency for segregation on the roadway but does not always eliminate it. Use of a batcher system generally provides a better means of solving the segregation problem (see Figure 11-5).

With such a system, a temporary holding hopper is used at the top of the silo to momentarily store the mix being transported by the conveying device. This hopper collects the continuous flow of mix. When the hopper

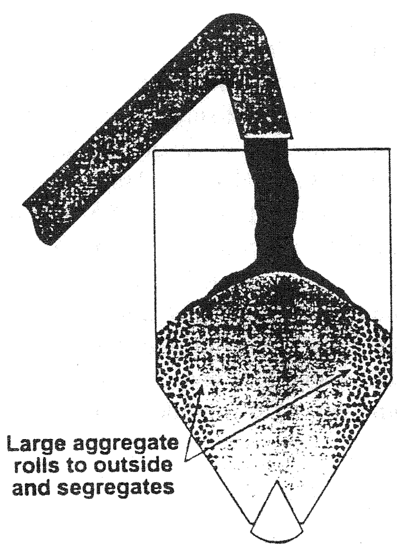


FIGURE 11-4 Segregation at top of silo without batcher.

is nearly full and the hopper gates are opened, the mix is deposited into the silo in a mass. The mass of mix hits the bottom of the empty silo or the top of mix already in the silo. Upon contact, the mix disperses in all directions uniformly, minimizing segregation. Moving HMA in a mass will always minimize segregation.

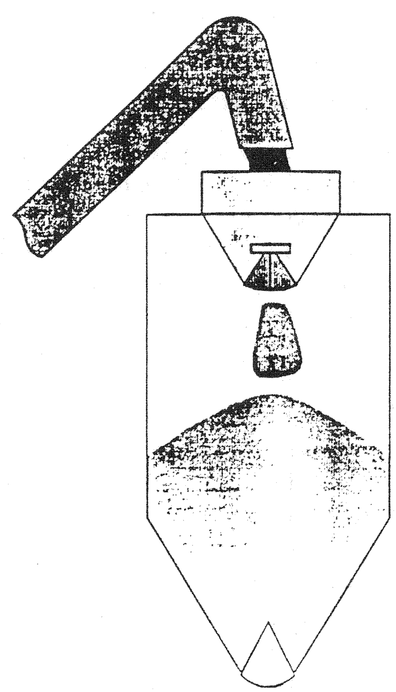


FIGURE 11-5 Use of batcher to prevent top-of-silo segregation.

The batcher system functions well unless the silo is almost full. In the latter case, the mix does not fall very far when released from the hopper. When the falling mix hits the mix already in the silo beneath the hopper, it lacks the momentum to spread out over the area of the silo and forms a conical-shaped pile instead. This pile can be the beginning of a segregation problem as more mix is deposited on top of it. Most silos are therefore equipped with high silo indicator warning systems that alert the plant operator to cut off the flow of incoming mix when the silo becomes too full.

The batcher may not prevent a segregation problem if the mix is delivered improperly. In some cases, the transporting device places the mix all on one side of the hopper, as shown in Figure 11-6. This practice causes rolling of the coarse aggregate in the batcher itself. It also causes the mix to be dropped into the silo off center. Thus to prevent segregation of mixes containing a large portion of coarser aggregate, the mix must be deposited uniformly into the center of the hopper and delivered from the batcher into the center of the silo.

The batcher is typically equipped with a timing device that opens the discharge gates at the bottom of the silo on a regular basis. The amount of time between drops can be altered to match the production rate of the plant. If properly set, the timer will open the gates before the batcher is too full and will close the gates before the batcher is completely empty. This allows the conveying device to operate continuously while preventing discharge from the conveyor directly into the silo through the open batcher gates.

If the timer operates improperly, too much mix will be delivered into the batcher before the discharge gates are opened. If this occurs, the HMA material may overflow the batcher and back up into the conveying device. The conveyor will quickly become overloaded and then stop functioning. The plant will, in turn, have to cease

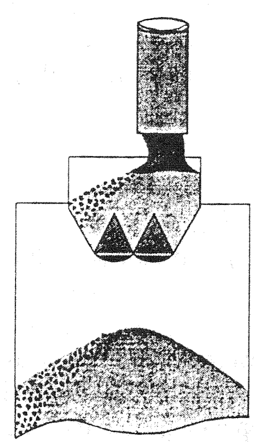


FIGURE 11-6 Segregation caused by feeding batcher off center.

production to prevent this problem, particularly if the timing device is not functioning properly. The plant operator may improperly leave the gates on the bottom of the batcher wide open. Doing so defeats the purpose of the batcher and allows the mix to dribble into the silo in a continuous stream, just as if the batcher were not there.

In other cases, the batcher may be emptied more often than is necessary—when only partially full. Such continual dumping of the hopper reduces the mass of material dropped into the silo at one time and increases the opportunity for formation of a conical pile of mix. The timer device should be set so that the gates of the batcher are closed before the batcher is empty. This practice will ensure that all the mix falls in a mass and will minimize segregation.

The capacity of the batcher at the top of the silo is related to the production capacity of the plant and is usually in the range of 2 to 5 tonnes (2 to 5 tons). A typical haul truck can hold from 14 to 20 tonnes (15 to 22 tons). Thus, depending on the capacity of both the batcher and each haul truck, it will take 3 to 11 batcher drops of mix to make up a full load in the haul truck.

Longitudinal (Side-to-Side) Segregation

Longitudinal (side-to-side) segregation will occur on one side of the lane being paved if the coarser aggregate particles are allowed to roll to one side of the silo. Depending on how the mix is delivered into the silo from the conveying device, the coarsest aggregate particles in the mix may collect on the opposite or the same side of the silo as the conveyor. In either case, those coarse aggregate particles will travel down one side of the silo and end up on one side of the haul truck and thus on one side of the laydown machine.

Longitudinal segregation will normally be found on only one side of the paver. In most cases, it will be relatively continuous on that side of the laydown machine if the plant is operated in a consistent manner. An easy way to determine the cause of this type of segregation is to reverse the direction in which the haul truck is being loaded underneath the silo and see whether the longitudinal segregation changes sides at the paver. If, for example, the longitudinal segregation is seen on the left-hand side of the paver lane and the haul truck is being loaded under the silo in its normal direction, the loading direction for the truck should be reversed. When the mix is subsequently delivered into the paver hopper—either directly from the haul truck or by means of a windrow and pickup machine—the longitudinal segregation should occur on the opposite side (the right side in this example) of the paver lane. If the position of the longitudinal segregation changes sides at the paver when the direction of the truck loading is reversed, the cause of the side-to-side segregation is in the loading of the mix into the silo from the conveying device. The direction of the mix entering the silo at the top of the silo must then be changed so that the mix is deposited directly into the center of the silo and not permitted to roll to one side or the other.

LOADING OF TRUCKS FROM SILOS

Just as it is important to deliver mix in a mass into the center of the silo in order to avoid causing longitudinal segregation, it is important to deposit the asphalt mix in a mass into multiple locations in the bed of the haul truck in order to avoid truckload-to-truckload (or end-of-load) segregation.

Most silos have only one discharge opening, equipped with a single or double gates. The gates on the bottom of the cone should be opened quickly and completely so that the flow of mix begins immediately and is unrestricted. Once the proper weight has been discharged into the truck bed, the gates should be closed quickly. For silos equipped with double (clamshell-type) gates, closing of the gates generally does not create any problems. For silos equipped with a single gate, however, it is possible for the mix to be thrown to one side of the truck bed as the gate is closed. To minimize this problem, it is important to close the single gate as quickly as possible.

Some silos are equipped with two separate discharge openings. These silos distribute the mix over a greater length of the truck bed and thereby reduce the amount of segregation that may occur. The silo gates may be parallel or perpendicular to the direction of the truck. Both systems can deliver mix into the haul vehicle without segregation as long as the correct amount of mix is placed into the right position in the truck bed.

Segregation can be eliminated by moving the HMA in a mass and by reducing the distance that the coarse aggregate can roll. Multiple discharges of mix into the haul vehicle are very beneficial in keeping the mix uniform and in reducing the amount of segregation. Some plants are equipped with automatic silo discharge systems. The number of each truck is entered into the computer system, and that truck is loaded at predetermined intervals with preselected amounts of mix for each drop. With a manual system, the silo discharge operator should be able to determine the time it takes to deliver the proper amount of mix, per drop, into each haul vehicle. This can be done by timing the discharge of the mix and comparing that time with the weight of mix delivered. Because trucks come in a variety of sizes, the time per drop and the number of drops per truck may differ from truck to truck. With practice, however, the operator should be able to judge accurately the time needed to place the proper amount of material in each truck bed. This amount can be confirmed visually by watching the height of the growing pile of mix in the truck as the loading continues. Specific loading practices for the different types of haul trucks—end-dump, belly- or bottom-dump, and live-bottom—are described later in this section.

The operator should not be allowed to "top off" or dribble mix into the haul vehicle. The gates on the silo should not be opened and closed continually to deliver only small amounts of mix to the truck. This practice occurs most frequently in plants where the surge silos are placed directly over the truck scales. Because the operator can quickly determine the amount of mix actually in the truck bed by observing the scale readout on the control console, the tendency is to load the vehicle up to the legal limit by using multiple drops of small quantities of mix at the end of the main delivery. This topping-off process causes the coarsest aggregate particles in the mix to roll down the slope of the mix in the truck bed toward both the front and back of the truck, significantly contributing to segregation of the mix. If the discharge of mix from the silo is timed, however, this procedure is unnecessary, and the potential for mix segregation is reduced accordingly.

Some silos have a loading hopper or batcher under the cone. In many cases, this hopper is supported on load cells to measure the amount of mix being delivered from the silo into the haul vehicle. The mix from such a hopper or batcher must still be deposited into different sections of the truck bed in order to minimize segregation by reducing the distance that the coarsest aggregate particles can roll. It is important to determine the size of the batch being loaded into the truck from the hopper versus the amount of mix needed in each portion of the truck bed. Depending on the capacity of the hopper and the size of each truck, multiple batches may be needed at each loading location. The hopper should not be used to top off drops of mix already in the truck bed.

End-Dump Trucks

If the mix is deposited into the center of an end-dump truck bed, the material will build up into a conical pile. Because the growth of the pile will be restricted by the sides of the truck, the larger aggregate particles will roll toward both the front and the back of the truck bed. In most cases, because of truckload weight laws and the amount of HMA that can be carried legally on the back axles, the mix is actually deposited into the truck bed to the front of the center of the length of the bed. This practice reduces the distance that the coarse aggregate particles can roll to the front of the bed but increases the distance that they can roll toward the tailgate.

The coarse aggregate pieces that accumulate at the tailgate area of the truck bed of an end-dump truck are deposited first into the paver hopper when the material is delivered to the laydown machine, while the pieces that accumulate at the front of the truck bed are deposited into the paver hopper last. Truckload-to-truckload segregation with this type of truck, then, is really a combination of what comes out of one truckload last (coarse aggregate at the front of the truck bed) and what comes out of the next truckload first (coarse aggregate at the tailgate of the truck bed). Because of the way trucks are often loaded—one drop of mix into the bed, generally forward to the length of the truck bed—most of the total amount of truckload-to-truckload segregation is caused not by what comes out of the truck bed last (end of load), but by what comes out of the next truck bed first (beginning of load).

As noted earlier, this segregation problem can be significantly minimized by dividing the delivery of the asphalt mix from the silo into multiple drops, each delivered to a different section of the bed of the hauling vehicle. If a tandem-axle or triaxle dump truck is being used, about 40 percent of the total weight of the mix to be hauled should be loaded into the center of the front half of the truck. The truck should then be pulled forward so that the next 40 percent or so of the total load can be deposited into the center of the back half of the bed, near the tailgate. The vehicle should then be moved backward so that the remaining 20 percent of the mix can be dropped into the center of the bed, between the first two piles.

A complaint commonly expressed about this type of loading procedure is that the truck driver must back the truck up under the silo in order to load the back of the bed. Yet the same driver will have to back the truck up once he or she reaches the paving site in order to deliver the HMA into the hopper of the paver. Another complaint is that it takes longer to load the truck when multiple drops are used as compared with a single drop of mix. While this is certainly true, the total number of tons of mix produced each day will almost always be limited by the capacity of the plant and not by the time it takes to load individual trucks. If segregation is to be eliminated, the truck driver will have to learn to move the haul vehicle back and forth under the silo and allow the mix to be deposited into the proper locations in the truck bed in order to reduce the distance that the coarse aggregate pieces can roll.

If a large end-dump truck is used to deliver the mix, the number of drops of material from the silo should be increased to distribute the mix along the length of the truck bed. The first drop of mix should be into the front portion of the bed and the second near the tailgate. The remaining mix should be delivered in evenly divided drops into the rest of the length of the truck bed. In no case should the truck be loaded continuously by the truck driver's moving forward under the silo as the mix is being discharged. This practice will cause the coarse aggregate particles to roll toward and then collect at the tailgate of the truck and increase the amount of segregation. Thus for a semi-truck trailer type of truck, five drops of mix should be made into the truck bed: the first at the front of the truck, the second at the tailgate, the third in the middle of the length of the bed, the fourth between the first and third drops, and the fifth between the second and third drops. This loading sequence requires that the truck driver reposition the truck after each drop of mix and increases somewhat the time needed to load the truck, but it also minimizes the segregation problem, which is the most important thing.

Because of weight laws in some states, it may not be possible to deposit a batch of mix directly in front of the tailgate of an end-dump truck and still legally scale the truck axles. In this case, the second batch of mix delivered into the truck should be placed as close to the tailgate as feasible while allowing the axle weight restrictions to be met.

Since different trucks have beds of different lengths, it is important to provide the truck driver with some sort of positive guidance on where to place the truck so that the mix will be discharged into the correct location along the length of the bed. One way to accomplish this is to paint a series of numbers, one foot apart, on the edge of the truck scale and have the driver stop at different numbers to load different parts of the bed. For example, the driver might position his or her door (or rearview mirror) above number 6 to be in the proper position to load the front of the bed—Drop 1. The driver would then move the truck forward until the door or mirror was above number 22 (or whatever the correct number was for the particular truck being loaded). The second drop of mix would then be placed near the tailgate of the truck. The driver would next back the truck up until the door or mirror was above Number 14, for example, in order to have Drop 3 placed in the center of the length of the bed. Different sets of numbers are used for trucks of different sizes and bed lengths.

A second method is similar to the first, but uses a horizontal piece of wood or board that extends between the legs of the silo and out in front of the silo legs for some distance at a height equal to the driver's position in the cab of the truck. For a tandem-axle truck, for example, red tape is used to indicate the proper loading position. A piece of red tape is placed on the rearview mirror of the truck, and the driver is asked to pull under the silo until the mirror is even with a piece of red tape under which is the number 1. The front of the truck bed is then loaded. Next the driver pulls the truck forward until the mirror is even with the piece of red tape numbered 2, and the rear of the truck (tailgate area) is then loaded. Finally, the driver is asked to back the truck up until the red tape on the mirror is even with the piece of red tape numbered 3, and mix is delivered into the middle of the truck bed.

For triaxle trucks, which have a longer bed length, blue tape (or any other color) can be used to indicate the proper loading positions. For semi-trucks, yellow tape can be used, for instance, to show the driver the correct locations at which to stop the truck in order to properly load the truck bed with five different drops of HMA. In any case, the truck driver must be given positive guidance on the correct place to stop the haul vehicle so that the proper amount of mix will be placed in the right position to eliminate the segregation problem.

Belly- or Bottom-Dump Trucks

If a belly- or bottom-dump truck with a single discharge gate is used to haul the HMA, it, too, is frequently loaded in a single drop of mix from the silo. The mix is deposited into the center of the length of the bed, directly over the discharge gates. This practice results in a mound of mix inside the bed, and the coarse aggregate pieces in the mix have a tendency to segregate. Those particles roll toward both the front and back of the truck bed at the top of the load since this type of truck has sloping front and back walls. Loading this type of truck in one drop of mix into the bed is therefore an improper procedure. Segregation of the mix occurs not at the beginning of the load when the mix is first deposited from the gates of the truck into the windrow, but at the end of the load when the coarse aggregate particles that have rolled to the front and back of the top of the load are discharged from the gates into the end of the windrow. Coarse aggregate pieces are often found in the windrow at the end of the load, resulting in segregation on the roadway at this point.

The proper loading sequence for this type of truck is to deposit about 70 percent of the total weight of the load into the center of the truck bed, directly over the discharge gate. This practice results in a slight mound of mix in the center of the length of the bed. The truck should then be moved backward and about 15 percent of the total weight discharged into the front portion of the truck, between the initial portion of mix and the sloping front wall of the truck bed. Once this has been done, the truck should be backed up and the final 15 percent of the total weight delivered into the back portion of the truck, between the initial portion of the mix and the sloping back wall of the truck bed. This loading procedure greatly reduces the rolling of coarse aggregate particles to the front top and back top of the truck bed and eliminates the segregation that occurs when the mix in the two corners (front and back tops) is finally deposited into the windrow.

A slightly different loading sequence is used if the belly- or bottom-dump truck is equipped with double discharge gates. In this case, the first drop of mix should be about 40 percent of the total load and should be placed directly over the front discharge gate. The truck should then be moved forward and a second 40 percent of the total load deposited directly over the second (rear) discharge gate. Once this has been accomplished, the truck should be moved forward once again and approximately 10 percent of the weight placed on the back top portion of the bed—between the second drop of mix and the sloping back wall of the truck bed. The truck should then be backed up and the fourth and final drop of mix, about 10 percent of the total load, placed on the top forward portion of the bed—between the first drop of mix and the sloping front wall of the truck bed. Thus with double-gated bottom-dump trucks, four different loading positions should be used to reduce the distance that the coarse aggregate particles can roll.

As with end-dump truck-loading procedures, positive guidance should be provided to the belly- or bottom-dump truck driver so that he or she knows where to stop the truck under the silo in order to load the vehicle in three or four drops of mix, depending on the number of discharge gates on the truck. Again, although this loading sequence takes longer than loading the truck in only one drop, such a procedure is absolutely necessary if segregation is to be prevented.

Live-Bottom Trucks

For live-bottom (also known as flow-boy or horizontal discharge) trucks, segregation can be a problem if coarse aggregate particles are allowed to roll to the back of the truck bed—to the discharge gate. If this type of truck is loaded with the truck moving slowly forward, the coarsest aggregate particles will move backward toward the tailgate as the mix is deposited into the bed. Upon completion of loading, those coarse particles will have accumulated at the discharge gate and will be delivered first into the paver hopper. Thus for this type of truck, segregation on the pavement surface is typically related to what comes out of the truck bed first, or beginning-of-load segregation.

The proper loading procedure for a live-bottom truck is to place the first drop of mix at the back of the bed, as close to the discharge gate as possible. Doing so will minimize the distance that the coarse aggregate particles can roll to the tailgate. The truck should then be backed up under the silo and the next drop of mix placed as close to the front of the bed as possible. Then because of the conveyor belt or slat conveyors in the bottom of the truck bed, the rest of the total weight of mix can be deposited into the truck bed with the truck moving slowly forward. When the mix reaches the end of the bed, the first drop will already be there, and the rolling of the coarse aggregate pieces will be halted.

As for the other truck types, positive guidance needs to be provided to the truck driver so that he or she knows the proper location at which to stop in order to allow the first drop of mix from the silo to be placed as close to the discharge gate as possible. Different types and lengths of live-bottom trucks will require different loading positions under the silo.

SUMMARY

Segregation usually begins at the surge or storage silo in the loading and unloading process. The key operating factors that should be monitored to prevent segregation include the following:

- Top-of-silo segregation is typically caused by the way the HMA mix is placed into the top of the silo as the mix is discharged from the conveying device.
- Longitudinal (side-to-side) segregation is caused by loading the silo to one side, so that the coarser aggregate particles roll to the opposite side inside the silo.

▒ The conveying device from the discharge chute of a drum-mix plant or the hopper under the pugmill of a batch plant must deposit the mix into the center of the batcher at the top of the silo.

▒ If longitudinal segregation is present behind the paver, several haul trucks should be loaded under the silo facing in the opposite direction from their normal loading pattern. When these truckloads of mix are unloaded at the paver, the location of the segregation should change sides in the lane being paved. If this happens, the cause of the longitudinal segregation probably lies in the procedure used to place the mix into the silo from the conveying device.

▒ A batcher should be used at the top of the silo. The batcher should not be operated with its gates wide open, allowing the mix to pass right through it. The batcher should be filled up with mix and should then drop the mix in a mass into the center of the silo. Further, the gate on the bottom of the batcher should be closed before all of the mix is discharged from the batcher.

▒ If the silo is to be used for overnight storage of asphalt mix, the cone should be heated and the silo walls insulated. If mix is stored for more than 2 days, a small quantity of mix should be withdrawn from the silo at least every other day to prevent plugging of the cone.

▒ If the mix is stored for more than 2 or 3 days, it should be checked upon discharge for temperature and for properties of the asphalt cement recovered from the mix. The mix should meet the same specifications and requirements as a mix placed immediately after manufacture.

▒ The plant operator should not top off the load of mix in the truck or dribble mix into the truck bed in small drops to fill the truck to legal capacity.

▒ Truckload-to-truckload segregation is typically caused by the way the HMA mix is discharged from the silo and where it is delivered into the length of the truck bed.

▒ An end-dump truck should never be loaded in only one drop of mix into the center of the truck bed. Multiple drops of mix are necessary, the first located near the front of the bed and the second near the tailgate. A third drop of mix should be made in the middle of the first two drops.

▒ If a long end-dump truck (semi-truck) is used, at least five drops of HMA mix should be made into the truck bed: the first at the front of the bed; the second at the back of the bed at the tailgate; the third in the middle of the length of the bed; and the fourth and fifth drops between the second and third and the first and third drops, respectively.

▒ An end-dump truck should never be loaded by slowly driving the truck forward as mix is being delivered from the silo. This will cause the coarser aggregate particles to collect at the tailgate of the truck and significantly increase the amount of segregation that occurs.

▒ If a belly- or bottom-dump truck is used, three or four drops of mix should be used to load the haul truck, depending on the number of discharge gates at the bottom of the bed.

▒ If a live-bottom truck is used, the first drop of mix should be delivered into the back end of the truck.

12 Emission Control

The primary source of emissions from a batch or drum-mix plant is the carryout of fines during the aggregate heating and drying process. In this section the three types of emission-control equipment that may be found on batch and drum-mix plants are described: dry collectors, wet collectors, and baghouses or fabric filters. If used, the dry collector is usually placed in front of one of the other two types and is termed the primary collector; the wet collector or baghouse is the secondary collector through which the exhaust gases flow after passing through the primary collector. The primary collector is used to remove the larger fine particles from the exhaust gases and reduce the loading on the secondary collector, which is used to capture the very fine particles.

All batch and drum-mix plants have a small amount of fines aggregate carryout from the dryer or the drum mixer. To meet federal and state air quality codes, emission-control equipment is necessary to capture particulate emissions that might otherwise be released to the atmosphere. In addition, some emission-control devices permit the plant operator to control the amount of fines returned to the asphalt mixture.

The velocity of the exhaust gases inside a dryer or drum mixer is a function primarily of the diameter of the drum, the capacity of the exhaust fan, and the speed of the exhaust fan. A minimum volume of air is needed for proper operation of the burner. This air, combined with the products of combustion from the burner and the moisture vapor from the aggregate, moves through the dryer or drum mixer at a velocity that varies with the operating conditions of the plant. The amount of fines carryout increases as the exhaust gas velocity rises.

In a parallel-flow drum mixer, the amount of fines carryout can be reduced significantly by encapsulating or coating the aggregate with the asphalt cement early in the drying process. The farther up the drum (toward the burner) the asphalt cement is injected, the greater is the amount of fines that will be captured in the asphalt cement before the fines can become airborne. Typically, the amount of fines carryout increases as the asphalt cement pipe is positioned farther down the drum toward the discharge end of the parallel-flow drum.

The amount of fines carryout is a function of the amount of very fine material in the new aggregate; the size, weight, and moisture content of the fines; and the amount of very fine particles in the RAP (if used in a parallel-flow drum-mix plant). The amount of fines is also related to the operation of the drum—the production rate (density of the aggregate veil), the location of the asphalt cement injection pipe (for a parallel-flow drum mixer), and the velocity of the exhaust gases. The amount of carryout can vary widely with a change in the properties of the incoming aggregate and the production rate of the plant.

The efficiency of the emission-control equipment is related to the amount of particulates that is captured by the equipment versus the amount that enters the emission-control equipment. If 1,000 particles per minute enter a baghouse, for example, and 990 of those particles are caught in the baghouse, the collection system is 99 percent efficient. The efficiency can be determined, in part, by observing the amount of particulates being emitted from the stack. This is done by checking the opacity of the exhaust gas beyond the end of the steam plume (if one is present). If a dust trail is seen, the operation of the emission-control equipment must be checked.

DRY COLLECTOR

Dry collectors are not used or needed on all asphalt plants. If used, they may be of several types, used singly or in combination. The original dry collector was a cyclone device that forced the exhaust gases to swirl inside the collector (see Figure 12-1). The dust in the gases was removed by centrifugal force, being thrown to the side of the cyclone as the gases moved in a circular motion. The operation of a cyclone dry collector is shown in Figure 12-2.

Most dry collector systems in use today have an expansion chamber combined with a baghouse. The expansion chamber or knockout box (see Figure 12-3) has a greater cross-sectional area than the ductwork through which the exhaust gases pass between the dryer (batch plant aggregate dryer or counter-flow drum mixer) or parallel-flow drum mixer and the secondary collector.

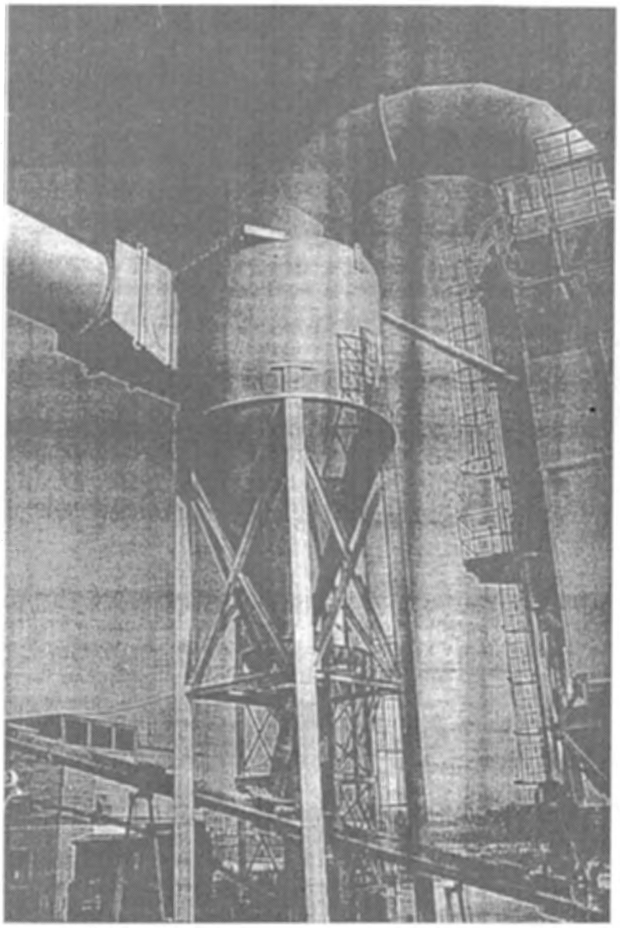


FIGURE 12-1 Vertical cyclone dry collector.

A typical knockout box used in combination with a baghouse is shown in Figure 12-4.

The exhaust gases from the dryer or drum mixer travel through the ductwork into the front end of the knockout box. At that point, the velocity of the exhaust gases is significantly decreased as the gases enter the expanded area. The amount of dust that falls out of the gas stream is directly related to the size of the expansion chamber and the decrease in the velocity of the gases. The velocity of the larger particles decreases such that the slow-moving particles drop to the bottom of the expansion chamber. The collected particles can then be returned uniformly to the batch plant or the drum mixer, either alone or in combination with the fines collected by the baghouse, or they can be wasted.

The efficiency of the dry collector depends in part on the size of the fine particles in the exhaust gases and on the type of collector used. Primary collectors can have an efficiency (percentage of amount of fines removed from the exhaust gases as compared with the total amount of fines in the gases) as low as 50 percent for a knockout box to as high as 70 to 90 percent when a dry cyclone is used. Thus only a portion of the fines in the exhaust gases is removed by this equipment. The main purpose of the dry collector is to improve the operation of the secondary collector by reducing the fines loading on the wet collector or baghouse.

WET COLLECTOR

After moving through a primary dry collector (if used), the exhaust gases on most newer plants equipped with a wet collector (wet scrubber) system are forced through a narrowed opening, or venturi, as shown in Figure 12-5. When the gas flow is concentrated in a small area, it is sprayed with water from multiple nozzles, and the fines are wetted. The exhaust gases and wet fines then travel into the separator section of the collector.

The exhaust gases are sent around the circumference of the unit in a circular motion, as seen in Figure 12-5. The wetted fines, which have increased in weight because of the added water, are removed from the gas stream by centrifugal force and fall to the bottom of the collector. The clean gas continues to swirl around the collector until it reaches the end, when it travels into the stack and then out to the atmosphere.

Depending on the size of the fine particles in the exhaust gases, a wet collector system is usually 90 to 99 percent efficient in removing particulates from those gases. In addition to being related to the size and amount of fines present, efficiency is a function of both the cleanliness and the volume of water used to spray the exhaust gases. If the water sprayed is clean and free from sediment and if all of the nozzles in the scrubber are open and working, the amount of fines removed by the wet collector system, and thus the efficiency, will increase.

The cleanliness of the water and the condition of the nozzles are related in turn to the size of the settling pond used to collect the water discharged from the scrubber. The water and fines, in the form of a sludge, are sent from the bottom of the collector through a pipe to the first section of the pond, where the heaviest fines settle out of the water. The cleaner water at the top of the pond in this first section is drawn off through an outlet on the opposite side of the pond. Additional settling of the fines occurs in each succeeding section of the pond.

The efficiency of the settlement process is directly related to the size of the settling pond: the bigger and deeper the pond, the more water is available, and the more time there is for the fines to separate and settle before the water

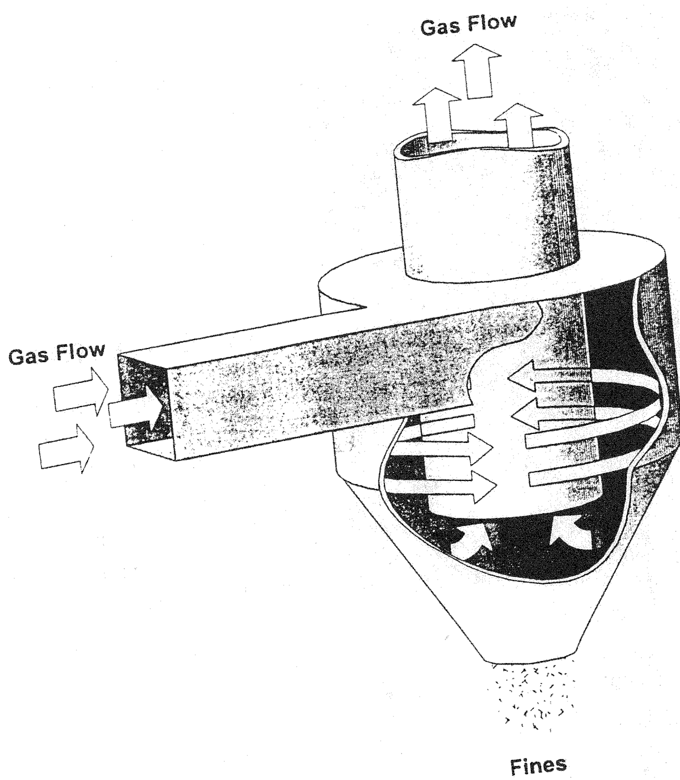


FIGURE 12-2 Flow through a typical cyclone dry collector.

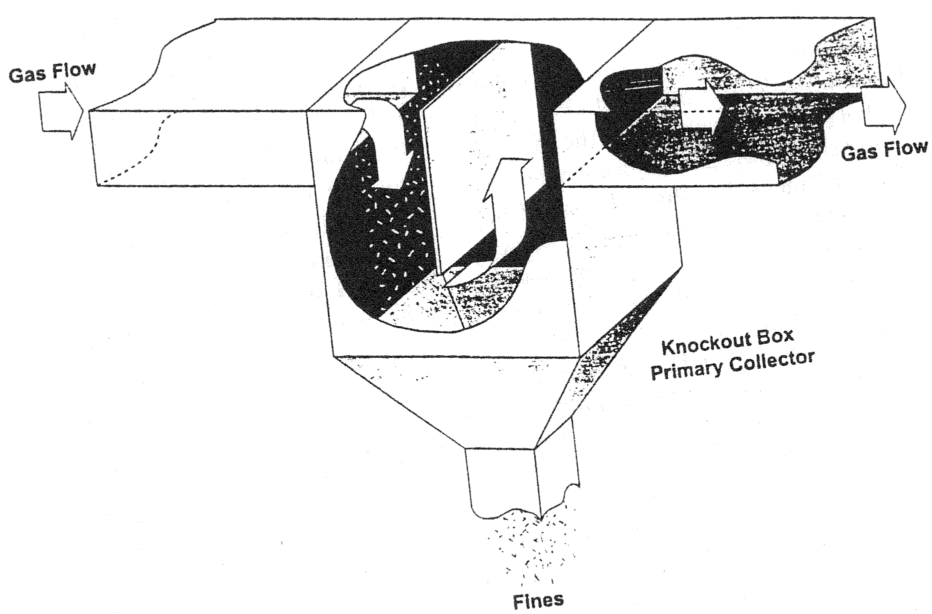


FIGURE 12-3 Flow through a typical knockout box.

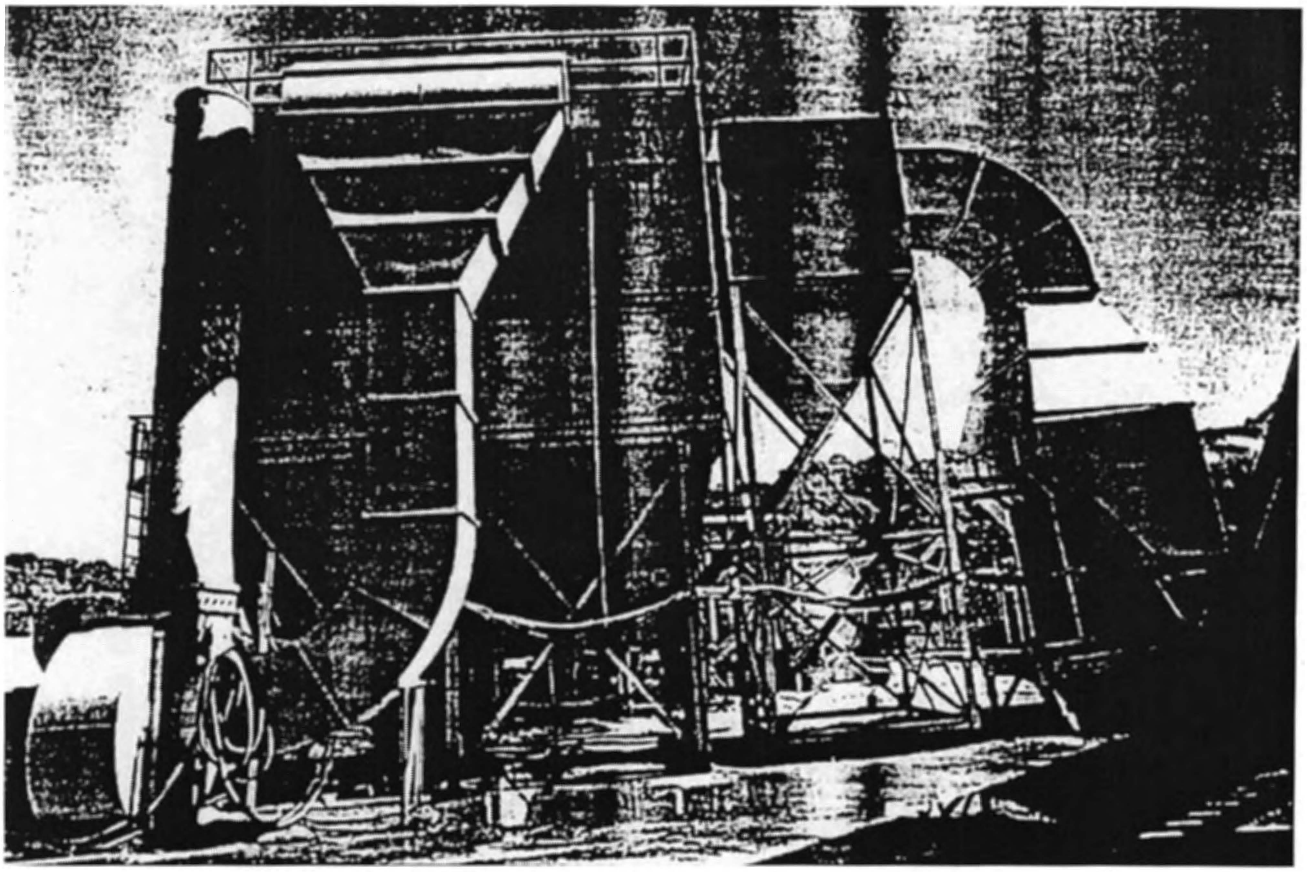


FIGURE 12-4 Knockout box installed prior to baghouse.

is pumped from the pond back to the wet collector unit. A settling pond is illustrated in Figure 12-6. As the settling pond fills up with fines, the time the water remains in the pond and the amount of settlement that can occur decrease. When a pond becomes too shallow, dirty water will be sent back to the scrubber. To maintain a supply of clean water for use in the fines collection equipment, the sediment on the bottom of the pond must be removed periodically. In addition, water lost from the pond through evaporation and leaks in the piping system should be replaced as often as necessary.

Any fines removed from the exhaust gases by the wet scrubber are no longer available for use in the mix. The gradation of the mix produced in the batch or drum-mix plant is thus not the same as the gradation of the incoming new and/or reclaimed aggregate. In most cases in which the amount of fines carryout is not great, the change in gradation will be small; if a large volume of fines is captured in the exhaust gases, however, a significant change can occur in the aggregate gradation, particularly in the very fine particle sizes.

BAGHOUSE

The exhaust gases that pass through the primary collector (if used) can be pulled by the exhaust fan on the plant through another type of secondary collector called a baghouse or fabric filter, as shown in Figures 12-7 and 12-8. It should be noted that although baghouses can be operated without the gases being passed through a primary collector first, doing so generally reduces the efficiency of the system and is not usual practice. The material used as the filter cloth is generally a special type of synthetic fiber that is resistant to high fines loadings, high humidity, and high temperature while undergoing multiple cycles of bending and flexing. The fabric is dense enough to catch the particulates while still permitting the air to pass through.

The fabric is made into a cylindrically shaped bag and placed on a circular metal framework or cage that is closed on the bottom and open on the top. The filter bags on the cages are arranged in rows inside the baghouse, as illustrated in Figure 12-9. The number of bags needed depends on the size of the dryer or drum mixer,

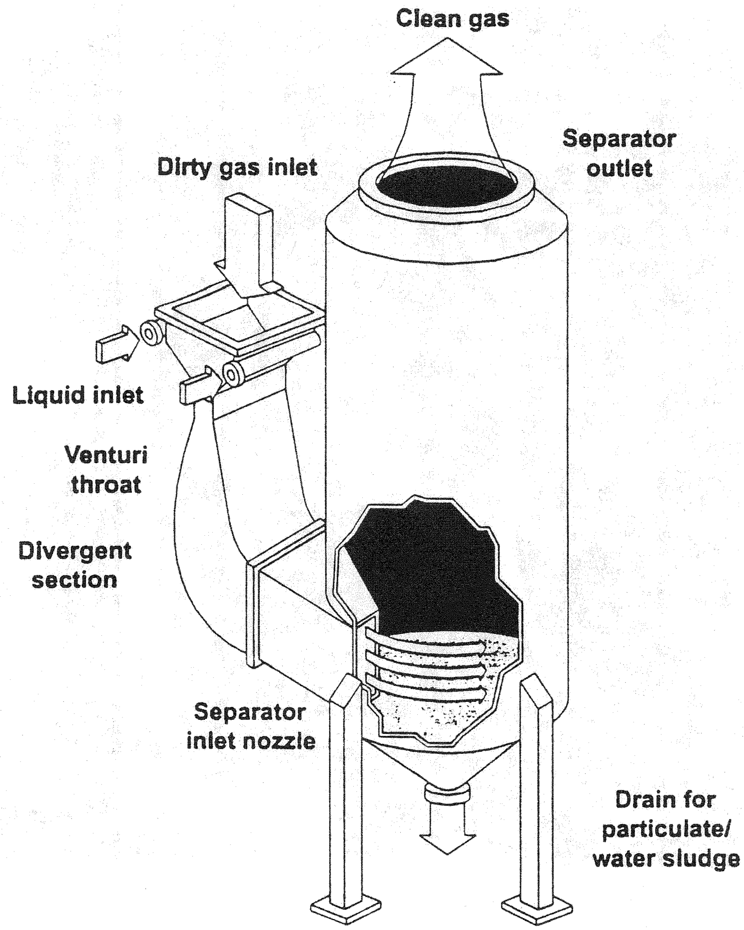


FIGURE 12-5 Flow through typical venturi scrubber.

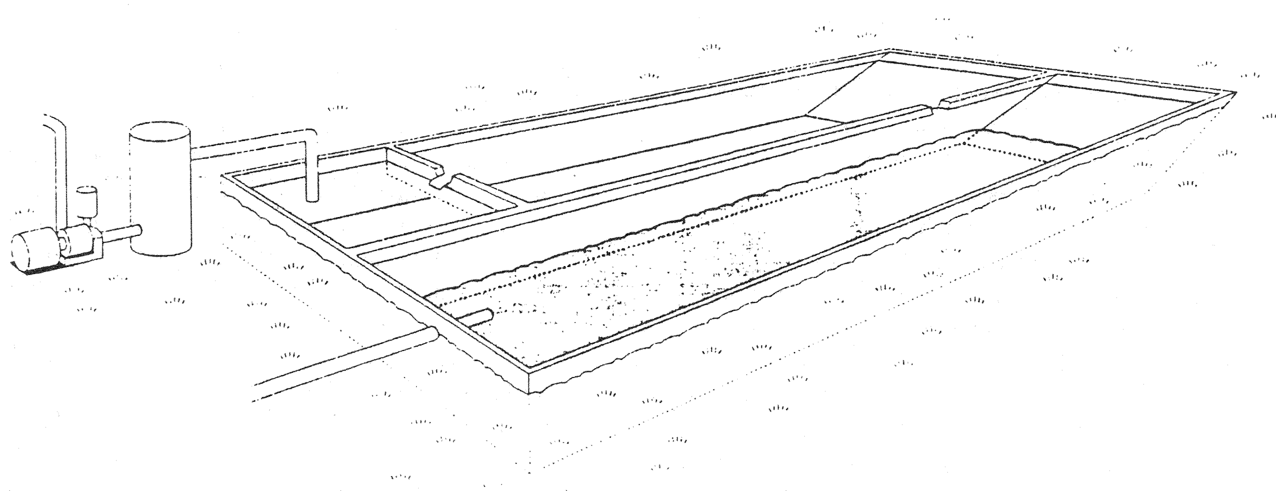


FIGURE 12-6 Typical settling pond.

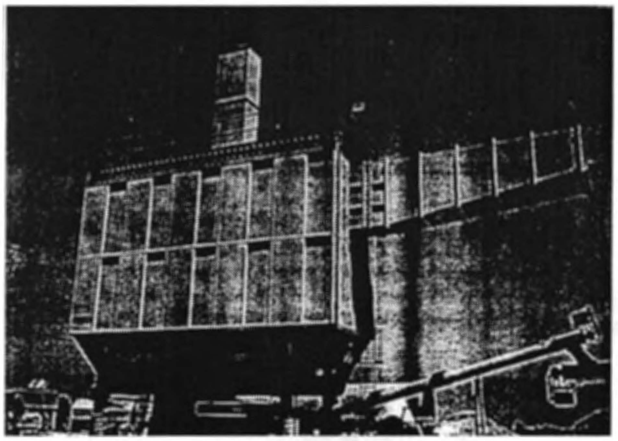


FIGURE 12-7 Pulse-jet baghouse.

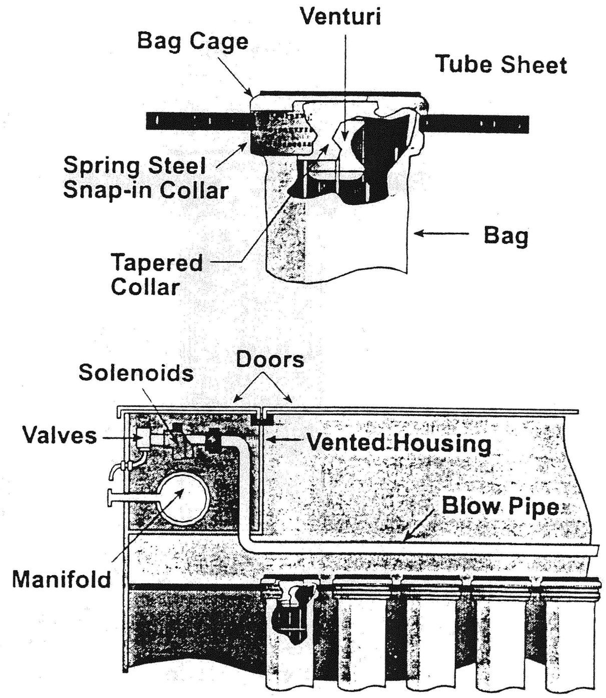


FIGURE 12-9 How bags are mounted to cage, sealed to tube sheet, and installed in baghouse.

the diameter and length of the individual bags, and the emission-control specifications. Each baghouse has a clean-air and a dirty-air side. The exhaust fan pulls the dirty air from outside the filter fabric through the material to the inside. The fines are caught on the outside surface of the bag, and the cleaned exhaust gases, relieved of the dust, are carried out the top of the bag and to the stack. The fines build up on the outside of the bag with time and form a dust cake or coating on the bag. The extent of the dust coating determines the efficiency of the filter: if the bags are too clean, only the coarser fines will be caught, and the finer particles will pass through the fabric; if the bags are too dirty or blinded, the exhaust gases will be unable to pass through the dust cake, and the baghouse will eventually stop operating. The thickness of the dust cake is generally determined by the frequency of the filter bag cleaning cycle.

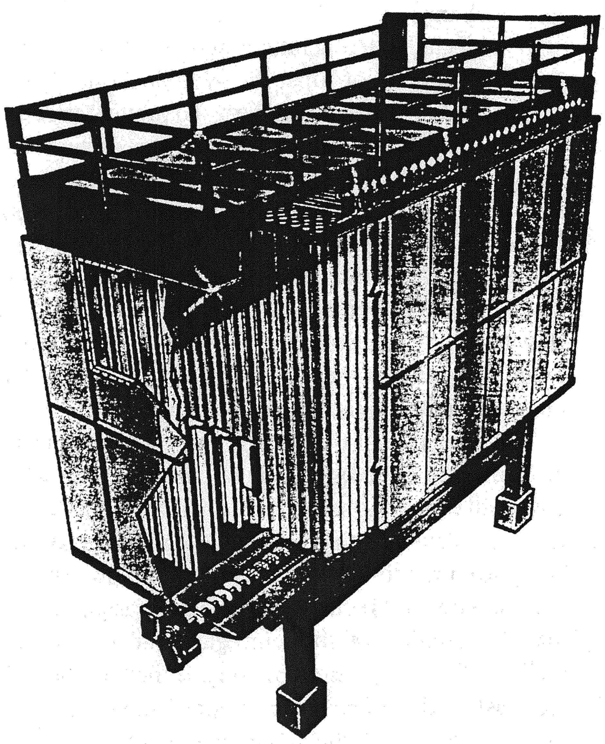


FIGURE 12-8 Cutaway view of typical baghouse.

To remove a portion of the built-up dust on the filter bags, the bags must be cleaned periodically (see Figure 12-10). Bags are cleaned in rows or in groups so that most of the baghouse is in the collecting mode while some of the bags are being cleaned. One of two primary processes is used for the cleaning—reverse air or pulse jet. Reverse-air cleaning is done by passing a large volume of low-pressure air backward through each bag (from the clean side to the dirty side) to release the pressure on the dust cake adhering to the outside of the bag and cause the dust to fall off. Pulse-jet cleaning is done by injecting a small volume of high-pressure air into the bag, causing the fabric on the cage to expand. The expansion of the bag fabric knocks the dust cake loose from the outside of the bag, and the dust then falls to the bottom of the baghouse. Pulse-jet cleaning is the

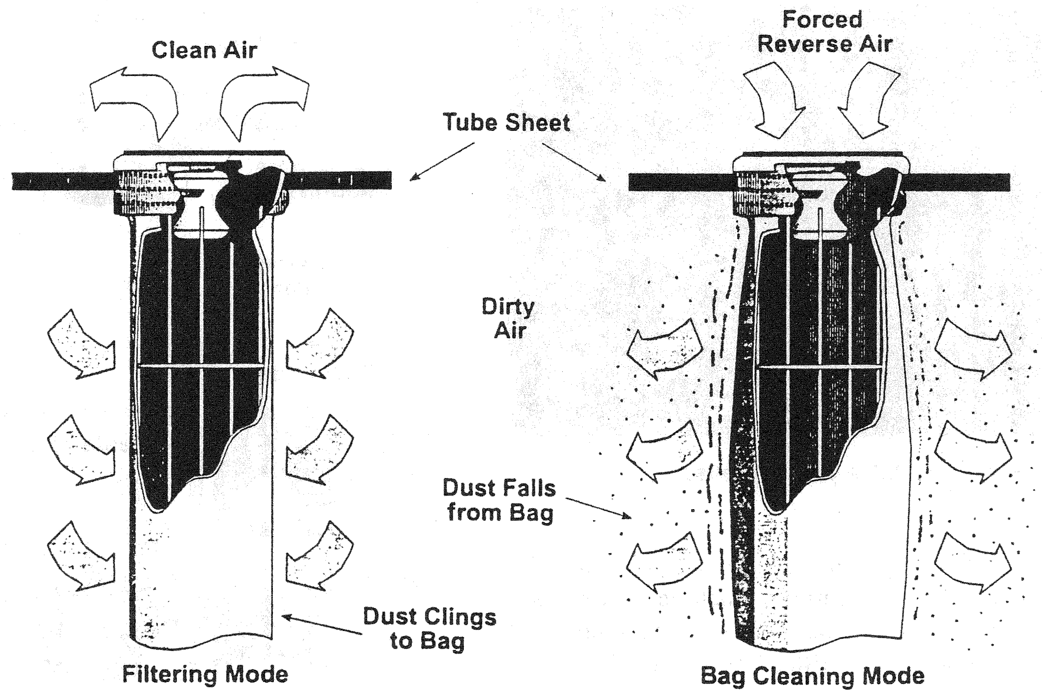


FIGURE 12-10 Bags filtering air and being cleaned.

method used most commonly on most of the newer fabric filters. The particulates removed from the bags are collected for return to the plant or are wasted.

A baghouse can remove up to 99.9 percent of the fines in the exhaust gas stream. This efficiency is measured in part by the amount of pressure drop—generally in the range of 50 to 150 mm (2 to 6 in.) of water column—between the dirty and clean sides of the bags. If the pressure drop is too low [25 to 50 mm (1 to 2 in.)], the bags are too clean, so that some of the very fine dust particles will pass through the filter and travel up the stack and out to the atmosphere. If the pressure drop is too high [greater than 150 mm (6 in.)], the fines buildup on the bags is excessive, the exhaust gases will be restricted from passing through the fabric, and the capacity of the dryer or drum mixer will be reduced.

The efficiency of the baghouse will be affected if the temperature of the exhaust gases entering the baghouse is below the dew point—the temperature of the exhaust gas at which moisture begins to condense. The moisture, combined with the fines in the exhaust gases, forms a mudlike coating on the outside of the bags that cannot easily be removed during the bag-cleaning cycle. Should this happen, the pressure drop across the bags will increase significantly, reducing the efficiency of the baghouse and even choking off the burner flame in extreme cases. To prevent this from occurring, the baghouse must be preheated by running the burner on "low fire" without aggregate in the drum before mix production begins each day.

