PART I

Project Organization, Mix Design, and Quality Control

1 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.

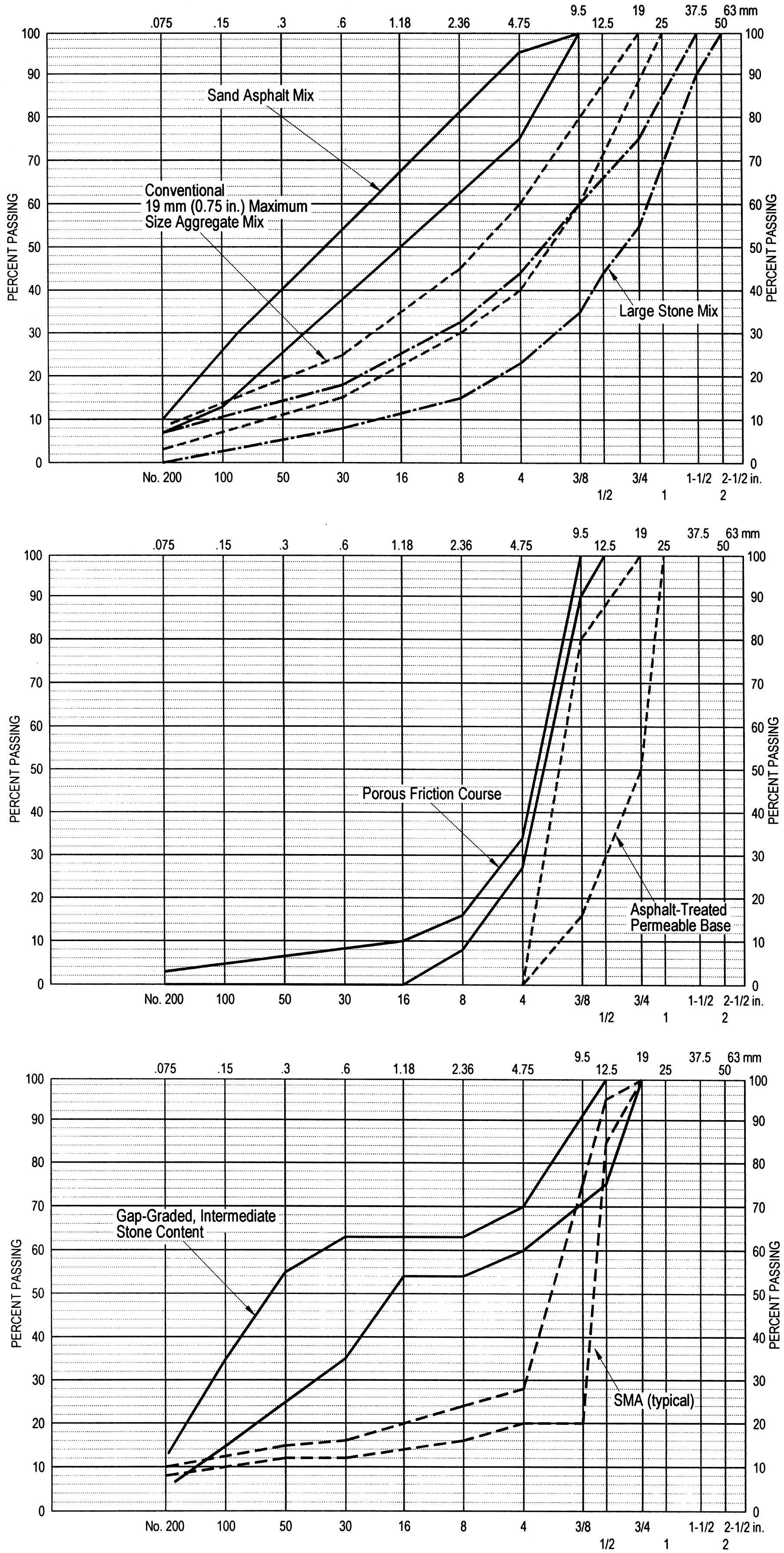
As noted, there are two types of open-graded mixes. The first comprises mixes used as a surface course to provide a free-draining surface in order to prevent hydroplaning, reduce tire splash, and reduce tire noise; this type of mix is frequently termed an *open-graded friction course*. The second type, 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



a. Dense-graded

b. Open-graded

c. Gap-graded

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.

SECTION

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.

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.

