WesTrack Forensic Team Consensus Report

SUPERPAVE MIXTURE

design guide

U.S. Department
of Transportation

Federal Highway
Administration

foreword

WesTrack was the Federal Highway Administration's (FHWA) test facility in Nevada for developing performance-related specifications for hot-mix asphalt pavement construction. It also provided some of the earliest data on the performance of Superpave asphalt mixture designs under high rates of heavy truck loading. When Superpave-designed test sections placed at the track in June 1997 had very rapid rutting failures, the highway community was concerned that the mixture design and construction procedures might be missing important, but unknown, constraints. A forensic team composed of academicians, asphalt industry representatives, and State highway agency engineers was assembled to study the early failures and, if appropriate, to make recommendations for revising the Superpave procedures. Their examination of the failures resulted in Report No. FHWA-RD-99-134, *Performance of Coarse-Graded Mixes at WesTrack—Premature Rutting*, which is available from FHWA or on the Internet at the Turner-Fairbank Highway Research Center homepage at ***www.tfhrc.gov***.

During the team's investigation, its members concluded that the asphalt paving community needed a good guide on the design of Superpave mixtures. Such a guide would supplement existing specifications and supporting literature and would incorporate the experience of engineers across the country, including the WesTrack designers, in the initial years of Superpave mixture design and placement. It would be a useful companion to the National Asphalt Pavement Association's *Superpave Construction Guidelines*. This publication, *Superpave Mixture Design Guide*, was prepared by the forensic team. Its contents are the views of the team and do not necessarily reflect the views of the U.S. Department of Transportation.

Note that this version of the guide is not expected to be the final word on Superpave mixture design. Both current research studies and additional field experience are likely to yield refinements in the future.

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Introduction

Superpave design methods and tools are being implemented by many State agencies to replace the Marshall and Hveem design methods. In 1999, 2,515 projects, specifying some 73 million metric tons of Superpave, were let.[1] The majority of the projects in 1999 and in previous years were constructed with little or no difficulty. On several projects, there were some problems during this initial implementation. For the most part, the causes of the problems have been identified and have been solved. In 2000, estimates were that more than 3,900 projects, specifying some 134 million metric tons of Superpave, would be let; this would represent 62 percent of the total hot-mix asphalt (HMA) tonnage expected to be contracted for by State agencies during 2000 in the United States.[1] Superpave has become the mixture design method of choice by most State transportation departments across the country.

This document, intended as a companion to the National Asphalt Pavement Association's (NAPA) *Superpave Construction Guidelines*,[2] is a guide for the HMA designer to maximize the benefits of Superpave while avoiding potential problems. The Superpave design process is part of a total pavement design system. Superpave is a system of components that work together to provide a SUperior PERforming asphalt PAVEment. As traffic levels and loading conditions increase above 1 million 80-kN (18,000-lb) equivalent single-axle loads (ESALs) during a pavement's design life, some design areas are not adequately addressed by the current Superpave specifications.

This guide discusses several issues that should be considered during the mixture design process to maximize the benefits of this method. The Superpave design process is documented in publications from the Federal Highway Administration (FHWA), the Strategic Highway Research Program (SHRP), the Asphalt Institute (AI), and the American Association of State Highway and Transportation Officials (AASHTO).[3-8] Those publications should be used for detailed design information. This guide is intended to serve as a bridge between existing knowledge and additional tools being developed to measure and predict Superpave mixture performance under traffic.

This document is a guide for the HMA designer to maximize the benefits of Superpave while avoiding potential problems.

A Superpave mix design includes several processes and decision points. First, design compaction levels are established and materials are selected and characterized. Then, mixture samples are prepared and laboratory test results are compared to design criteria. However, the existing Superpave design system does not properly address performance prediction testing on mixture samples or decision-making during the design process. This guide will address both of these areas.

Superpave Mixture Design Compaction Level Determination

Prior to 1999, the design ESALs shown in the Gyratory Compaction Criteria table of PP-28 (in *AASHTO Provisional Standards*[8]) did not clearly indicate that they represent the pavement's cumulative ESALs for a 20-year design life, rather than the cumulative ESALs for a shorter or longer design life. The WesTrack Forensics Team and the Lead States Team both recently reminded users that, regardless of the actual design life of the pavement, the user should determine the expected ESALs for 20 years and select the design level for that traffic and loading. For example, a project with a 5-year intended life may have a 5-year cumulative ESAL count of 2.9 million. This corresponds to a

20-year cumulative ESAL count of 11.6 million (neglecting traffic growth compounding), and this latter ESAL count should be used in the design. The 1999 version of PP-28 includes a footnote to the Gyratory Compaction Criteria table with the appropriate guidance.[8]

Experience has shown that rutting damage often occurs in the first few years of a pavement's life; therefore, the design should be based on the rate of loading. To properly account for this in the mix design, the mix designer should always use 20-year design ESALs, essentially converting total loads to a rate of loading. Estimating ESALs over a 20-year life, instead of the actual design life, may affect the mixture design compaction level, the performance-graded (PG) binder selection, and the aggregate consensus properties specified for the project. Compaction criteria, aggregate properties, and volumetric properties are all more stringent at higher ESAL levels.