If subjected to temperatures above 225°C (440°F) for extended periods of time, the synthetic fiber bags can char, disintegrate, and then burn. To prevent this, a temperature sensor and automatic shutdown devices are installed in the ductwork upstream of the baghouse. The sensor is typically set at a temperature of 205°C (400°F). If the temperature of the exhaust gases exceeds this value, the sensor sends a visual and/or audible signal to the plant operator or may automatically shut off the fuel flow to the burner. Some baghouses are fitted with automatic fire extinguisher devices to control a fire should one occur in the emission-control equipment.

The gradation of the asphalt mix produced in a batch or drum-mix plant may change depending on whether any or all of the baghouse fines are returned to the plant. If the collected dust is returned, the mix gradation will be approximately the same as the gradation of the incoming new and reclaimed aggregate (assuming minimal degradation of the aggregate during processing through the dryer or drum mixer). If the baghouse fines are wasted, there may be a considerable change in the mix gradation. Note that if the fines are returned, it is important that they be introduced into the batch or drum-mix plant continuously and uniformly.

FUGITIVE DUST

Although the primary source of emissions from a batch or drum-mix plant is fines carryout, additional emissions are possible in the form of fugitive dust. This dust consists of material that leaks from the plant through holes in the equipment or ductwork while the plant is operating.

For a batch plant, the three most likely sources of fugitive dust are the hot elevator, the plant screens, and the pugmill. As the aggregate is delivered from the hot elevator to the screen deck, it passes over the vibrating screens. This movement creates dust, as does the mixing of aggregate in the plant pugmill during the dry-mix cycle. Fugitive dust can be eliminated by enclosing the screen deck area completely and tightly and by keeping the dry-mix time in the pugmill to a minimum. In addition, a scavenger air system (fugitive dust evacuation system) creates a negative air pressure inside the plant housing and greatly reduces the amount of dust carryout during plant operations. This system usually consists of ductwork with adjustable dampers extending from the screen deck, hot bins, weigh hopper, and pugmill to the inlet of a fugitive dust fan, which then blows the dust to the dust collection system. On some plants, a fugitive dust fan is not used; in this instance, the ductwork extends directly to the inlet of the secondary collector.

For both batch and drum-mix plants, holes in the emission-control equipment, primarily in the ductwork between the end of the dryer or drum mixer and the dry or wet collector, may allow the escape of fine aggregate particles or dust. These holes should be patched so that all of the dust in the exhaust gases will be drawn into the emission-control collectors. Further, the holes should be eliminated in order to prevent the exhaust fan from drawing in excess (leakage) air and reducing the amount of air available for proper combustion of the fuel at the burner.

SUMMARY

The following key factors should be considered when monitoring the operation of the emission-control equipment:

- The discharge of the exhaust gases from the stack should be observed for a dust trail at the end of the steam plume. If one exists, the operation of the emission-control equipment should be checked.
- If a wet scrubber is used, the spray nozzles in the venturi should be checked to ensure that all are open and spraying water properly.
- The cleanliness of the water being returned to the spray nozzles from the pond should be checked at the point at which the water is drawn from the pond to be returned to the plant by the water pump.
- If a baghouse is used, the pressure drop across the bags should be in the range of 50 to 150 mm (2 to 6 in.) of water column.
- The temperature of the exhaust gases entering the baghouse should be less than 205°C (400°F). An automatic shutoff device should be used to stop the operation of the plant if the exhaust gas temperature exceeds this value. The temperature of the gases entering the baghouse should be considerably less than this if the veil of aggregate inside the dryer or drum mixer is correct.
- The gradation of the mix produced in the batch or drum-mix plant should be compared with the gradation used in the mix design process. The amount of change in gradation will depend on whether a wet scrubber system is used and whether the baghouse fines are returned to the plant or wasted.

PART III

Hot-Mix Asphalt Laydown and Compaction

SECTION

13 Mix Delivery

The purpose of the haul vehicle is to transport the asphalt mixture from the asphalt plant to the paver. This must be done without delay and with minimal change in the characteristics of the mix during the delivery process, and without segregation. Three primary types of trucks are usually employed to transport HMA—end-dump, bottom- or belly-dump, and live-bottom. The loading of the three types of trucks, either directly from the pugmill at a batch plant or from the surge silo at a batch or drum-mix plant, is reviewed in Section 11, with emphasis on techniques for preventing segregation. This section focuses on the unloading of the mix at the paving site from each type of truck; use of a material transfer vehicle is also briefly discussed. A review of hauling procedures is then presented.

UNLOADING OF MIX

End-Dump Trucks

An end-dump truck delivers the HMA directly from the truck bed into the hopper of the paver. The mix is unloaded by raising the truck bed and allowing the mix to slide down the bed into the hopper. When the bed is raised, it should not come into contact with the hopper and should not be carried by or ride on any portion of the paver. For smaller-capacity end-dump trucks, contact with the paver is normally not a problem. Such contact can be a problem, however, when large tractor-semitrailer units are used as haul vehicles, particularly when the truck bed is extended to its highest point. When a portion of the weight of the truck is being carried by the paver, the screed tow points of the laydown machine may be changed, which in turn will affect the smoothness of the finished mat. A typical end-dump truck is shown in Figure 13-1.

An end-dump truck can also be used to deliver the mix to a windrow on the roadway in front of the paver. The windrow can be formed in one of two ways. First, a spreader box or windrow sizer can be used. In this case, the mix is deposited into the box and is uniformly metered out onto the roadway as the truck moves forward, typically pulling the windrow box behind it. The amount of HMA placed in the windrow is determined by the setting of the discharge opening in the box. This procedure provides the most accurate means of keeping a constant supply of mix in front of the paver. The mix is then picked up from the roadway surface by a windrow elevator attached to the front of the paving machine.

A second means of creating a windrow using an end-dump truck is to use a windrow blender device, which is usually attached to a small front-end loader. In this case, the mix is dumped onto the existing pavement surface across the full width of the truck bed. The amount of HMA discharged from the truck is controlled by both the width of the opening of the truck bed tailgate, which is chained to prevent full opening, and the forward speed of the truck. The mix is folded into a windrow by the blending unit as that device is pushed forward by the loader. As a result of the tumbling action that occurs as the mix is being shaped into the windrow, some remixing of the material occurs, and segregation may be reduced or eliminated. The size of the windrow is controlled by the height of the discharge opening at the back of the blender. Because of the length of the wings on the windrow blender, mix can be carried for some distance if the truck deposits too much mix at some point on the existing pavement surface.

Bottom- or Belly-Dump Trucks

A bottom- or belly-dump truck delivers its load onto the roadway in front of the paver. The mix is deposited from underneath the truck bed into a windrow, as seen in Figure 13-2. For this method of mix delivery, it is important that the correct amount of material be placed down the length of the windrow to match the paving width and depth being placed without allowing the hopper to run out of mix or become overloaded. Continuous operation of the paver, which must be equipped with a pickup machine (windrow elevator) (see Figure 13-3), can be accomplished only if a continuous and consistent supply of mix is available. It is more difficult, however, to maintain a consistent amount of mix in the paver hopper for leveling courses of HMA, which are necessarily

FIGURE 13-1 Typical end-dump truck.

FIGURE 13-3 Material pickup machine.

of variable thickness, than for courses whose thickness is more constant.

Control of the amount of HMA discharged from a bottom-dump truck is based on the width of the gate opening under the truck and the speed of the truck. The amount of mix deposited at any time is therefore highly dependent on the skill of the person controlling the discharge gates and on the truck driver's attention to operating the truck at the required speed. Manual control of the discharge requires constant attention to ensure that neither too little nor too much mix is fed into the paver hopper (the hopper should be filled to a level above the top of the flow gates or tunnel openings at all times). The amount of mix needed in the windrow depends on the width and thickness of the layer being placed. Thus a different gate opening on the truck bed is needed according to variations in project conditions and truck speed.

The amount of mix available to be picked up by the windrow elevator on the front of the paver should be consistent. Should the amount of mix being delivered to the paver become out of balance with the quantity of mix needed by the paver, an adjustment must be made in the discharge operation of the bottom-dump truck. If the problem is noticed before the paver is under- or overloaded, the amount of mix deposited on the roadway can easily be altered by changing the width of the gate opening on the truck or by adjusting the forward travel speed of the truck during discharge.

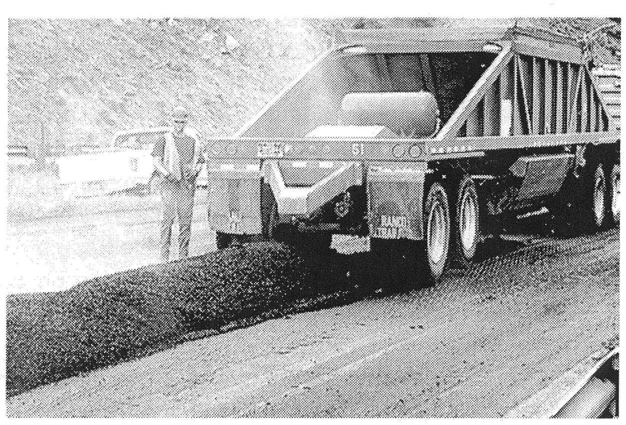


FIGURE 13-2 Typical bottom- or belly-dump truck.

Should the paver run out of mix in the hopper, additional HMA should be placed in the hopper without the paver moving forward. Depending on the equipment available to the contractor at the paving site, such as a small loader, doing so may be very difficult. In some cases, the paver operator may have to raise the paver screed and then move the paver forward to pick up mix. When enough mix is in the hopper, the paver must be backed up, the screed set back down, more mix placed in the windrow in front of the paver, and paving started once again. Needless to say, this is not good paving practice and does not usually result in placement of a smooth mat.

Should the hopper become overloaded with mix, some of the material in the windrow in front of the paver must be removed so that the paver can move forward without additional mix being picked up. Once the mix in the hopper has reached the desired level, the paver must again start picking up additional mix from the windrow.

The ability of the paver to place a smooth mat will be affected by the uniformity of the volume of mix being fed to it. Because of the difficulty in adjusting the quantity of mix needed by the paver when the hopper is either under- or overloaded, it is important that the size of the windrow of mix produced by the bottom-dump truck be as consistent as possible. Keeping the size of the windrow constant is easier than correcting the problem of too little or too much mix in the paver hopper.

One method to better control the amount of material in the paver hopper is to form a windrow that is a little short of that needed by the paver. An additional bottom-dump truck is then kept just in front of the laydown machine, traveling over the windrow placed by the earlier truck or trucks, to supplement the amount of mix in the windrow as needed. This type of operation overcomes the potential problem of under- or overfilling the paver hopper and greatly speeds up the paving process.

Live-Bottom Trucks

A live-bottom truck (also known as a flow-boy or horizontal-discharge truck) employs a conveyor belt or slat conveyor in the bottom of the truck bed to discharge the mix without the need to raise the bed. This type of truck usually deposits the mix directly into the hopper of the paver, as does an end-dump truck, but it can also deliver the mix to the existing pavement surface for pickup by a windrow elevator on the paver, as does a bottom-dump truck. Further, the live-bottom truck moves the HMA in a mass, which minimizes segregation as compared with end-dump trucks. Because the bed of this type of truck is not raised, there is no potential problem with the bed pressing on the paver hopper. A typical live-bottom truck is shown in Figure 13-4.

Material Transfer Vehicle

An additional method used to deliver mix to the paver is a material transfer vehicle (MTV) (see Figure 13-5). An MTV is basically a surge bin on wheels that can hold up to 32 000 kg (35 tons) of mix, depending on the size of the unit. HMA is deposited from an end-dump or live-bottom truck into the hopper on the front of the vehicle, which may be equipped with a remixing auger or augers. The purpose of the auger system is to reblend the coarse and fine particles of the HMA and reduce any segregation and temperature variation that may have occurred in the mix as a result of the operation of the surge or storage silo or truck-loading procedures (see Section 11). The mix is carried from the hopper through the augers and then to a conveyor, which delivers the mix into a vertical extension or insert in the hopper.

FIGURE 13-4 Typical live-bottom truck.

FIGURE 13-5 Material transfer vehicle.

The MTV should allow the paver to operate almost continuously, without stopping between truckloads of mix, as long as a continuous supply of mix is available from the asphalt plant. Therefore, the paver operator can keep the head of material in front of the screed constant by supplying a continuous amount of mix back to the screed and obtain a smoother mat. Use of an MTV also eliminates the problems of the haul truck bumping the paver and the truck driver holding the brakes on the truck when being pushed by the paver. As noted, however, the MTV is essentially a mobile surge bin; when it runs out of material, the paver must stop, and a continuous paving operation is not possible. Keeping a constant stream of trucks in front of the paver or MTV is therefore necessary if a continuous paving operation is to be achieved. If a gap occurs, the MTV should be stopped without being completely emptied when waiting for trucks, so that a consistent minimum amount of mix is retained on the augers to mix with the new, possibly segregated, material delivered from the next haul truck. In addition, the paver should be stopped with the hopper half full so that the amount of HMA in front of the paver screed remains constant and the proper smoothness of the mat is achieved. Indeed, the head of material in front of the paver screed is the most important factor in obtaining a smooth-riding pavement layer (see Section 16).

The MTV can be operated directly in front of the paver or off to one side. Because of the weight of this piece of equipment when full of mix, it is necessary to determine ahead of time that the pavement over which this machinery will be operated can support the loaded weight without being overstressed and damaged. Several smaller, simpler MTVs have been developed by various equipment manufacturers. Because of the limited surge capacity of most of these smaller devices, however, it is more likely that the paving operation will have to stop because of the MTV running out of material.

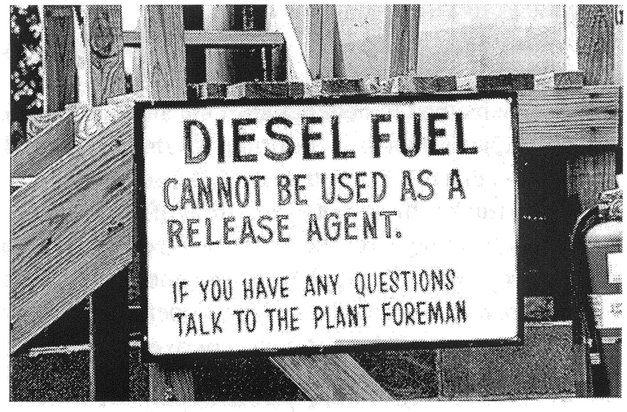


FIGURE 13-6 Diesel fuel is an unacceptable release agent.

HAULING PROCEDURES

Cleaning of the Bed and Application of Release Agent

The bed of the haul truck, whether an end-dump, bottom-dump, or live-bottom truck, should be free of all deleterious materials before mix is placed in it. Any debris in the bed from previous use of the truck should be removed. The bed should be reasonably smooth and free of any major indentations or depressions where the truck bed release agent and HMA could accumulate.

Once the bed is clean, it should be coated with a release agent to prevent the HMA from sticking to the bed. Nonpetroleum-based materials, such as limewater or one of a variety of commercial products, should be used for this purpose. The release agent should be sprayed uniformly over the sides and bottom of the truck bed and should be used in the minimum quantity necessary to cover most of the surface area of the bed without runoff. Any excess agent should be drained from the bed before the truck is loaded with mix.

Diesel fuel should not be used as a release agent for the truck bed (see Figure 13-6). If an excessive amount of diesel fuel is used and accumulates in depressions in the bed of the truck, it can cause changes in the properties of the binder material with which it comes in contact. If an area of the finished HMA mat contains excessive diesel fuel, a soft spot and maybe a pothole will result (see Figure 13-7). In addition, use of diesel fuel can contribute to environmental problems as the fuel evaporates or if it soaks into the ground. Thus, although often convenient and economical, diesel fuel should not be used as the release agent in the bed of a haul truck.

Insulation

If warranted by environmental conditions, the sides and bottom of the truck bed should be insulated. The insulation should be tight against the body of the bed, and there should be no gaps between the side of the truck and the insulation through which wind could enter. The insulation material should be protected on its outside face with plywood or a similar cover. Missing or torn insulation should be replaced.

Some coarse-graded mixes, such as friction courses, stone-matrix asphalt, and coarse-graded Superpave, tend to cool more quickly than fine-graded mixes, and mixes containing polymer tend to stiffen more quickly as they cool. A well-insulated truck will help minimize any temperature loss.

FIGURE 13-7 Pothole caused by overlaying of spilled diesel fuel.

Use of Tarpaulins

Every haul truck should be equipped with a tarpaulin that can be used as needed to protect the HMA in case of inclement weather. The tarp should be made of a water-repellent material, be of sufficient weight and strength to resist tearing, and be in good condition with no holes or tears. Most important, the tarp should be large enough to cover the top of the load and extend down over the sides and the tailgate of the truck at least 0.3 m (1 ft) all around the truck bed to ensure that the mix is protected adequately from wind and rain. The tarp should also have enough tie-down points so that it will be properly secured and will not flap in the wind during delivery of the mix from the plant to the paver.

Some trucks are equipped with tarps that run from the front to the back of the truck in a rail atop the sideboards of the truck. The rail keeps the tarp stretched across the top of the load of mix and covers the mix without the tarp having to extend over the sides of the truck bed. As long as the tarp is tight, this arrangement can provide adequate cover for the mix. For safety reasons, it is desirable to use tarps that can be extended by mechanical means over the length of the bed of the truck without the driver having to climb up the sides of the vehicle.

A tarp that does not completely cover the load during transport may be worse than having no tarp at all on the load. Research has shown that unless the tarp extends over the sides of the truck, airflow under the tarp will increase the rate of cooling of the mix. In addition, any water that falls on the tarp during rainy weather will run into the truck bed instead of off the side of the vehicle. Indeed, even when the tarp covers the bed, if there is any water on the tarp when the truck is ready to discharge mix into the paver hopper, the water should first be removed by raising the bed of the truck and letting the water run off before the truck backs into the hopper. This water removal operation should not be done on the pavement in front of the laydown machine.

Tarps are not normally necessary in warm weather and for relatively short haul distances between the plant and the paver. If a tarp is used, however, it should be removed from the top of the bed before the truck is unloaded into the laydown machine. Doing so allows the mix to be inspected visually for defective material, such as uncoated aggregate or excessive asphalt content, before being discharged into the paver.

Crusting of the Mix

There is no set limit on how far a load of HMA can be transported. Many variables affect the maximum haul distance, but the key factors are the workability of the mix while it is passing through the paver and the ability to compact the mix once it has been placed by the paver. Both of these factors are highly dependent on the temperature of the mix.

HMA in a mass, such as when the mix is confined in a truck bed, will maintain a reasonable temperature for as long as 2 or 3 hours. The rate of cooling of the mix depends on such variables as its temperature at the time of production, the ambient air temperature, and the efficiency of any insulation used on the sides and bottom of the truck. When hauled long distances without being covered by a tarp, HMA will cool and develop a crust on the top. The crust serves as an insulating layer for the rest of the mix in the truck bed and reduces the rate of cooling for the remainder of the material. Thus within limits, crust formation can be beneficial. However, the crust must be completely broken down before reaching the paver, or tears and pulls in the finished mat surface will occur.

If the load of mix is properly tarped, the amount of crust buildup will be minimized because the wind will have significantly less effect on the rate of cooling of the mix. The slight crust thickness that does form during transport will usually be broken up completely as the mix is discharged from the haul vehicle into the paver, carried by the slat conveyors back to the augers, and passed under the paver screed. As long as chunks of asphalt mix do not affect the quality of the mat behind the paver, the crust that forms on top of the mix during delivery will not be detrimental to the long-term performance of the mix. If chunks of mix can be seen behind the screed, however, changes need to be made in the mix production temperature, the amount of insulation on the truck bed, the covering of the load with the tarp, the paving schedule (waiting for warmer ambient temperatures), or any combination of these factors. It has also been shown that using an MTV results in some remixing, which helps break down any chunks that may exist.

Rain

Judgment is required when rain occurs at the paving site and mix is still in the trucks waiting to be unloaded. One alternative is to stop paving and return any mix in the trucks to the plant to be recycled at a later date. If the rain is relatively light and appears likely to continue for some time, and if the pavement surface has been tacked and does not contain puddled water, the trucks can be unloaded as quickly as possible and the rollers brought up directly behind the paver to compact the mix before it cools completely. If the existing pavement surface contains puddles of water, however, placement of the HMA should not be continued.

Some specifications permit the contractor to place mix that is "in transit" on the roadway even during a rainstorm. Although most of the HMA placed during rain performs adequately over time, it is better practice to refrain from placing the mix if the rain is heavy and the pavement surface is very wet or standing water exists on the surface. With the advent of pavement recycling, the material not placed can easily be recycled later. The only cost involved is that of hauling the mix back to the plant and reprocessing it through the plant. Any mix that is placed during rain will cool very quickly as a result of the rapid heat transfer from the mix to the wet underlying pavement surface and the cooling of the mix by the rain itself. It is thus very difficult to obtain proper density in the mix because of its low temperature. A lack of compaction, and therefore a high air void content in the mix, leads to poor pavement performance.

If the rain appears to be of short duration—a passing shower—the mix can be held in the haul truck instead of being dumped into the paver hopper. It should then be laid after the shower has passed and the pavement surface is free of puddles. Again, because of the mass of mix in the truck bed, the mix will lose temperature slowly if the load is properly tarped—no water can get into the bed. Once the rain has stopped and any puddles of water have been swept from the roadway surface, the mix can be unloaded from the waiting trucks into the paver and laid down. As long as chunks of mix do not appear behind the screed and the rollers can properly densify the mix, little harm is done by holding the mix in the haul trucks for even 2 or 3 hours, depending on environmental conditions.

Bumping of the Paver

When an end-dump or live-bottom truck is used to deliver mix to the paver, the truck driver should back the truck up to the laydown machine but stop just short of touching the paver. Once the truck has come to a halt and the driver has released the brakes on the vehicle, the paver operator should start the machine moving forward, picking up the stopped truck. The key to this process is that the paver picks up the truck instead of the truck backing into and bumping the paver. Use of this procedure will reduce the incidence of screed marks and roughness in the mat. Given the smoothness specifications now being implemented in most states, it is imperative that the truck-unloading operation not add to the problem. Upon being told why it is important not to bump the paver, most truck drivers will use the correct unloading techniques.

Unloading

If an end-dump truck is used and if the mix being delivered to the paver has a tendency to segregate, the bed of the truck should be raised a short distance to break the load to the rear and allow the mix in the bed to shift and slide back against the tailgate before it is opened. This practice will cause any segregated coarse aggregate material to be incorporated back into the mass of mix rather than being delivered first into the paver hopper. Once the tailgate is opened, this procedure will also allow the mix to be discharged from the truck in a mass and to flood the hopper of the paver, further reducing the possibility of segregation behind the paver screed. In addition, raising the bed before the truck backs into the paver reduces the time required to unload the truck and makes the truck exchange more efficient.

The same procedure should be employed, if possible, when a live-bottom truck is used to transport the mix. On some such trucks, it may be possible to start the belt or slat conveyor for a few seconds before the end gate on the truck is opened. Doing so will create a mass of material that can be delivered to the hopper, instead of allowing any coarse aggregate particles that have rolled to the end gate to exit into the hopper first.

For bottom-dump trucks, the gates on the bottom of the truck bed should be opened wide to allow a mass of mix to be discharged, instead of only some of the mix dribbling out if the gates are partially opened. The size of the windrow should then be controlled by the forward speed of the haul truck. If only a small amount of mix is needed in the windrow, the gates can be chained so they do not fully open, thus limiting the amount of HMA deposited on the roadway and creating the correct-size windrow. These procedures all require coordination between the paver crew and the truck driver.

SUMMARY

The following key factors should be considered when monitoring truck loading, hauling, and unloading operations:

- The truck bed should be free of all contaminants. The bed should be lightly and uniformly coated with a nonpetroleum release agent; diesel fuel should not be used for this purpose.

- If insulation around the truck bed is required, it should be tight to the sides and bottom of the truck.
- The truck should be equipped with a tarpaulin that is in good condition, without tears and holes. The tarp should be large enough to cover the bed and wrap over its sides and end. The tarp should have enough fasteners so that it can be tied down completely and will not flap in the wind. If side rails are used to hold the tarp in place, the tarp should be stretched tightly over the load of mix.
- End-dump and live-bottom discharge trucks should stop short of the paver and allow that machine to pick up the truck on the move, instead of bumping into the stopped paver.
- The bed on an end-dump truck should be raised a short distance and the mix in the truck allowed to break and slide against the tailgate before the tailgate is opened to discharge mix into the paver hopper. The belt or slat conveyor on a live-bottom truck should be started a few seconds before the end gate is opened, if possible, to discharge a mass of asphalt mix into the hopper instead of just a dribble of coarse aggregate particles.
- The load carried in a bottom-dump truck should be deposited uniformly on the roadway in front of the paver so that the amount of mix picked up by the windrow elevator enables the paver operator to maintain a uniform head of material in front of the paver screed. Alternatively, the windrow should purposely be built slightly short of mix and one truck kept in front of the paver, acting as a mobile surge bin to provide any additional mix needed by the paver.
- End-dump trucks should not be allowed to contact or transfer any weight to the paver hopper.

14 Surface Preparation

The performance of HMA under traffic is directly related to the condition of the surface on which the pavement layers are placed. For a full-depth asphalt pavement, if the condition of the subgrade soil is poor (particularly if it is wet and rutted under the haul trucks), the ultimate life of the roadway may be significantly reduced. For HMA layers placed on top of a new, untreated granular base course, that base material should be stable, the surface should be dry, and the base should not be distorted by the trucks carrying mix to the paver. For mix laid on top of existing asphalt layers, that surface should be properly prepared—potholes filled, cracks sealed, and the surface cleaned. A tack coat should also be used to ensure a bond between the existing pavement surface and the new asphalt overlay.

BASE PREPARATION FOR NEW HMA PAVEMENTS

Subgrade Soil

If the asphalt pavement is to be placed directly on the subgrade soil, that subgrade material should meet all applicable requirements for moisture content, density, structural support, and smoothness. After the subgrade soil has been determined to be ready for paving and before paving is allowed to commence, the subgrade should be checked to ensure that it will be able to support the weight of the haul traffic. The subgrade must provide a firm foundation before the asphalt paving begins. If distortion of the subgrade soil occurs during the paving operation, placement of the mix should be stopped until the condition of the soil can be corrected.

There is generally no need to place a prime coat of asphalt emulsion or cutback asphalt on the subgrade soil. This is especially true when the soil is a silty clay or clay material because the prime coat material cannot be absorbed into that subgrade material. The use of a prime coat on sandy subgrade soils is also questionable. If the sandy material displaces excessively under the wheels of the haul trucks, it should be stabilized with some type of binder material before paving to achieve the required load-bearing properties. In such cases, the application of a prime coat will generally not be enough to hold the sandy soil in place during paving operations. A prime coat should not be used as a substitute for proper preparation of the subgrade soil.

Granular Base Course

If the asphalt layer is to be constructed directly on a new or existing untreated granular base layer, that base material should meet all the requirements for moisture content, density, structural strength, and smoothness. Proof rolling should be done, however, on top of the granular base material, and the amount of deflection of the base and the amount of indentation of the truck wheels in the granular base course material should be noted. If the base material is stable and dry and does not deflect and indent significantly under the wheels of a loaded tandem-axle truck, placement of the prime coat or the new asphalt mix should be permitted to start. If the condition of the granular material is not satisfactory, the base course should be reworked or stabilized until it is in the proper condition for overlaying.

The prime coat acts as a temporary waterproofing layer that protects the base course and prevents it from absorbing excess moisture during rain before paving. It also allows the base course to be used for light traffic, binds together any dust on the surface of the granular base layer, promotes the bond between the base-course material and the new HMA overlay, and prevents slippage of thin overlying pavement layers. However, the purpose of a prime coat is to protect the underlying materials from wet weather. If the underlying materials can be covered prior to the rainfall, then a prime coat is not needed. When a prime coat is used, the prime coat material should be applied to the base course with a pressure distributor at least 48 hours before paving is to begin. Typically, a cutback asphalt (MC-30 or MC-70) is used as the prime coat material, if available. An inverted asphalt emulsion (emulsion containing limited amounts of cutter stock material) also has been applied successfully. The application rate should vary with the openness (porosity) of the base course material. Typical application rates range from 0.65 l/m^2 (0.15 gal/yd^2) or less for a very tight surface to 1.8 l/m^2 (0.40 gal/yd^2) for an open surface. No more prime coat material should be applied than can be absorbed completely by the granular base course in 24 hours. If all of the prime coat material is not completely absorbed, the excess should be blotted with sand or removed.

PREPARATION OF EXISTING SURFACES FOR HMA OVERLAYS

HMA over HMA

The degree of preparation needed for an existing asphalt pavement depends on the condition of that surface. At a minimum, failed areas should be removed and replaced; potholes properly patched; cracks cleaned out and sealed; and ruts filled in or, preferably, removed by cold milling.

Pavement Replacement and Patching

It is generally inadvisable to attempt to bridge failed areas with new overlay material unless a very thick overlay is to be constructed. Removal and replacement should be carried out on all existing pavement areas where severe load-related distress has occurred. All HMA and granular base materials that have failed should be excavated or cold milled and then either recycled or wasted. Subgrade distortion should be repaired by undercutting and replacement with suitable backfill material. Proper subsurface drainage should be installed as necessary. New granular base course material, stabilized base course layers, or HMA mix should be placed in order to bring the strength of the pavement structure in each failed area to the same level as the surrounding good pavement layers. If HMA is used to patch a large area, it should be placed with a paver and compacted with one or more large rollers (see Figure 14-1).

Localized failed areas should be patched properly. Each should be cut back to sound pavement and squared up, with the sides as vertical as possible, the loose material and water in the hole removed, a tack coat applied to the sides and bottom of the hole, the mix placed in the hole, and the new material adequately compacted, preferably with a roller (see Figures 14-2 and 14-3). If the pothole is deeper than 100 mm (4 in.), the mix should be placed in more than one layer and each layer compacted properly.

Crack Filling

Badly cracked pavement sections, especially those with pattern cracking (e.g., map or alligator), must be patched or replaced. The benefits of filling other cracks in the existing surface depend, in part, on the width of the cracks. If the cracks are narrow [less than 10 mm ($\frac{3}{8}$ in.) in width], it is doubtful that the crack-sealing material will actually enter the crack instead of pooling on the pavement surface. Such cracks can be widened, if desired, with a mechanical router before sealing is attempted. If wider cracks are present, they should be blown out with air and cleaned of debris. The crack-sealing material should be inserted when the cracks are clean and dry. The level of the crack-filling material should be slightly lower than that of the surrounding pavement surface and should not spill over the top of the crack, where it could create a bump in the new pavement layer during the rolling process (see Figure 14-4).

Depending on the cause of the cracking, the amount of reflective cracking that occurs in an overlay can sometimes be reduced by the use of a surface treatment (seal coat) on the existing pavement. If that pavement structure contains a great number of cracks, consideration should be given to applying a surface treatment instead of filling

FIGURE 14-1 Patches placed with paving machine.

FIGURE 14-2 Removal of existing pavement prior to patching.

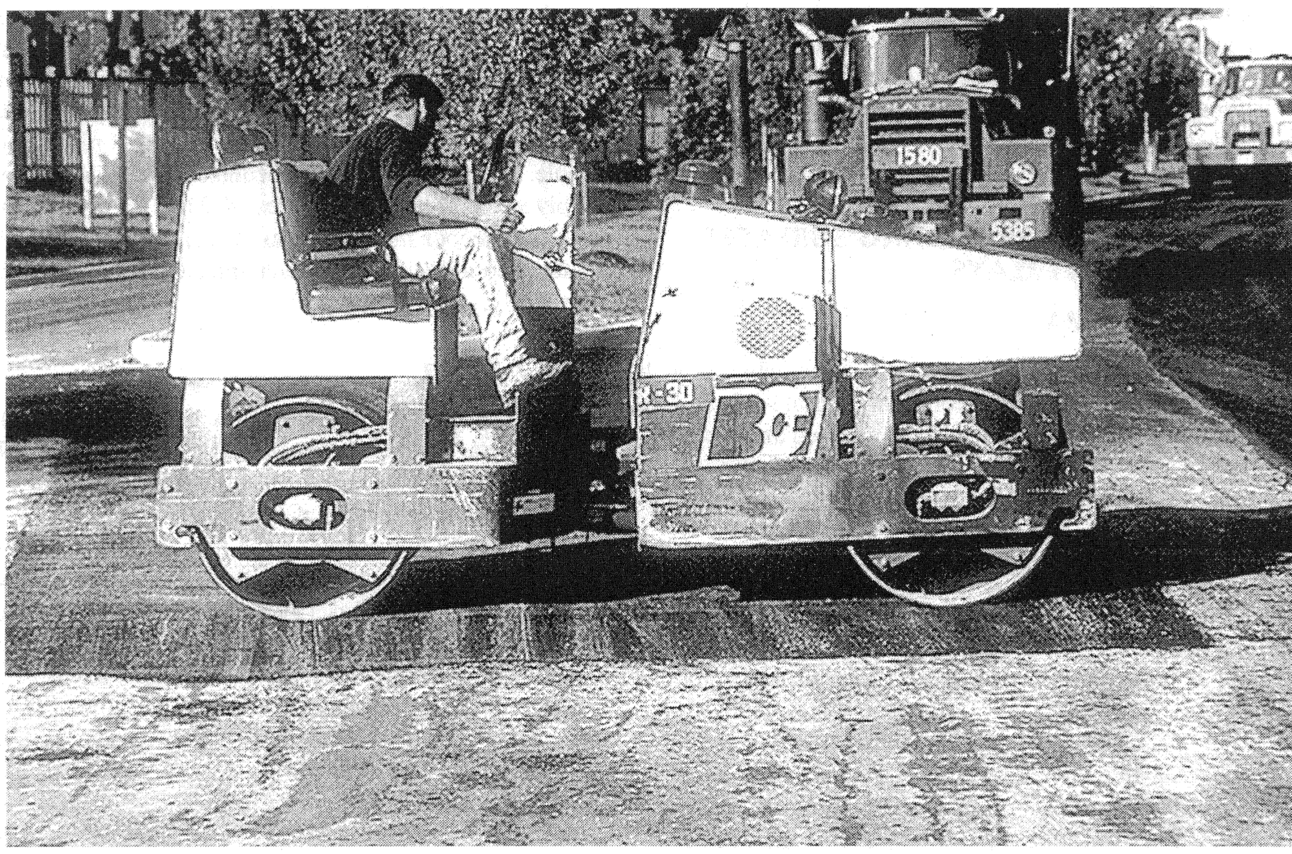


FIGURE 14-3 Compaction of patch.

individual cracks. The cracks should be cleaned, if feasible, by being blown out with air. The surface treatment should be applied when the pavement surface is clean and dry and should consist of a single application of asphalt binder material (asphalt cement, cutback asphalt, or asphalt emulsion) and cover aggregate. Alternatively, a slurry seal consisting of an asphalt emulsion, fine aggregate, and water may be used.

FIGURE 14-4 Bump caused by use of excessive crack sealant.

Leveling Courses

Common practice in the past has been to place a leveling course on the existing pavement surface to improve the rideability of the pavement structure. This leveling course, sometimes called a wedge and level course or a scratch course, is designed to fill in the low spots on the pavement surface. This leveling action is accomplished using the floating screed on the paver, with more HMA being placed in the low spots than on the high spots in the existing pavement surface. The areas with thicker mix, however, typically compact more than areas with thinner mix. This problem, termed differential compaction, requires that multiple courses be constructed over a pavement surface that is badly out of shape before a smooth surface can be obtained. As the mix passes from under the paver screed, it is in loose condition. Compaction by the rollers reduces the thickness of the newly placed layer. The rule of thumb is that conventional mixes will compact approximately 6 mm per 25 mm ($\frac{1}{4}$ in. per 1 in.)

of compacted thickness. Thus to achieve a compacted course 25 mm (1 in.) thick, about 31 mm (1¼ in.) of mix would have to be placed by the paver. Similarly, approximately 95 mm (3¾ in.) of mix would need to pass from under the paver screed to construct a layer with a compacted thickness of 75 mm (3 in.).

When a leveling course is placed, the HMA laid in the low areas (in the wheelpaths if the pavement is rutted) will be thicker than the mix placed over the high points in the surface (between the wheelpaths). The thicker mix will compact more under the rollers, particularly if a pneumatic tire roller is used, than will the mix that is thinner. Thus, low spots will still exist in the wheelpaths where the mix has been compacted to a different degree (and thus a different air void content) than the mix between the wheelpaths. Because of the problem of differential compaction, multiple layers of mix are usually needed to completely eliminate the roughness in the existing pavement surface. A rule of thumb is that one layer after compaction will remove approximately 80 percent of a low spot. Two layers, each being compacted separately, will remove approximately 95 percent of a low spot.

Milling

Milling, also called cold planing, can be used to remove the high points in the existing surface in lieu of placing a leveling course (filling in the low spots). Milling can be accomplished in any width necessary, from 150 mm (6 in.) to more than 4 m (13 ft). Figure 14-5 illustrates a typical milling machine. If equipped with automatic grade and slope controls similar to those used on an asphalt paver, the milling machine is capable of producing a level surface in one pass over the existing surface. The RAP produced by the milling process can be hauled back to the asphalt plant for future recycling. In addition, if the milled surface is properly cleaned, its texture can enhance the bond between the new and old layers and may reduce the possibility of slippage of the overlay over the existing surface.

A pavement surface that has been milled is typically very dusty and dirty. Once the pavement has dried, multiple sweepings with a mechanical broom are usually needed to remove all of the residual grit from the milled surface. In some cases, it may be necessary to dampen the milled surface before sweeping or to air blow or flush the milled surface with water to remove dust and very fine material completely. Any dust and dirt left on the milled surface will greatly affect the bond between that course and the new asphalt overlay. Because of the increased surface of the milled pavement (from the grooves left by the cutting teeth on the milling machine), an additional quantity of tack coat material may be required to ensure an adequate bond between the old and new layers (see Figure 14-6). That increased quantity is a function of the type, number, condition, and spacing of the teeth on the cutting mandrel of the milling machine but is typically in the range of 20 to 30 percent more than for an unmilled surface.

HMA over Portland Cement Concrete

When HMA is placed over a portland cement concrete (PCC) pavement, the PCC surface should likewise be properly prepared. Any severely distressed areas in the concrete slabs should be cut out, removed, and replaced with either PCC or HMA using full-depth slab repair techniques. Corrective work should also be completed on the underlying subbase or subgrade material, if necessary. Any severely spalled areas at joints should be repaired using partial-depth slab replacement methods.

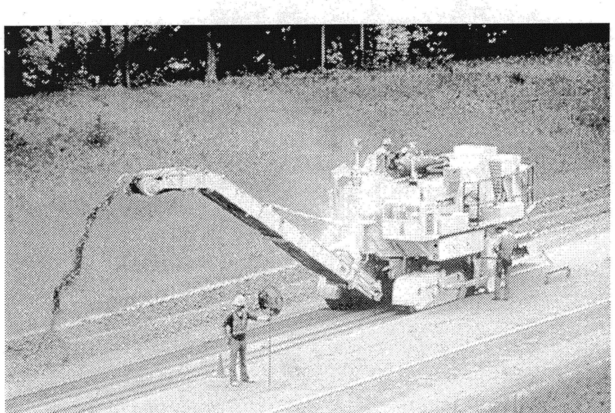


FIGURE 14-5 Typical milling machine.

FIGURE 14-6 Tack coat on milled surface.

PCC should be used for partial-depth repairs. Rocking slabs should be stabilized. Depending on the condition of the PCC pavement, procedures such as crack and seat, break and seat, or rubblizing of the existing pavement can be used before the overlay is placed, particularly if the slabs are rocking under traffic loading. Consideration can also be given to the use of a crack-relief layer between the existing PCC pavement and the new overlay.

For joints that are poorly sealed, the old seal material should be removed and the joints cleaned. When dry, the joints should be resealed with appropriate joint-sealing material. Care should be taken not to overfill the joints, particularly in cool weather when they are open wide. In all cases, as with crack sealant, the final level of the joint-sealing material should be below the top of the surrounding pavement surface. Once the patching and resealing have been accomplished, the surface of the PCC pavement should be cleaned completely using mechanical brooms and air blowing or water flushing, or both, where needed.

Tack Coat

The purpose of a tack coat is to ensure a bond between the existing pavement surface and the new asphalt overlay. The tack coat should not be used in lieu of cleaning the existing surface—removing accumulated dust and dirt by mechanical brooming or by flushing with air or water. If a good bond is not formed between the existing surface and the new overlay, slippage may occur. The new overlay may be shoved in a longitudinal direction by traffic, particularly at locations where the traffic accelerates or where vehicle brakes are applied. Thus the pavement surface must be clean before the tack coat is applied.

The tack coat material—which is normally asphalt emulsion but can also be asphalt cement or cut-back asphalt—should be applied by a pressure distributor, as shown in Figure 14-7. All nozzles on the distributor should be fully open and functioning and should be turned at the same angle to the spray bar, approximately 30°. In addition, the spray bar should be at the proper height above the pavement surface to provide for a double or triple lap of the liquid asphalt material. The result will be the proper amount of overlap between the nozzles and a uniform application of the tack coat to the road surface. The tack coat material should be heated to the proper temperature so that it is fluid enough to be sprayed uniformly from the nozzles instead of coming out in strings.

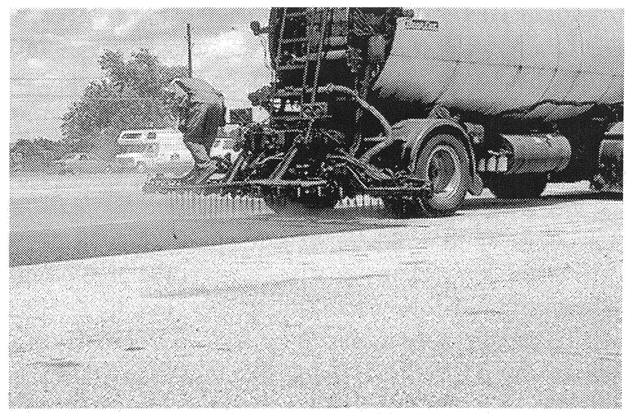


FIGURE 14-7 Distributor applying tack coat.

Application Rate Versus Residual Rate

Uniformity of application and a proper application rate are key to achieving a successful tack coat. Figure 14-8 illustrates a tack coat application that is uneven as a result of improper equipment operation, with too much tack coat in some areas and not enough in others. If the correct amount of tack coat is sprayed on the surface, some of the existing surface will still be visible through the tack coat; not all of the existing pavement surface will be covered. Use of a diluted asphalt emulsion tack coat (slow-setting asphalt emulsion diluted 1:1 with water) will result in complete coverage and a very thin residual asphalt film on the pavement surface. Proper tack coat application will leave a residual asphalt cement content of approximately 0.18 to 0.27 l/m^2 (0.04 to 0.06 gal/yd^2) on the roadway. The amount of residual tack coat needed will depend on the condition of the pavement surface. An open-textured surface requires more tack coat than a surface that is tight

FIGURE 14-8 Improperly adjusted distributor.

or dense, and a dry, aged surface requires more tack coat than a surface that is "fat" or flushed. In addition, more tack coat may be needed on a milled surface because of the increased surface area, as discussed earlier; a residual rate of as much as 0.36 l/m² (0.08 gal/yd²) of asphalt cement may be needed to ensure a proper bond.

It is essential to differentiate between the residual tack coat rate (the amount of asphalt cement remaining on the pavement surface after the water has evaporated) and the application rate (the amount of emulsion sprayed from the distributor). Most asphalt emulsions contain 60 to 65 percent residual asphalt cement and 35 to 40 percent water, plus a small amount of emulsifying agent. For ease of calculation, it can be assumed that an asphalt emulsion is approximately two-thirds asphalt cement and one-third water. The amount of asphalt cement left on the pavement surface after the water has evaporated from the emulsion is the most important factor in obtaining a bond between the existing pavement surface and the new overlay. To determine the application rate for the tack coat material, start with the amount of residual asphalt cement required on the pavement surface and work backward.

As an example, suppose that the present pavement surface is relatively tight and dense. It is determined that the residual amount of asphalt cement on the pavement surface needs to be 0.18 l/m² (0.04 gal/yd²). If an undiluted SS-1 asphalt emulsion is used for the tack coat, the application rate for that material should be approximately 0.27 l/m² (0.06 gal/yd²), calculated as $(0.18) \div (2/3) = 0.27$ l/m² $[(0.04) \div (2/3) = 0.06$ gal/yd²$]$. If the SS-1 asphalt emulsion has been diluted with equal parts water, the application rate needed to obtain the same amount of residual asphalt on the pavement surface will be different. Using a 1:1 dilution rate, the application rate for a residual amount of 0.18 l/m² (0.04 gal/yd²) will be 0.54 l/m² (0.12 gal/yd²). Thus with the use of a 1:1 diluted emulsion, twice as much emulsion must be applied to the pavement surface from the distributor to have the same amount of residual asphalt when all of the water has evaporated.

If the amount of water in an asphalt emulsion is not taken into account when determining the application rate from the distributor, the correct degree of adhesion may not be achieved. Too little tack coat will not provide sufficient bond between the old and new pavement layers. On the other hand, too much tack coat may contribute to slippage of the overlay on the existing pavement surface and bleeding of the tack coat material through a thin overlay.

If asphalt cement instead of an asphalt emulsion is used as the tack coat material, the residual amount of asphalt on the pavement surface should be the same as the applied amount. Thus if 0.18 l/m² (0.04 gal/yd²) of residual binder material is desired, the application rate from the distributor should also be 0.18 l/m² (0.04 gal/yd²).

Breaking and Setting Time

When an asphalt emulsion is applied as a tack coat, it is brown in color because it contains both asphalt cement and water. After a very short period of time, the emulsion will break—change color from brown to black—and the water will begin to evaporate. The rate of evaporation will depend on the type and grade of the emulsion used, the application rate, the temperature of the existing pavement surface, and environmental conditions. Once all the water is gone, the emulsion is said to have "set." The rate of set depends on the same conditions that control the rate of break of the emulsion. Under most circumstances, an emulsion will set in 1 to 2 hours.

There is some controversy about whether HMA can be placed on top of an asphalt emulsion before the emulsion is set—while some water is still retained on the pavement surface. There is even more controversy about whether HMA can be placed on top of an asphalt emulsion before it has broken—while the asphalt cement and water are still combined. In the past, it was generally believed that the emulsion should be completely set before new mix is laid on top of the tack coat material. Experience has shown, however, that new HMA can usually be placed on top of an unset tack coat and even over an unbroken tack coat emulsion with no detrimental effect on pavement performance; the bond will still be formed. Indeed, in Europe the emulsion tack coat is often applied to the pavement surface underneath the paver—from a spray bar located just behind the paver drive tires or tracks and just before the head of HMA in front of the paver screed. With this tack coat application point, the emulsion will be unbroken when the mix is laid on top of it, but the emulsion will break immediately upon contact with the new HMA. The water, 0.36 l/m² (0.08 gal/yd²), typically will evaporate and escape as steam through the loose hot mix. There is not enough water to lower the mat temperature significantly.

While it is believed that the asphalt emulsion can be properly paved over before being fully set, and even before being broken, it is also important that the tack coat material remain on the pavement surface to create the bond between the layers. If the tack coat material is not set and a significant amount of haul truck traffic runs over the unset material, much of the tack coat may be picked up by the truck tires and tracked down the roadway. Thus either the tack coat should be allowed to set before haul truck traffic is permitted to run over it, or the amount of truck traffic should be minimized.

If asphalt cement is used as the tack coat material, it will cool to ambient temperature very quickly. Further, because there is no carrier material (water) to evaporate, paving may immediately follow the asphalt cement tack coat application.

If the overlay is to be constructed under traffic, the tack coat is normally placed only a short distance in front of the paver—within the lane closure and far enough ahead for the tack to set properly before the HMA is laid on top of it. Traffic is kept off of the tack coat at all times. If the roadway being paved is closed to traffic, the tack coat can be placed as much as 24 hours ahead of the laydown operation. Doing so will ensure that the tack coat is completely set before the mix is placed on top of it. Under unusual circumstances, if traffic must travel over the tack coat before the overlay is placed, a light layer of sand can be spread on top of the tack coat to prevent its pickup by traffic. The application rate of the sand should be in the range of 2.2 to 4.4 kg/m^2 (4 to 8 lb/yd^2), depending on the application rate of the tack coat material and the gradation of the sand. Excess sand should be broomed from the pavement surface before the overlay is placed to ensure a proper bond between the overlay and the existing surface.

If equipment problems (plant or paver breakdowns) prevent tack coat material that has been applied from the distributor from being paved over before traffic must use the roadway, it is suggested that posted speed limits on that section of roadway be significantly reduced until the overlay operation can take place. It is not good practice to place the tack coat one day, permit traffic to run over the tack coat for a period of time, and then place the overlay at a later date. Depending on the amount of residual asphalt cement on the pavement surface and environmental conditions, the level of friction available for traffic at the pavement surface may be greatly reduced by the presence of the tack coat material. The excess tack will also be thrown on vehicles, creating a major public relations problem. In addition to lowering the posted speed limits, it may be advisable to apply sand to the tacked surface as discussed above.

The application of tack coat material is essential when an overlay is being constructed on an old existing pavement surface—either HMA, PCC, or surface treatment. A tack coat often is not needed, however, when a layer of new mix is being placed over another layer of asphalt pavement that has been laid within a few days, as long as the underlying new layer has not become dirty under traffic or from windblown dust. If a tack coat is used on a recently placed HMA layer, the residual asphalt content should be minimal—in the range of 0.09 l/m^2 (0.02 gal/yd^2), or half of what is needed for most old, tight, existing surfaces. Thus the application rate for an undiluted SS-1 emulsion should be only approximately 0.14 l/m^2 (0.03 gal/yd^2). Additional tack coat material is not necessary since the material will not be absorbed into the new underlying pavement surface.

SUMMARY

The following key factors should be considered when monitoring surface preparation operations:

- A prime coat is generally not needed on subgrade soil. There is a difference of opinion on the benefits of using a prime coat on a granular base course, but in many cases a prime coat can be eliminated without detrimental effect on the performance of the pavement structure.
- Before paving an existing surface, any failures in the surface must be removed and replaced or repaired by patching unless a very thick overlay is constructed.
- If there are cracks in an existing asphalt pavement surface, they generally should be sealed individually, or some type of surface treatment should be applied to the whole roadway area. Joints in PCC pavement that are poorly sealed should be routed out and sealed. Rocking PCC slabs should be stabilized.
- A rough, uneven asphalt surface should be leveled with asphalt mix (using a paver to place the mix) to fill in the low spots in the surface or should be cold milled with a milling machine to remove the high spots.
- Once the needed repairs have been completed, the pavement surface should be cleaned of all dust, dirt, and other debris. This should be accomplished using multiple passes of a mechanical broom. If brooming does not remove all accumulated dirt, flushing with air or water may be required.
- The application of a tack coat must be accomplished before an overlay is constructed on an existing asphalt or PCC surface. The distributor used should be checked to ensure that all the nozzles are open and set at the correct angle and that the spray bar is at the proper height above the pavement surface.
- The application rate for the tack coat should be based on the desired residual amount of asphalt cement on the road surface, which should be between 0.18 and 0.27 l/m^2 (0.04 and 0.06 gal/yd^2) for normal surfaces.

The application rate should also be based on the actual amount of asphalt cement in the emulsion—whether the emulsion is diluted or not before it is applied. An undiluted SS-1 emulsion should be applied from the distributor at a rate of 0.27 l/m^2 (0.06 gal/yd^2) to obtain 0.18 l/m^2 (0.04 gal/yd^2) of residual asphalt on the pavement surface.

Milled pavements may need a greater amount of residual tack coat. Too little tack coat will not provide the needed bond between the old and new layers. On the other hand, too much tack coat may promote slippage of the new overlay on the old pavement or bleeding of the tack material through a thin overlay.

HMA usually can be placed on top of an emulsion tack coat before it has completely set, and even before it has broken—changed color from brown to black. The tack coat should not be picked up and tracked by the haul trucks, however.

Tack coat should not be left exposed to traffic. If doing so is necessary, proper precautions, such as reducing the posted speed limit on the roadway and sanding the surface, should be taken.

A tack coat is normally not needed between layers of new HMA. If used, the amount of residual asphalt on the roadway surface should be approximately half that appropriate for an old, tight, existing pavement surface.

15 Mix Placement

The primary purpose of the paver is to place the HMA to the desired width, grade, cross slope, and thickness and to produce a uniform mat texture. The paver should also be able to place the HMA in a manner that results in improved ridability and smoothness of the roadway.