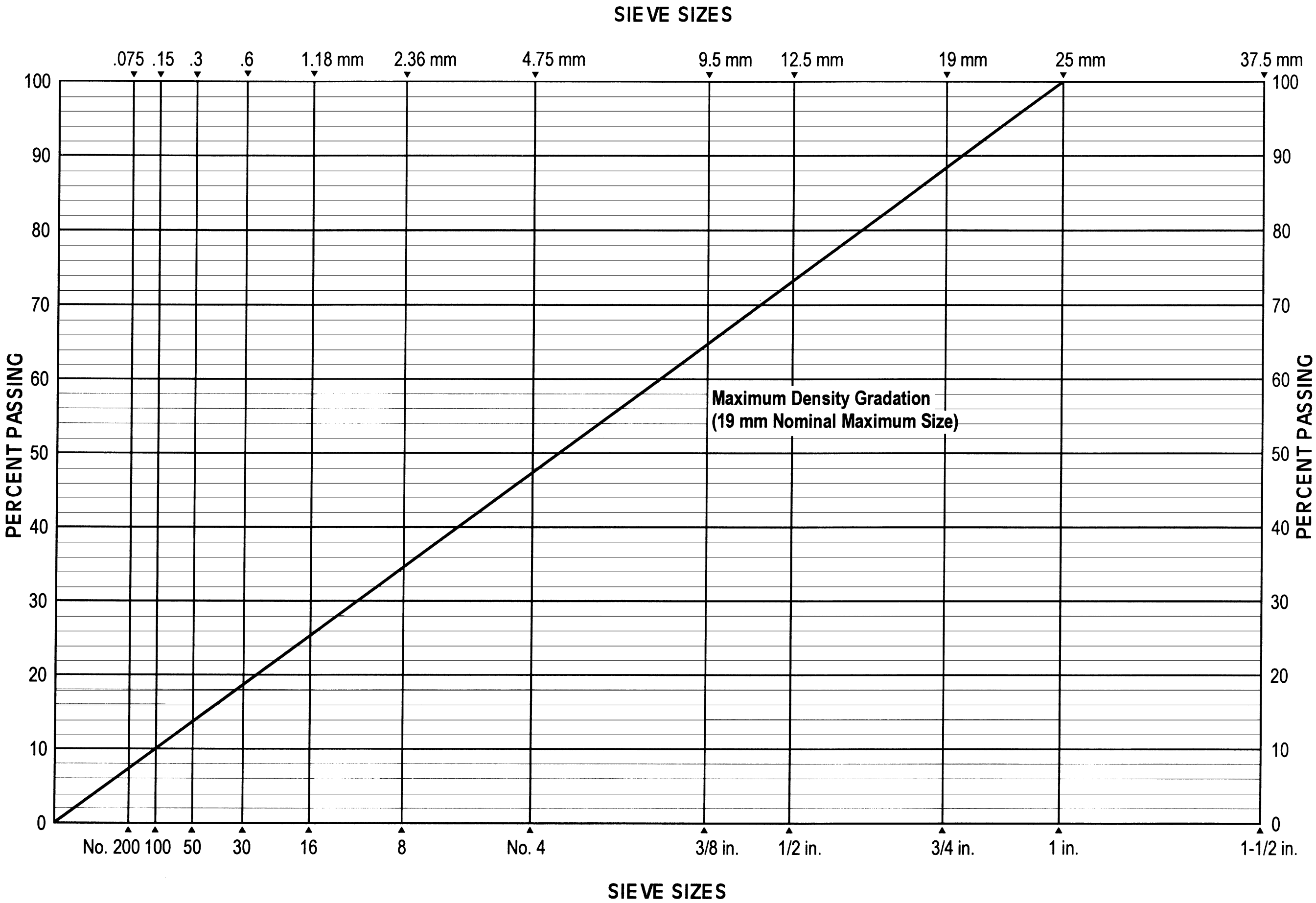


FIGURE 3-1 Gradation chart, exponential scale (*n* = 0.45).

