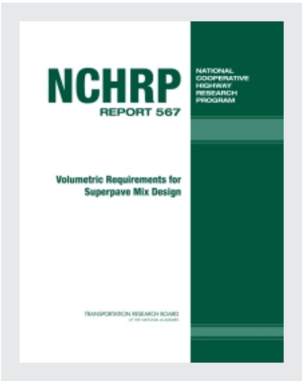

Volumetric Requirements for Superpave Mix Design

DETAILS

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AUTHORS

Donald W Christensen; Ramon F Bonaquist; Transportation Research Board

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 567

Volumetric Requirements for Superpave Mix Design

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AND

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Sterling, VA

Subject Areas
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FOREWORD

By Edward Harrigan
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This report presents the findings of two coordinated research projects that investigated whether changes to the recommended Superpave mix design criteria for voids in mineral aggregate, voids filled with asphalt, and air voids content might further enhance the performance and durability of hot mix asphalt. Its main finding is that, based on an evaluation of the performance properties of hot mix asphalt, major revisions to these volumetric criteria are not needed, although some refinements are possible. The report will be of particular interest to materials engineers in state highway agencies, as well as to materials suppliers and paving contractor personnel responsible for the specification and production of hot mix asphalt.

The Superpave mix design method (AASHTO M323 and R35) uses stringent criteria for air voids content (*Va*), voids in mineral aggregate (VMA), and voids filled with aggregate (VFA) to develop satisfactory hot mix asphalt (HMA) designs. The long delay in developing a suite of reliable material response tests (termed *simple performance tests*) to verify the performance characteristics of volumetric designs has made the fundamental soundness of these criteria a matter of critical importance. This great reliance on volumetric design criteria has been validated by the successful implementation and adoption of the Superpave design method in the United States since its introduction in 1993.

Many highway agencies have investigated changes to these volumetric criteria in response to their particular climatic or traffic conditions and local materials properties or to their past experience with HMA designs. The most common changes considered have been (1) establishing maximum VMA values 1.5% to 2.0% above the minimum values; (2) increasing minimum VMA values by 0.5% to 1.0%; and (3) broadening the design air voids content from a fixed value of 4.0% to a range of 3.0% to 5.0%. While there may be sound engineering rationales for such changes in the short term, there is a concern that changes could trigger unacceptable long-term effects on HMA performance and durability, especially since these key volumetric properties are, obviously, interdependent.

Under coordinated NCHRP Projects 9-25, "Requirements for Voids in Mineral Aggregate for Superpave Mixtures" and 9-31, "Air Void Requirements for Superpave Mix Design," Advanced Asphalt Technologies, LLC was assigned the tasks of determining the impact of potential changes in the current criteria for *Va*, VMA, and VFA on the performance and durability of HMA and recommending any changes deemed desirable. The research team (1) conducted a literature search and critical review of the impact of variation in HMA volumetric properties on mixture performance and durability; (2) carried out a program of laboratory testing to evaluate the effect of changes in *Va*, VMA, VFA, aggregate specific area, and related factors on several performance-related properties of HMA;

and (3) used these results along with data sets from the literature to develop and validate semi-empirical models for estimating HMA rut resistance, fatigue resistance, mixture permeability, and age hardening.

Based on this experimental work and associated modeling, the research team concluded that the present Superpave volumetric mix design criteria do not need major revision. However, the team found that broadening the air voids content requirement to 3% to 5% is reasonable as long as the potential effects on HMA performance are understood. Moreover, while it is not unreasonable to consider changes in the minimum VMA or imposition of a maximum VMA limit, the effects of such changes, especially if coupled with a broader range of air voids content, must be carefully evaluated to avoid lowered rutting and fatigue resistance.

This final report includes a detailed description of the experimental program, discussion of model development and research results, a summary of findings, and recommendations for implementation of key findings. These findings have been referred to the FHWA Asphalt Mixture Expert Task Group for its review and possible recommendation to the AASHTO Highway Subcommittee on Materials for revision of applicable specifications and recommended practices.

CONTENTS

AUTHOR ACKNOWLEDGMENTS

The research documented in this report was performed under NCHRP Projects 9-25 and 9-31 by Advanced Asphalt Technologies, LLC. Donald W. Christensen, Jr., Senior Engineer for Advanced Asphalt Technologies, LLC, was Principal Investigator for NCHRP Projects 9-25 and 9-31 and was primarily responsible for technical supervision of this research, including developing the research approach, experiment designs, and writing reports documenting the progress and results of the research. Dr. Ramon F. Bonaquist provided significant assistance and technical oversight, including evaluation and revision of various aspects of the research approach, experiment designs, data analysis, and interpretation and editing of reports. The laboratory testing was supervised jointly by Mr. Kevin Knechtel and Mr. Donald Jack.

SUMMARY

VOLUMETRIC REQUIREMENTS FOR SUPERPAVE MIX DESIGN

During NCHRP Projects 9-25 and 9-31, laboratory tests were conducted to evaluate the effect of changes in voids in the mineral aggregate (VMA), air void content, voids filled with asphalt (VFA), aggregate specific surface, and related factors on various performance related properties of hot mix asphalt (HMA). These data, along with several data sets in the literature, were used to develop semi-empirical models for estimating rut resistance, fatigue resistance, and mixture permeability. The Mirza–Witczak global aging system was modified to provide a more rational model for predicting age hardening (*1*), consistent with both the Christensen–Anderson model for binder modulus (*2*) and the newly developed Hirsch model for estimating the modulus of HMA (*3*). The following important findings were made based upon these tests and analyses:

- It appears reasonable to allow design air voids for Superpave® mixtures to vary within the range from about 3% to 5%; however, engineers and technicians who wish to deviate from the current design air voids level of 4.0% should understand how such changes can affect HMA performance.
- A variety of models for relating mixture volumetric composition to performance was identified in the literature; however, these models are not well suited for evaluating the effect of mixture composition on performance for the Superpave system of mixture design and analysis. Therefore, as part of NCHRP Projects 9-25 and 9-31, models have been developed (or existing models refined) for estimating mixture performance on the basis of volumetric composition.
- Many state highway agencies have modified the requirements for VMA, air voids, and related factors for Superpave mixtures. Three modifications are most common: (1) an expansion of the design air void content from 4% to a range of 3% to 5%; (2) establishing a maximum VMA value at 1.5% to 2.0% above the minimum value; and (3) a slight increase in the minimum VMA values, typically by about 0.5%.
- Aggregate specific surface is very nearly proportional to the sum of the weight percent material passing the 75-, 150-, and 300-μm sieves. This factor—called the fineness modulus 300 μm basis (FM_{300})—can be used to control aggregate specific surface in mixtures made using the Superpave system to ensure adequate mixture performance and good workability.
- FM_{300} is somewhat more effective in controlling aggregate specific surface than using either the percent finer than 75 μm or the dust-to-binder ratio.
- Rut resistance as indicated by laboratory tests and as measured in a wide range of field test tracks/test roads was predicted to within about a factor of 2 using a model incorporating mixture resistivity, design compaction, and relative field compaction.

- The rutting/resistivity model suggests that each 1% decrease in VMA at constant design air voids, 1% increase in design air voids at constant VMA, or 1% decrease in field air voids also at constant VMA increases rut resistance by about 20%, as indicated by rutting rate in mm/m/ESALs$^{1/3}$ (equivalent single axle loads).
- In this project, increasing FM_{300} by 6% (at constant VMA) typically increased rut resistance by about a factor of 2.0 to 2.5.
- For the types of HMA used in NCHRP Projects 9-25 and 9-31—that is, mixtures made using good quality, highly angular aggregates with little or no natural sand—increasing the high temperature binder grade one level will increase rut resistance by about a factor of 2.5, as indicated by rutting rate in mm/m/ESALs$^{1/3}$. For HMA designed according to current Superpave requirements, binder grade appears to be the most important consideration in determining rut resistance of HMA; volumetrics are an important but secondary factor. It must be emphasized that replacing the good quality aggregates normally used in Superpave mixes with poorly crushed gravel and/or large amounts of natural sand would almost certainly cause a substantial decrease in rut resistance and might also result in mixtures that are much more sensitive to changes in volumetric composition.
- Increase in N_{design} by one level increased rut resistance by about 15% to 25%.
- A practical approach to fatigue analysis of HMA based on continuum damage theory was developed during NCHRP Projects 9-25 and 9-31. This technique was initially developed through analysis of laboratory test data collected during the projects and was then verified and refined through successful application to flexural fatigue data gathered during the Strategic Highway Research Program (SHRP) at the University of California at Berkeley.
- Fatigue resistance of the HMA analyzed during NCHRP Projects 9-25 and 9-31 was found to be affected by effective asphalt content (VBE), design compaction (N_{design}), and field compaction, expressed in terms of field density relative to laboratory/design density. Every 1% increase in VBE increased fatigue life by about 13% to 15%. Every 1% increase in field air void content (at a constant design air void content) decreased fatigue resistance by about 20%.
- Data analyzed during NCHRP Projects 9-25 and 9-31 showed that permeability of HMA increases with increasing air voids and decreasing aggregate specific surface. Permeability can be effectively modeled using the concept of effective air voids—the total air void content minus the air void content at zero permeability. Furthermore, the zero air voids content increases with increasing aggregate fineness.
- A simple, reasonably accurate equation has been developed based upon permeability data gathered by Choubane et al. in a study on the permeability of Superpave mixtures in Florida (*4*). According to this model, permeability increases by about 100×10^{-5} cm/s for every 1% increase in air voids or 3% decrease in FM_{300}, for air void contents above the zero-permeability limit.
- The permeability of HMA specimens prepared in the laboratory tends to be significantly lower than permeability values measured on field cores of comparable mixtures. For this reason and because of the highly variable nature of permeability measurements, laboratory measurements of mixture permeability are not recommended for use in routine mixture design. However, the effect of air void content and aggregate fineness on permeability should be considered during the mix-design process.
- The age hardening of the HMA studied during NCHRP Projects 9-25 and 9-31 depended not only upon air void content, but also upon the specific combination of aggregate and asphalt binder. Additional research is needed to better understand the effect of aggregate/asphalt binder combinations on mixture age hardening.
- A modified version of the Mirza–Witczak global aging system was used to examine the effects of air voids, aggregate fineness and other factors on mixture and binder age hard-

ening (*1*). For a mean annual air temperature (MAAT) of 15.6°C, the mixture age hardening ratio decreased about 2% to 7% for every 1% increase in FM_{300}. The age hardening ratio increased about 5% to 14% for every 1% increase in in-place air voids. Although not extremely large effects, when considered over the possible range for FM_{300} and field air voids, these factors can significantly affect mixture age hardening.

- The modified global aging system predicted extreme amounts of age hardening as indicated by binder viscosity. These extreme age hardening ratios are the result of changes in binder rheology that occur during the aging process and could significantly affect mixture performance because of the severe reduction in healing rates that might occur with such large increases in binder viscosity. Additional research is needed to better understand the relationship among age hardening, binder viscosity, healing, and fatigue cracking in HMA pavements.
- The various models developed during NCHRP Projects 9-25 and 9-31 suggest that several indirect relationships exist between apparent film thickness (AFT) and various aspects of HMA performance. The most significant of these is between AFT and rut resistance—as AFT increases, rut resistance decreases. Mixtures with AFT values greater than 9 μm may be prone to excessive rutting. However, because the relationships between AFT and performance are indirect, it is not recommended that AFT be used in specifying or controlling HMA mixtures.

The results of NCHRP Projects 9-25 and 9-31 suggest that current Superpave requirements for volumetric design of HMA do not need major revision; however, there appears to be some need for refinements in the system because many highway agencies have recently funded research and engineering projects dealing with both top-down cracking and permeability of HMA. It appears that current HMA mixtures tend to be somewhat leaner (lower in asphalt binder content) compared with mixtures designed and placed prior to the implementation of Superpave; this may be a contributing factor to the observed frequency of raveling and surface cracking in Superpave mixtures. Because the Superpave system has encouraged the use of coarse aggregate gradations—below the maximum density gradation—they also contain relatively few fines, which, in combination with relatively high in-place air voids, can result in mixtures with high permeability and less resistance to age hardening. The potentially low fines content, when combined with high VMA values, can also lead to poor rut resistance, although this problem is relatively uncommon in HMA that has been designed using the Superpave system.

Many highway agencies have already modified volumetric requirements in the Superpave system, the most common changes being establishing maximum VMA values 1.5% to 2.0% above the minimum values, increasing minimum VMA by 0.5% to 1.0%, and/or a broadening of design air void content from 4.0% to a range of 3.0% to 5.0%. Establishing maximum VMA values and eliminating VFA requirements make the Superpave system simpler and more direct and reduce the chances of designing HMA with poor rut resistance. Increasing VMA while maintaining design air voids at 4.0% will improve fatigue resistance because this will increase VBE. However, unless care is taken to ensure that adequate aggregate specific surface is maintained while increasing VMA, rut resistance will be reduced when increasing VMA. Increasing aggregate specific surface while increasing minimum VMA will improve both fatigue resistance and rut resistance and will tend to decrease permeability. Changing design air voids in essence has the effect of changing the design compaction level because this changes the amount of compaction energy that will be required in the field to reach the target air void levels. Since most agencies specify minimum VMA rather than minimum VBE, changing design air voids will also change VBE. Design air void contents below 4.0% reduce the required field compaction effort and will tend to decrease both fatigue resistance and rut resistance; increasing design air voids to levels above 4.0% has the opposite effect—increasing the required field compaction effort and improving both fatigue resistance and rut resistance. The effect on fatigue resistance of changing design air voids at constant in-place voids may surprise some engineers. Decreasing design air voids at constant VMA increases VBE, which normally would increase fatigue resistance; increasing design air voids at constant VMA decreases VBE, which normally would decrease fatigue resistance. However, in this case the effect of changing VBE is less than the effect of changing relative compaction. This illustrates the importance of field compaction on pavement performance and also emphasizes that care is needed when changing requirements in HMA in an attempt to address specific performance issues. Decreasing design air voids to from 4.0% to 3.0% while decreasing the target air voids in the field a similar amount will improve both fatigue resistance and rut resistance while decreasing permeability. Other approaches are possible to improving the fatigue resistance of HMA while maintaining or improving rut resistance and decreasing permeability.

Agencies contemplating modification in Superpave specifications should first evaluate the level of in-place air voids being achieved during flexible pavement construction and should verify that acceptable levels of field compaction are being achieved—poor field compaction will have a significant negative impact on pavement performance that can only be partially offset by proper mix design. Any changes in current Superpave requirements should be carefully evaluated using performance models tempered with engineering judgment and experience with local conditions and materials. Although performance models are useful tools for evaluating the effects of modifications in HMA specifications, they should be used with caution because such models provide only approximate results. Care is also needed when instituting multiple changes in Superpave specifications or in specifications for any other HMA mix type; changes in volumetric requirements, compaction levels, materials specifications, and other mixture characteristics are additive, and unless such changes are carefully evaluated and implemented, significant and unanticipated reductions in pavement performance can result.

Chapter 3 of this report includes an Extended Work/Validation Plan, which is described at the end of Chapter 3. This plan has been devised to extend the results of this research to mixtures made with larger aggregate sizes (25- and 37.5-mm) and also to validate the results of this research using accelerated pavement testing and other field data.

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CHAPTER 1

Introduction and Research Approach

The purpose of this report is to present the results of two closely related projects: NCHRP Project 9-25, "Requirements for Voids in Mineral Aggregate for Superpave Mixtures" and NCHRP Project 9-31, "Air Void Requirements for Superpave Mix Design." The objectives of these projects are so closely related that the results cannot be separated in a useful way; voids in the mineral aggregate (VMA), air voids, effective binder content, voids filled with asphalt (VFA), and other factors related to mixture composition are interrelated. This chapter summarizes the objectives of these projects, the scope of the research performed, and the general approach taken in performing the work. The problem statement and research objective that follow paraphrase and, in some cases, directly quote the research project statements (RPSs) for NCHRP Projects 9-25 and 9-31.

Problem Statement and Research Objective

Problem Statement

Before the advent of the Superpave system of mixture design and analysis, 80% of the dense-graded HMA produced in the United States used aggregate gradations that passed above the maximum density gradation—that is, they were fine gradations. Under the Superpave system, most mixtures use coarse gradations that pass below the maximum density gradation. Mixture volumetric requirements developed from the 1960s through the 1980s, including VMA and air voids, were based largely on the performance of fine-graded mixtures rather than on the typical coarse-graded Superpave mixture. Recent research at the National Center for Asphalt Technology (NCAT) and especially results of the WesTrack study have shown that some coarse-graded Superpave mixtures can exhibit very poor rut resistance (*1, 2*). At the same time, durability problems have been observed in a significant number of pavements constructed using Superpave surface-course mixtures. A study in Florida has documented the relatively high permeability of Superpave surface-course mixtures (*3*); NCHRP Project 1-42 has been initiated to evaluate the increasing occurrence of top-down cracking in hot mix asphalt (HMA) pavements since the implementation of Superpave.

A closely related issue is that of design air void content. Since the early 1990s, the Marshall mix design system has allowed design air void content for HMA to vary from 3% to 5% (*4*). The Superpave system, as originally developed, specified a single design air void content of 4%. In recent years, some agencies have modified the design air void content for Superpave mixtures in order to improve their performance. The Arizona DOT, for example, currently specifies a design air void content of 5% for Superpave mixtures.

Evidence suggests that the composition of HMA—as indicated by VMA, air void content (total voids in mix, or VTM), effective asphalt content (VBE), VFA, and the ratio of VBE and/or VMA to aggregate specific surface (often expressed as a binder film thickness)—can affect both rut resistance and durability. Effective and efficient guidelines are needed for Superpave volumetric composition to ensure that these materials exhibit adequate levels of resistance to rutting, fatigue cracking, and age hardening.

An important related issue, besides how composition affects the performance of Superpave mixtures and the optimal ranges in composition for different applications, is how to most effectively and efficiently specify these compositions. This problem is complicated by the inter-relationship of volumetric factors such as VMA, VBE, VTM, and VFA and also by controversial terminology such as "binder film thickness," which some engineers believe to be a useful concept in evaluating HMA durability, while others strongly believe it to be misleading and potentially useless. Developing specifications involving multiple constraints on mixture compositional factors, without carefully considering the full range of potential mixtures and performance, can produce overly complicated, inconsistent, and/or redundant specifications. Any modification in the current Superpave specifications should address not only the performance of the resulting mixtures, but also the clarity and efficiency of the resulting specification.

Research Objective

The research objective for NCHRP Project 9-25 is stated in the RPS:

> The objective of this research is to develop recommended mix design criteria for VMA, VFA, or calculated binder film thickness, as appropriate, to ensure adequate HMA durability and resistance to permanent deformation and fatigue cracking for coarse and fine, dense-graded mixes in the context of the Superpave mix design method.

The research objective for NCHRP Project 9-31 is also stated in its RPS:

> The objective of this research is to recommend for future field validation the range of design air void content, within the context of the Superpave mix design method, required for adequate durability and resistance to permanent deformation and fatigue cracking of dense-graded HMA.

Scope of Study

The laboratory testing for this research was limited in the RPS for NCHRP Project 9-25 to 9.5-, 12.5- and 19-mm nominal maximum aggregate size (NMAS) mixtures. Therefore, the laboratory work did not involve 25- and 37.5-mm NMAS mixtures, and the findings of the report tend to be focused more on the properties and performance of surface-course mixtures rather than on base course mixtures. However, it is believed that most of the findings presented in this research are applicable to all HMA, regardless of the aggregate size.

The RPSs for both projects required two phases: Phase I, involving a review of literature and current practice; and Phase II, involving laboratory testing and data analysis. Neither RPS contemplated using sections at test tracks, test roads, or other forms of accelerated pavement testing in performing the research. Therefore, mixture evaluations performed during this research were limited to laboratory tests. However, to verify the results of this research, significant use was made of data previously published from several test tracks/test roads, including WesTrack, the Minnesota Road Research Project (MnRoad), and the NCAT test track (*2, 5, 6*).

Because climate, type and amount of traffic loading, and subgrade soil types vary enormously across North America, some flexibility is desirable in HMA specifications. For this reason, the findings of this report (given in Chapter 2) are presented in general terms—equations, graphs, and summary statements describing clearly the effect of changing a particular aspect of HMA composition on rut resistance, fatigue resistance, permeability, and age hardening. This presentation should give pavement engineers the specific information they need to evaluate potential modifications in their Superpave specifications. Interpretation of the research findings (given in Chapter 3) is also described in general and flexible terms, for two reasons. First, many agencies have already implemented a variety of changes in Superpave, so a number of such changes are discussed in Chapter 3 of this report as an aid to agencies that are evaluating the effectiveness of these modifications. Second, some agencies may be considering changes in Superpave requirements, but the nature of such changes will no doubt vary depending on climate, traffic and the nature of local materials; therefore, practical application of the findings of NCHRP Projects 9-25 and 9-31 must consider a variety of scenarios. It is acknowledged that some agencies may be quite happy with the performance of HMA produced according to existing specifications and thus may feel no need for modifying their requirements for VMA, air voids, and related factors.

Research Approach

The initial phase of both NCHRP Projects 9-25 and 9-31 involved a review of literature and current practice. Because NCHRP Project 9-25 was initiated prior to Project 9-31, the literature review for the latter project was essentially an extension and refinement of the Project 9-25 literature review. Much of the literature review focused on studies in which an attempt was made to relate volumetric properties to one or more performance-related properties. Phase I of NCHRP Project 9-31 included a survey of current practice, in which the manner that state highway agencies were specifying Superpave mixtures was reviewed and summarized.

The laboratory testing performed as part of NCHRP Projects 9-25 and 9-31 involved a range of procedures designed to provide information relating various aspects of HMA performance to mixture composition. Laboratory tests were performed on a variety of HMA mixtures composed of four different aggregate types, three different aggregate gradations, and four different binders. Laboratory tests performed on these mixtures included repeated shear at constant height (RSCH), uniaxial fatigue, permeability, uniaxial compressive strength, indirect tensile (IDT) strength, and dynamic modulus before and after long-term oven conditioning. The results of these tests were analyzed using a variety of methods, typically including an initial graphical analysis, followed by an in-depth statistical analysis.