Superpave Performance-Graded Binder Selection

The Superpave Performance-Graded Binder Specification (AASHTO MP-1) is based on providing a binder that is resistant to rutting, fatigue cracking, and low-temperature cracking at specific pavement temperatures. The binder temperature ranges in the specification are based on the high and low temperatures at which a binder reaches critical values of distress-predicting properties. Reliability factors included in the design method account for normal pavement temperature variations and allow the designer to make a rational decision regarding the range of temperature extremes for which to design. Binder grade is selected based on design high and low pavement temperatures expected at the construction site and on desired reliability.

The most common method of selecting a binder grade is to determine the design air temperature range for the specific project and then to establish the corresponding design pavement temperatures. Before selecting the grade to be used, the designer must also consider traffic volume and traffic speed.

The owner should consider factors such as cost and traffic levels in establishing reliability, and hence, the final binder grade selection, for a specific project. For example, if a PG 64 binder provides 94 percent reliability for high temperatures, it may not be cost-effective to specify a PG 70 binder to obtain 98 percent reliability. However, if a PG 64 binder only provides 52 percent reliability, it would probably be reasonable to specify a PG 70 binder to obtain 98 percent reliability.

With respect to traffic volume, when the design traffic exceeds 10 million ESALs, Superpave suggests that an increase in the high-temperature binder grade be considered. When design traffic is more than 30 million ESALs, Superpave requires a one-grade increase in the high-temperature binder grade. With respect to traffic speed, Superpave recommends increasing the high-temperature binder grade by one grade for slow transient traffic (20 to 70 km/h) and by two grades if standing traffic conditions (< 20 km/h) exist. The binder specifier should increase the high-temperature grade for traffic volume or traffic speed, but not for both. If the system is used correctly, a pavement with high design ESALs with stopped traffic conditions will require an asphalt binder that is two high-temperature grades higher than that required by the pavement temperature alone.

It should be realized that when the high-temperature grade is increased by one grade, the stiffness of the binder will approximately double. In other words, a PG 70 binder will be twice as stiff as a PG 64 binder at a temperature of 64°C. Furthermore, a PG 76 binder will be four times stiffer than a PG 64 binder at a temperature of 64°C. Traffic speed will also have an effect on binder stiffness in the pavement. At 50 km/h, a binder will have a lower apparent stiffness than it does when carrying traffic at 100 km/h. In other words, a mixture containing PG 70 binder in a pavement with traffic moving at 50 km/h will have roughly the same stiffness as a mixture containing PG 64 binder in a pavement with traffic moving at 100 km/h; thus, the increased high-temperature grade of the binder effectively offsets the effect of slower traffic speeds.

Consideration should be given to the impact that increasing the binder grade will have on the construction process. Depending on the grade, such an increase could require mixing and compaction temperatures beyond reasonable construction temperatures.

Only strong aggregate skeletons can experience significant performance increases with increased asphalt binder stiffness. The stiffer binder locks the aggregate particles in place to prevent rutting. The binder cannot carry the load alone and cannot overcome a poor aggregate skeleton by itself.

The final step before selecting the binder grade to be specified is to compare the grade being considered with grades historically used in the area. If the binder seems unreasonably soft for preventing rutting based on past history, or unreasonably stiff for construction purposes, the selected grade should be reconsidered.

Superpave Aggregate Selection

Aggregates are the largest component of HMA, making up 80 to 85 percent of the mixture by volume and roughly 95 percent of the mixture by weight. Aggregate characteristics and quality are major factors in the performance of HMA. As part of its focus on binder and mixture properties, in the early 1990's SHRP convened an expert panel to determine which aggregate properties were most important for pavement performance. The properties selected included coarse aggregate angularity, fine aggregate angularity, flat and elongated particles, clay content, and gradation. Aggregate source properties, such as soundness, toughness, and deleterious materials, were also found to be important. However, the criteria applied to the source properties were found to reflect regional differences in aggregate quality, and were usually based on aggregate availability. The panel determined that the source properties were best left for each State or local agency to establish. The following discussion addresses various aggregate properties (consensus and source) and their effect on the Superpave design process.

Coarse Aggregate Angularity Mixtures with crushed coarse aggregate with sharp, angular shapes will usually have the greatest shear resistance and, hence, the highest resistance to rutting. These materials create HMA mixtures with the highest voids in the mineral aggregate (VMA). Coarse aggregate angularity is defined as the percentage by weight of the aggregate with one or more fractured faces according to American Society for Testing and Materials (ASTM) D5821. Superpave requires increased percentages of crushed faces as the design ESAL

AGGREGATE PROPERTIES

CONSENSUS PROPERTIES
(required)

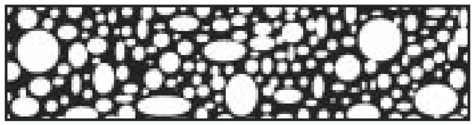
- coarse aggregate angularity (CAA)
- fine aggregate angularity (FAA)
- flat and elongated particles
- clay content

SOURCE PROPERTIES
(agency option)

- toughness
- soundness
- deleterious materials

CONTRASTING STONE SKELETONS

Angular Aggregate



Rounded Aggregate

level increases. VMA increases somewhat as coarse aggregate angularity increases.