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-

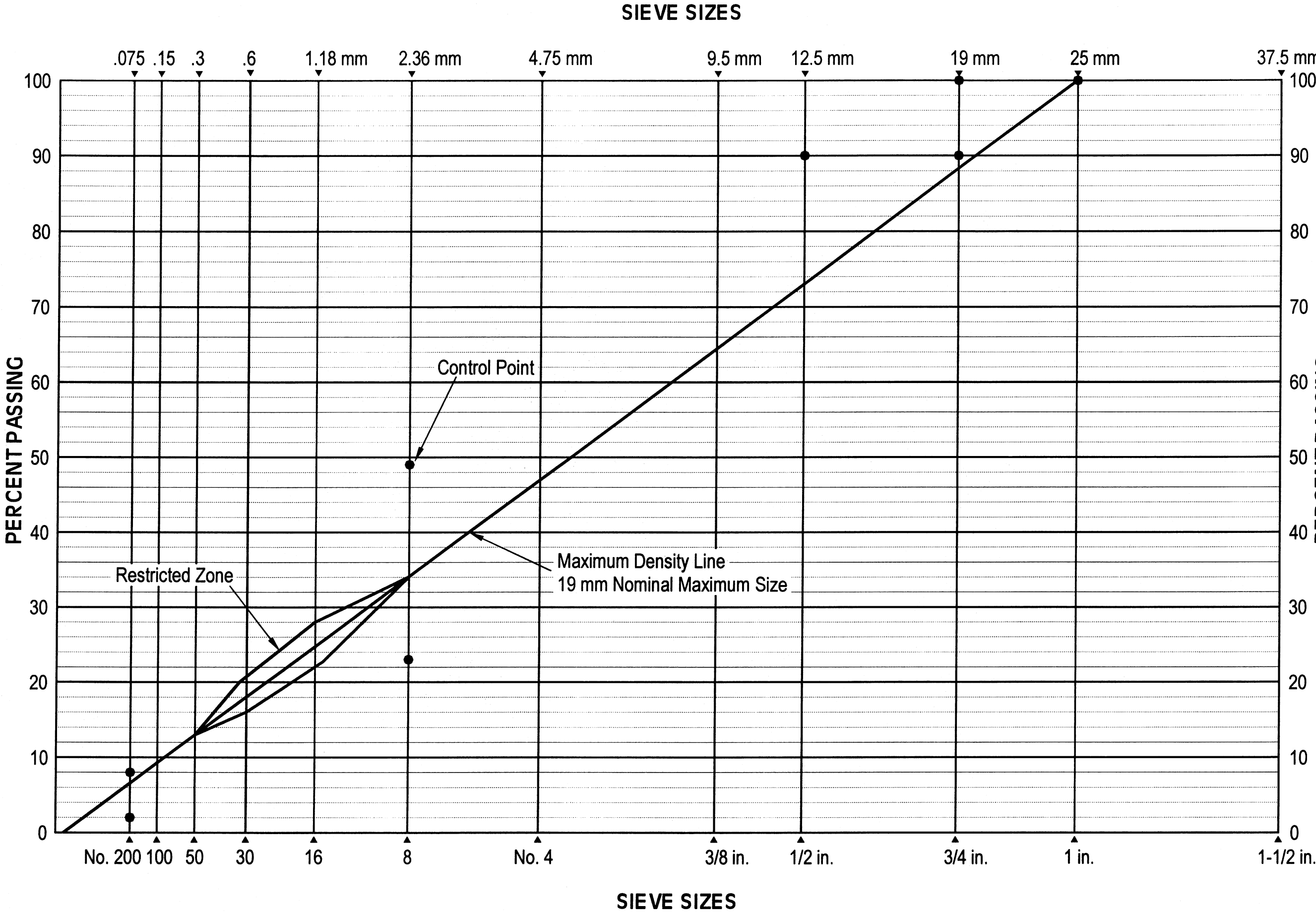


FIGURE 3-2 Control points and restricted zone for aggregate gradation with 19-mm nominal maximum size.

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

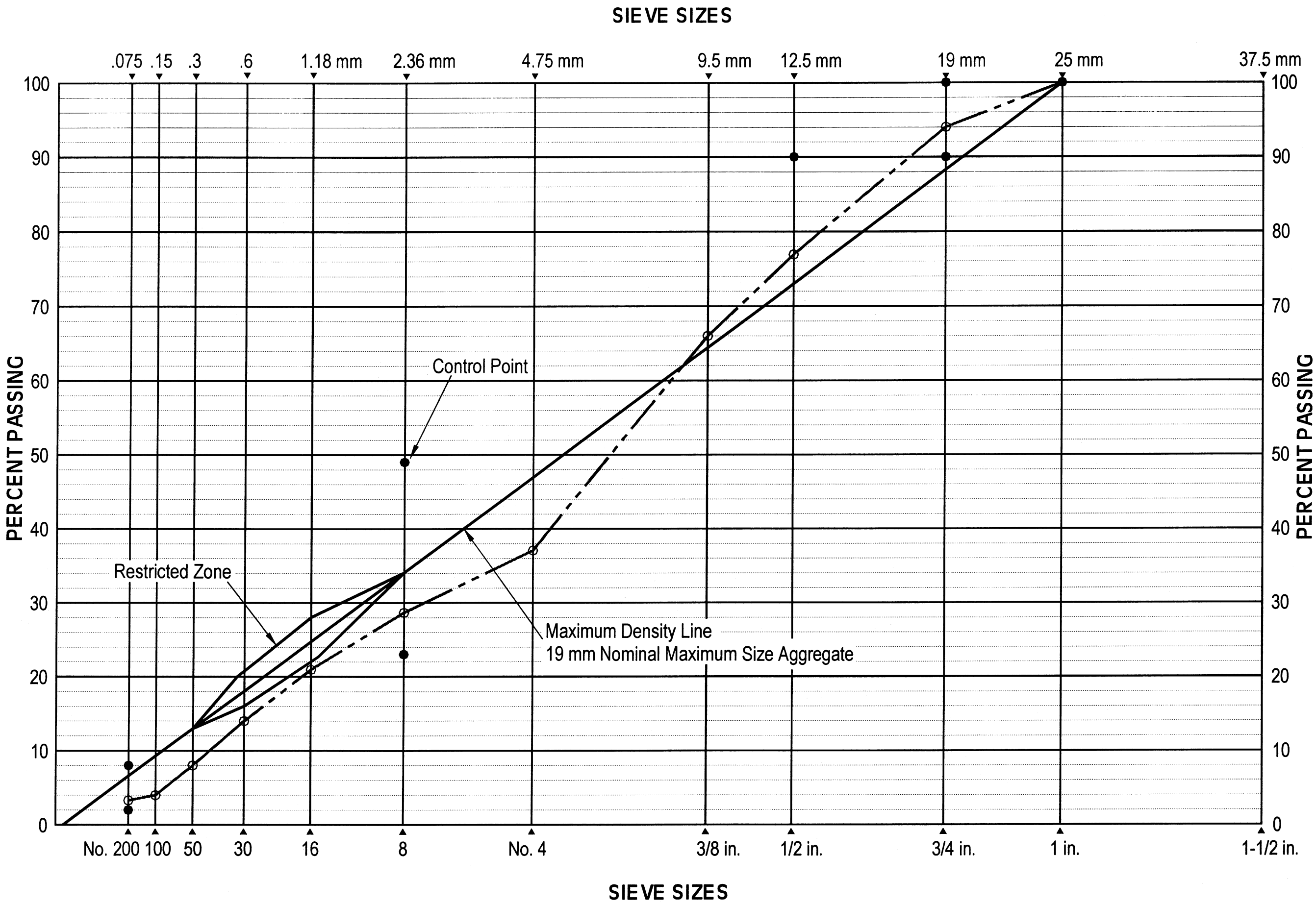
The size distribution of the material passing the 0.075-mm sieve influences the stiffness of the binder dust mixture as well and therefore may also affect the compactibility of the mix. For the same asphalt, if the majority of the fines are smaller than 0.020 mm (20 microns), the stiffness of the binder 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-