In general, existing models for relating mixture performance to volumetric composition were found to be inappropriate for use in NCHRP Projects 9-25 and 9-31. In some cases this was because of inaccuracy of the model; in other cases, it was because the model was developed using obsolete parameters, such as asphalt softening point temperature or ductility. Some models, such as the well-known Witczak model for HMA stiffness, rely heavily on parameters such as aggregate gradation data that cannot be directly related to mixture volumetric composition (*7*). Because of the shortcomings of existing models for estimating mixture performance, newer models were developed or existing models refined during the course of NCHRP Projects 9-25 and 9-31. As much as possible, these mathematical models were selected (or designed) to reflect reasonable theoretical and/or physical models for the given mode of distress. The fatigue model proposed in this research, for example, is based largely on continuum damage theory, reduced through mathematics and calibration with laboratory data to a simple formula comparable with traditional empirical equations for flexural fatigue life.

To refine the models developed from analysis of laboratory data and to verify their validity in application to field data, in most cases they were applied to other data sets generated in independent research. These data sets included performance data from WesTrack, MnRoad and the NCAT test track and also permeability data collected in a study by the Florida DOT on the permeability of Superpave mixtures (*2, 3, 5, 6*). After refining/verifying the proposed models for estimating mixture performance from mixture composition, plots were developed showing different aspects of performance as a function of VMA, air void content, and related characteristics. These plots and the underlying analyses were further analyzed and summarized in terms of typical effects of changing VMA, VTM, VBE, and related factors on performance. These specific findings are presented in Chapter 2. The final stage in the analysis involved interpreting these findings in terms of practical applications to HMA mix design technology. This discussion is presented in Chapter 3. The most significant sections of this chapter involve discussion of how recent changes in HMA mix design have affected pavement performance, discussion of how possible modifications of Superpave requirements might affect performance, and general guidelines for modifying HMA specifications to improve fatigue resistance and durability. As discussed under Scope of Study, the findings and recommendations of this research have been presented in a format designed to provide for some flexibility in implementation so that when modifying their Superpave specification, agencies can effectively address local conditions and materials. As suggested in NCHRP report guidelines, the body of this report includes only the most important technical information and related findings, conclusions, and recommendations.

CHAPTER 2

Findings

The sections below present the specific findings of NCHRP Projects 9-25 and 9-31. This chapter is divided into eight sections: Literature Review and Survey of Practice, Laboratory Testing, Analysis of Other Data Sets, Rut Resistance, Fatigue Resistance, Permeability and Age Hardening, Apparent Film Thickness and HMA Performance, and Summary. These discussions describe the most effective relationships between performance-related properties and volumetrics as identified and/or developed during this research and graphically illustrate what these models predict in terms of property changes as a function of VMA, design air voids, and related compositional factors. The practical implications of the findings presented here are discussed in Chapter 3.

Literature Review and Survey of Practice

A variety of research papers and engineering reports were reviewed during the first few months of NCHRP Project 9-25 and presented in the Interim Report for that project; an updated version of the Literature Review was included in the NCHRP Project 9-31 Interim Report.

One of the most important issues in HMA mix design is how to define "optimum" asphalt content. In the current Superpave system, this is defined as the binder content that produces 4% air voids at the given compaction level. In order to evaluate the effectiveness of this practice, a range of Superpave mix designs, Marshall mix designs, and stone matrix asphalt (SMA) mix designs were reviewed, and the optimum binder content—defined in this case as the point at which minimum VMA is obtained—was determined. This is a more fundamental definition of optimum asphalt content than that which is currently used in the Superpave system. It was found that for these data, the optimum binder content based on minimum VMA occurred at an average air void content of 3.4%, but could also be defined as occurring at an average of 75.3% VFA. In fact, the optimum asphalt content based on minimum VMA for these mixtures appeared to cover a range of air void contents—from about 2% to 5%. A dramatic increase in rutting potential has been associated with in-place air void contents of around 2% or less (*8*). Thus, very low design air void contents (say less than about 3%) should be avoided in wearing and intermediate course mixtures because low design air void contents should be expected to promote low in-place air voids and increase the possibility of constructing a pavement with poor rut resistance. Therefore, it appears reasonable to use a range for design air voids of from 3% to 5%. However, as discussed later in this report, engineers and technicians should be aware that changing the value for design air void content will significantly affect HMA performance.

A variety of models were identified in the literature review for predicting performance-related properties from HMA composition and other properties. The Hirsch model for predicting HMA modulus, as developed during the early phases of NCHRP Project 9-25, was found to be more suitable for relating modulus to volumetric composition than other existing models—Bonnaure's equation and Witczak's equation (*7, 9, 10*). Two models for predicting rut resistance were identified, both developed by Witczak and associates (*11, 12*). In both cases, the model predicted the results of a laboratory test for evaluating rut resistance and not field rutting. The models were similar, and both found that rut resistance increased with decreasing binder volume and air voids and increasing binder viscosity. A serious shortcoming of both models was the use of binder apparent viscosity values at 21.1 °C, rather than Superpave binder properties. A more useful model for predicting rut resistance was developed during NCHRP Projects 9-25 and 9-31: it predicts that rut resistance increases with decreasing VMA relative to aggregate fineness and increasing binder viscosity (or complex modulus).

Existing models for predicting the fatigue resistance of HMA have been empirically derived from laboratory flexural fatigue tests. Typically, such fatigue equations relate applied stress or strain, initial complex modulus, and either VBE or VFA to cycles of failure. In all cases, better fatigue resistance is predicted as a mixture becomes increasingly rich in asphalt binder, either as indicated by VBE or VFA (*13–15*). The empirical nature of these relationships and their relatively poor accuracy when applied to fatigue of actual pavements are serious shortcomings that lead to the development of a practical continuum damage approach to characterizing fatigue phenomena in HMA as part of NCHRP Projects 9-25 and 9-31 (*16*).

A number of researchers in the past attempted to relate mixture volumetrics (most often VMA and or asphalt binder film thickness) to durability. This work mostly involved conjecture without substantial supporting data and so was inconclusive. The concept of binder film thickness remains controversial. In general, there is agreement in this early research that a certain amount of asphalt binder is needed in a mixture to ensure adequate durability and that the optimal binder content will depend to some extent on the properties of the aggregate used, including NMAS and specific surface (*17–19*). Most researchers have found a decrease in permeability and age hardening with decreased air void content, although such relationships usually exhibit a large amount of variability (*19–21*). Recent research on the permeability of Superpave mixtures in Florida has demonstrated that unlike the relatively fine, dense-graded HMA used in the past, coarse-graded Superpave mixtures can exhibit relatively high levels of permeability unless thoroughly compacted (*3*). The substantial data set published by the Florida researchers has been analyzed to generate a useful equation for estimating mixture permeability from air void content and aggregate fineness, which is discussed later in this report.

Only one method for predicting age hardening was located in the literature—Mirza and Witczak's global aging system (*22*). This model predicts age hardening of asphalt binder in pavements based upon mean annual air temperature (MAAT), binder viscosity, depth in the pavement, and air void content. This model has several shortcomings, the most important being a reliance on binder apparent viscosity values estimated from obsolete empirical measures of binder consistency and the prediction of age hardening only in terms of a change in apparent viscosity, rather than in terms of changes in the overall flow characteristics of the binder. A modification of the global aging system was developed that addresses some of these problems while maintaining consistency with the original model. This model is used later in this report to estimate the effect of changes in mixture composition on typical age hardening of asphalt mixtures and binders.

Although not specifically listed as one of the project objectives, analysis of laboratory data generated during NCHRP Projects 9-25 and 9-31 and of field data generated in a variety of other projects indicated that any modeling of the relationship between volumetric composition and performance must account for relative compaction—the air void content of either the laboratory specimen or in-place pavement relative to the air void content as designed. It is essential that this information be included in this report so that researchers attempting to validate the results of this research will understand the importance of accounting for the effects of relative compaction. However, to place the findings of NCHRP Projects 9-25 and 9-31 in proper perspective, research found in the literature concerning the effect of in-place air voids on performance must also be discussed. Two significant such studies are NCHRP Project 20-50(14) and the research of Linden et al. (*23, 24*). In NCHRP Project 20-50(14), Seeds et al. analyzed data from the Long-Term Pavement Performance (LTPP) program. They found that the data could not be used to develop performance models relating in-place air voids to either fatigue or permanent deformation (*23*). In 1988, Linden et al. published results of a study conducted by Washington State evaluating the relationship between pavement performance and in-place air voids (*24*). They reported that as a "rule of thumb," every 1% increase in in-place voids results in about a 10% reduction in performance. This figure was a very rough, typical value, based on the results of several studies: (1) three analytical studies relating fatigue life to in-place voids; (2) a survey involving 28 state highway agencies; (3) an unpublished study of flexible pavements in Washington State; and (4) observed fatigue cracking in *three* pavements placed in Washington with high air void contents. The analytical studies cited by Linden and Mahoney reported a 10% to 30% reduction in fatigue life for every 1% increase in in-place voids (*25–27*). No analytical studies on the effect of in-place air voids on rut resistance were cited in this study. The results of these studies should be considered inconclusive—NCHRP Project 20-50(14) was unable to develop any useful, reliable relationships between in-place air voids and performance; the study by Linden et al. was limited in scope, and even the authors admitted their conclusions represented only "a rule of thumb."

As part of NCHRP Projects 9-25 and 9-31, in late 2001 and early 2002, a survey was conducted of the manner in which state highway agencies are implementing Superpave specifications for volumetric composition. Many states have slightly modified the requirements for Superpave mixture composition as given in AASHTO M323 and R35. Most commonly, the design air voids content is expanded to a range of 3% to 5% and a maximum VMA is established at 1.5% to 2% above the established minimum values. A number of states have also slightly increased minimum VMA values, providing for somewhat richer mixtures than produced by the current version of Superpave.

Laboratory Testing

As part of NCHRP Projects 9-25 and 9-31, a wide range of laboratory tests was performed on a variety of HMA. The laboratory tests were designed to provide information concerning the rut resistance, fatigue resistance, permeability, and resistance to age hardening of the mixtures studied. The most important of the procedures performed as part of this research included the following tests:

- RSCH testing using the Superpave shear tester, at 58°C and 64°C (AASHTO T320-03);
- Uniaxial fatigue testing at 10 Hz and 4°C and 20°C, which includes an initial measurement of the complex modulus $|E^*|$ (*16*); and
- Mixture permeability, using the Florida permeability test (Florida Test Method FM 5-565).

The mixtures tested were made using eight different aggregates and gradations:

- A 9.5-mm limestone from Virginia, coarse and fine gradations;
- A 19-mm gravel from Pennsylvania, coarse and dense gradations;
- A 19-mm limestone from Kentucky, coarse and dense gradations; and
- A 12.5-mm granite from California, dense and fine gradations.

All of these mixtures were combined with a performance grade (PG) 64-22 binder. Some were also combined with a PG 58-28 binder and/or an air blown PG 76-16 binder. In most cases, the design gyration level was 100, but for some mixtures, N_{design} was 75. All of the California granite mixtures were designed using 125 gyrations. Early in the project, an attempt was made to design and evaluate some mixtures at 50 gyrations, but these were typically very weak and difficult to test; further testing of these mixtures was therefore abandoned. All mixtures were made using three binder contents: the optimum binder content, optimum −1%, and optimum +1% (by total mix weight). The materials used represented a range of aggregate types, gradations, binder grades, and mixture compositions.

Analysis of Other Data Sets

As discussed later in this short report, some of the findings made during the research appeared very promising, but somewhat controversial. Therefore, in several cases verification of the findings was attempted using data sets from other research projects. In evaluating the rut resistance of the NCHRP Projects 9-25 and 9-31 mixtures, the concept of resistivity was developed and appeared to relate very well to the results of the RSCH test. To further verify these results, field data from three sources was compiled and analyzed:

1. The MnRoad test track, as discussed in numerous reports by the Minnesota DOT and the University of Minnesota (*5*);
2. The NCAT test track, as documented by Brown et al. (*6*); and
3. The WesTrack project, as documented in FHWA's *Performance of Coarse-Graded Mixes at WesTrack—Premature Rutting* (*2*).

The approach in analyzing the uniaxial fatigue results involved a further development and simplification of continuum damage theory. Because of the variability in fatigue data, the relatively small amount of testing performed as part of NCHRP Projects 9-25 and 9-31 and because of the novelty of the approach, further verification of the results was desired. This verification was performed by applying the same analytical approach to fatigue data gathered during the Strategic Highway Research Program (SHRP), as summarized in *SHRP Report SHRP-A-404: Fatigue Response of Asphalt-Aggregate Mixes* (*15*). Although these data were gathered using flexural fatigue tests, continuum damage theory predicts that the damage in the extreme fiber at the test conclusion for this procedure should be constant and can thus be related to the results of uniaxial tests.

The permeability tests performed during this research were very limited. This occurred for two reasons—(1) the air void content of the mixtures was relatively low, resulting in low permeability values and (2) permeability tests performed in the laboratory will usually show lower values than those determined from field cores. Therefore, most of the specimens tested during NCHRP Projects 9-25 and 9-31 showed very low or zero permeability. To better understand the relationship between mixture composition and permeability, data from the Florida permeability study was included in this analysis (*3*).

Because understanding the extent and scope of the data used in developing the performance models developed during this research is essential to interpreting the findings presented in this chapter, the external data sets summarized above are discussed in more detail in the sections below. This unfortunately increases the length and complexity of this report, but makes clear the fact that the findings are based on a much more robust set of data than that which was collected during testing performed under NCHRP Projects 9-25 and 9-31.

Rut Resistance

A very good relationship has been found between mixture rut resistance and mixture resistivity. *Resistivity* indicates the resistance to binder flow exhibited by a particular aggregate structure. It is analogous to electrical resistivity, defined as "a materials opposition to the flow of electrical current." Resistivity can also be thought of as the inverse of the coefficient of permeability for a granular material. It increases with increasing binder viscosity, increasing aggregate specific surface and decreasing VMA. Because HMA is almost always designed at close to 4% air voids, VMA will normally be proportional to VBE so that resistivity is closely but indirectly related to apparent film thickness; mixtures with thin binder film thickness will generally exhibit high resistivity values. Resistivity can be calculated using the following formula:

$$P = \frac{|\eta^*| S_a^2 G_{sb}^2}{4.9 VMA^3} \tag{1}$$

where

- P = resistivity, s/nm;
- $|\eta^*|$ = binder viscosity at the temperature of interest, Pa-s;
- S_a = aggregate specific surface, m²/kg;
- G_{sb} = aggregate bulk specific gravity; and
- VMA = voids in the mineral aggregate, volume %.

It should be emphasized that Equation 1 is not an empirical relationship developed during NCHRP Projects 9-25 and 9-31 for characterizing the rut resistance of HMA. Instead, it is the inverse of an existing equation for estimating the permeability of a granular material (*28*). Therefore, the choice of variables, the values of the exponents, and the value of the constant 4.9 are not of the authors' choosing—they result directly from Winterkorn's formula for permeability and reflect on a fundamental level the factors governing fluid flow through porous media.

Because of the extreme influence of temperature on the flow properties of asphalt, care must be taken in selecting the temperature at which viscosity is determined when calculating resistivity for HMA. For laboratory tests, the viscosity should be determined at the same temperature at which the HMA is being characterized. For field rutting, the situation is more complicated. The value used should be some temperature estimated to be characteristic of the overall potential for permanent deformation in the given climate. For example, within the current Superpave system, the critical temperature for rutting used in selecting PG binders is the yearly, 7-day-average, maximum pavement temperature, measured 50 mm below the pavement surface. This is the temperature used in this research in calculating resistivity for field projects. However, it should be kept in mind that the manner of calculating the critical rutting temperature will likely evolve as further research is done on performance modeling of HMA pavements. Furthermore, some researchers and engineers may prefer other approaches to estimating characteristic temperatures for rutting in HMA pavements.

An important practical question in applying Equation 1 is how to estimate the specific surface of the aggregate. In analyzing a wide range of aggregate gradation data, it was found that for routine purposes the aggregate specific surface can be accurately estimated by summing the percent passing the 75-, 150-, and 300-μm sieves and dividing the total by 5. The sum of the percent passing the 75-, 150-, and 300-μm sieves is called the fineness modulus, 300-μm basis, abbreviated as FM_{300}. The relationship between this parameter and aggregate specific surface was evaluated using data from eight projects, as shown in Figure 1; the data used in this analysis was as reported for NCHRP Project 9-9, the NCAT Test Track, Pooled Fund Study 176, the Florida permeability study, MnRoad, FHWA's Accelerated Loading Facility (ALF) rutting study, WesTrack, and data from NCHRP Projects 9-25 and 9-31 (*2, 3, 5, 6, 29–31*). This was the best and one of the simplest methods found for relating aggregate gradation to aggregate specific surface and is well suited for routine use in mix design work and HMA specifications. Specific surface can be estimated reasonably accurately simply by dividing FM_{300} by 5. The r^2 for this relationship is 90%, while the 95% prediction limit for new observations (including in Figure 1) is about ± 0.8.

The current method of controlling aggregate specific surface involves establishing limits on the amount of aggregate passing the 75-μm sieve and controlling the dust-to-binder ratio. To compare this approach with FM_{300}, Figure 2 shows the same data set used in Figure 1, but in this case the horizontal axis is the percent finer than 75 μm. The r^2 value in this case is only 76%, and the 95% prediction limit increases to ±1.3. Clearly there is a relationship between the specific surface of a given aggregate and its mineral filler content, but this relationship is only moderately strong. FM_{300} appears to be a significantly more accurate approach and is also more flexible in

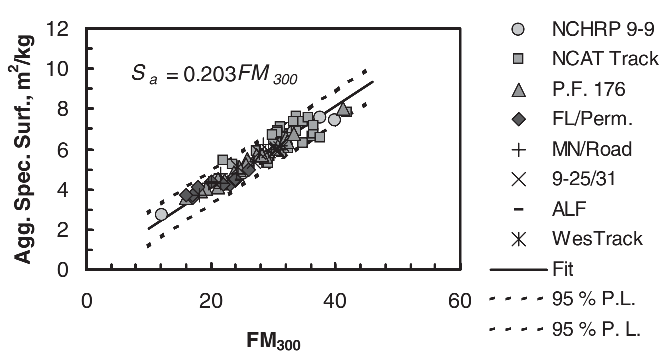

Figure 1. Estimated Aggregate Specific Surface as a Function of $FM_{300} = P_{75} + P_{150} + P_{300}$ (r^2 = 90%; Plot Includes 95% Prediction Limits for New Observations).

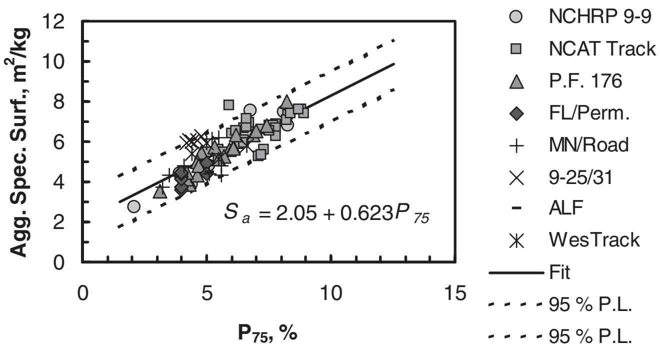

Figure 2. Estimated Aggregate Specific Surface as a Function of Material Finer than 75 µm (r^2 = 76%; Plot Includes 95% Prediction Limits for New Observations).

that it will allow producers with materials deficient in mineral filler to provide additional surface area by increasing the amount of material in the 75- to 300-µm size range. Some engineers may object to the use of FM_{300} because it appears possible to meet requirements stated in this manner using aggregate with little or no mineral filler; however, it should be remembered that current Superpave requirements have clear minimum and maximum values on the amount of material finer than 75 µm.

Figure 3 is a plot showing maximum permanent shear strain (MPSS) determined using the RSCH test as a function of N_{design} × resistivity. Multiplying resistivity by N_{design} is necessary to account for differences in compaction energy, which can increase resistance to permanent deformation independent of mixture composition. RSCH tests were performed at 54 °C and 60 °C, and the HMA tested incorporated a range of asphalt binders; the viscosity values used in calculating resistivity were determined for each binder at the temperature for the corresponding RSCH test. The specimens tested represent a wide range of mix composition and N_{design} levels. Additionally, air void contents were varied for these mixtures by altering the asphalt content ± 0.5% from the design value. The relationship in Figure 3 is quite good although it appears that the MPSS values at a given level of N_{design} × resistivity are somewhat higher for mixtures containing limestone aggregate compared with the gravel and granite aggregates. One possible explanation for this is that the limestone aggregate, being relatively soft, breaks down during the RSCH test more than do the harder aggregates. As discussed below, limited calibration of the resistivity equation suggests that this is not a serious problem in applying this approach to field-rutting data.

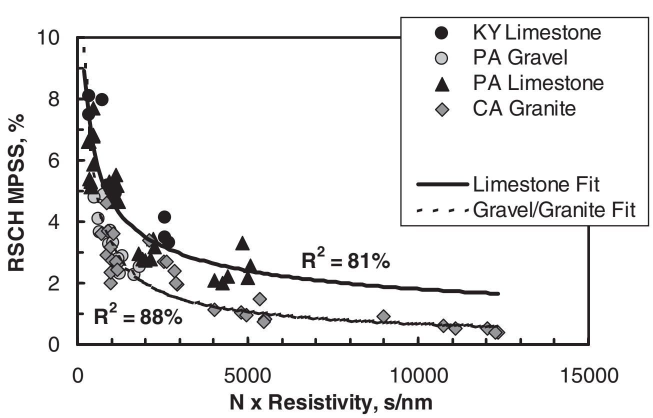

Figure 3. RSCH Permanent Shear Strain as a Function of Gyrations × Resistivity.

The resistivity approach to estimating mixture rut resistance was verified by using field-rut data from the MnRoad, NCAT, and WesTrack project (*2, 5, 6*). It must be emphasized that this calibration was performed using a substantial set of existing field data and not the limited laboratory data collected during NCHRP Projects 9-25 and 9-31. The data used in calibrating the rutting model is summarized in Tables 1 and 2. In calculating resistivity, the 7-day average high pavement temperature at a depth of 50 mm was used. Furthermore, the amount of binder age hardening was estimated using a modification of Mirza and Witczak's global aging model (discussed below). A statistical analysis of this data resulted in the following semi-empirical equation:

$$RR = 224P^{-1.08}N_{eq}^{-0.650}RD^{-18.6} \tag{2}$$

where

- RR = Rutting rate, mm rutting/m thickness/ESALs$^{1/3}$ (equivalent single axle loads);
- P = Resistivity, in s/nm;
- N_{eq} = N_{design} or number of blows with Marshall compaction hammer; and
- RD = Relative field density = (100% − in-place voids)/(100% − design voids).