Uncompacted Void Content of Fine Aggregate (Fine Aggregate Angularity) Similar to coarse aggregate, crushed angular fine aggregate will usually have the greatest shear resistance. The use of crushed angular fine aggregate typically increases the mixture VMA. Fine aggregate angularity is established by AASHTO T304, Method A, which measures the percentage of air voids present in loosely compacted aggregate that passes the 2.36-mm sieve. More fractured faces generally result in higher uncompacted void contents in this test. Superpave specifies uncompacted void contents of at least 45 percent on high-volume roads ($>3 \times 10^6$ ESALs). Crushed manufactured fine aggregates generally have uncompacted void contents of at least 44.5 percent, while rounded natural sands typically are less than that value. When a fine aggregate known to be angular has test results lower than expected, the aggregate's bulk specific gravity should be verified since the test result is sensitive to this property; a significant change in the bulk specific gravity should trigger a redesign of the mixture.

Particle shape can also influence the uncompacted void content. Some very cubical manufactured fine aggregates, especially some limestones, have had less than 45 percent (but more than 40 percent) uncompacted void contents, but still have provided good performance in pavements. If the performance has been satisfactory, the cubical manufactured fine aggregate may be used (with caution).

The fine aggregate's uncompacted void content significantly influences the VMA. The use of cubical angular fine aggregate is recommended to increase the VMA. Care should be taken when using aggregate with uncompacted void contents higher than 47 percent; use of these aggregates may result in mixtures with excess VMA, which leads, in turn, to a very high binder content.

Flat and Elongated Particles The percentage of flat and elongated particles (not flat or elongated) in coarse aggregate is another important aggregate parameter. Flat and elongated particles can break during the construction process, changing the mixture gradation and the overall mixture properties. Soft aggregate has a greater tendency to break than hard aggregate. Flat, slivered aggregate particles also have a tendency to lie flat in the pavement, creating slippage planes and reducing aggregate interlock. A small percentage of flat and elongated particles in the mixture may increase the VMA in the laboratory-designed mix. A further increase may, however, decrease the VMA in the plant-produced mixture because of aggregate breakage during mixing.

The critical measurement for a flat and elongated particle is the ratio of its maximum and minimum dimensions. Current Superpave standards allow no more than 10 percent of the coarse aggregate particles to be flat and elongated (i.e., a ratio greater than 5:1). Testing is performed according to ASTM D4791, "Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate." Superpave establishes that testing be done on material retained on the 4.75-mm sieve, instead of on the 9.5-mm sieve as specified in the ASTM method.

Testing aggregate particles passing the 9.5-mm sieve and retained on the 4.75-mm sieve will be more difficult and results may be more variable.

Sand Equivalent Sand equivalent, as measured by AASHTO T176, "Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test," identifies the presence of clay in the fine aggregate. Clay can make the mixture moisture sensitive and/or combine with moisture to cause the mixture to act "tender" (i.e., to lose density with continued compaction in the field). Clay content must be controlled by satisfying the minimum sand equivalents specified in the Superpave standards.

Aggregate Toughness Typically, mixtures containing very hard aggregate (i.e., a Mohs hardness of 7 or greater) do not have a problem meeting VMA criteria. A very hard aggregate, such as basalt, does not easily crush or degrade during laboratory compaction or during mix production in an HMA plant. These aggregates can produce mixtures that have an adequate VMA.

Soft aggregates, such as some types of limestone having a Mohs hardness of about 5, are often abraded during the gyratory compaction process; this can make it difficult to meet VMA criteria during the design phase. During production, the aggregates are often abraded in the hot-mix plant to an even greater degree than in the laboratory design using a gyratory compactor. When plant-produced material is compacted in a gyratory compactor, the aggregate is abraded further and even more fines are generated in the mixture; this further reduces the VMA. Mixtures designed with soft aggregates often have a problem meeting VMA criteria in the design stage and, particularly, during production. It is extremely important that the plant-produced mixture satisfy the minimum VMA requirement.

Mixtures designed with a blend of hard and soft aggregate could have difficulty meeting VMA specifications. The addition of hard, coarse, or fine aggregate to these types of aggregate blends will usually increase the VMA.

Superpave Mixture Design Considerations

Superpave mixture design criteria include air voids, VMA, and voids filled with asphalt (VFA). Meeting the VMA minimum criterion is usually difficult to achieve during mix design and typically even more difficult to achieve in the plant-produced material. This document will only discuss VMA.

Voids in the Mineral Aggregate In many cases, achieving minimum VMA requirements during the design phase can be difficult. Many factors affect VMA. The most critical of these are aggregate characteristics such as gradation, surface texture, and shape. If the design VMA is close to (i.e., no more than 0.6 percent above) the minimum, aggregate properties may change during production and cause the VMA to drop below the minimum during mixture production. Differences between as-designed and plant-produced properties and other field problems are documented in the NAPA publication, *Field Management of Hot-Mix Asphalt*.[9]

As noted above, VMA is affected by both the aggregate gradation (relationship to the aggregate maximum density line) and the aggregate's characteristics and properties. For all designs, VMA should be plotted as a function of binder content and the resulting graph should be evaluated to check the VMA. Typically, VMA will decrease with increasing binder content to some minimum, then increase as binder content continues to increase. The design binder content, selected at 4 percent air voids, should be near the minimum of the plotted curve or preferably on the lean binder content side of the curve. If the VMA at the design binder content is on the rich side of the VMA curve, adjustments to the gradation should be considered; these are discussed later in this section. In Superpave mixtures, however, VMA is sometimes insensitive to binder content and shows little change. If the VMA at the design binder content is close to the minimum allowable VMA value and the curve is relatively flat, the mixture should be redesigned.