There are two types of pavers—track (crawler) and rubber-tire—which are basically the same and perform similar functions in a paving operation. The track paver, whose tracks may be all steel, steel equipped with rubber pads, or an endless rubber track, offers a high degree of flotation and traction when traveling across weak underlying pavement structures by providing an increased area over which to spread the weight of the paver. This type of paver is therefore typically used when paving on a soft or yielding base. A rubber-tire paver is generally used when placing HMA over well-compacted granular base course layers or over existing HMA or PCC pavements. In addition, if the paver is to be moved regularly under its own power between paving locations, a rubber-tire paver or track paver with an endless rubber track is generally used because the travel speed of these vehicles is much greater than that of the other types of track pavers.

The paver consists of two primary parts—the tractor unit and the screed unit. The tractor unit provides the motive power to the paver and pushes the haul truck in front of the paver during the unloading process if the mix is being delivered directly from the truck into the paver hopper (see Section 13). The tractor unit also transfers the asphalt mixture from the receiving hopper on the front of the machine to the augers at the back of the paver. The screed unit is attached to the tractor unit at only one point on each side of the paver and "floats" on the HMA. The screed provides the initial texture and compaction to the HMA as it passes out from under the unit. Figure 15-1 is a schematic showing the tractor and screed units.

TRACTOR UNIT

The tractor unit fulfills all of the functions necessary to receive the asphalt mix directly from the haul trucks or to pick the mix up from a windrow, carry it through the machine back to the augers, and then distribute it across the width of the screed. The tractor unit, equipped with either rubber tires or tracks, is powered by its own engine and provides the propulsion energy required to move the machine forward, pushing the haul vehicle ahead of it if necessary. It has the following major components: the truck push rollers, and a material feed system consisting of a mix-receiving hopper, slat conveyors, material flow gates (usually), and a pair of augers. The tractor unit also provides the motive power for the screed by pulling it behind the tractor.

Push Rollers

The push rollers, located on the front of the paver hopper, are used to maintain contact with the tires of the haul truck and to push that truck ahead of the paver. The rollers must be clean and free to rotate in order to allow smooth forward travel of the paver. If the push rollers are not cleaned periodically and do not rotate freely, the truck tires will slide on the rollers and increase the load on the paver. Moreover, if one roller rotates freely and the other does not, the paver may be more difficult to steer.

Many pavers are equipped with a truck hitch that is located underneath or incorporated into the push rollers on the front of the paver. The purpose of the hitch is to keep the truck in contact with the paver and thereby prevent the truck driver from pulling away from the paver and inadvertently dumping mix on the pavement in front of the paver. The hitch, controlled by the paver operator, has arms, with rollers attached, extending forward. The rollers are retracted into the truck tire rim and against the tire itself, preventing the truck from losing contact with the paver during the unloading process. Once the truck bed has been emptied of mix, the truck hitch is withdrawn, and the truck is able to pull away from the paver.

Material Feed System

The material feed system on the tractor unit plays a very important part in producing a consistent, high-quality mat behind the laydown machine. In this section the

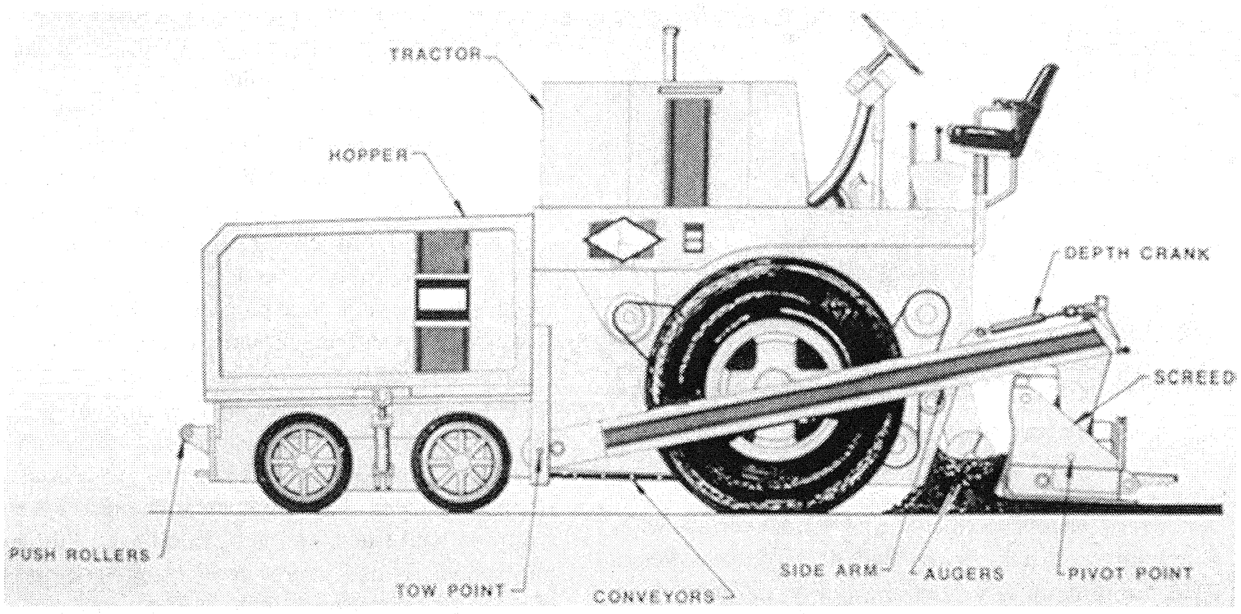


FIGURE 15-1 Schematic of HMA paver.

components of the material feed system and its basic operation are reviewed.

Material Feed System Components

As noted, the material feed system typically consists of a paver hopper, slat conveyors, material flow gates, and a pair of augers.

Paver Hopper The paver hopper, shown in Figure 15-2, is used as a temporary storage area for the asphalt mix delivered from the haul vehicle, the windrow elevator, or the material transfer vehicle (MTV). The hopper capacity compensates for the fluctuating material demands encountered when paving over irregular grades

FIGURE 15-2 Loaded HMA paver hopper.

and thus helps maintain a constant paving speed. When mix is delivered with a haul vehicle, the hopper must be wide enough to allow the body of the haul vehicle to fit within it. In addition, particularly for smaller pavers, the hopper must be low enough to permit the truck bed to be raised without the bed placing weight on the front of the hopper.

The front of the hopper is designed to minimize the spillage of mix out of the hopper during operation or while dumping the hopper wings. Overflow guards or flashing further reduces spillage out of the hopper during raising or dumping of the paver wings. The condition of these guards should be checked regularly since they are often damaged by haul truck beds as HMA is unloaded. In addition, for certain types and sizes of haul trucks, the shape of the guards may need to be changed to prevent spillage of the mix onto the existing pavement surface.

If a windrow elevator (see Figure 15-3) is used to feed mix to the paver, the hopper should have enough volume so that the paver can temporarily store the HMA if the demand for mix at the screed varies, such as when placing a leveling course. In addition, since the amount of mix in the windrow itself may vary, the hopper must be large enough to hold fluctuating amounts of mix delivered to it without overflowing or allowing the screed to run out of material. The blades on the slat conveyor of the windrow elevator must be set at the right level to pick up as much of the mix that has been placed on the existing pavement as possible. Essentially no mix should be left in the windrow, except perhaps a minimal

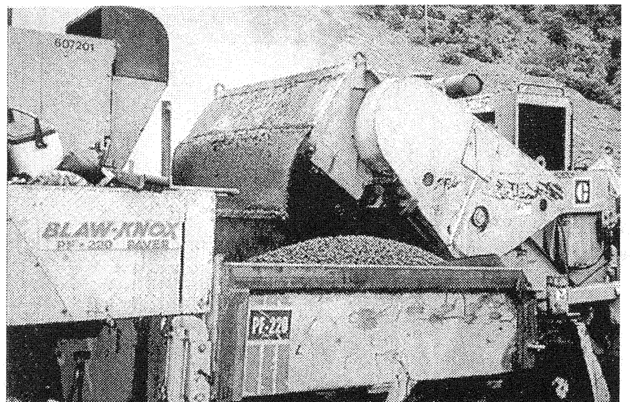


FIGURE 15-3 Windrow elevator.

amount in the low spots on the pavement surface when a leveling course is being placed. Any thin layer of material remaining will cool quickly and may result in difficulties in compacting the HMA. In addition, longitudinal streaks may occur in the mat behind the paver at the same location as the outside edges of the windrow.

The amount of mix in the paver hopper should always be kept at a level above the top of the flow gates or tunnel openings at the back of the hopper. Doing so permits the paver operator to keep the conveyors on the paver full and thus maintain a constant head of HMA in front of the paver screed, providing for a smooth mat behind the screed. This practice is particularly important between truckloads of mix in order to reduce segregation problems.

As shown in Figure 15-4, the sides, or wings, of the hopper are movable. Any mix left to stand for a long period of time in the corners of the hopper will cool and may appear as chunks of material in back of the screed

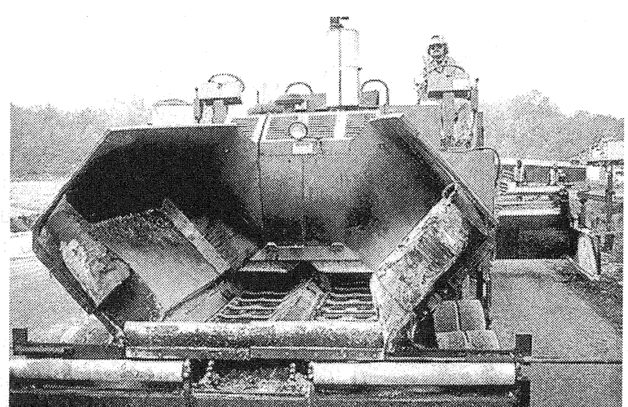


FIGURE 15-4 HMA paver with wings lifted.

when it passes through the paver. Thus the mix is periodically moved from the sides of the hopper into the middle of the hopper by folding the wings (sides) and depositing the mix on top of the area of the conveyors.

Many paver operators dump (fold) the wings of the paver after each truckload of mix has been emptied into the hopper. This is not good practice and should generally be avoided. Moreover, to prevent spillage of the mix out of the front of the hopper when the wings are folded, the operator often pulls down the amount of mix left in the hopper by continuing to run the slat conveyors to feed mix back to the augers after the truck has pulled away from the paver. This practice may result in the slat conveyor running nearly empty and can lead to increased mat problems if segregated mix is deposited on the conveyor slats, either from the paver wings or from the haul truck, and is carried back to the augers and screed. Thus it is not good practice to dump the paver wings after each truckload of mix has been delivered or to deposit the mix held in the wings into the empty paver hopper, because either procedure can significantly decrease the quality and smoothness of the finished mat.

To minimize segregation, the paver operator should fold the wings as infrequently as possible—only often enough to keep the material sufficiently hot for proper placement and compaction. The frequency with which the wings are dumped depends on the rate of delivery of the mix to the paver, the temperature of the mix, and environmental conditions. The wings should be emptied before the mix that collects in the corners of the hopper has cooled to the point where chunks are formed that cannot be broken up as that mix moves through the paver to the augers and under the screed. On colder and windier days, the hopper wings must be dumped more frequently than on warmer and calmer days.

When it is necessary to dump the wings, the sides of the hopper should be slowly raised as soon as the haul truck has been emptied and has pulled away from the paver. A steady forward paving speed of the laydown machine should be maintained as the hopper sides continue to rise. The wings should be fully elevated before the amount of mix remaining in the hopper is lower than the top of the flow gates or the openings at the back of the hopper. (The slat conveyors should never be visible at the time the wings are raised—or at any other time during the paving operation.) The paver should be stopped before the tunnel openings or flow gates are visible, and the sides of the hopper then lowered. This procedure minimizes the segregation problem that often occurs when the sides of the hopper are emptied, while still cleaning the cooler mix out of the corners of the hopper. As discussed later, keeping the hopper relatively full between truckloads of mix maintains a constant head of asphalt mix in front of the paver screed and also reduces any segregation that might be present in the mix. In addition, the wings should not be "banged" repeatedly as they are emptied.

To prevent the HMA from collecting in the corners of the paver hopper and thus avoid having to dump the hopper wings to remove the cold material, a fillet can be placed in each corner of the hopper. A triangular piece of sheet steel can be bolted to the sides of the hopper, reaching from the top back corner to the floor of the hopper just outside the flow gate opening, and also to the lower front corner of the hopper. This fillet prevents mix from being carried in the corners of the hopper and eliminates the need to empty the hopper wings. The fillet can be sized and located so that it is still possible to completely fit the apron of an end-dump truck bed into the paver hopper and empty the truck without the truck bed coming in contact with the hopper.

It is also possible simply not to empty the wings of the paver at all during the paving day. If the HMA is allowed to collect in each wing, it will cool and build up a natural angle of repose. This cold HMA will then prevent new mix from the haul trucks, windrow elevator, or MTV from collecting in the wings. At the end of the day, the cold material can be removed from each wing area by raising and shaking the sides of the hopper. The two big chunks of mix can then be transported back to the asphalt plant for recycling. Although this method does prevent mix from collecting in the hopper wings following the initial buildup, it is better practice to install a fillet in each wing to eliminate both the collection and need for disposal of HMA in the wing area.

Slat Conveyors At the bottom of the paver hopper there is typically a set of slat conveyors consisting of heavy chains and flight bars (see Figure 15-5). The slat conveyors are a continuous system, with the slats being rotated back to the bottom of the hopper underneath the paver itself. These devices are used to carry the asphalt mix from the hopper through the tunnels on the paver and back to the augers. The slat conveyor on one side of the paver operates independently from that on the other side. On most newer pavers, the conveyor system operates independently of the speed of the paver, and on some pavers, the speed of the conveyors is also independent of the speed of the augers. Thus the amount of mix being carried back through the paver on one side may differ from that being delivered on the other side, and the paver operator can feed more or less material to either side of the paver to pave ramps, mailbox turnouts, and tapers.

FIGURE 15-5 Slat conveyors at bottom of paver hopper.

On some pavers, the slat conveyor system has been replaced by a screw conveyor system. The purpose of this latter system is to remix the HMA in the paver hopper and reduce segregation behind the screed. Two parallel screw conveyors—one with left-hand pitch and one with right-hand pitch—run longitudinally down the length of the paver, one on each side of the machine, pulling the mix from the paver hopper and discharging it to the transverse augers in front of the screed. The screw conveyors are equipped with mixing paddles to blend the mix from side to side as it is moved along by the conveyor. For this system to function properly, however, there must be enough mix retained in the paver hopper between truckloads of mix—the level of mix remaining in the hopper should be above the level of the flow gates or tunnel openings at the back of the hopper—so that there is material to blend together. If the screw conveyors are visible between truckloads of mix, this system will not properly address the potential segregation problem.

To carry the mix farther back to the augers when the mix is delivered by the slat conveyors, some pavers are equipped with an extended floor plate at the rear end of the conveyor system. This plate is used to deposit the mix closer to the augers instead of letting it fall quickly to the underlying pavement surface when it comes off of the conveyors. This system is used to eliminate longitudinal segregation at the auger gearbox.

Flow Gates At the back of the paver hopper on most pavers is a set of flow gates. These gates, one over each of the two slat conveyors, are used to regulate the amount of mix that can be delivered by each conveyor to the corresponding auger on the paver. Flow gates are found on pavers on which the speed of the slat conveyor system and that of the auger on each side of the machine are interlocked, so that the speed of the auger increases when that of the slat conveyor is increased. The gates can be moved vertically, either manually or mechanically (electrically). Depending on the vertical setting of the gates, more or less mix is permitted to enter each paver tunnel. The location of the flow gates is shown in Figures 15-6 and 15-7.

The flow gates should be adjusted to provide a uniform head of material (at a level at or just above the center of the auger shaft) in front of the screed for each particular mat width, mat thickness, and paving speed. If the demand for mix is different on each side of the machine (different paving width or mat thickness), the elevation of the flow gates should differ on each side of the hopper accordingly. On some pavers, a sensor is located behind the flow gates to monitor the amount of mix passing into the tunnel and alert the operator of a low- or a no-material flow condition.

Flow gates are not used with pavers on which the conveyor and the auger on each side of the machine are driven separately. On such machines, the speed of each conveyor can be adjusted independently of the speed of the corresponding auger. If more mix is required on one side of the machine than on the other, the speed of the conveyor on that side is increased by the paver operator or by the automatic flow control system to deliver more HMA back to the augers, thus keeping the head of material in front of the screed consistent.

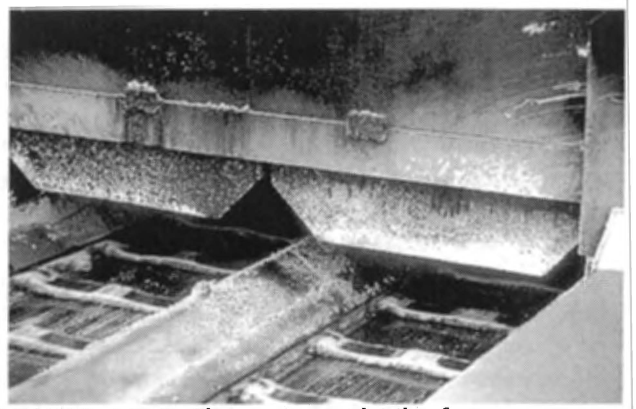


FIGURE 15-7 Flow gates at back of paver hopper.

Augers The mix carried to the back of the tractor unit by the slat conveyors is deposited in front of the augers (see Figures 15-8 and 15-9). Like the two slat conveyors, the augers on each side of the paver are operated independently of one another. The auger on one side of the paver, however, is usually run in conjunction with the slat conveyor on that same side of the paver (unless a paver with independent conveyor and auger drive motors—and no flow gates—is used). In addition, the paver operator has the option of running the left or right conveyor and auger system in either manual or automatic mode. In automatic mode, a feed control sensor on that side of the machine controls the level of material at the outside edge of the auger. It is extremely important that the augers carry a consistent amount of mix across the front of the screed so that the head of material in front of the screed remains as constant as possible.

The mix placed in the auger chamber from the slat conveyors is distributed across the width of the paver screed by the movement of the two independent augers. At the junction of the two augers in the center of the

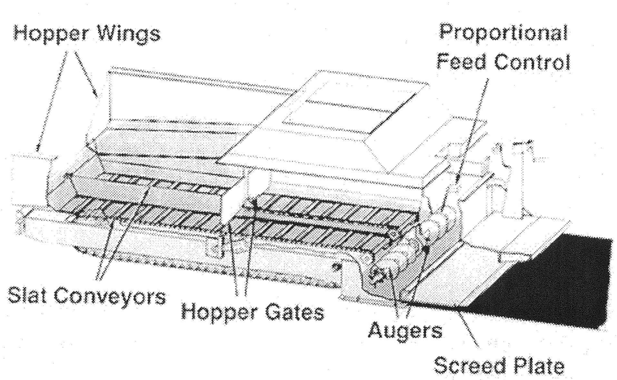


FIGURE 15-6 Material flow through paver.

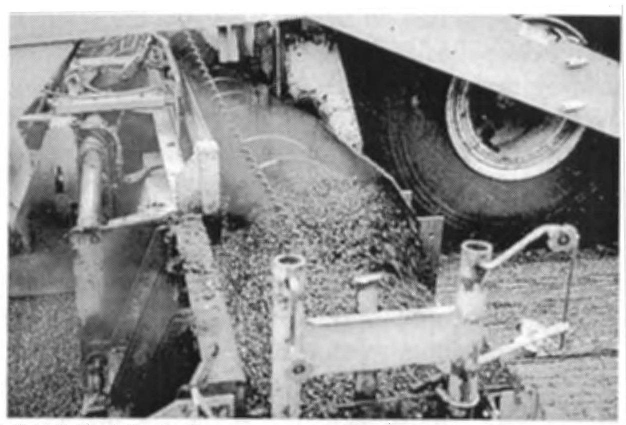


FIGURE 15-8 Paver auger.

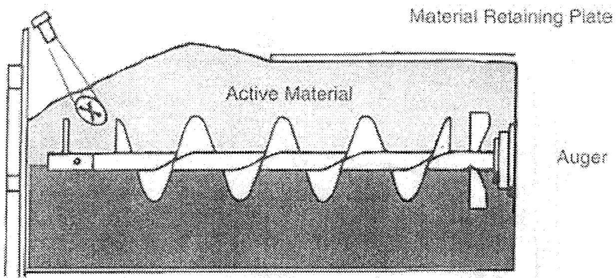


FIGURE 15-9 Schematic of paver auger.

paver, adjacent to each side of the auger gearbox, there typically is a different-shaped auger (reverse auger) or a paddle used to tuck mix under the gearbox and ensure that the mix placement at this location is the same as that across the rest of the width of the mix being laid. A paver equipped with a pair of reverse paddles is shown in Figure 15-10.

If sufficient mix is not placed under the center of the screed because of a lack of mix being tucked under the gearbox, a longitudinal streak may be seen behind the paver at the center of the screed. It is sometimes thought that such a streak is a form of segregation because the surface texture of the mat at that location is more open than that of the adjacent mix and is generally darker in color. This, however, is not really a segregation problem. Rather, the rougher texture and darker color are generally caused by a lack of mix placed under the gearbox and thus passing under the screed at that point. Indeed, if carefully measured, the elevation of the mix in the streak will be slightly below that of the surrounding mix—the streak is a low spot in the mat surface. If a gearbox streak is visible at the center of the main paver screed, installation of a reverse auger or paddle system on the paver should be considered if such a system is not already present. If the reverse augers or paddles are present, adjustments should be made to tuck more mix under the gearbox; worn augers or paddles should be replaced if necessary.

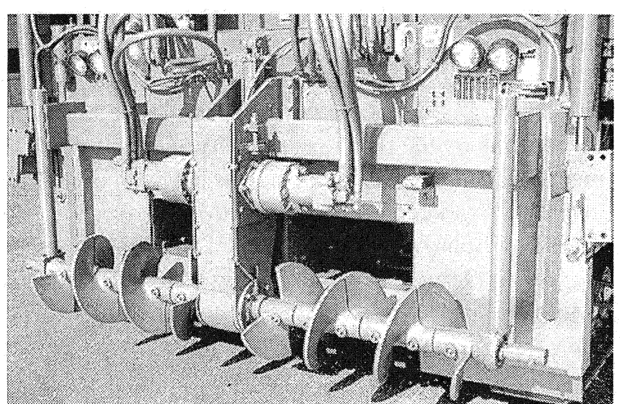


FIGURE 15-10 Paver auger with gearhousing at midpoint equipped with reverse paddles.

Newer pavers are equipped with variable-height augers—the elevation of the auger can be changed. The height of the auger is normally set in accordance with the paving depth. As a general rule, the augers should be set as low as possible to minimize the amount of mix carried in the auger chamber. The elevation of the bottom of the auger, however, should never be even with or lower than the top of the mix being laid, as this may result in differences in mat texture.

Operation of Material Feed System

The amount of mix carried in the auger chamber should be as constant as possible. The proper depth of material on the augers is at the center of the auger shaft, as seen in Figure 15-11. The level of material carried in front of the screed should not be so low as to expose the lower portion of the screw conveyor flights. Further, the level of mix delivered to the screed should never be so high as to cover the upper portion of the auger, as shown in the figure.

If the feed system is set and operating properly, the slat conveyors and augers on each side of the paver will rarely shut off; they will operate in a slow continuous manner. This continuous action of the conveyors and augers is accomplished by setting the proper position for the hopper flow gates (if any) and determining the correct speed setting for the slat or screw conveyors and for the augers. *The key to placement of a smooth pavement layer is use of the material feed system to maintain a constant head (level) of material in front of the screed, primarily by keeping the slat conveyors and augers running as close to 100 percent of the time as possible.* Intermittent operation of the slat conveyor and auger systems may cause roughness in the mat, as well as both auger shadows and ripples in the mat behind the screed, as discussed elsewhere in this section.

There are two types of material feed control systems conventionally used on paving machines—constant speed and variable or proportional speed. Many newer pavers have an automatic feed system based on sonic control.

Constant Speed As noted earlier, the slat conveyor and auger on one side of the paver act independently from the slat conveyor and auger on the other side of the paver. On older pavers, the speed of the slat conveyors

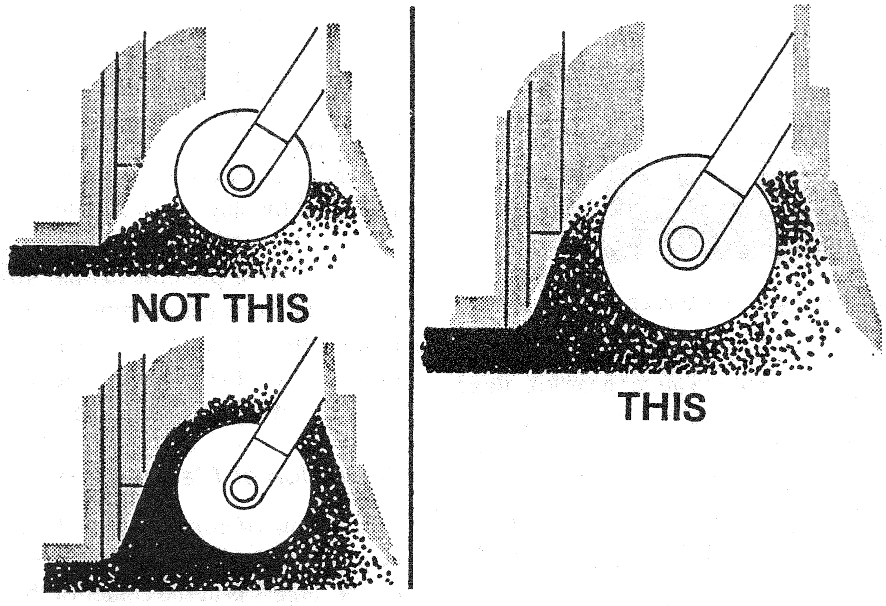


FIGURE 15-11 Correct and incorrect mix levels in paver auger chamber.

and augers is constant in manual mode. The paver operator can control the amount of mix being carried back to the screed only by adjusting the height of the flow gates.

If the gates are set too high, the material feed system will provide too much asphalt mix to the augers whenever the slat conveyors and augers are running. The result will be a significant increase in the head of material in front of the screed and increased pressure on the screed. This increased pressure will in turn change the angle of attack of the screed and increase the thickness of the mat being placed, and the angle of attack of the screed will be increased slightly as the screed rotates around its pivot point. On the other hand, if the gates are set too low, the material feed system will not be able to deliver enough material to the augers, thus reducing the head of mix in front of the screed and the force pushing on the screed. The result will be a reduction in the thickness of the mat being placed as the screed rotates around its pivot point and a decrease in the angle of attack of the screed.

As noted, with these older systems, the only way the operator can control the head of material in front of the screed is by proper setting of the flow gates at the back of the paver hopper. The flow gates and feeder on–off switches must be set at a position that allows the slat conveyors and augers on each side of the machine to run as close to 100 percent of the time as possible. For most paving operations, if the flow gates are properly set for the paver speed, paving width, and mat thickness, the conveyor and auger systems will typically run about 80 to 90 percent of the time under manual control.

A flow control sensor or paddle can be placed on each side of the paver near the outer ends of the augers. This sensor monitors the amount of mix being carried in front of the screed and activates the corresponding slat conveyor and auger when mix is needed. This flow control system is really a limit switch in which a mechanical wand or paddle floats on top of the mix and rotates the limit switch shaft as the level of mix in front of the screed changes. When too much mix is sensed in front of the screed, the limit switch shuts off the mix delivery system. When mix is needed, the paddle rotates downward on top of the lesser quantity of mix in front of the screed, and the conveyor–auger system starts up. Even with use of a flow control sensor, however, the amount of mix delivered to the screed is actually controlled only by the position (elevation) of the flow gate on the back of the paver hopper. The height of each flow gate is set to keep the head of HMA in front of the screed constant—near the center of the auger shaft—and the delivery system running as close to full time as possible. This is very difficult to accomplish, especially if the paver is being used to level an existing pavement surface and the demand for mix is variable.

Changes in the head of material may result from the off-on-off-on operation of a constant-speed feed control system. These changes may in turn cause surface shadows and ripples in the surface of the mix. This problem can be avoided through use of a variable-speed or sonic automatic feed control system.

Variable (Proportional) Speed Some pavers are designed so that in manual mode, the paver operator can select one of several speeds for the slat conveyors, each essentially a percentage of the maximum conveyor speed. Once the conveyor speed has been selected, the speed of the auger is set proportionately. The operator is responsible for controlling the speed of the slat conveyors and augers to keep a constant level of asphalt mix in front of the paver screed. The flow of material to the screed is still essentially regulated by the height of the hopper flow gates, however, and by the starting and stopping of the slat conveyor and auger on each side of the paver. With this manual system, changes in demand for mix are met by changing the speed of the feed system.

A flow or feed control sensor can also be used with this system to monitor the amount of HMA in the auger chamber in front of the screed. As the level of HMA in front of the screed rises and falls, the speed of the feed system increases or decreases to maintain a constant level and uniform flow of mix across the width of the screed.

For the automatic feed control system to function properly, the feed sensor paddle or wand should be located as close to the outside ends of the augers as possible. If rigid paver screed extensions are used, the control arm should be mounted beyond the ends of the augers, just inside the end gate on the paver screed. If a hydraulically extendable screed is used, the location of the feed sensor control arm should be such that the amount of mix carried in front of the extensions is minimized. In most cases, this means the sensor should be mounted on the end gate of the paver screed and the sensor paddle or wand hung only a short distance in front of the end of the extendable screed.

For rear-mounted hydraulic screed extensions, discussed later in this section, it is important to minimize the amount of mix carried in front of the screed on the extension. A flow control sensor system should be employed to severely limit the amount of HMA carried in front of the screed extension. That sensor should be mounted on the end gate of the screed just in front of the leading edge of the screed.

Sonic Control Newer pavers are often equipped with an automatic feed system that uses ultrasound to monitor the amount of mix being carried on the augers. This system basically operates on the same basis as a variable-speed limit switch system by measuring the amount of mix in front of the screed and controlling the speed of the slat conveyors and auger system to maintain a constant head of material at the screed. The sonic feed system uses reflected sound waves to sense the level of mix. The system sends out pulses several times per second. A timing circuit is started when the pulse is sent out and is stopped when the first echo is received back. The length of time between when the pulse is sent out and the echo is received is used to calculate the distance to the material being sensed—the head of material in the auger chamber. The controller then varies the speed of the conveyors and augers on each side of the machine proportionally to maintain a constant level of mix across the front of the screed.

SCREED UNIT

The screed unit, which is towed by the tractor unit, establishes the thickness of the asphalt layer and provides the initial texture to the new surface. In addition, through its weight and vibratory action, the screed imparts some level of density to the material being placed. Figure 15-12 shows the paver screed and tow arms.

The concept of the free-floating paver screed was developed in the early 1930s. That concept allows the paver screed, which is attached to the tractor unit at only one point on each side of the machine, to average out changes in grade or elevation experienced by the wheelbase (rubber tires or crawler tracks) of the tractor unit. The floating-screed concept is employed on all modern asphalt pavers in use today.

Tow (Pull) Points

The screed unit is attached to the tractor unit at only one point on each side of the paver. This point, shown in Figure 15-12, is called the tow (or pull) point. The tow points are really pin-type connections that allow the leveling arms (also called side arms or pull arms) of the screed to rotate or pivot around those points. This pin connection reduces the transmission of movement between the tractor and screed units.

The concept of the tow points and the free-floating screed allows the tractor unit to provide the wheelbase for the screed unit. The screed then pivots around the tow points, which are located in the center of the length of the wheelbase on the tractor unit and respond to the average grade being spanned by the tractor wheelbase. When paving over irregular grades, the tractor can pivot much like a see-saw without changing the line of pull for the screed.

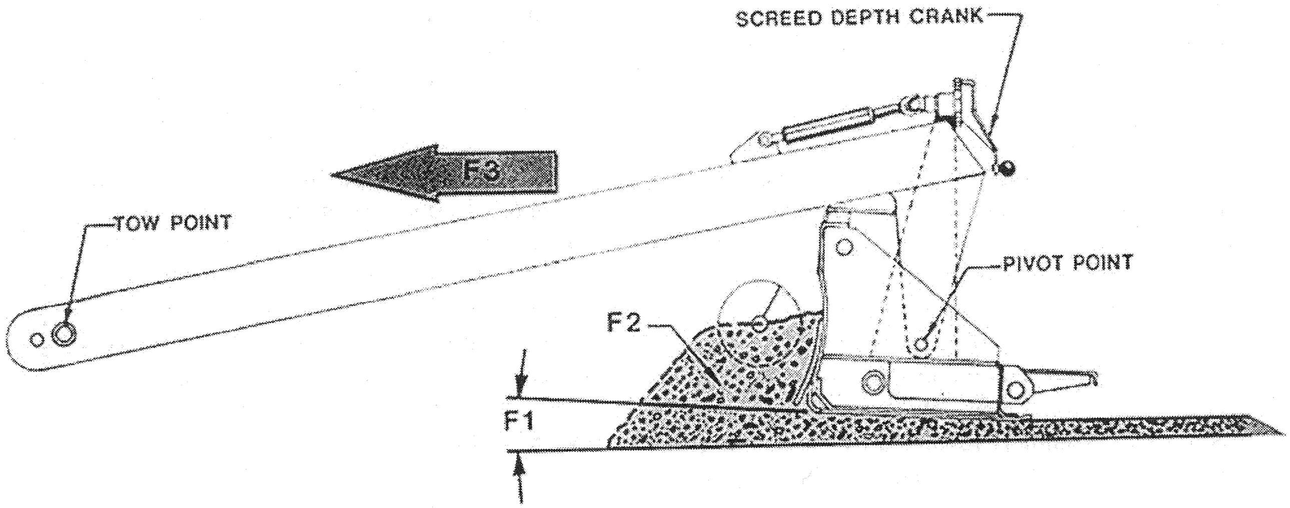


FIGURE 15-12 Action of paver screed and tow arms.

For the floating-screed principle to work properly under manual control, it is important that the tow points on both sides of the tractor be at the same level above the ground. (Automatic screed control is addressed in Section 16.) The position of the tow points can be altered by raising or lowering the rods on which the tow points are mounted. For most asphalt mixtures, the tow points are positioned near the center of the rod. For some asphalt mixtures, however, such as those that are very stiff or very tender, it may be advantageous to raise or lower the elevation of the tow points to improve the texture of the mat being placed. (If the paver is being operated under automatic grade and slope control, as discussed in the following section, the elevation of the tow points is typically centered when paving begins. The location then changes as paving proceeds to maintain the proper angle of attack of the screed.)

When some pavers are operated under manual control and the tow points are too high, the front of the screed is tilted down to maintain the proper angle of attack for the desired mat thickness. This can result in premature wear on the strike-off and the leading edge of the screed, a reduction in the smoothness of the mat, and a decrease in the degree of compaction imparted to the mix. When the tow points are too low, on the other hand, the front of the screed is tilted up to maintain the correct thickness of the asphalt mix being placed. Additional wear can then occur on the trailing edge of the screed.

For a paver not equipped with automatic screed controls, there is typically an 8:1 ratio between the movement of the tow points and the change in the angle of attack of the front edge of the paver screed. Thus if the tow points are moved upward 25 mm (1 in.), the angle of attack of the screed will be increased by 3 mm ($\frac{1}{8}$ in.). As discussed in detail below, the paver must move forward approximately five lengths of the leveling arms before the screed moves up to the new level of the tow points and the forces on the screed are again in equilibrium.

The combination of the screed pivot points at the ends of the leveling arms attached to the tractor and the thickness control device at the screed makes it possible to adjust the angle of attack of the screed unit. The angle of attack is illustrated in Figure 15-13. Because of the way the screed is attached to the tractor, the screed acts in a manner similar to that of a water skier being pulled by a speedboat. As the motorboat goes faster, the water skier comes farther out of the water, and the angle of attack of the water skis decreases. Similarly, as the paver goes faster, the angle of attack of the screed decreases, and the mat being placed by the paver is thinner. If the skier is traveling over a calm water surface, the angle of attack of the skis will remain constant. If the skier attempts to cross the wake of the boat, however, the angle of attack of the

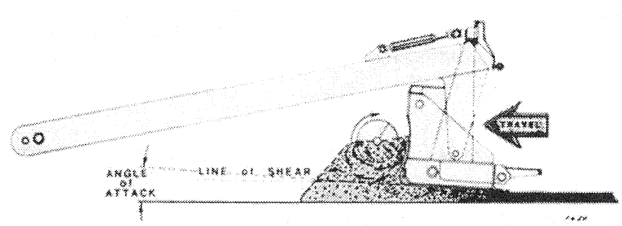


FIGURE 15-13 Angle of attack for paver screed.

skis will increase as the skis climb up over the wave. Similarly, if the head of material in front of the paver screed increases, the angle of attack of the screed will increase as the screed reacts to the increase in force on it. The result will be a thicker mat being placed by the paver.

Manual screed control is discussed in detail later in this section. First, however, forces acting on the screed and the effects of starting and stopping the paver are reviewed.

Forces Acting on the Screed

Two primary forces constantly act on the paver screed as the paver places the mix. The first is the towing force of the tractor, which varies as the speed of the paver increases and decreases. The second is the head of material pushing against the screed. As the amount of asphalt material in the auger chamber that pushes against the screed changes, the net force acting on the screed also changes. As the forces acting on the screed change, the screed must come to a new angle of attack to compensate for the change in force acting on it. In addition, the line of pull—the angle at which the tractor pulls the screed forward—will influence the attack angle of the screed.

The forces on the screed must be in equilibrium (the sum of all forces equal to zero) for the screed to remain at a constant angle of attack as it is towed by the tractor unit. When a change in any one force occurs, the screed will rise or fall, and the thickness of the mat being placed will change accordingly. A change in the angle of attack of the screed will also result. The screed will react to the change in the force against it until it reaches a new equilibrium elevation where the forces are in balance.

Paver Speed

Because the speed of the paver has a major effect on the angle of attack of the paver screed, it is good paving practice to keep the speed as consistent as possible during laydown operations. Under manual material flow control and screed control, if the other forces on the screed remain constant, an increase in the paver speed results in a decrease in the thickness of the asphalt layer being placed. This occurs at the faster paver speed because the angle of attack of the screed has changed. As the speed is increased, the angle of attack of the screed decreases, and the thickness of the mat placed also decreases until an equilibrium condition is again reached. Similarly, a decrease in the speed of the paver causes an increase in the thickness of the mat. The screed then climbs to a new elevation until its equilibrium is reestablished.

The above occurs, however, only as long as no other changes are made in the system—if the level of the tow points and the amount of mix in the auger chamber remain constant. It should be noted, however, that as the paver speed is increased or decreased, the rate of feed of HMA through the paver must also be changed to maintain a constant head of material in the auger chamber. As the paver speed increases, if no additional mix is delivered by the slat conveyors to the augers to compensate for the change in demand for mix, less mix is available to pass under the screed, and the thickness of the layer is further reduced.

If the paver operator manually changes the amount of mix fed back to the augers or if the feed control sensors accomplish the same function automatically, the angle of attack of the screed remains constant because of the effect of the head of material in front of the screed. As discussed above, however, the thickness of the mat placed still changes because of the change in paver speed. To maintain a constant mat thickness with a change in paver speed, therefore, a manual change must be made in the setting of the thickness control screws (depth cranks) located at the paver screed. For an increase in paver speed, the depth crank must be turned so that the screed rotates around its pivot point, and the angle of attack is increased manually to compensate for the decrease in angle of attack that naturally occurs when the speed is increased. Similarly, for a decrease in paver speed, the depth crank must be turned in the opposite direction so that the angle of attack of the screed is manually decreased to compensate for the automatic increase in the angle of attack that occurs when the speed of the paver is decreased. The amount of manual change needed in the setting of the thickness control screws, up or down, depends on the amount of change in the speed of the paver, faster or slower, respectively.

Those not familiar with the forces acting on the paver screed often assume that the thickness of the mat being placed increases as the speed of the paver increases (for a constant head of material maintained in front of the screed). This assumption is incorrect, as explained above. In fact, the opposite is true. Thus to fully understand the effect of a change in the speed of the paver on the angle of attack of the screed, one must remember that for the forces on the screed to be in equilibrium, each change in force must be accompanied by an equal, but opposite, change in force.

It is highly desirable to keep the speed of the paver constant in order to maintain a constant angle of attack of the screed and thus a constant thickness of the mat being placed. The speed of the paver should thus be matched to the production rate of the asphalt plant and to the thickness and width of the mat being placed. The maximum paver speed can be determined for different combinations of plant production rates and mat thicknesses.

As an example, for a mat that is 3.7 m (12 ft) wide, the paver should be operated at a speed of only 4.6 m (15 ft) per minute in order to place all of the mix provided by a plant producing HMA at a rate of approximately 91 tonnes (100 tons) per hour at a compacted layer thickness of 25 mm (1 in.). Similarly, for a plant production rate of 454 tonnes (500 tons) per hour, for the same mat width of 3.7 m (12 ft) and for a compacted layer thickness of 50 mm (2 in.), the maximum paver speed should be approximately 11.5 m (38 ft) per minute.

As noted earlier, to achieve the smoothest possible mat behind the paver screed, it is essential to keep the paver moving at a constant speed at all times. There is no sense in running the paver faster than necessary to place all of the delivered mix and then stopping to wait for the next haul truck to arrive at the paving site. The subject of slowing the paver down or stopping it between truckloads of mix is discussed further below.

Head of Material

If the volume of mix in the auger chamber is increased, the force on the screed also increases, causing the screed to rotate around its pivot point and thus rise. This action then causes the angle of attack of the screed to increase until a new equilibrium position is reached, resulting in placement of a thicker mat. If the amount of material being carried on the augers is decreased, the thickness of the mat is reduced, all other factors being equal, as the angle of attack of the screed decreases. Thus one of the primary factors affecting the consistency of the thickness of the layer being constructed is the consistency of the head of material (amount of HMA) in front of the paver screed.

The head of material in the auger chamber is directly affected by the operation of the slat conveyors and augers on each side of the paver. When the slat conveyors and augers are operating, the mix is pulled from the paver hopper, through the tunnel, and is distributed across the front of the screed by the augers. As long as this flow of material is relatively constant, the head of material pushing against the screed remains relatively constant as well, and the mat being placed has a smooth and consistent texture.

If the head of material is allowed to vary, however, the screed moves up and down in relation to and reaction to the forces acting on it. As the amount of mix being carried by the augers is decreased because the slat conveyor and auger systems are shut off, the screed moves downward, thus reducing the thickness of the mat behind the screed. As the slat conveyor and auger systems come on, more mix is carried back to the augers and across the front of the screed. This increases the force on the screed and causes it to rise to a new elevation, resulting in a thicker mat. Thus, the position or elevation of the flow gates is very important in regulating the amount of mix in front of the screed.

The head of material is affected each time the slat conveyors and augers are turned off and on. This is true particularly if the position of the flow gates is not properly set initially. For this reason, as suggested earlier, the use of a variable-speed or sonic automatic feed control system is important because these types of devices keep the slat conveyors and augers running as much of the time as possible, provided the flow gates are properly set. This in turn keeps the head of material relatively constant and allows the screed to place a mat of consistent thickness. A constant head of material against the paver screed also significantly reduces the occurrence of ripples and auger shadows.

If the paver is not equipped with flow gates, the speed of the conveyors and augers must be controlled so that the head of material is kept constant. For either type of system, however, with or without flow gates on the paver, a consistent head of material in front of the screed is associated with a consistently smooth mat behind the paver.

Another factor that affects the uniformity of the head of material in front of the screed is the temperature of the mix. If a cold load of material is deposited in the paver hopper and carried back to the screed by the slat conveyors and the augers, the colder, stiffer mix increases the force acting on the screed and causes the screed to rise, increasing the thickness of the layer placed. If, on the other hand, a hot load of mix is delivered to the paver, the decrease in viscosity of the binder material reduces the stiffness of the HMA and reduces the force of the mix on the screed when the mix is deposited in front of it. This situation causes the screed to fall and reduces the layer thickness.

Line of Pull

The line of pull refers to the angle at which the screed is pulled forward. A smoother pavement surface is generally placed when the towing force is applied relatively parallel to the grade over which the tractor unit is running. Thus the elevation of the tow points should be set in relation to the thickness of the mat being constructed. As a general rule, thin lifts of HMA require a lower initial tow point setting, while thick lifts of mix require a higher initial setting. Setting the initial tow point height to match the thickness of the material being placed results in the towing forces applied to the screed being relatively parallel to the grade. Unwanted influences that might cause texture and smoothness problems are not applied to the screed.

For a relatively thin mat, if the tow point setting is extremely high, the towing forces are applied at an upward angle that increases the lift forces acting on the screed. To maintain a given thickness of material, the angle of attack of the screed must then be decreased to compensate for the increased lift. In this condition, the screed runs at a slightly nose-down angle of attack. Only the front portion of the screed is then compacting and finishing the HMA being placed; the result is poor mat texture and extreme wear on the front portion of the bottom of the screed plate. In addition, when the paver stops, the screed has more of a tendency to rock or teeter as the tractor relaxes the tension on the screed. This may increase the amount of settling of the screed and introduce bumps into the mat.

For a relatively thick mat, if the tow point setting is extremely low, the towing forces are applied at a downward angle that decreases the lift forces applied to the screed. To maintain a given thickness of HMA, the angle of attack of the screed must then be increased to compensate for the decreased lift. In this condition, the screed runs at a slightly nose-up angle of attack, with only the rear portion of the screed compacting and finishing the mix being placed. This causes poor mat texture and extreme wear on the rear portion of the bottom of the screed plate. Increased control of the forces applied to the screed is thus gained by setting the tow points in relation to the thickness of the mat being placed.

Effects of Stopping and Starting the Paver

Short Stops

If the paver can be operated continuously at a constant speed without stopping, the smoothness of the mix placed should be excellent, as long as the screed operator does not continually change the angle of attack of the screed by turning the thickness control cranks and the head of material in front of the screed remains constant.

If bottom-dump trucks are used to deliver the mix from the plant to the laydown machine, there is a chance that the paving operation can be continuous if there is a long enough windrow of mix out ahead of the paver. If the next truck does not arrive at the paving site before the end of the windrow is reached, however, the paver will obviously have to stop and wait until more HMA is windrowed by the truck and is available to be picked up by the windrow elevator on the paver.

If an MTV is used to deliver mix from the haul vehicles to the paver hopper, there is also a chance that the paving operation can be continuous as long as the haul trucks arrive at the MTV before it runs out of mix. Since the MTV is essentially a surge bin on wheels, as discussed in Section 13, the amount of mix it can carry is limited, even taking into account the additional mix in the extended hopper on the paver. If the next haul truck does not arrive in time to keep the MTV and the paver hopper from becoming empty, the paving operation must come to a halt.

If end-dump or live-bottom trucks are used to deliver the mix to the hopper on the paver, there is little chance that a continuous paving operation can be accomplished unless the paving speed is very slow. Since the speed of the paver affects the angle of attack of the screed, and therefore the smoothness of the mat being placed, maintaining a constant speed without stopping is a desirable but unrealistic goal. For the paver to be able to keep moving forward at the selected paving speed while the truck exchange process was being completed, the following things would have to occur very efficiently if end-dump trucks were being used: the bed of the empty truck would have to be lowered, that truck would have to pull out away from the paver, the next truck would have to back up to the paver, the bed of that truck would have to be raised (if not done ahead of time, as it should be in order to move the mix back against the tailgate of the truck; see Section 13), and the tailgate would have to be opened and mix delivered into the paver hopper. All of this would have to happen before the amount of mix in the paver hopper had been reduced to a level below the top of the hopper flow gates so that the head of material in front of the screed would not be affected. On real paving projects, this level of efficiency is not normally obtained consistently.

Typically, the paver operator starts to slow the paver down once the haul truck is empty, the windrow runs out, or the MTV is almost empty. The operator usually hopes that the next truck will arrive before the paver is out of mix. Sometimes that occurs, but often it does not, and the paver is stopped. As the paver is gradually slowed down, however, the angle of attack of the screed changes (increases), and the thickness of the mat increases slightly. If the hopper is emptied of mix, the head of material in front of the screed is reduced, the angle of attack of the screed is decreased, and the thickness of the mat is also decreased—a gradual dip is built into the pavement surface.

Once new mix has been delivered into the empty paver hopper, either from the haul vehicle, from the windrow elevator, or from the MTV, the paver operator usually starts the slat conveyors on the paver and pulls a slug of mix back to the augers. The head of mix in the auger chamber builds up, and the paver is quickly brought back to paving speed by the operator. The high head of material causes the screed to rise and the mix thickness to increase. Because the paver reaches paving speed quickly, the paver speed has little effect on the angle of attack of the screed, given the delayed reaction time of the screed. The net effect of the high head of material and the quick increase in paver speed is a thicker pavement section—a bump is built into the pavement surface.

If the mix in the haul truck is segregated, and if that segregated mix is delivered into the empty paver hopper from both the end of one truckload and the beginning of the next truckload, the segregated coarse aggregate particles will be carried back to the augers and dumped on the pavement surface immediately in front of the low spot just constructed by the screed. If this occurs, truckload-to-truckload segregation (see Section 13) will be both felt (as a gradual dip and then a bump in the pavement surface) and seen.

If the paver needs to be stopped because additional mix is temporarily not available, it should be stopped as quickly and smoothly as possible, and before the level of mix in the hopper is drawn down below the top of the flow gates or the tunnel openings. This will keep the head of material in front of the screed constant at the same time that the effect of the change in the paver speed on the angle of attack of the screed is minimized because of the rapid speed change.

When more HMA arrives, it should be placed into the "half-full" paver hopper from the haul truck, windrow elevator, or MTV. The paver operator should then return the laydown machine to the desired paving speed as quickly as possible, again minimizing the effect of the change in paver speed on the angle of attack of the screed. Since the head of material has been kept constant, a smooth mat will be constructed—no dip, no bump, and no segregation. It has been found that the "rapid stop, rapid start" procedure for stopping the paver provides for good mat smoothness and consistent mat thickness.

Longer Stops

If there is going to be a long delay before the arrival of the next haul vehicle, consideration should be given to constructing a transverse joint, as discussed in Section 17. The acceptable length of a delay so that it is still possible to place and compact the mix to obtain the required level of smoothness and density will depend on a number of factors, including the environmental conditions (air temperature, surface temperature, and wind velocity) at the paving site, the temperature of the mix in the paver hopper, and the uncompacted thickness of the mat beneath the screed.

If it is decided not to construct a transverse joint but to put the paving operation on temporary hold until the next haul truck arrives, the paver should be stopped with the hopper as full as possible—above the level of mix that is typically kept in the hopper (above the top of the flow gates or tunnel openings) during short stops. Keeping the hopper full will reduce the rate of cooling of the mix during the waiting time because the mix will remain in a mass. In addition, the paver should not be moved forward during the waiting period, but should remain in one position until the new mix is available.

There is a tendency for the paver operator to sit in one spot for a while, move the paver forward a short distance, and then wait again. If the next truck does not arrive shortly, the operator often repeats this process until the paver hopper is empty. This practice is incorrect and can lead to the construction of a significant length of poor-quality pavement.

While the paver is sitting in one spot, the mix in the paver hopper will cool. The rate of cooling will be reduced if the amount of mix in the hopper is kept constant; as suggested above, the greater the mass of mix, the slower will be the rate of temperature loss. If the paver is moved forward periodically and the amount of mix in the hopper is decreased as some of the mix is laid by the paver, the rate of cooling of the remaining mix will increase. Depending on when the next haul truck arrives and how many moves the paver makes, the level of mix left in the paver hopper may become very low and the material quite cold.

Further, while the paver is stopped, a certain amount of mix will be retained in the auger chamber—the head of material in front of the screed. Since a portion of this HMA is in contact with the underlying pavement surface, cooling of this material will take place. In addition, the HMA that is actually under the paver screed and in contact with the existing surface will cool—even more rapidly than the mix in the auger chamber—because of the thinner layer and lesser volume of the uncompacted mix under the screed. Further, there will be some distance of mix behind the paver screed that cannot be reached by the rollers. Typically this length is about 1 m (3 ft) and is related to the amount of overhang of the walkway on the back of the screed and the curvature of the roller drum or tires. For most pavers, the total length of mix from the front of the auger chamber to the front edge of the roller drum that will cool quickly and be uncompacted will range from 2 to 3 m (6 to 9 ft). If the paver remains in one spot while waiting for the next truck to arrive, that distance of mix will usually have a lower level of density than the rest of the mat since the compactive effort of the rollers cannot be applied in this area, and the mix will be cooler when the paver finally moves forward.

Even more low-density mix will be placed if the paver moves forward periodically while awaiting the arrival of more mix. Each time the paver moves and stops, another distance of mix in contact with the existing pavement surface between the augers and the rollers will cool quickly, and proper density will probably not be achieved. In addition, as the hopper is periodically emptied, not only will the remaining mix lose temperature more rapidly, but the head of material in front of the screed will be reduced, and a low spot or dip will be built into the pavement surface. Good paving practice therefore dictates that the paver remain in one position, with the hopper as full as possible and the head of material constant, until additional mix arrives.