The relationship between this function and the observed rutting rate is shown in Figure 4. The r^2 value for this model was 89%, which is very good considering that this model includes data from three widely different climates and uses only laboratory mix data and in-place air voids to predict the rutting rate. The 90% prediction limits shown in Figure 4 correspond closely to plus or minus a factor of 2.0 in the estimated rut depth. Thus, if the estimated rut depth found with Equation 2 were 8 mm, the 90% prediction limits would be 4 to 16 mm. The 90% confidence level was chosen because for rutting, only the upper confidence level is of practical interest, so this corresponds to a 95% one-sided prediction limit for design purposes. Although a factor of 2 might seem large for a confidence limit, this is equivalent to a factor of safety of 2, which is common in much practical engineering work.

It should be emphasized that N_{design} in Equation 2 refers to the number of gyrations (or Marshall blows) required to

Table 1. Properties of mixtures used in calibration of rutting model.

Section	Mix Design Method	N_{design} or Blows	Aggregate Type	Aggregate NMAS *mm*	Aggregate Gradation	Binder Grade	Modifier Type
NCAT Test Track Mixtures							
N1	Superpave	100	Slag/Limestone	12.5	ARZ	PG 76-22	SBS
N2	Superpave	100	Slag/Limestone	12.5	ARZ	PG 76-22	SBS
N3	Superpave	100	Slag/Limestone	12.5	ARZ	PG 67-22	N/A
N4	Superpave	100	Slag/Limestone	12.5	ARZ	PG 67-22	N/A
N5	Superpave	100	Slag/Limestone	12.5	BRZ	PG 67-22	N/A
N6	Superpave	100	Slag/Limestone	12.5	BRZ	PG 67-22	N/A
N7	Superpave	100	Slag/Limestone	12.5	BRZ	PG 76-22	SBR
N8	Superpave	100	Slag/Limestone	12.5	BRZ	PG 76-22	SBR
N9	Superpave	100	Slag/Limestone	12.5	BRZ	PG 76-22	SBS
N10	Superpave	100	Slag/Limestone	12.5	BRZ	PG 76-22	SBS
N11	Superpave	100	Granite	12.5	TRZ	PG 76-22	SBS
N12	SMA	50	Granite	12.5	SMA	PG 76-22	SBS
N13	SMA	50	Gravel	12.5	SMA	PG 76-22	SBS
S1	Superpave	100	Granite	12.5	BRZ	PG 76-22	SBS
S2	Superpave	100	Gravel	9.5	BRZ	PG 76-22	SBS
S3	Superpave	100	Limestone/Gravel	9.5	BRZ	PG 76-22	SBS
S4	Superpave	100	Limestone	12.5	ARZ	PG 76-22	SBS
S5	Superpave	100	Gravel	12.5	TRZ	PG 76-22	SBS
S6	Superpave	100	Limestone/RAP	12.5	ARZ	PG 67-22	N/A
S7	Superpave	100	Limestone/RAP	12.5	BRZ	PG 67-22	N/A
S8	Superpave	100	Marble/Schist	12.5	BRZ	PG 67-22	N/A
S9	Superpave	100	Granite	12.5	BRZ	PG 76-22	SBS
S10	Superpave	100	Granite	9.5	ARZ	PG 67-22	N/A
S11	Superpave	100	Marble/Schist	12.5	BRZ	PG 76-22	SBS
S13	Superpave	100	Granite	12.5	ARZ	PG 76-22	SB
MnRoad Mixtures							
1	Marshall	75	Gravel/Granite	12.5	ARZ	PG 58-28	N/A
2	Marshall	35	Gravel/Granite	12.5	ARZ	PG 58-28	N/A
3	Marshall	50	Gravel/Granite	12.5	ARZ	PG 58-28	N/A
4	Superpave	100	Gravel/Granite	12.5	ARZ	PG 64-22	N/A
14	Marshall	75	Gravel/Granite	12.5	ARZ	PG 58-28	N/A
15	Marshall	75	Gravel/Granite	12.5	ARZ	PG 58-28	N/A
16	Superpave	100	Gravel/Granite	12.5	ARZ	PG 64-22	N/A
17	Marshall	75	Gravel/Granite	12.5	ARZ	PG 58-28	N/A
18	Marshall	50	Gravel/Granite	12.5	ARZ	PG 58-28	N/A
19	Marshall	35	Gravel/Granite	12.5	ARZ	PG 58-28	N/A
20	Marshall	35	Gravel/Granite	12.5	ARZ	PG 58-28	N/A
21	Marshall	50	Gravel/Granite	12.5	ARZ	PG 58-28	N/A
22	Marshall	75	Gravel/Granite	12.5	ARZ	PG 58-28	N/A
23	Marshall	50	Gravel/Granite	12.5	ARZ	PG 58-28	N/A
WesTrack Mixtures							
35	Superpave	96	Andesite	19.0	BRZ	PG 64-22	N/A
38	Superpave	96	Andesite	19.0	BRZ	PG 64-22	N/A
39	Superpave	96	Andesite	19.0	BRZ	PG 64-22	N/A
54	Superpave	96	Andesite	19.0	BRZ	PG 64-22	N/A

Notes: SMA = stone matrix asphalt; RAP = recycled asphalt pavement; ARZ = above restricted zone; BRZ = below restricted zone; TRZ = through restricted zone; SBS = styrene-butadiene-styrene rubber; SBR = styrene-butadiene rubber; SB = styrene-butadiene

compact the specimen during quality-control (QC) testing, corresponding to N_{design} for the job mix formula (JMF). The air void content at N_{design} will, in this case, often deviate from 4.0%; however, changes in air void content and VMA are accounted for in Equation 2 in the resistivity term, which should also be calculated using QC data when possible. It should also be noted that using as-designed data when applying Equation 2 to field data will often result in poor predictions of rutting rate because HMA mixes as-placed often vary substantially from their as-designed characteristics. If an estimate is needed of the effect of deviations during production from as-designed characteristics, rutting should be calculated

Table 2. Summary of factors and levels included in calibration of rutting model.

Factors	*Types/Levels*
Sections/mixtures	43
U.S. climates	Southeastern (Alabama), Northcentral (Minnesota), Intermountain (Nevada)
Aggregate type	Andesite, granite, gravel, limestone, marble, schist, slag
Mix design methods	Superpave—29 (96 and 100 gyration), Marshall—12 (35, 50 and 75 blows), SMA—2 (50 gyration)
Aggregate NMAS	36 mixtures 12.5-mm, 3 mixtures 9.5-mm, 4 mixtures 19.0-mm
Aggregate gradation	22 mixtures ARZ, 17 BRZ, 2 TRZ, 2 SMA
PG grades	PG 58-28, PG 64-22, PG 67-22, PG 76-22
Modified/unmodified binders	15 mixtures modified, 28 unmodified
Modifier types	SBS, SBR
FM_{300} **(QC)**	Min. 21.6, Max. 42.8, Avg. 29.4
VMA (QC)	Min. 10.9 %, Max. 16.3 %, Avg. 14.6 %
VTM (QC)	Min. 1.9 %, Max. 7.4 %, Avg. 3.7 %
VTM (In-Place)	Min. 3.3 %, Max. 8.2 %, Avg. 6.2 %

Notes: SMA = stone matrix asphalt; ARZ = above restricted zone; BRZ = below restricted zone; TRZ = through restricted zone; SBS = styrene-butadiene-styrene rubber; SBR = styrene-butadiene rubber

using both as-designed and as-produced data (using field air voids in each case to calculate relative density). The difference between these rutting rates will then provide an estimate of the effect on rutting rate of deviations from the mix design.

A series of simple plots can be constructed using Equations 1 and 2 to illustrate the specific effect of changing VMA, design air voids, and aggregate fineness on rutting rate. These plots were constructed assuming typical values for Superpave mixtures for $|\eta^*|$, aggregate specific surface and N_{design} – 5,000 Pa-s, 4.8 m^2/kg and 75 gyrations, respectively. Figure 5 shows estimated rutting rate (mm/m/$ESALs^{1/3}$) as a function of design VMA and design air void content for a constant in-place air void content of 7%. As VMA increases, rut resistance decreases; the estimated rutting rate decreases by about 20% for each 1% decrease in VMA. Each 1% increase in design air voids decreases rutting rate by 18%. This might at first seem counter-intuitive, but by increasing the design air void level while maintaining the in-place air void content, the energy of compaction required to construct the pavement is increased significantly. Conversely, decreasing air voids under constant in-place air voids decreases the energy required for field compaction.

Figure 6 shows the effect of in-place air voids on rutting rate at a constant design air void content of 4%. Each 1% decrease in in-place air voids decreases the rutting rate by about 18%. Note that the magnitude of the effect of changes in design air void content and in-place air void content appear to be nearly identical. In fact, if in-place air void content is allowed to vary with design air voids (i.e., in-place air voids of 8% for 5% design air voids, in-place air voids of 6% for design air voids of 3%), the factors nearly offset each other and there is little net change in rut resistance. As will be emphasized repeatedly in this report, in order to develop efficient HMA mix designs

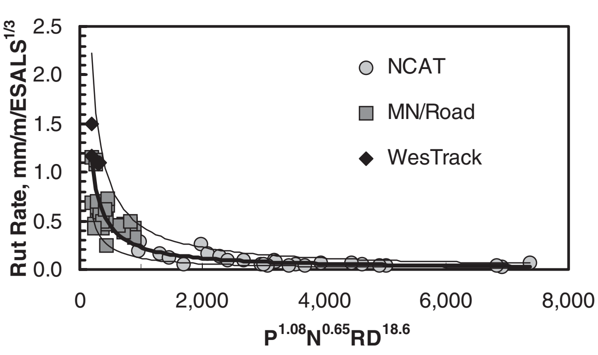

Figure 4. Relationship Between Field Rutting Rate and Proposed Function of Resistivity, N_{design} and Air Voids; the Heavy Center Line Represents the Rutting Rate Predicted Using Equation 2 While the Thinner Lines Represent 90% Prediction Limits for New Observations.

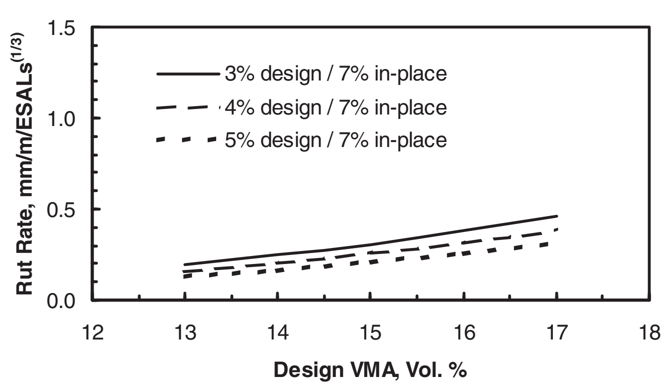

Figure 5. Effect of Design VMA and Air Voids on Rut Resistance of Superpave Mixtures at a Constant In-Place Air Void Content of 7%.

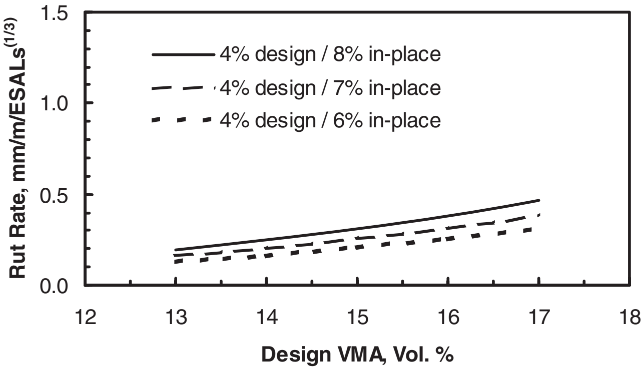

Figure 6. Effect of VMA and In-Place Air Voids on Rut Resistance of Superpave Mixtures at a Constant Design Air Void Content of 4%.

in the laboratory and then to effectively control these mixtures in the field, it is essential to understand how changes in design air void content effect performance. If in-place air voids are assumed to be independent of design air voids, increasing design air void content will improve performance because greater compaction energy is required to reach the target value for in-place voids. Under these conditions, decreasing design air void content will reduce performance because less compaction energy is then required to reach the target in-place air void level. However, if in-place air voids more or less follow changes in design air voids, there will be little effect on performance as a result of changing design air voids. It should be noted (as discussed later in this chapter) that changes in in-place air void level also significantly affect permeability. Engineers contemplating changes in design air void content should carefully and realistically consider the ways in which such changes will affect pavement performance.

Figure 7 is similar to the previous two plots and shows the effect of VMA and aggregate fineness, as indicated by FM_{300}. This value was allowed to vary from 20% to 40%, which is a typical range for Superpave mixtures based upon quality control gradation data from the NCAT Test Track, the MnRoad Project, and the WesTrack project. The aggregate fineness has a very large effect on rut resistance; changing the value of FM_{300} from 20 to 30 decreases the rutting rate by more than a factor of 2; increasing FM_{300} from 30 to 40 further decreases the rutting rate by a factor of about 1.9. It can be concluded that aggregate fineness, as indicated by FM_{300}, should be carefully controlled in order to better design Superpave mixtures for specific levels of rut resistance. Because rut resistance depends on both VMA and aggregate specific surface (as indicated in this case by FM_{300}), these factors should ideally be controlled simultaneously. As discussed later in this report, control of aggregate specific surface also helps to limit mixture permeability. The main practical problem is how to establish such control without being unduly restrictive in the requirements for VMA and aggregate gradation.

In order to put the previous analysis into perspective, Figure 8 was constructed, which shows the relationship between rutting rate, asphalt binder grade, and N_{design}. Binder PG grade, like FM_{300}, is a very important factor in determining mixture rutting rate; in this analysis, increasing the binder grade from a PG 58-28 to a PG 64-22 increases the rutting rate by a factor of 2.6. Increasing the binder grade from a PG 64-22 to a PG 70-22 increases the allowable traffic by a factor of 2.4. The effect of compaction is not nearly as large as that of binder grade. Increasing N_{design} from 50 to 75 reduces the estimated rutting rate by 23%. Increasing N_{design} again from 75 to 100 further decreases rutting rate by 17%, while again increasing N_{design} from 100 to 125 decreases rutting rate by 14%.

In summary, the effects of changing various aspects of mixture composition on rutting resistance (mm/m/ESALs$^{1/3}$) are as follows:

- Decrease VMA 1%, increase design VTM 1%, or decrease field VTM 1%: decrease rutting rate by about 20%.
- Increase in aggregate fineness by 10 as indicated by FM_{300}: decrease rutting rate by a factor of about 2.

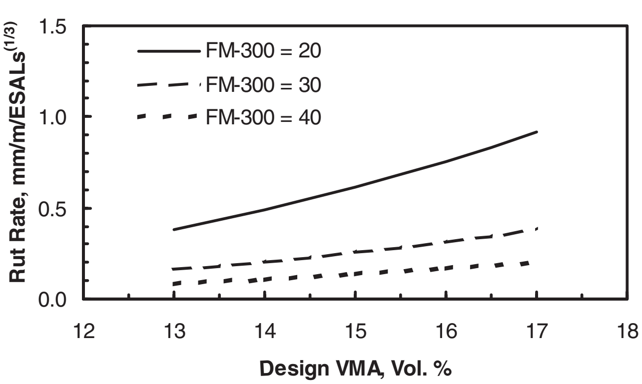

Figure 7. Effect of Aggregate Fineness and Design VMA on Rut Resistance of Superpave Mixtures at a Constant In-Place Air Void Content of 7%.

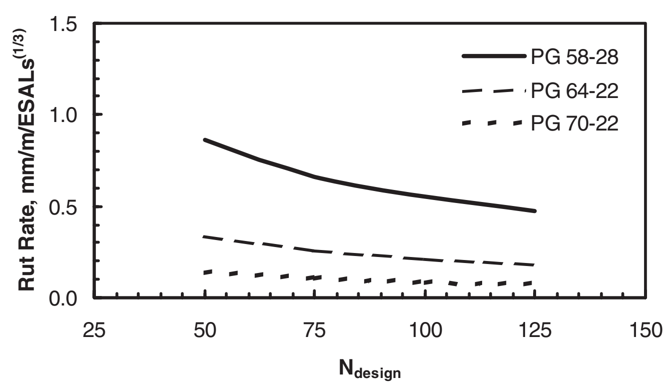

Figure 8. Effect of Binder Grade and N_{design} ***on Rut Resistance of Superpave Mixtures (Design Air Voids = 4%, In-Place Air Voids = 7%).***

- Increase of one level in high-temperature PG-grade: decrease rutting rate by a factor of about 2.5.
- Increase N_{design} by one level: decrease rutting rate by about 15% to 25%.

Several comments should be made concerning this analysis. First, although the model used in this analysis was based on a substantial data set, further refinement of the model using an even wider range of data is needed before it can be used with confidence for a wide range of conditions. Of particular concern are the specific effects of mineral filler and polymer modification on rut resistance; the data set used in calibration of the resistivity model included mixtures made using a large number of modified binders, but these mixtures also tended to be those with the highest specific surface. Therefore, there is some confounding of these effects. As part of NCHRP Project 9-33, the rutting/resistivity model is being re-evaluated and refined; preliminary results indicate that the general form of the model is correct, as are most of the trends predicted by the model. Specific exponents in the final model will be somewhat different from those given in Equation 2. For example, initial analysis suggests that the exponent to N_{design} in Equation 2 should be –.949 rather than –0.595. Most importantly, it appears that, all else being equal, many mixtures made using polymer modified binders will exhibit substantially better rut resistance than predicted on the basis of resistivity alone (*32*).

It must be emphasized that the various factors affecting rut resistance are additive and that although some may seem relatively insignificant, if these act together in the same way the results can be quite large. Engineers contemplating modification in current Superpave requirements (or specifications for other HMA types) must consider not only the effect of a particular change in a given characteristic, but also the combined effects of all other such changes.

Although aggregate angularity and gradation do not appear in either the resistivity equation or the related equation for rutting rate, Equation 2 does include terms for both design compaction level and field compaction, which is accounted for through relative density—that is, field density/air voids compared with design density/air voids. As aggregate quality decreases—that is, as an aggregate becomes less angular and/or cubical and/or resistant to crushing—N_{design} (i.e., gyrations required to reach 4% air voids) will decrease, which will cause the rutting rate estimated using Equation 2 to increase. Thus, the proposed approach for accounting for the affect of mixture composition on rut resistance indirectly includes the effect of aggregate angularity and gradation through inclusion of terms for laboratory and field compaction effort. Because the proposed relationship for rut resistance was based on mixtures that were mostly made with cubical, well-crushed aggregates with little or no natural sand, extreme caution should be used in applying this model to mixtures containing poor quality aggregates. Aggregate gradations included in the mixtures upon which Equation 2 were based included mostly coarse gradations, with significant numbers of fine and dense gradations, and a few gap-graded materials (SMA mixtures). However, no open-graded mixtures were included in these data. Therefore, Equation 2 should also not be applied to open-graded friction course mixtures until its accuracy for such materials has been verified.

A second important limitation to the proposed model for rut resistance involves the behavior of mixtures at very low air void contents. It is well known that at in-place air void contents below about 2% to 3%, many HMA pavements will exhibit a sudden and dramatic decrease in rut resistance. This is attributable to excessive asphalt binder content, which prevents aggregate particles from developing the internal friction needed for good rut resistance. For this reason, it is generally accepted that air void contents below about 3% should be avoided when designing HMA mixes. This phenomenon is not directly addressed in the resistivity equation (Equation 1) or the associated equation for rutting rate (Equation 2). Therefore, the proposed approach to accounting for the effect of mixture composition on rut resistance should not be applied to mixtures with very low air void contents. Based upon the range of air void contents included in this analysis, the proposed equations should not be applied to mixtures designed at air void contents below about 3%, or to field produced mixtures with air void contents in QC testing below about 2.5%, or to pavements with in-place air void contents below about 4%. This qualification does not mean that the model is not accurate for these conditions—only that its accuracy has not been evaluated for such circumstances.

Although these caveats to the proposed rutting model are substantial, in essence the proposed model should be valid for mixtures meeting or nearly meeting current requirements for Superpave mixtures, heavy-duty Marshall mix designs, and SMA mixtures. As discussed in Chapter 3, it appears that the overall level of rut resistance in the vast majority of HMA designed using the Superpave system is adequate. However, some agencies have noted a decrease in fatigue resistance and an increase in permeability with the widespread adoption of Superpave mix design requirements, and some have increased minimum VMA requirements to improve fatigue resistance of these materials. The findings above suggest that aggregate specific surface should be increased along with VMA in order to maintain good rut resistance. As discussed below, this will have the added benefit of helping to limit HMA permeability. This and other ramifications of the findings presented above are discussed in greater detail in Chapter 3.

Fatigue Resistance

Continuum Damage Approach to Fatigue Phenomena in HMA

During NCHRP Projects 9-25 and 9-31, a practical approach was developed by applying continuum damage theory to characterizing and analyzing the fatigue response of HMA. The following discussion is a summary of this method of analysis and is a relatively minor extension of previous work on continuum damage theory done by other researchers (*16, 33–37*). The following equation for fatigue life was derived based upon continuum damage theory and an exponential damage rate:

$$N = \frac{2^{\alpha} f\left(C^{-\alpha} - 1\right)}{\alpha\left(-C_2\right)^{1+\alpha} \epsilon_0^{2\alpha} \left|E^*\right|_{LVE}^{2\alpha}} \qquad (3)$$

where

N = fatigue cycles;
α = a material constant for viscoelastic material;
f = loading frequency, Hz;
C = damage ratio (damaged/undamaged modulus);
C_2 = continuum damage fatigue constant;
ϵ_0 = applied strain amplitude (½ of peak-to-peak strain); and
$|E^*|_{LVE}$ = linear viscoelastic (LVE) complex modulus.