There are two competing demands during the mix design process: sufficient inter-particle space must be available for a minimum amount of binder, but, at the same time, the aggregate must have a sufficiently strong skeleton to carry the traffic loads. Superpave mixture design specifications require that adequate VMA be obtained without weakening the aggregate skeleton.

Having representative aggregate bulk specific gravity values is necessary in order to accurately calculate a mixture's VMA during design and production. For this reason, aggregate bulk specific gravity should be determined at a frequency appropriate for the variability of the source.

Mixtures with high VMA need to be reviewed for possible performance problems. The WesTrack Forensic Team recommended that the VMA of coarse-graded Superpave mixtures be no more than 2.0 percent above the minimum required value.[10] Furthermore, the Team recommended running a draindown test (AASHTO T305-97) on these mixtures if the VMA is 1.5 percent or more above the minimum value. If a gradation yields a mixture with too high of a VMA and, consequently, too high of a binder content, the mixture design should be repeated with a new gradation with lower VMA.

• **Gradation Effect** Problem mixes typically will have a low VMA and may not be responsive to changes in gradation (when aggregate sources are not changed). Usually, however, changing the gradation of a mixture will influence the amount of void space in the aggregate skeleton. The effect of gradation is separate from the shape and surface texture effects if all particles have the same shape and texture. If the stockpiles in the blend are of dissimilar materials, changing the stockpile percentages will change the gradation, but it will also influence the shape and texture of the aggregate blend. Thus, VMA will change not only because of gradation changes, but also because of shape and texture changes.

Research papers published by Nijboer in the 1940's, Goode and Lufsey in the 1960's, and the Asphalt Institute in the 1980's provide a basis for the 0.45 power chart. Nijboer investigated aggregate gradations plotted as the log percent passing versus log particle size. He showed a maximum packing density for both gravel and crushed aggregates when the slope was 0.45. Goode and Lufsey confirmed Nijboer's results on gravel aggregates. Work by the Asphalt Institute evaluated the maximum density line on a 0.45 power chart for both gravel and crushed limestone mixtures and reconfirmed the previous results.

Moving the gradation away from the 0.45 power maximum density line generally increases the VMA for a fine gradation, i.e., when the gradation is above the maximum density line. For a coarse gradation, VMA may decrease slightly and then increase as the gradation moves away from the maximum density line. For hard aggregates, the Job Mix Formula (JMF) should be parallel to the maximum density line until after passing the restricted zone, i.e., for aggregate retained on the 4.75-mm sieve (for 25-mm or larger mixes) or on the 2.36-mm sieve (for 19-mm or smaller mixes). Then the gradation line should be taken to the desired -0.075-mm content. Therefore, with fine gradations, the JMF should be above and parallel to the maximum density line. For a coarse gradation, it should be below and parallel to the maximum density line.

Many coarse Superpave mixes have an "S" shape, starting on the fine side of the maximum density line and finishing the S on the coarse side. If the same particle shape and texture are used (same aggregate source, different sizes), the highest VMA that can be achieved is that for the gradation that is the farthest from the maximum density line. To minimize the chance of mix tenderness during construction, the JMF should be 3 to 4 percent above the lower control point for the 2.36-mm sieve.

If the aggregate is obtained from a gravel source, normally the fine aggregate must be removed before the coarse aggregate enters the crusher. The crushed material should be divided into three or more stockpiles that can then be blended into a combination that meets the minimum VMA requirements. All of the aggregate processed may not be usable; it may be necessary to waste some of the material in order to meet the requirements of the mixture design.

If the aggregate is obtained from a quarried source, the crushed material should not be placed into a single stockpile, but should be divided into at least three separate size ranges, depending on the nominal maximum size of the aggregate required in the mix. The use of multiple stockpiles allows more flexibility to change gradation and, thus, VMA. In addition, it may still be necessary to incorporate another size of aggregate from the quarry or from a different source.

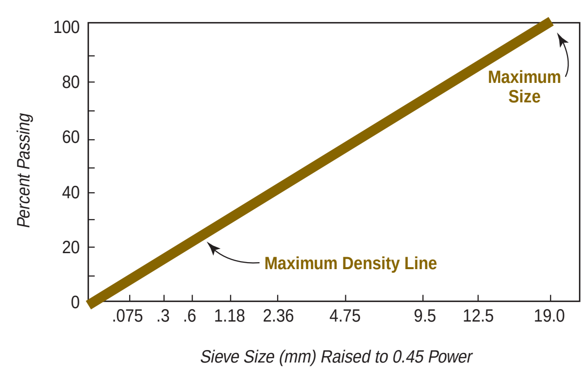
The VMA of coarse-graded mixes can generally be increased by reducing the amount of material passing the 4.75- and 2.36-mm sieves. The reason has to do with packing—smaller particles fill the spaces between larger ones. By reducing the amount of material passing the 4.75- and 2.36-mm sieves, intermediate material is removed and more space is created between the coarse aggregate particles. Hence, the mixture cannot compact as tightly, i.e., VMA is increased.

In fine-graded mixes, VMA is created by fine aggregate—the material passing the 2.36-mm sieve. To increase the VMA in fine-graded mixes, the percentage of material passing the 2.36-mm sieve should be increased. Care should be taken not to create a hump in the gradation on the 0.6- to 0.3-mm sieves using an aggregate that has a low fine-aggregate angularity value.