F I G U R E 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.

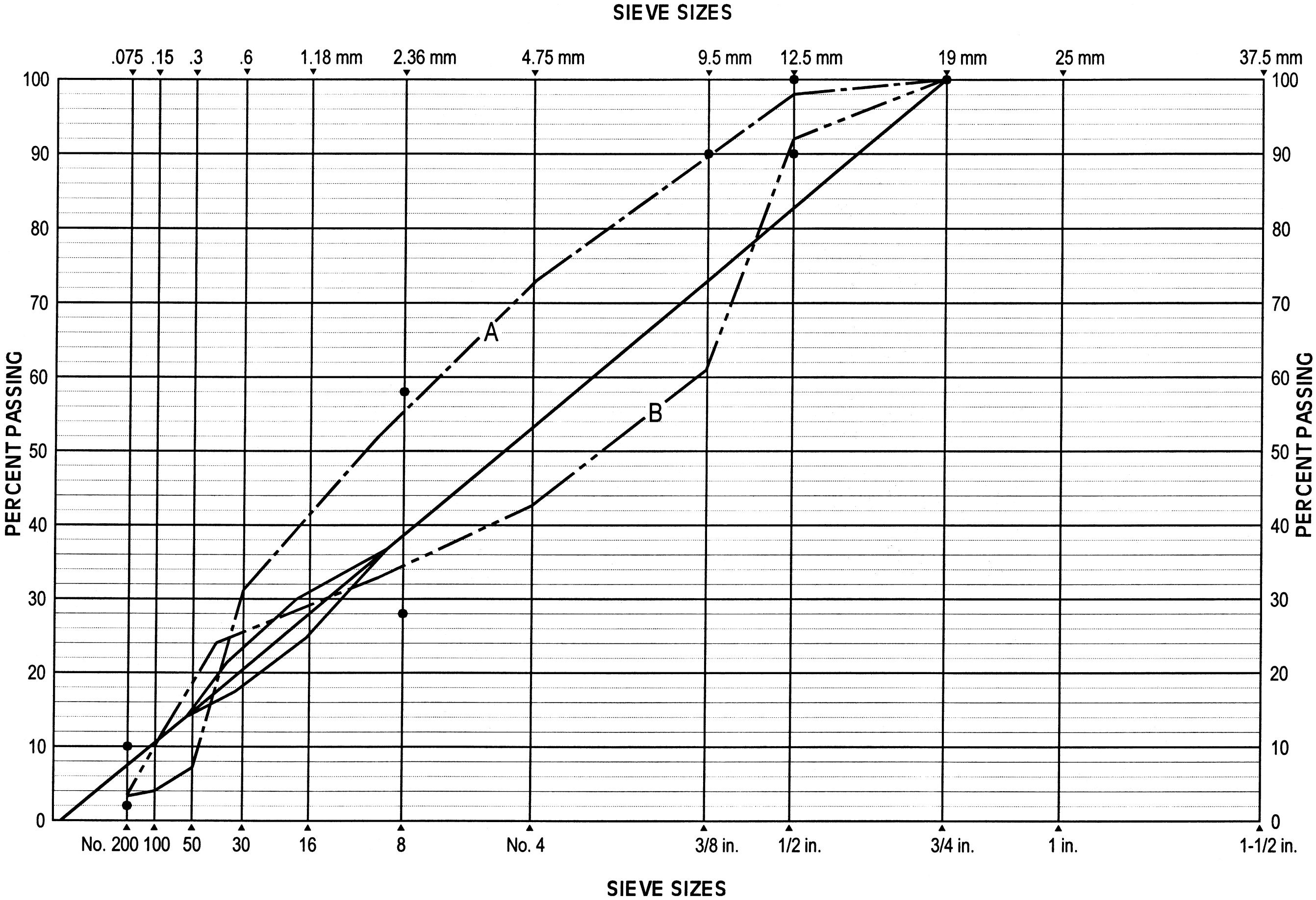


FIGURE 3-4 Examples of aggregate grading that is likely to produce tender mixes.