Manual Screed Control

In this section, procedures involved in manual screed control are reviewed. Automatic screed control and the ways in which it differs from manual control are covered in Section 16.

Thickness Control Cranks

As noted earlier, the screed is attached to the leveling or tow arms on each side of the paver through pivot points. The thickness control mechanism, usually either a crank or a handle, allows the screed to be moved or rotated around the pivot points. The key to the leveling action of the screed is its ability, by rotating around the pivot points and being attached to the tractor unit only at the tow points, to establish an equilibrium position based on the forces applied to it. As the mix passes under the screed plate, the screed floats on the mix, establishing the mat thickness and the texture of the material, as well as providing the initial compaction of the HMA.

For a constant position of the tow points (the tractor unit running on a level surface and without automatic screed controls), altering the setting of the thickness control devices changes the angle of attack of the screed and the forces acting on the screed. This in turn causes the screed to move up or down to a new elevation as the paver moves forward, thus altering the thickness of the mat being placed. The reaction of the screed to changes in the position of the thickness control settings, however, is not instantaneous. Rather, there is a lag in the reaction that allows the screed to average out variations in the input forces acting on it.

Yield

There is a tendency for the screed operator to continually turn the thickness control cranks in order to control the amount of mix being placed. This is particularly true of paving projects on which the yield—the amount of mix available to be laid (set up in the plans) over a given area—is tightly controlled. Frequently the screed operator will check the mat thickness using a rod or ruler (depth gauge) at a given point. On the basis of that single reading, the operator often will then adjust the setting of the thickness control cranks, changing the angle of attack of the screed and thus the thickness of the mat. When a subsequent check is done a short time later and the depth measured does not match the required uncompacted thickness, another change is made in the setting of the thickness control cranks and the angle of attack, so that the thickness of the mat is altered once again. This approach of using individual measurements to set the screed does not accomplish the desired goal of obtaining a smooth mat, nor does it typically accomplish the goal of correctly controlling the amount of mix placed along a given length of pavement.

Because of the delayed reaction time of the screed, discussed further below, there is a significant lag between the time the thickness control cranks are turned and the time the screed attains the new equilibrium point at the new thickness level. A single mat depth measurement should not be used to justify a change in the angle of attack of the screed. Indeed, even two or three measurements should not be averaged to determine whether a change in the setting of the thickness control cranks is needed. If the uncompacted thickness of the mat is to be checked using a depth gauge, the mat thickness behind the screed should be measured at least five times at 2-m

(6-ft) intervals longitudinally. The thickness control cranks should then be turned only if the average measured thickness is more than 6 mm (¼ in.) less or more than the desired uncompacted thickness of the mat.

A better way to check yield, if it must be measured periodically, is to determine the distance that the amount of mix in 10 truckloads of HMA should cover, based on the width and uncompacted thickness being laid. This distance is then compared with the length the paver has actually placed using the same number of tonnes (tons) of mix. If the distance covered is significantly less than it should have been, the setting of the thickness control cranks should be changed to slightly decrease the angle of attack of the screed, decreasing the amount of mix placed and therefore increasing the distance a given amount of material will cover. If the distance covered is significantly greater than it should have been, the thickness control cranks should be turned a small amount in the opposite direction to thicken the mat.

Screed Reaction Time

Figure 15-14 shows the reaction time of the screed when a change is made in its angle of attack, either at the screed or at the tow points. After the tow points have been raised, it takes approximately five times the length of the leveling or tow arms on the paver screed for the screed to complete 99 percent of the change, up or down, to the desired new elevation. This means that if the length of the leveling arms is 3 m (10 ft), the paver must move forward at least 15 m (50 ft) before the required input to the thickness control device is completely carried out by the paver screed. The same applies if the angle of attack of the screed is changed by turning the thickness control cranks on the back of the paver at the screed itself.

Changing the Screed Pivot Point As an example, assume that it is desired to increase the thickness of the mat being placed from 25 mm (1 in.) to 37 mm (1½ in.). An input is made to the thickness control crank by turning it to change the angle of attack of the screed. The movement of the thickness control mechanism causes the screed to move around the pivot points and increases the angle of attack.

As shown in Figure 15-14, approximately 63 percent of the thickness change in the mat is accomplished after the paver has moved forward a distance equal to one leveling arm length, or 3 m (10 ft) in this example. As the paver moves forward another 3 m (10 ft), about 87 percent of the desired thickness change is completed. Approximately 95 percent of the thickness change is accomplished by the time a distance of 9 m (30 ft) has been traveled—three leveling arm lengths of 3 m (10 ft) each. Only when the paver has moved down the roadway a distance equal to at least five leveling arm lengths, however, is some 99+ percent of the thickness change completed.

The above example applies also to a reduction in the thickness control settings at the screed. A screed operator desiring to reduce the depth of the asphalt layer turns the thickness control crank in the opposite direction and causes the screed to rotate around the pivot points. As the paver moves forward, the decreased angle of attack of the screed causes it to move downward, thereby reducing the amount of mix being fed under the screed. The screed continues its downward movement until the forces acting on it are again in equilibrium. If the pavement layer depth were being changed from 37 mm (1½ in.) to 25 mm (1 in.), the paver would still have to move more than five lengths of the leveling arm before 99+ percent of the thickness change would be completed.

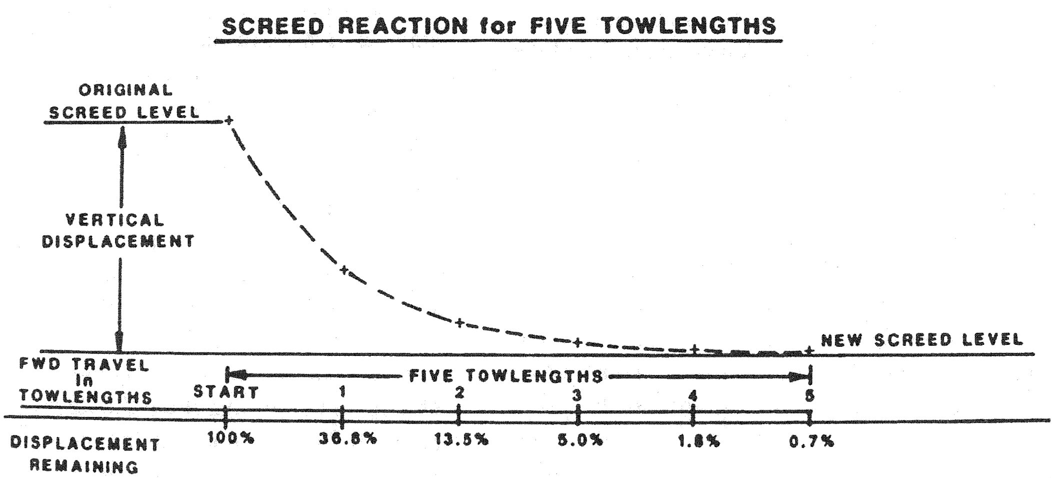


FIGURE 15-14 Screed reaction time.

The reaction time of the screed is the same regardless of the amount of change input to the thickness control cranks. Thus whether the cranks are turned enough times to increase the thickness from 25 mm (1 in.) to 50 mm (2 in.) or more times to increase the thickness from 25 mm (1 in.) to 75 mm (3 in.), at least five times the length of the tow arm will be required for the change to be completed. The reaction time is also the same if the thickness is decreased, from any level to any other thickness, regardless of the actual amount of the thickness change.

When a paver is being operated manually, it is essential for the screed operator to be aware of this lag in the reaction time of the screed. As noted, the paver must move forward at least one leveling arm length before 63 percent of the thickness change is completed. If a second change in the setting of the thickness control crank is made before the first change has been accomplished, the first change will never be completed, and it will still take an additional five times the length of the leveling arm for the second thickness change to be carried out. For this reason, continual changes in the setting of the thickness control devices are likely to be highly detrimental to the development of a smooth mat.

Changing the Tow Point Elevation The above discussion applies to a change in the location of the tow points of the screed leveling arm where it is attached to the tractor unit. If the tow points are displaced, the change in their elevation translates to a change in the angle of attack of the paver screed. The paver must still move forward for a distance of approximately five times the length of the leveling arm on the machine for the screed to react to the change in the location of the tow points and move up or down to the new elevation.

As a roadway is being paved without the use of automatic grade and slope controls, the tractor unit moves upward and downward in response to the grade of the underlying pavement. The vertical movement of the tractor translates into vertical movement of the tow points on the sides of the paver. Each time the tractor goes over a hump or into a dip in the existing pavement surface, the elevation of the tow points changes. This in turn alters the angle of attack of the screed, causing the amount of material flowing under the screed to be decreased or increased. The fact that it takes five times the length of the leveling arm before the screed reacts completely to a change in the location of the tow points allows the screed to reduce the thickness of the asphalt mix being placed over the high places in the existing surface and to place more mix in the low spots on the present roadway. It is this averaging or leveling action that forms the basis for the floating-screed principle discussed earlier.

The use of automatic paver controls, discussed in the next section, allows the paver to construct a smoother pavement by keeping the location of the screed tow points constant, relative to a predetermined reference, as the tractor unit moves up and down vertically in response to small changes in the grade of the underlying pavement surface. By maintaining the tow points at a constant relationship to the predetermined reference while the tractor moves vertically, the force on the screed remains constant, and the angle of attack of the screed is consistent in comparison with the reference. This allows the screed to carry out the leveling action needed over a longer reference length in order to reduce the roughness of the existing surface through the application of the new asphalt layer.

Screed Strike-Offs

The screed on some pavers is equipped with a device on its front edge called a strike-off (or sometimes a pre-strike-off). The purpose of this device is to control the amount of HMA allowed to pass under the nose of the screed, thereby affecting the screed's angle of attack. The strike-off is also used to reduce the wear on the leading edge of the screed. The proper positioning of the strike-off assembly is illustrated in Figure 15-15.

When the strike-off is attached to the front of the screed, its position becomes important relative to the ability of the screed to handle the asphalt mix properly. If the strike-off is set too high, as shown in the figure, extra material is fed under the screed, causing the screed to rise. The resulting increase in the mat thickness must be overcome by manually reducing the angle of attack of the screed, using the thickness control cranks. This in turn causes the screed to pivot around its pivot points and ride with a slight nose-down-lower angle of attack. Rapid wear of the screed nose plate results. Moreover, only the front portion of the screed is compacting and finishing material being placed, and this often leads to inconsistent mat texture. In addition, the screed settles when the paver is stopped between truckloads of mix because the screed's weight is carried only on its front.

On the other hand, when the strike-off is set too low, the thickness of the lift is reduced because not enough HMA is allowed to pass under the screed. To maintain the proper mat thickness, the angle of attack of the screed must be altered, causing the screed to ride on its tail in a slight nose-up attitude. This increases the wear on the back edge of the screed and reduces the compactive effort applied by the screed. It also causes the screed to settle whenever the paver is stopped because

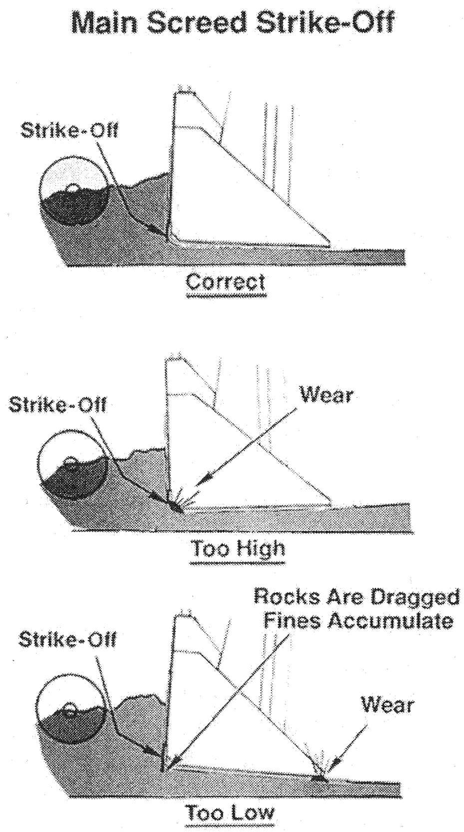


FIGURE 15-15 Proper positioning of strike-off assembly.

of the concentration of the screed's weight on a smaller surface area. The exact location of the strike-off depends on the make and model of paver being used and on the depth of the layer being placed by the paver. For relatively thin layers of pavement [25 mm (1 in.) thick or less], the strike-off is usually placed lower than when thicker lifts of mix are being placed. Similarly, for thick lifts of asphalt pavement [greater than 50 mm (2 in.)], the strike-off assembly is usually raised slightly above the normal position. In general, the strike-off is located in the range of 5 to 13 mm ($\frac{3}{16}$ to $\frac{1}{2}$ in.) above the bottom plane of the main screed plate. No compaction of the mix occurs under the strike-off.

Screed Heaters

The screed is equipped with two or more heaters or burners, depending on the age and model of the paver. The purpose of the heaters is to preheat the plate on the bottom of the screed to the temperature of the HMA being laid. The screed should be heated before paving operations begin and at any time the screed has been raised out of the mix for an extended period. The screed must be at nearly the same temperature as the asphalt material passing under it to ensure that the mix does not stick to the screed plate and tear, imparting a rough texture to the mat. A properly heated screed provides for a more uniform mat surface texture and a more consistent mat thickness.

To preheat the screed, the burners are normally operated for a period of 10 to 20 minutes before the laydown operation begins. Care should be taken to avoid overheating, which can cause permanent warping of the screed plate. Electric screed heaters are now sometimes used and tend to provide more uniform heating of the screed. Usually within 10 minutes after paving has begun, the temperature of the screed plate has increased to the point at which it can generally be maintained by the temperature of the mix passing under it. Thus the burners are not needed and are shut off. A major misconception is that the heaters can be used to heat up cold material as it passes under the screed. This is simply not true: at the very best, only the very top surface of the mix is warmed up slightly, while the bottom of the screed may be superheated to the point of warping. For the same reasons, the screed heaters should not be used in an attempt to increase the temperature of the mix sitting under the screed for a period of time while awaiting the arrival of the next haul truck.

In cool weather—during start-up when the plant is cold, the haul truck beds are cold, and the paver metal is cold—it is sometimes advantageous to start paving with the second or third truckload of mix delivered to the paver, rather than the first load produced and delivered. This second or third load of mix is typically higher in temperature than the first load and will therefore serve to heat the paver more and reduce the amount of tearing that might occur under the screed. Placing the second or third truckload of mix first can provide for a more uniform surface texture when paving must be accomplished in lower ambient temperatures.

Screed Crown Control

The screed can be angled at its center to provide for positive or negative crown. The amount of crown that can be introduced into the screed varies with the width of the screed and with the make and model of the equipment. The crown is typically adjusted using a turnbuckle device to flex the bottom of the screed and impart the desired degree of crown. When rigid extensions are used in conjunction with the screed, the crown being placed in the pavement by the paver can usually be altered as well at any of the points where the extensions are joined. If a hydraulically extendable screed is being used with the paver, the crown can be introduced not only in the center of the screed, but also at the points between the screed and the hydraulic extensions.

Most of the paver manufacturers recommend that the screed be warped slightly, from front to back in its center, to facilitate the passage of mix under the screed and to obtain a more uniform texture on the asphalt mat. This process involves setting the lead crown on the screed slightly above the tail crown on the screed. In general, there should be more lead than tail crown, but the amount of difference depends on the make of paver and the type of screed. Normally the lead crown setting is 1 to 5 mm ($\frac{1}{32}$ to $\frac{3}{16}$ in.) greater than the tail crown setting, with 3 mm (1/8 in.) being the average difference between the crown settings.

For hydraulically extendable screeds, discussed below, some paver manufacturers do not recommend setting any amount of lead crown into the front edge of the screed. Because of differences in the recommendations for different makes and models of pavers, it is suggested that the manufacturer's operation manual be consulted before the crown is set into the screed.

Screed Vibrators

The amount of compaction imparted to the asphalt mix by the screed is a function of many variables. The properties of the mix itself are important—its stiffness, its temperature, and the amount of asphalt cement and moisture it contains all affect the ability of the screed to densify the mix. The degree of compaction achieved is also affected by the amount of bearing pressure applied to the mix by the screed, as well as the thickness of the HMA passing under the screed.

Two factors within the screed itself also contribute to the degree of compaction achieved: the frequency of vibration (number of vibrations per minute) and the amplitude (amount of force) imparted by the screed. The frequency of vibration is controlled by the rotary speed of the vibrator shaft and is adjusted by turning a control valve located on the screed. Increasing the revolutions per minute of the shaft will increase the frequency of the vibration and thus the compactive effort. In general, the vibrators should be used at the highest frequency setting to obtain the maximum compactive effort from the screed.

The applied amplitude is determined by the location of the eccentric weights on the shaft. The position of the eccentric weights can be altered to increase or decrease the amount of compactive effort applied to the mix by the screed, as illustrated in Figure 15-16. Typically, the amplitude setting selected is related to the thickness of the mat being placed—lower amplitude for thinner lifts and higher amplitude for thicker lifts.

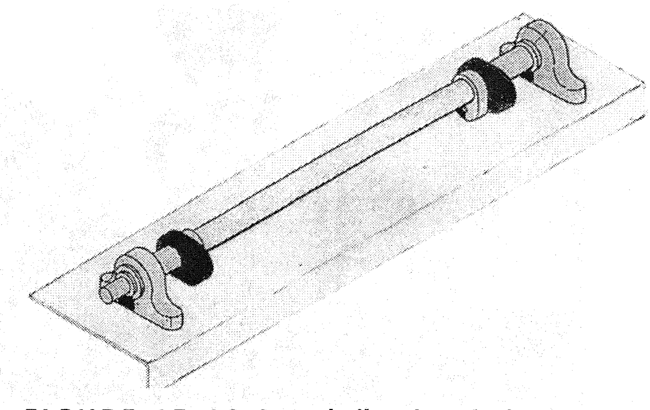


FIGURE 15-16 Screed vibration shaft with weights.

The density achieved by the paver screed is also a function of the speed of the paver. As the paver moves faster, the screed dwells for less time over any particular point in the new mat, and thus the amount of compactive effort applied by the screed decreases. It can be expected that approximately 75 to 85 percent of the theoretical maximum density of the HMA will be obtained when the mix passes out from under the paver screed.

On some paving projects, the screed is not used in the vibratory mode—the vibration is shut off. This is often done so that members of the paving crew can walk across or ride on the screed in relative comfort; it is difficult to ride on the screed all day if it is vibrating. To derive the benefits of the screed in obtaining the density of the mat, however, the screed should be operated in the vibratory mode, and the crew members should find another means of traveling along the length of the paving site.

Screed Extensions, Cut-Off Shoes, and End Plates

Rigid Extensions When the basic width of the screed [2.4 m (8 ft) for small pavers and 3.0 m (10 ft) for larger machines] needs to be changed to accommodate increased paving widths, rigid screed extensions can be used, as illustrated in Figure 15-17. These extensions come in several widths, usually 150 mm (6 in.), 0.3 m (1 ft), 0.6 m (2 ft), and 0.9 m (3 ft). To keep the paver in balance, the width of the rigid extensions added to the paver screed should be approximately equal on both sides of the machine, if possible.

It is important that the screed extensions be attached securely to the screed. Further, it is essential

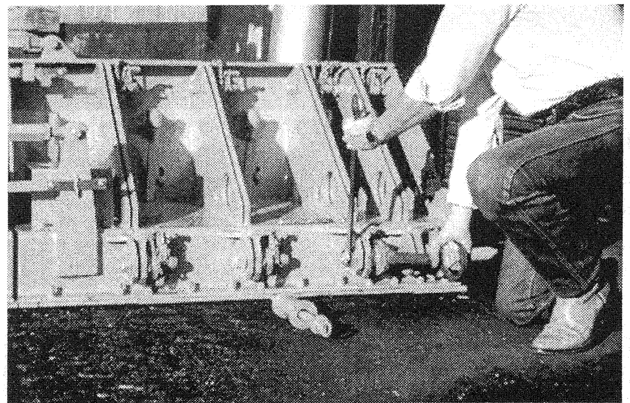


FIGURE 15-17 Rigid screed extension.

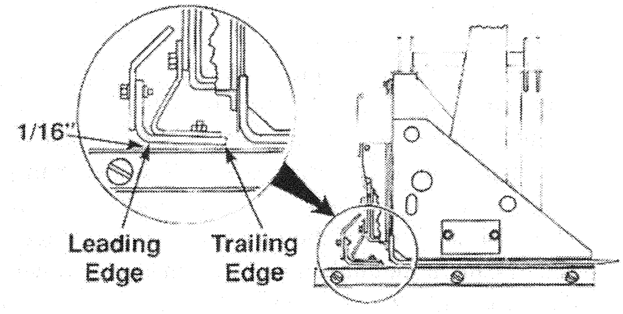


FIGURE 15-18 Strike-off extension.

that the extensions be set at the same elevation and angle as the screed to prevent the presence of a transition line or ridge at the intersection of the screed and the extensions or between the different extensions. Alignment of the front edge of an extension is typically controlled independently of the alignment of the rear edge.

Whenever a rigid extension is used on the screed, auger extensions and the accompanying auger tunnel extensions should also be used. The length of all the auger and tunnel extensions should in general be the same as that of the screed extensions to allow room between the end of the auger and the end plate of the screed. Typically, the distance between the end of an auger extension and the end plate should be about 450 mm (18 in.). Further, whenever rigid screed extensions are employed on a paver with a strike-off, a strike-off assembly must also be added to the extensions and set at the same elevation as the strike-off on the screed.

Strike-Off Extensions Strike-off extensions are often used to increase the paving width on projects that do not require an actual screed extension with heat and vibratory compaction capability. Such strike-off extensions are used for driveway and mailbox turnouts and for some types of intersection paving where variable widths are frequently encountered. Typically, this type of extension is merely a vertical blade that cuts off the mix as it passes under the strike-off unit (see Figure 15-18). In some cases, a very short section of horizontal plate is attached to the strike-off assembly.

When correctly installed and adjusted, strike-off extensions can be extended and retracted without influencing the mat directly behind the screed. When these strike-off extensions are extended, the HMA placed by the extensions must be thicker than the mix that passes under the screed because the mix laid by the extensions is not compacted as is that under the screed. The difference in the two thicknesses should be adjusted, depending on the properties of the mix being placed, so that after compaction by the rollers, no difference remains in the compacted thickness of the two portions of the mat. In addition, the mix laid by the strike-off extension will typically have a significantly rougher texture than the mix laid by the screed, as shown in Figure 15-19. Sometimes this difference in texture will remain visible even after the mix has been compacted.

It is suggested that strike-off extensions not be used for mainline paving so that the surface texture and compaction of the entire traveled width will be consistent. Thus for a typical lane 3.7 m (12 ft) wide, the screed should be extended either with rigid extensions or with a hydraulically extendable screed.

End Plates and Cutoff Shoes An end plate (or end gate or edger plate) is attached to the end of the screed to restrict the outward movement of the mix around the end of the screed, as shown in Figure 15-20. The vertical alignment of the end gate is adjustable so that mix can be bled out from under the gate if necessary. In typical operating mode, however, the end plate is positioned tight to the surface being paved to retain the mix and control the width of material being placed.

Cutoff shoes can be used, if necessary, to reduce the width of mix placed so it is less than the screed width.

FIGURE 15-19 Difference in texture under strike-off extension.

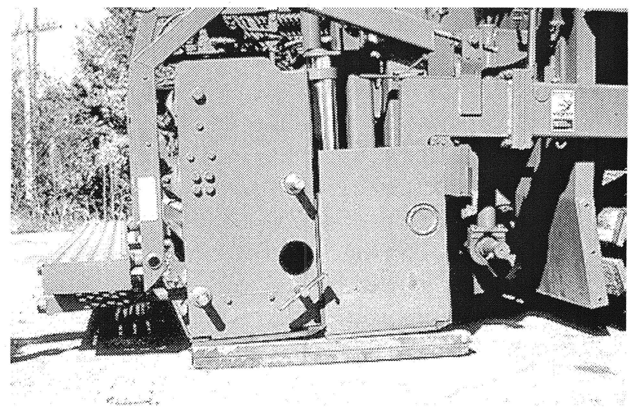


FIGURE 15-20 End plate on paver.

Standard cutoff shoes are attached to the paver end gate. Typically, the cutoff shoes come in widths of 0.3 m (1 ft) or 0.6 m (2 ft) and are adjustable in increments of 37 mm (1½ in.) or 75 mm (3 in.), depending on the paver manufacturer.

Hydraulically Extendable Screeds Most paver manufacturers have developed hydraulically extendable screeds that trail the main screed on the paver. One make of pavers, however, is equipped with an extendable screed that places the extendable portion of the screed in front of the main screed. An example of an extendable screed is shown in Figure 15-21.

For all hydraulically extendable screeds, it is important that the height and the angle of attack of the extendable screeds (on each side of the main screed) be properly set. If the extensions on the extendable portion of the screed are not properly aligned with the main screed, a longitudinal mark or ridge will occur in the surface of the mix at the junction between the two screeds, indicating a difference in thickness. This mark can easily be eliminated by adjusting the elevation of the extendable screed in relation to that of the main screed. In addition to the longitudinal mark, a mismatch in elevation between the two screeds can result in a difference in surface texture, as well as a difference in the degree of compaction obtained. For front-mounted extensions, the extendable screed is usually set at a height slightly below the main screed. For rear-mounted extensions, the height of the extendable portion of the screed is normally set at the same height as the main screed, but the extensions usually have a slightly more positive attack angle as compared with the main screed. In general, however, the forces that act on the extendable screeds and the main screed are similar.

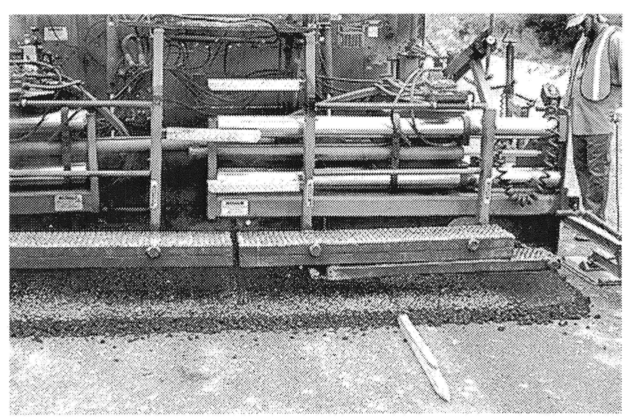


FIGURE 15-21 Hydraulically extendable screed.

Further, if a strike-off assembly is used on the main screed, similar strike-off devices should be used on the extendable screed sections.

If a front-mounted hydraulically extendable screed is to be used at a fixed extended width for a period of time, the paver should be equipped with auger extensions equal to the width of the extended screed and ending approximately 450 mm (18 in.) from the end plate. Use of these auger extensions will enhance the distribution of the asphalt mix across the width being paved and help maintain a constant head of material pushing on the entire width of the screed. Auger tunnel extensions should also be added to the paver.

For pavers equipped with a rear-mounted hydraulically extendable screed, auger extensions often are not employed even when the screed will be used at a fixed extended width for a period of time. If auger extensions are used on such pavers, an excess of mix may build up in front of the screed extensions, as shown in Figure 15-22. This condition may result in several problems with the mat behind the screed, such as nonuniform texture and variable mat thickness, and therefore should not be allowed to occur. With rear-mounted extensions, the HMA material will naturally flow out to the end of the screed without assistance from auger extensions. In addition, without auger extensions, less mix will typically be carried in front of the extendable section of the screed. For rear-mounted extensions, the material feed sensors must be mounted on the end gate of the screed to limit the amount of mix carried in front of the extendable portion of the screed.

If a hydraulically extendable screed—especially a front-mounted extension—is to be employed where the width being paved changes frequently, some paver manufacturers recommend that the machinery be equipped with kickout paddles or augers at the end of the main auger. This device helps push the mix out to the end of the extendable screed and keeps the head of material in front of the screed as constant as possible. Other pavers are equipped with augers that extend automatically as the screed is extended. For either type of paver, the material feed sensors should be mounted on the end gate of the screed to ensure that an adequate amount of material is delivered to the outside edge of the screed.

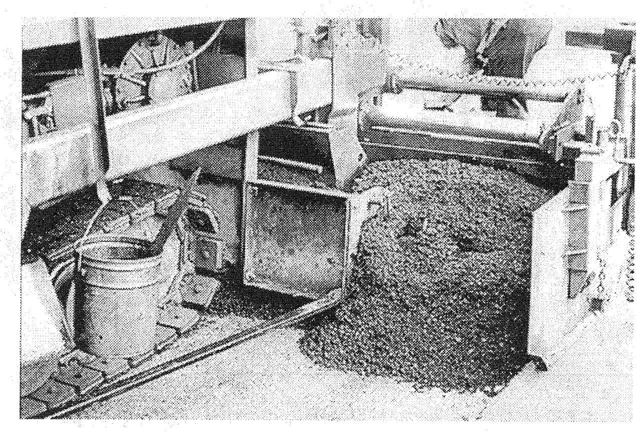


FIGURE 15-22 Buildup of excess mix in front of extended screed.

SUMMARY

The following key factors should be considered in monitoring mix placement operations:

- If the mix is being delivered by a haul truck that dumps it directly into the paver hopper, the truck should stop just short of the paver. The paver should be moving forward when it comes in contact with the truck—the paver should pick up the truck instead of the truck backing into the paver. When raised, the bed of the haul truck should not rest on any portion of the paver.
- Before the tailgate on the haul truck is opened to deliver mix to the paver hopper, the truck bed should be raised slowly until the mix in the bed moves against the tailgate. This procedure allows the mix to move in a mass into the paver hopper when the tailgate is opened and reduces the amount of segregation behind the screed. If the tailgate-opening lever cannot be reached when the truck bed is raised, it should be modified to allow for operation from ground level when the bed is raised.
- If a windrow elevator is used to gather mix from a windrow on the roadway and deliver it to the paver hopper, the slat conveyors should pick up essentially all of the mix that is in the windrow, leaving none on the existing surface. For the placement of a leveling course, it may be necessary to leave some minimum amount of mix on the pavement surface under the windrow elevator because of the unevenness of the existing pavement surface.
- The windrow should be sized so that the amount of mix in the paver hopper is always above the top of the flow gates or the tunnel openings.
- When a paver must be stopped to wait for trucks, it should be stopped as quickly and smoothly as possible. Enough mix should remain in the paver hopper to be at least at the level of the top of the flow gates or tunnel openings. In no case should the hopper be emptied to the point that the slat conveyors at the bottom of the hopper are visible. The slat conveyors also should never

be visible when a windrow elevator or MTV is used to deliver mix to the paver hopper. The amount of mix in the hopper should be consistent so that the head of material in front of the paver screed remains constant.

When the paver is stopped to allow the next truckload of mix to move into position, the wings on the paver may be folded, but only when necessary to prevent buildup of cold mix in the hopper corners. The wings should not be banged repeatedly as they are emptied. The wings should be dumped into a relatively full paver hopper: the amount of HMA in the hopper should be above the top of the flow gates or tunnel openings when the wings are emptied. Dumping the wings into a relatively full hopper may result in some mix spilling out of the front of the hopper; overflow guards should be used to contain as much mix as possible.

Once a new truckload of mix has begun to be emptied into the hopper, the paver should be brought up to paving speed as quickly as feasible and operated at a constant speed in accordance with the amount of mix being delivered from the plant. This practice will keep the head of material in front of the screed as constant as possible.

The paver should not be operated at a slower-than-normal speed while the truck exchange is being completed. If the paver continues to move forward while one truck is leaving and the next is moving into delivery position, the amount of mix in the hopper will be drawn down, possibly to the point that the hopper is emptied. This procedure will cause the amount of mix at the augers to be reduced, in turn causing the angle of attack of the screed and thus the thickness of the mat to decrease. Reducing the speed of the paver from normal paving speed to crawl speed between truckloads will also change the forces acting on the screed, further altering the thickness of the asphalt layer. In addition, when the newly delivered mix is emptied into the hopper and pulled back to the augers by the slat conveyors, the large mass of mix (head of material) against the screed will cause the screed to rise, increasing the thickness of the mat. Thus slowing the paver down between truckloads of mix while emptying the hopper should be avoided because it causes significant changes in the forces acting on the screed and accompanying changes in the thickness of the layer being constructed.

The flow gates on each side of the machine on the back of the paver hopper should be set at a height that permits the slat conveyors and corresponding augers to operate as close to 100 percent of the time as possible. The key to a smooth layer of mix is maintaining a constant head of material in front of the screed. The key to a constant head of material is a constant paver speed and continuous operation of the paver augers.

If the paver is equipped with automatic flow control devices, that equipment should be set at a location near the end plate in order to maintain a constant head of mix in front of the screed by keeping the auger running continuously. The location of the device is important to preventing too much or too little mix from being carried at the outside edge of the screed.

If the paver screed is being operated under manual control, the screed operator should not change the angle of attack of the screed by turning the thickness control cranks except to increase or decrease the thickness of the layer being placed. Once the controls have been turned, it takes at least five times the length of the tow arm on the paver before the screed completes the input change in thickness. If the paver is being operated under automatic grade and slope control, the screed operator should not attempt to change the angle of attack of the screed by turning the thickness control cranks at all.

SECTION

16 Automatic Screed Control

As discussed in Section 15, the screed unit on the paver is attached to the tractor unit at only one point on each side of the paver, called the tow (or pull) point. As the tractor follows the existing grade with its rubber tires or crawler tracks, the length of the paver wheelbase becomes the reference for the screed. Because of the reaction time required for the screed, the screed will respond more slowly to changes in grade than will the tractor. Thus under manual screed control (covered in Section 15), the screed will average out deviations in the roughness of the underlying pavement layer, placing more mix over the low points and less mix over the high points in the existing pavement.

Automatic screed controls are used to keep the elevation of the tow points on the paver at a predetermined elevation relative to the reference (either a preset stringline or a long mobile ski). Deviations in the pavement surface are averaged out over the length of the reference. As the tractor unit moves up and down over the existing grade, the elevation of the tow points moves over a smaller range than would be the case if the relatively short wheelbase of the tractor provided the reference. Keeping the elevation of the tow points constant in direct relationship to the reference permits the screed to maintain a more consistent angle of attack, which in turn provides for a smoother mat behind the screed. It should be noted, however, that many factors affect the smoothness of the mix placed by the paver. The use of automatic screed controls by itself does not ensure that the mat constructed will be smooth. Proper attention to the operation of the paver, as discussed in Section 15, is extremely important to obtaining a smooth-riding pavement layer.

MANUAL VERSUS AUTOMATIC SCREED CONTROL

If the paver always moved over a level grade, the forces on the screed would be constant as long as the paver was moving at a constant speed and there was a consistent head of material in front of the screed. The towing force on the screed would be stable and the head of material in front of the screed consistent as long as the feed control system was set to operate as much of the time (close to 100 percent) as possible. Under these conditions, a very smooth asphalt mat could be obtained from behind the paver without the screed operator ever changing the setting of the thickness control cranks on the back of the screed. Indeed, once the angle of attack of the screed had been set when the paver started up in the morning, no changes to the setting of the thickness control cranks would ever be needed.

In the real world, however, the tractor unit operates over a variable grade. As the elevation of the existing surface moves up and down, the wheelbase of the tractor unit follows that grade (see Section 15). This vertical movement of the tractor as it moves forward causes the elevation of the tow points on the tractor to change in direct relation to the movement of the tractor unit. As the location of the tow points is thus altered, the angle of attack of the screed changes.

If the elevation of the tow points is raised, the screed will be rotated upward relative to the change in elevation of the tow points. As the paver moves forward a distance equal to at least five times the length of the leveling or tow arms on the machine, the screed will float up to the new elevation, and the asphalt mat placed will be thicker. If the tractor unit moves into a dip in the existing pavement surface, the elevation of the tow points will be lowered, reducing the angle of attack of the screed. If no other changes are made in the forces acting on the screed, the screed will move downward as the paver travels forward, lessening the thickness of the layer being placed.

The self-leveling action of the screed takes place continuously as the tractor unit travels over the roadway. The thickness of the mat being laid is determined by the reaction of the screed to the location of the tow points, the speed of the tractor, and the head of material in the auger chamber. The entire operation occurs without the thickness control cranks on the screed ever being changed. The floating-screed principle permits the paver to reduce the thickness of the mix placed on high points in the existing pavement surface and to increase the depth of the material deposited on low points.

If the thickness control cranks or handles are turned by the screed operator, the screed will react (change its angle of attack) by rotating around the hinge or pivot points where it is attached to the leveling arms and thus to the tow points of the screed. As the paver moves forward, the screed will float up to or down to the new elevation. As with a change in elevation of the tow points on the leveling arms, the paver must travel forward a distance of at least five lengths of the leveling arms before the change in the depth of the mat is fully realized.

On many projects, particularly those involving the resurfacing of an existing pavement, the screed operator is forced by the job specifications to maintain a certain yield of asphalt mix per square yard or per station. It is not uncommon to see a screed operator continually checking the thickness of the mat being placed by the paver and adjusting the setting of the thickness control cranks to increase or decrease the amount of mix being placed. These changes in the setting of the thickness control system are made without regard to the simultaneous changes to the screed as the elevation of the tow points changes while the tractor unit moves forward over the variable grade.

Two inputs, then, are being provided to the self-leveling system at the same time. The first is the vertical movement of the tow points of the screed in reaction to changes in the movement of the paver wheelbase. The second is the screed operator's manual changing of the thickness control cranks, illustrated in Figure 16-1. These two inputs may be in the same direction, or they may be in opposite directions, even canceling each other out.

Under manual screed operation, the ability of the screed operator to produce a consistently smooth asphalt layer is dependent on a number of factors. The first is the frequency at which the operator adjusts the setting of the thickness control cranks: the more the screed operator changes the angle of attack of the screed, the more uneven the resulting pavement will be. The second factor is the roughness of the existing pavement surface: the more the screed operator tries to assist the self-leveling action of the screed, the rougher the resulting pavement surface will be. Third is the need to meet a certain maximum yield specification. It is difficult, particularly for thin courses, to produce a smooth pavement layer while staying within a certain volume of material usage. This is particularly true if a minimum overlay thickness is specified along with the yield criteria. This problem is discussed in detail later in this section. The fourth factor is related to the screed operator's need to match the elevation of the longitudinal joint in the adjacent lane. As paving speeds have increased because of higher plant production rates, it has become more difficult to manually maintain the level of the new mat relative to the adjacent mat.

When it is desired to produce a constant cross slope across the width of the lane being paved, automatic grade and slope controls can be used to control the elevation of the tow points of the screed on both sides of the paver at the same time. This is very difficult to do manually, even with two experienced screed operators. A grade control can be used on both sides of the machine; more commonly, a grade control is used on one side of the paver and a slope control on the other.

The primary purpose of automatic screed controls is to produce an asphalt pavement layer that is smoother than the paver can accomplish by itself using only the wheelbase of the tractor unit and the free-floating screed, and smoother than a screed operator can achieve by continually changing the setting of the thickness control cranks. As noted, automatic screed controls function by maintaining the elevation of the screed tow points in relation to a reference other than that of the wheelbase of the paver itself. That reference is typically longer than the wheelbase of the tractor unit. Figure 16-2 illustrates a screed and attached ski.

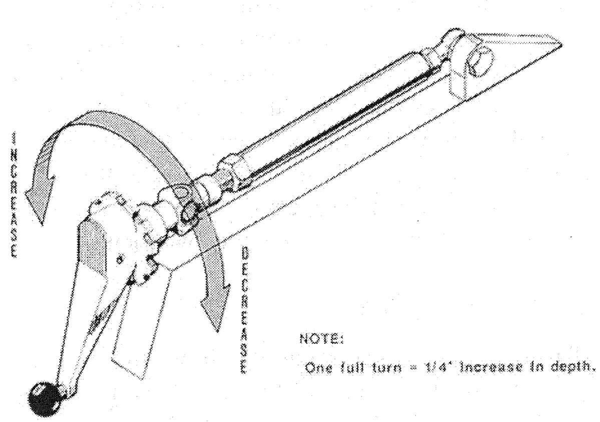


FIGURE 16-1 Thickness control crank.

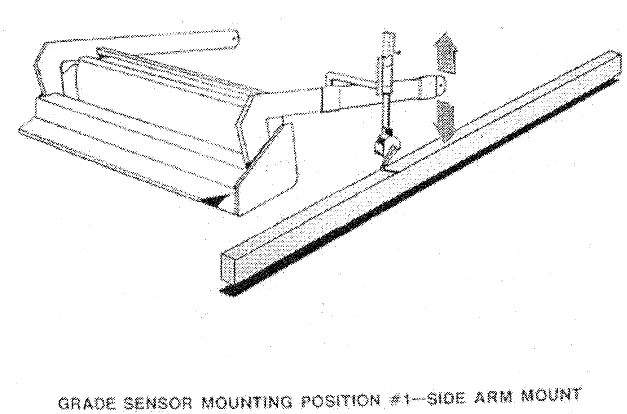


FIGURE 16-2 Screed and attached ski.

The elevation of the tow points is kept constant in relation to a given grade reference. The automatic system does not permit the relative position of the tow points to change even though the tractor unit is moving up and down vertically in response to the roughness of the surface over which it is traveling. By maintaining the tow points at a constant elevation, the angle of attack of the screed is also maintained at a constant setting. This allows the screed to ride at a consistent angle, permitting it to do an even better job of reducing the quantity of mix placed over the high spots in the existing pavement surface and increasing the amount of mix laid in the low spots.

Before the automatic screed control is engaged and before paving starts, the screed should be "nulled" (i.e., angle of attack set at a flat or zero angle position). Once the paver is moving, the proper angle of attack should then be set for the thickness being placed, and the control engaged. If automatic controls are being used on the paver, the screed operator should not try to change the angle of attack of the screed manually by turning the thickness control cranks. If such an attempt is made while the machine is moving, the automatic grade and slope controls will attempt to compensate for the manual input by changing the elevation of the tow points. Manual input will be needed only if the tow point actuator (hydraulic ram) has reached the limit of its travel—if the tow point ram is at its upper or lower limit. In this case, the paver should be stopped and the tow arm reset at the centerpoint of its length of travel. The screed should be nulled, the paver restarted, and the proper angle of attack input to the screed before paving continues.

Note that when a superelevated curve that requires a change from the existing cross slope is being paved, it is necessary to run the grade sensor on one side of the paver automatically and the slope sensor on the other side of the paver manually. This practice allows changes to be made in the amount of superelevation and provides the required degree of cross slope.

GRADE CONTROL

Types of Grade References

Grade sensors are used to monitor the elevation of the existing pavement surface in a longitudinal direction. Three basic types of grade references can be used to maintain the elevation of the screed tow points: (*a*) erected stringline, (*b*) mobile reference or ski, and (*c*) joint matching shoe. On some paving projects with proper sight distance, such as an airport runway or large vehicle test pad, a laser system can also be used.

Each type of grade reference can be used alone on either side of the paver; each can also be used on both sides of the paver at the same time. The same type of grade reference can be used on both sides of the machine, or a different type can be mounted on each side. For example, a preset stringline can be used on one side and a mobile reference on the other. This use of double grade references makes it possible to average out the variations in the profile of the existing pavement surface on both sides of the lane being paved. However, use of double grade references generally will not produce a uniform cross slope for the new asphalt layer unless a preset stringline is used on both sides of the laydown machine. An effective approach is to combine the use of grade and slope controls. When a grade reference is used in conjunction with a slope control device, the grade sensor is typically positioned on the centerline side of the paver, with the slope control determining the depth of the mat on the outside edge of the pavement.

The grade sensor or wand is in contact with the reference in all but sonic systems. As the grade of the reference changes, the wand senses that change and sends an electrical signal to the control panel on the paver. A signal is then sent, in turn, to the tow points on either side of the paver, and their elevation is changed relative to the change sensed by the grade sensor.

If a sonic or noncontact system is used, a sound pulse is sent out from a transducer toward the reference—stringline, mobile reference, or existing pavement surface. When the sound pulse hits the reference, a portion of that pulse is reflected back to the transducer, which also acts as a receiver. The time required for the sound to travel to the reference and back is measured, and the distance is calculated on the basis of the speed of sound. Thus the elevation of the tow points is controlled without the sensor actually coming in contact with the reference itself. On one sonic system, a "working window" is used to prevent the system from making a major change in the elevation of the tow points when a false signal is received. This window is plus or minus 61 mm (2.4 in.) from the elevation of the reference. If the distance measured by the sonic system is greater than the window range, the control of the grade sensor is switched to manual, and no changes are sent to the tow points.

Erected Stringline

The use of an erected stringline, shown in Figure 16-3, provides for placement of the smoothest possible asphalt mat behind the paver screed. The stringline can be made of wire or nylon cord. This method of supply-

FIGURE 16-3 Stringline for grade control.

ing elevation input provides the most consistent reference for the paver tow points, enabling a predetermined grade to be matched very accurately if the controls are used properly.

In application, the use of an erected stringline has a number of drawbacks that may offset the increased smoothness obtained. First, the elevation of the erected stringline must be set by a surveying crew. The accuracy of the elevation of the line and the resulting pavement smoothness are directly dependent on the care taken during erection. If the grade set by the surveyors is incorrect in any way, the paver screed will duplicate that error in the pavement surface. On horizontal curves, it is very difficult to use an erected stringline to control the grade of the new pavement layer. Since the string cannot be set in a curve, a series of chords must be used to simulate the radius of the curve. This in turn requires the positioning of a large number of support posts and rods, usually at intervals of 1.5 to 6.0 m (5 to 20 ft), around the curve.

The stringline must also be very taut when it is set. Typically, the string is supported at intervals of 8 m (25 ft) on metal posts and rods. The string or wire is first anchored at one end of its length and then pulled tight and anchored at the other end. It is extremely important that there be no dips or sags between the support rods. If the string is not stretched tightly, the sensor wand on the paver, which can run either atop or below the stringline, will react to the sags in the line and duplicate those sags in the new pavement surface. Even when high-strength line is used, it is not always possible to keep the line tight enough to prevent small sags from occurring.

It should be noted that any sags in the stringline will not be duplicated at the exact same longitudinal location in the pavement surface because of the delay in the reaction time of the screed once an input has been made to the elevation of the tow points (see Section 15). As the grade sensor travels over the dip in the stringline, the elevation of the tow points changes. The paver must travel a distance equal to five times the length of the tow arm, however, before the change in the mat thickness is fully completed. Thus any sag in the stringline will be manifested in the pavement surface, but at some length down the roadway from the position of the sag in the stringline.

Another disadvantage of the erected stringline is that the haul trucks and all paving personnel must keep away from the line and not disturb it in any way. Once the line has been set at the proper elevation, it must remain untouched both before and after passing of the paver sensor over the line. Any change in the elevation of the line will result in a change in the input to the grade sensor and movement of the tow points on the paver leveling arms.

With a properly set and maintained stringline, the mat placed by a paver equipped with automatic screed controls can be very smooth and at the correct elevation, primarily because of the extended length of the reference being used as compared with the more limited length of a mobile reference. However, unless smoothness or compliance with a predetermined grade reference is extremely important, as with an airport runway where a consistent longitudinal and transverse profile is required, it is questionable whether the added expense of erecting and maintaining a stringline is cost-effective for the typical HMA paving job. Thus for the vast majority of highway paving projects, an erected stringline is not used.

Mobile Reference

The various paver manufacturers use different types of mobile reference devices to extend the relative wheelbase for the automatic screed control system. The operation of these reference systems, however, is essentially the same. The purpose of the mobile reference is to average the deviations in the existing pavement surface out over a distance that is greater than the wheelbase of the tractor unit itself.

One version of a mobile reference employs a rigid tubular grade reference (pipe) that is 6.1, 9.1, or 12.2 m (20, 30, or 40 ft) in length, as seen in Figure 16-4. For this version, the pipe or tube rides directly on the existing pavement surface. A spring-loaded wire is typically stretched along the ski on top of the pipe. The grade sensor that inputs the electrical signal to the paver tow points rides on top of the wire. As the ends of the pipe move up and down over the existing grade, the stretched wire on the ski is used to average out the differences in elevation that occur under the mobile reference.

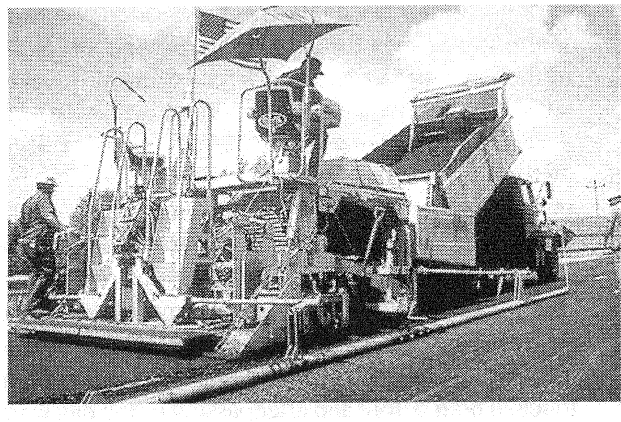


FIGURE 16-4 Paver with mobile reference employing rigid pipe.

The primary problem with the use of a rigid pipe or any rigid reference is the fact that if a singular high point is present in the pavement under the reference, the front end of the pipe will ride up over the hump until the midpoint on the length of the pipe is reached. At that time, the pipe will break over, and its front end will tip downward, like a seesaw. That change in slope will continue until the back end of the reference is off of the high point. The bump duplicated in the mat behind the paver may be more pronounced than it would have been if a floating-beam reference had been used.

A floating-beam mobile reference consists of a series of feet or shoes attached to the bottom of a beam, as shown in Figure 16-5. One or more of the feet can pass over a singular high or low point in the existing pavement surface without altering the slope of the entire beam. The feet are spring loaded so they can be deflected by a large stone on the pavement surface, for example, without pushing the whole beam upward. The grade sensor usually rides directly on the beam at its midpoint. As with the other types of mobile references, this floating-beam system averages out the variation of the existing grade over a 9.1- or 12.2-m (30- or 40-ft) distance.

Another type of floating-beam mobile reference system is illustrated in Figure 16-6. The beam is normally 9.1 or 12.2 m (30 or 40 ft) in length. Instead of multiple feet spread out along the length of the beam, however, a series of shoes is placed at each end of the beam. These shoes are allowed to rotate and can be individually displaced by isolated disruptions in the existing pavement surface without changing the elevation of the entire beam. Thus the beam can average the grade of the surface over the length of the reference without being influenced by the presence of a single high point or dip.

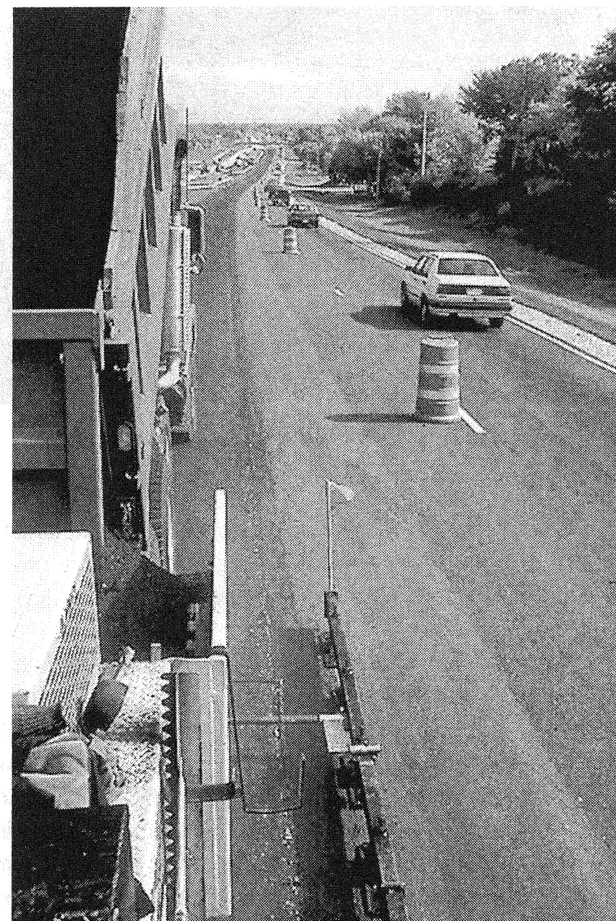


FIGURE 16-5 Floating-beam mobile reference.