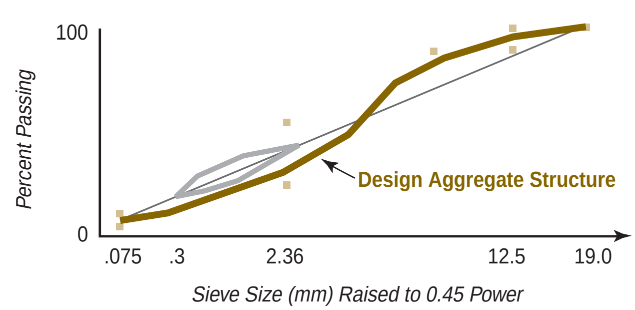
The dust content (i.e., the amount of material finer than 0.075 mm) in a mixture has a significant effect on the VMA. Lowering the dust content will increase the VMA. This effect may not be entirely due to the gradation, but may also be due to characteristics of the dust, such as shape and size. In general, reducing dust content to the extent that the dust-to-binder ratio will allow will maximize the amount of VMA that can be obtained for the specific gradation.

If the dust content is coming from the addition of mineral filler, adjusting the dust con-

FHWA 0.45 POWER GRADING CHART



SUPERPAVE AGGREGATE GRADATION



tent can be simply a matter of reducing the amount of filler being used. If the dust is predominantly from one of the aggregate stockpiles, e.g., screenings, reducing the percentage of that stockpile used in the blend should be tried. If the screenings are the only manufactured fines coming into the mix, using washed screenings or blending with a washed screening may be necessary.

If baghouse fines will be introduced back into the mix during production, some of the same fines should be added during the mix design. During the design, adding half of the quantity of baghouse fines expected to be added during production is an appropriate procedure. These fines should be obtained from the actual plant that will be used for production; otherwise, mineral filler or an alternate source of baghouse fines could be used. These fines will reduce the VMA of the mixture. If the aggregate in the mix contains friable particles, a greater quantity of dust should be used in the laboratory mix design since the friable particles tend to create more dust during mix production. A mix design that includes baghouse fines will be more representative of the mix as produced. The addition of baghouse fines during the mix design will better simulate the reduction in VMA that typically occurs during production.

• **Surface Texture Effect** The way in which aggregate particles pack together for any given gradation is influenced by the surface texture of the particles. Rougher texture generates more friction between aggregate particles and the mixture therefore resists compaction. Hence, for a given number of design gyrations, the mixture will not compact as much and the VMA will be higher. Smooth texture, by contrast, does not generate as much friction between aggregate particles. For a given number of design gyrations, the mixture containing smoother particles will compact more easily and the VMA will be lower.

Typically, crushed faces have more texture than uncrushed faces. In the case of gravel aggregate, the uncrushed portion of the particles tends to have a smooth texture. The greater the percentage of each individual particle surface area that is fractured, the more surface texture that will be present. Usually, the more a gravel is crushed, the more surface texture it will have. Particles with two crushed faces tend to have a greater percentage of surface area with rough texture than will particles with only one crushed face. However, crushing will not always increase texture, because some aggregates fracture with very smooth faces.

If manufactured sand and natural sand are being used together in a mix design, the percentage of manufactured sand can be increased to increase surface texture. Substituting 20 percent washed manufactured sand (with good "bite") for an equivalent amount of natural sand can increase the VMA substantially. (What is good bite? Squeeze a handful of angular manufactured sand, then a handful of rounded natural sand, and feel the difference in the way the particles bite into one another.) If the manufactured sand contains more dust than the natural sand, gains in VMA from the surface texture may be decreased by the increase in dust content. For example, if the natural sand is relatively clean and the manufactured sand has a high minus 0.075-mm dust content, the benefit of increased surface texture may be partially or completely offset by the increased dust content.

• **Shape Effect** For any given gradation, the density to which aggregate particles will pack is influenced by the shape of the particles. Angular particles (i.e., those with sharp, defined edges) tend to produce mixtures with a higher VMA than mixtures containing rounded particles. Cubical particles that retain a sharp, angular edge tend to create a higher VMA than particles with rounded edges.

The effect of flat and elongated particles depends on the laboratory compaction method. Under Marshall compaction, the particles were not as free to rotate as they are in a Superpave gyratory compactor. In fact, flat particles tend to bridge in a Marshall mold and give a high VMA. Therefore, flat and elongated particles tend to increase asphalt content in a Marshall mix design. In the Superpave gyratory compactor, where the particles are kneaded into a more stable condition, flat and elongated particles tend to lie horizontally; this reduces the VMA and the optimum binder content.

During construction, rollers tend to orient flat and elongated particles horizontally. A Marshall mix design containing excess flat and elongated particles could compact very easily or be compacted to a lower air void content than desired during the roadway compaction process. A Superpave mix design will have a more appropriate binder content since gyratory compaction better simulates compaction during construction than does Marshall compaction. Therefore, the influence of particle shape must be considered when comparing the VMA of Marshall specimens to that of Superpave specimens.

If a mix design has a low VMA, the amount of flat and elongated particles must be determined. Superpave specifications limit the percentage of particles with a maximum-to-minimum dimension ratio of greater than 5. If flat and elongated particles are contributing to a low VMA in a mixture, the percentage of particles that exceed a 3:1 ratio should be determined. If the percentage of particles exceeding the 3:1 ratio is high (i.e., greater than 40 percent), material from a coarse aggregate stockpile that has a lower percentage should be added. It may be possible to change one of the coarse aggregate stockpiles for another that contains more cubical and angular aggregate particles. Adding an intermediate-size coarse aggregate with cubical and angular shapes will prevent the larger particles from lying flat. Thus, VMA will increase.