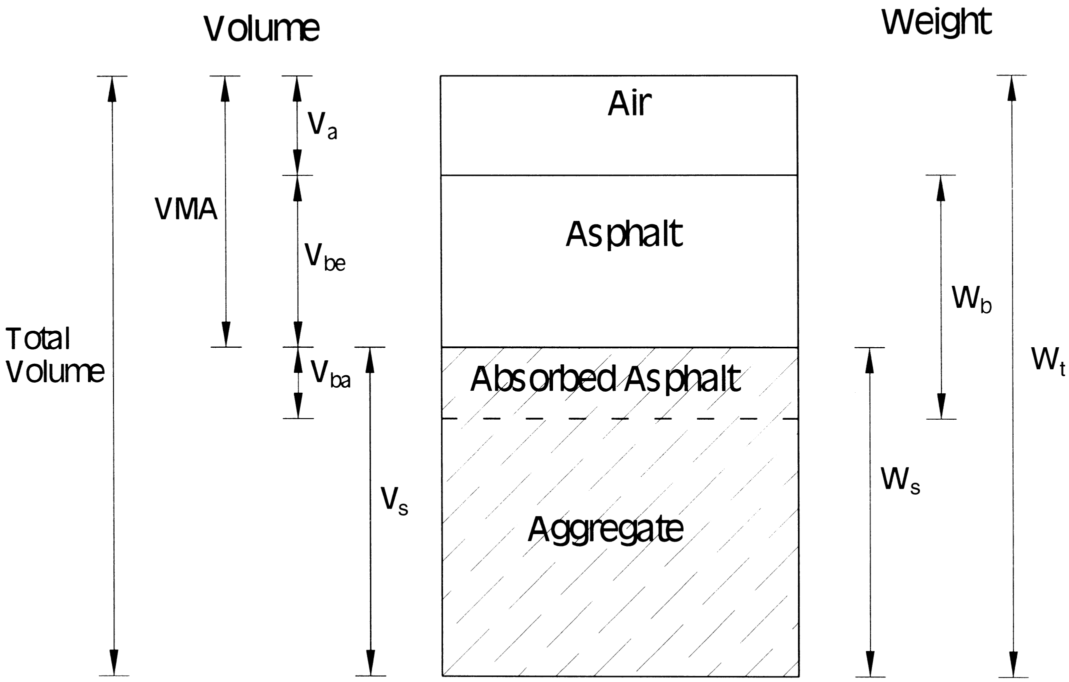
Marshall Method

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,

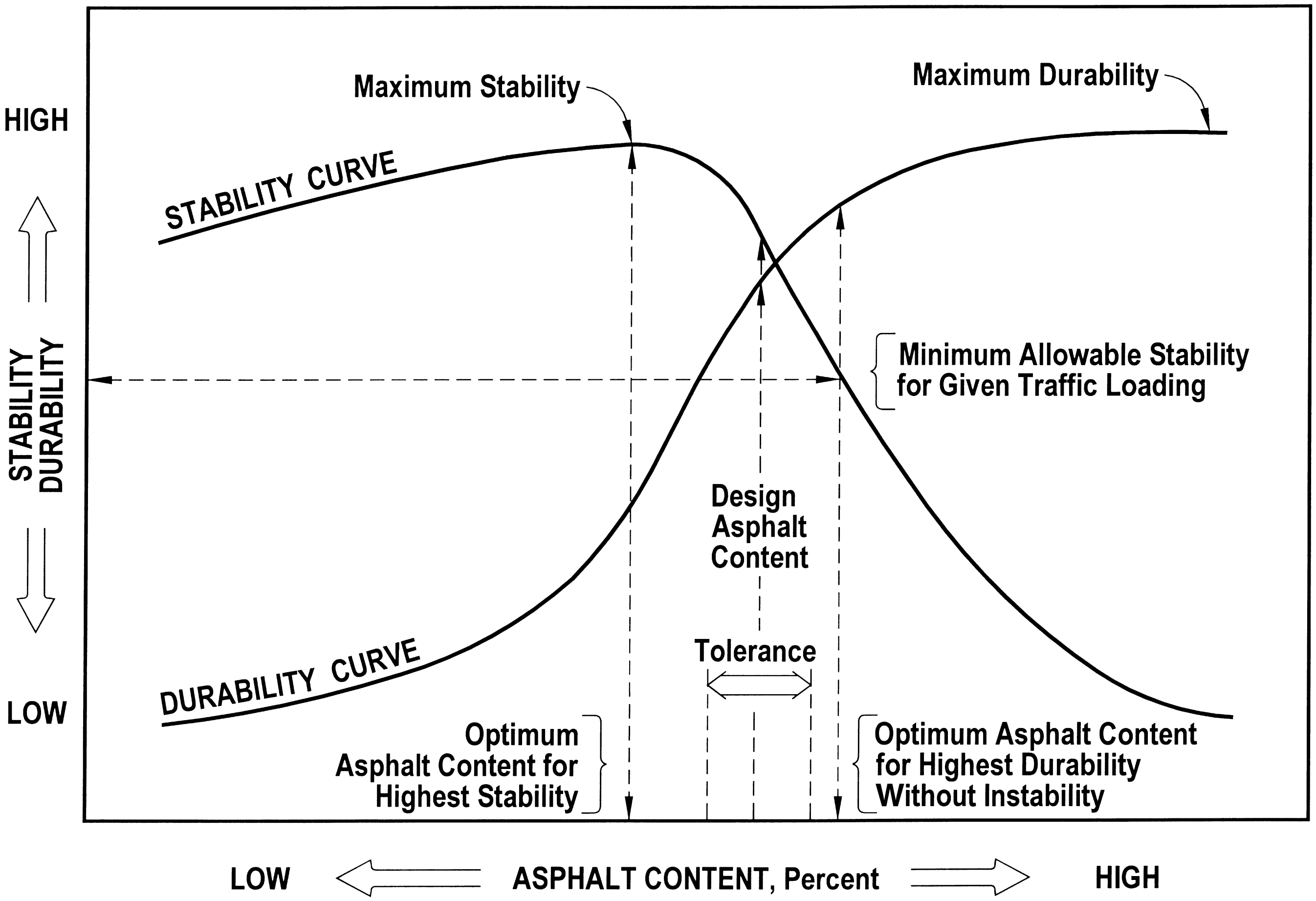


FIGURE 3-6 Schematic of stability–durability relationship of hot-mix asphalt, illustrating philosophy of selecting design asphalt content.