To apply Equation 3 (and related functions) to fatigue phenomena in HMA, the values of α and C_2 must be known along with the values for frequency and modulus. Analysis of uniaxial fatigue data gathered during NCHRP Projects 9-25 and 9-31 lead to the following empirical equation for estimating C_2 as a function of $|E^*|$, VFA, and the rheological index of the binder, R:

$$C_2 = -30.1\left|E^*\right|_{LVE}^{-0.629} VFA^{-0.576} R^{-1.54} \qquad (4)$$

The rheological index R of the binder is a constant in the Christensen–Anderson and Christensen–Anderson–Marasteanu (CAM) models for complex modulus and phase angle of asphalt binders (*38, 39*). This constant is directly related to the dispersion of relaxation times for the binder, and so it increases as the width of the relaxation spectrum increases. In the literature of paving technology the width of the relaxation spectrum is often referred to as "rheologic type" and was traditionally characterized by empirical constants such as the penetration index (PI) and penetration-viscosity number (PVN) (*40*). The value of R relates well to these older indexes but is more rational and more exact in the way it characterizes the flow properties of asphalt binders (*38, 40*). Values for R typically range from about 1.2 to more than 3.0, with a typical value for an unaged binder being about 2.0 (*38–40*). Oxidation, both during refining and during age hardening, can dramatically increase the value of R (*38, 40*). The primary objective of NCHRP Projects 9-25 and 9-31 was to develop relationships among mixture compositional characteristics and HMA performance. Although R is not a mixture compositional characteristic, it must be included in fatigue equations to ensure that the models are valid and accurate. It is not recommended that the R value be controlled as part of the mix design process; control of R must be done through the binder specification and should be the topic of other research projects. However, it must be emphasized that none of the fatigue models presented here involve interactions between R and other mixture characteristics. Therefore, even though variations in R are not directly addressed in this report, the effects of changes in mixture composition on fatigue resistance are still accurate and valid.

Another important finding in analyzing the NCHRP Projects 9-25 and 9-31 fatigue data was that the complex modulus in tension/compression, as determined at the start of the uniaxial fatigue tests, was significantly lower than that measured in dynamic compression. Based upon comparing the measurements made during these fatigue tests and dynamic compression values predicted using the Hirsch equation, the following empirical equation was developed for estimating tension/compression modulus values ($|E^*|_{TC}$) from $|E^*|$ values determined for dynamic compression:

$$|E^*|_{TC} = 0.000209|E^*|^{1.57} \qquad (5)$$

It was found that tension/compression modulus values computed using this equation agree well with flexural stiffness values predicted with Bonnaure's equation and as measured during SHRP. Figure 9 is a comparison of tension/compression modulus values predicted using the Hirsch equation and Equation 5 with measured flexural stiffness values ($|S^*|$) measured during SHRP as part of the SHRP fatigue tests (*15*).

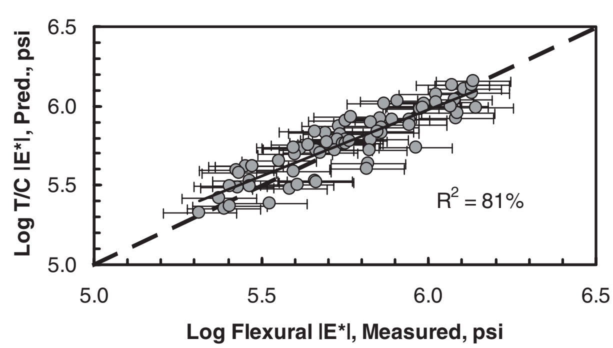

Figure 9. Predicted Complex Modulus in Tension/Compression Compared with Measured Flexural Complex Modulus for SHRP Mixtures (Bars = d2s Confidence Limits, Solid Line = Regression Function, and Dashed Line = Equality).

Equations 3 and 4 potentially can be used to evaluate the effect of changes in mixture composition on fatigue resistance. However, because the fatigue testing upon which Equation 4 was based was somewhat limited and because of the newness of continuum damage theory, further verification of these results is desirable prior to application to HMA mix design and analysis. This verification was done by applying continuum damage theory to flexural fatigue data gathered during SHRP (*15*). These data included the results of 185 tests on mixtures made using eight different asphalt binders and three aggregates. Properties of this data set are summarized in Table 3. Application of continuum damage theory to flexural fatigue data in part is dependent upon the finding that at completion of a flexural fatigue test, when the flexural stiffness has decreased by 50%, the extreme fiber damage will be constant at about 86.4%, corresponding to a damage ratio of 0.136.

In analyzing the SHRP fatigue data, the data was first analyzed statistically using a model of the following form:

$$\log N = A + B\log|E^*|_{TC} + D\log(\epsilon_0) + E\log(VFA) + F\log(R) + error \quad (6)$$

In analysis of the SHRP data, the value of the complex modulus in compression was estimated from the Hirsch model and then converted to a tension/compression value using Equation 5. This approach was taken, rather than using measured flexural modulus values, because in the mix design process only estimated modulus values are available. In Equation 6, the coefficients to the log of the predictor variables correspond to exponents for these terms; according to continuum damage theory, the exponent for the strain term is $\alpha/2$. The model represented by Equation 6 was reasonably accurate, with an r^2 value of 84% (adjusted for degrees of freedom) and gave a value for $D = \alpha/2 = 1.74$, slightly lower than the value of 2.00 that was used in analyzing the uniaxial fatigue data generated during NCHRP Projects 9-25 and 9-31. The next step in analyzing the SHRP data was to calculate the value of C_2 for each test, using a rearranged form of Equation 3 and a value for the terminal damage ratio C of 0.136 and $\alpha = 1.74$:

$$-C_2 = \left[\frac{2^{\alpha} f\left(C^{-\alpha} - 1\right)}{\alpha N \epsilon_0^{2\alpha} |E^*|_{LVE}^{2\alpha}}\right]^{\frac{1}{1+\alpha}} \quad (7)$$

Uniaxial fatigue test data collected during NCHRP Projects 9-25 and 9-31 were re-analyzed using $\alpha = 1.74$ rather than $\alpha = 2.00$ (as was done in the initial analysis of these data). Then, C_2 values and related information for both the SHRP data and for the NCHRP Projects 9-25 and 9-31 data were combined and analyzed statistically. The best model for estimating C_2 for this combined data set was somewhat different from that given earlier as Equation 4:

$$C_2 = -466 VBE_{design}^{-0.612} N_{design}^{-0.380} D_{relative}^{-8.88} R^{-1.22} |E^*|_{LVE}^{-0.780} \quad (8)$$

Table 3. Summary of properties of data used in developing fatigue model.

Property	Average Value	Minimum	Maximum
Total number of tests	200		
Number of uniaxial tests (n = 4 analyzed together)	43		
Number of replicated flexural tests (n = 2, analyzed separately)	61		
Number of non-replicated flexural tests	35		
Mix design methods	Superpave, Marshall		
Aggregate types	Greywacke gravel, low absorption limestone, limestone (2 sources), granite, gravel		
Binder types	SHRP core asphalts—eight binders of widely varying rheology and grade; one SHRP asphalt modified with three modifiers; NCHRP 9-25/31 binders: PG 58-28, PG 64-22, PG 76-22, all unmodified		
Estimated compaction (N_{design}), gyrations	76	29	125
Air void content, Vol. %	5.1	0.8	8.8
Voids in mineral aggregate, Vol. %	16.5	11.5	21.5
Effective asphalt binder content, Vol. %	11.3	6.1	16.4
Voids filled with asphalt binder, %	69.2	42.4	94.3
Test temperature, °C	19	4	25
Test frequency, Hz	10		
Applied strain, $\times 10^6$ (uniaxial tests)	50 to 100 at 4 °C and 100 to 200 at 20 °C		
Applied strain, $\times 10^6$ (flexural tests)	339	200	1,200
Initial $|E^*|$ uniaxial at 20 °C, uniaxial tests, GPa	5.76	1.24	9.52
Initial flexural stiffness, GPa	4.53	1.02	11.35
Cycles to failure (50 % stiffness lost)	119,000	10,000	685,000

where

VBE_{design} = the effective asphalt binder content at the design compaction level, in volume %;

$D_{relative}$ = the bulk density relative to the design bulk density;

R = the rheological index of the binder; and

$|E^*|$ = in lb/in^2.

The inclusion of N_{design} in this model significantly improved its accuracy, but was complicated because of the different compaction methods used in the two data sets—the SHRP mix designs were prepared using Marshall compaction, while the NCHRP Projects 9-25 and 9-31 mix designs were prepared using gyratory compaction. Two different levels of design compaction were used in the SHRP mix designs: 50 blows and 75 blows (*15*). In the model represented by Equation 8, the number of gyrations for each compaction level for the SHRP mix designs were included as predictor variables; the analysis indicated that the equivalent number of gyrations for 50-blow Marshall compaction was 73 and for 75-blow Marshall compaction was 92. Equation 8 differs from Equation 4 in the use of effective binder content rather than VFA. In analyzing the combined set of fatigue data, it was found that VFA could be used as an effective predictor if it is adjusted to 4% air voids. However, this is a cumbersome calculation and in fact provides essentially the same information as VBE. VBE has the additional advantage that it is nearly independent of changes in design air void content for the range from 3% to 5%. The model represented by Equation 8 was very effective, with an r^2 value of 89% (adjusted for degrees of freedom). The results are shown graphically in Figure 10, which shows predicted and observed values for C_2 for both data sets.

As a final check on the accuracy of this analysis, the cycles to failure for the SHRP flexural fatigue data were predicted using Equations 3 and 8, which can be combined to form a single function for predicting fatigue life to a given damage ratio C:

$$N = \frac{1.05\times10^{-6}\, f VBE_{design}^{1.677} N_{design}^{1.041} D_{relative}^{24.34} R^{3.335}\left(C^{-1.74}-1\right)}{\left(2\epsilon_0\right)^{3.48} |E^*|_{LVE}^{1.342}} \quad (9)$$

where the damage ratio at the end of the test (when the flexural stiffness falls to 50% of its initial value) is 0.136 and the modulus values are as predicted using the Hirsch model corrected for tension/compression loading using Equation 5. Figure 11 shows the cycles to failure predicted using Equation 9 and as measured during SHRP. Each point represents the average of two tests and includes d2s confidence limits, which represent a 95% prediction limit for the difference between two independent observations. If most of these confidence limits include the line of equality, it indicates that the predictions agree well with the experimental value. In this case, 57 of 61 data points agree to within the d2s limits, indicating exceptionally good agreement between the predicted values and the observed fatigue limits. If two independent sets of fatigue measurements were compared, it would be expected that 58 of the 61 data points would agree to within the d2s limits, so the predicted values appear to be almost interchangeable with experimentally determined values.

Effect of Mixture Composition on In Situ Fatigue Resistance

Some discussion of the relationships among fatigue resistance and binder content, design compaction level, and field compaction is useful at this point to illustrate the practical implications of Equation 9. Many pavement engineers and technicians assume that lower values of N_{design} automatically result in higher binder contents, so lowering N_{design} will improve fatigue resistance because increased binder content will improve fatigue life. This is true if N_{design} is changed

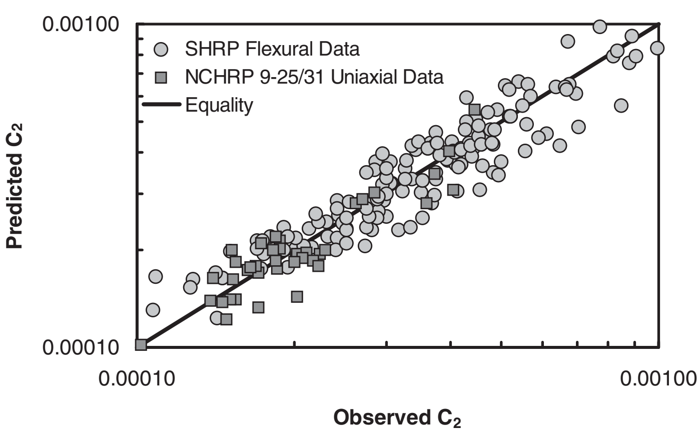

Figure 10. Predicted and Observed Values for Continuum Damage Fatigue Constant C_2 for SHRP Flexural Fatigue Data and NCHRP Uniaxial Fatigue Data.

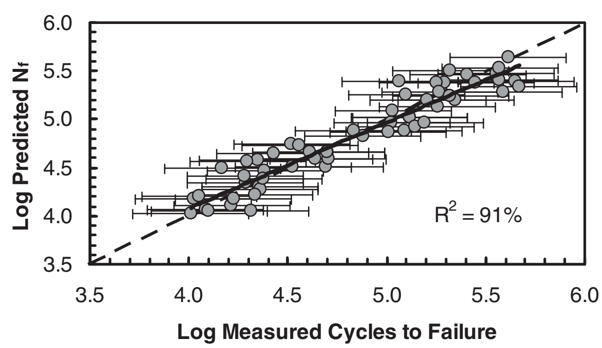

Figure 11. Predicted and Measured Log Cycles to Failure for SHRP Flexural Fatigue Data, with d2s Confidence Limits.

without modifying the given aggregate blend, but it is not true when a range of aggregates and mixtures are considered. Furthermore, there is no reason to believe that if N_{design} requirements are changed, materials suppliers will not change aggregate gradations for their mixtures. In fact, in cases where asphalt binder is not paid as a separate item, there is strong economic incentive to modify aggregate gradations to obtain the minimum binder content that will not incur a penalty. Because changes in volumetric requirements cannot possibly include a requirement that N_{design} should be changed without any modification in aggregate gradation or sources, there is no basis for suggesting that implementing lower N_{design} values will result in increased binder contents and improved fatigue resistance. Decreasing N_{design} may improve the ease with which a mixture can be compacted in the field, but this will not necessarily mean that field compaction will be improved since there is an economic incentive to compact a pavement only to the highest air void content that will not incur a significant penalty. In summary, all else being equal, increasing N_{design} will improve fatigue resistance, and decreasing it will do the opposite. If an agency feels that higher binder contents and lower in-place air voids are needed to improve fatigue resistance, higher minimum binder contents (higher minimum VMA at a given design air void level) and improved field compaction requirements should be specified, perhaps in combination with lower N_{design} values if it is felt that this latter change will help materials suppliers and contractors deal with the first two changes.

Fatigue resistance in situ involves more than the inherent fatigue resistance of the mixture because mixture stiffness will affect the magnitude of strains resulting from traffic loading, in addition to affecting the resulting rate of damage as predicted by Equation 9 and similar functions. Therefore, in order to evaluate the overall relationships among volumetric composition and fatigue resistance, a simplified evaluation of field fatigue resistance was performed. The general approach involved using the Illipave algorithms, as described by Huang (*41*), to estimate tensile strains at the bottom of the bound materials in various pavement structures; Equation 9 was then used to determine the pavement fatigue life using a terminal damage ratio of 0.20. A variety of climates, pavement structures, and mixture compositions were considered:

- Two climates: New York state and South Carolina;
- Two pavement structures: 100-mm bound material over 150-mm granular subbase and 200-mm bound material over 300-mm granular subbase;
- Three average subgrade stiffness conditions: weak, moderate, and stiff;
- Four different times of year: mid-winter (January), early spring (March/April), spring thaw (April/May), and late summer (August);
- Two binder grades: PG 64-22 and PG 76-22;
- Design VMA ranging from 13 to 16;
- N_{design} of 75; and
- Design air voids of 3%, 4%, and 5%.

It should be pointed out that the level of N_{design} was not varied since Equation 9 (and any similar fatigue equation derived from this analysis) predicts that fatigue life will increase with increasing values of N_{design} and will decrease with lower values of N_{design}, all else being equal. There is no mechanism for changing this relationship in the field. Mixture modulus values were estimated using the Hirsch model. Binder *R* values were 1.70 for the PG 64-22 and 2.17 for the PG 76-22; these and other binder properties were taken from actual materials tested in Advanced Asphalt Technologies' laboratory. As discussed above, the statistical analyses showed no interaction between mix composition and binder *R* value. Therefore, using typical values for *R* should not affect the sensitivity of this analysis to changes in mix composition. Although an analysis of the affect of changes in *R* on fatigue resistance might be enlightening, it is clearly outside the scope of NCHRP Projects 9-25 and 9-31 and is not included in this report. The subgrade modulus values were allowed to vary according to the time of year, using the same values incorporated into the 1991 edition of the Asphalt Institute's *Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types (42)* for the thickness design of flexible pavements as reported by Huang (*41*). The results of this analysis were then compiled in terms of relative fatigue life—in this case, fatigue life expressed as a fraction of that for a design VMA of 15%, design air voids of 4%. These relative fatigue life values were then summarized statistically using means and standard deviations. Plots were prepared showing average changes and d2s confidence limits in relative fatigue life with design VMA, design air voids, and in-place air voids. The results are shown in Figures 12 through 15. In Figure 12, the effect of changes in design air

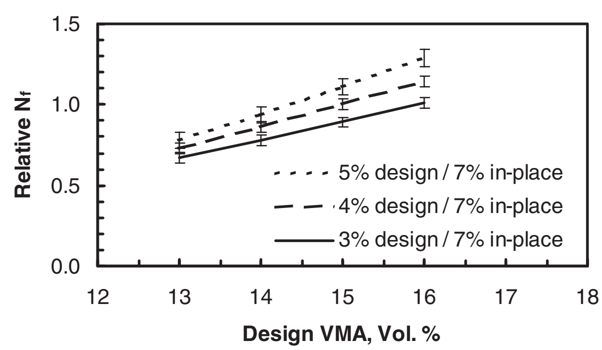

Figure 12. Effect of Design Air Voids and Design VMA on Relative In-Situ Fatigue Life, In-Place Air Voids Constant at 7% (Errors Bars = 2s Confidence Limits).

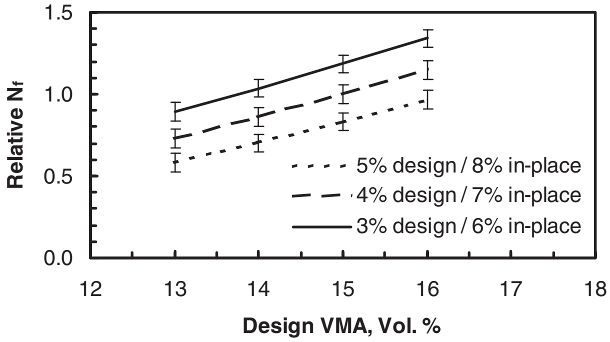

Figure 13. Effect of Design Air Voids and Design VMA on Relative In-Situ Fatigue Life, In-Place Air Voids of 6%, 7%, and 8% for Design Air Voids of 3%, 4%, and 5%, Respectively (Errors Bars = 2s Confidence Limits).

voids and design VMA are shown at a constant in-place air void level of 7%. For every 1% increase in VMA, the fatigue life increases from about 13% to 21% (typically about 16%). For every 1% increase in design air void content, the fatigue life increases about 7% to 14% (typically about 10%). This later finding may at first seem counter-intuitive, but it must be remembered that the analysis summarized in Figure 12 was generated assuming constant in-place air voids—therefore, increasing design air voids mostly has the effect of increasing the compaction effort during construction. For comparison, Figure 13 represents an analysis in which in-place air voids are allowed to vary with design air voids—that is, in-place air voids were assumed to be 6%, 7%, and 8% for design air voids of 3%, 4%, and 5%, respectively. In this case, the advantage of using higher air voids disappears—and, in fact, it appears to become a disadvantage in that it significantly decreases fatigue life. However, this is only because as design air voids change at constant VMA, it directly affects VBE—*as air voids increase at constant VMA, VBE decreases*.

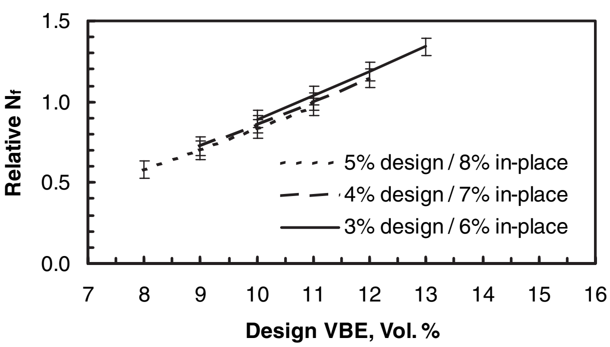

Figure 14. Effect of Design Air Voids and Design VBE on Relative In-Situ Fatigue Life, In-Place Air Voids of 6%, 7%, and 8% for Design Air Voids of 3%, 4%, and 5%, Respectively (Errors Bars = 2s Confidence Limits).

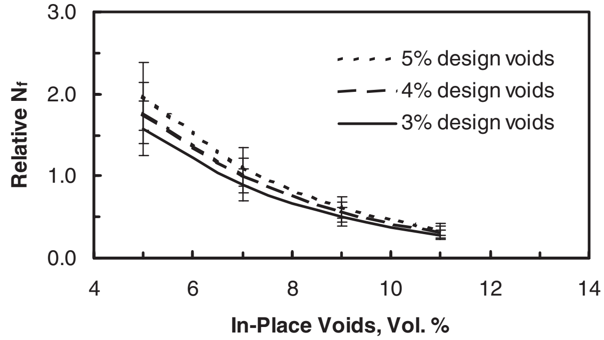

Figure 15. Effect of In-Place Air Voids and Design Air Voids on Relative In-Situ Fatigue Life (Errors Bars = 2s Confidence Limits).

To illustrate the good relationship between effective binder content and fatigue resistance, Figure 14 was constructed. This plot is nearly identical to Figure 13, but the horizontal axis is VBE rather than VMA. There is an excellent, nearly linear relationship between relative fatigue life and effective binder content—even though this figure was generated using different pavement structures, climates, and times of the year. For every 1% increase in VBE, there is typically a 13% to 15% increase in relative fatigue life. Therefore, to control the fatigue resistance of HMA, VBE should be specified. Alternately, asphalt binder content by weight can be specified as a function of aggregate specific gravity, but this is a somewhat more cumbersome approach. Furthermore, it is clear that if in-place air voids are allowed to vary with design air voids, there is little net affect on fatigue resistance. As discussed previously, the same situation exists for rut resistance—that is, changing in-place air voids simultaneously with design air voids has little net effect on rut resistance.

Although there appears to be some advantage to linking design and in-place air voids, such an approach would be impractical since in most paving projects the in-place air voids cannot be predicted with any certainty. Paving engineers and technicians should nevertheless understand the relationship among design air voids, in-place air voids, and performance:

- At a constant level of in-place air voids, increasing design air voids will improve performance because it forces more compaction energy to be used during construction.
- At a constant level of design air voids, increasing field air voids will decrease performance because it will result in less compaction energy being used during construction (it will also increase the permeability of the pavement, potentially decreasing resistance to age hardening and moisture damage).
- If design air voids and in-place air voids vary in a similar way, there will be little effect on performance.