Crushing operations influence the amount of flat and elongated particles produced. If excess flat and elongated particles are being produced, the crushing operation should be evaluated. In some instances, the amount of flat and elongated particles produced can be reduced by changing the aggregate feed rate, or by changing the opening of the cone or jaw crushers. In some cases, it might be necessary to modify the crushing operation by adding to or changing the equipment used. Vertical-shaft impact crushers, for example, tend to produce more cubical particles than do some cone crushers (especially older models).

In summary, VMA depends on the gradation, surface texture, and particle shape of the aggregate. In designing a mix, all of these characteristics must be considered. When there is difficulty in meeting the minimum VMA requirements, some or all of the above characteristics must be adjusted. It should be remembered that the VMA of a plant-produced mixture is typically lower than the VMA of the laboratory trial mix formula. Allowances should be made for the reduction in VMA that *will* occur between the laboratory-designed and the plant-produced mixtures.[9]

Mixing and Compaction Temperatures

For unmodified binders, the mixing and compaction temperatures used during the design process should be established with a rotational viscometer. If the binder is modified, the binder supplier must provide recommended mixing and compaction temperatures. If the binder content determined in the mix design process seems unrealistic, the supplier should be consulted to determine whether the mixing and compaction temperatures being used are still appropriate for the material being delivered. The compaction temperature used during design should also be used in plant production quality control and quality assurance testing.

The laboratory mixing and compaction temperatures may not be appropriate for use in actual plant production and laydown. Environmental conditions at the time of construction and other factors, such as haul length and lift thickness, need to be considered in establishing the actual mixing temperature used at the plant. These temperatures should not be any greater than those necessary to ensure complete mixing of the HMA while minimizing premature aging of the binder and providing for adequate compaction in the field.

If the quality control and/or quality assurance sample is taken behind the paver and the sample requires reheating before compaction, a comparison should be made between the properties of the reheated samples and samples that are compacted before cooling. Detailed procedures for quality assurance sampling and testing should be established before construction begins.

Dust-to-Binder Ratio Superpave calculates the dust-to-binder ratio using the effective binder content. Using the effective binder content rather than the total binder content will normally result in a higher dust-to-binder ratio because of binder absorption into the aggregate. To account for absorption, the limit for the dust-to-binder ratio should be increased. In the original Superpave specification, the dust-to-binder ratio was 0.6 to 1.2 by weight. FHWA's Asphalt Mixture Expert Task Group and the AASHTO Lead States recommended changing the limit to 0.6 to 1.6; AASHTO subsequently added a note to the mix design specification suggesting that agencies consider changing the limit for coarse-graded mixes to 0.8 to 1.6.

During design, mixtures that are above the maximum density line at the 2.36-mm (for 19-mm or smaller mixtures) or 4.75-mm (for 25-mm or larger mixtures) critical sieve should have a dust-to-binder ratio of no more than 1.4. For mixtures that pass below the maximum density line at the critical sieve size, the ratio should not exceed 1.6. Characteristics of the fines will control the amount that can be added to a mixture. Changing the fines source or production process will change how the fines affect the mixture characteristics. For fine-graded mixtures (above the maximum density line at the critical sieve), a ratio of about 1.0 has provided satisfactory performance. For coarse-graded mixtures (below the maximum density line at the 4.75-mm sieve), as the VMA increases the dust-to-binder ratio should increase toward 1.6. If the mixture VMA is high (more than 2.0 percent above the minimum), the ratio should approach 1.6.

High dust-to-binder ratios will typically stiffen the mixture and improve permanent deformation resistance. However, if the VMA is more than 1.5 percent above the minimum, it is preferable to adjust the aggregate properties to reduce the VMA instead of increasing the dust content.

Performance Indicator Tests No test is currently available that is satisfactory, by itself, as a performance predictor for mixtures generated by Superpave volumetric procedures. Appendix A contains a discussion of various tests that may be used to indicate the relative performance of different mixtures. The designer should have experience with one of the tests before assuming that the test results will actually predict field performance. Criteria developed elsewhere may not apply to a particular combination of materials, environmental conditions, pavement structure, and traffic.

Completing the Design After the Superpave design is completed, the designer needs to ask two final questions:

- Is this HMA design reasonable and logical?
- Is the binder content reasonable for the type of aggregate, the nominal maximum aggregate size, the VMA, and the gradation used in the mixture?

If the answer to either question is "No," the design should be re-evaluated and/or redone. Once the answers to both questions are "Yes" and mixing plant operation has begun, the mixture volumetrics of the plant-produced mixture *must* be checked and those volumetrics must meet the minimums required in the design. In addition, performance tests should be repeated on the plant-produced mixture if these tests were performed during the original design phase. During plant verification, enough mixture should be produced to ensure that the plant is operating uniformly. The designer should be prepared to make mixture adjustments to account for changes caused by plant production. If changes are made, the mixture should be re-verified. A key to good mixture performance is to verify the HMA plant-produced mixture properties.

DESIGN CHECK LIST

1. Use a performance-graded (PG) binder and an N-design value appropriate for the weather, traffic level, and traffic speed for the project under consideration. Heavy, slow traffic will require a stiffer PG binder than may have been used in the past.