On mobile reference systems other than the floating-beam type, the grade sensor should be located in the center of the length of the beam to ensure that the input to the paver tow points will be made equally over the length of the reference. If the grade sensor is not located in the center of the length of the mobile reference, the ski will not average out the changes in elevation in the existing pavement surface uniformly. As suggested earlier, the ski can be thought of as a seesaw, and the location of the grade sensor can be regarded as similar to the seesaw's pivot point. If the sensor is offset (closer to one end of the ski than the other), a change in elevation at the longer end of the reference will be magnified and result in a greater input change to the elevation of the tow points. Conversely, a change in elevation on the shorter end of the ski will result in a lesser change in the location of the screed tow points. Thus, except for unusual circumstances, the grade sensor should be located in the center of the length of the ski.

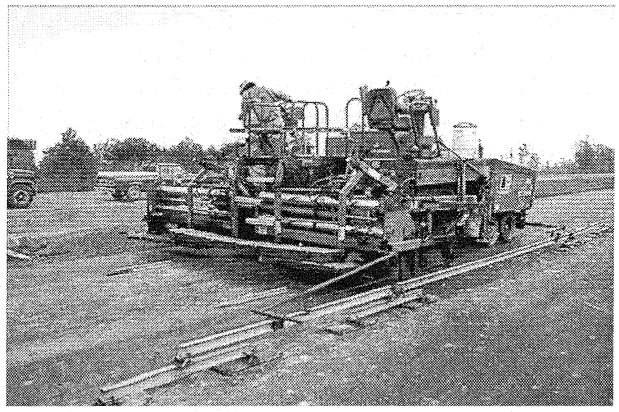


FIGURE 16-6 Floating-beam mobile reference with shoes at ends of beam.

Of the mobile reference devices described above, the floating-beam type with multiple feet or shoes typically results in a smoother pavement because of its ability to ignore isolated deviations in grade (a rock on the roadway, for example). Moreover, the longer the grade reference used, within reason, the better the paver will average out variations in the elevation of the existing pavement surface. A mobile reference will not, however, ensure that the mix being placed is at the proper elevation. The elevation is controlled by the elevation of the underlying pavement surface and the thickness of the mat being laid.

One paver manufacturer has produced a mobile reference ski that is 16.8 m (55 ft) in length from front to back, termed an over-the-screed reference (see Figure 16-7). On this device, part of the reference beam is located in front of the screed. This portion of the reference is basically a floating-beam system, equipped with a series of spring-loaded shoes, that senses the grade of the existing pavement surface. To the rear of the screed, riding on a series of spring-loaded wheels or large shoes, is another floating beam that is used to reference the grade of the newly placed asphalt mix. A set of intermediate bridge beams that extends up and over the screed is used to join the two parts of the floating beam. The grade sensor rides on one of the intermediate bridge beams and transmits the average grade of the front and back beams to the paver tow points to control their elevation.

Another version of the over-the-screed reference is available. On this device, the front ski consists of a floating beam in front of the screed that rides on the existing pavement surface. Another floating beam rides on the newly placed mat behind the screed. Instead of the bridge beams connecting the two beams, however, a stringline or wire is used. The grade wand rides on the stringline and senses the average change in grade between the front and back reference beams.

Because of its greater length relative to the other types of reference, the over-the-screed reference provides for a smoother mat. In addition to the greater length of the reference, however, the fact that the rear ski rides on the new mix is also important for smoothness. Since the new mat should be significantly smoother than the existing pavement surface, the average variation sensed by the grade wand is limited, resulting in fewer changes to the elevation of the tow points as the paver moves down the roadway. This device may not be practical, however, in hilly terrain or on pavement that has a large number of vertical curves.

Joint-Matching Shoe

The joint-matching shoe, shown in Figures 16-8 and 16-9, consists of a short shoe or ski [approximately 0.3 m (1 ft) long] that is used to reference the grade of an adjacent pavement lane. This type of mobile reference is used only when the grade being sensed is relatively smooth. The shoe rotates around its own pivot point and when displaced supplies an electrical input signal to the paver tow points. The shoe should be checked to ensure that it is free to rotate properly.

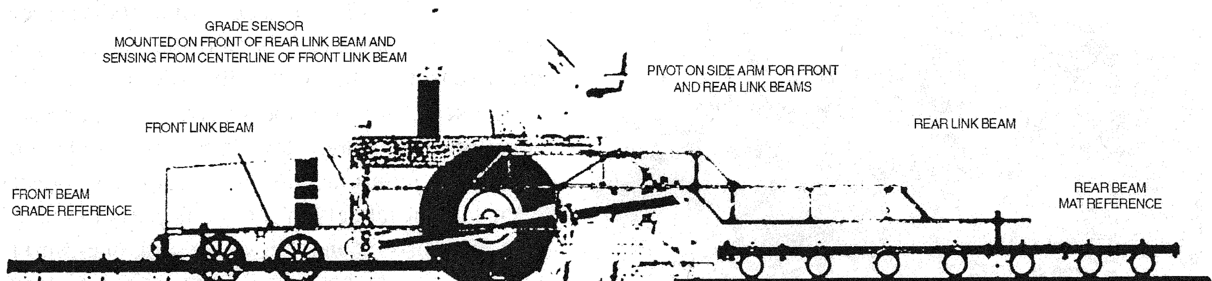


FIGURE 16-7 Over-the-screed reference.

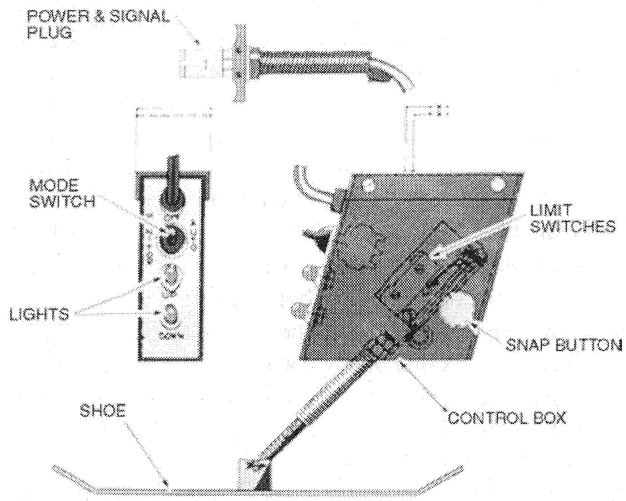


FIGURE 16-8 Shoe for matching joints.

Because of its short length, the joint-matching shoe will not significantly reduce major variations in the pavement surface. Indeed, the purpose of the shoe is to duplicate the grade of the adjacent surface. This grade-control device should be used with caution because pebbles, rocks, and other obstructions over which the shoe may ride will result in grade changes being input to the screed tow points. Further, because of the delay in the reaction of the screed once the tow point elevation has been changed (see Section 15), the input from the pavement surface over which the joint-matching shoe is passing will not be duplicated at the same longitudinal location in the new pavement surface. The joint-matching shoe thus does not truly match the joint. However, if the shoe is placed at the tow point, the screed is about 1 baseline length behind the shoe, and 63 percent of any thickness change will occur when the screed arrives at the point where the shoe called for the change.

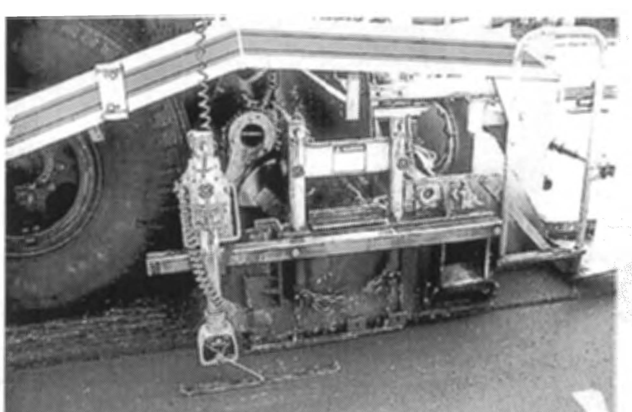


FIGURE 16-9 Operation of joint-matching shoe.

When placing the second lane of a base course or a binder course layer, it may be better to use a longer mobile reference [a ski 9.1 m (30 ft) long] instead of a joint-matching shoe. The mobile reference will provide better input for constructing a smooth pavement surface than will the joint-matching shoe. For a surface course layer, however, the joint-matching shoe may be used to ensure that the elevation of the mix on both sides of the longitudinal joint is the same, although the use of a longer mobile reference is still better paving practice.

Lasers

Laser technology has been used successfully on a number of paving projects. For locations where the sight distance is adequate and the pavement being placed has a constant slope, a laser system can be employed to control the elevation of the tow points on the paver. A transmitter sends a laser signal to a receiver unit on the laydown machine. This signal controls the grade of the mat by regulating the tow point location in relation to the laser beam. When used properly, the laser grade control system is capable of providing a very smooth mat behind the paver. To keep the tow points from moving randomly if a haul truck or other object passes through the laser beam, a delay is built into the control system so that the beam can be interrupted briefly without changing the position of the tow points.

Location of Grade Reference

The various paver manufacturers make different recommendations regarding placement of the grade-control sensors. In the past, it was often suggested that the sensor be mounted adjacent to the tow point on the side(s) of the paver on which the grade control was being used. Because of the delayed reaction time of the screed, however, it has been found that a better place to mount the grade sensor is either part of the way up the leveling arm of the screed or near the screed. The grade sensor is sometimes hung at the tow point when used in conjunction with a joint-matching shoe, but it is suggested that, even with the latter type of reference, a better place to locate the sensor is on the leveling arm, one-third to two-thirds of the way between the tow point and the screed.

The tow arm or side mounting position typically is recommended when long vertical deviations in the present pavement surface need to be corrected. When the sensor is located on the leveling arm, less time is required to react to changes in grade, and the angle of attack of the screed is altered quickly. On some occasions, particularly for wide paving, it is best to mount the grade sensor near or on the paver screed. To function properly, the sensor must be located in front of the pivot or hinge point of the screed.

The location of the grade sensor makes a difference in the reaction of the tow points and the screed to the grade being sensed. There is no set rule, however, for the proper location in which to place the grade sensor. It is recommended, therefore, that the paver manufacturer's suggested placement be used. If no location is suggested, it is recommended that the sensor be hung on the leveling arm, at a point one-third to two-thirds the length of the arm between the tow point and the screed.

The operation of the grade-control sensor should be checked regularly. The sensor wand should be lifted a very short distance, less than 3 mm (⅛ in.), when the machine is stopped and the movement of the tow points is observed. Manually moving the sensor should result in a corresponding movement of the tow points. If the wand is raised or lowered and the actuator or ram does not move, either the system is turned off, or the sensitivity of the sensor is set too wide. In the latter case, the dead-band range or the sensitivity setting is too great.

When the paver is moving, the up and down lights on the grade sensor should blink to indicate that a signal is being sent to the tow point actuator. If the grade sensor uses a meter instead of lights, the reading on the meter should change when the sensor wand is moved, as well as when the paver is placing mix on the roadway. In addition, the elevation of the tow points should change occasionally, depending on the roughness of the existing pavement surface, so that the angle of attack of the screed will remain constant as the tractor unit follows the underlying pavement grade. The change in elevation of the tow points, however, should be smooth. The tow points should not be moving up and down rapidly or constantly as the paver travels forward.

SLOPE CONTROL

As noted earlier, paving that is done with automatic screed controls is usually accomplished with a combination of grade control on one side of the paver and slope control to determine the grade on the other side of the machine. The slope control operates through a slope sensor that is located on a cross-beam between the two side arms of the screed. One side of the screed is controlled by the grade sensor, while the other is controlled by the slope controller. In almost every case, the inside or centerline edge of the mat is controlled by grade and the outside edge by slope, because it is much more difficult to subsequently match the centerline joint if slope control is used on that side of the paver.

When slope control is used, the thickness of the mat on the side of the machine that is controlled by the slope sensor may be variable in depth, depending on the condition of the existing pavement surface. The desired degree of cross slope is dialed in to the slope controller, shown in Figure 16-10. This cross slope is then regulated by a pendulum device that is part of the slope-control system. Without regard to the grade of the existing pavement, the slope controller maintains a constant cross slope regardless of the resulting thickness of the asphalt layer placed. If there is a high point in the present pavement surface, the slope controller causes the screed to place less material over that location; if there is a low point in the existing pavement, the slope controller causes the screed to deposit more mix in that location. It is good practice to check the slope of the lane routinely with a carpenter level or other method (Figure 16-11).

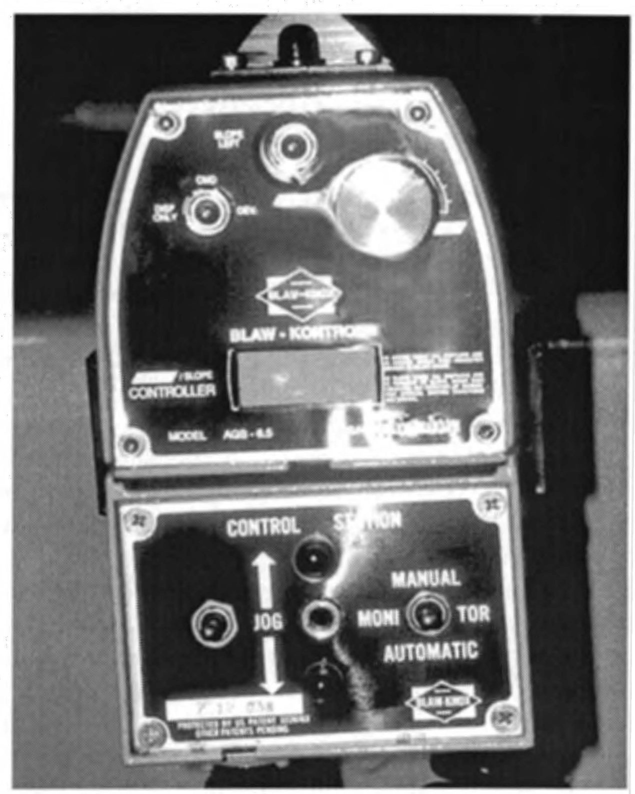


FIGURE 16-10 Slope-control device.

FIGURE 16-11 Checking slope of mat surface behind paver.

For a wide pavement, such as an airport runway, it is good practice to check the elevation of the outside edge of the mix being placed after two passes of the paver in the longitudinal direction. If the slope is not set properly or the slope sensor setting is changed accidentally, the error may be compounded in the slope setting all the way across the pavement. The result may be a very thick or very thin layer of mix on the edge of the runway. Use of one or more stringlines across a wide pavement can help provide the proper cross slope.

YIELD, MINIMUM THICKNESS, AND SCREED CONTROLS

The paving specifications for HMA overlay projects are written in a variety of ways. The specifications may call for a minimum thickness of mix to be placed. In such cases, it is usually necessary that the paver place a mat thickness that is greater than the minimum depth required in the contract for the minimum thickness specification to be met at all points in the pavement layer. The amount of extra thickness depends on the roughness of the existing pavement: the more uneven the surface being paved, the greater will be the volume of mix needed to ensure compliance with the minimum thickness requirement.

To illustrate, if the existing pavement is relatively uneven and a minimum HMA overlay thickness of 25 mm (1 in.) is required, the paver thickness-control system must be set to place an average depth of uncompacted HMA of approximately 38 mm (1½ in.). This means the angle of attack of the screed must be such that the average thickness placed will ensure the minimum depth of mix over all the high spots in the pavement surface.

A second type of specification calls for placement of a given amount of mix, in terms of kilograms of mix per square meter (pounds of mix per square yard), over the pavement surface area. In this case, the thickness requirement is an average, not a minimum, depth. If the specifications for a project call for placement of 60 kg of mix per m^2 (approximately 110 lb per yd^2) or approximately 25 mm (1 in.) of compacted thickness for an HMA mixture, the paver screed need not be set at as great an angle in order to place the mix to an average compacted depth of 25 mm (1 in.), as compared with a minimum specification thickness of 25 mm (1 in.).

The paver screed, if left to operate without human intervention on the thickness-control cranks and running either with or without automatic controls, will typically overyield mix. This means the paver will require more material than would otherwise be expected in order to react to variations in the grade of the existing pavement and to place less mix on the high spots and more on the low spots. To meet the yield requirement, therefore, it is usually necessary to reduce somewhat the thickness of the mat being placed, and this means that any minimum thickness requirement will not be met.

Conversely, if the paver is allowed to operate on its own, the machine will be able to place a smooth mat, but the amount of mix required will typically be greater than plan quantity. In this case, an extra quantity of mix must be available beyond that calculated from the length, width, and thickness of the paving project area. Such an operation will thus not be practical for a project with a yield specification.

An additional problem with a yield specification is the longitudinal distance used to determine the yield value. In some cases, yield is checked after every truckload of mix. This frequency of checking often leads to continual changes in the thickness-control cranks on the paver. Yield should be checked only periodically—for example, the tons of mix placed over a distance of 300 m (1,000 ft). Another option is to check the yield no more than once per hour of paving.

A third type of specification requires a certain degree of smoothness for the finished pavement surface. Many such specifications exist. Most are related to the amount of deviation permitted from a straightedge of a given length, or a certain maximum number of millimeters (inches) of roughness per unit of length, typically a kilometer (mile) or some fraction thereof. Although it is normally possible to meet such smoothness requirements through the use of automatic screed controls, ultimate success in doing so will depend on the amount of mix available to be placed, the condition of the existing pavement, and the number of layers of mix to be laid. The amount of mix necessary to meet a smoothness requirement will usually be greater than the amount needed to meet a given yield requirement. For most existing pavement surfaces, it is not reasonable to expect to achieve a smooth overlay if only one resurfacing course is placed. Indeed, if the existing pavement surface is quite rough, it may be difficult to meet a smoothness requirement even after two new layers of mix have been constructed. Smoothness specifications should therefore be related to the condition of the present pavement surface unless the existing surface is milled or the overlay consists of at least two layers.

A significant problem arises when it is necessary to meet some specified yield requirement and a minimum thickness or smoothness requirement simultaneously. Because of the principle of the floating screed (see Section 15), it generally is not possible to meet both of these requirements at the same time on the same project, depending on the smoothness of the pavement being overlaid. This is particularly true for thin overlays. The governing criterion (yield, minimum thickness, or smoothness) should be determined at the time the job is designed and should be stated in the contract documents. That same criterion should also be discussed and agreed upon between contractor and agency representatives before paving begins (during the preconstruction meeting).

SUMMARY

The following factors should be considered in monitoring automatic screed control operations:

- The screed operator should not attempt to make manual changes in the angle of attack of the screed by turning the thickness-control cranks, because the automatic controls will attempt to change the elevation of the tow points to compensate for the manual input to the screed.
- The grade sensor should be checked to ensure that it is working properly. If the wand (which rides on the stringline or mobile reference beam) is raised 3 mm ($\frac{1}{8}$ in.), there should be a corresponding movement of the actuator or ram at the tow points on the paver. If the wand is raised (or lowered) and the actuator does not move, either the system is not turned on or the sensitivity of the sensor is set too wide—with too great a deadband or sensitivity setting.
- When the sensor is set on the grade reference and the paver is moving forward, the up and down lights on the sensor should blink occasionally or the constantly blinking lights should change in intensity occasionally, both top and bottom, to indicate that a signal is being sent from the sensor to the tow point cylinder. On grade sensors that use a meter, the meter should indicate a change in reading as the paver travels down the roadway. Further, the movement of the tow point actuator should be smooth, without constant or rapid up and down movement.
- If a stringline or wire is used as the grade reference, the line should be very taut; there should be no sags in the line, particularly between the vertical support locations. Tautness can be checked by sighting down the line. The grade sensor wand should ride easily over the stringline and not be displaced in a vertical direction when it passes over a support arm. Every effort should be made to keep all personnel and equipment from coming in contact with the stringline and disturbing it, either longitudinally or vertically.
- If a mobile reference is used for grade control, the sensor should ride on the reference at the midpoint of the reference length. This placement allows the input to the paver to be made equally over the length of the mobile reference. If the mobile reference is equipped with multiple feet or shoes, each device should be checked to ensure that it is clean and free to move or rotate around its own hinge or spring point. The length of the mobile reference should be as long as practical to provide for the greatest averaging out of variations in the elevation of the existing roadway surface. The length of the reference should be longer than the wheelbase of the tractor unit.
- If a joint-matching shoe is used for grade control, it should be checked to ensure that it is free to move or rotate around its own hinge or spring point.
- If the automatic control system includes grade control on one side of the paver and slope control on the other, the layer being placed should be checked regularly to ensure that the proper elevation is being built into the pavement layer by the paver. This regular checking is particularly important on very wide pavements, such as an airport runway.
- On most paving projects, the grade-control sensor should be hung on the leveling (tow) arm of the paver, typically between one-third and two-thirds of the distance between the tow point and the screed. On some projects, the sensor can be placed just in front of the screed, but it should never be placed behind the pivot point of the screed. The sensor, except when used in conjunction with a joint-matching shoe, should generally not be located at the tow point.

17 Joint Construction

During the construction of HMA pavements, two types of joints are encountered. The first is a transverse joint, which is constructed whenever the paving operation is interrupted for a period of time—anywhere from 15 minutes to several weeks or more. The second is a longitudinal joint, which is built when a lane of HMA is constructed adjacent to a previously placed lane of mix. The techniques for constructing each type of joint are discussed in this section.

TRANSVERSE JOINTS

Suspension of Paving

The way a transverse joint is constructed depends primarily on whether traffic will be traveling over the asphalt mix before the paving is restarted. If traffic will not be passing over the end of the pavement, a vertical butt joint can be constructed; otherwise, a tapered joint must be built. In either case, the operation of the paver is essentially the same, but the construction of the joint itself is different.

It is important that the paver be run in normal fashion right up to the point at which the transverse joint is constructed. This means the head of material in front of the screed should remain as consistent as possible up to and at the location of the joint, so that the forces acting on the screed will be constant, and a consistent angle of attack will be maintained for the screed. The result will be a uniform mat thickness at the joint—the same thickness as that of the previously placed mix.

It is common but incorrect practice to empty out the paver hopper when a transverse joint is to be built. The paver operator runs the hopper out of mix, and the transverse joint is constructed at the point where the empty paver has stopped. As the hopper is emptied, however, the amount of mix carried on the augers is reduced until it is minimal. This process reduces the head of material in front of the paver screed, causing the screed angle to fall. The thickness of the mat then gradually decreases as the joint location is approached. The transverse joint is thus built at a low point in the new pavement surface, resulting in a dip that will be felt by traffic.

It is much better practice to locate the transverse joint at a point where the head of material in front of the screed is normal. This type of operation, however, requires more work on the part of the paving crew. If the joint is made where the pavement thickness (head of material) is constant, the paver screed is simply raised up at the point where the joint is to be built. Doing so leaves a great deal of mix on the roadway—the amount of mix that was in front of the screed. Except for the amount of mix needed to construct a taper, this material will have to be removed and then wasted or returned to the asphalt plant to be used as RAP. In addition, it will be necessary to dispose of the amount of mix remaining in the paver hopper. The advantage of this practice, however, is a smooth transition across the joint instead of a dip.

Butt Joints

For a butt joint (Figure 17-1), a vertical face is constructed by hand across the width being paved. This operation consists of raking, shoveling, and then removing the mix that is located downstream of the selected joint location. The mix thus removed is discarded or returned to the plant to be recycled. The mix that is in place upstream of the joint is not touched in any manner.

Compaction of the mix on the upstream side of the joint is accomplished in normal fashion. It is necessary, however, for the rollers to compact the mix immediately adjacent to the joint. For this to be done properly, runoff boards must be placed next to the joint. The thickness of the boards should be approximately equal to the compacted thickness of the layer being placed. In addition, the boards must be wide and long enough to support the full size of a roller. The compaction equipment passes over the mix at the joint and onto the boards before the rolling direction is reversed. This practice ensures that the transverse joint receives the same degree of compaction as the rest of the mix in the pavement layer.

If runoff boards are not used, the front wheel of the compaction equipment is normally run up to the transverse joint, stopping just short of the joint. The roller di-

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It is important that the paver be run in normal fashion right up to the point at which the transverse joint is constructed. This means the head of material in front of the screed should remain as consistent as possible up to and at the location of the joint, so that the forces acting on the screed will be constant, and a consistent angle of attack will be maintained for the screed. The result will be a uniform mat thickness at the joint—the same thickness as that of the previously placed mix.

It is common but incorrect practice to empty out the paver hopper when a transverse joint is to be built. The paver operator runs the hopper out of mix, and the transverse joint is constructed at the point where the empty paver has stopped. As the hopper is emptied, however, the amount of mix carried on the augers is reduced until it is minimal. This process reduces the head of material in front of the paver screed, causing the screed angle to fall. The thickness of the mat then gradually decreases as the joint location is approached. The transverse joint is thus built at a low point in the new pavement surface, resulting in a dip that will be felt by traffic.

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Butt Joints

For a butt joint (Figure 17-1), a vertical face is constructed by hand across the width being paved. This operation consists of raking, shoveling, and then removing the mix that is located downstream of the selected joint location. The mix thus removed is discarded or returned to the plant to be recycled. The mix that is in place upstream of the joint is not touched in any manner.

Compaction of the mix on the upstream side of the joint is accomplished in normal fashion. It is necessary, however, for the rollers to compact the mix immediately adjacent to the joint. For this to be done properly, runoff boards must be placed next to the joint. The thickness of the boards should be approximately equal to the compacted thickness of the layer being placed. In addition, the boards must be wide and long enough to support the full size of a roller. The compaction equipment passes over the mix at the joint and onto the boards before the rolling direction is reversed. This practice ensures that the transverse joint receives the same degree of compaction as the rest of the mix in the pavement layer.

If runoff boards are not used, the front wheel of the compaction equipment is normally run up to the transverse joint, stopping just short of the joint. The roller di-

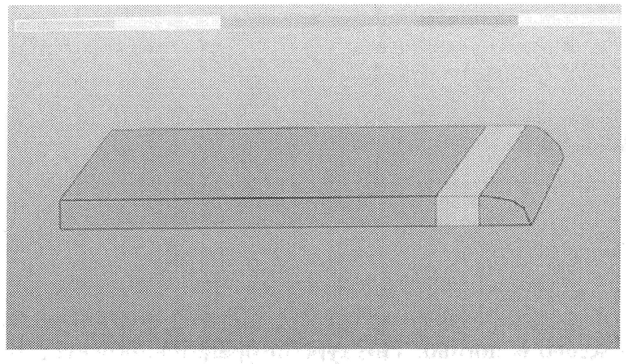

FIGURE 17-1 Construction of transverse butt joint.

FIGURE 17-2 Removal of material at butt joint.

rection is then reversed and the rest of the mat compacted. Occasionally, one wheel of the roller will be driven over the end of the course, over the vertical face of the joint. If a roller passes over the edge of the transverse joint with no board being in place beyond the edge to support the weight of the rollers, rounding of the edge of the joint will result. The extent of rounding will depend on the number of times the roller runs off the edge of the joint and the thickness of the layer being constructed. Two problems result in such cases. First, the rounding of the edge of the butt joint prevents the construction of a proper vertical joint face when paving is restarted. Second, the amount of compactive effort applied to the asphalt mix adjacent to (upstream of) the joint is typically inadequate. The lack of proper compaction in turn results in a high air void content in the mix upstream of the joint and a weak spot and dip in the pavement surface.

Runoff boards should therefore be used in the construction of butt transverse joints. If runoff boards are not used, however, one way to overcome the end-rounding problem is to cut back the mix to a location where the mat thickness is constant and the density meets specifications. This practice is illustrated in Figures 17-2 and 17-3. The rounded end of the butt joint is cut back, and the excess material removed and discarded. However, because no release paper has been placed under the mix that will be cut back and removed, it is often difficult to remove that mix. Thus the best practice is to build the transverse joint properly in the first place.

After materials have been removed and discarded, the area adjacent to the joint should be cleaned of all dust and other loose particles. The exposed edge should be lightly tacked with an acceptable tack coat.

Tapered Joints

If traffic will be passing over the transverse joint, a tapered joint or ramp must be built. For this type of joint, as for the butt joint, it is important that the paver operator keep the head of material in front of the paver screed as consistent as possible up to the point at which the joint is to be built to ensure that the thickness of the mix being placed will be uniform up to the joint. This can be accomplished more easily with a tapered than with a butt joint because a portion of the mix left in the paver hopper and in front of the screed can be used to build the taper.

At the location of the transverse joint, the asphalt mix downstream of the joint is temporarily pushed longitudinally away from the joint. A vertical edge is formed at the upstream face of the mix. If the taper is to be removed before construction continues, treated release paper or some similar material to which the asphalt mix will not stick is then placed downstream of the joint directly on

FIGURE 17-3 Application of tack at butt joint.

the existing pavement surface (see Figure 17-4). The length of the paper depends on the thickness of the course just placed, but is typically about 1 to 1.5 m (3 to 4 ft) and equal to the width of the lane being paved. If the paper is too short, the roller may tend to shove the mix, causing rounding of the joint at the upstream side of the paper. Once the paper is in place, the asphalt mix is shoveled back over it, and a taper is formed in this mix with a lute or rake. Any mix not used to construct the taper is discarded. If the joint is to be left in place permanently, the taper is constructed in the same manner, except that the treated paper is not used.

Sand or dirt from the edge of the roadway is sometimes used as a substitute for treated paper. This is not good practice. Although the sand or dirt does prevent the asphalt material in the taper from sticking to the underlying pavement surface, it is very difficult to remove the sand or dirt from the surface completely once the mix in the taper has been removed.

Typically, some of the bond-breaking material remains on the existing surface even after the surface has been swept with a hand broom. This dirty surface provides a slip plane for the new asphalt mix, and a shoving failure may occur at that point when the new pavement is subjected to traffic. This is true even if a tack coat is applied on top of the dirty surface to improve the bonding of the new mix to the existing pavement. Indeed, in many cases an extra amount of tack coat is applied near the joint to compensate for the dirt at that location. The extra material, particularly if not broken before the new mix is placed on it, can increase the chances for slippage at that point. Constructing a temporary tapered transverse joint using sand or dirt as the bond-breaking medium is therefore not acceptable paving practice.

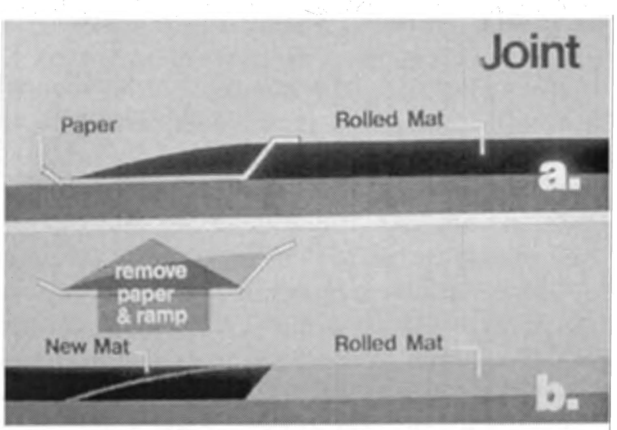

FIGURE 17-4 Use of treated paper in construction of tapered transverse joint.

Another type of tapered joint is the nonformed, sawed joint. For this type of joint, the paver operator keeps the paver operating normally until there is no more mix in the hopper or in the auger chamber. At the point where the mix becomes nonuniform across the width of the lane being paved, a taper is constructed with the leftover mix. No vertical face is formed, and the mix is merely tapered from the proper layer thickness to the level of the adjacent existing pavement. Any mix not needed to make the taper is removed and wasted. When it is time for construction to continue, a saw cut is made at the point at which the taper begins. All material from the taper is removed and wasted, although it is difficult to remove this material because it is typically bonded to the underlying layer (see the section below on "Removal of Taper"). As discussed further below, the vertical face where the saw cut was made should be treated with tack coat before construction continues.

One advantage of the tapered joint is the fact that the compaction equipment can run over the edge of the joint and down the taper without rounding the joint. Because the rollers can pass over the end of the mat easily, the compaction of the mix upstream of the joint is usually superior to that of the mix adjacent to a butt joint. A second advantage is that there generally is less mix to shovel from the joint because some of the extra mix is used to make the taper. The disadvantage of this kind of joint is that the mix must eventually be removed before paving restarts downstream of the transverse joint.

The length of a tapered joint is related to the thickness of the compacted pavement layer: the thicker the HMA lift, the longer the taper. Many agencies use a minimum ratio of 12 : 1 for the length of the taper and the thickness of the mat. For a mix that is 25 mm (1 in.) thick, therefore, the length of the taper should be at least 300 mm (1 ft). For a layer that has a compacted thickness of 50 mm (2 in.), the taper should be at least 600 mm (2 ft) long. This ratio allows traffic to travel safely from one pavement level to the adjacent higher or lower level.

Handmade Joints

In areas where the new HMA layer abuts an existing structure, such as a bridge deck, it is often necessary to place the mix adjacent to the joint by hand. The mix needed to complete the joint is deposited in the area to be paved either by the paver or by a haul truck. To avoid overworking the mix and possibly causing segregation, the mix should be placed as close as feasible to its final location. The mix is then spread by hand, using shovels, rakes, or lutes.

For such handwork, the mix must be left high to allow for compaction of the material by the rolling equipment. Because the mix is being placed by hand, it will not be as compacted as it would be if laid by the paver. Most paver-placed dense-graded HMA will compact roughly 6 mm ($\frac{1}{4}$ in.) for each 25 mm (1 in.) of compacted mat thickness. Mix placed by hand, however, will be fluffier and not nearly as dense as machine-laid material. To permit proper compaction of the mix and ensure that it will be at the right elevation to match the adjacent structure, the level of the mix should be approximately 9 mm ($\frac{3}{8}$ in.) higher than the surrounding pavement for each 25 mm (1 in.) of compacted layer thickness.

The handwork area must be rolled by the compaction equipment as soon as possible after the mix is in the proper location. Because of the time required to place the mix, rolling will normally be delayed, and the mix will be cooling during the placement process. To achieve the required density, therefore, extra rolling may be needed.

Restart of Paving

Removal of Taper

If a tapered transverse joint has been constructed, the mix in the taper must be removed before paving can be restarted. For a taper built with treated paper, there is little bond between the mix in the taper and the underlying pavement. The paper and mix are readily removed and returned for recycling. A vertical face is left at the upstream edge of the joint.

As noted earlier, if a nonformed tapered transverse joint is built, a transverse saw cut must first be made in the asphalt mat where the taper begins. An advantage of this type of joint is that the saw cut can be made at any longitudinal point in the asphalt layer to ensure that the thickness of the layer is constant. Once the joint has been cut completely through the asphalt mat, a front-end loader is used to pry up the mix that is downstream of the saw cut. As discussed above, one disadvantage of this type of joint is that it is often very difficult to remove the mix from the existing roadway downstream of the saw cut. As an alternative, before construction resumes, a cold-milling machine can be used both to form the vertical edge of the transverse joint and to remove the mix in the taper.

A straightedge should be used to determine the condition of the transverse joint before paving begins. If the mix upstream of the joint is level, the location of the transverse joint is fine. If the straightedge indicates that the previously placed mix is not level, the location of the transverse joint should be moved upstream to a point where the pavement layer is of the proper thickness and smoothness. The mix downstream of the new joint location should be removed and discarded or recycled.

Application of Tack Coat

The existing pavement surface downstream of the transverse joint should be cleaned and made as free as possible of all loose materials and dust. As noted earlier, a tack coat should be applied to the vertical face of the transverse joint before paving starts (see Figure 17-3); the rate of application of the tack coat should be adjusted to the amount of dust remaining on the pavement surface. The tack coat should be permitted to break, but not necessarily set, before paving begins.

Use of Starting Blocks

As a rule of thumb, HMA is expected to densify approximately 20 percent under the action of compaction equipment. This means that the mix must be placed about 30 mm ($1\frac{1}{4}$ in.) thick to produce a compacted mix that is 25 mm (1 in.) thick. This rule must be applied when the paver is used to place mix at a transverse joint.

If the layer being placed is to be 50 mm (2 in.) thick, the mix passing out from under the screed should be approximately 65 mm ($2\frac{1}{2}$ in.) thick to allow for compaction. It is therefore improper practice to set the paver screed directly on the old mat upstream of the transverse joint and start placing the new mix by dragging the screed off of the previously placed material. If this is done, an insufficient amount of mix will be placed on the downstream side of the joint, and a dip in the compacted pavement surface will result. Instead, proper paving practice requires that the paver screed be placed on a set of starting blocks, or strips of wood on the upstream side of the transverse joint. These blocks should be about 6 mm ($\frac{1}{4}$ in.) thick for each 25 mm (1 in.) of compacted lift thickness, as stated above.

The starting blocks should be placed completely under the length of the screed, front to back, as illustrated in Figure 17-5. At least four strips of wood should be used for a standard screed up to 3.65 m (12 ft) wide equipped with rigid extensions. If the width of the screed with rigid extensions is greater than 3.65 m (12 ft), at least five or six blocks should be used, depending on the width of the screed. If the paver is equipped with hydraulically extendable screeds, either front or rear mounted, at least four blocks should be placed under the main screed and two additional blocks under each extension.

If the paver is starting out at a new location where there is no old mat on which to set the starting blocks

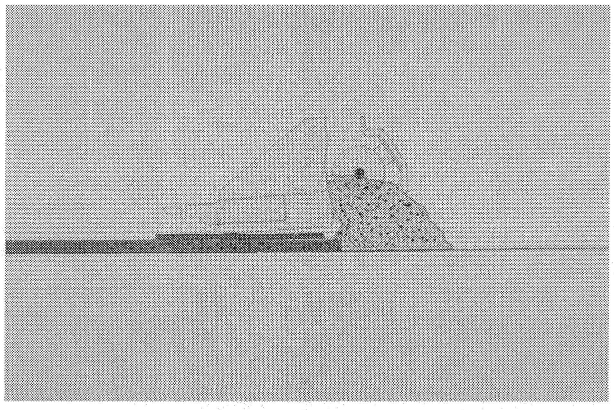

FIGURE 17-5 Use of starting blocks for paving at a transverse joint.

and screed, the thickness of the starting blocks must be increased to compensate for the lack of mix on the upstream side of the joint. In this case, if a compacted layer of mix 50 mm (2 in.) thick is being constructed, the blocks should be about 65 mm ($2\frac{1}{2}$ in.) thick to allow for the compaction of the mix by the rollers. For a compacted mat 75 mm (3 in.) thick, the starting blocks should be approximately 95 mm ($3\frac{3}{4}$ in.) thick. Thus the thickness of the starting blocks should be about 125 percent of that of the compacted HMA layer.

Nulling the Screed and Setting the Angle of Attack

After having been set on starting blocks of the proper thickness, the screed should be nulled. This means the screed's angle of attack should be set in the neutral or flat position. It should be possible to turn the thickness control cranks slightly in both directions when the screed is in the nulled position without putting any pressure on the screed and without setting its angle of attack.

Once the screed has been nulled, the angle of attack should be set. This is done by turning the thickness control cranks approximately one full turn (depending on the make and model of the paver) and introducing an up angle to the front of the screed. Both thickness control cranks or handles (one on each side of the machine) must be adjusted for the screed to be set properly.

Before the paver leaves the starting blocks, the material feed system should be activated and mix deposited in the auger chamber in front of the screed. To provide the proper head of material in front of the screed, enough mix should be deposited to cover the augers up to the center of the auger shaft. Once the auger chamber has been properly filled, the paver is started, the screed is pulled off of the starting blocks, and the paver is brought up to the desired laydown speed as quickly as feasible. As the paver moves down the roadway, the angle of attack of the screed is adjusted, as necessary, to provide the proper loose thickness of the asphalt mat. If the paver screed is nulled and the angle of attack set correctly while the screed is on the starting blocks, any necessary adjustment to the screed should be minimal.

Raking the Joint

If the transverse joint has been constructed properly up to this point, the amount of raking required will also be minimal, as shown in Figure 17-6. If the paver screed starts out on blocks and if the head of material against the screed is constant, the thickness of the mat downstream of the joint will be correct. Very little mix, if any, will need to be brushed back from the joint. There is never any reason to rake a transverse joint excessively (Figure 17-7).

When a joint is raked, there is a tendency for the raker to reduce the thickness of the new, uncompacted mat to match the elevation of the compacted pavement on the upstream side of the transverse joint by pushing the mix at the joint downstream farther onto the new mat. When the level of the new, uncompacted mat is the same as that of the old, compacted mat, however, the final elevation of the newly placed material, after compaction by the rollers, will be below that of the mix on the upstream side of the joint. The result will be a dip in the pavement surface at the transverse joint. Thus only minimal raking should be done.

Before the material on the downstream side of the joint is compacted, a straightedge should be used to determine whether the joint is smooth, as seen in Figure 17-8. The straightedge should rest on the uncom-

FIGURE 17-6 Raking of transverse joint.

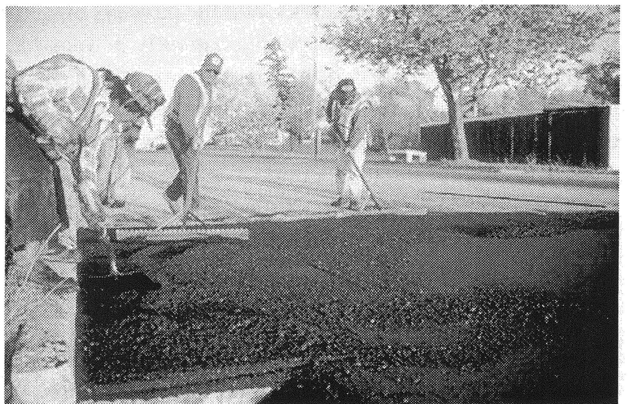

FIGURE 17-7 Excessive raking of transverse joint.

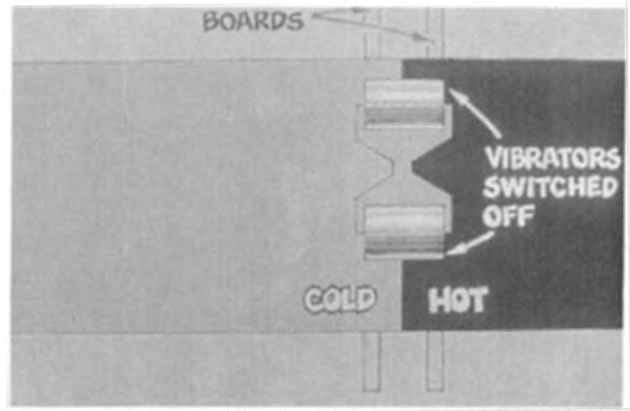

FIGURE 17-9 Horizontal rolling of transverse joint.

pacted mat and extend over the already compacted mix. The distance between the bottom of the straightedge and the top of the compacted mat should be equal to the amount of rolldown that will occur during the compaction process—approximately 6 mm per 25 mm (¼ in. per 1 in.) of compacted mat thickness. The straightedge should be used again to check the level of the joint once the compaction process has been completed. Obviously, the compacted mix should be level on both sides of the finished transverse joint.

Compacting the Joint

Ideally, a transverse joint should be compacted transversely (see Figure 17-9). This means the equipment used to roll the joint should operate across the width of the lane instead of longitudinally down the mat. If the rolling is done transversely, however, runoff boards must be used to support the roller as it moves beyond the longitudinal edge of the pavement. The roller should be operated so that the entire width of the joint receives equal compactive force. This is difficult to accomplish unless the wooden boards placed on each side of the lane are long enough to allow the roller to move completely off the mix on both sides of the pavement. Moreover, site restrictions, such as an adjacent guardrail or a steep side slope, may prevent the roller from operating in a transverse direction, and a safety problem is often created by operating the roller in a transverse direction if traffic is being maintained on the adjacent lane.

For these reasons, the transverse joint is usually rolled in the longitudinal direction (Figure 17-10). The initial (breakdown) rolling should be accomplished, however, as quickly as possible after the paver has moved off the

FIGURE 17-8 Checking smoothness at transverse joint.

FIGURE 17-10 Longitudinal rolling of transverse joint.

joint. The roller should pass slowly and completely over the joint before the machine is reversed. If the joint has been constructed properly, the compaction process for the transverse joint is no different from that for any other part of the asphalt mixture.

LONGITUDINAL JOINTS

Construction of the First Lane

Two key factors that affect the long-term durability of a longitudinal joint are built into the pavement during construction of the first lane. One is the importance of running the paver in a straight line so the joint can be matched on the next pass of the paver. The other is the need to properly compact the unconfined edge of the first lane (see also the detailed discussion of compaction in Section 18).

If the paver operator does not provide a straight line of mix that can be matched on the adjacent pass of the laydown equipment, it will be extremely difficult to construct a long-lasting longitudinal joint. It is suggested that the paver operator use a stringline to guide the paver as the first lane is being placed. In addition, if an extendable screed is used, its width must be kept constant; if the extendable screed is moved in and out, it will create an uneven edge that will be very difficult to match.

The compaction of the unconfined edge of the first lane is also extremely important. If the proper degree of density is not obtained in the first lane, the joint will deteriorate under traffic. It is critical that the roller make the same number of passes over the edge of the first lane as are made over the rest of the width of the lane. The edge of the drums of the vibratory or static steel wheel roller should extend over the free edge of the lane by at least 150 mm (6 in.). This practice will ensure that the compactive effort of the roller is applied in a vertical direction on the unconfined edge and will greatly reduce any tendency for the HMA mix to shove sideways during the compaction operation.

At no time should the edge of the drums of a vibratory or static steel wheel roller be located just on top of or just inside the unconfined edge of the lane. In either of these two positions, the mix may shove laterally under the forward movement of the roller, particularly if the mix is tender. If the mix does move, not only will the compaction of the mix adjacent to the unconfined edge be significantly less than required, but a dip will also be formed along the joint.

If a pneumatic tire roller is used in the breakdown position, the edge of the outside tire should not be placed either on top of or over the edge of the mix. Rather, the outside edge of the tire should be about 150 mm (6 in.) inside the unconfined edge of the mat. This will prevent rounding of the edge of the mat, prevent the mix from shoving laterally as a result of the high pressure in the pneumatic tires, and prevent excessive pickup when the rubber tires pass over the edge. Compaction of the mix at the unconfined edge must then be accomplished with a steel wheel roller, in either the vibratory or static mode.

It is important to note that most of the mass of a core cut from a longitudinal joint to measure joint density is actually taken out of the first lane of pavement, not the second. The unconfined edge of the mix that passes out from the end gate on the paver typically slopes at an angle of about 60 degrees. The mix placed in the adjacent lane is then laid against this slope. When a core is taken for density, however, it is typically drilled from the top of the joint that is visible at the pavement surface—half on each side of the joint line.

Cutting Back of the Joint

In some cases, before the longitudinal joint between two adjacent lanes of pavement is constructed, the longitudinal edge of the previously placed mix is cut back for a distance of 50 to 150 mm (2 to 6 in.). This is accomplished with a cutting wheel that is usually attached to a roller (Figure 17-11), but may be attached to a grader or front-end loader. The purpose of this operation is to remove that portion of the mix at the longitudinal joint that may have a lower density than the main portion of the mat because of the lack of confinement of the mix during the compaction process. This lack of density is normally due to improper overhang of the edge of the roller over the unconfined edge of the first lane during con-

FIGURE 17-11 Cutting wheel used to construct longitudinal joint.

struction. If the first lane is cut back, a tack coat should be placed on the newly exposed face of the longitudinal joint just before the adjacent lane is placed.

During this process, a vertical face, instead of the normal 60-degree inclined face, is formed at the longitudinal joint. This practice generally permits an increase in density to be obtained in the newly placed mat adjacent to the cut joint. Adequate joint density, however, can be obtained without cutting back the longitudinal joint—by properly compacting the first lane, as discussed above, and by properly overlapping and compacting the mix in the second lane, as discussed below.

Application of Tack Coat

If the free edge of the first lane is not cut back and the mix along the joint is clean, a tack coat is normally not needed. Although some agencies require that the edge of a longitudinal joint be tack coated before the next lane is constructed, many others do not. A tack coat along the joint, if not applied too heavily, should help create a bond between the two adjacent mats. On the other hand, there is no evidence that use of a tack coat significantly increases the durability of the joint under traffic. Other operational techniques generally affect the longevity of the joint more than the presence or absence of a tack coat.

Overlapping of the Joint

One key to the construction of a good longitudinal joint between lanes of HMA is the amount of overlap between the new and previously placed mats. The typical overlap at longitudinal joints is not more than 25 to 38 mm (1 to 1½ in.), as shown in Figure 17-12. This amount of overlap provides just enough material on top of the joint to allow for proper compaction without having extra mix that must then be pushed back from the joint by a raker. If properly done, however (see Figure 17-13), raking normally allows for increased compaction at the joint. The height of the new mix above the compacted mix should be 6 mm for each 25 mm (¼ in. for each 1 in.) of compacted mix.

As the mix is carried out to the sides of the paver by the augers, the HMA is pushed toward the end gate on the paver screed. Since the augers do not extend across the full width of the screed, however, the mix immediately adjacent to the end gate along the longitudinal joint is much less dense than the mix that passes under the main screed or the center portion of an extendable screed. In addition, because the mix at the end gate is not confined for as long a period of time as the mix that is along the interior of the screed, the mix at the former location is typically less dense. And because of the fluffier nature of the mix at the end gate, less mix is actually placed at that location. Consequently, many paver manufacturers have recently modified the design of the end gate to provide for greater confinement of the mix.

One problem that can occur with longitudinal joint construction is an excessive amount of overlap of the paver screed over the previously placed mat. This problem may arise because the screed operator simply has the end gate on the screed hanging too far over the first lane. It also may result, in part, from a ragged or wavy longitudinal edge on the first paver pass. Because the extra HMA cannot be pushed into the already compacted mat of the first lane, it is normally raked or luted onto the new mat. If the longitudinal edge of the first lane is straight and if the correct amount of overlap is used, the amount of raking required will be minimal.

The importance of putting the right amount of mix in the right place when constructing a durable joint cannot be overemphasized. If the amount of overlap of the first

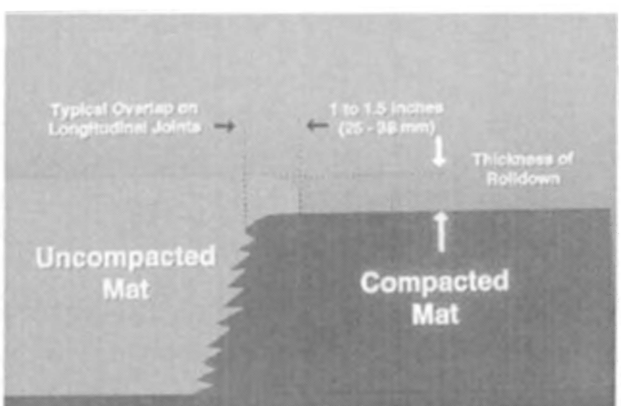

FIGURE 17-12 Thickness increase for uncompacted mix at longitudinal joint.

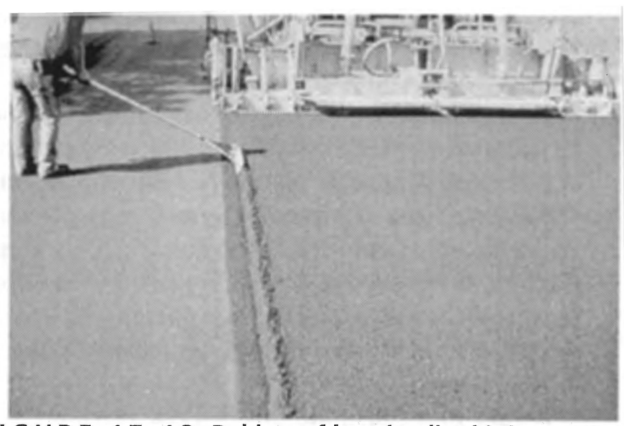

FIGURE 17-13 Raking of longitudinal joint.

lane is correct [no more than 40 mm (1½ in.) at the top of the joint] and if the height of the mix is correct [no more than 6 mm per 25 mm (¼ in. per 1 in.) of compacted mat thickness], there will be no excess mix to push away from the joint onto the new mat. The small amount of mix that overlaps the first lane will blend easily into the joint during rolling.

Raking of the Joint

There are those who believe it is always necessary to rake a longitudinal joint. As discussed above, however, if the right amount of mix is put in the right place, there should be minimal, if any, raking required. Raking may, of course, be required when driveway or mailbox turnouts are being paved, when an intersection is being constructed, or when it is necessary to match the grade of existing drainage inlets or manholes. As discussed earlier, however, raking should never be excessive, and the amount of mix moved should be consistent, especially along the longitudinal joint.

Some believe a raker should "bump" the joint, pushing the mix off the top of the first lane and onto the new mat directly over the joint, leaving a small mound of mix humped up for the rollers to compact. If too much material is left over the joint, the roller will tend to ride on the top of the hump and not come in contact with the adjacent mix, which also needs to be compacted. Further, because there is no place for this extra mix to go, a small bump usually remains along the joint after the compaction process has been completed. In addition, if the amount of mix overlapped on the first lane is not consistent, the volume of the bump created will be variable, and this variability will also affect the consistency of the joint density and evenness. Excessive mix at the joint is therefore not recommended.