Because of the strong relationship between VBE and fatigue resistance, VBE should be kept constant if design air voids are varied—that is, VMA should be increased or decreased in the same way as design air voids. This approach is, in fact, not at all new as it is the precise methodology suggested for Marshall mix designs in the Asphalt Institute's *Superpave Mix Design* (SP-2 Manual) *(43)* where minimum VMA values increase 1% for each 1% increase in design air void content. For example, the minimum VMA value for a 9.5-mm NMAS aggregate blend is 14% for 3% design air voids, 15% for 4% design air voids, and 16% for 5% design air voids. The effective asphalt binder content in each case is 11%.

The last plot in this series is Figure 15, which summarizes the effects of design air voids and in-situ air voids simultaneously. For every 1% increase in in-place air voids, relative fatigue life decreases by a nearly constant amount of about 22%. This means that an increase in in-place air voids of 2% will decrease fatigue resistance by nearly 50%. However, as mentioned above, this probably understates the importance of in-place air voids to fatigue life because it neglects the effect of changes in air voids on permeability and age hardening. This finding can be compared with those of Linden et al. cited earlier (*24*). Linden et al. cited three analytical studies in which a 10% to 30% reduction in fatigue life was predicted for every 1% increase in in-place air voids (*25–27*). This is in good agreement with the findings of NCHRP Projects 9-25 and 9-31. However, the rule of thumb of a 10% overall reduction in performance for every 1% increase in in-place air void content by Linden et al. is somewhat lower than the figure found in this analysis, but considering the very approximate nature of the research of Linden et al., the results should not be considered to contradict the findings of NCHRP Projects 9-25 and 9-31. Although an in-depth study of the effect of in-place air voids on pavement performance is outside the scope of this research, successful implementation of the results of this research will depend in part on achieving proper field compaction of mixtures designed according to the recommendations put forth in this report.

In summary, the analysis presented above indicates several important relationships exist between the fatigue resistance of HMA mixtures and volumetric composition:

- At given values for N_{design}, design air voids, and in-place air voids, fatigue resistance increases with increasing VBE.
- At a given design values for VBE, design air voids, and in-place air voids, fatigue resistance will increase with increasing values of N_{design}.
- At given design values for VBE, air void content, and N_{design}, fatigue resistance will increase with decreasing in-place air void content.

Permeability and Age Hardening

Permeability Tests

As discussed earlier in this report, the permeability tests performed as part of NCHRP Projects 9-25 and 9-31 were unfortunately of limited value. This was for two reasons: (1) the air void content of the specimens was relatively low (typically from about 3% to about 7%), which, even in field specimens, would result in very low permeability values; and (2) the permeability of laboratory specimens is often much lower than that of field cores. Therefore, the permeability of most of the specimens fabricated during this research was so low as to be impractical or even impossible to measure. This does however lead to an important finding: permeability testing of laboratory-fabricated specimens is usually not effective because the permeability will be much lower than that of field specimens and will tend to be quite variable. For purpose of mix design and mix design selection, it is probably more practical to rely upon models for estimating permeability rather than measuring permeability in the laboratory, which perhaps might show fairly low permeability values for mixtures that might exhibit unacceptably high permeability in the field.

Because of the shortcomings of the permeability tests performed during NCHRP Projects 9-25 and 9-31, use has been made of the substantial permeability data set generated during the Florida study reported on by Choubane et al. (*3*). Properties of this data set are summarized in Table 4. This study involved permeability testing of a large number of field cores and a limited number of laboratory-fabricated specimens. It should be pointed out that these pavements were constructed relatively early during the implementation of Superpave and their composition does not reflect that of Superpave pavements currently being constructed in Florida, which in general now have higher VMA and binder contents. A number of approaches were used to analyze these data statistically to develop an accurate and useful function for predicting the permeability of HMA. It was determined that the most effective approach was to use a relatively simple model in which permeability is proportional to effective air void content (VTM_{Eff}), which in turn is a function of total air void content and aggregate specific surface:

$$k = 108VTM_{Eff} \tag{10}$$

where

$$VTM_{Eff} = VTM - V_0 \text{ and} \tag{11}$$

$$V_0 = 1.53S_a - 1.87. \tag{12}$$

Table 4. Summary of properties of Florida permeability study data set.

Property	Average Value	Minimum	Maximum
Total number of tests	113		
Total number of field projects	7		
Total number of mixtures	13		
Aggregate types	Alabama limestone, Florida limestone, Georgia granite, RAP		
Aggregate NMAS and gradation	12.5-mm and 19-mm, all BRZ		
Binder grade, type	PG 67-22, unmodified		
Estimated aggregate specific surface, m^2/kg	4.47	3.57	5.34
Air void content, Vol. %	8.1	3.7	14.6
Voids in mineral aggregate, Vol. %	17.7	13.2	23.7
Effective asphalt binder content, Vol. %	9.6	8.5	10.7
Voids filled with asphalt binder, %	54.9	38.5	73.3
Permeability, $\times 10^{-5}$ cm/s	344	5	1014

The r^2 for this model, adjusted for degrees of freedom, was 65%. Although this does not appear to be an extremely strong correlation, the high variability in the permeability measurements must be considered when evaluating this model. Choubane et al. did not evaluate the repeatability of their measurements (*3*). However, as part of NCHRP Projects 9-25 and 9-31, an estimate of the standard deviation of these measurements was made by grouping specimens from the same project and same material and having air void contents within 1% of each other. Variance values were then estimated for each of these groups. An overall average variance was then calculated, weighted according to the number of specimens in each group. Because very low permeability values (below 50×10^{-5} cm/s) showed much lower variability than the other measurements, these were eliminated from the calculation. The estimated variances for the remaining permeability measurements appeared to fall into a similar range: the pooled estimate of the standard deviation using this method of 150×10^{-5} cm/s and incorporating 80 different measurements. The large number of measurements incorporated into this estimate means that it should be quite reliable.

Figure 16 is a plot of measured permeability versus effective air void content for several sets of data. This plot includes data for the Florida field cores, Florida laboratory specimens, and NCHRP Projects 9-25 and 9-31 laboratory specimens. The plot includes the 95% prediction interval for new observations for the Florida field cores. The width of this prediction interval—about 310×10^{-5} cm/s—is very nearly equal to twice the estimated standard deviation of 150×10^{-5} cm/s. It therefore appears most of the scatter observed in Figure 16 is probably the result of experimental error rather than of lack of fit in the model and that the proposed method of estimating mixture permeability is significantly more accurate than indicated by the r^2 value of 65%.

One of the problems associated with permeability testing of HMA is that permeability values measured on field cores generally are much higher than comparable specimens prepared in the laboratory. In Figure 16, the permeability for the laboratory specimens is about 1/6 of the value for similar field cores. The very low permeability of laboratory prepared specimens suggests that testing such specimens is probably not useful since it will almost always show very low or zero permeability and when it does not, the results are likely to be highly variable. Instead, Equations 10 through 12 should be used to estimate in-place permeability, based upon aggregate specific surface and measured or anticipated in-place air void content. In specifying Superpave and other HMA types, reasonably low levels of permeability should be maintained to help prevent excessive age hardening and to reduce susceptibility to moisture damage. In order to achieve such control, aggregate specific surface and in-place air void content must be simultaneously controlled. As with other aspects of controlling Superpave volumetric composition, a critical issue becomes how specifically to exert such control. Florida researchers have suggested that Superpave surface-course mixtures should exhibit permeability values below 100×10^{-5} cm/s. For an in-place air void content of 7%, this corresponds to an FM_{300} value of 26%. However, minimum FM_{300} values

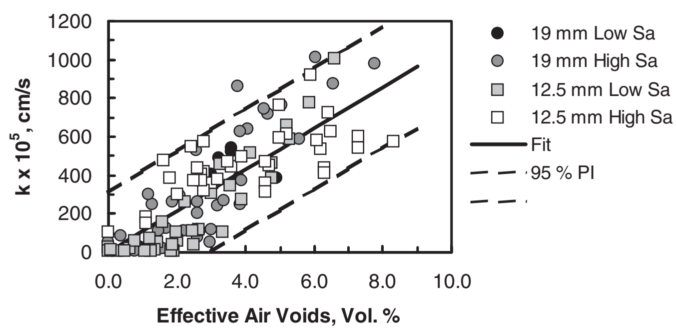

Figure 16. Permeability of Specimens Tested During the Florida Study and During NCHRP Projects 9-25 and 9-31 as a Function of Effective Air Void Content (Solid Line = Regression Line for Predicted Permeability; Dashed Lines = 95% Prediction Interval).

should vary both with air void content and with application—that is, mixtures in protected layers of the pavement can have higher permeability values. Specific guidelines for minimum FM_{300} values are given in Chapter 3.

Age-Hardening Tests

As part of NCHRP Projects 9-31 and 9-25, a variety of mixtures were subjected to long-term oven conditioning and the extent of the resulting age hardening was measured using the field-shear test to measure the complex modulus before and after conditioning. It was expected that the results of this experiment could be related to the permeability of the mixtures. The results in part did confirm a relationship between permeability and age hardening, in that the amount of age hardening clearly increased with increasing air voids. However, equally clear was that the extent of age hardening also depended strongly on the specific aggregate and binder used in a mixture. The age-hardening data was analyzed using a multiple regression model with indicator variables to account for the effects of aggregate/binder combinations and using air void content as a covariate:

$$AHR_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \beta_4 X_{i4} + \beta_5 X_{i5} + \beta_6 X_{i6} + \beta_7 VTM_i + \epsilon_i \quad (13)$$

where

AHR_i = age-hardening ratio for i^{th} observation;
β_0 = intercept (average response for aggregate/binder "0" [Virginia limestone and PG 64-22 binder]);
β_1 = average effect for aggregate/binder "1" (Virginia limestone and PG 58-28);
X_{i1} = indicator variable for aggregate/binder "1" and = 1 for aggregate/binder "1" and 0 otherwise;
β_2 = average effect for aggregate/binder "2" (Virginia limestone and PG 76-16);
X_{i2} = indicator variable for aggregate/binder "2" and = 1 for aggregate/binder "2" and 0 otherwise;
β_3 = average effect for aggregate/binder "3" (Pennsylvania gravel and PG 64-22);
X_{i3} = indicator variable for aggregate/binder "3" and = 1 for aggregate/binder "3" and 0 otherwise;
β_4 = average effect for aggregate binder "2" (Kentucky limestone and PG 64-22);
X_{i4} = indicator variable for aggregate/binder "4" and = 1 for aggregate/binder "4" and 0 otherwise;
β_5 = average effect for aggregate binder "5" (California granite and PG 64-22);
X_{i5} = indicator variable for aggregate/binder "5" and = 1 for aggregate/binder "5" and 0 otherwise;
β_6 = average effect for aggregate binder "6" (California granite and PG 58-28);
X_{i6} = indicator variable for aggregate/binder "6" and = 1 for aggregate/binder "6" and 0 otherwise;
β_7 = coefficient for effect of air void content (VTM_i) on age-hardening ratio; and
ϵ_i = error term for i^{th} observation.

The r^2 value for this model was 90.5%. All coefficients were highly significant, with the exception of the coefficient for the indicator variable for the Virginia limestone/PG 76-16 binder combination. Figure 17 shows the average effect of different aggregate/binder combinations on age hardening—that is, on the vertical axis are the values of the constant β_0 and the coefficients β_{i1} through β_{i5}. The differences are significant and cannot be easily interpreted in terms of mineralogy or binder grade. Figure 18 shows the effect of air void content on age hardening, after removing the effect of different aggregate/binder combinations. As an example of this adjustment, consider mixtures

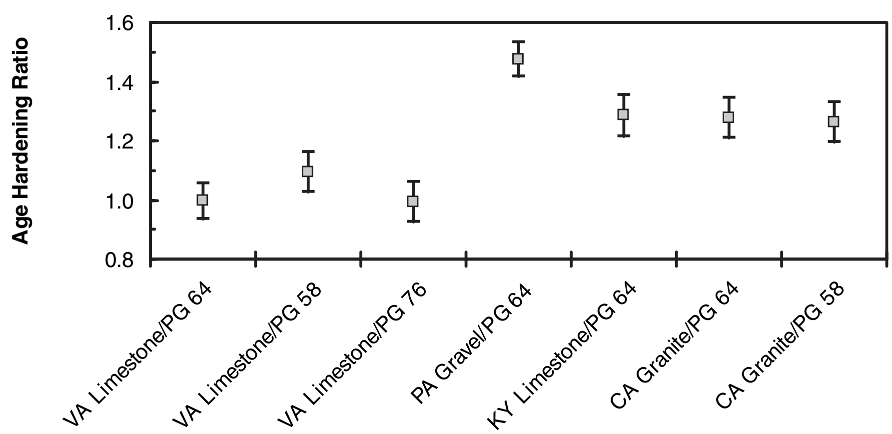

Figure 17. Average Age Hardening for Various Mixtures Subjected to Long-Term Oven Conditioning, as Calculated from Dynamic Modulus at 25 °C and 5 Hz Using the Field Shear Test (Error Bars are for Bonferroni Joint 95% Confidence Intervals).

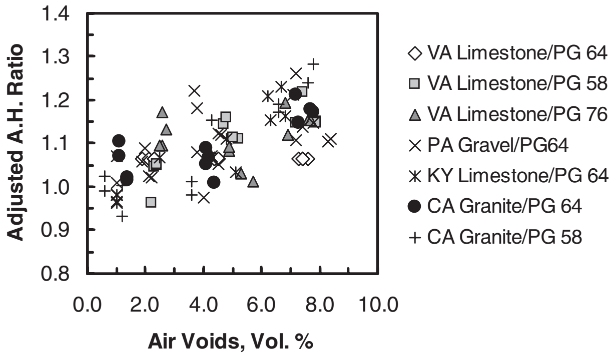

Figure 18. Age-Hardening Ratio after Removing Aggregate/Binder Effect as a Function of Air Void Content.

made using the California granite and the PG 64-22 binder. The average age-hardening ratio for all such mixtures was 1.28, while the average age-hardening ratio for the Virginia limestone/PG 64-22 binder (the "0" aggregate) was 1.00 (see Figure 17). Therefore, the California granite/PG 64-22 mixtures had an average effect on age-hardening ratio of +0.28. To remove this effect from the data plotted in Figure 18, 0.28 was subtracted from the observed age-hardening ratios for all California granite/PG 64-22 mixtures. Figure 18 then shows the effect of air voids along with all errors. The effect of increased air void content on age hardening is significant ($p<0.001$), but the effect of different aggregate/binder combinations appears to be stronger than the effect of air void content. It can be concluded that control of air voids in HMA can only partially control the extent of age hardening in flexible pavements. This might mean, for example, that surface cracking in some mixtures might be the result of a particular combination of aggregate and asphalt binder being especially susceptible to age hardening and not necessarily the result of an inappropriate mix design or poor construction. Additional research is needed to better understand the relationship between aggregate mineralogy, asphalt-binder chemistry, and age hardening of HMA. In study of mixtures prone to surface cracking, evaluation of the age-hardening resistance of specific aggregate/binder combinations should be considered along with other tests.

Some additional comments on Figures 17 and 18 are warranted. It appears from examining this plot that the amount of age hardening increases more rapidly at higher air void contents than at lower. However, the amount of variability makes such a hypothesis difficult to evaluate with certainty. Increased age hardening at air void contents above 4% is consistent with the concept of effective air voids—that is, that permeability of HMA is effectively zero below a certain air void content, which varies from mixture to mixture. An attempt was made to relate the age hardening of the different mixtures to the estimated zero permeability air voids content (related to aggregate fineness), but no such relationship was apparent. This should not be taken as definitive proof that such a relationship does not exist, only that it could not be statistically detected in this particular experiment.

Effect of Mixture Composition on Age Hardening

The only model identified in the literature review for estimating the effect of mixture volumetrics on age hardening is the global aging system developed by Mirza and Witczak (*22*). Unfortunately, this model makes use of traditional measurements such as penetration, softening-point temperature, and capillary viscosity, which are then converted to apparent viscosity values. This makes the model difficult to apply in a meaningful way to the Superpave system. Furthermore, the age hardening is predicted only in terms of age-hardening ratios and not in terms of binder master curve parameters, which means that the global aging system is also difficult to apply in developing models and plots to illustrate the effect of changes in mixture composition on age hardening. For these reasons, a modification of Mirza and Witczak's global aging system was developed, which provides results very similar with the original system but makes use of rational rheological measurements and binder master curve parameters.

The modified global aging system was used to analyze several hypothetical situations to evaluate the effect of air voids and aggregate specific surface on age hardening. Age-hardening ratios were predicted at an age of 60 months for MAAT values of 7.2 °C, 15.6 °C, and 23.9 °C. In-place air void contents were assumed to be 5%, 7%, and 9%, while assumed values for FM_{300} were 20, 30, and 40. Age-hardening ratios were calculated for both mixture complex modulus ($|E^*|$) at 10 Hz and binder steady-state viscosity at temperatures of 0, 25, 40 and 60 °C. The analysis was performed for the PG 58-28 and PG 76-16 binders used in various other parts of NCHRP Projects 9-25 and 9-31. The age hardening for binder viscosity was estimated because high binder viscosities could contribute significantly to pavement distress by preventing healing of surface cracks during hot weather. Two examples of this analysis are shown in Figures 19 and 20. Figure 19 shows mixture age hardening at 25 °C and 10 Hz for the PG 58-28 binder for a MAAT of 15.6 °C. Figure 20 shows binder age hardening at 40 °C, also for a MAAT of 15.6 °C. Estimated age-hardening ratios, as should be expected, increase dramatically with increasing MAAT. The mixture age-hardening ratios were generally highest for the PG 58-28 binder at "test" temperatures of 25 °C and/or 40 °C; age-hardening ratios for binder viscosity decrease with increasing "test" temperature. Also, the age-hardening ratios for the PG 58-28 binder were always higher than for the PG 76-16 binder. Several important,

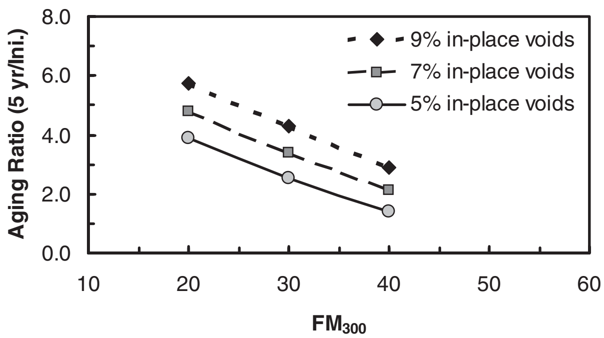

Figure 19. Predicted Mixture Age-Hardening Ratio at 25 °C and 10 Hz as a Function of In-Place Air Void Content and FM_{300} for a MAAT of 15.6 °C.

practical findings can be made based upon the results of this analysis:

- Mixture age hardening as indicated by complex modulus increases with increasing air voids and decreasing aggregate specific surface. This effect is not extremely large—typically, age-hardening ratios decrease 2% to 7% for each 1% increase in FM_{300} and increase 5% to 14% for each 1% increase in field air voids at a MAAT of 15.6 °C. However, the combined effect of high air voids and low aggregate specific surface can increase age hardening by 50% or more. The amount of age hardening that occurs in a mixture not only is dependent upon the air voids and aggregate fineness, but also is strongly dependent upon the specific binder used and the MAAT.
- Age hardening as indicated by binder viscosity values can be extremely high—often greater than 100. The effect of increasing air voids by 2% is to increase age hardening by about a factor of 2 at a MAAT of 15.6 °C and by a factor of about 3 at a MAAT of 23.9 °C. The very high binder viscosities that can potentially exist in aged pavements could contribute significantly to surface cracking by preventing any healing from occurring at the pavement surface during hot summer weather.
- In general, the effect of increasing air voids by 2% on age hardening is comparable with the effect of decreasing FM_{300} by 5%. More careful control of aggregate specific surface should help maintain good resistance to age hardening in HMA.

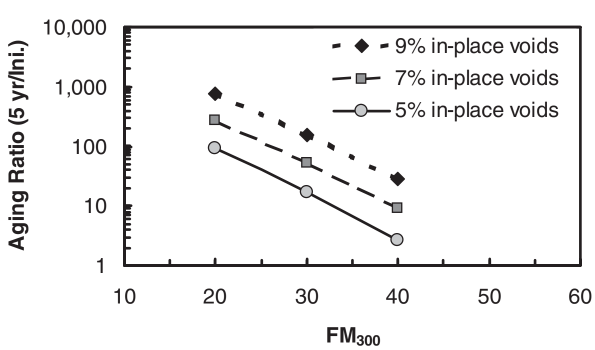

Figure 20. Predicted Binder Age-Hardening Ratio at 40 °C as a Function of In-Place Air Void Content and FM_{300} for a MAAT of 15.6 °C.

Apparent Film Thickness and HMA Performance

One of the objectives of this project was to evaluate the relationship between film thickness and HMA performance. Since the 1950s, some pavement engineers have proposed that film thickness is an important characteristic in determining the durability and fatigue resistance (*44–48*). Film thickness is generally estimated by dividing the effective volume of binder in a mix (in units of m^3/kg aggregate) by the specific surface of the aggregate (m^2/kg). In the late 1950s Campen and his associates proposed that HMA mixes should be designed with film thickness values between 6 and 8 µm (*44, 45*). Much later, Kandhal and Chakraborty suggested that film thickness values between 9 and 10 µm should be used with mixes designed according to the Superpave system in order to prevent premature aging (*48*).

Despite the many proponents of film thickness, its use to design or specify HMA mixes remains controversial. The Superpave system does not include any requirements or guidelines for film thickness. Many pavement engineers object to the term "film thickness" on the grounds that individual asphalt films do not exist in an HMA mix and that instead asphalt is a continuous phase in what is in reality a particulate composite. Although this latter view is technically correct, the fact remains that film thickness values can be calculated for HMA mixes and these values relate two important characteristics of HMA mixes—asphalt binder content and aggregate specific surface. To address the objection that asphalt films do not really exist in asphalt mixes, the term "apparent film thickness" (AFT) is in general used throughout this report.