2. Check that a complete mix design has been done in accordance with specifications and that it meets all of the aggregate consensus property requirements and specified volumetric criteria.

3. Check that the submitted design contains a reasonable binder content for the materials used and the design level specified.

4. Generally, more dust (material passing the 0.075-mm sieve) is needed for coarse-graded mixtures. The character of the dust will control how much can be added to the mixture. Laboratory samples should contain the expected plant-produced amount of material finer than 0.075 mm.

5. In coarse-graded mixtures, if the VMA is more than 1.5 percent above the specified minimum, check for binder draindown. Excessive draindown is an indication that the binder content is too high for the binder grade, aggregate type, and/or gradation being used.

6. Evaluate the mixture with a performance indicator test that has worked satisfactorily based on local experience (until a universally acceptable test is included in Superpave). Does the mixture perform as expected?

7. Verify the properties of the plant-produced mixture to check volumetric properties. Repeat the performance test on the plant-produced mixture if the test was run during the mixture design.

appendix a.

PERFORMANCE TESTS

Introduction

Many different types of performance tests are currently available for assessing a mixture's ability to resist permanent deformation (commonly referred to as "rutting"). These tests, which include Marshall flow/stability, Hveem stability, the gyratory testing machine, wheel-track testers, the Superpave Shear Test device, and triaxial testers, generally attempt to quantify mixture strength and/or stiffness. The individual tests have shown varying levels of success in capturing a mixture's ability to resist rutting. Therefore, the designer must know the limitations of each test and how to incorporate test results into mixture design selection. This appendix describes each test and examines how suitable each is for assisting engineers in designing rut-resistant mixtures. At the same time, mixture designers are reminded that a mixture that is resistant to rutting will not necessarily resist thermal or fatigue cracking, moisture damage, or durability problems such as raveling.

Marshall

The Marshall mixture design process seeks to optimize a mixture's performance with regard to fatigue cracking, rutting, and durability by determining the optimum binder content for the gradation selected. Once the optimum binder content is selected, the mixture must meet minimum stability values and maximum flow values. A number of European countries have modified the specification criteria to use a stability quotient (stability/flow) criterion in lieu of the minimum stability and maximum flow values. Many mixtures have stability values that are two or three times the minimum, but also exceed the maximum flow value. The European approach appears more logical because it normalizes the stability/flow values. Marshall flow does provide an indication when a mixture is over-asphalted—high flow values indicate excess binder content.

The Marshall test conditions may significantly affect the test's value in predicting rutting performance. First among these is the ratio of the test specimen's size to the nominal maximum aggregate size. A 100-mm- (4-in.-) diameter specimen that includes a large nominal maximum aggregate size (37.5 mm) or a more open-graded mixture (one containing little intermediate-size material) does not provide good-quality test data. The effects of the specimen edges are amplified and the assumption that the Marshall breaking head is applying a uniform load across the specimen is no longer valid. The effective load on the specimen (load divided by the contact area) is higher for larger nominal maximum aggregate size mixtures. Another shortcoming of the procedure is the 60°C (140°F) temperature at which the Marshall test is conducted. The mixture may encounter temperatures 5 to 10°C (9 to 18°F) higher in place in some parts of the country.

Hveem

The Hveem Stabilometer is a mixture design tool used primarily in the western United States. The concept behind the Hveem Stabilometer is an empirical measurement of the internal friction within a mixture, resulting from application of a vertical axial load. Like the Marshall Method, Hveem testing is conducted on 100-mm- (4-in.-) diameter specimens at 60°C (140°F). As noted above, this temperature does not always represent the highest temperature a mixture will experience in the field. Furthermore, stabilometer values are measurements of internal friction, which is more a reflection of the properties of the aggregate than of the binder. As with Marshall flow values, Hveem stability does provide an indication when a mixture is over-asphalted—low stability values indicate excess binder content.

Gyratory Testing Machine

The gyratory testing machine (GTM), developed by the U.S. Army Corps of Engineers, measures the increase in the angle of gyration during compaction. The gyratory shear index, a measure of a mixture's stability, is the initial angle of gyration divided by the maximum angle. Shear indices above 1.1 usually indicate poor mixture stability, while values nearer to 1.0 are more stable.

Wheel-Track Testers

Currently, three wheel-track testers are available commercially—the French LCPC [Laboratoire Central des Ponts et Chaussées] Rutting Tester, the Georgia Loaded-Wheel Tester (marketed as the Asphalt Pavement Analyzer), and the Hamburg Wheel-Tracking Device. Conceptually, the three devices are the same (a rolling load is applied to laboratory-scale specimens), but they differ significantly in design, load configuration, and test conditions. To complicate the comparison, each device has a different recommended pass/fail criterion for mixtures. The machine design for each of the devices significantly affects how well its results can be correlated with field performance.[11]

The French LCPC Rutting Tester uses a 90-mm-wide pneumatic tire to test specimens that are 180-mm wide. This specimen width and the closeness of the confining rigid specimen holder to the location of repeated loading distorts the development of the mixture's shear plane, especially for mixtures containing larger aggregate. As a result, poor mixtures tend to perform better than expected in the French device, and discriminating between good- and poor-performing mixtures becomes difficult. The device should not be used to test mixtures that have aggregate larger than 20-mm.