Raking is generally not performed consistently. The rake or lute is typically used to push mix off the first lane and onto the new one. Sometimes the mix is deposited only a short distance from the joint, while at other times it is tossed halfway across the width of the new lane. If the adjacent lane is overlapped too far and too much mix is deposited on the old mat, the excess material should be pulled away from the joint instead of being pushed onto the new mix. The extra mix should not be broadcast across the new lane, but should be picked up and discarded. Better yet, it should not have been placed over the top of the first lane initially.

The raker typically places the rake or lute flat on the existing pavement surface, outside the edge of the new mix on top of the first lane. As the rake is moved transversely into the mix and across the top of the joint, all the mix is cleaned off the existing mat and pushed onto the new mat.

Because the raker does not lift the rake at the joint but moves the rake back and forth in a continuous sweeping or rocking motion, there is a lack of mix at the joint. The mix that should have been in place and ready to be compacted along the joint is now located partly across the width of the new mat. In most cases, the level of the uncompacted mix adjacent to the joint on the new mat is at the same elevation as the compacted mix on the other side of the joint. In some cases, so much mix is raked off the joint that a dip occurs at the longitudinal joint even before compaction of the mix begins. When either of these two problems occurs, it becomes impossible to obtain the required degree of density at the joint because there is not enough mix at the joint for compaction by the rollers. Moreover, when mix that is pushed off the longitudinal joint is deposited on the new asphalt mat, it changes the surface texture of the mat where it is deposited. Depending on the gradation of the mix being placed, the result can be a significant difference in the texture of the mat from one side of the lane to the other.

Excessive raking of the longitudinal joint is highly detrimental to the long-term performance of the joint because of the effect on the density along the joint. Excellent longitudinal joints can be constructed with minimal or no raking, if the proper amount of overlap of the new mix on the previously placed mat is achieved. It is therefore recommended that raking of the longitudinal joint be eliminated if proper overlap and compaction can be obtained.

Compaction of the Longitudinal Joint

If the level of the new, uncompacted mix is even with or below the level of the compacted mix in the adjacent lane, steel wheel compaction equipment will not be able to properly densify the mix along the joint. Whether the first pass of the roller is on the hot side of the joint or on the cold side (Figure 17-14), part of the weight of the roller drums will be supported on the previously compacted mat. As a result, the compaction equipment will bridge the mix at the joint, leaving it essentially uncompacted or only partially compacted. Thus, the level of the mix at the longitudinal joint must be above that of the compacted mix by an amount equal to approximately 6 mm for each 25 mm (¼ in. for each 1 in.) of

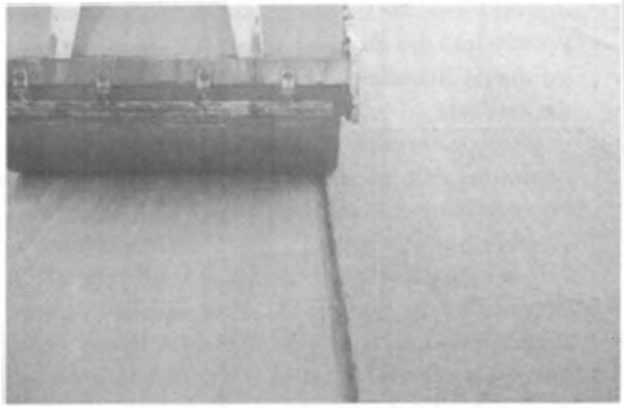

FIGURE 17-14 Starting compaction of longitudinal joint from the cold side, no longer a recommended practice.

compacted pavement if proper compaction of the mix at the joint is to be accomplished.

The use of a steel wheel roller, operated in either the vibratory or static mode, to compact the longitudinal joint generally results in bridging of the mix at the joint, and therefore a lack of density due to a lack of mix. Density can be obtained along the joint through the use of a pneumatic tire roller. The outside rubber tire on this type of compaction equipment can be placed directly over the mix at the joint. The compactive force applied by this tire can significantly increase the density obtained at that point. Nevertheless, a dip in the pavement surface will still occur along the joint if there is a lack of mix at that location. If proper density is to be achieved along the joint, there must be enough HMA there to compact, regardless of the type of roller used.

Rolling from the Hot Side

The most efficient way to compact a longitudinal joint is to place the roller on the hot (new) mat and overlap the joint by a distance of approximately 150 mm (6 in.) over the cold mat. The majority of the compaction equipment weight is where it is needed most—on the new mat. The mix at the joint is compacted into the joint area by the roller as long as the new mix at the joint is of the proper height. The slope along the edge of the first lane and the lower density of the mix placed beside the paver end gate provide the volume required for the mix to be blended in along the joint without leaving a hump at the joint. Any type of roller used for the breakdown rolling of the mix—vibratory or static steel wheel roller or pneumatic tire roller—can be used to compact the longitudinal joint as long as the elevation of the mix at the joint is above that of the cold mat and the new mix is still hot. Figure 17-15 shows a longitudinal joint being compacted with a pneumatic tire roller.

Sometimes the first pass of the roller is completed with the edge of the equipment about 150 mm (6 in.) away from the longitudinal joint (see Figure 17-16), in the belief that the mix will be shoved toward the joint by the roller, and better compaction will thereby be obtained. If the mix being placed is stable enough, however, the roller should not be able to move the material laterally to any significant extent. Thus if the mix design is proper, this method of compacting the joint provides no advantage over performing the first pass of the roller 150 mm (6 in.) outside the joint. Even if the mix is tender, there is no advantage to this method of compaction. If the mix can be moved laterally by the

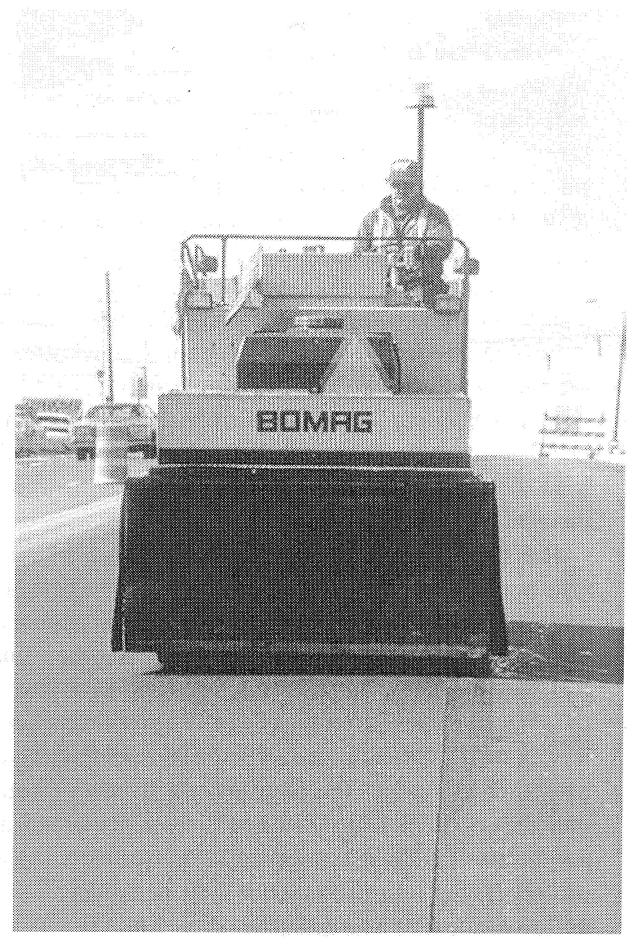

FIGURE 17-15 Compaction of longitudinal joint with pneumatic tire roller.

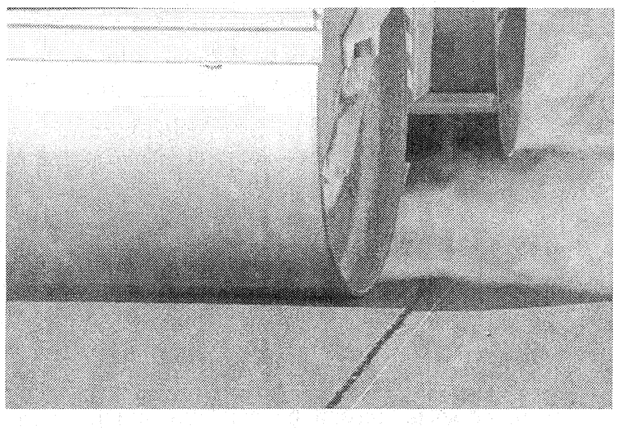

FIGURE 17-16 Compaction with edge of equipment inside longitudinal joint.

roller, the mix design should be reviewed to determine whether a more stable mix can be produced. If the mix does move toward the joint, excess mix in the form of a hump will be present along the joint, resulting in turn in a lack of mix just outside the edge of the roller drum, between the roller and the joint. When the roller moves over to compact the mix at the joint, the drums will ride on top of the excess mix, trying to shove the mix back where it came from. With this procedure, the level of density obtained at the joint may be highly variable.

In summary, there appears to be no advantage to performing the first pass of the roller inside the joint by some distance. Lapping the roller over the adjacent old pavement typically is the most efficient way to provide roller coverage for the entire pavement width. Further, the overlap method provides for a more uniform density level at the longitudinal joint than does performing the first pass of the roller inside the joint.

Rolling from the Cold Side

In the past it was common practice to do the initial rolling of the longitudinal joint from the cold (previously placed mat) side of the joint, as seen in Figure 17-14. With this method, the major portion of the weight of the roller is supported by the cold, compacted mat. Only about 150 mm (6 in.) of the width of the roller hangs over the fresh mat, compressing the mix along the joint. The majority of the compactive force is wasted because the roller is essentially applying its compactive force to an already compacted HMA material.

While the roller is operating on the cold side of the longitudinal joint, the mix on the hot side of the joint, as well as the rest of the mix in the course being laid, is cooling. Depending on environmental conditions and the thickness of the mix being placed, compacting the joint from the cold side often hampers the ability to obtain the desired density over the entire pavement width.

The reason often given for rolling the joint from the cold side is that this method allows the rollers to "pinch" the joint so a greater degree of density is obtained. One edge of the roller drum rides on the new mix, while the other edge is in contact with the old mix some distance away across the first lane. More weight from the roller is thus applied to the new mix, which supposedly results in more density. Recent research, however, has indicated that the same density can be obtained at the longitudinal joint whether the initial rolling is accomplished from the hot or the cold side. Since it is more efficient to compact the whole mat, as well as the joint, from the hot side, compaction from the cold side is not recommended.

Regardless of the method used to compact the longitudinal joint, the level of density obtained at that location is typically at least 2 percent below the average density that can be produced in the main portion of the mat. This difference occurs primarily because the first lane has an unconfined edge that tends to move laterally. Even if the unconfined edge of the first lane is compacted, allowing the roller to hang over the edge, the density at the joint typically will still be less than that achievable in the main portion of the mat. If a particular level of joint density is to be required in the specifications, the percentage of the theoretical maximum density of the mix at the joint should be less than that required for the rest of the mat.

Wedge Joints

If traffic is allowed to cross a longitudinal joint before the second lane is constructed, some agencies limit the compacted depth of HMA that can be placed. In such cases, a wedge joint may be specified.

The wedge is usually formed during the first pass of the paver by attaching a metal form to the end gate of the paver screed. The degree of slope on the wedge varies, typically from 6:1 to 12:1 horizontally to vertically. The top of the wedge should have a notch so that sufficient material for compaction can be placed directly in the joint during the second pass. Formation of the wedge is not particularly problematic.

The cross slope of the wedge is different from that of the mainline mat. In addition, the wedge is quite narrow. Thus it is difficult to obtain adequate density on the HMA in the wedge before the adjacent lane is placed. If the rollers used to compact the rest of the mat width are used to compact the wedge, rounding of the edge may occur. This in turn will make it significantly more difficult to match the top of the joint when the next lane is constructed.

Different types of small rollers have been used to compact the mix in the wedge. Figure 17-17 illustrates one such attempt. In general, because of the lack of weight of this type of compaction equipment, it cannot be used to attain the desired level of density in the wedge material. However, when the adjacent lane is placed, the heat softens the wedge, allowing for some additional compaction.

Another potential problem associated with joints relates to the ability to match the joint uniformly when the adjacent lane is placed. There are two reasons for this problem. First, if the edge has been rounded during the compaction operation, the resulting ragged edge will be difficult to match with the second pass. Further, it will be necessary to feather out the mix in the new lane and attempt to blend that material into the mix in the first lane. Depending on the size of the aggregate incorporated into the mix, this feathering process may not be uniformly successful. When the second lane is placed and the mix is blended into the first lane, the larger aggregate particles in the mix will be exposed where the mix is feathered. The result may be a much rougher surface texture in the joint area and potential crushing of the coarse aggregate under the rollers. Significant raveling of the mix will then occur under traffic. Because of the feathering of the new mix into the old mix at the wedge joint, then, the performance of some wedge joints under traffic has been less than desirable.

One way to improve the performance of a wedge joint is to construct a short vertical face on the edge of the first lane before the wedge is formed. In this case, the depth and size of the wedge are reduced. Typically one-half of the uncompacted lift thickness is constructed vertically by a metal form attached to the end gate on the paver screed; the remaining thickness is shaped into a wedge by the same form. This type of wedge joint has several advantages. First, since the amount of mix in the wedge is reduced, there is less mix at the longitudinal joint with lower density than the full wedge joint. Second, because of the vertical face on the upper portion of the joint, it is easier to tie in the mix in the second lane without having to make a feathered joint. The potential for raveling of the new mix at the joint is thereby greatly reduced. Further, the surface texture of the mix at the joint is uniform since the mix does not have to be feathered, and the coarse aggregate in the mix will not be crushed by the rollers.

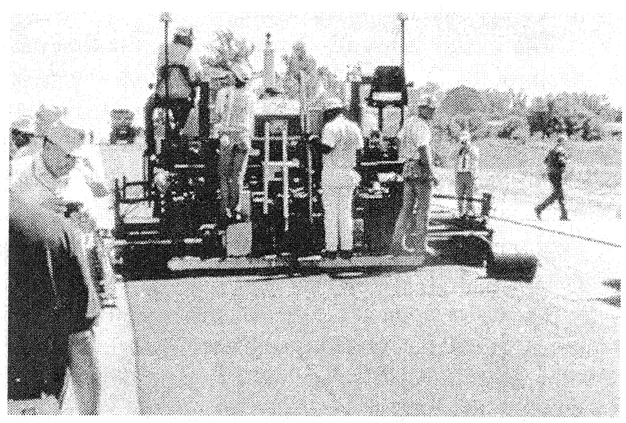

FIGURE 17-17 Compaction of mix in wedge joint.

The wedge joint built with a short vertical face also works well from the standpoint of traffic safety during construction. The key to good performance at the joint is to ensure that adequate density is obtained. The joint construction process should ensure good joint density.

Echelon Paving

If echelon paving (two pavers running next to each other in adjacent lanes) is used, construction of the longitudinal joint is changed so that the compaction of the unconfined edge of the first lane is delayed until the second lane is placed. The amount of overlap between the first and second lanes is also modified. The distance that the screed end gate of the trailing paver extends over the uncompacted mat behind the first paver should be no more than 25 mm (1 in.). The end gate of the second paver screed must be set at the same level as the bottom of the screed plate of the first paver. Doing so will prevent the end gate of the screed of the second paver from dragging on the mix placed by the first or leading paver and changing the surface texture of the mix in the area of the overlap.

No raking of the joint is needed. The compaction process is modified so that the rollers densifying the mix behind the lead paver are required to stay about 150 mm (6 in.) away from the free edge of the mat on the side toward the second paver. Once the mix from the second or trailing paver has been placed against the uncompacted edge of the mix from the first paver, the rollers compacting the second lane are used to densify the mix across the joint. With proper lapping and compaction, it is usually difficult to see the position of the longitudinal joint produced by the echelon paving process. In addition, use of this technique normally results in the density of the longitudinal joint being equal to that of the adjacent mat.

SUMMARY

The following factors should be considered in monitoring joint construction operations:

- If a transverse butt joint is to be built, the paver operator should maintain a constant head of material in front of the screed to a point downstream of the location where the joint is to be constructed. To prevent a decrease in the layer thickness upstream of the transverse joint, the operator should not be allowed to run the hopper, slat conveyors, and augers empty of mix before the joint location is reached.
- For the construction of a transverse butt joint, provision must be made for compacting the mix adjacent to the butt joint to the same degree as the previously placed mix without rounding off the end of the mix at the joint.
- For the construction of a tapered transverse joint, the thickness of the layer should be maintained to a point downstream of the location where the vertical face of the joint will eventually be constructed. Treated release paper, not sand or dirt, should be used as a bond-breaking material under the mix in the taper.
- When paving is restarted, the asphalt mix in the taper should be removed and then discarded or recycled. A vertical face should be present at the selected joint location, or the mix should be cut back to create a vertical face. A tack coat should be applied to the existing pavement surface at the joint location.
- The screed of the paver should be set on starting blocks on the cold side of the transverse joint. The thickness of the starting blocks should be 6 mm ($\frac{1}{4}$ in.) for each 25 mm (1 in.) of compacted layer thickness when the blocks and paver screed are set on another pavement layer. If the paver is starting to place mix at a new location, the thickness of the starting blocks should be the same as that of the compacted new layer plus 6 mm per 25 mm ($\frac{1}{4}$ in. per 1 in.) of compacted layer thickness. It is impossible to construct a proper transverse joint if blocks are not used to bring the screed to the proper elevation on the cold side of the joint before paving is started.
- The mix on the downstream side of the transverse joint must be higher than that on the previously compacted side of the joint to allow for adequate rolldown of the freshly placed mix.
- Minimal raking is needed at a properly constructed transverse joint.
- Ideally, a transverse joint should be compacted with the roller in a transverse direction. On a practical basis and for safety reasons, however, a transverse joint can be compacted properly with the roller running in a longitudinal direction as long as the initial elevation of the new mix is above that of the old mix on the cold side of the joint.
- To achieve proper density at the longitudinal joint, it is essential to compact the unconfined edge of the first lane correctly. The edge of the drum on a vibratory or static steel wheel roller should extend out over the edge of the mix a minimum of 150 mm (6 in.) when the first lane is being densified.
- During the construction of a longitudinal joint, the end gate of the paver should overlap the previously placed lane by no more than 40 mm ($1\frac{1}{2}$ in.). Any increase in the overlap beyond this distance will result in excess material that will need to be raked off of the joint. The new mix should be 6 mm per 25 mm ($\frac{1}{4}$ in. per in.) thicker than the compacted mix.
- Minimal or no raking of the longitudinal joint should be necessary if the overlay of the paver screed on the adjacent lane is 40 mm ($1\frac{1}{2}$ in.) or less. The mix should not be bumped against the joint since it will then be impossible to blend the extra mix into the new mix during the compaction process. In no case should the raker broadcast the mix across the width of the new lane.
- Compaction of the longitudinal joint should be accomplished by rolling from the hot side of the layer with the roller wheels lapping approximately 150 mm (6 in.) over onto the cold mat. It is not recommended that the initial pass of the roller on the hot side of the joint be inside of the joint. It is much more efficient to have the first pass of the roller extend over the joint for a short distance onto the cold side of the joint.
- If a wedge joint is constructed, a short vertical face should be formed into the top of the joint to minimize the amount of mix contained in the wedge and permit the mix in the second lane to be placed and compacted against the first lane. This procedure will also minimize the amount of raveling that can occur at this type of joint if the second lane is feathered into the first.

SECTION

18 Compaction

Compaction is the most important factor in the performance of an HMA pavement. Adequate compaction of the mix increases fatigue life, decreases permanent deformation (rutting), reduces oxidation or aging, decreases moisture damage, increases strength and stability, and decreases low-temperature cracking. An HMA mixture with all the desirable mix design characteristics will perform poorly under traffic if it has not been compacted to the proper density level. Indeed, a properly compacted mix with marginal properties will often outperform a mix with desirable properties that has been inadequately compacted.

DEFINITIONS

The *density* of a material is simply the weight of the material that occupies a certain volume of space. For example, an HMA mixture containing limestone aggregate might have a compacted density of 2355 kg/m^3 (147 lb/ft^3). This density, or unit weight, is an indication of the degree of compaction of the mixture. Paving materials made with different aggregates can have significantly different densities. An HMA mixture manufactured with lightweight aggregate, for example, might have a compacted density of only 1362 kg/m^3 (85 lb/ft^3).

Compaction is the process by which the asphalt mix is compressed and reduced in volume. Compaction reduces air voids and increases the unit weight or density of the mix. As a result of the compaction process, the asphalt-coated aggregates in the mix are forced closer together; this increases aggregate interlock and interparticle friction and reduces the air void content of the mix.

It is possible, under controlled laboratory conditions, to determine the density of HMA required to provide zero air voids. At this point, called the theoretical maximum density, no air voids would remain in the mix. Theoretical maximum density can be calculated from the percentages and specific gravity of each component of the mix. It can also be determined from a laboratory test, ASTM Test Method D2041, Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures, sometimes called the Rice test. The latter procedure is preferred for determining the theoretical maximum density compared with the mix component calculations.

On the roadway it is not possible to compact a well-designed mix to a voidless condition; therefore, all asphalt mixes will contain some air voids once the compaction process has been completed. The air void content of the mix is simply the volume of the spaces between the asphalt-coated particles. Because this volume cannot be measured directly, a ratio of the unit weight of the compacted mixture to the theoretical maximum density is used. Air void content is determined from the ratio of the bulk specific gravity of the mix to the theoretical maximum density as given by the following formula: percent air voids = 100[1 − (bulk specific gravity/theoretical maximum specific gravity)]. Thus if the bulk density is 95 percent of the theoretical maximum density, the mix has 5 percent air voids.

As an example, assume that the compacted density of an HMA mix is 2355 kg/m^3 (147.0 lb/ft^3) and that the maximum theoretical density of the same mix is 2467 kg/m^3 (154.0 lb/ft^3). The air void content of the mix will be the difference between the two values, 2467 − 2355 = 112 kg/m^3 (154.0 − 147.0 = 7.0 lb/ft^3), divided by the value of the maximum theoretical density of 2467 kg/m^3 (154.0 lb/ft^3), that is, 4.5 percent.

FACTORS AFFECTING COMPACTION

Four primary factors affect the ability of the compaction equipment to densify an asphalt mixture: properties of the materials in the mixture, environmental variables, conditions at the laydown site, and type of compaction equipment used. Each of these factors is discussed below.

Properties of the Materials

Aggregates

The compactibility or stiffness of an HMA mixture is influenced by the nature of the aggregate particles and aggregate gradation in the mix. Three properties of the coarse aggregate particles used in an asphalt mixture can affect the ability to obtain the proper level of density:

surface texture, particle shape, and number of fractured faces. With increases in aggregate angularity, nominal maximum size of the aggregate, and hardness of the aggregate (granite compared with limestone, for example), the compactive effort needed to obtain a specific level of density increases. Angular particles offer more resistance to reorientation by rollers than do rounded particles; hence, increased angularity increases resistance to densification from applied compactive effort.

The surface texture of the individual aggregate particles is also important. Aggregates that have a rough surface texture are more difficult to compact than aggregates with a smooth surface texture. The compactive effort required is affected as well by the shape of the aggregate. A cubical or block-shaped aggregate requires greater compactive effort than does a rounded particle before a given density level is achieved.

A continuously graded (dense-graded) aggregate, from coarse to fine, is generally easiest to compact. Open-graded or cap-graded mixes typically require a significant increase in compactive effort to obtain the desired level of density. An oversanded or finely graded mix, because of its inherent tender nature, may be difficult to compact.

Mixes that contain an excess of midsize fine aggregate [between the 0.60- and 0.3-mm (No. 30 and No. 50) sieves or between the 0.425- and 0.180-mm (No. 40 and No. 80) sieves] also are difficult to compact because of their lack of internal cohesion. These mixes tend to displace laterally rather than compress vertically. In addition, dust content [amount of aggregate passing the 0.75-mm (No. 200) sieve] affects the compactive effort needed. A mix designed with a high dust content will generally be more difficult to compact than one with a lower dust content, depending on the angularity and fineness of the dust particles.

In general, aggregates with properties that improve resistance to fatigue and permanent deformation require increased compaction effort to obtain a desired density.

Asphalt Cement

The grade and amount of asphalt cement used in a mix affect the ability to densify the mix. An asphalt cement that is higher in viscosity or lower in penetration will generally cause a stiffer mix at a given mix temperature, which will require a greater compactive effort to achieve density. Thus a mix produced with an AC-20 viscosity-graded asphalt will typically be stiffer, at a given temperature, than a similar mix containing an AC-10 asphalt cement. Within the PG binder classification system (see Section 3), a mix produced with a PG 70-22 graded binder will usually be stiffer, at a given temperature, than a mix produced using a PG 58-22 binder material. The stiffer the mix, the more compactive effort is needed to achieve a given density level.

The degree of hardening (aging) that occurs in asphalt binder during manufacture of the mix also affects the compactibility of the mix. Various asphalts age differently during the mixing process, depending, in part, on the chemical properties of the asphalt cement. Aging is also influenced by the type and operating characteristics of the HMA plant—more hardening will typically occur when a drum-mix plant is operating at partial capacity than when it is operating at full capacity. Moreover, higher manufacturing temperatures generally produce somewhat stiffer mixes.

The asphalt cement content of the mix also influences its compactibility. In general, a mix with too little asphalt cement may be stiff and require increased compactive effort, whereas a mix with too much asphalt cement will compact easily or may become tender and shove under the rollers.

Mix Properties

A mix that is at a higher temperature when laid [for example, 150°C (300°F)] will be easier to compact than a mix that is at a lower temperature [for example, 125°C (260°F)]. If the initial mix temperature is too high, however, the mix may be tender and difficult to compact until the temperature decreases and the viscosity of the asphalt binder increases. Conversely, if the mix temperature is too low at the time the initial compactive effort is applied, increased compactive effort will be needed to obtain the required density; indeed, the required density may never be achieved.

The workability of the mix is also affected by the temperature susceptibility (sensitivity of mix stiffness to temperature) of the asphalt cement. For highly temperature-susceptible asphalt binder, less time will be available for compaction because the mix will increase in stiffness more quickly with a decrease in temperature than mix containing a less temperature-susceptible asphalt.

The fluids content of the mix also affects the compactive effort needed. The fluids content is the sum of the asphalt cement content and the moisture content of the mix. If the amount of moisture in the mix from the plant is high (greater than 0.2 percent, by weight of mix), the extra fluids content will act like asphalt binder and may make the mix unstable and difficult to compact. Thus, the moisture content of plant-produced mix should be measured regularly. Most specifications require that moisture content be less than 0.5 percent, by weight of mix, when the mix is discharged from the plant. If the mix characteristics are marginal, however, a residual moisture content of as little as 0.2 percent may significantly alter the tenderness of the mix, and therefore its compactibility.

Environmental Variables

Research completed in the early 1970s determined the time available for compaction of various HMA mixes. The time available for compaction is defined as the time, in minutes, for a mix to cool from its laydown temperature when it passes out from under the paver screed to a minimum compaction temperature. Minimum compaction temperature for that study was set at 80°C (175°F). It was found that below this temperature, little density gain was achieved with the application of additional compactive effort. Any additional rolling with steel wheel rollers, except to remove roller marks, may result in fracture of the aggregate in the mix and a decrease in density. It is emphasized, however, that rolling should occur at as high a temperature as possible, given the properties of the asphalt mix, in order to achieve the required level of density with minimum compactive effort. At temperatures near 80°C (175°F), the probability of significantly increasing density or reducing air voids is very low. This lower cutoff temperature may vary somewhat with grades of asphalt.

In the 1970s study, six variables were found to have an effect on the rate of cooling: layer thickness, air temperature, base temperature, mix laydown temperature, wind velocity, and solar radiation. "Cooling curves," shown in Figures 18-1 and 18-2, illustrate the amount of time available for compaction under different combinations of these variables. For these two figures, it is assumed that the material being compacted is a dense-graded HMA mix. The surface temperature of the underlying pavement is assumed to be equal to the ambient air temperature. A constant wind velocity of 10 knots [about 18 km/h (11 mph)] and a constant degree of solar radiation are also assumed. The curves then show the estimated time, in minutes, required for the mix to cool from its laydown temperature to the minimum compaction temperature of 80°C (175°F) for different compacted layer thicknesses.

To use these graphs, three input variables are needed: initial mix laydown temperature, base surface temperature (assumed to be equal to the ambient air temperature), and compacted layer thickness. Figure 18-1 is to be used for mix laydown temperatures of both 121°C and 149°C (250°F and 300°F). Figure 18-2 is to be used when the mix laydown temperature is 107°C or 135°C (225°F or 275°F). The range of base temperatures for each set of curves is from −12°C to 15°C (10°F to 60°F). The range of mix layer thicknesses is from 13 to 150 mm (½ to 6 in.).

Layer Thickness

Layer thickness is probably the single most important variable in the rate of cooling of asphalt mixtures. Dur-

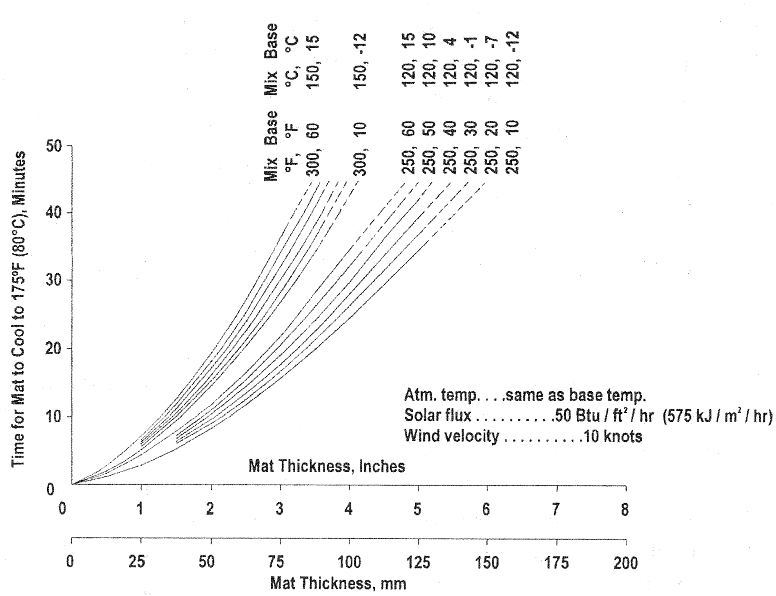

FIGURE 18-1 Time for mat to cool to 80°C (175°F) versus mat thickness for lines of constant mix and base temperatures [121°C (250°F) or 149°C (300°F) behind paver].

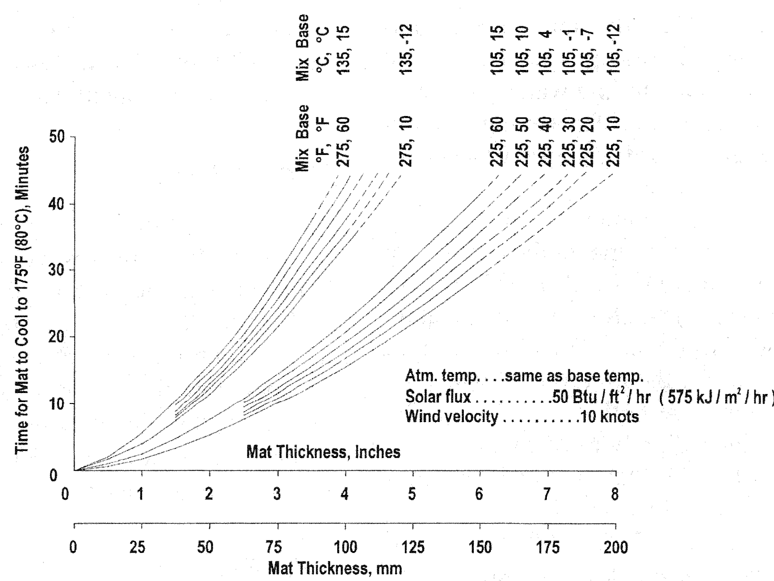

FIGURE 18-2 Time for mat to cool to 80°C (175°F) versus mat thickness for lines of constant mix and base temperatures [107°C (225°F) behind paver].

ing early spring and late fall, thin lifts are difficult to compact properly. Layers of mix less than 50 mm (2 in.) in compacted thickness are highly susceptible to premature failure because of the inability to densify the mix adequately before it cools. The desired density is very difficult to obtain on thin lifts of mix in cool weather because of the mix's rapid decline in temperature.

As the thickness of the layer being placed increases, the time available for compaction also increases. For example, referring to Figure 18-1, for a mix laydown temperature of 121°C (250°F) and a base temperature of 5°C (40°F), a mat 25 mm (1 in.) thick will cool to the 80°C (175°F) compaction cut-off temperature point in less than 4 minutes. For a layer 50 mm (2 in.) thick under the same mix and base temperature conditions, it will take about 10 minutes for the material to cool to 80°C (175°F). Doubling the lift thickness from 25 to 50 mm (1 to 2 in.) increases the time available for compaction from 4 to 10 minutes. If the layer depth is 100 mm (4 in.), the time to cool becomes about 29 minutes, a significant increase in available compaction time under similar temperature conditions.

Referring again to Figure 18-1, the relative effect of pavement lift thickness is the same for a mix laydown temperature of 149°C (300°F) and a base temperature of 5°C (40°F). As the depth is decreased from 100 to 50 to 25 mm (4 to 2 to 1 in.), the time available for the mix to cool from 149°C (300°F) to 80°C (175°F) decreases from more than 40 to 16 to only 6 minutes, respectively. From these data, it is apparent that the time available to compact a thin layer of HMA is extremely limited in cold weather.

Air and Base Temperature

A portion of the heat in the asphalt layer is lost to the air. Heat is also lost to the layer on which the new material is placed. Cooling of the mix near the base is more rapid than near the surface. Thus, base temperature is actually more important than air temperature in determining the time available for compaction.

Most specifications require a minimum air temperature for paving and compaction operations. It is often assumed that air and base temperature are the same. This is not necessarily true, particularly in cool weather. In early spring, the base temperature (surface temperature of an existing pavement layer) will be lower than the ambient air temperature early in the morning. The air temperature might be 5°C (40°F) and rising, but the base temperature might be 3°C to 6°C (5°F to 10°F) below the air temperature. The low base temperature will reduce the time available to achieve adequate density. On the other hand, base temperatures are often higher in the late fall than in the early spring for the same overnight air temperature. Thus, a given thickness of material is easier to compact in the fall than in the spring for the same air temperature conditions.

A moist base layer significantly increases the cooling rate of the new overlying asphalt layer. Heat is lost from the mix to the moisture, turning water into steam and increasing the rate of heat transfer. Paving on a wet surface therefore hampers the ability to gain proper density in the mix.

As the temperature of the ambient air and existing pavement surface increases, the time for the mix to cool from the laydown temperature to 80°C (175°F) also increases. Referring to Figure 18-2, for a mix temperature of 135°C (275°F) and a lift thickness of 75 mm (3 in.), it takes only 22 minutes for the mix to cool when the base and air temperatures are both –7°C (20°F). The time available is extended slightly to 25 minutes for a base/air temperature of 5°C (40°F) and to 30 minutes for a base/air temperature of 15°C (60°F).

Again referring to Figure 18-2, for a lift thickness of 50 mm (2 in.), using the same mix laydown temperature of 135°C (275°F), the time to cool to 80°C (175°F) increases from 11 to 13 to 15 minutes for a base/air temperature of –7°C, 5°C, and 15°C (20°F, 40°F, and 60°F), respectively. Thus the temperature of the ambient air and base surface is important, though not nearly as important as mat lift thickness, in determining the time available for compaction.

Mix Laydown Temperature

Asphalt mixes are usually produced at temperatures between 130°C and 165°C (270°F and 325°F). Depending on environmental conditions and the length of the haul, the mixture can decrease in temperature from 3°C to 14°C (5°F to 25°F) between the plant and the paver. The plant mixing temperature is not important in determining the time available for compaction, but mix temperature as it comes out from under the paver screed is. As the initial mix laydown temperature is increased, the time available for compaction also increases. Thus within limits, the mixing temperature should be determined by the laydown and compaction temperature requirements.

Referring to Figure 18-1, for a lift thickness of 50 mm (2 in.) and a base/air temperature of 5°C (40°F), the time to cool to 80°C (175°F) increases from 9 to 16 minutes as the laydown temperature increases from 121°C (250°F) to 149°C (300°F). For a lift thickness of 100 mm (4 in.) and a base/air temperature of 15°C (60°F), a change in laydown temperature from 149°C (300°F) to 121°C (250°F) reduces the time available for compaction from 36 to 21 minutes.

The effect of mat laydown temperature is more significant for thinner mats and lower base temperatures. As the time to cool to 80°C (175°F) becomes shorter, an increase in the mix laydown temperature extends the compaction time significantly in most cases.

Wind Velocity

A thin layer of mix will cool more quickly when there is a strong wind than when there is little or no wind. Wind has a greater effect at the surface of the mix than within and can cause the surface to cool so rapidly that a crust will form. This crust must be broken down by the rollers before the compaction process can begin. The velocity of the wind is more of a concern for thin layers of mix placed in cool weather than for thicker layers laid in warmer weather.

Solar Flux

The amount of radiant energy available from the sun (solar flux) depends on many variables, including the position of the sun above the horizon, the distance above sea level of the paving project, the amount of haze in the air, and the degree of cloud cover. A mix will cool more slowly on a sunny than on a cloudy day. The amount of solar flux has more effect on base temperature than on mix temperature. For a given ambient air temperature, the base temperature will be higher on a sunny day than on a day with heavy cloud cover. The higher base temperature will reduce the rate of cooling of the mix and increase the time available for compaction.

Obtaining Proper Density Under Varying Environmental Conditions

Compaction of asphalt mix requires common sense. If lift thickness, air and base temperatures, laydown temperature, or solar flux decreases or the wind increases, less time will be available to obtain the required level of density before the mix cools to 80°C (175°F). Thus a significant change in any one of these factors can make the difference between constructing a durable pavement and building one that will be subject to early failure.

If possible, the best solution to a potential compaction problem is to increase the thickness of the material being placed. A layer 25 mm (1 in.) thick cools so quickly, even in good environmental conditions, that proper density is difficult to obtain. The minimum course thickness that should be specified under the best of circumstances is 38 mm (1½ in.). For paving conducted in early spring or late fall, at least 50 mm (2 in.) of compacted asphalt mix should be placed in a single lift, if possible.

The easiest solution to a potential time availability problem is to increase the discharge temperature of the asphalt mix at the plant, if doing so does not cause other problems with the mixture. The higher discharge temperature will permit an increase in the laydown temperature of the mix behind the paver screed, thereby allowing more time for the mix to cool to 80°C (175°F), all other factors being constant. It is also important to remember that as temperature rises, aging of binder and absorption increase, so increasing the mix temperature requires careful consideration. Increasing the mix temperature may not be enough, however, to provide adequate time for compaction under adverse environmental conditions and for thin layers of material. If the mix temperature is increased too much, the mix may be tender under the compaction equipment, and smoke or other emissions may become a problem. The mix must then be allowed to cool before the compaction process can begin. Thus there is an upper limit to the temperature increase to which the mix can be subjected.

Compaction effort can be increased simply by using more rollers to compact the pavement layer. In addition, wider or heavier rollers can be substituted for narrower or lighter equipment. A double-drum vibratory roller, for example, that is 2.1 m (7 ft) wide can be used in place of a static steel wheel tandem roller that is only 1.4 m (4½ ft) wide.

Another means of achieving desired compaction levels is to use the compaction equipment more effectively. Depending on the width being paved and the width of the rollers, the rollers can be placed almost side by side instead of end to end. Two rollers running in this fashion can cover a given area much more quickly than two rollers operating in the conventional manner. Density will increase because more compactive effort can be applied before the asphalt mat cools to 80°C (175°F). In essence, this method provides for two breakdown rollers instead of one breakdown and one intermediate roller. To obtain the required density levels, however, use of an intermediate roller or rollers may still be necessary. Increasing the speed of the rollers is not a good means of improving compaction. Two passes at high speed are less effective than one pass at half the speed.

If two different types or sizes of rollers (such as a vibratory and a pneumatic tire roller) are used for echelon rolling, it is important that each roller cover all of the mix surface. This may mean that the rollers must cross back and forth and run different roller patterns and numbers of passes. In addition, if one of the rollers is compacting a longitudinal joint, this must be considered in setting the rolling pattern for each piece of compaction equipment. It is very important that all rollers be able to keep up with the speed of the paver and that the density obtained be measured to ensure that the required level of compaction is achieved uniformly across the width of the mat.

One procedure that should *not* be used in an attempt to increase the level of density in the mix is to increase the asphalt cement content of the mix arbitrarily. Although the additional asphalt cement may be beneficial in increasing the workability of the mix, it defeats the purpose of mix design and has been linked to long-term performance problems for the mix under traffic, such as rutting and shoving.

Laydown Site Conditions

A number of factors at the laydown site directly affect the ability of the compaction equipment to create the required level of pavement density. As discussed previously, the most important of these factors is the thickness of the layer being placed. The relationship between lift thickness and nominal maximum aggregate size in the mix is also important. If the course depth is at least three times the nominal maximum aggregate size, adequate density can be achieved with normal compactive effort.

Uniformity of lift thickness is another factor to be considered. Density is much easier to obtain in an asphalt layer that has a constant thickness as compared with one that varies in depth. A variable thickness layer is often difficult to densify to a given air void content uniformly, especially when placed over a rutted or uneven pavement surface. Static steel wheel rollers tend to bridge over ruts, particularly if the ruts are relatively deep and narrow. Vibratory rollers tend to be supported by the high points in the surface, although the vibratory action has some beneficial effect in compacting the mix in the ruts. Thus adequate density is usually not obtained throughout the mix with steel wheel rollers, particularly in rutted areas where it is needed the most. Use of a pneumatic tire roller is very helpful in achieving density in both ruts and high spots if proper tire inflation pressure and wheel load are used.

Compaction Equipment

The type of equipment used to compact the asphalt mix obviously has a significant effect on the density that can be obtained with a given number of passes. Three primary types of self-propelled compaction equipment are currently being used—static steel wheel rollers, pneumatic tire rollers, and vibratory steel wheel rollers. A combination roller, equipped with both a vibratory drum and a set of four pneumatic tires, is also sometimes used.

Static Steel Wheel Rollers

Static steel wheel rollers, shown in Figure 18-3, normally range in weight from 2.7 to 12.7 tonnes (3 to 14 tons) and have compression drums that vary in diameter from approximately 1.0 m (3.3 ft) to more than 1.5 m (5 ft). The gross weight of the roller can usually be altered by adding ballast, but this adjustment cannot be made while the roller is operating and is not normally made during the course of a paving project. For this type of roller, both the gross weight of the machine and the contact area of the drums with the mix are important in determining the compactive effort applied by the roller to the surface of the new mat.

Effective contact pressure, in terms of kilopascals (kPa) [pounds-force per square inch (psi)] over the contact area, is the key variable for this type of equipment and is dependent on the depth of penetration of the drums into the mix: the greater the depth of penetration, the greater is the contact area and so the less is the contact pressure. Thus on the first pass of the roller, when the indentation of the drums into the mix is the greatest, the roller exerts less compactive effort on the mix. On subsequent passes as the mix becomes more dense, the drums penetrate to a lesser degree, and the compactive effort of the roller is increased.

Drawbar pull is defined as the horizontal force required to move the roller forward. The most efficient roller is that with the smallest drawbar pull. Rollers with large-diameter drums have lower drawbar pull (rolling resistance) because they do not tend to penetrate as far into the mix to develop a contact area as a roller with smaller-diameter drums.

Once the size and weight of a static steel wheel roller have been selected, the variables under the control of the roller operator are the speed of the roller, the position of the roller on the mat in relation to the paver, operation with the drive wheel or drum toward the paver, and the number of passes made with the roller over each point in the pavement surface.

Pneumatic Tire Rollers

Pneumatic rollers are usually operated in the intermediate roller position, behind a vibratory or static steel wheel breakdown roller and in front of a static steel wheel finish roller. Pneumatic rollers are sometimes used, however, for initial rolling of the mix, and occasionally for finish rolling.

For a pneumatic roller, shown in Figure 18-4, the compactive effort applied to the mix is a function of the wheel load of the machine, the tire pressure, the tire design (tire size and ply rating), and the depth of penetration of the tires into the mix. All of the tires on the roller should be the same size, ply, and tire pressure. The area of each tire footprint and the wheel load of the roller are the primary factors in the effectiveness of a pneumatic tire roller. The greater the contact pressure between the tire and the mix, the greater is the compactive effort applied by the roller.

To be effective when used in the breakdown roller position, rollers with larger tires should be used. Rollers equipped with tires 7.50 × 15 or smaller are normally not effective as breakdown rollers. If pneumatic tire rollers are used as intermediate rollers, the minimum tire ply rating should be 12, and the tire pressure should be 400 kPa (60 psi) or greater.

The tire pressure used depends in part on the number of plies in the tires. In general, a 6-ply tire is limited to a

FIGURE 18-3 Static steel wheel roller.

FIGURE 18-4 Pneumatic tire roller.

tire pressure of 400 kPa (60 psi), whereas a 10-ply tire can carry a pressure of up to 600 kPa (90 psi). A 12-ply tire, normally used on most large pneumatic tire rollers, can be inflated up to 800 kPa (120 psi) to compact asphalt mixes. The minimum weight of the pneumatic tire roller should be 13.6 tonnes (15 tons).

If the mix is tender, use of a lower tire pressure will displace the mix less than will use of a higher pressure. For a stiff mix, a higher tire pressure can be used because the mix will be stable enough to support the weight of the roller without shoving laterally under the tires. Tire pressure is normally kept constant for a given project, but the level selected should be dependent on the properties of the mix being compacted and the position of the roller on the mat. Tire pressure should not necessarily be the same if the pneumatic tire roller is used in the breakdown position as if used in the intermediate position. Higher tire pressure can often be employed when the pneumatic tire roller is used in the intermediate position because the mix should be stiffer at the lower temperatures in this stage of the process and can thus support more compactive effort without distortion.

The tires on the pneumatic roller will pick up the mix if the roller moves into the mix when the tires are cold. The tires will also often pick up the mix when an oversanded surface course mix is being compacted. Pickup may be a significant problem as well when the mix has been modified with polymer additives. If the mix contains a rubber additive, the pickup problem may be so severe that this type of roller cannot be used. If pickup of the mix on the tires is found to be a major problem, it should be determined whether the mix contains a modified binder material, although if the asphalt cement has been formulated to meet a PG binder grade, the binder supplier may be unwilling to reveal its composition for proprietary reasons.

Attempts are frequently made to eliminate the pickup problem by spraying water or a release agent on the tires during the rolling process. This practice does not always solve the problem. If the roller is not damaging the mat, a better solution is to allow the tires on the roller to reach the same temperature as the mix being compacted without spraying water or release agent on the tires. Pickup will be minimized or eliminated. Skirts consisting of pieces of plywood or rubber sheeting, shown in Figure 18-5, are sometimes hung from the sides of the roller around the tires to shield the tires from the wind and prevent them from cooling off. This approach is effective, especially on windy, cool days.

If a pneumatic tire roller is to be used as the breakdown roller in the roller train at the start of paving in the morning, it is suggested that to minimize pickup, the roller be run back and forth for 10 to 15 minutes on the cold pavement before the paver begins to lay mix in order to start building up heat in the tires. Once paving begins, the roller should be operated in the intermediate position, behind a static steel wheel or vibratory roller, for another 10 minutes while the temperature of the tires increases to the same level as that of the mix. No water or release agent should be applied to the tires during this warmup time.

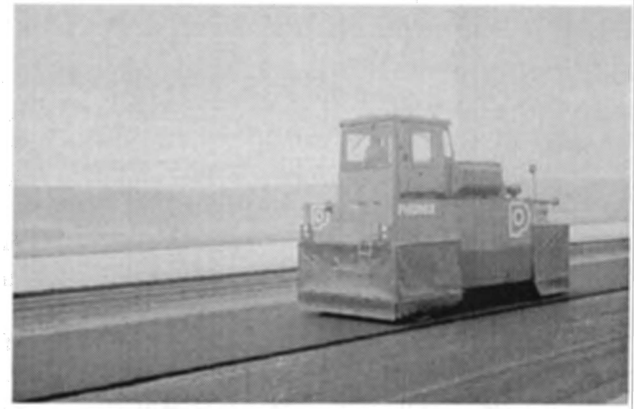

FIGURE 18-5 Pneumatic tire roller with skirts.

During the heating process, some pickup of the mix on the tires may occur. Once the tires have reached the same temperature as the mix, however, the amount of pickup will decrease. At this time, the roller should be briefly moved off of the paving lane, the tires quickly cleaned off, and the roller moved back onto the hot mix. The pneumatic tire roller can then be moved into the breakdown position and should be able to operate successfully without pickup of the mix. If the paving process is interrupted for any significant length of time, however, this preheating startup procedure will have to be repeated. In no case should the pneumatic tire roller be parked on the hot mat in an attempt to keep the tires warm while waiting for the paving operation to restart.

Once the size of the pneumatic tire roller and the tire pressure to be used have been selected, the only variables that can be controlled easily by the operator are the rolling speed, the location of the roller with respect to the paver, and the number of roller passes over each point in the pavement surface. If the compactive effort applied by the pneumatic tire roller is not adequate, the operator should alter the wheel load on the tires or change the inflation pressure, or both.

Vibratory Rollers

Vibratory rollers (see Figure 18-6) come in a variety of configurations. Single-drum vibratory rollers are manufactured with both a rigid and an articulated frame. Double-drum vibratory rollers come with rigid, single-articulated, and double-articulated frames. These rollers can be operated in any of three modes: static (with the vibrators off), with one drum vibrating and one drum static, and with both drums vibrating.

Vibratory rollers apply two types of compactive effort to the HMA—static weight and dynamic (impact) force. The compactive effort derived from the static weight of the roller is caused by the weight of the drums and frame. The compactive effort derived from the dynamic force is produced by a rotating eccentric weight located inside the drum (or drums). As the eccentric weight rotates about the shaft inside the drum, a dynamic force is produced. This force is proportional to the eccentric moment of the rotating weights and the speed of rotation. Changing the eccentric moment arm or adjusting the eccentric mass has a directly proportional effect on the dynamic force.

Although it is possible to combine the static weight and dynamic force to determine a total applied force, this procedure is not recommended for comparing vibratory rollers of the same or different classes. Rather, components of the total applied force should be evaluated separately. The elements of comparison for the dynamic component of a vibratory roller are the magnitude of the centrifugal force, its vibrating frequency, the nominal amplitude, and the ratio of the vibrating and nonvibrating masses acting on the drum. Nominal amplitude is defined as the weight of the drum divided by the eccentric moment of the rotating weight and is a function of the weight of the drum and the location of the eccentrics.

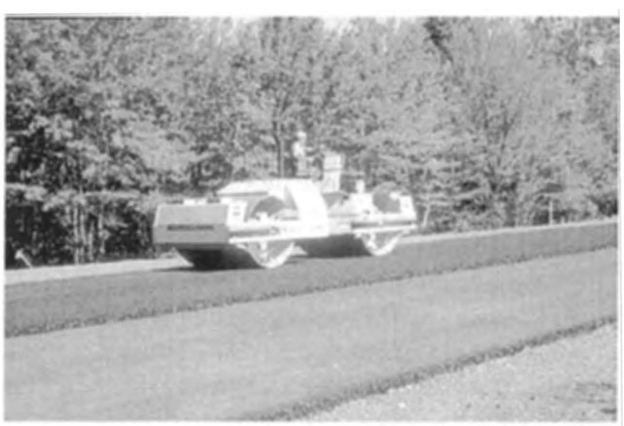

FIGURE 18-6 Vibratory steel wheel roller.

Normal values of nominal amplitude range from 0.25 to 1.02 mm (0.01 to 0.04 in.). Some rollers can operate at only one fixed amplitude. Others have high and low amplitude positions. For these rollers, the low nominal setting is typically 50 percent of the high setting. On some vibratory rollers, several (up to eight) different amplitude settings can be selected. The actual amplitude differs from the nominal amplitude because of the variation in the damping effect of different materials at different states of compaction. An increase in the applied nominal amplitude of vibration increases the compactive effort applied to the asphalt mixture. For a given frequency, changing the amplitude setting has a proportional effect on the dynamic force. For a given amplitude, changing the frequency influences the dynamic force to the second power.