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-

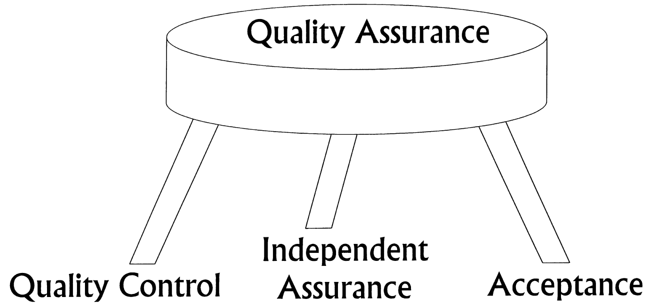

FIGURE 4-1 Elements of quality assurance.

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.

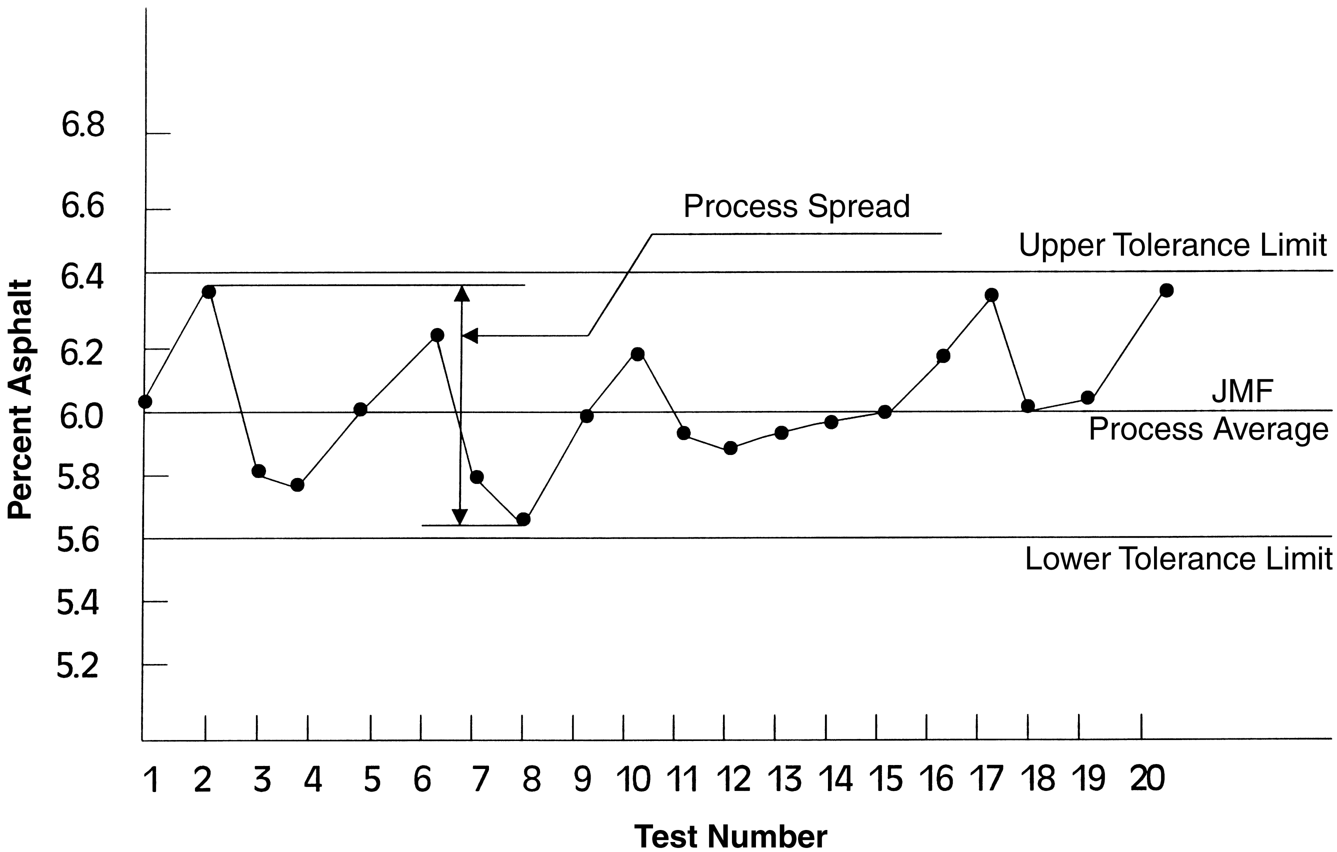

FIGURE 4-2 Asphalt content of paving mixture.