The Georgia Loaded-Wheel Tester (GLWT) runs a concave steel wheel over a pressurized 29-mm-wide hose to apply loads on specimens. Testing can be conducted on dry specimens or underwater. For mixtures containing a larger size of aggregate, aggregate bridging becomes a problem. The applied footprint from the pressurized hose is much narrower than the footprint of a vehicle tire that the mixture will be subjected to under field conditions. As a result, the GLWT test criteria may allow for some poor mixtures to be placed.

The Hamburg Wheel-Tracking Device (HWTD) applies a sinusoidal load on specimens using a steel wheel underwater at an elevated temperature. The HWTD measures a mixture's ability to resist rutting and stripping. The probability that these same test conditions will coincide in the field is unlikely. The use of a steel wheel further increases the severity of the test. Because a steel wheel does not deform under the test conditions like a pneumatic tire, the effective load per unit area is much higher than that occurring during actual field loading. A mixture that survives the HWTD test should be rut-resistant in the field; however, mixtures that do not survive the test may also perform well in the field. Use of this device in mixture pass/fail situations can result in the rejection of acceptable mixtures.

FHWA's Asphalt Mixture Expert Task Group recommends the following cautionary note for wheel-track testers:

> *Rut testers, properly calibrated, have been utilized by some agencies as effective proof testers. However, they should not be used to predict actual pavement performance because of differences in in-service temperature and loading conditions. The devices use empirical evaluation of some measured response to a loaded wheel as an indicator of performance. Local criteria from one region are not applicable in another. As such, each potential user needs to develop his/her own evaluation of wheel test results using local conditions.*

Superpave Shear Tester

The Superpave Shear Tester (SST) can be operated in any of six different modes: volumetric, uniaxial strain, repeated shear at constant stress ratio, repeated shear at constant height, simple shear at constant height, and frequency sweep at constant height. All but the repeated shear at constant height test were included in the original Superpave performance testing program. The report, *Background of SUPERPAVE Asphalt Mixture Design and Analysis*,[4] describes the test modes in detail. Problems have been encountered in interpreting data from the repeated shear at constant stress ratio test, the simple shear at constant height test, and the frequency sweep at constant height tests.[12-14] As a result of these problems, no attempt was made to link the predicted performance from the laboratory tests to the field performance.

Romero and Mogawer presented additional SST results and compared the results of repeated shear at constant height tests with those from full-scale accelerated tests.[15] They stated that the repeated shear at constant height test mode is able to rank mixtures with different binders, but with high variability in mixture stiffness. This variability often makes it impossible to place each mixture into statistically different groups. SST results have shown significant variability between laboratories for the simple shear at constant height test mode. Until this variability can be reduced, it will not be possible to adopt universally acceptable criteria. In summary, the SST is still being studied to determine the usefulness of the results from each of its six test modes; work with the device has not reached a point where its results can be used in any standard mode to predict rutting performance.

Creep Tests

Triaxial testing equipment has been used for many years in soil mechanics and on asphalt materials. The creep test and, to a lesser extent, the creep-creep recovery (CCR) test have been used for HMA under various triaxial stress states. The creep and CCR tests are used to estimate rutting potential. Most commonly, a uniaxial static test is used in either a confined or an unconfined mode. The unconfined test does not simulate field conditions. The applied pressure cannot exceed 207 kPa (30 psi) without specimens failing, and the test temperature is kept at 40°C (104°F) in the unconfined test, well below actual field loading conditions that often reach 830 kPa (120 psi) and 60°C (140°F). The confined creep test can be run at higher pressures and temperatures, with a confining pressure of 138 kPa (20 psi). Research has shown that confined creep testing has a higher correlation to permanent deformation than unconfined testing.[16] A viscoelastic layered pavement performance system that uses creep and CCR testing to estimate the permanent deformation in asphalt mixtures subjected to repeated haversine loading of in-service loading frequencies already exists.[17] However, this CCR testing does not exist as input directly into constitutive models for asphalt pavements. Research is underway to examine the ability of this equipment to measure "fundamental" material properties and to include these measurements in constitutive modeling. Currently, the equipment and procedures to help engineers make rational mixture design decisions are not available in the context of measuring engineering properties as input to constitutive models.

One test that is being recommended for performance evaluation of HMA by the researchers on NCHRP Project 9-19 is the Static Creep/Flow-Time test. In this test, a cylindrical sample of bituminous paving mixture is subjected to a static axial load. The test can be performed without confinement or with a confining pressure applied to better simulate in situ stress conditions. The flow time is defined as the time after initial load application when shear deformation, under constant volume, starts. The applied stress and the resulting permanent and/or axial strain response of the specimen are measured and used to calculate the flow time. Using this test, the selection of the design binder content and aggregate structure can be fundamentally enhanced by the evaluation of the mix's resistance to shear flow (flow time). This fundamental engineering property can be used as a performance criteria indicator for permanent deformation resistance of the asphalt concrete mixture, or can simply be used to compare the shear resistance properties of various bituminous paving mixtures.

Conclusions

Currently, no single test is suitable as a national standard for predicting rutting. The development of such a procedure is urgently needed, but a satisfactory procedure may be years away. In the meantime, if an agency has extensive experience with a particular test over a range of materials typical of its geographic area, it should consider using the test to predict rutting performance. Each of the devices outlined here has difficulty in predicting the true performance of an asphalt mixture and should be used with great caution.

Currently, no single test is suitable as a national standard for predicting rutting.

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