The effectiveness of an increase in the amplitude value, however, is sometimes dependent on the thickness of the layer being densified. For relatively thin layers of mix, generally less than approximately 30 mm (1¼ in.) in compacted thickness, the vibratory roller should typically be operated in the static mode—without vibration. Otherwise, as the mix densifies under the applied compactive effort of the vibratory roller, the drums will begin to bounce. This in turn may cause the mix to shove and decompact instead of densifying, depending in part on the stiffness of the underlying pavement structure. In addition, when the roller is operated in the vibratory mode on a thin lift, some of the aggregate in the HMA will be crushed.

In general, for layers with a thickness of 30 mm (1¼ in.) or more, a low amplitude setting should be used on the vibratory roller. This setting should be maintained unless the compacted thickness of the layer is at least 65 mm (2½ in.). As the thickness of the layer increases beyond this level, the amplitude setting on the roller can generally be raised to increase the compactive effort applied to the mix. It should be noted, however, that very few layers of HMA are more than 65 mm (2½ in.) in compacted thickness.

If there is a problem in achieving density quickly, roller operators will sometimes raise the amplitude setting on the roller. This is not necessarily the correct practice. In most cases, particularly for lifts 65 mm (2½ in.) or less, increasing the applied force may cause the aggregate in the mix to fracture and actually reduce rather than increase density. Better practice is to increase the number of passes made over the mix with the vibratory roller operated at the low amplitude setting. The vibratory roller should be operated at low amplitude unless high amplitude is needed to achieve a particular density level. If so, the mix should be stiff and internally stable enough to support the added compactive effort without checking of the mix or fracturing of the aggregate.

Vibration frequency is the number of complete rotations per minute of the eccentrics: the faster the rotation, the greater the frequency. Some vibratory rollers can operate at only one frequency; others have a choice of two or more frequency settings. Most older vibratory rollers can operate with frequencies in the range of 1,600 to 2,400 vibrations per minute, whereas newer rollers can operate at up to 3,600 vibrations per minute. In general, to apply adequate compactive effort to the HMA without introducing ripples or roughness into the surface of the layer, a vibratory roller should be operated at a frequency of at least 2,000 vibrations per minute. Further, with few exceptions, the vibratory roller should be operated at as high a frequency setting as possible.

Spacing of the impacts depends on the frequency of the vibration and the travel speed of the roller. As frequency decreases and roller speed increases, the distance between impacts on the surface of the mix increases. Conversely, an increase in the vibratory frequency and a decrease in the roller speed both cause the number of impacts per foot of distance to increase, thereby increasing the compactive effort applied by the roller. A smaller impact spacing (a greater number of impacts per foot) is usually preferred. It must be realized, however, that the productivity of the roller can decrease as the roller speed is reduced.

Several roller manufacturers suggest that the ideal impact spacing is in the range of 30 to 40 impacts per meter (10 to 12 impacts per foot) in order to provide a balance between roller productivity and layer smoothness. This spacing can be determined by dividing the roller speed by the frequency of vibration: impact spacing = roller speed in meters (feet) per minute, divided by frequency of vibrations. An applied force of 30 impacts per meter is equal to approximately 33 mm between impacts, whereas 40 impacts per meter is equal to 25 mm between impacts (an applied force of 10 impacts per foot is equal to 1.2 in. between impacts, while 12 impacts per foot is equal to 1.0 in. between impacts).

At a frequency of 2,400 vibrations per minute, a roller speed of about 4.8 km/h (80 m/min) will result in an impact spacing of 33 mm (30 impacts per meter), and a roller speed of about 3.6 km/h (60 m/min) will result in an impact spacing of 25 mm (40 impacts per meter) (at a vibratory frequency of 2,400 vibrations per minute, a roller speed of approximately 2.7 mph will result in an impact spacing of 10 impacts per foot, and a roller speed of about 2.3 mph will result in an impact spacing of 12 impacts per foot). If the vibratory frequency is set at 3,000 vibrations per minute, the corresponding roller speeds will be approximately 5.6 and 4.2 km/h for impact spacings of 30 and 40 impacts per meter, respectively (if the vibratory frequency is set at 3,000 vibrations per minute, the corresponding roller speeds will be about 3.4 and 2.8 mph for an impact spacing of 10 and 12 impacts per foot, respectively).

As noted, the vibratory roller should generally be operated at as high a frequency as possible. A roller capable of 2,000 to 2,400 vibrations per minute, for example, should be operated at the upper end of this frequency range. Using the highest possible frequency of vibration increases the number of impacts per meter (foot) at a given roller speed. For the vast majority of paving projects encountered, the properties of the HMA will not affect the selection of the frequency setting, nor will the thickness of the layer being compacted, as long as the thickness is greater than 25 mm (1 in.). Most vibratory rollers are designed so that the highest frequency can be used at the highest amplitude setting, although for some rollers, it is necessary to operate at a somewhat lower frequency when the roller is used at the highest amplitude setting. The optimum combination of vibratory amplitude, vibratory frequency, and roller speed will provide for the greatest gain in density for each pass of the roller and also the greatest smoothness for the pavement surface.

When using a vibratory roller, the operator is in control of more variables than when using the other types of rollers and thus should be well versed in the proper selection and interaction of those variables. Nominal amplitude and frequency can be varied in addition to the roller speed, the location of the roller with respect to the paver, and the number of passes made over each point on the pavement surface.

For double-drum vibratory rollers, the operator can vibrate either one or both drums. Thus the operator can control the compactive effort applied to the mix to a greater degree than is possible with either static steel wheel or pneumatic tire rollers. In most cases, it is most efficient to operate both drums of a double-drum vibratory roller in the vibratory mode. The only exception is when the roller is moving up or down a steep hill, in which case it may be necessary to run only one drum in the vibratory mode so the roller can maintain forward motion on the hill without sliding off the mat.

Some roller operators run in the vibratory mode while moving only in one direction behind the paver—usually toward the paver. When the roller is moving away from the paver, the operator switches off the vibration and runs in the static mode. For the vast majority of HMA mixes, there is no reason to operate the roller in the static mode and reduce the compactive effort of this type of roller.

Construction of a roller test strip may be necessary to determine the optimum combination of roller speed and vibratory amplitude for a particular set of project conditions. If the required density cannot be achieved, the speed of the roller typically should be decreased and the nominal amplitude setting changed, unless the roller is already at the lowest amplitude setting.

Care should be taken when a vibratory roller is operated in the vibratory mode if underground utilities or drainage structures are directly beneath the pavement layer being compacted. If there is any chance that those utilities or structures might be damaged by the vibrations from the roller, the equipment should be operated in the static mode.

Combination Rollers

Combination rollers combine a vibratory roller drum on the front of the roller and a set of four rubber tires on the back. It has been suggested that these rollers are the best of both worlds since they combine two distinctly different types of compactive effort—vibratory force and pneumatic tire kneading action. In reality, however, this type of roller may produce a significant variation in density across the width of the lane being compacted.

The outside width of the rubber tires is generally equal to the width of the vibratory drum. The problem is, however, the gaps between the four rubber tires on the back of the roller. Unlike a standard pneumatic tire roller in which the tires on the back of the roller fit into the spaces left by the gaps between the front tires, the combination roller has no extra tires to fill in the gaps. It would be unrealistic to expect the roller operator to be able to overlap each succeeding pass of the roller by exactly one tire width to obtain uniform density across the entire lane width. This type of roller should therefore be used with caution when compacting HMA.

COMPACTION VARIABLES UNDER OPERATOR CONTROL

For all types of rollers, the primary compaction variables that can be controlled during the rolling process are roller speed, number of roller passes, rolling zone, and rolling pattern. For vibratory rollers, direction of travel and mode of operation are also under the operator's control. Each of these factors has an effect on the level of density achieved under the compactive effort applied to the mix.

Roller Speed

The more quickly a roller passes over a particular point in the new asphalt surface, the less time the weight of the roller "dwells" on that point. This in turn means that less compactive effort is applied to the mixture. As roller speed increases, the amount of density gain achieved with each roller pass decreases. The roller speed selected is dependent on a combination of factors: paver speed, layer thickness, and position of the equipment in the roller train.

Static steel wheel rollers can operate at speeds of 3 to 9 km/h (2 to 5 mph); pneumatic tire rollers typically run at 3 to 11 km/h (2 to 7 mph); and vibratory rollers can operate at speeds of 3 to 6 km/h (2 to 3½ mph). In the breakdown position, each type of roller should be operated at the lower end of its speed range. In the intermediate position, the speed of the roller can be increased somewhat, typically to the middle of the speed range. In the finish rolling position, the roller can be near the upper end of its speed range. Table 18-1 shows the range of roller speeds for three different types of rollers and three different operating positions. Rollers can move more quickly or more slowly than these speeds, but compactive effort is significantly improved at slower roller speeds.

Roller speed is also governed by the lateral displacement or tenderness of the asphalt mix. If the mixture moves excessively under the rollers, the speed of the compaction equipment should be reduced. In addition, roller speed affects the impact spacing for vibratory rollers. As discussed earlier, this spacing is important for controlling the amount of dynamic compaction energy applied to the mix, as well as for obtaining the proper surface smoothness.

Roller speed is usually established by the speed of the paver. Too often if the paver pulls away from the rollers, the rollers increase speed to catch up, which causes density in the asphalt mixture to be lower after applying the same number of roller passes. Paver speed should be selected to match the production rate of the asphalt plant, and that speed should be kept constant. The speed for each roller should then be determined based on the paver speed and the number of passes each roller must apply.

TABLE 18-1 Range of Roller Speeds (mph)

	Operating Position		
Type of Roller	**Breakdown**	**Intermediate**	**Finish**
Static steel wheel	2–3½	2½–4	3–5
Pneumatic	2–3½	2½–4	4–7
Vibratory	2–3	2½–3½	—

Note: 1 mph = 1.6 km/h.

Changing roller speed merely causes variations in density. "Slow and steady" is the key to proper compaction.

If the paver continually pulls ahead of the rollers, several courses of action can be taken. First, paver speed can be reduced to match both plant and roller production. Too often the paver is operated on a "hurry and wait" basis between truckloads. If plant production capacity necessitates continued higher paver speeds, additional rollers are required to achieve adequate density. Wider rollers can also be employed. For example, a vibratory roller 2.1 m (7 ft) wide can be used in place of a tandem roller 1.4 m (4½ ft) wide. The type of roller used can be changed as well; for example, a double-drum vibratory roller can be used instead of a single-drum vibratory or static steel wheel roller.

The breakdown roller and sometimes the intermediate roller may stop whenever the paver stops to wait for trucks, even though the rollers have not completed their roller patterns. When the next truck arrives and the paver again starts moving, the rollers also restart and finish compacting the mix. While the rollers have been idle, however, the mix on the roadway has cooled, and the density obtained in the cooled area will usually be less than that in the surrounding area. The roller should keep rolling until the established pattern and number of passes over each point have been completed.

Number of Roller Passes

To obtain the target air void content and uniform density in an asphalt mixture, each point in the pavement must be rolled a certain number of times. The number of required passes depends on many variables, including, most important, the type of compaction equipment. Three-wheel steel wheel rollers, tandem steel wheel rollers, pneumatic tire rollers, and single- or double-drum vibratory rollers all have different capabilities. At the same time, the capabilities of each type of roller depend on mat thickness, mix temperature, mix design properties (binder content, binder stiffness, and aggregate characteristics), and environmental conditions. Finally, the number of passes required depends on the position of the roller in the roller train.

One or more test strips should be constructed at the start of any major paving project to determine the minimum number of roller passes needed to achieve proper density levels. Different combinations of rollers and roller patterns should be tried to determine the optimum combination of compaction variables that will achieve the required density level as efficiently as possible. Rarely will the first trial combination of rollers, roller passes, and rolling zones provide the most economical rolling sequence, unless the mix is one the contractor has used many times in the past.

Roller passes must be distributed uniformly over the width and length of the mat. All too often the center of the paver lane (the area between wheelpaths of a single-lane pavement) receives adequate roller coverage, whereas the edges of the mat receive considerably less compactive effort. As discussed further below in the section on rolling patterns, the uniformity of roller passes across the lane width is just as important as the number of passes.

Rolling Zone

Compaction must be achieved while the viscosity of the asphalt binder in the mix and the stiffness of the mix are low enough to allow for reorientation of the aggregate particles under the action of the rollers. In other words, the mat must still be hot enough for effective compaction. As discussed earlier, the rule of thumb commonly used is that the proper level of air voids should be obtained before the mix cools from its laydown temperature to 80°C (175°F).

To obtain the required density level most quickly, initial compaction should occur directly behind the laydown machine. If the asphalt mixture is stable enough, breakdown rolling can be carried out very close to the paver, while the mat temperature is still high. More density is obtained with one pass when the mix temperature is 120°C (250°F) than when it is 110°C (230°F). Thus the front of the rolling zone should be as close as possible to the back of the paver.

Sometimes when a tender mix is placed, initial rolling is delayed to avoid excessive shoving or checking of the mix by the rollers. Depending on mix characteristics, the required density can be achieved as long as the proper combination of rollers and compactive effort is applied. In some cases, however, the mix is so tender that rolling must be delayed to the point that the desired density level cannot be achieved. In this case, other solutions must be tried. When a tender mix is encountered, the cause of the tenderness must be determined and changes made in the mix production and paving operation to ensure adequate density. Compaction of tender mixes is discussed later in this section.

Rolling Pattern

Rollers should be operating most of the time. The question is whether they are operating correctly and effectively. Compaction is frequently not applied in the right place. Numerous compaction studies have shown that the middle of the width of the paver pass typically receives much more compactive effort than the edges. Unfortunately, traffic uses the wheelpath areas near the edge of the pavement more often than the center of a lane.

For example, on an actual HMA paving project on an Interstate roadway, the mixture was placed in a trench section 3.7 m (12 ft) wide in two compacted lifts 75 mm (3 in.) thick. Initial or breakdown rolling on the first layer was accomplished using a vibratory roller 2.1 m (7 ft) wide. For the 3.7-m (12-ft) wide paver pass, two passes of the vibratory roller could cover the whole mat width, with about a 0.5-m (2-ft) overlap in the center. To gain adequate density, the operator of the breakdown roller had to keep the vibratory roller tight to each side of the trench. To cover the complete width of the lane, the operator would need only to make a roller pass on each side of the lane directly toward and then away from the paver without ever attempting to roll the center of the lane.

Instead, the roller operator made his first pass, 3.7 m (7 ft) wide, up the left-hand side of the mat. Upon reaching the back of the paver, the operator reversed direction, changed lateral direction slightly, and moved away from the paver by traveling down the center of the mat, with 0.8 m (2½ ft) of free area on each side of the roller. The third pass, again toward the paver, was along the right-hand edge of the driving lane. The fourth pass (away from the paver) was once more down the center, similar to the second pass. The final pass, to catch up to the paver, was a reversal of the fourth—up the center of the lane. The roller operator continued to repeat this five-pass pattern as the paver moved down the roadway.

Five passes of this breakdown roller were applied to the center of the 3.7-m (12-ft) wide area, an area not used by traffic. Only one pass was applied over each wheelpath and each outside edge of the lift. The roller was simply not being used properly. A future failure was built into this pavement structure because proper density was not obtained in the wheelpaths where it was needed. If the number of roller passes made on each edge of the lane being compacted is adequate to meet specifications, the density level in the center of the lane will always be more than enough to also meet specifications. Thus roller patterns should be designed to ensure proper, uniform compaction of the entire lane width.

For each roller used on a project, the mat width can be divided by the width of the compaction drums to determine the number of passes needed to cover each transverse point in the surface. A pass is defined as one trip of the roller in one direction over any one spot. Multiple passes are needed to completely compact each point in the pavement surface over the transverse width of the lane being paved to the required level of density.

If the width of the roller drums (or tires) is 2.1 m (7 ft), only two passes are needed to cover a lane 3.7 m (12 ft) wide, including an overhang 150 mm (6 in.) wide over each edge of the pavement. Two passes of the 2.1-m (7-ft) wide roller overlap for a distance of about 300 mm (12 in.) in the center of the lane. If allowance is made for the fact that the roller operator may not always be able to maintain a 150-mm (6-in.) overhang on the edge of the pavement, the 300-mm (12-in.) wide overlap in the center of the lane is still sufficient to permit the entire pavement width to be compacted in two passes with a minimum 150-mm (6-in.) wide overlap needed between roller passes.

A roller that is 1.8 m (6 ft) wide cannot cover a complete 3.7-m (12-ft) lane width in only two passes. Two passes do not allow for any overhang at the edge of the lane or any overlap at the center. Thus three passes of a 1.8-m (6-ft) wide roller are necessary to compact the lane properly.

If the roller has drums or tires that are only 1.5 m (5 ft) wide, three passes of the roller are required, as with a roller with 1.8-m (6-ft) wide drums. If 150 mm (6 in.) is allowed for the edge-of-lane overhang, the amount of overlap between roller passes should be about 300 mm (12 in.). This overlap allows for ample steering variation by the roller operator and permits a 3.7-m (12-ft) lane width to be covered with three passes of the 1.5-m (5-ft) wide roller.

A roller with drums 1.4 m (4.5 ft) wide needs to make four passes across the width of a 3.7-m (12-ft) lane to completely cover the lane width. If this roller overhangs each edge of the pavement by 150 mm (6 in.) and only three passes across the lane width are made, the roller drums will overlap only 75 mm (3 in.) between the first and second passes and 75 mm (3 in.) between the second and third passes across the width. This amount of overlap between passes is not adequate to ensure uniform compaction. Thus four passes of the 1.4-m (4.5-ft) wide roller are necessary to properly compact a paving lane 3.7 m (12 ft) wide.

In a longitudinal direction, the rollers should not stop at the same transverse end point with each pass of the roller; the reversal points should be staggered to prevent shoving of the mix. A slight change in direction, or curl, may be beneficial at each reversal spot to further reduce the tendency of the mix to shove under the compactor and to eliminate the possibility of a bump at the point where the roller reversal occurs. The roller should not sit and wait while parked on the hot mat. A long delay caused by a lack of haul trucks at the paver or filling of the compactor with water allows the roller to indent the new mat. It is generally impossible to roll out these marks once the mat has cooled. Thus when idle, all rollers should be parked on the shoulder or at an angle back on the cooler mat.

Many old compaction specifications require the compaction process to start at the low side of the pavement lane and proceed toward the high or upper side on subsequent passes of the roller. With modern compaction equipment and more stable asphalt mixes, this requirement is usually unnecessary, but it may be advisable for superelevations and lifts that are thick in relation to maximum particle size. In addition, some older specifications stated that the rollers had to overlap the width of the previous pass by at least half the width of the roller. This procedure leads to nonuniform compaction across the width of the pavement lane and a distinct lack of density on the outside edges of the lane. Modern standard practice is to have each roller overlap its own pass by a minimum of 150 mm (6 in.).

Determination of the rolling pattern is discussed in detail in the next section.

Direction of Travel and Mode of Operation for Vibratory Rollers

When using a single-drum vibratory roller, the compression drum should normally be operated toward the paver. This practice ensures that the maximum compactive effort of the compression drum is placed on the mat before the lesser compactive effort of the steering drum. In addition, this practice results in a denser layer to better resist displacement of the mix caused by the continual movement of the tiller drum during the steering action. A single-drum articulated-frame roller should also be operated with the driven drum toward the laydown machine, again to ensure that the maximum compactive effort is applied to the mix as quickly as possible.

When only one drum of a double-drum roller is operated in vibrating mode, the roller is often operated with the vibrating drum toward the laydown machine and the static drum trailing. A double-drum articulated-frame roller that has two driven drums (a vibratory tandem roller) operates the same in either direction. Thus for this type of roller, the direction of travel is not a consideration.

For harsh or stiff mixtures, breakdown rolling is normally accomplished with both drums of a double-drum roller vibrating. Subsequent passes are made in the full vibratory mode as well. For mixtures with normal stability, breakdown rolling with a vibratory roller should also generally be accomplished in the full vibratory mode. For tender mixtures, as discussed below, initial breakdown rolling is sometimes accomplished in the static mode or in a combination mode. Subsequent passes are usually made in the combination mode if mixture displacement is not too great. When operating in the combination mode for tender mixtures, the trailing drum instead of the front drum is usually vibrated.

DETERMINATION OF ROLLING PATTERN

Different mixes may require considerably different levels of compactive effort and thus different compaction equipment and rolling procedures. Different types or combinations of rollers may be needed to achieve a required level of density for an asphalt mix containing large aggregate, for example, than for a mix made with smaller-size coarse aggregate.

As suggested earlier, the rolling pattern to be used on a particular paving project should be determined at the start of the project through the construction of one or more roller test strips. The strip(s) should be located at a convenient point where the pavement layer placed will remain as part of the final pavement structure. The mix should be representative of the material to be produced for the project; generally the plant should produce mix for a short period of time before the mix for the compaction test section is made so the mix will be as consistent as possible. The thickness of the layer compacted should be the same as that to be used for the rest of that layer, and the length of the test strip(s) should be at least 100 m (330 ft). The condition of the underlying layers should be representative of that on the rest of the project.

Due consideration should be given to the selection of the rollers to be used. The combination of rollers used on a previous project might not be the most cost-efficient or effective for the variables involved in the present job. Although vibratory rollers are generally used for breakdown rolling and pneumatic tire rollers for intermediate rolling, a greater degree of density with fewer roller passes may be obtained for some stiff mixes when a large pneumatic tire roller is used in the breakdown position, with the vibratory roller following in the intermediate position.

If a large pneumatic tire roller is used in the breakdown position, it is generally difficult to determine the degree of density obtained in the mat by using a nuclear gauge (discussed below) because of the uneven surface of the mat after the first several passes of the pneumatic tires. Nuclear readings must be taken after the mix has been smoothed out with the intermediate steel wheel roller, either vibratory or static. A compaction test strip should be used to determine the most effective sequence of rollers to achieve the required degree of compaction, smoothness of the mat, and economical production.

Desired density levels are easier to obtain when the asphalt mix is hot. As discussed earlier, instead of using the rollers in the traditional roller train formation, consideration should be given to using two breakdown rollers, preferably of the same type, instead of a breakdown roller followed by an intermediate roller. This practice is particularly beneficial on thin layers of mix under unfavorable environmental conditions.

As noted earlier, two breakdown rollers can be operated side by side to expedite rolling. Depending on the width of each roller and the width of the lane, complete compaction across the paving width can normally be accomplished very quickly. If two different rollers are employed side by side in the breakdown position—a double-drum vibratory roller and a pneumatic tire roller, for example—it is important that each roller cover the whole width of the lane at some point during the compaction process. The two rollers will have to leapfrog each other for this to be accomplished, but with a little practice, the operation can be done easily. Again, the purpose of using two rollers, both running in the breakdown position, is to apply compactive effort to the mat before it cools.

Calculation of Rolling Pattern

To determine the optimum rolling pattern, the first calculation needed is the paver speed, which is based on the amount of mix to be produced by the plant, the width of the pavement lane, and the depth of the mix. Once the average paver speed is known, the maximum speed of the rollers should be selected. The speed selected for each roller will depend on the type of roller and its width, as well as its position in the rolling sequence. The selected speed will also depend on the ability of the roller to strike a balance among achieving density, smoothness, and a uniform pavement surface.

The second calculation involves comparing the width of the layer being placed and the width of the rollers to be used in order to determine the number of transverse roller lanes needed to cover the entire width of the pavement. The number of passes must be matched to the speed of the paver. (A pass is defined as a trip of the roller in one direction over any point on the pavement surface.) Given the paver speed, the roller speed, and the number of transverse lanes needed to obtain full-width coverage of the roadway surface, it is possible to determine the number of passes each roller can make over each point in the pavement while still keeping up with the paver.

As discussed earlier, the number of roller passes needed over each point on the pavement surface depends on a large number of variables. One of the most important of these is the level of density required in the pavement layer. If a method specification is being used, the required number of passes can simply be counted. What is not known, however, is the degree of density (air void content) that will be obtained in the mix after the specified number of passes has been completed. If a certain percentage of laboratory density or theoretical maximum density is required, the higher is the required percentage, the more compactive effort will have to be applied to the pavement layer.

The type of breakdown roller used will also be very important. Under some conditions, one vibratory roller may be sufficient to achieve the required density, depending on the properties of the mix. In other cases, say, if the mix is tender and checking occurs, several passes of a pneumatic tire roller may be necessary to achieve the required density level. One or more passes of a static steel wheel roller are normally needed to remove roller marks, particularly if a pneumatic tire roller has been used. Because of the number of variables involved, it is impossible to generalize about the best combination of rolling and roller pattern to use in all cases.

Some contractors always use the same rollers in the same order making the same number of passes over the mix, regardless of the project variables. The same overall compactive effort is applied to a thin lift as to a thick lift, to a mix placed during hot summer months as to one placed during the cool spring or fall season, to a mix placed on top of a very strong foundation and to one placed on top of a weak base, and to a mix that is very stiff and one that is tender. As noted, however, different mixes and different project conditions require different compactive efforts to obtain the same degree of density.

Monitoring Density

The most common method of monitoring changes in density with roller passes is with a nuclear density gauge, shown in Figures 18-7 and 18-8. Density is estimated by transmitting gamma rays into the mix and measuring the amount of radiation reflected back to the device in a given amount of time. The data obtained can be related to the relative density of the layer. Nuclear gauge readings should be taken after each pass of each roller, and the rate of increase in density after each pass determined. When no appreciable increase in density is obtained with

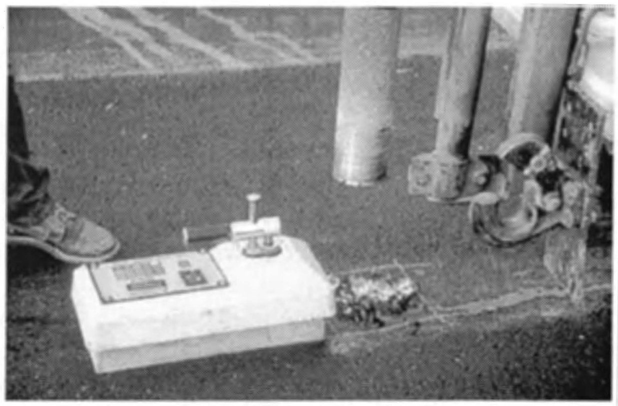

FIGURE 18-7 Nuclear gauge for monitoring density.

the application of additional roller passes, the maximum relative density for that mix has usually been obtained. As noted above, when a pneumatic tire roller is used in the compaction process, particularly in the breakdown mode, it is often very difficult to obtain an accurate density reading with a nuclear gauge. One or more passes with a steel wheel roller may be necessary before a valid nuclear gauge reading can be obtained.

The density value determined with a nuclear gauge is relative and is generally not the same as the density value obtained from cores cut from the pavement. A correlation must be made between the nuclear density reading and the actual unit weight of the pavement using cores that are cut from the test section after the rolling process has been completed. The actual unit weight must be compared with the maximum theoretical unit weight of the mix or the laboratory chemistry to determine whether the required density was achieved.

Because different nuclear gauges provide different readings, a single gauge should be used throughout the project. If more than one gauge is used, each should be

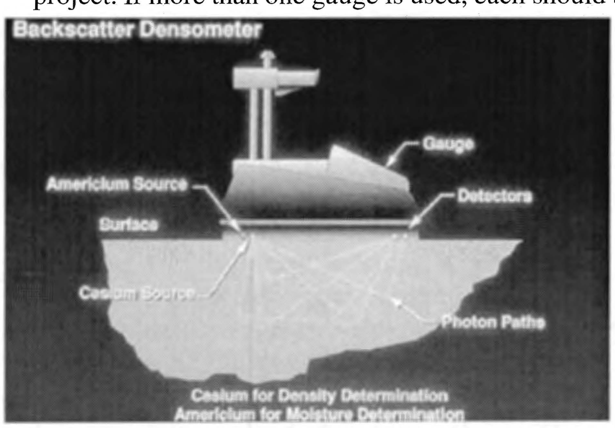

FIGURE 18-8 Schematic of nuclear gauge.

properly correlated to the core density so that the nuclear readings from each will accurately monitor the level of density being obtained in the mat. A new correlation relationship should be developed each time there is a significant change in the design of the HMA mix, the thickness of the layer being compacted, or the stiffness of the underlying pavement structure.

Usually a nuclear density gauge is correlated to unit weight by extracting cores from one of the test strips at the start of the project. A number of locations—10 locations are commonly used—are selected by random number. Multiple density readings are taken on top of each marked spot. Cores are then cut and tested to determine density. A graph is made, with the average nuclear density reading at each location plotted on one axis and the corresponding core density plotted on the other. A best-fit correlation line is drawn through the data points. Later, when the nuclear gauge is used to monitor density, the gauge reading is converted to a core density using the best-fit line.

To obtain a correlation, some operators calculate the average nuclear density reading and compare it with the average core density. In effect, they assume that there is a constant difference between the two methods. In fact, the difference is not constant but depends on the nuclear gauge reading. Therefore, a constant offset should not be used.

Compaction of Stiff Mixes

HMA mixtures that are properly designed will be reasonably stiff and stable and will require a considerable amount of compactive effort to attain the required degree of density. This type of mix will support the weight of the compaction equipment directly behind the paver. If the mix is placed at a temperature of 135°C (275°F) or higher, the rollers will typically be able to compact the mix properly before it cools to a temperature of 80°C (175°F).

Most often, three rollers are used—a breakdown roller, an intermediate roller, and a finish roller. For breakdown rolling, as discussed above, a vibratory steel wheel roller is most often used. For intermediate rolling, a pneumatic tire roller is generally employed, although sometimes a second vibratory roller is used. Finish rolling is normally done with a static steel wheel roller.

The breakdown and intermediate rollers should stay close to the paver. If the mix is stable, a bow wave will not occur in front of the vibratory roller drum, and the mix will not exhibit any cracking or checking. With a relatively stiff mix, the finish roller should also be close to the paver since there will be minimal marks from the breakdown and intermediate rollers to be removed.

For very stiff mixes or when a high degree of density is desired, a pneumatic tire roller should be used for breakdown rolling. For intermediate rolling, a vibratory steel wheel roller should follow directly behind the pneumatic tire roller, and the finish rolling should be done with a static steel wheel roller. Because of the internal stability and strength of the stiff mix, more compactive effort may be needed to obtain a given level of density (percent of theoretical maximum density), but the mix will not move under the compaction equipment during the rolling process.

Compaction of Tender Mixes

A tender mix is generally an internally unstable mix that will not properly support the weight of the compaction equipment when hot and will move under the applied compactive effort. The movement of the mix can take various forms. First, a bow wave may occur in front of the steel wheel on both a vibratory and static steel wheel roller as these rollers move longitudinally up and down the mat. Second, the mat may widen out when the rollers are used to compact the unsupported edge of the lane—mix placed 3.7 m (12 ft) wide, for example, may squeeze out to a width of 3.9 m (12½ ft) or more. Third, checking—short, transverse cracks that develop during the compaction process—may occur in the mix. Fourth, longitudinal humping up and checking of the mix may occur immediately outside of the edges of the steel wheel on the rollers.

Tenderness usually comes in one of two forms. Classical tenderness occurs when the breakdown roller is unable to approach the paver without the mixture beginning to move. Mid–temperature range tenderness occurs when the mixture behind the paver will support the roller but begins to move when the mixture starts to cool off.

When classical tenderness is encountered, roller operators do not approach the back of the paver. They trail some distance behind the paver waiting for the mixture to cool sufficiently until the roller is supported. The main approach to handling classical tenderness is to allow the mixture to cool. The best method is to redesign the mixture. If the mixture is used on a high-traffic route, the mix should be redesigned because classical tenderness is usually a sign of a non-rut-resistant mixture.

When mid–temperature range tenderness is encountered, the rollers can approach right up to the paver. The characteristics of mid–temperature range tenderness normally show up under breakdown rolling if the temperature of the mix at that point is above approximately 115°C (240°F). Whether the initial rolling is completed by a vibratory or pneumatic tire roller, the mix is generally stable at higher temperatures. When the temperature of the mat drops below this level, however, the mix may become very unstable and tender. A bow wave may be seen in front of the steel wheel rollers, checking may occur in the surface of the mat, and the mix may hump up outside the edges of the steel drums on the rollers. Further, the mix may start to creep out transversely along any unsupported longitudinal edge of the mat.

The mix may continue to exhibit these tenderness characteristics as the temperature of the mat decreases to approximately 90°C (193°F) or lower. If rolling is attempted in this middle temperature range, the mix will decompact instead of compacting. It is not until the mix is quite cool, generally less than 90°C (193°F), that it becomes stiff enough to again support the weight of the compaction equipment. Finish rolling can often be accomplished at temperatures of 70°C (158°F) or less. Further, it is typically difficult for the finish roller to completely remove all of the roller marks left in the mix by the breakdown and intermediate rollers.

It should be noted, however, that the temperatures cited above—115°C (240°F) down to 90°C (193°F)—do not represent exact values. Initial tenderness of the mix may be evident at temperatures as high as 120°C (248°F) or as low as 110°C (230°F), depending on the characteristics of the mix. Further, the mix may continue to exhibit tenderness characteristics at temperatures as high as 95°C (203°F) or as low as 80°C (175°F).

Several different techniques can be used to compact mid-temperature tender mixes to the required level of density. First, tender mixes generally do not become tender until the mix temperature falls. This means a significant amount of compactive effort can be applied to the mix before it becomes tender and starts to move. If a vibratory roller is used as the breakdown roller, it should be kept as close to the paver as possible. The roller should make as many passes as possible over the mat, as quickly as possible, before the mix begins to move, check, or mark. Once the movement starts, additional passes of the breakdown roller should not be made. For most tender mixes, three to five passes of the breakdown roller can be made over each point in the mat surface before the movement or checking begins.

Second, if the mix is moving under the rollers in the middle temperature range, steel wheel rollers, either vibratory or static, should be kept off the mix until it cools to the point where it is again stable enough to support the weight of the compaction equipment. If rolling is continued when the mat is moving, even more movement will typically occur; the mix will become less stable with the application of additional compactive effort. For some mixes, severe shoving of the mix may occur at the outside edge of a steel wheel roller drum with continued rolling.

In the middle temperature range at which decompaction of a tender mix will occur if steel wheel rolling is carried out, a pneumatic tire roller can be used. The rubber tires on this roller are less likely to shove or check the mix, and a bow wave will not develop. The pneumatic tire roller thus can be used to gain density in the middle temperature range.

The static steel wheel finish roller should be kept well back of the paver. This roller should move up toward the paver, compacting the mix and taking the roller marks out, until the temperature is reached at which the mix begins to move or check under the applied compactive effort. When the checking or bow wave starts, the finish roller should be backed off, and finish compaction should be carried out at lower temperatures.

If a pneumatic tire roller is not available for use once the mix has begun moving and checking, two double-drum vibratory rollers can be used together, in echelon formation or side by side, immediately behind the paver. The use of two rollers will permit more passes of the two breakdown rollers to be made over each point in the mat surface before the mix cools to the temperature at which movement and checking occur. Because each of the two rollers has less surface area to compact, it is often possible to make five to seven passes over each point in the mat before the decompaction process begins. For a tender mix, this is usually sufficient to obtain the required density level. Finish rolling is accomplished only to remove any roller marks, with extreme care taken to roll at a low enough temperature not to disturb the already compacted mix.

Tender Zone

Many contractors have observed a tender zone when using Superpave mixes, referred to earlier as mid-temperature tender mixes. The following comments about the tender zone were taken from National Asphalt Pavement Association *Special Report 180*:

> On some Superpave designed mixtures, a tender zone has been identified in temperature ranges of approximately 200–240°F (93–115°C). The mixture can be satisfactorily compacted above this range or below this range, but the mixture is tender within the temperature range and cannot be adequately compacted. This is not true for all mixtures, but it has been observed for some Superpave designed mixtures. The mixture can be satisfactorily rolled with rubber-tire rollers within this tender range but, as stated earlier, these rollers may have a pick-up problem when modifiers are used. Contact the roller manufacturers regarding procedures for eliminating asphalt pick-up on rubber-tire rollers.
>
> When a mixture is being produced that is tender within the mid-temperature range, the preferred compaction method is to obtain density prior to cooling to the tender zone. This may require an additional breakdown roller or other changes in rolling techniques, but obtaining density prior to reaching the tender zone is preferable. In some cases, the mixture temperature may be increased slightly to provide more compaction time. However, excessive temperatures will magnify the problem. Another alternative is to use a vibratory steel-wheel breakdown roller above the tender zone, followed by a rubber-tire roller which can be operated in the tender zone. The finish roller should be used after the mixture has cooled below the tender zone. This second method may not be satisfactory if the rubber-tire roller picks up excessively.
>
> Another possibility is to breakdown with a steel wheel roller above the tender zone then complete the rolling process after the HMA has cooled to below the tender zone. This has been used on a number of projects, but problems may occur due to differential cooling of the mixture and due to excessive aggregate breakdown when rolling in the vibratory mode after the mixture has cooled to below 200°F. Therefore, vibratory rolling should not be used below approximately 200°F.
>
> If the tenderness problem yields a pavement with poor in-place density, or if the paving train length is excessively long due to the time required for the mixture to cool, adjustments to the mixture design must be made to eliminate, or at least reduce, the temperature tenderness zone. It is important that the paving crew working at the laydown site communicate with plant personnel.

SUMMARY

The following factors should be considered in monitoring the compaction process (the factors that should be considered when monitoring joint construction, as outlined in Section 17, apply here as well):

- To compact an asphalt layer properly, the rollers should be used efficiently while the mix is still above the minimum compaction temperature.
- The time available for compaction is related primarily to the thickness of the layer being placed. An increase in lift thickness can substantially increase the time available for the roller to densify the mix.

- An increase in the laydown temperature of the mix behind the paver can also increase the amount of time available for compaction. The feasibility of this approach, however, depends on the properties of the asphalt mix at that elevated temperature and the tenderness of the mix under the compaction equipment.
- A decrease in the speed of the rollers will increase the compactive effort applied to the mix.
- The breakdown and intermediate rollers should be operated as close to the paver as possible to obtain density before the mix cools to a minimum temperature of 80°C (175°F).
- If the mix cannot support the weight of the compaction equipment, the mix should be redesigned or the compaction procedures changed.
- The rolling pattern should be monitored to ensure that the compaction equipment is applying the same amount of compactive effort at all points transversely across the lane being paved.
- The speed of the compaction equipment will depend on the type of roller being used and its position in the compaction process. For static steel wheel and pneumatic tire rollers in the breakdown position, the maximum speed should not exceed 4.0 km/h (2½ mph). For a vibratory roller in the same position, the maximum speed should not exceed 6 km/h (3½ mph), depending on the frequency of vibrations.
- A vibratory roller should be operated at the maximum possible vibratory frequency in order to increase the number of impacts per foot. At least 30 to 40 impacts per meter (10 to 12 impacts per foot) are needed to obtain adequate density and layer smoothness.
- The nominal amplitude setting on the vibratory roller should be determined in accordance with the characteristics of the mix and the thickness of the layer being compacted. In general, vibratory rollers should be operated in the static mode when the compacted lift thickness is less than about 30 mm (1¼ in.). For greater lift thicknesses, the roller should normally be operated at low nominal amplitude. If density cannot be obtained, the nominal amplitude may be increased to determine whether additional compactive effort will be beneficial in achieving the required density level. In general, the nominal amplitude setting can be increased in proportion to the increase in compacted thickness of the layer.
- The optimum combination of rollers and rolling patterns for a past project may not be the same as that for a current project or even for a different type or layer of mix on the same project. One or more test sections should be constructed to determine the most efficient and effective combination of compaction equipment and rolling patterns to use for each combination of job variables.
- Two similar rollers run side by side (in echelon) will typically produce a greater level of density in the mix with the same number of roller passes than will result with the same two rollers operated end to end as breakdown and intermediate rollers.
- If the rollers cannot keep up with the speed of the paver, more rollers should be used, or the paver should be slowed down.
- A mid-temperature tender zone has been identified for some Superpave mixes. These mixes show tenderness in the approximate temperature range of 95°C to 115°C (200°F to 240°F). Close attention to rolling procedures can minimize this problem.

SECTION

19 Mat Problems

Mat problems can be defined as defects that occur in the asphalt mixture during or soon after the laydown and compaction operations have been completed. These problems fall into two primary categories: (*a*) equipment-related problems and (*b*) mixture-related problems. In this section, major mat problems are reviewed and a description of each problem is presented, including its causes, solutions, and effects on long-term pavement performance.

Table 19-1 summarizes the problems reviewed. The first column lists the various problems, while the remaining columns enumerate possible causes for each. The checks indicate equipment-related causes, while the x's indicate mix-related causes, which should generally be corrected by changes in the mix design. Provided throughout the discussion of causes are cross-references to earlier sections where greater detail can be found. Note that because of the interaction of various equipment-related and mix-related causes, no attempt has been made to rank the various causes.

SURFACE WAVES

Description

An asphalt surface can have two types of waves: short and long. Short waves, also sometimes called ripples or auger shadows, are generally 0.3 to 0.9 m (1 to 3 ft) apart, with 0.45 to 0.60 m (1½ to 2 ft) being the most common separation. Long waves are considerably farther apart. The distance between them may correspond to the distance between truckloads of mix. Long waves may also be associated with the reversal points of the compaction equipment, particularly on thick-lift construction or when the HMA being placed is tender and moving longitudinally under the compaction equipment.

An additional type of defect in the pavement surface is a roughness or washboard effect caused by improper operation of a vibratory roller. The distance between these waves is generally very small, typically less than 75 or 100 mm (3 or 4 in.).

Causes

A major cause of short waves or ripples is a fluctuating head of material in front of the paver screed. The variation in the amount of mix being carried back to the augers by the slat conveyors and deposited in front of the screed causes the screed to rise and fall as the force pushing against it changes. Too much mix (at the top of the augers) and then too little mix (at the bottom of the augers) being carried in the auger chamber in front of the screed causes the wavy surface as the screed reacts to this variation in force. The fluctuating head of material causes the screed to rotate around its pivot point and "hunt" for an angle of attack. As the angle of attack of the screed changes, the thickness of the mat being placed also changes, and the smoothness of the new layer is directly affected. (See Section 15.)

Another cause of short waves is a screed that is in poor mechanical condition—one with excessive play in the screed control connections. Short waves can also be formed in the mat by improper mounting or sensitivity of the automatic grade control on the paver or by use of an inadequate grade reference device. Or the problem may be related to a mobile reference (floating beam) that is bouncing, or to the truck driver's holding the brakes while the truck is being pushed by the paver. (See Section 16.)

Short waves can also be related to the mix design, particularly with a mix that varies in stiffness as a result of changes in the mix temperature or composition. (See Section 3.) As the stiffness of the mix varies, the forces of the mix pushing on the screed vary as well, causing the screed to rise and fall and resulting in a mat with short waves. Finally, if the mix design is improper in aggregate gradation, asphalt content, mix temperature, or moisture content (the mix is tender), the rollers may shove and displace the mix during the compaction process. Normally, however, short waves are placed in the mat by the paver because of either its operation or changes in mix stiffness, rather than by the operation of the compaction equipment.

Long waves are caused by some of the same variables that result in short waves. Fluctuation in the amount of material in front of the screed and variation in mix stiff-

TABLE 19-1 Mat Problems and Their Causes

Problem \ Causes	Fluctuating Head of Material	Feeder Screws Overloaded	Finisher Speed Too Fast	Too Much Lead Crown In Screed	Too Little Lead Crown In Screed	Overcorrection of Thickness Control Screws	Excessive Play in Screed Mechanical Connection	Screed Riding on Lift Cylinders	Screed Plates Worn Out or Warped	Screed Plates Not Tight	Cold Screed	Moldboard on Strikeoff Too Low	Running Hopper Empty Between Loads	Feeder Gates Set Incorrectly	Kicker Screws Worn Out or Mounted Incorrectly	Incorrect Nulling of Screed	Screed Starting Blocks Too Short	Screed Extensions Installed Incorrectly	Vibrators Running Too Slow	Grade Control Mounted Incorrectly	Grade Control Hunting (Sensitivity Too High)	Grade Control Wand Bouncing on Reference	Grade Reference Inadequate	Sitting Long Period Between Loads	Improper Joint Overlap	Improper Mat Thickness for Max. Agg. Size	Trucks Bumping Finisher	Truck Holding Brakes	Improper Base Preparation	Improper Rolling Operation	Reversing or Too Rapidly Turning Rollers	Parking of Roller on Hot Mat	Improper Mix Design (Aggregate)	Improper Mix Design (Asphalt)	Mix Segregation	Moisture in Mix	Variation of Mix Temperature	Cold Mix Temperature
Wavy Surface—Short Waves (Ripples)	✓	✓	✓				✓	✓		✓										✓	✓	✓	✓						X	X			X	X	X		X	
Wavy Surface—Long Waves	✓	✓				✓	✓	✓					✓	✓						✓			✓	✓			X	X	X		X	X			X		X	
Tearing of Mat—Full Width			✓						✓		✓															X							X	X	X	X	X	X
Tearing of Mat—Center Streak					✓				✓		✓			✓	✓																							X
Tearing of Mat—Outside Streaks				✓					✓		✓	✓		✓				✓																				X
Mat Texture—Nonuniform	✓	✓	✓					✓	✓	✓	✓		✓					✓	✓					✓		X			X				X	X	X		X	X
Screed Marks							✓																				X	X										
Screed Not Responding to Correction			✓				✓	✓		✓										✓						X											X	X
Auger Shadows		✓																															X	X	X			
Poor Precompaction			✓					✓											✓							X			X									X
Poor Longitudinal Joint	✓	✓				✓		✓												✓	✓	✓			✓					X								X
Poor Transverse Joint		✓					✓	✓		✓						✓	✓													X								X
Transverse Cracking (Checking)																													X	X			X	X		X	X	
Mat Shoving Under Roller																													X	X	X		X	X		X	X	
Bleeding or Fat Spots in Mat																																	X	X		X	X	
Roller Marks																													X	X	X	X					X	
Poor Mix Compaction																													X	X	X	X	X	X		X	X	X

1. Find problem above.
2. Checks indicate causes related to the paver. X's indicate other problems to be investigated.

NOTE: Many times a problem can be caused by more than one item; therefore, it is important that each cause listed be eliminated to ensure that the problem will be solved.

ness cause the screed to react to the change in the force exerted on it. If the distance between the wave peaks corresponds to the length of pavement between truckloads of mix, however, the waves may have been caused by incorrectly set hopper flow gates on the paver or by the paver hopper and slat conveyors being emptied between loads of mix. (See Section 13.) Poor mechanical condition and improper operation of the screed (continually changing the manual thickness control cranks, for example; see Section 15), as well as incorrectly mounted automatic grade controls (see Section 16), can cause a long-wave problem. If a stringline is being used as a grade reference, a sag in that line between support posts can also be a cause of long waves (see Section 16). Another factor contributing to long-wave roughness is improper delivery of the mix to the paver, particularly if the haul truck bumps into the paver or if the truck driver holds the brakes while the truck is being pushed by the paver (see Section 13). One additional factor can be the condition of the underlying surface: the long waves may be a reflection of the waves in the base material.

Long waves may also be found at those points where the compaction equipment reverses direction. This problem is most prevalent when the asphalt layer being placed is more than about 100 mm (4 in.) thick. The problem may be exacerbated when the maximum-size aggregate used in the mix is relatively small compared with the lift thickness. The waves are caused by a bow wave that forms in front of the roller when the mix is tender.

In terms of mix design, long waves can be caused by truckload-to-truckload segregation of the mix and by changes in mix temperature (see Section 3). Both of these deficiencies cause the forces on the screed to vary, resulting in a wavy surface. The compaction equipment can also create a wavy mat if the roller operator turns or reverses the machine too abruptly.

Roughness or washboarding is normally caused by improper operation of a vibratory roller (see Section 18). This type of equipment should be operated at as high a frequency as possible and at an amplitude setting related to the thickness of the layer being compacted—usually a higher amplitude setting for a thicker layer of mix and a lower amplitude setting for a thinner lift. Further, the washboard effect can be worse if the roller is operated at a high speed, particularly if the frequency setting is less than 2,400 vibrations per minute.

Solutions

Short waves (ripples) can be eliminated only by preventing their formation. The most important factor in preventing short waves is to keep the amount of mix (head of material) in front of the screed as consistent as possible. In addition, the stiffness of the mix, which is related to both its temperature and its composition, should be maintained as constant as possible. The amount of mix is controlled by properly setting the hopper flow gates and by keeping the slat conveyors and augers operating as much of the time as possible (close to 100 percent) while the machine is moving forward. Mix stiffness is controlled at the asphalt plant by keeping the mix temperature, aggregate gradation, and fluids content (asphalt content plus moisture content) as constant as possible. Any factors that cause either the volume or stiffness of the mix at the screed to change can cause short waves or ripples in the HMA mat.

Surface waves caused by problems with automatic grade controls can be detected by shutting off the grade controls and determining whether the waves continue to form. If the grade controls are at fault, the operation and maintenance manual supplied with those controls should be consulted to determine the proper corrective action. Sags in a stringline reference can be found by sighting down the line as the grade sensor wand passes along the string. Short or long waves caused by the mechanical condition or operation of the paver screed can usually be detected by careful observation of the paver during mix laydown. The long waves formed by incorrect operation of the haul truck or compaction equipment can also be detected easily by observing those operations.

If washboarding is caused by incorrect operation of a vibratory roller, a change should be made in one or more of the following: the vibratory amplitude setting, the vibratory frequency, and the speed of the roller.

Effects on Performance

Long-term pavement performance is affected by surface waves, both short and long, in two ways. First, the waves reduce the smoothness of the pavement, which lowers the pavement condition rating or the present serviceability index of the roadway. The structural performance of the pavement will be changed, however, only if the waves are severe enough to increase the dynamic or impact loading of the pavement under heavy truck traffic. Second, short waves and the factors that cause them can affect pavement density levels. A tender mix is generally more difficult to compact properly than is a stable mix; the result may be a decrease in density and a corresponding increase in air void content.

Washboarding is basically roughness built into the pavement surface during the compaction operation. Because it affects the degree of density obtained during the compaction process, this type of defect can significantly reduce the long-term durability of the pavement layer. In addition, washboarding contributes to a rough ride for the vehicles using the pavement.

TEARING (STREAKS)

Description

There are three general types of mat tearing, or pulling of the asphalt mix under the screed of the paver. The three types are defined by the location of the tear marks in the mat: (*a*) in the center of the lane, (*b*) on the outside edges, and (*c*) across the full lane width.

Causes

A gearbox streak can sometimes be seen in the surface of the mat directly behind the center of the main screed. This streak is typically 150 to 200 mm (6 to 8 in.) wide and is normally caused by a lack of asphalt mix being pushed under the auger gearbox located in front of the center of the screed. This lack of mix may be the result of improper flow gate settings—not enough mix being fed back to the screed. It is more likely to be caused, however, by missing, worn, or improperly set reverse augers or paddles on the augers (located adjacent to the gearbox) that are used to force mix underneath the gearbox. (See Section 15.)

A gearbox streak is often thought to be a type of segregation. It is not. The rough surface texture is the result of a lack of mix at that point in the pavement width—less mix passes under the screed at the auger gearbox than passes under the screed on either side of the gearbox. The rougher texture, or tearing, makes the surface appear more open or segregated. Gearbox streaks are more prevalent with harsher mixes—those containing larger-size aggregate, more crushed aggregate, or lesser amounts of asphalt.

A centerline streak can also be caused by improper setting of the crown on the main paver screed. The appearance of streaks behind the screed is caused primarily by an improper relationship between the crowns at the leading (front) and trailing (back) edges of the screed. A tearing or open texture about a meter (several feet) wide in the center of the mat may be caused by a lack of lead crown in the screed. Conversely, a tearing or open texture along both outside edges of the asphalt mixture is normally caused by an excess of lead crown in the screed. For most mixes, the lead crown of the screed should be set slightly higher [approximately 3 mm (⅛ in.)] than the tail crown. A proper relationship between lead and tail crowns will result in a uniform texture of the mat across its full width. Edge streaks can be caused by improper flow gate settings or incorrect installation of the screed extensions. Partial-width tearing can also result from a cold screed plate if the screed has not been uniformly preheated before paving begins. (See Section 15.)

Full-width tearing of the mat can be attributed to a number of factors. One such factor is warped or worn screed plates. Another is the forward speed of the paver being too high for a particular mix. The use of a mixture with aggregate that is large compared with the mat thickness being laid can also be responsible for full-width tearing of the mat. A good rule of thumb for the relationship between the maximum aggregate size in the mix and the minimum compacted course thickness is that the depth of the compacted layer should be at least twice the largest coarse aggregate particle size or three times the nominal maximum aggregate size. Thus a mix containing a maximum aggregate size of 19.0 mm (¾ in.) [nominal maximum aggregate size of 12.5 mm (½ in.)] should be placed at least 38 mm (1½ in.) thick. Lastly, cold mix temperatures, particularly when combined with a cold paver screed, can significantly affect the amount of tearing that occurs. (See Section 15.)