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.

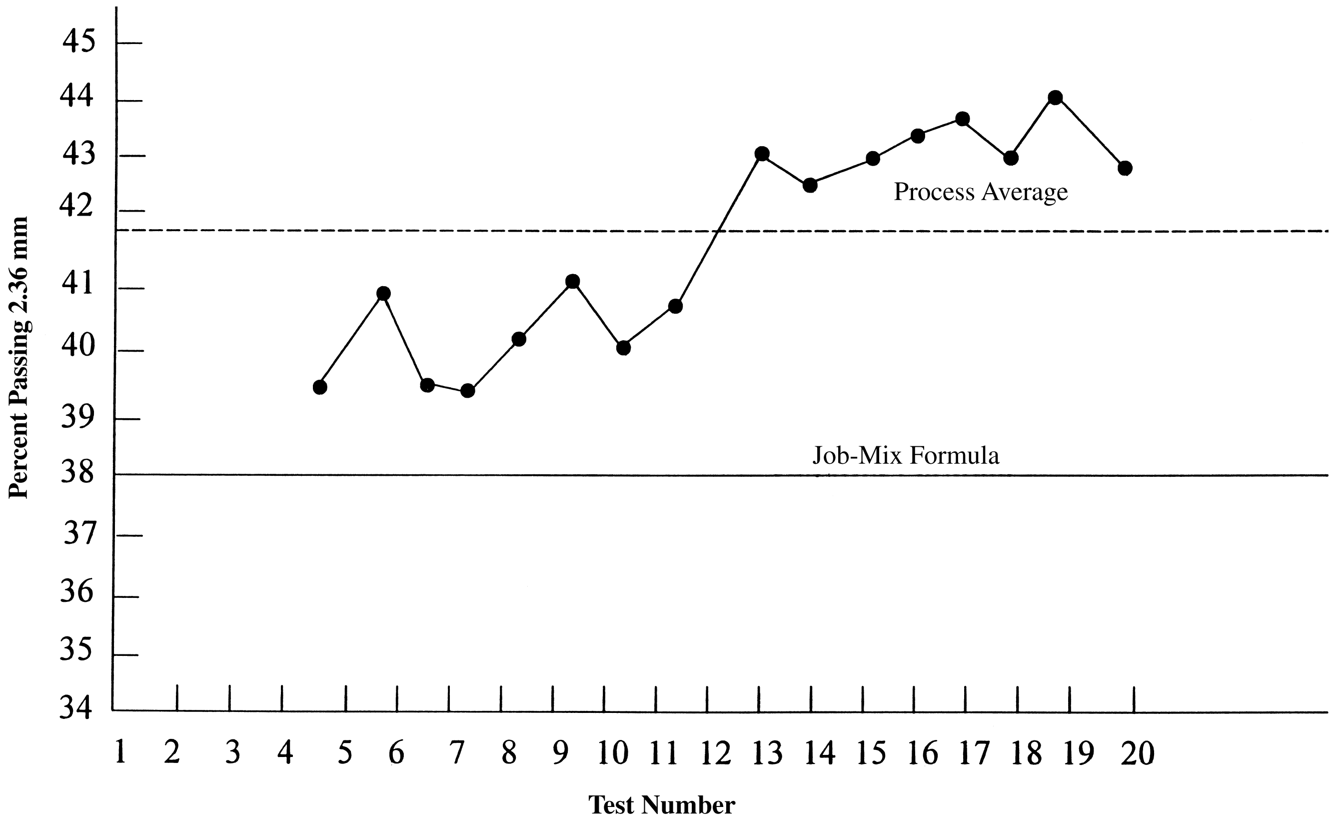

FIGURE 4-3 Moving average of five measurements, percent passing 2.36-mm (No. 8) sieve extraction gradation.