In general, the research performed during this project does not support the direct use of AFT values in the design and specification of HMA mixes. At the same time, it should be pointed out that this research has demonstrated that AFT in many cases will indirectly relate to HMA performance. The strongest of such relationships is that between rut resistance and AFT. Resistivity is proportional to the square of aggregate specific surface and is inversely proportional to the cube of VMA, and because most Superpave mixes are designed at or very close to 4.0% air voids, there is a direct relationship between VMA and effective binder content. Therefore, there should be a very good relationship between AFT and resistivity and between AFT and rut resistance. To evaluate this rela-

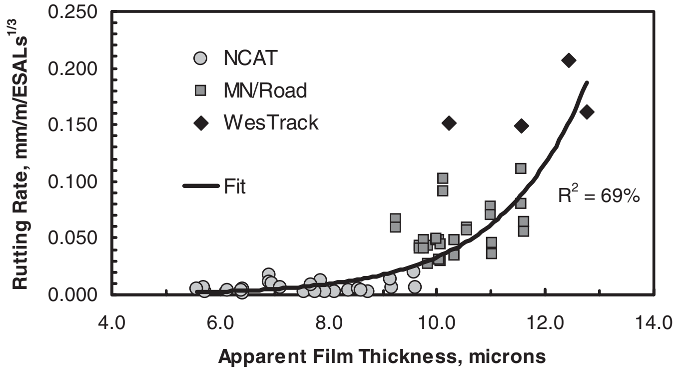

Figure 21. Relationship Between Rutting Rate and Apparent Film Thickness.

tionship, Figure 21 shows rutting rate as a function of AFT for data from the NCAT test track, MnRoad, and WesTrack (this plot can be compared with Figure 3). The relationship is only moderately strong, but rutting rate clearly increases with increasing AFT film thickness. This plot would suggest that HMA mixes with AFT values greater than 9 μm may be prone to excessive rutting.

The relationships between AFT and other aspects of HMA performance are not as straightforward. Fatigue resistance increases with increasing effective binder content; therefore, if aggregate specific surface is kept constant, fatigue resistance will increase with increasing AFT. Permeability decreases with increasing specific surface and decreasing in-place voids. Therefore, at a constant value of in-place air voids, permeability will decrease with decreasing AFT. However, as asphalt binder content is reduced for a given HMA mix, AFT will decrease and the mix will become more difficult to compact, potentially leading to higher in-place voids and greater permeability. Mixes with higher binder contents will be easier to compact and so may often exhibit lower in-place air voids and lower permeability. This phenomenon is possibly the source of the proposed relationship between AFT and durability.

In summary, the results of this study suggest that AFT should relate to most aspects of HMA performance. All else being equal, rut resistance will in general increase with decreasing AFT. Other relationships between AFT and performance are indirect; therefore, the use of AFT for specifying and/or controlling HMA mixes is not recommended. Instead, such control should be exerted through the relationships presented previously, linking various aspects of HMA composition to rut resistance, fatigue resistance, and permeability.

Summary

During NCHRP Projects 9-25 and 9-31, laboratory tests were conducted to evaluate the effect of changes in VMA, air void content, VFA, aggregate specific surface, and related factors on various performance-related properties of HMA. These data, along with several data sets in the literature, were used to develop semi-empirical models for estimating rut resistance, fatigue resistance, and mixture permeability. Mirza and Witczak's global aging system was modified to provide a more rational model for predicting age hardening, consistent with both the Christensen–Anderson model for binder modulus and the newly developed Hirsch model for estimating the modulus of HMA. The following important findings were made based upon these tests and analyses:

- **It appears reasonable to allow design air voids for Superpave mixtures to vary within the range from about 3% to 5%.** However, engineers and technicians that wish to deviate from the current design air void level of 4.0% should understand how such changes can affect HMA performance.
- **A variety of models for relating mixture volumetric composition to performance were identified in the literature; however, these models are not well suited for evaluating the effect of mixture composition on performance for the Superpave system of mixture design and analysis.** Therefore, models have been developed (or existing models refined) during NCHRP Projects 9-25 and 9-31 for estimating mixture performance on the basis of volumetric composition.
- **Many state highway agencies have modified the requirements for VMA, air voids, and related factors for Superpave mixtures.** Three modifications are most common: (1) an expansion of the design air void content from 4% to a range of 3% to 5%; (2) establishing a maximum VMA value at 1.5% to 2.0% above the minimum value; and (3) a slight increase in the minimum VMA values, typically by about 0.5%.
- **Aggregate specific surface is very nearly proportional to the sum of the weight percent material passing the 75, 150, and 300 μm sieves.** This factor, called the fineness modulus, 300 μm basis (FM_{300}), can be used to control aggregate specific surface in mixtures made using the Superpave system to ensure adequate mixture performance and good workability.
- **Rut resistance as indicated by laboratory tests and as measured in a wide range of field test tracks/test roads was predicted to within about a factor of 2 using a model incorporating mixture resistivity, design compaction, and relative field compaction.**
- **The rutting/resistivity model suggests that each 1% decrease in VMA, 1% increase in design air voids, and/or 1% decrease in field air voids increases rut resistance by about 20%, as indicated by rutting rate in mm/m/ESALs$^{1/3}$.**
- **Increasing FM_{300} by 6% (at constant VMA) typically increases rut resistance by about a factor of 2.0 to 2.5.**

- **For the types of HMA used in NCHRP Projects 9-25 and 9-31—that is, mixtures made using good-quality, highly angular aggregates with little or no natural sand—increasing the high temperature binder grade one level will increase rut resistance by about a factor of 2.5, as indicated by rutting rate in mm/m/ESALs$^{1/3}$.** For HMA designed according to current Superpave requirements, binder grade appears to be the most important consideration in determining rut resistance of HMA; volumetrics are an important but secondary factor. It must be emphasized that replacing the good-quality aggregates normally used in Superpave mixes with poorly crushed gravel and/or large amounts of natural sand would almost certainly cause a substantial decrease in rut resistance and might also result in mixtures much more sensitive to changes in volumetric composition.
- **Increase in N_{design} by one level decreased rut resistance by about 15% to 25%.**
- **A practical approach to fatigue analysis of HMA based on continuum damage theory was developed during NCHRP Projects 9-25 and 9-31.** This technique was initially developed through analysis of laboratory test data collected during NCHRP Projects 9-25 and 9-31 and then verified and refined through successful application to flexural fatigue data gathered during SHRP at the University of California at Berkeley.
- **Fatigue resistance is affected by VBE, design compaction (N_{design}), and field compaction, expressed in terms of field density relative to laboratory/design density.** Every 1% increase in VBE increases fatigue life by about 13% to 15%. Every 1% increase in field air void content (at a constant design air void content) decreases fatigue resistance by about 20%.
- **Permeability of HMA increases with increasing air voids and decreasing aggregate specific surface.** Permeability can be effectively modeled using the concept of effective air voids—the total air void content minus the air void content at zero permeability. Furthermore, the zero air voids content increases with increasing aggregate fineness.
- **A simple, reasonably accurate equation has been developed based upon permeability data gathered by Choubane et al. in a study on the permeability of Superpave mixtures in Florida (*3*).** According to this model, permeability increases by about 100×10^{-5} cm/s for every 1% increase in air voids or 3% decrease in FM_{300} for air void contents above the zero-permeability limit.
- **The permeability of HMA specimens prepared in the laboratory tends to be significantly lower than permeability values measured on field cores of comparable mixtures.** For this reason and because of the highly variable nature of permeability measurements, laboratory measurements of mixture permeability are not recommended for use in routine mixture design. However, the effect of air void content and aggregate fineness on permeability should be considered during the mix design process.
- **The age hardening of the HMA studied depended not only upon air void content, but also upon the specific combination of aggregate and asphalt binder.** Additional research is needed to better understand the effect of aggregate–asphalt binder combinations on mixture age hardening.
- **A modified version of the Mirza–Witczak global aging system was used to examine the effects of air voids, aggregate fineness, and other factors on mixture and binder age hardening.** For a MAAT of 15.6 °C, the mixture age-hardening ratio decreased about 2% to 7% for every 1% increase in FM_{300}. The age-hardening ratio increased about 5% to 14% for every 1% increase in in-place air voids. Although not extremely large effects, considered over the possible range for FM_{300} and field air voids, these factors can significantly affect mixture age hardening.
- **The modified global aging system predicted extreme amounts of age hardening as indicated by binder viscosity.** These extreme age-hardening ratios are the result of changes in binder rheology that occur during the aging process and could significantly affect mixture performance because of the severe reduction in healing rates that might occur with such large increases in binder viscosity. Additional research is needed to better understand the relationship among age hardening, binder viscosity, healing, and fatigue cracking in HMA pavements.
- **The various models developed during this study suggest that several indirect relationships exist between AFT and various aspects of HMA performance.** The most significant of these is between AFT and rut resistance—as AFT increases, rut resistance decreases. Mixtures with AFT values above 9 μm may be prone to excessive rutting. However, because the relationships between AFT and performance are indirect, it is not recommended that AFT be used in specifying or controlling HMA mixtures.

CHAPTER 3

Interpretation, Appraisal, and Applications

The purpose of this chapter is to discuss and interpret the findings presented in Chapter 2, with special emphasis on the practical application of these findings. This chapter is presented in four sections:

1. A summary of the relationships among HMA mixture characteristics and performance;
2. A discussion of how HMA mix design specifications have evolved over the past 30 years, and how the resulting changes have affected potential pavement performance;
3. A discussion of potential revisions in Superpave requirements for HMA composition and compaction, and how these revisions might affect various aspects of performance; and
4. A discussion of the implementation of the results of this research, which includes an Extended Work and Validation Plan.

Summary of Relationships Among HMA Mixture Characteristics and Performance

The findings presented in Chapter 2 dealt primarily with relationships among mixture characteristics and various aspects of performance. Before discussing the practical implications of these findings, a summary of these relationships is useful. The following factors tend to improve the rut resistance of Superpave and other HMA mix types:

- Increasing binder viscosity;
- Decreasing VMA;
- Increasing aggregate specific surface;
- Increasing design compaction (N_{design}); and
- Increasing field compaction (decreasing in-place air voids).

The relationship among these factors and observed rut resistance for a wide range of field data has been quantified in a rutting/resistivity model (Equations 1 and 2). This model allows some quantitative (but approximate) estimates to be made regarding how changes in the composition requirements of HMA might affect rut resistance.

The following factors tend to improve the fatigue resistance of Superpave and other HMA mix types:

- Increasing effective asphalt binder content, at given levels of N_{design}, design air voids, and in-place air voids;
- Increasing N_{design}, at given levels of VBE, design air voids, and in-place air voids; and
- Decreasing in-place air voids, at given levels of design voids, VBE, and N_{design}.

Asphalt binder rheologic type, as reflected in the rheological index *R*, also affects fatigue resistance; in the laboratory, increasing values for *R* tend to improve fatigue resistance. However, significant experience with actual pavements suggests that HMA made using binders with high *R* values often exhibit extensive premature surface cracking, contradicting the results of most laboratory fatigue tests. Therefore, it is not recommended that mix designers attempt to improve the fatigue resistance of HMA mixes by selecting binders with high *R* values. These findings on fatigue resistance are largely based on continuum damage theory, which was used to analyze a large amount of laboratory fatigue data, including data gathered during NCHRP Projects 9-25 and 9-31 and flexural fatigue data collected during SHRP. This analysis resulted in a fatigue model (Equation 9) for predicting the number of cycles required to reach a given damage level for an HMA with specified characteristics (VBE, N_{design}, etc.).

The relationships between mixture composition and age hardening are not as easily quantified as other aspects of performance. A large amount of the age hardening observed in a given HMA in laboratory tests appears to be a function of the specific asphalt-aggregate composition and cannot be predicted at this time on the basis of aggregate and/or binder type. Air void content also has a significant effect on age hardening—as air void content increases, the amount of age hardening increases. This is most likely because increasing air voids will cause an increase in permeability, in turn causing an increase in age hardening. Although not observed in the testing and analysis performed as part of NCHRP Projects 9-25 and 9-31, it is likely that increasing aggregate specific surface will also reduce age hardening because this would decrease mixture permeability. During this research, a model was developed for estimating mix permeability from air void content and aggregate specific surface (Equations 10–12). This model was combined with a modification of the Mirza–Witczak global aging system to provide a means for evaluating the relationships among mixture characteristics and age hardening. However, the results of this analysis should be considered approximate, since there are many questions concerning the accuracy of the global aging system.

Recent Evolution of HMA Composition and Effects on Performance

Some insight into the practical aspects of the relationships among HMA composition and performance can be gained by examining recent changes in typical mix designs. Table 5 is a summary of average characteristics for five different projects and/or mix types:

- A large number of Marshall mix designs as reported by Brown and Cross in their National Rutting Study (*8*);
- Ten Marshall mix designs placed on MnRoad in 1992 and 1993 (*5*);
- Several 12.5-mm Superpave mixtures placed in Florida in 1996, as reported by Choubane et al. in their permeability study (*3*);
- A large number of Superpave mixtures placed at the NCAT Test Track (*6*); and
- Typical SMA mixtures, according to information reported during NCHRP Project 9-8 (*49*).

Two different SMA mixtures are given—one compacted using 50-blow Marshall and one compacted using a gyratory compactor with $N_{design} = 100$. In order to compare compaction levels for Marshall compaction and gyratory compaction, the number of blows for Marshall compaction must be converted to equivalent gyrations. As discussed in Chapter 2, it appears that for modeling rutting, Marshall blows are roughly equivalent to number of gyrations. When modeling fatigue, it was found that 50 Marshall blows is approximately equivalent to 73 gyrations, while 75 Marshall blows is approximately equivalent to 92 gyrations. In calculating equivalent values of N_{design} in Table 5, these data were used to develop a power law relationship relating Marshall blows to design gyrations: N_{design}.

Examining Table 5, several observations can be made. Compaction levels are relatively high for the Superpave mixes although it should be noted that the most common compaction level for Superpave mix designs is probably 75 gyrations, which is close to the equivalent N_{design} value for the Marshal mixes. VBE is significantly lower for the Superpave mixes than for the other HMA types. The SMA mixes have the highest VBE values. The MnRoad Marshall mixes and the Superpave mixes included in the Florida permeability study have low values for aggregate specific surface; the Superpave mixes placed on the NCAT Test Track have much higher aggregate specific surface values than do the Superpave mixes placed on MnRoad.

Table 5. Typical composition of various HMA mixtures.

Compositional Characteristic	Marshall/ c. 1970/80	Marshall/ c. 1992/93	Superpave c. 1996	Superpave c. 2000	SMA/ 50-blow Marshall	SMA/ $N_{design} = 100$
Project (reference)	National Rutting Study (*8*)	MnRoad (*5*)	Florida Perm. Study (*3*)	NCAT Test Track (*6*)	NCHRP Project 9-8 (*49*)	NCHRP Project 9-8 (*49*)
Comp. Method	Marshall	Marshall	Gyratory	Gyratory	Marshall	Gyratory
Blows/Gyrations	52	56	109	100	50	100
N_{design} /equivalent						
Rutting	52	56	109	100	50	100
Fatigue	75	78	109	100	73	100
VBE (Vol. %)	12.4	11.6	9.8	10.7	13.5	13.5
Specific Surface (m^2/kg)	6.42	4.83	4.20	6.46	7.90	7.90
VTM, as designed (Vol. %)	4.1	3.7	4.3	4.0	4.0	4.0
VTM, in-place (Vol. %)	5.1	6.4	8.1	6.2	6.0	6.0
Relative Density	0.994	0.971	0.960	0.977	0.979	0.979

The effect of these trends on performance—rut resistance, fatigue resistance, and permeability—can be calculated using the models presented in Chapter 2. Figure 22 illustrates these estimated trends expressed as relative performance—higher values indicating better performance. Relative performance values for rut resistance were calculated as the average rutting rate for the six mixes divided by the rutting rate for the given mix, multiplied by 100. Thus a relative performance of 50 for rut resistance indicates a rutting rate twice the average value. Relative performance for fatigue resistance was calculated as the number of cycles to failure for the given mix divided by the average number of cycles to failure. Relative performance for permeability was determined as follows. For mixes with a permeability value near zero, performance was set at 100%. For mixes with non-zero permeability, relative performance was calculated by dividing the estimated permeability by 100 and multiplying by 75%. Thus, a mix meeting the minimum requirement suggested by Choubane et al. (a maximum permeability of 100 cm/s) would have a relative performance of 75%. Because materials specifications for Marshall mix designs in the 1970s and 1980s were so much different than those for Superpave mixes, it was felt that the rutting/resistivity model could not be accurately applied to the National Rutting Study data; therefore, no relative performance data for rutting is given for this case.

In interpreting Figure 22, it must be remembered that differences in binder properties were not considered in constructing this plot—the relative performance values reflect only differences in composition and compaction level. It is surprising that over all, the worst mixes appear to be the Superpave mixes included in the Florida permeability study. The poor relative performance of these mixes is primarily due to (1) poor compaction, (2) low aggregate specific surface values, and (3) low VBE. As noted previously, these represent early Superpave mix designs and specifications and construction practice in Florida have evolved since these mixes were placed and Superpave mixtures currently placed in Florida would no doubt exhibit substantially improved performance. It should also be noted that many other state highway agencies probably placed similar mixes in the mid-1990s. Another surprising observation is that the Superpave mixes placed at the NCAT Test Track exhibit excellent values for estimated relative performance. The significant difference in the relative performance of the two sets of Superpave mixes is due to three factors—the NCAT mixes had substantially higher values for aggregate specific surface, were compacted much better during construction, and had higher effective binder contents. As should be expected, the relative performance of the SMA mixes is very good to excellent. The high performance of the SMA mixes is attributable to (1) high VBE values, (2) high aggregate specific surface, and (3) good field compaction (if constructed as specified).

This analysis suggests that under the current Superpave system, requirements for volumetric composition could potentially be improved. The wide difference in potential performance between the Superpave mixes included in the Florida permeability study and those placed at the NCAT Test Track are of particular concern and suggest that research is needed to address the workability and ease of compaction of HMA. There may also be a need to refine requirements for aggregate fineness in order to avoid mixes deficient in fines, leading to poor rut resistance and high permeability. Agencies concerned with the fatigue resistance of their HMA mixes should consider modest increases in minimum VBE. The excellent performance predicted for SMA mixes is consistent with experience and lends credence to the findings of this analysis. It also suggests that optimal performance for Superpave mixes and other HMA mix types can be ensured through three steps:

1. Including enough asphalt binder to ensure good fatigue resistance,
2. Including adequate mineral filler and fine aggregate to keep permeability low and rut resistance high, and
3. Obtaining proper compaction in the field.

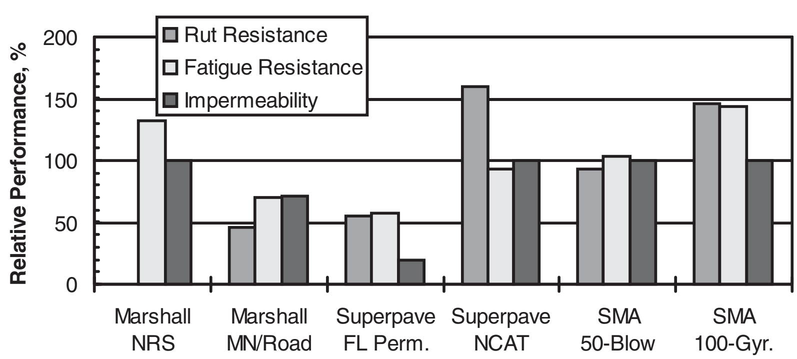

Figure 22. Relative Performance of Various HMA Mixes Based on Volumetric Composition and Compaction; Differences in Binder Properties Ignored.

Further insight into potential improvements in the volumetric requirements for Superpave can be gained by examining the performance history of Superpave mixes. In general, the rut resistance of Superpave mixes has been very good to excellent. The notable exception was the extreme rutting observed in most of the mixes placed at WesTrack. The resistivity/rutting model accurately predicts that these mixes should be prone to rutting because of high VMA, low specific surface, marginal compaction, and a binder that would perhaps be adequate in a normal pavement but was marginal in an accelerated loading environment because there was little opportunity for long-term age hardening to occur within the pavement surface. The most important lesson of WesTrack is that the various factors that affect pavement performance are additive; individual factors that may not result in serious degradation of performance can cause premature failure if a number of them acts simultaneously. This should be kept in mind in any attempts to modify current requirements for volumetric composition.

Many state highway agencies have become concerned over the durability of Superpave mixes because of high levels of permeability and an apparent increase in the incidence of top-down cracking; this is evidenced by the recent large number of research projects dealing with these topics (*3*, *50–54*). The analysis above offers a clear explanation for the recent increase in HMA permeability—the decreased aggregate specific surface and the increased difficulty of field compaction can both act together to substantially increase the permeability of mixes designed using the Superpave system. Explaining the increase in top-down cracking is not as easy. Certainly significant increases in the permeability of surface-course mixtures would contribute to top-down cracking by increasing age hardening and by decreasing resistance to moisture damage at the pavement surface. Poor compaction would also tend to produce a relatively weak pavement surface, prone to cracking under repeated loading. The lower asphalt binder contents that have been used under the Superpave system would also contribute to top-down cracking by reducing the fatigue resistance of the HMA. However, it is not clear if these are the primary factors that are increasing the extent of surface cracking in HMA pavements. Other factors that could contribute to top-down cracking include increased tire-pavement stresses, changes in asphalt binder chemistry and flow properties, and a general increase in pavement modulus brought about by the use of stiffer asphalt binders (*50*).

Possible Revisions in Volumetric Requirements for Superpave Mixtures and Their Effect on Performance

In the Survey of State Practice, it was found that a number of highway agencies have modified volumetric requirements for Superpave mixes. The most common such modifications are allowing a design air voids range of from 3.0% to 5.0%, rather than using a single target value of 4.0%, and establishing a maximum VMA 1.5% or 2.0% above minimum requirements. A number of states have increased minimum VMA requirements by 0.5% to 1.0%. An optional modification to original Superpave requirements that already is included in AASHTO specifications is an increase in the dust-to-binder ratio from 0.6–1.2 to 0.8–1.6. The methods used above can be applied to analyze the potential effects on HMA performance of these modifications to Superpave requirements.