Solutions

A gearbox streak can usually be eliminated only by changing the amount of mix being forced under the screed at the auger gearbox. This change is made by installing reverse paddles or reverse augers on each side of the gearbox in order to push more mix under the gearbox. If the paver is already equipped with such devices, they should be checked to see whether they are worn and need to be replaced.

Constant center or outside edge mat tearing can usually be eliminated by adjusting the relationship between the lead and tail crowns on the paver screed. If this change does not solve the problem, the setting of the paver flow gates should be modified. Full-width tearing can be eliminated by increasing the mix temperature, preheating the screed properly before paving starts, replacing warped or worn screed plates, or increasing the lift thickness.

Effects on Performance

Tearing of the mat affects long-term pavement performance by causing changes in density in those areas where the tearing has occurred. Torn areas may appear segregated and are usually deficient in mix quantity. Pavement performance will be reduced in relation to the degree to which the tearing reduces the density and increases the air void content of the mat. In addition, the torn areas will be more susceptible to raveling and to the effects of moisture (stripping).

NONUNIFORM TEXTURE

Description

Nonuniform mat texture (see Figure 19-1) can be described as differences in the appearance of the mix, both transversely and longitudinally, as it is placed and compacted. Normally, minor differences in surface texture will be apparent because of differences in the alignment of the larger coarse aggregate particles as the mix passes out from beneath the paver screed. In addition, a mix with a higher fine aggregate (sand) content will have a more uniform surface texture than a mix containing a larger percentage of coarse aggregate.

Causes

Many factors related to the operation of the asphalt paver affect the uniformity of the surface texture of the mix. (See Section 15.) A variable amount of mix against the screed, caused by overloading the augers or running the hopper empty between truckloads, can cause variations in the amount of mix tucked under the screed and thus produce a nonuniform texture. Improper screed maintenance,

FIGURE 19-1 Nonuniform mat texture after compaction.

including worn or loose screed plates or screed extensions incorrectly installed, as well as low screed vibratory frequency, may alter the mat texture and cause nonuniformity. In addition, a low mix temperature, caused either by plant problems or by the paver sitting too long between truckloads of mix, can be a factor in uneven mat texture, especially if the paver screed is also cold. The tearing that results when the compacted layer thickness is less than twice the dimension of the largest aggregate particles (as discussed above) is still another contributing factor.

A soft or yielding base under the course being constructed may cause the new layer to have a variable surface texture (see Section 14). Moreover, segregation of the mix caused by poor mix design (Section 3) or improper handling of the mix during mixing (Section 3), loading (Section 11), hauling (Section 11), unloading (Section 13), or placing (Section 15) operations can contribute to a nonuniform surface texture. The variability of the texture will be affected as well by any factors that cause nonuniformity in the mix, such as deviations in aggregate gradation, asphalt content, or mix temperature (see Section 3).

Solutions

The solutions for nonuniform surface texture are as varied as the causes. Paver operation, particularly with regard to the need for a constant head of material in front of the screed, should be monitored closely. The paver and screed should both be well maintained and in good operating condition. The compacted thickness of the mat being placed should be designed so that it is at least twice the size of the largest coarse aggregate particles incorporated into the mix. Finally, a mix that is tender, variable in aggregate gradation or asphalt content, or easily segregated should be modified to increase its stiffness and improve its properties before it is produced at the plant and delivered to the paver for laydown.

Effects on Performance

Nonuniform surface texture is usually associated with nonuniform density. The same compactive effort will generally achieve lower density in areas in which the coarse aggregate has been dragged by the paver screed or segregation of the mix has occurred, as compared with areas having uniform surface texture. As density decreases and air void content increases, the durability and serviceability of the asphalt mat decrease markedly.

SCREED MARKS

Description

Screed marks are transverse indentations in the surface of the asphalt mat. They occur when the paver stops between truckloads of mix. Depending on the mixture being placed, some screed marks are barely noticeable, whereas others are very distinct and deep. Screed marks can also occur in the longitudinal direction when rigid or hydraulic extensions are used and the elevation of the extension is not the same as that of the main screed.

Causes

There are several causes of transverse screed marks. (See Section 15 for a discussion of screed operations.) One is excessive play in the mechanical connections on the screed. Such marks also result when the screed is set up incorrectly and rides heavily on its rear end. If the asphalt mix is tender and if the paver is equipped with a very heavy screed, such as hydraulic extensions with additional rigid extensions attached, the screed will tend to settle into the mix and leave marks. If any of these causes are involved, the screed marks will be visible each time the paver stops.

Another cause is the haul truck bumping into the paver when preparing to discharge the mix or the truck driver holding the brakes on the truck when the paver starts to push the truck. In these cases, the screed marks will appear only when the truck–paver interchange is improper.

Longitudinal screed marks are caused by improper setting of the screed extensions relative to the main screed. When extensions are used, their vertical position and angle of attack must be the same as those of the main screed. If rigid extensions are set at the wrong elevation, a longitudinal mark will occur at the point where the different screed sections are joined. If hydraulic extensions are used, two longitudinal marks may occur—one at the end of the main screed and one at the inside edge of the extension on each side of the machine.

Solutions

If the transverse screed marks are a result of the mechanical condition or improper setup of the paver screed, the screed should be repaired. If the marks are caused by the truck bumping into the paver, the laydown operation should be altered so that the paver picks up the haul truck instead of the truck backing into the paver. In addition, once the paver has established contact with the truck, the truck driver should apply only enough pressure to the brakes to keep the truck in contact with the paver.

In some cases, particularly if the mix is very tender, screed marks can be eliminated by not stopping the paver between truckloads of mix. This can be accomplished by using a windrow elevator or material transfer vehicle to deliver mix to the paver hopper. If dump trucks are used to haul the mix, however, it is generally better to stop the paver between truckloads of material (stopping and restarting the paver as quickly as practical) instead of allowing the paver operator to run the paver hopper dry, reduce the head of mix in front of the paver screed, and increase the opportunity for truckload-to-truckload segregation.

To achieve uniform surface texture, the elevation and angle of attack of the screed extensions must be matched to those of the main screed. Longitudinal screed marks caused by improperly setting the elevation of the extensions can be eliminated by correcting the position of each extension relative to that of the main screed. Adjustments to both the vertical position and the angle of attack of the extensions may be needed. These adjustments should be made whenever hydraulic or rigid extensions are used.

Effects on Performance

Transverse screed marks generally are not detrimental to the durability of the mat. They may, however, affect the ride by creating a bump whenever the marks cannot be completely rolled out by the compaction equipment. In many cases, the screed marks have less of an effect on the performance of the mix than does the slowdown and startup of the paver when the operator attempts to keep it moving as the empty truck pulls away and the loaded truck backs into the hopper.

Longitudinal screed marks indicate that the level of the mix under the screed extensions is different from that under the main screed. If the screed marks are severe, differential compaction may occur across the mark or "joint," with the compaction equipment initially riding on the higher mat. The marks can leave a ridge in the mix if they cannot be completely rolled out.

SCREED RESPONSIVENESS

Description

As the thickness control cranks on the screed are changed, the screed's angle of attack increases or decreases. As the paver moves forward to place the mix, the screed moves up or down to the new equilibrium point for the newly set mat thickness. When the screed fails to respond to changes in the setting of the thickness control cranks, the operator is unable to alter the depth of the layer being placed. The paver also loses its inherent ability, through the principle of the floating screed, to provide the self-leveling action needed to place a smooth asphalt mat.

Causes

An extremely high paver speed [more than 25 m (83 ft) per minute for thin lifts or more than 15 m (50 ft) per minute for layers more than 63 mm (2½ in.) thick] may cause a lack of responsiveness of the screed (see Section 15). The mechanical condition of the screed affects its ability to react. The screed riding on its lift cylinders or loose connections on the thickness control cranks will cause the screed to be unresponsive. If automatic grade controls are used (see Section 16), an incorrect sensor location will render the screed unable to react to input signals from the grade sensors.

If the maximum aggregate size used in the mix is too great compared with the depth of mix being placed, the screed will ride on or drag the largest aggregate pieces. As a result, the screed will be unable to change its angle and will thus be unresponsive to changes in the thickness control settings. Variations in mix temperature will also cause the screed to be unresponsive to changes in the angle of attack because the mix stiffness variations themselves will cause the screed to continually seek new equilibrium levels for the forces acting on it.

Solutions

The paver and screed must be in good operating condition. The sensor for automatic grade controls must not be located either at the tow points or behind the pivot points of the screed; rather, it should be located in the area between one-third and two-thirds of the length of the leveling arms. If the mix texture is uniform (indicating a proper relationship between course thickness and maximum aggregate size), the screed will be able to respond to changes in the thickness control settings.

Effects on Performance

An unresponsive screed causes a rough asphalt mat. The screed is unable to react to manual changes in the thickness settings. It also loses its ability to self-level on an existing pavement surface because it cannot reduce the thickness of mix placed over the high points in that surface and increase the thickness placed in the low areas.

Thus the ridability of the course being placed can be affected significantly if the paver screed is unresponsive.

SURFACE (AUGER) SHADOWS

Description

Surface (auger) shadows are dark areas that appear in the surface of an HMA mix. In most cases, the shadows cannot be seen until some time after the pavement has been used by traffic and some of the asphalt cement film has been worn off the exposed aggregate particles by the vehicle tires. Surface shadows are seen most easily when the sun is low on the horizon and the pavement is viewed when looking toward the sun. The shadows are also visible when the pavement surface is damp or when the surface is viewed from the shoulder of the roadway at night and vehicle headlights are shining on the surface.

In severe cases, surface shadows may be visible immediately behind the screed during the laydown operation. Even in this latter case, the shadows will disappear when the mix is being compacted by the rollers, only to be visible again later under the conditions described above. The shadows may be completely across the lane width being placed, or they may be only partially across the width. The extent of the shadows depends on how the paver is operated, particularly the portion of on to off time of the augers on each side of the machine.

Causes

Surface shadows are caused primarily by overloading of the augers on the paver (see Section 15). If the head of material in the auger chamber is large enough to "bury" the augers, the screed will react to the variable forces acting on it. The spacing between the shadows will normally correspond to the starting of the augers when operated in a stop–start manner. Whenever the amount of mix in front of the screed is at or above the top of the augers, the shadows will be formed and seen later in the pavement.

On most pavers it is possible to adjust the distance between the screed and the tractor unit. This is accomplished by unbolting connections on the leveling or tow arms of the paver and moving the tractor forward (or backward) while the screed remains stationary on the pavement surface. Depending on the make and model of the paver, there is typically a 100-mm (4-in.) length of slide for the screed connection. The severity of surface shadows may increase with the screed in the back position—when more mix is being carried in the auger chamber and the augers are being overloaded.

The shadows are thought to be the result of a slight increase in mix density caused by the restarting of the augers and the subsequent forcing of additional mix under the screed. There is no difference in surface texture associated with the location of the surface shadows; they can be seen only from an angle. Their intensity often increases when a tender mix is being laid.

Solutions

The HMA mixture carried in the auger chamber should be maintained at a level near the center of the auger shaft. This means the flow gates should be set so that the augers operate as close to 100 percent of the time as possible and stopping and starting of the augers is minimized. In no case should the top of the augers be completely covered with mix. Further, the location of the screed should be set as far forward as possible so that the amount of material in the auger chamber is reduced and the head of material in front of the screed is kept to a minimum. The screed should not be set in the back position unless a large-stone mix [one in which the maximum size of the aggregate is more than 37.5 mm (1½ in.)] is being placed.

Effect on Performance

Surface shadows are not necessarily detrimental to the performance of the mix, except for a minor effect on ridability. The difference in the density of the mix in areas with and between shadows is generally not great enough to be determined accurately. The main concern with surface shadows is the visual appearance of the mix to vehicle drivers.

POOR PRECOMPACTION

Description

A modern asphalt paver is normally equipped with a vibratory screed. This type of screed allows the mix to be partially compacted as it passes beneath the screed. Depending on such variables as forward paver speed, layer thickness, mix temperature, and ambient environmental conditions, the density of the asphalt mixture measured behind the screed before compaction is usually in the range of 70 to 80 percent of the theoretical maximum density (a voidless mix).

A few pavers are equipped with combination screeds, which have both tamper bars and vibrators. At slow paver speeds, the combination screed typically achieves greater compaction of the mix than is obtained with the vibratory screed alone. At paver speeds greater than 7.5 m (25 ft) per minute, however, the increased compactive effort achieved with the tamper bar is typically lost, and the degree of compaction obtained is similar to that achieved with a simple vibratory screed.

Causes

The amount of precompaction achieved with the screed decreases as the paver speed increases (see Section 15). Precompaction generally increases slightly as the frequency of the screed vibration increases. Precompaction decreases significantly, however, if the screed is riding on the screed lift cylinders, thereby limiting the available compactive effort. The level of precompaction obtained is also limited if the mat is too thin for the maximum aggregate size used in the mix (less than twice the largest-size aggregate; see the earlier discussion of nonuniform texture), if the mix being placed is too cold, or if the base on which the new layer is being laid is soft and yielding.

Solutions

Decreasing the paver speed and increasing the frequency of vibration of the screed should, within limits, increase the level of precompaction achieved during the laydown operation. It is also possible on some pavers to increase the amplitude of the vibration in order to increase the impact force of the screed on the mix. Proper maintenance of the screed helps as well in obtaining a uniform compactive effort from the screed.

Effects on Performance

As long as the required density level is obtained using conventional rollers behind the paver, the level of precompaction accomplished by the screed will not affect the long-term performance of the HMA layer. It may be possible, however, to reduce the number of roller passes needed to meet the density and air void content criteria if the amount of precompaction obtained by the screed is higher. In addition, increased precompaction density can reduce the amount of differential compaction that occurs in low spots and rutted areas.

JOINT PROBLEMS

Description

Poor transverse joints are associated either with a bump at the joint, a dip in the pavement surface several meters (feet) beyond the joint, or both. Poor longitudinal joints (Figure 19-2) between passes of the paver are

FIGURE 19-2 Poor longitudinal joint due to unsatisfactory workmanship.

usually characterized by a difference in elevation between the two lanes, by a raveling of the asphalt mix at the joint, or both. The area adjacent to the longitudinal joint is usually depressed below the level of the surrounding pavement surface.

Causes

Joint problems are caused by poor construction of the joint, inadequate compaction of mix placed along the joint, improper start-up procedures when paving resumes after a stoppage, or improper construction and removal of tapers.

Solutions

One key to a good transverse joint is to construct the joint at the end of the paving day at a location in the mat where the layer thickness is constant. (See Section 17 for a discussion of joint construction.) This means the compacted thickness of the mat at the end of the paver run is the same as that of the previously placed mat.

At the start of paving the following day, the paver screed should be placed on blocks on the cold side of the transverse joint. The thickness of the blocks should be related to the depth of the course being laid—approximately 5 mm ($\frac{1}{4}$ in.) thick for each 25 mm (1 in.) of compacted layer thickness. The front edge of the paver screed should then be placed directly over the vertical face of the joint. Once the paver pulls away from the joint, the right amount of mix should be in the right place, and only minimal raking, if any, normally needs to be done. The mix at the joint should then be compacted as quickly as possible.

For longitudinal joint construction, it is extremely important to compact the edge of the first lane properly. Doing so requires that the vibratory or static steel wheel roller hang out over the unsupported edge of the mat by about 150 mm (6 in.). This practice provides the most compactive effort along the unconfined edge without causing undue lateral displacement of the mix along the edge of the pavement.

When placing the second (adjacent) pavement lane, the end plate on the paver screed should overlap the first lane by 25 to 40 mm (1 to 1½ in.). Minimal raking, if any, should be done on the mix placed over the first lane. The rollers—vibratory, pneumatic tire, and static steel wheel—should operate on the hot side of the joint and extend over the joint on the cold side by approximately 150 mm (6 in.). The same number of roller passes should be made over the longitudinal joint as over each point in the interior of the HMA mat.

Effects on Performance

A poor transverse joint will not affect pavement performance to any significant degree if proper density levels are obtained by the compaction equipment. A poor ride will usually be the only negative result. An improperly constructed longitudinal joint, however, can seriously decrease the serviceability of the pavement structure. A poorly placed and compacted joint will ravel and cause one side of the joint to be lower than the other. If the density level is too low, the whole pavement layer thickness at the longitudinal joint may wear away under the action of traffic. A poor joint will also be porous, allowing water to enter the underlying pavement courses.

CHECKING

Description

Checking can be defined as short transverse cracks, usually 25 to 75 mm (1 to 3 in.) in length and 25 to 75 mm (1 to 3 in.) apart, that occur in the surface of the HMA mat at some time during the compaction process (see Figures 19-3 and 19-4). The checks are not visible immediately behind the paver screed. Rarely does checking occur during the first or second pass of the compaction equipment over the mat. If checking is going to occur, it will normally take place after the mix has cooled to a temperature of less than 115°C (240°F) and additional passes of vibratory or static steel wheel rollers (or both) are made over the mat. Checking does not usually occur when the mix is compacted with a pneumatic tire roller.

Most HMA mixtures do not check at all during compaction, whereas others exhibit tender characteristics and check readily. As checking becomes severe, the cracks become longer and are spaced closer together. The cracks do not extend completely through the depth of the course, but are only 10 to 13 mm (⅜ to ½ in.) deep.

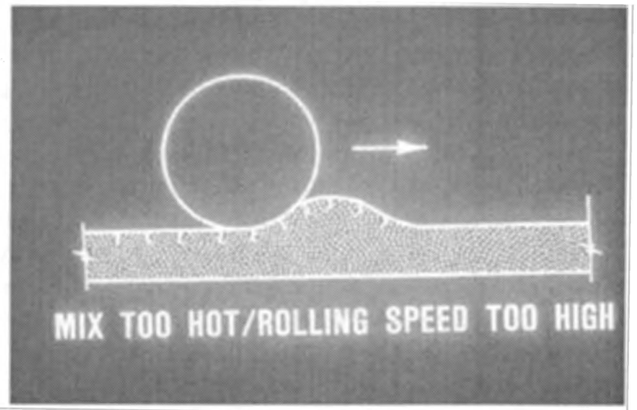

FIGURE 19-3 Roller checking during compaction.

Causes

A mix that checks during compaction is a tender mix. The mix shoves or moves in front of the drums on either vibratory or static steel wheel rollers. Checks or cracks are formed when a bow wave occurs in front of the roller drums as the mix moves longitudinally before the roller reaches that location.

Checking may be caused by two primary factors: (*a*) excessive deflection of the pavement structure under the compaction equipment (see Section 14) and (*b*) one or more deficiencies in the asphalt mix design (see Section 3). A mix that checks is not internally stable enough—does not have enough internal strength at elevated temperatures—to support the weight of the compaction equipment during the rolling process.

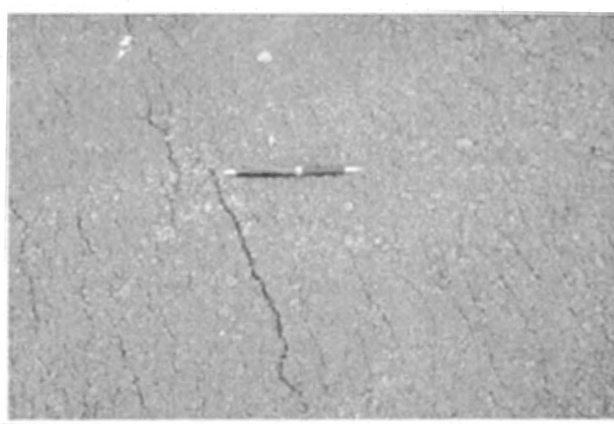

FIGURE 19-4 Hairline cracks caused by roller checking.

When a yielding foundation is the cause of the checking problem, the underlying pavement on which the new HMA layer is being placed is weak and yields under the movement of the compaction equipment (see Section 14). The weight of the rollers causes the layers in the pavement structure to move, shove, and bend excessively, placing the new mix in tension at its surface. The check marks are then formed when the surface of the new HMA is pulled apart as the pavement structure deflects during the rolling operation. The checks should appear in the new mix surface only at locations where there is movement of the pavement structure under the compaction equipment. If the paver passes over a soft spot in the underlying structure, for example, the checking should occur only where the soft spot exists.

A more common cause of checking is one or more deficiencies in the HMA mixture: (*a*) an excess of fluids in the mix—too much asphalt cement or too much moisture in the mix, or both; (*b*) a hump in the sand gradation curve—too much midsize sand material [1.18-mm and 0.600-mm (No. 16 and No. 30) sieve size] and too little fine sand material [0.300-mm and 0.150-mm (No. 50 and No. 100) sieve size]; and (*c*) a lack of room in the aggregate gradation for the asphalt cement (low VMA).

An excess of fluids in the HMA mix makes the mix tender and allows it to be displaced easily under the applied compactive effort of the rollers. The mix will be tender if the binder content is too high for the gradation and characteristics of the aggregate used, particularly if the mix has a low VMA content. If the mix contains too much moisture because the aggregate was not completely dried when passing through the batch plant drier or drum mixer (parallel flow or counter flow), the excess moisture will act as asphalt cement at elevated temperatures and overlubricate the mix. The moisture remaining in the aggregate pores will prevent the binder material from entering those pores in the aggregate, in effect leaving more binder material between the aggregate particles instead of partly inside the aggregate.

If tenderness is due to an excess of asphalt cement in the mix, checking should occur in the mix on a regular, daily basis. If tenderness is due to an excess of moisture in the mix, checking should occur whenever the plant is not being operated properly. For example, checking may occur in the mat the day after a rain, but not the day before. If operations at the asphalt plant do not include removing the extra moisture in the aggregate resulting from the rainfall on the stockpiles, that moisture will add to the asphalt binder fluids and cause the mix to be tender.

A hump in the fine aggregate gradation curve—an excess of midsize sand in the mix—can also cause the mix to be tender. In addition, mixes low in VMA content will generally be tender and move easily under the force of a vibratory or static steel wheel roller. Further, the various characteristics of the aggregate particles, such as surface texture, angularity, crushed faces, and amount of dust coating, can play a major role in the amount of checking that occurs during compaction. Mixes that are deficient in fine aggregate gradation or lack adequate VMA content will normally check continuously, not periodically. If the sand gradation is variable, however, checking may occur only when the sand gradation is improper.

The above mix deficiencies are compounded, and the amount of checking that occurs may be increased, when the mix temperature is too high for the particular asphalt cement grade being used in the mix. As the mix temperature increases, the viscosity of the asphalt cement decreases, causing the mixture to be more tender. An additional factor that can affect the amount of checking is the temperature susceptibility of the asphalt cement itself: the greater the degree of temperature susceptibility of the binder material, the more checking may occur in the HMA mix.

Occasionally, checking can be caused by temperature differentials within a layer of HMA mix (heat checking). On a cool day and under windy conditions, the temperature of the mix that is in contact with the existing pavement surface may decrease quickly. The top surface of the mix will also cool quickly. The temperature of the mix in the middle of the layer, however, will remain high. This temperature differential can cause the mix to check under the compactive effort of the rollers.

There are also a number of secondary causes of checking. One is a mix whose temperature is too high: the mix was overheated in the plant. In addition, improper rolling techniques can cause checking—rolling too fast, stopping too quickly, making sharp turns on the hot mat, or making an excessive number of passes with the finish roller or finish rolling when the mat is still at too high a temperature (see Section 18). Finally, checking may be increased by a poor bond between the new mat and the underlying surface because of a dirty surface or the lack of a tack coat.

Solutions

If checking is caused by the presence of a yielding foundation underneath the new HMA layer, the solution is to repair and properly prepare the existing pavement structure before the new HMA layer is placed. Soft spots should be removed and replaced. All areas of excessive deflection should be removed and replaced or stabilized. Uniform support is needed in the underlying pavement structure if the new pavement layers are to perform adequately.

If checking is caused by a deficiency in the mix design—an excess of fluids in the mix or a problem with the gradation of the fine aggregate or the VMA content of the mix—the long-term solution is to change the mix properties. Those changes must be made at the asphalt plant and cannot be made at the paving site. If the mix contains an excess of fluids—either asphalt cement or moisture—the binder content should be reduced or the aggregate properly dried to remove all of the moisture. In some cases, the production rate of the plant will have to be reduced for the moisture to be completely removed from the aggregate. In other cases, plant operating conditions may need to be changed (e.g., flights, drum angle).

If checking is caused by the gradation of the fine aggregate incorporated into the mix, the gradation should be changed. It may be necessary to increase or decrease the amount of fine aggregate used, add a small amount of fine aggregate with a different gradation, increase the angularity of the fine aggregate, or use a completely different material from a different source. If checking is caused by a lack of VMA in the HMA mix, changes need to be made to increase the VMA.

Checking is often thought to result from the mix being too hot. This is only partially correct; the mix is too hot at some temperatures to support the weight of the compaction equipment because the mix lacks internal strength and stability. If the mix were properly designed, it would not be too hot to be compacted at any temperature below about 150°C (300°F). Most checking occurs when the mix temperature is decreasing from about 115°C (240°F) down to about 90°C (190°F); rarely does checking occur when the mix temperature is above approximately 115°C (240°F) or below approximately 90°C (190°F).

In the short term, changes in both the rolling zone and the type of rollers used to densify the mix can be made to reduce the amount of checking that occurs. If the mix is tender because of excess fluids, a problem with the fine aggregate gradation, or lack of VMA, it may be possible to densify the mix properly at an elevated temperature without causing the checking.

A mix that checks is tender, but this mix can usually be compacted satisfactorily at high temperatures—above 120°C (250°F). The required level of density can generally be obtained if enough roller passes can be applied to the mix before it cools to the point at which the checking begins. This can be done by using two breakdown rollers instead of one—using two rollers operating in echelon (side by side) instead of using a breakdown roller followed by an intermediate roller. The two breakdown rollers each apply their compactive effort to one side of the newly placed lane. Many passes are made over each point in the pavement surface before the mix begins to check. Once checking starts, the rolling process is temporarily suspended.

If compaction operations are attempted when the mix is moving, shoving, and checking under the action of vibratory or static steel wheel rollers, the mix will decompact rather than compact. Rolling should not be carried out with steel wheel rollers when the mix is tender and checking. Most tender mixes will remain tender until the surface of the mix cools to a temperature of approximately 90°C (190°F). At this temperature, the mix has cooled sufficiently so that the viscosity of the asphalt binder has increased to the point where the mix can again support the weight of the compaction equipment. Static steel wheel rollers can then be used to achieve the final density in the mix and remove any roller marks in the pavement surface.

When a tender mix is in the middle temperature range, between about 115°C (240°F) and 90°C (190°F), rolling should not be attempted, as discussed above, with either vibratory or static steel wheel rollers. A pneumatic tire roller, however, can be used in this temperature zone since the rubber tires on this roller will typically not shove the mix and a bow wave will not form in front of the tires. The tender mix will densify, instead of check, under the compactive effort of the pneumatic tire roller. Finish rolling using a static steel wheel roller can be completed once the mix has cooled to a temperature below about 90°C (190°F).

In most cases when checking occurs in the mix, the roller operators tend to back off the mix and allow it to cool. This is the wrong approach to the problem. Delaying the compaction permits the mix to cool and stiffen but most often does not then allow enough time for the mix to achieve the required level of density. With a tender mix, it may not be possible to accomplish both objectives (no checking and adequate density) at the same time if the mix is allowed to cool before rolling operations are started. It is much better to compact the mix as much as possible before checking starts, stay off the mix in the middle temperature zone when checking is most likely to occur, and then finish roll the mix once it has cooled enough to support the weight of the final roller.

If the mix delivered to the paver is too hot—above 165°C (325°F)—it should be allowed to cool after laydown before the compaction process is started. Improper rolling techniques should be corrected. The surface of the underlying pavement should be clean and properly tack coated before placement of the new mix begins.

None of the solutions to the checking problem will work in all cases. Each mix will have its own compaction characteristics. For some extremely tender mixes, checking may occur at a wider range of temperatures, from as high as 130°C (270°F) down to as low as 75°C (170°F). As noted, mixes that lack internal stability will generally check under steel wheel rollers (operated in either the vibratory or static mode), and thus these mixes should be redesigned.

Effects on Performance

Although checks extend only a short distance down from the surface, they are highly detrimental to long-term performance because the tender mix characteristics affect the level of density obtained. If the rollers are kept back from the paver in an attempt to decrease the amount of checking that occurs, the level of density obtained by the compaction equipment will normally be reduced significantly. Thus the air void content of the HMA mat will increase. A mix that contains checks will therefore lack density and have a greatly reduced pavement life under traffic.

SHOVING AND RUTTING

Description

Shoving of an HMA layer is displacement of the mixture in a longitudinal direction. Such displacement may take place during the compaction operation or later under traffic. In most cases, shoving during construction is accompanied by a large bow wave in front of the breakdown roller, particularly if that roller is a vibratory or static steel wheel machine. Shoving may also occur in conjunction with mix checking if the mix is tender enough as a result of faulty aggregate gradation or excess fluids (asphalt binder or moisture) content. Finally, mat or mix shoving can occur at the reversal point of the rollers, especially at the location closest to the paver. A pavement layer that has shoved under the action of traffic is shown in Figure 19-5.

Rutting, illustrated in Figure 19-6, shows displacement of the mixture in both vertical and transverse directions. Rutting occurs when heavy traffic passes over an unstable mix. In a few cases, the rutting is purely vertical (consolidation rutting). In this situation, the mix was not adequately compacted at the time of construction, and the traffic loads are essentially finishing the compaction process. The most common form of rutting is transverse distortion—the mix distorts or shoves transversely as a result of lateral flow of the mix under applied traffic loads.

FIGURE 19-5 Shoving due to unsatisfactory mix.

Causes

Shoving and rutting are due primarily to an unstable HMA mixture (see Section 3). This instability can be caused by the same variables that are responsible for checking—an excess of fluids (asphalt binder or moisture) in the mix, a hump in the fine aggregate grading curve, or the properties of the aggregate and the asphalt cement. A mix that has a high Marshall or Hveem stability may still distort longitudinally under the compaction equipment and later both longitudinally and transversely under traffic. Shoving and rutting can be highly prevalent when a sand mix is placed in a thick layer [more than 40 mm (1½ in.)] at a high temperature [more than 140°C (280°F)]. Further, thicker lifts in pro-

FIGURE 19-6 Rutting of unstable asphalt mixture.

portion to the maximum-size aggregate used in the mix will tend to shove more than thinner lifts with the same aggregate size and grading.

Improper roller operation, particularly sudden reversal of the roller, can also contribute to the shoving of the mix during construction (see Section 18). If a vibratory roller is run at too great a speed and the impact spacing is too far apart, the mat may develop a washboard effect, where the peak-to-peak distance is equivalent to the impact spacing. Washboarding or shoving is more likely to occur at normal frequencies but at high speeds where the impact force is greater. If a pneumatic tire roller with high tire pressure is used for breakdown compaction, a tender mix may shove laterally under the tires. Shoving can occur under any roller that is operated improperly.

Another possible cause of shoving is an excess of tack coat material that may be pulled into the mix. In a similar manner, excess asphalt from a bleeding underlying surface or from joint filler material can be pulled into the mix and increase its fluidity and tenderness. Shoving may occur as well when the underlying surface is dusty or dirty—a slippage failure. (See Section 14.)

Solutions

The solution to a mix that shoves under the compaction equipment is to increase its internal stability. This can be accomplished by reducing the fluids content (asphalt or moisture, or both) of the mix, but only after determining the effect of a change in asphalt binder content on the mechanical properties of the mix. The internal friction can be increased by lowering the mix temperature. Alternatively, the internal friction among the aggregate particles can be increased by changing the aggregate gradation or increasing the amount of angular (crushed) particles in the mix.

The compaction process for a tender mix should be changed, as discussed above under checking, to obtain sufficient density at the time of construction. An increase in the density achieved during the construction process will generally reduce the amount of shoving and rutting that may occur later under applied traffic. Sand mixes, because of their inherent tender nature, should be placed in several thin layers instead of one thick layer when used as base or binder courses.

The compaction equipment should be operated properly so as to reduce the opportunity to displace the mix during the rolling operation. Further, if the underlying pavement surface is dirty, it should be cleaned and a proper tack coat applied.

Effects on Performance

Mats that tend to shove under the compaction equipment are basically unstable. These mixtures will usually continue to distort under traffic, both longitudinally and laterally. Shoving of the HMA mixture during construction is a strong indication that the pavement will rut later and not perform properly under traffic.

BLEEDING AND FAT SPOTS

Description

Bleeding of an asphalt mixture (see Figure 19-7) occurs when the asphalt cement flows to the top of the mix surface under the action of traffic loading. Bleeding is often seen as two flushed longitudinal streaks in the wheelpaths of the roadway. Fat spots in an asphalt mixture (Figure 19-8) are isolated areas where asphalt cement has come to the surface of the mix during the laydown and compaction operation or later under traffic. These spots can occur erratically and irregularly, or they may be numerous and in a fairly regular pattern.

Causes

Fat spots are caused primarily by excessive moisture in the mix (see Section 3). The problem is more common with mixtures that contain a high percentage of fine aggregate (oversanded mixes) and those that contain aggregates with a high porosity. If all the moisture in the coarse and fine aggregate is not removed during the drying and mixing operation at the asphalt plant, the moisture vapor will force asphalt cement to the surface of the mix behind the paver as the moisture escapes from the mix and evaporates. Fat spots occur more frequently when aggregate stockpiles are wet or when the moisture

FIGURE 19-7 Asphalt bleeding in travel lane.

FIGURE 19-8 Fat spot caused by localized excess asphalt.

content varies in different portions of the stockpiles. Fat spots sometimes occur in areas where petroleum products, such as oil and diesel fuel, were spilled onto the pavement surface prior to overlay (see Figure 19-9; see also Section 14) or have contaminated the mix. In addition, fat spots can be associated with segregated areas in the mix. If the mix deposited on the roadway by the paver is segregated, areas in which excess asphalt cement is present in the mix can result in free binder material on the top of the layer being placed.

The causes of bleeding normally fall into two categories. The first is an excess of fluids in the asphalt mixture—either asphalt cement or moisture or both. Under traffic, the extra moisture and asphalt cement will be pulled to the surface by the passage of vehicle tires. This bleeding phenomenon usually occurs on new mix and during hot weather when the viscosity of the asphalt cement is at its lowest level. Typically the bleeding occurs shortly after traffic is allowed to travel over the fresh mix—while there is still some moisture in the mix and while the viscosity of the asphalt cement binder is still relatively low.

FIGURE 19-9 Fat spot caused by fuel oil spill prior to overlay construction.

Bleeding may also be associated with a lack of adequate space in the mix for the asphalt cement. If the VMA content and air void content of the mix do not provide enough room for the binder material, bleeding can occur as the mix is densified by traffic, both shortly after construction and later. The traffic compaction process will decrease the air void content of the mix and may, in turn, squeeze some of the asphalt cement out of the mix. The "extra" asphalt will appear as a longitudinal streak or fat spot throughout the length of each wheelpath.

One additional possible cause of bleeding is the condition of the pavement layer on which the new mix is placed. If the underlying layer has excess asphalt on its surface or excess crack seal material in the cracks and joints, some of this material may be drawn up through a thin new mix layer. Further, if too much tack coat is applied to the original pavement layer, the excess material may be pulled up through a thin overlay and contribute to the bleeding problem.

Solutions

Variations in the asphalt mix temperature behind the paver indicate that the moisture content of the mix may also be variable. Where moisture has evaporated, the temperature is lower. This latter phenomenon can contribute to both the bleeding of the mix later under traffic and the generation of fat spots in the mix during construction. It is important, therefore, that the aggregate used in the mix be relatively dry and that the moisture content of the mix upon discharge from the asphalt plant be as low as possible, but not more than 0.5 percent. Extra care needs to be taken in drying when producing mixtures that incorporate highly absorptive aggregate.

Bleeding problems caused by excess asphalt cement in the mix can most easily be solved by reducing the asphalt content, consistent with other properties of the mix, such as air voids, VMA, and strength or stability. Bleeding problems that occur in conjunction with pavement rutting usually can be solved, however, only by a complete redesign of the asphalt mixture, with emphasis on proper air void content and VMA criteria.

Effects on Performance

Occasional fat spots in the mix should not affect the ultimate durability of the pavement to a significant degree. A large number of fat spots or bleeding in the wheelpaths does affect pavement performance, however, because of variable asphalt and air void content in different parts of the mix. In addition, other mix problems, such as shoving, rutting, and loss of skid resistance, may occur in a mix that contains many fat areas or bleeding in the wheelpaths. The design of the asphalt mixture, the operation of the asphalt plant (more complete removal of moisture), or both should be checked to ensure that the mix produced will provide adequate pavement performance under vehicular loading.

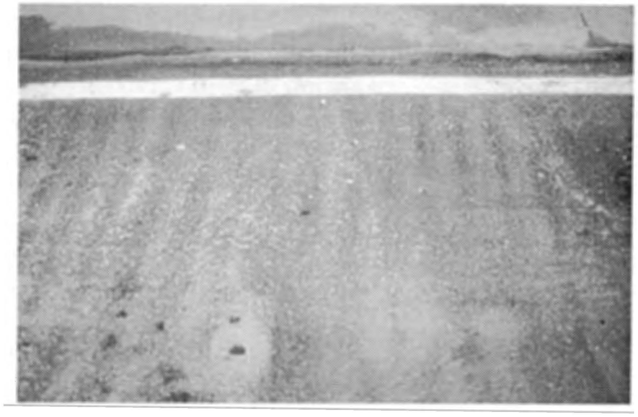

FIGURE 19-11 Washboard marks left by improperly operated vibratory roller.

ROLLER MARKS

Description

During the compaction process—whether vibratory static steel wheel or pneumatic tire rollers are used—longitudinal creases or marks are left in the surface of the mix. Once the mix has cooled to a temperature range of 70°C to 60°C (160°F to 140°F), these marks are typically removed by the finish roller. Roller marks are indentations that remain in the surface of the mix after rolling has been completed (see Figure 19-10).

Roller marks may also exist in the asphalt surface when any roller is parked on the hot mat for a period of time or when a vibratory roller is vibrated in place. Particularly when used in the breakdown position, pneumatic tire rollers can leave visible longitudinal marks that can still be seen after the finish rolling has been completed. Vibratory washboard marks may be visible if that roller is operated at an improper vibratory amplitude, frequency setting, or speed, as shown in Figure 19-11.

Causes

Roller marks can be an indication that the proper number of roller passes has not been made over the mix (see Section 18). If the compaction process is halted before the required amount of rolling has been completed or if the mix cools before the compaction process has been finished, the longitudinal marks or creases made by the rolling process will remain in the surface of the mix.

FIGURE 19-10 Roller marks in freshly laid asphalt pavement.

Roller marks left in an asphalt layer also may indicate a tender mix (see Section 3). The roller operator will normally be unable to remove all the marks left by the compaction equipment if the mix is tender or unstable. A tender mix usually will not support the weight of the finish roller until it has cooled to the point at which the viscosity of the asphalt cement has increased enough to stiffen the mix. By the time the mix has decreased in temperature to this point, however, the required level of density can generally no longer be achieved because the mix has lost its workability. For this reason, the roller marks or indentations left during the breakdown and intermediate roller passes usually cannot be removed during the finish rolling process. All of the asphalt cement, aggregate, and mix properties that contribute to the formation of a tender mix, as discussed above, also contribute to the inability of the finish roller to eliminate roller marks.

Solutions

If the cause of roller marks is inadequate compaction, additional roller passes should be made with the breakdown, intermediate, or finish rollers to properly densify the mix. The solutions for inadequate compaction related to mix design deficiencies all involve changes to the mix design and to the production of the mix at the asphalt plant. Asphalt cement quality and content, aggregate properties and characteristics, and mix temperature all play a significant role in the workability and stability of the asphalt material under the compaction equipment.

Roller marks normally cannot be removed from a tender mix until the mix temperature has decreased to a relatively low level—usually less than 70°C (160°F).

Sometimes it is possible, depending on environmental conditions and the properties of the mix, to remove roller marks left in the mix by using a pneumatic tire roller. If the surface of the mix is hot enough [60°C (140°F) or more], several passes with a pneumatic tire roller can be made to "iron out" the surface of the pavement. Finally, roughness or washboarding caused by incorrect operation of a vibratory roller should be eliminated by using proper operating techniques with this equipment.

Effects on Performance

Roller marks are normally an indication that the proper level of compaction has not been achieved. In terms of ultimate pavement durability, the air void content or density of the mix is the single most important characteristic that governs the performance of the asphalt mixture under traffic. If the air void content of a dense-graded mix is high—the density is too low—the pavement generally will not perform well under traffic.

SEGREGATION

Description

Segregation is the separation of the coarse aggregate from the rest of the mix in an HMA mix. Segregation results from mishandling the mix at any of several points during the mix production, hauling, and placing operations. When segregation occurs in a paving project, it is likely to lead to forms of long-term pavement distress such as wavy surface and poor compaction. It can occur as the mix is delivered from the asphalt plant to a surge silo, as the mix is deposited into the haul truck from the silo, and as the mix is discharged from the truck into the paver hopper. Segregation that is evident behind the paver screed generally takes one of three forms: it may consist of areas of coarse aggregate (rock pockets) that occur randomly across the length and width of the layer; it may occur at a transverse location across the width of the lane (truckload-to-truckload segregation); or it may occur along one side of the paver width (longitudinal or side-to-side segregation).

Causes

The cause of segregation behind the paver is directly related to the type of segregation involved. Rock pockets are generally caused by improper handling of the aggregate in the stockpiles, cold-feed bins, or storage of the HMA at the asphalt plant (see Section 6). They seldom occur when a batch plant is used to produce the mix (without a silo), because the screens and hot bins in the plant recombine any segregated material before it is fed into the pugmill (see Section 8). Further, the pugmill blends all the aggregates together and normally eliminates any segregation that might have occurred previously. If a silo is used on a batch plant, however, the mix may segregate for all the same reasons that affect a mix produced in a drum-mix plant and passed through a surge or storage silo (see Section 11).

Rock pockets and random segregation are occasionally found on the roadway when the mix was manufactured in a drum-mix plant (see Sections 9 and 10). If the loader operator places a bucketful of segregated aggregate in a cold-feed bin, that material can pass through the drum, surge silo, haul truck, and paver without being completely mixed in with the other aggregate. This is because the drum-mix plant operates on a continuous-flow instead of a batch basis. If the aggregate in the cold-feed bins is segregated, that material will show up on the roadway in a random pattern both transversely and longitudinally.

Some mixes are more prone to segregation than others (see Section 3). Asphalt mixes that have large maximum-size coarse aggregate [25 mm (1 in.) or greater], have low asphalt cement content, or are gap-graded will tend to segregate more readily when handled than a dense-graded mix containing optimum asphalt content and a smaller maximum-size coarse aggregate.

Segregation that occurs on one side of the paver (side-to-side segregation) when a batch plant without a silo is used to produce the mix is normally caused by improper loading of the haul truck from the pugmill (see Section 11). If the mix is not loaded in the center of the width of the truck bed, the coarse aggregate particles in the mix may roll to one side of the truck and accumulate along that side. When the mix is delivered to the paver hopper, the segregated mix will be placed on the roadway along the same side, and the segregation will appear as a longitudinal streak on one side of the paver only.

Segregation that occurs on one side of the paver when a batch plant with a silo or a drum-mix plant is used to produce the mix is typically caused by improper loading of the mix into the surge silo (see Section 11). As the mix is deposited into the silo from the conveying device (slat conveyors, belt conveyor, or bucket elevator), the mix is thrown to one side of the silo, and the coarse aggregate particles are separated from the finer materials. When the silo is emptied, the coarse aggregate is deposited on only one side of the truck. This segregated material then passes through the paver and is seen on one side of the mix after laydown. Further, as with a batch plant, if the truck is not loaded in the center of its width under the silo, rolling of the coarse aggregate particles may occur, and longitudinal segregation will then appear on one side of the new mat.

Truckload-to-truckload segregation has many potential causes (see Section 11). The most common is improper loading of the haul truck from the silo. If mix is placed in the truck bed in one drop from the silo, the coarse aggregate particles in the mix have a tendency to run to both the front of the bed and the back tailgate. This rolling of the coarse aggregate is exacerbated if the plant operator continuously opens and closes the silo gates near the end of the truck-loading procedure to ensure that the full weight of mix is placed on the truck.

Some believe that truckload-to-truckload segregation can also be caused by improper discharge of the mix into the silo. Mix that is dribbled into the silo from the conveying device is said to be susceptible to segregation inside the silo. Even if this occurs, the mix that is segregated in the silo will appear only as random rock pockets in the layer behind the paver, instead of in a systematic manner between truckloads of mix delivered to the paver. Thus it is doubtful that any segregation of the mix that occurs during the continuous process of loading the silo will appear on the roadway in a discontinuous pattern—only at the beginning or the end, or both, of a truckload of mix.

Temperature segregation of the mix has also been shown to be a problem. The mix cools more quickly near the edge, bottom, and top of the truck during haul. This cooler material is not always remixed with the hotter HMA, leading to temperature segregation during the laydown operation. The result can be more variability in density during construction and a nonuniform surface. This problem can be monitored by infrared technology.

Solutions

The solution to each type of segregation is related to its cause. For random rock pockets that appear intermittently in the mat, the method of stockpiling the coarse aggregate at the asphalt plant and the charging of that material into the cold-feed bins by the front-end loader should be checked to ensure that proper aggregate handling techniques are used. Further, all points in the mix-production system at which coarse aggregate particles might accumulate should be inspected to determine whether the flow of the coarse and fine aggregate pieces is uneven. A batcher should be used at the top of the silo to direct the mix into the center of that piece of equipment.

For longitudinal (side-to-side) segregation, the loading of the haul truck from the batch plant pugmill or from the silo at either the batch or drum-mix plant should be monitored to ensure that the mix is being delivered into the center of the width of the vehicle. When a drum-mix plant is used to manufacture the mix and the segregation always appears on one side of the paver, several trucks should be loaded at the silo while facing in the opposite direction from their normal loading procedure. When the mix is passed through the paver, the longitudinal segregation should change sides—go from one side of the paver lane to the other. If the transverse position of the longitudinal segregation does change (and it should), the solution to the side-to-side segregation problem must take place at the top of the silo. The mix deposited into the silo from the conveying device must be directed into the center of the silo instead of to one side, so that the coarse aggregate particles in the mix are not thrown to only one side of the silo. This solution requires some changes in the configuration of the equipment at the top of the silo. If the transverse position of the longitudinal segregation does not change, the segregation is probably caused by a paver problem.

Most truckload-to-truckload segregation can be reduced significantly by using multiple drops of mix to load the haul trucks. If a tandem-axle truck is being loaded, at least three different drops of mix should be made—into the front of the truck near the front bulkhead, into the back of the truck near the tailgate, and into the center of the truck bed between the first and second drops. If a larger truck is used, additional drops of mix should be made—the first into the front of the truck bed and the second near the tailgate. One of the main solutions for truckload-to-truckload segregation is to minimize the distance the coarse aggregate particles can roll. This is accomplished by making multiple drops of mix into the truck.

The plant operator should be prohibited from topping off the load of mix at the end of the loading process. Each time the silo gates are opened and a little bit of mix is dribbled into the truck, the coarse aggregate particles will tend to separate from the finer material. This problem can be eliminated only by preventing it from occurring.

If segregation does take place during the loading of the truck and there is an accumulation of coarse aggregate particles at the tailgate of the truck, at the front of the bed, or both, the amount of segregation that appears on the roadway can usually be reduced by proper unloading of the haul truck at the paver. First, the truck bed should be raised a short distance, before the tailgate of the truck is opened, so that the mix can shift in the bed and slide against the tailgate. This procedure surrounds any coarse particles that have rolled to the tailgate area with non-segregated mix. Instead of only the coarse aggregate being deposited first into the paver hopper, a mass of mix is discharged when the truck tailgate is opened, flooding the hopper with mix and typically incorporating the segregated coarse aggregate into that mass of HMA mix.

The operation of the paver can also increase or reduce the amount of segregation that occurs behind the screed. If the paver hopper is emptied of mix, if the slat conveyors are visible, and if the wings of the hopper are dumped after each truckload of mix, any coarse aggregate particles that have collected at the tailgate of the next truckload of mix will be deposited into the bottom of the hopper and then carried directly back to the empty auger chamber in front of the screed. This segregated material will appear behind the screed as soon as the paver moves forward. This transverse segregation, therefore, does not really occur at the end of the truckload, but rather at the beginning of the next truckload of mix.

Segregation can be reduced by keeping the hopper full of mix between truckloads. The mass of mix that floods the hopper from the haul truck will be blended with the mix already in the paver hopper. Any segregated material will be further incorporated in the mix that is pulled back to the augers by the slat conveyors and passed under the paver screed. The amount of truckload-to-truckload segregation can be decreased significantly, but not always eliminated completely, by good paver operating techniques. The problem should really be solved during the truck-loading procedure.

The use of MTVs has also shown some benefit in reducing segregation. The MTV remixes the HMA, and this reduces aggregate segregation, as well as differential temperatures within the mix (also known as temperature segregation).

Effects on Performance

Segregation can affect pavement durability directly by increasing the air void content of the mix in the segregated areas and increasing the potential for moisture damage. Further, the segregated locations are very susceptible to raveling and, if bad enough, to total disintegration under traffic. Segregation, whether in the form of rock pockets, longitudinal (side-to-side) segregation, or transverse (truckload-to-truckload) segregation, is extremely detrimental to the long-term performance of the pavement.

POOR MIX COMPACTION

Description

The HMA mixture should be compacted so that the in-place air voids are at an acceptable level. If the air voids are above 7 to 8 percent, the mix will be permeable to air and water and will not have the required durability. If the initial compaction results in air voids of approximately 4 percent or lower, the mix may become unstable under traffic after additional densification; the result will be shoving and rutting of the mixture, as discussed earlier. Most mixes require a significant level of compaction to reach the desired 7 to 8 percent or less air voids.

Causes

When the mix is too stiff or too tender, compaction is difficult. The primary cause of poor compaction is low design mix density (high design air voids) (see Section 3). Other causes include inadequate underlying support (Section 14), improper type and weight of rollers (Section 18), improper tire pressure in rubber tire rollers (Section 18), improper rolling procedure (Section 18), improper mix design (Section 3), mix segregation (see above), moisture in the mix (Section 3), variation in mix temperature, and low mix temperature.

Solutions

Solutions to compaction problems include taking the necessary steps to ensure adequate support, producing an acceptable mixture, and using satisfactory laydown and rolling techniques. When support is inadequate, the compaction requirements may have to be relaxed, or the mix may have to be redesigned to allow for satisfactory compaction.

When the asphalt content is too high, the mix may compact too easily, resulting in low air voids (which leads to rutting; see the earlier discussion). When the asphalt content is too low, the mix may be stiff and difficult to compact to the specified density. A satisfactory mix design will produce a mix with optimum asphalt content that can be compacted with reasonable effort to the required density.

Good laydown and rolling techniques, as discussed earlier, are necessary for good compaction. Density can normally be increased by reducing the speed of the paver or rollers. Density can also be increased by increasing the weight and number of rollers. The compaction process must be adjusted to produce optimum density.

Effects on Performance

When the compaction is inadequate (more than 7 to 8 percent air voids) the mix will be permeable to air and water. Water can flow through the HMA and reduce the strength of the underlying base course. The high voids also result in excessive oxidation of the HMA, which leads to raveling, cracking, and general deterioration of the HMA over a period of time.

When the air voids are excessively low after compaction (less than 4 percent) the mix is likely to rut and shove under traffic. The low voids are the result not of too much compaction, but of an unsatisfactory mixture.

OTHER PAVEMENT PROBLEMS

The above discussion has addressed only those problems that occur at the time of the asphalt mix production, laydown, and compaction. A number of other deficiencies can occur on an asphalt pavement structure with time and traffic loading once construction has been completed. Those distresses include fatigue cracking, rutting, shoving, raveling, and disintegration. A discussion of such distresses is beyond the scope of this handbook.

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt cement
ESAL	equivalent 80-kN (18,000-lbf) single-axle load
FHWA	Federal Highway Administration
HMA	hot-mix asphalt
JMF	job-mix formula
MTV	material transfer vehicle
OSHA	Occupational Safety and Health Administration
PCC	portland cement concrete
PD	percent defective
PG	performance grading
PWL	percent of material within specification limits
QA	quality assurance
QC	quality control
RAP	reclaimed asphalt pavement
SHRP	Strategic Highway Research Program
SMA	stone-matrix asphalt
SSU	saybolt seconds universal
USACE	U.S. Army Corps of Engineers
VFA	voids filled with asphalt
VMA	voids in the mineral aggregate

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