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

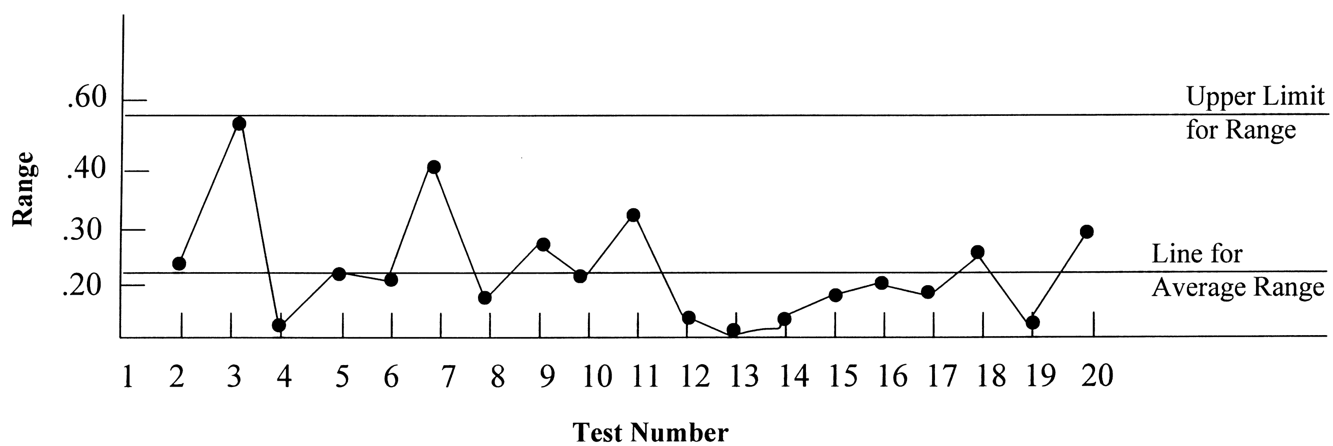

FIGURE 4-4 Moving ranges of two measurements, asphalt content in paving mixtures.

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.

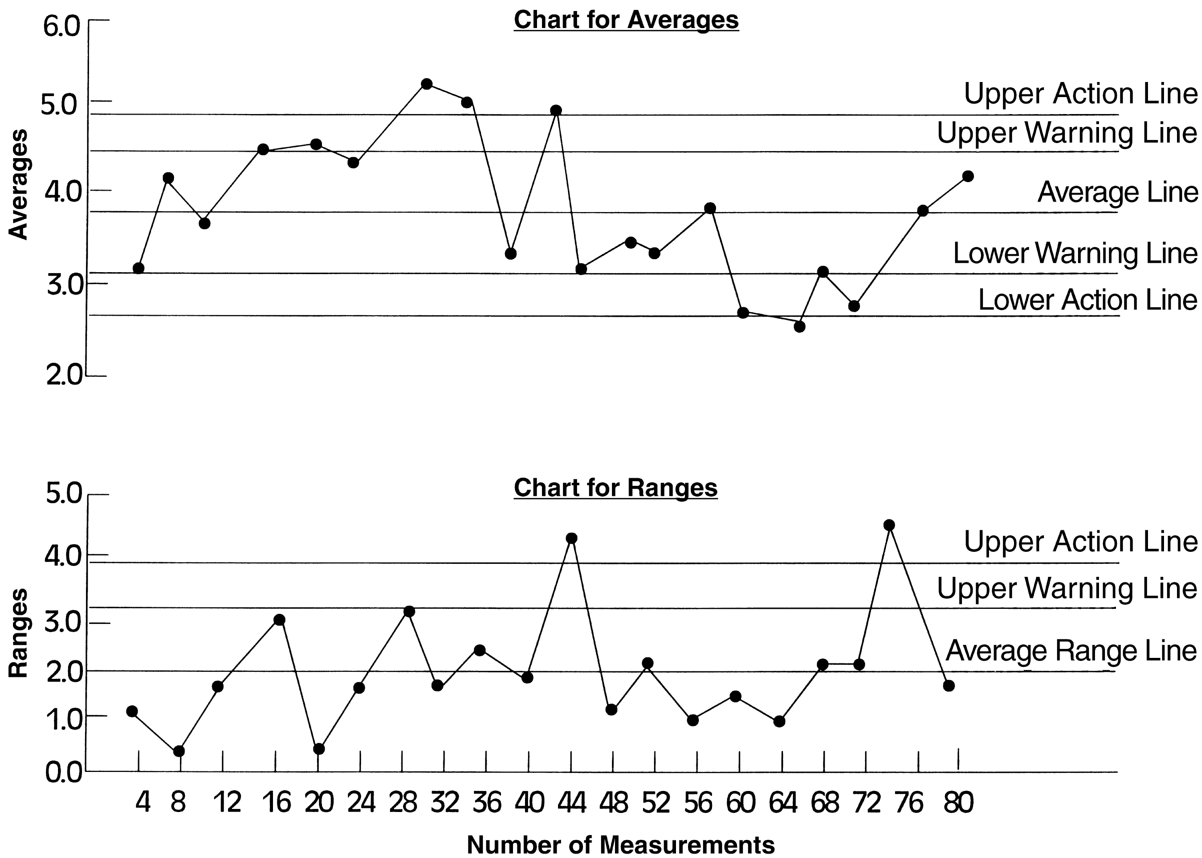

FIGURE 4-5 Average and range statistical control charts for air voids (four measurements).

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.

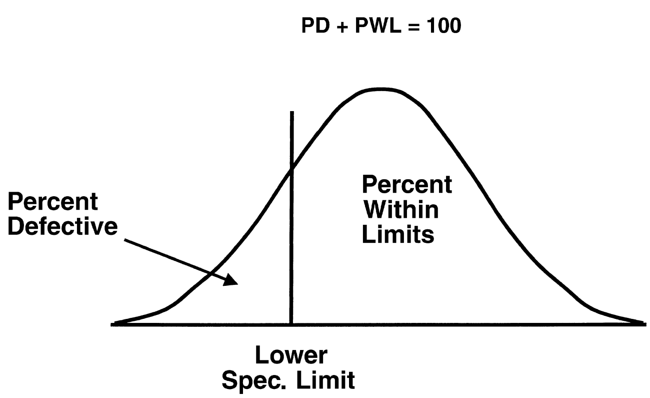

FIGURE 4-6 Relationship between percent within limits and percent defective.

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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