Changing Design Air Voids

There are two different ways in which design air void content can be changed: (1) at constant VMA and (2) at constant VBE. If design air void content is changed at constant VMA, then VBE must change an amount equal in magnitude but opposite in sense from the change in design air voids. For example, if the design air void content for a 9.5-mm NMAS mixture is changed to 3% from 4% and no changes are made in VMA, then the minimum VBE content will be increased from 11% to 12%. If design air void content is changed at constant VBE, then VMA will change along with changes in air void content—if design air voids are decreased 1%, then VMA will decrease 1%, and vice versa

Changing design air voids can affect HMA performance through two mechanisms: (1) the change in design air voids relative to in-place air voids will effect relative compaction; and (2) changes in design air voids will change either VBE or VMA, depending on the manner in which the change is accomplished. Reducing design air voids will decrease as constructed relative density if in-place air voids are assumed constant—this will tend to reduce both rut resistance and fatigue resistance. Similarly, increasing design air voids will increase as constructed relative density, improving rut resistance and fatigue resistance. However, if design air voids are reduced at constant VMA, VBE will increase, which will tend to improve fatigue resistance, somewhat offsetting the effect of the reduced relative density. Increasing design air voids at constant VMA will decrease VBE, decreasing fatigue resistance and, again, somewhat offsetting the effect of increased as-constructed relative density. The net effects on performance for changes in design air voids are summarized in Table 6. These estimates are based on an HMA mix with a design air void content of 4%, a VMA of 14%, a VBE of 10%, and an N_{design} of 75 gyrations. The in-place air void content is assumed to be 7%. At constant VMA, reducing design air voids from 4% to 3% decreases rut resistance about 18% and fatigue resistance about 9%. Increasing design air voids from 4% to 5% improves rut resistance about 22% and fatigue resistance about 8%.

When air voids are changed at constant VBE, a reduction in design air void content from 4% to 3% increase rut resistance

Table 6. Effect of change in design air void content on HMA performance.

Approach	Design Air Void Content	Change in Rut Resistance	Change in Fatigue Resistance
Constant VMA	3%	–18%	–9%
	4%	—	—
	5%	+22%	+8%
Constant VBE	3%	+5%	–22%
	4%	—	—
	5%	–3%	+29%

Table 7. Minimum and maximum VMA values for mixes designed using the Superpave system at 4% design air voids and for traffic levels of 3 million ESALs and higher (AASHTO M323-04).

Aggregate NMAS *Mm*	Minimum VMA *%*	Maximum VMA *%*	VMA Range *%*
19.0	13.0	16.0	3.0
12.5	14.0	16.0	2.0
9.5	15.0	16.7	1.7
4.75	16.0	18.2	2.2

a small amount (5%) while fatigue resistance is decreased by about 22%. An increase in design air void content from 4% to 5% has almost no effect on rut resistance, but increases fatigue resistance by about 29%.

When contemplating increases in design air void content, engineers should consider that this will increase the difficulty of field compaction, which in some cases might increase in-place air voids. This would reduce or eliminate all of the potential benefits of a higher design air void level and would also increase the permeability of the pavement surface, rendering it more susceptible to age hardening and moisture damage. On the other hand, even though decreasing design air void content to 3% reduces performance when in-place air void contents are held constant as discussed in Chapter 2, the effect on performance would be negligible if the reduction in design air voids were to be accompanied with a similar decrease in allowable in-place air void contents. This might be an effective approach to reducing permeability of surface-course mixtures for some agencies.

Establishing Maximum Limits for VMA

A number of state highway agencies have established maximum limits for VMA, generally either 1.5% or 2.0% above the minimum VMA for a given aggregate size. AASHTO M323-04 includes a note warning that mixtures made with VMA values more than 2.0% above the specified minimums might be prone to rutting and flushing. For surface-course mixtures designed for higher traffic levels (3 million ESALs and above), capping VMA at 2.0% above current minimum values is largely a matter of practicality and does not have a significant effect on performance. The reason for this is that current Superpave requirements include indirect limits on VMA that result from the interaction of design air void requirements and maximum values for VFA. Table 7 lists the current, indirect limits on VMA as given in AASHTO M323-04. The maximum VMA values range from 1.7% to 3.0% above the minimum values. For mixtures made using 12.5-mm NMAS and smaller, the maximum values are 1.7% to 2.2% above the minimum. For most surface-course mixtures designed at high traffic levels, establishing explicit maximum VMA values has little effect on allowable ranges for VMA and HMA performance. However, it is extremely important to realize that if design air void levels are allowed to change, and no other changes are made in volumetric requirements, the indirectly specified VMA values inherent in the Superpave system can change dramatically. For example, for a 12.5-mm mixture for heavy traffic, the maximum allowable VFA is currently 75%. At 4% design air voids, this translates to $4/[1-(75/100)] = 16\%$ maximum VMA. *However, if design air voids are increased to 5%, the maximum allowable VMA becomes 20%; if design air voids decrease to 3%, the maximum VMA becomes 12%—lower than the minimum VMA of 14% for this aggregate size.* Agencies that alter design air void levels in the Superpave system must either adjust VFA requirements to establish reasonable VMA limits, or they should eliminate VFA requirements and rely on explicit maximum VMA limits.

Indirect maximum VMA values are higher at design traffic levels below 3 million ESALs because maximum VFA limits increase to 78% and 80%, depending on the traffic level. At design traffic levels below 0.3 million ESALs, the maximum VFA of 80% results in a maximum allowable VMA of 20% for all aggregate sizes. At design traffic levels of from 0.3 million ESALs, the maximum VFA is 78%, resulting in maximum VMA of 18.2%. Some of the complexity and confusion inherent in this system could be avoided by eliminating VFA requirements and relying solely on VMA and air voids to control this aspect of mixture composition. As discussed previously, this has an advantage in that it is effective even when design air void levels vary. A reasonable scheme would be to allow maximum VMA to vary according to design traffic level:

- $<$ 0.3 million ESALs: maximum VMA of 4.0% above minimum value;
- $\geq$ 0.3 to $<$ 3 million ESALs: maximum VMA of 3.0% above minimum value; and
- $\geq$ 3 million ESALs: maximum VMA of 2.0% above minimum value.

Other similar schemes are possible. Establishing explicit limits on VMA is simpler than the current system and involves less possibility of misinterpretation. It is also more flexible, but maintains a similar degree of control over VMA, VFA, and related factors.

Increasing Minimum VMA Limits

A number of agencies have increased minimum VMA limits by 0.5% to 1.0%. Given the recent concern over top-down cracking and high permeability in mixtures designed using the Superpave system, this modification would appear to be an attempt to improve durability of HMA pavements. Increasing VMA will improve fatigue resistance, but applying the models developed during NCHRP Projects 9-25 and 9-31, this improvement is probably not as large as what many engineers might suppose—only about 17% improvement for a 1% increase in VMA (assuming constant design air voids). Furthermore, unless aggregate specific surface is increased along with minimum VMA, there is a risk that rut resistance will be decreased. This decrease could be as much as 19% or roughly equal to the gain in fatigue resistance. To avoid a reduction in rut resistance, agencies should consider increasing the minimum dust-to-binder ratio when increasing minimum VMA requirements.

Although only a 17% improvement in fatigue resistance is predicted for an increase of 1% in VMA, other factors may be at work that will improve the durability of HMA made with higher VMA and binder contents. An important issue is the ease of compaction of the mixture. It is possible that higher VMA and binder contents might improve field compaction for HMA, which would substantially improve durability above and beyond the improvement resulting from increased binder content alone. It is also possible that alternate cycles of fatigue damage and healing could mean that relatively small improvements in fatigue resistance might significantly improve field performance. The fact that top-down cracking in HMA pavements has recently been observed to increase at the same time VMA requirements have been reduced supports the use of increased VMA to improve HMA durability. Further research is needed to better understand the relationship between HMA mixture characteristics, binder rheology, laboratory fatigue test data, and fatigue performance in situ.

Increasing Dust-to-Binder Ratio and Related Modifications

AASHTO M323-04 already includes an option for an increase in dust-to-binder ratio from 0.6–12 to 0.8–1.6 for mixtures made using coarse aggregate gradations. It is not clear why this requirement should only be applied to such mixtures although in most cases, fine and dense gradations would probably meet this stricter requirement anyway, so enforcing this increased dust-to-binder ratio for such mixtures might be redundant. In any case, the findings of NCHRP Projects 9-25 and 9-31 suggest that including an adequate amount of fines—mineral filler and material in the 75- to 300-μm-size range—is one of the most important factors affecting HMA performance. It should be emphasized that a general increase in the aggregate specific surface for all mixtures does not appear to be needed—what is needed is an increase in the minimum requirements for aggregate fineness in order to avoid designing and producing HMA mixtures deficient in fines. Such mixtures will potentially exhibit poor rut resistance and high permeability, which will in turn increase their susceptibility to age hardening and moisture damage.

There are three possible specification modifications related to this aspect of HMA composition. First, the dust-to-binder ratio could be increased either to the currently optional range of 0.8 to 1.6 or to some other value. Second, the requirements for dust-to-binder ratio could be replaced with requirements for minimum FM_{300} as a function of VMA or aggregate NMAS. Although this approach may at first seem somewhat more complicated than the current system, dust-to-binder ratios are generally calculated on the basis of effective asphalt content, the determination of which is not simple. Furthermore, controlling FM_{300} as a function of VMA or aggregate NMAS would be a somewhat more effective approach since FM_{300} is a better indicator of aggregate specific surface compared with the percent passing 75 μm alone. A third approach would be to eliminate the requirements for dust-to-binder ratio and increase the requirements for percent finer than 75 μm in the aggregate gradation specifications. This approach is the simplest of all and probably is just as effective as controlling dust-to-binder ratio.

Before these alternate approaches are evaluated, it is useful to try to determine some rational limits for aggregate specific surface. With the exception of the WesTrack mixtures, there is little evidence that mixtures designed according to the Superpave system are prone to rutting. On the other hand, recent research suggests that there is significant concern about the relatively high permeability of HMA mixtures being placed in North America. Furthermore, increasing minimum requirements for aggregate specific surface can only improve rut resistance because of its beneficial effect on resistivity. Therefore, permeability requirements will control any modification to the dust-to-binder ratio requirements. Control of in-place permeability is relatively straightforward since permeability is mostly a function of in-place air voids and aggregate specific surface (Equations 10–12). If in-place air voids are assumed constant, at an average value of 7.0%, permeability then becomes only a function of aggregate specific surface, which in turn can be estimated from either percent finer than 75 μm or FM_{300} (see Figures 1 and 2).

A complicating factor in this analysis is the variability in the relationships between the percent finer than 75 μm and

FM_{300} and specific surface (referring again to Figures 1 and 2). The relationship between FM_{300} and specific surface is significantly better than that between the percent finer than 75 μm and specific surface, and neither is close to perfect. To account for variability in these relationships, the following approach was used in analyzing the effectiveness of different means of controlling aggregate specific surface and permeability. The data set used was the same as that plotted in Figures 1 and 2 and included data from eight projects: NCHRP Project 9-9, the NCAT Test Track, Pooled Fund Study 176, the Florida permeability study, MN/Road, FHWA's ALF rutting study, WesTrack, and data from NCHRP Projects 9-25 and 9-31 (*2, 3, 5, 6, 29–31*). Four approaches to controlling specific surface were initially considered: (1) direct control of specific surface (minimum value for calculated S_a), (2) minimum value for percent finer than 75 μm, (3) minimum value for FM_{300}, and (4) minimum dust-to-binder ratio (by weight, calculated using effective binder content). It was decided (somewhat arbitrarily) that three levels of control would be examined, corresponding to rejection rates of about 30%, 20%, and 10%. "Rejection rate" in this case means the percentage of mixtures that fail to meet the given criteria. The minimum values for the various control parameters were varied until the rejection rate matched the target value as close as possible, then, the average permeability and maximum permeability for the mixes meeting this criteria were estimated using Equations 10–12. Because Choubane et al. recommended lowering target in-place air voids from 7.0% to 6.0%, both of these values were used in the analysis. Using this analysis, the more effective a given approach, the lower will be the average and maximum values for permeability. The results are summarized in Table 8. With no control, the average permeability for the data set is 100 cm/s and the maximum value is 510 cm/s. The high degree of control would most likely be considered too restrictive to be practical: the lowest level of control appears to yield only modest decreases in permeability at 7% in-place air voids, although the reduction at 6% in-place air voids is significant. It would appear that to gain significant reductions in in-place permeability, either the moderate level of control is needed while maintaining current levels of in-place air voids, or the low level of control can be applied along with a 1% reduction in target in-place air voids.

Rather than control permeability at a constant level, an alternative approach is to try to control permeability as a function of aggregate NMAS. For example, FM_{300} limits can be established as a function of aggregate NMAS; an example of this type of control is given in Table 9. In this case, maximum FM_{300} values range from 19 for 19.0-mm NMAS to 25 for 9.5-mm NMAS. The rejection rate for this scheme using the same data set used in the previous analysis was 15%. This approach allows for a very low permeability level for mixtures with small NMAS, with gradually increasing permeability

Table 8. Effectiveness of various approaches to controlling HMA permeability and aggregate specific surface, 7% in-place air voids.

Control Level	Average In-Place Air Voids *Vol. %*	Property	*Control Method* Minimum Aggregate Specific Surface *m²/kg*	Minimum Percent Passing 75 µm	Min. FM_{300}	Min. Dust/ Binder Ratio
None	7.0	Avg. k × 10^5, cm/s	100			
		Max. k × 10^5, cm/s	510			
	6.0	Avg. k × 10^5, cm/s	50			
		Max. k × 10^5, cm/s	400			
High	N/A	Min. Value	4.5	4.5	24	1.1
		% Failing Spec.	28	28	28	27
	7.0	Avg. k × 10^5, cm/s	30	40	30	50
		Max. k × 10^5, cm/s	170	250	230	320
	6.0	Avg. k × 10^5, cm/s	4	10	10	20
		Max. k × 10^5, cm/s	60	140	120	210
Moderate	N/A	Min. Value	4.4	4.3	22	1.0
		% Failing Spec.	19	21	20	17
	7.0	Avg. k × 10^5, cm/s	50	50	50	70
		Max. k × 10^5, cm/s	230	320	270	350
	6.0	Avg. k × 10^5, cm/s	20	20	20	30
		Max. k × 10^5, cm/s	120	210	160	240
Low	N/A	Min. Value	4.0	4.0	20	0.9
		% Failing Spec.	9	5	12	8
	7.0	Avg. k × 10^5, cm/s	70	80	60	80
		Max. k × 10^5, cm/s	290	370	280	370
	6.0	Avg. k × 10^5, cm/s	30	40	30	40
		Max. k × 10^5, cm/s	180	260	170	260

Table 9. Control of permeability by limiting FM_{300} as a function of NMAS.

NMAS	Min. *FM300*	Permeability×10^5 (cm/s) at Average In-Place Air Voids: 7.0 % Avg.	7.0 % Max.	6.0 % Avg.	6.0 % Max.
9.5 mm	25	3	20	0	0
12.5 mm	22	40	250	20	150
19.0 mm	19	110	290	50	180
Overall:		**60**	**290**	**20**	**180**

levels with increasing NMAS. This is consistent with the variation of VMA and VBE with NMAS—this approach is consistent with the general trend of increasing fatigue resistance and durability with decreasing NMAS. An advantage of this approach is that it provides for mixtures with very low permeability while maintaining an overall moderate level of control. Another advantage is that this method of controlling aggregate specific surface tends to provide similar levels of resistivity regardless of aggregate NMAS. Since specific surface increases with increasing NMAS, it will tend to increase with increasing VMA. A related approach would be to control FM_{300} directly as a function of VMA. An example of this type of control is given in Table 10. In this case, FM_{300} limits were calculated to give the same values for resistivity regardless of VMA; the FM_{300} values were calculated using the formula:

$$FM_{300} = \left(0.15 \times VMA^3\right)^{0.5} \quad (14)$$

The resulting limits are listed at the top of Table 10. This particular example is slightly more restrictive than that given in Table 9, with a rejection rate of 19%. It provides slightly less control over permeability compared with the previous example, but has the advantage of very good control over resistivity since specific surface is linked directly to VMA. This approach would however be slightly more difficult to implement.

Although controlling dust-to-binder ratio was listed in Table 8 with several other approaches that tend to provide similar levels of specific surface and permeability regardless of aggregate NMAS, this approach does in fact tend to result in some variation in aggregate specific surface and permeability with NMAS since as NMAS decreases, VMA and VBE will increase, increasing the amount of mineral filler that must be used to obtain the required minimum dust-to-binder ratio. Table 11 summarizes the control of permeability as a function of aggregate NMAS that results from setting a minimum dust-to-binder ratio of 1.0. This approach is moderately restrictive and is, in fact, identical to the dust/binder/moderate control level summarized in Table 8—the permeability values have now simply been broken down by aggregate NMAS. This approach appears to be similar to that given by linking FM_{300} to VMA. The main advantage of this approach is simplicity and that it is consistent with the current Superpave system. As with linking FM_{300} to aggregate NMAS, this method provides some control over resistivity, but not as good as does linking FM_{300} to VMA.

Table 10. Control of permeability as a function of NMAS by limiting FM_{300} as a function of VMA.

VMA, Vol. %	11	12	13	14	15	16	17
Min. *FM300*	14	16	18	20	23	25	27

NMAS	Permeability×10^5 (cm/s) at Average In-Place Air Voids: 7.0 % Avg.	7.0 % Max.	6.0 % Avg.	6.0 % Max.
9.5 mm	10	160	4	50
12.5 mm	50	320	20	210
19.0 mm	110	290	50	180
Overall:	**60**	**320**	**30**	**210**

Table 11. Control of permeability as a function of NMAS by limiting dust-to-binder ratio to 1.0.

NMAS	Permeability×10^5 (cm/s) at Average In-Place Air Voids: 7.0 % Avg.	7.0 % Max.	6.0 % Avg.	6.0 % Max.
9.5 mm	30	230	10	120
12.5 mm	40	320	20	210
19.0 mm	130	350	60	240
Overall:	**70**	**350**	**30**	**240**

A few comments are needed concerning the analysis presented above. Although the data set used is relatively large and robust, the results should be considered as only guidelines. Further analysis with additional data is needed to provide more confidence in the specific degree of control exerted by the various approaches. A large number of approaches were presented here because it is not clear at this time which approach will be most effective and efficient for the largest number of users over the widest range of situations—this is a decision that will be made during implementation. Furthermore, in some areas the aggregates locally available may be deficient in fines, and the cost of obtaining additional fines may be prohibitive. Such situations require flexibility and judgment when developing approaches for controlling aggregate specific surface and mixture permeability.

General Approaches to Improving the Durability of Mixtures Designed According to the Superpave System and Other HMA Mix Types

As discussed previously, there is substantial evidence that mixtures designed according to the Superpave system are more permeable and somewhat more prone to top-down cracking compared with HMA that is designed and placed using the Marshall system. There is therefore a desire within some highway agencies to improve the durability of HMA designed using Superpave methods, while still maintaining the excellent rut resistance that these materials have exhibited. Before discussing how this goal might be achieved, it must be noted that much evidence suggests it is not advisable to make large changes in the current requirements for HMA designed using the Superpave system—implementing drastic changes may have the effect of significantly decreasing rut resistance of HMA mixtures or causing other unforeseen problems. Furthermore, the differences in HMA composition between materials designed under the Superpave system and materials designed using the traditional Marshall system, although significant, are not so large to suggest that complete revision of the Superpave system is needed. Changes to the Superpave system implemented by various highway agencies support the advisability of measured changes in current specifications. Therefore, any modifications to current requirements in the Superpave system should be kept relatively minor.

Based upon the findings given in Chapter 2 and the discussion presented above, there are four critical aspects to improving HMA durability while maintaining good rut resistance:

1. Effective binder content should be increased to provide better fatigue resistance.
2. Aggregate fineness should be increased to decrease mixture permeability.
3. Design air voids can be decreased to improve compaction—lowering in-place air voids and decreasing permeability—but unless in-place air voids are in fact significantly decreased, both rut resistance and fatigue resistance will decrease if design air void content is reduced.
4. Requirements for in-place air voids can be decreased, improving both rut resistance and fatigue resistance.

These aspects to improving HMA durability can be combined in a number of reasonable ways. Listed below are two promising approaches, some aspects of which have already been implemented by highway agencies in attempts to improve the performance of HMA designed using the Superpave system:

- **Approach 1:**

1. Increase minimum VMA from 0.5% to 1.0% while maintaining design air voids at 4.0%; this produces an increase in minimum VBE of 0.5% to 1.0%.
2. Apply optional increased dust-to-binder ratio of 0.8 to 1.6 or even further to 1.0 to 2.0. Alternately, one of the other methods presented earlier for controlling aggregate specific surface can be used.
3. Review field compaction requirements to ensure that in-place air voids are sufficiently low to provide for low permeability and overall good performance.

- **Approach 2:**

1. Maintain current minimum VMA values while decreasing design air voids to 3.0% to 3.5%; this produces an increase in minimum VBE of 0.5% to 1.0%.
2. Reduce maximum allowable in-place air voids by an amount equal to the decrease in design air voids; also, review field compaction requirements to ensure that desired level of in-place air voids will in fact be achieved.
3. Consider applying optional increased dust-to-binder ratio of 0.8 to 1.6. Alternately, one of the other methods presented earlier for controlling aggregate specific surface can be used. However, reducing in-place air void requirements should reduce the need to increase minimum requirements for aggregate specific surface since mixture permeability will be significantly lower because of the improved field compaction.

The resulting improvements in performance for these two approaches, as estimated using the various models presented in this report, are summarized in Table 12. This example is for a 12.5-mm NMAS design, with N_{design} = 75. The "current HMA" design assumes a VMA of 14.0% and a design air void

Table 12. Relative performance of 12.5-mm NMAS mix designs modified using different approaches.

Characteristic	Current 12.5-mm HMA	Approach 1	Approach 2
Composition			
N_{design}	75	75	75
VMA, Vol. %	14.0	15.0	14.0
VTM_{design}, Vol. %	4.0	4.0	3.0
$VTM_{in\text{-}place}$, Vol. %	8.0	7.0	6.0
Dust/binder	0.6	0.8	0.6
S_a, m^2/kg	3.8	4.6	3.9
Estimated Performance			
Relative Rut Resistance, %	100	150	140
Relative Fatigue Resistance, %	100	150	150
Permeability × 10^5, cm/s	440	200	200

content of 4.0, resulting in a VBE of 10.0%. The dust-to-binder ratio is 0.6, corresponding to the current minimum value for the standard range for this characteristic in the Superpave system. Field air voids are assumed to be 8.0%, slightly above the standard assumed field air void content of 7.0%. The amount of aggregate finer than the 75-μm sieve was estimated from the mix composition and the dust-to-binder ratio and the aggregate specific surface then estimated using the relationship shown earlier in Figure 2. For Approach 1, the VMA was increased 1.0% to 15.0% while maintaining the design air voids at 4.0%, resulting in an increase in VBE to 11.0%. The dust-to-binder ratio was increased to 0.8, corresponding to the minimum value for the optional, higher range for this characteristic. It is assumed that a review of field compaction data has shown that field air voids are not as low as desired, and that modification in acceptance plans and enforcement result in achieving the desired level of 7.0% air voids in-place. Approach 2 keeps the VMA at 14.0% while decreasing design air voids to 3.0%, increasing VBE to 11.0%. The dust-to-binder ratio is kept at 0.6. It is assumed that field compaction is significantly improved by revising acceptance plans, resulting in an average in-place air void content of 6.0%. The resulting improvements in estimated performance are significant. Both rut resistance and fatigue resistance improve by 40% to 50% for both modifications, while permeability is roughly cut in half.

These approaches are only meant as general examples as to the type and magnitude of modifications that might prove successful in improving the durability of HMA designed according to the Superpave system while maintaining good rut resistance. Other approaches are possible and will be effective if proper consideration is given to how each specification change will affect various aspects of performance. Highway agencies must consider their local climate, traffic levels, and materials characteristics when attempting to modify requirements for HMA. Furthermore, although evaluating specification changes with performance models is a useful tool, engineers should note that existing performance models (including the ones developed as part of this research) provide only approximate results and should be used with discretion.

When making adjustments in the requirements for aggregate fineness—be it through dust-to-binder ratio, FM_{300}, percent finer than 75 μm, or some other means—it should be kept in mind that the analyses presented here were based on aggregate gradations from QC data—that is, these were aggregates that had gone through most or all of the batching, mixing, and transport processes. The amount of fine material, and the specific surface, and related parameters will therefore be somewhat higher than for aggregates taken from stockpiles without going through an HMA plant. This increase in fines during production compared with laboratory mix designs should be carefully considered when modifying requirements for aggregate fineness. For example, the data set used in the analyses of aggregate specific surface presented earlier in Chapter 3 included a total of 94 points. Of these, only 1 point had a dust-to-binder ratio below 1.60, and only 3 had a dust-to-binder ratio below 0.80. On the other hand, 42 mixtures had dust-to-binder ratios above 1.20, and 19 had values above 1.60. Although in some cases the mixes may have been purposely designed with gradations outside Superpave limits, much of this discrepancy between the observed dust-to-binder ratios and current specification limits is probably due to an increase in fines during batching, mixing, transport, and placement. The best approach to dealing with this problem would be to try to obtain information concerning the changes that occur in aggregate gradation within a specific plant during production and to adjust stockpile aggregates to try to mimic these changes in laboratory mix designs. Alternately, requirements for dust-to-binder ratio (or FM_{300} or percent finer than 75 μm) could be relaxed somewhat during the mix design process: dust-to-binder ratio could be set at 1.0 for production purposes, but allowed to go to 0.80 during the mix design process. It should however be understood that the increase in fine material that occurs in actual plant production will cause other changes in HMA characteristics—typically, air void content and VMA will decrease. This is why it is best to try to mimic aggregate gradations as they come out of the plant, rather than to make adjustments in going from a laboratory mix design to a production job mix formula.

Lowering N_{design} to Improve HMA Durability

Some engineers may suggest that simply lowering N_{design} will provide significant improvement in durability, believing that this will increase design binder content and improve field compaction, resulting in improved fatigue resistance and lowered permeability. However, lowering N_{design} will not necessarily increase design binder content—in this situation, many producers will adjust their aggregate gradation so that the design binder content remains as low as possible since this will minimize the cost of the HMA and maximize profits. Paying for asphalt binder as a separate item removes the incentive to minimize binder content, but in no way guarantees that binder contents will be sufficient for good fatigue resistance. If an agency believes that current minimum binder contents are too low for adequate fatigue resistance and/or durability, the most effective and efficient remedy is simply to increase these minimum values. A similar situation exists for field compaction. Lowering N_{design} values will tend to make HMA mixtures easier to compact, but will not guarantee that in-place air voids will decrease. Assuming most successful contractors are motivated not by maximizing losses but by maximizing profits (and therefore staying in business), the competitive marketplace demands that they adjust their compaction methods to optimize their profits, based on the cost of performing compaction and the penalties and/or bonuses that result from different levels of compaction. Lowering N_{design} will help improve field compaction, but unless this is combined with a payment schedule adjusted to provide additional incentive for thorough field compaction, in the long run it will not likely result in significant lowering of in-place air voids.

Linking Aggregate NMAS and Minimum VMA

Traditionally, HMA design has linked aggregate NMAS with requirements for minimum VMA—as NMAS decreases, minimum VMA increases. There are two reasons for this linkage: (1) smaller NMAS is usually associated with higher aggregate specific surface so that too maintain a more or less constant apparent film thickness, more binder is needed, and VMA should therefore increase; (2) smaller NMAS is in general associated with higher VMA—that is, all else being equal, aggregate gradations with smaller NMAS will tend to yield higher VMA. However, neither of these trends is extremely strong; aggregates with large NMAS may have a large amount of fines, leading to a high specific surface and requiring higher VMA to maintain a reasonable apparent film thickness. Similarly, aggregates with small NMAS may have inherently low VMA, making it difficult in the mix design process to achieve the higher VMA values required for aggregates with small NMAS. It can be questioned whether aggregate NMAS and minimum VMA should be linked. A theoretically more sound approach might be to establish aggregate NMAS on the basis of lift thickness and to set minimum VMA on the basis of desired fatigue resistance and durability. However, this would be a monumental change in the way people think about HMA and design mixes. It would be very difficult to implement and would probably lead to much confusion among engineers and technicians. Within the current approach, it is still possible to provide HMA mixtures with a reasonable range in fatigue resistance and durability. Maintaining the current system will help ease implementation of the more critical findings of this research, while still providing engineers with an adequate slate of mixtures to address most paving applications.

Effect of Multiple Changes in HMA Specifications

A number of the analyses presented previously involve multiple, simultaneous changes in specifications and illustrates how these changes work together to affect performance. Any engineer or agency contemplating changes in Superpave specifications, or in specifications for other HMA types, should consider in some way the way in which all changes in a specification act together to affect performance. This includes not only changes in volumetric composition and compaction, but also changes in materials specifications; especially important are how changes in aggregate specifications might affect performance. The models and analyses presented in this report were largely developed on HMA mixtures made with aggregates that either meet or come close to meeting current Superpave specifications. The models may or may not be accurate for aggregates that do not meet these requirements.

An example of how specification changes can negatively affect performance is useful to illustrate the importance of considering how these changes can work together. Consider again the mixtures listed in Table 12. Imagine a third alternative modification, Approach 3, in which design air voids are lowered to 3% to improve fatigue resistance. At the same time, N_{design} is reduced to 50 in order to try to improve compaction, but no effort is made to make specifications for field compaction more stringent so that in-place air voids remain at 8.0%. It might at first seem that these changes would be beneficial to fatigue resistance and durability, but the analysis suggests otherwise—rut resistance in this case is reduced by 30%, fatigue resistance is reduced by 40%, and permeability remains nearly constant at 440×10^{-5} cm/s. The proposed changes have significantly decreased fatigue resistance, done nothing beneficial for permeability, and decreased rut resistance. If these changes were to be simultaneously implemented with reduced standards for aggregate angularity, the results could go from simply being bad to being disastrous. It is suggested that agencies considering both changes in materials specification and changes in specifications for volumetric composition and compaction should implement and evaluate such changes separately, to avoid unanticipated negative impacts on pavement performance.

Implementation

Because of the execution of NCHRP Project 9-33, a complete and formal implementation of the results of NCHRP Projects 9-25 and 9-31 would be redundant. Most of the findings and recommendations of this research are being evaluated and refined as appropriate for possible incorporation into the Mix Design Manual being developed under NCHRP Project 9-33. It is therefore suggested that implementation of the results of this project be kept simple and informal. The initial phases of implementation have already taken place through publication of several papers dealing with the various models developed during this research. It is expected that one or two additional publications will be submitted summarizing the final results of NCHRP Projects 9-25 and 9-31.

Agencies that experience severe performance problems in a significant proportion of their HMA pavements may find it necessary to implement some of the recommendations of this research prior to development of the Mix Design Manual being developed as part of NCHRP Project 9-33—some agencies have already made significant modifications to the Superpave system. This report has intentionally been structured to provide flexibility in helping engineers to evaluate a wide range of possible changes in volumetric requirements for HMA mixtures designed using the Superpave system. Any such evaluation of the effects of changes in HMA specifications should be done not only using reasonably accurate performance models, but also using the experience of the engineer with local conditions and materials. Such changes should be done gradually and with caution. Demonstration projects using the proposed changes should be constructed and observed for several years prior to full-scale adoption of the proposed specification.

Extended Work and Validation Plan

The most significant general findings of NCHRP Projects 9-25 and 9-31 can be summarized as follows:

- **The impact on performance of various changes in HMA composition and compaction can be estimated using models.** Several such models were developed as part of NCHRP Projects 9-25 and 9-31 using a combination of laboratory data and a number of large data sets taken from the literature. These and other such models are useful tools for evaluating the effects of changes in HMA specifications for mixture composition and compaction.
- **Fatigue resistance of HMA tends to increase with increasing VBE and with increasing N_{design}.**
- **Rut resistance of HMA tends to increase with decreasing VMA, increasing aggregate specific surface, increasing binder stiffness at high temperature, and increasing N_{design}.**
- **HMA permeability decreases with decreasing in-place air voids and increasing aggregate specific surface.**
- **Fatigue resistance and rut resistance increase, and permeability decreases, with decreasing field air voids.** Of particular significance to fatigue and rut resistance is the in-place air void content relative to the design air void content: the lower in-place air voids relative to design air voids, the higher the fatigue and rut resistance of the pavement.
- **There is significant evidence that the implementation of the Superpave system has resulted in an increase in the permeability and a decrease in the fatigue resistance of HMA pavements.** A number of approaches to correcting these problems are possible, involving various combinations of increased VBE, increased aggregate specific surface, and/or improved field compaction.
- **The effect of changes in mixture composition are additive and must be considered together when evaluating potential changes in requirements for HMA designed using the Superpave system and other mix types.**

The research performed during NCHRP Projects 9-25 and 9-31 involved 9.5-, 12.5-, and 19-mm aggregate blends. The purpose of the Extended Work and Validation Plan is to extend the results of NCHRP Projects 9-25 and 9-31 to larger aggregate sizes and also to validate the findings of the research through accelerated pavement testing, evaluation in test roads, or full-scale field evaluation. Specifically, there is a need to extend the laboratory testing to 25- and 37.5-mm aggregate sizes. Because such mixtures should not be used for surface-course mixtures, there is no need for testing related to rut resistance or resistance to age hardening. However, there is a need to evaluate the permeability of such mixtures and their fatigue resistance. Because the permeability of most of the mixtures tested during NCHRP Projects 9-25 and 9-31 was very low, the permeability model developed during this research relied on permeability data gathered from other research projects—notably, research performed in Florida on the permeability of Superpave surface-course mixtures. In addition to evaluating the permeability of mixtures made using larger aggregate sizes, there is also a need to confirm the findings on permeability by testing Superpave surface-course mixtures prepared at air void contents of 6% to 10%.

Objective

The objective of this research is to extend the results of NCHRP Projects 9-25 and 9-31 to mixtures made using 25- and 37.5-mm NMAS aggregates and to validate the findings of these research projects through accelerated pavement testing, pavement test tracks, or evaluation of full-scale pavements.

Tasks

It is anticipated that the research will include the following nine tasks.

- *Phase I, Task 1—Review the findings of NCHRP Projects 9-25 and 9-31 and related research, including NCHRP Projects 9-19, 9-29, 9-33, and 1-37A.* Also, results of performance tests conducted using accelerated pavement testing facilities and test tracks or from monitoring of full-scale pavements should be identified and summarized. Performance data should include information on rutting, fatigue cracking, and age hardening. Some initial analyses of these data may be conducted, but the primary purpose of this effort is to identify data for analysis during Phase II. Special emphasis should be made in considering field data analyzed during Phase II of NCHRP Project 9-33.

- *Phase I, Task 2—Survey current practice among state highway agencies in their implementation of volumetric specifications for Superpave HMA.* A Survey of Current Practice was performed during the initial phases of NCHRP Project 9-31 and was updated near the completion of NCHRP Projects 9-25 and 9-31; the objective of this task is to review and update this survey.
- *Phase I, Task 3—Develop a revised Phase II Work Plan.* The task descriptions below represent an initial summary plan for Phase II of the Extended Work and Validation Plan. After the review of NCHRP Projects 9-25 and 9-31 and related research and updating the survey of current practice, a revised, more detailed plan for Phase II should be developed. This will be included in the Interim Report to be submitted as Task 4.
- *Phase I, Task 4—Submit an Interim Report to NCHRP within 4 months of the start of work.* This Interim Report will include as a minimum the review of findings of NCHRP Projects 9-25 and 9-31 and related research, an updated Survey of Current Practice, and the Revised Phase II Work Plan. Approximately 1 month will be allotted for review of the Interim Report by NCHRP.
- *Phase II, Task 5—Analyze the field performance data that was identified and summarized during Task 1 using the methods recommended in NCHRP Projects 9-25 and 9-31.* This analysis will include statistical comparisons of predicted and measured performance, including estimates of overall error compared with the error estimates reported in NCHRP Projects 9-25 and 9-31. Recommendations concerning the accuracy of the models will be made based upon the results of this analysis and the review of the findings of NCHRP Projects 9-25 and 9-31.
- *Phase II, Task 6—Execute accelerated pavement tests and/or field tests according to the Phase II Work Plan.* This should include 8 to 12 test sections of pavements at an accelerated pavement testing facility such as FHWA's ALF at the Turner–Fairbank Highway Research Center or at a test track such as exists at NCAT. Alternately, test sections could be constructed in actual pavements, but these must be carefully designed and constructed so that valid comparisons among the mixtures tested can be made. Approximately one-half of the test sections should represent a variety of mixtures prepared according to the procedures given in the NCHRP Projects' 9-25 and 9-31 final report; the balance should represent mixtures made according to current Superpave specifications, but in such a way that significant contrasts are made with the NCHRP Projects' 9-25 and 9-31 mixture designs. Of particular interest are contrasts in effective binder content, VMA, aggregate fineness relative to VMA, and high temperature binder grade. The performance of the sections should be evaluated and compared with the performance as predicted using the models developed during NCHRP Projects 9-25 and 9-31. This analysis should emphasize the apparent effects of specific recommendations of NCHRP Projects 9-25 and 9-31.
- *Phase II, Task 7—Perform laboratory testing.* These tests should include permeability tests and uniaxial fatigue tests. The permeability tests should be performed on a wide range of mixtures, including mixtures made using 9.5-, 12.5-, 19-, 25- and 37.5-mm NMAS aggregates. The specimens should be fabricated using rolling wheel compaction and/or should be field cores since specimens prepared using the gyratory compactor often exhibit significantly lower permeability values than do cores taken from pavements. The procedure used should be the Florida permeability test or similar procedure. The fatigue tests should be done in uniaxial mode, following the same procedures used in NCHRP Projects 9-25 and 9-31. The results should be analyzed using continuum damage methods and compared with the models developed during NCHRP Projects 9-25 and 9-31.
- *Phase II, Task 8—Evaluate and/or recalibrate performance models.* The specific findings of NCHRP Projects 9-25 and 9-31 were based on several semi-empirical models relating mixtures volumetrics to different aspects of pavement performance. These models are being refined and recalibrated as part of NCHRP Project 9-33. These models should be further refined using the results of the field tests and laboratory tests performed during Tasks 6 and 7 and also using the field data from other projects analyzed in Task 5. If appropriate, the proposed models should be refined or recalibrated using an expanded data set including both the data generated during NCHRP Projects 9-25, 9-31, and 9-33 and the data collected during this research. If the models appear to be inappropriate, alternate models should be proposed and evaluated. The final result of this task should be a final, refined set of recommendations concerning the volumetric composition of Superpave mixtures.
- *Phase II, Task 9—Prepare the Final Report.* This will constitute a clear and concise summary of all of the significant research performed during the extend work/validation effort. The report will be prepared according to NCHRP guidelines. Detailed information concerning laboratory testing, analyses, or derivations should be included in appendixes. Three months will be allowed for NCHRP review of the Draft Final Report, after which the contractor will prepare the Revised Final Report based upon the comments received from NCHRP after review of the draft report.

CHAPTER 4

Conclusions and Recommendations

Conclusions

Data from tests performed during NCHRP Projects 9-25 and 9-31 and data gathered from various previous research projects have been analyzed and effective models have been developed for predicting a range of performance-related properties for HMA. These models were used to analyze the effect of changes in VMA, air voids, aggregate fineness, and related factors on the potential performance of HMA. In general, rut resistance increases with decreasing VMA and increasing aggregate specific surface. Fatigue resistance increases with increasing effective binder content, which tends to increase with increasing VMA. Both rut resistance and fatigue resistance increase with increasing levels of design compaction and increasing levels of field compaction relative to design compaction, when other factors are held constant. The permeability of HMA increases with increasing air void content and decreasing aggregate specific surface.

Recommendations

The results of NCHRP Projects 9-25 and 9-31 suggest that current Superpave requirements for volumetric design of HMA do not need major revision. However, there appears to be some need for refinements in the system since many highway agencies have recently funded research and engineering projects dealing with both top-down cracking and permeability of HMA. Current HMA mixtures tend to be somewhat lower in asphalt binder content compared with mixtures designed and placed prior to the implementation of Superpave; this may be a contributing factor to the observed frequency of raveling and surface cracking in Superpave mixtures. Because the Superpave system has encouraged the use of coarse aggregate gradations—below the maximum density gradation—they also often contain relatively few fines; this lack of aggregate fines, in combination with relatively high in-place air voids, can result in mixtures with high permeability and less resistance to age hardening. The potentially low fines content, when combined with high VMA values, can also lead to poor rut resistance, although this problem is relatively uncommon in HMA designed using the Superpave system.

Many highway agencies have already modified volumetric requirements in the Superpave system, the most common changes being establishing maximum VMA values 1.5% to 2.0% above the minimum values, increasing minimum VMA by 0.5% to 1.0%, and/or a broadening of design air void content from 4.0% to a range of 3.0% to 5.0%. Establishing maximum VMA values and eliminating VFA requirements make the Superpave system simpler and more direct and reduce the chances of designing HMA with poor rut resistance. Increasing VMA while maintaining design air voids at 4.0% will improve fatigue resistance since this will increase VBE. However, unless care is taken to ensure that adequate aggregate specific surface is maintained while increasing VMA, rut resistance will be reduced. Increasing aggregate specific surface while increasing minimum VMA will improve both fatigue resistance and rut resistance, and will tend to decrease permeability. Changing design air voids in essence has the effect of changing the design compaction level since this changes the amount of compaction energy that will be required in the field to reach the target air void levels. The effect of changing design air voids depends in part on whether VMA or VBE is held constant. If VBE is held constant, design air void contents below 4.0% reduce the required field compaction effort, and both fatigue resistance and rut resistance will be decreased; increasing design air voids to levels above 4.0% has the opposite effect. If VMA is held constant, decreasing design air voids will still result in a decrease in field compaction effort, but this will be offset in part by increasing binder content. Decreasing design air voids to from 4.0% to 3.0% while decreasing the target air voids in the field a similar amount will improve both fatigue resistance and rut resistance while decreasing permeability. Decreasing N_{design} for a given aggregate blend will tend to produce a mixture with somewhat higher binder content, which is also easier to compact in the field. However, it should be recognized that many materials suppliers will adjust aggregate gradations in such a situation to maintain minimum allowable binder contents, and some contractors might also adjust field compaction practices so that in-place air voids are not reduced. Therefore, agencies that choose to reduce N_{design} in order to obtain higher binder contents and better field compaction should also increase minimum binder content requirements and decrease allowable in-place air voids. A slight increase in dust-to-binder ratio in such cases will help maintain current levels of rut resistance. Other approaches are possible to improving the fatigue resistance of HMA while maintaining or improving rut resistance and decreasing permeability.

Agencies contemplating modification in Superpave specifications should first evaluate the level of in-place air voids being achieved during flexible pavement construction and verify that acceptable levels of field compaction are being achieved—poor field compaction will have a significant negative impact on pavement performance that can only be partially offset by proper mix design. Any changes in current Superpave requirements should be carefully evaluated using performance models tempered with engineering judgment and experience with local conditions and materials. Although performance models are useful tools for evaluating the effects of modifications in HMA specifications, they should be used with caution—understanding that such models provide only approximate results. Care is also needed when instituting multiple changes in Superpave specifications or in specifications for any other HMA mix type: changes in volumetric requirements, compaction levels, and materials specifications are additive, and unless such changes are carefully evaluated and implemented, significant and unanticipated reductions in pavement performance can result.

Chapter 3 of this report includes an Extended Work and Validation Plan (see the end of Chapter 3). This plan has been devised to extend the results of this research to mixtures made with larger aggregate sizes (25- and 37.5-mm) and also to validate the results of this research using accelerated pavement testing and other field data.

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GLOSSARY

AASHTO: American Association of State Highway and Transportation Officials
AFT: apparent film thickness
ALF: Accelerated Loading Facility
ARZ: above restricted zone
ASTM: American Society for Testing and Materials
BRZ: below restricted zone
CAM: Christensen–Anderson–Marasteanu Model
DOT: Department of Transportation
ESALs: equivalent single axle loads
FHWA: Federal Highway Administration
FM_{300}: fineness modulus 300 µm basis
HMA: hot mix asphalt
IDT: indirect tensile
JMF: job mix formula
LTPP: Long-Term Pavement Performance (Program)
LVE: linear viscoelastic
MAAT: mean annual air temperature
MnRoad: Minnesota Road Research Project
MPSS: maximum permanent shear strain
NCAT: National Center for Asphalt Technology
NCHRP: National Cooperative Highway Research Program
N_{design}: design number of gyrations
NMAS: nominal maximum aggregate size
PG: performance grade
PI: penetration index
PVN: penetration-viscosity number
QC/QA: quality control–quality assurance
RAP: recycled asphalt pavement
RPS: research project statement
RSCH: repeated shear at constant height
SBR: styrene-butadiene rubber
SBS: styrene-butadiene-styrene rubber
SHRP: Strategic Highway Research Program
SMA: stone matrix asphalt
TRB: Transportation Research Board
TRZ: through the restricted zone
VBE: effective asphalt content by volume
VFA: voids filled with asphalt
VMA: voids in mineral aggregate
VTM: total voids in mix

Abbreviations and acronyms used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation