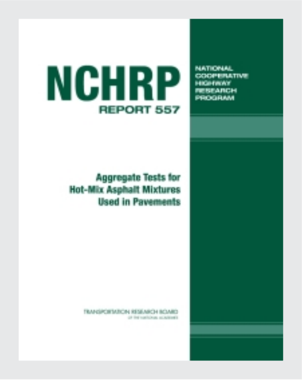

Aggregate Tests for Hot-Mix Asphalt Mixtures Used in Pavements

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 557

Aggregate Tests for Hot-Mix Asphalt Mixtures Used in Pavements

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TRANSPORTATION RESEARCH BOARD

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FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

This report presents recommendations for performance-based procedures to test aggregates for use in pavements utilizing hot-mix asphalt (HMA) mixtures and provides guidance on using these procedures for evaluating and selecting aggregates for use in specific mixture applications. This information will guide materials engineers in selecting the aggregates that should contribute to well performing pavements; this information can also be used in conjunction with performance-related specifications. The content of this report will be of immediate interest to materials engineers, researchers, and others concerned with the construction and performance of HMA pavements.

The properties of coarse and fine aggregates used in HMA mixtures significantly affect the performance of the highway pavements in which they are used. Despite their obvious importance, little consideration is usually given to the testing of aggregates. Many currently used aggregate tests are empirical—they were developed without establishing a direct relation to pavement performance. Furthermore, some of the most commonly used test methods are not easy to perform and do not yield reproducible results; compliance with these tests does not consistently result in acceptable performance. Thus research was needed to recommend precise tests that measure key aggregate properties related to pavement performance. The tests are for use in evaluating and selecting aggregates or in conjunction with performance-related specifications.

Research performed under NCHRP Project 4-19, reported in *NCHRP Report 405: Aggregate Tests Related to Asphalt Concrete Performance in Pavements,* evaluated aggregate tests through a study of literature and laboratory tests. The research then identified a set of nine aggregate tests that relate to the performance of HMA mixtures used in pavement construction and thus can be used as predictors of pavement performance. However, the project did not assess the validity of these tests by in-service performance tests or accelerated pavement tests. Under NCHRP Project 4-19(2), "Validation of Performance-Related Tests of Aggregates for Use in Hot-Mix Asphalt Pavements," Purdue University of West Lafayette, Indiana, (with Mississippi State University serving as a subcontractor) was assigned the objective of evaluating, by accelerated load tests and/or in-service pavement studies, the validity of the aggregate tests identified in NCHRP Project 4-19 as predictors of field performance of HMA mixtures and then recommending performance-based test methods. The research concentrated on dense-graded virgin HMA used in the top layers of high-load, high-volume pavements. To accomplish this objective, the researchers performed the following tasks:

1. Review and synthesis of information relevant to the testing and evaluation of aggregates used in HMA pavements;

2. Characterization of a wide variety of aggregate types and selection of five coarse and six fine aggregates representing a range of properties for use in the research;
3. Conduct of accelerated fatigue and rutting tests of full-scale pavement sections constructed with HMA mixtures containing aggregates of different types and properties to correlate performance with the aggregate properties measured in the laboratory using the test methods identified in *NCHRP Report 405;* data from rutting tests were also used to assess moisture susceptibility;
4. Analysis of test results to (a) evaluate the effect of specific aggregate properties on performance, (b) determine the sensitivity of these aggregate properties to traffic level, and (c) evaluate the validity of the previously identified tests; and
5. Recommendation of a set of tests for evaluating aggregates used in HMA pavements and proposed acceptance criteria for different levels of traffic.

The recommended set of eight aggregate tests deals with particle shape, angularity, surface texture, durability, and soundness of the aggregates and with the characteristics of the fines in aggregates. These tests and the proposed acceptance criteria can be used to select aggregates for use in HMA mixtures or in conjunction with performance-related specifications. These test methods will be particularly useful to highway agencies and are recommended for consideration and adoption by AASHTO as standard test methods.

Appendixes A through F contained in the research agency's final report are not published herein. These appendixes are accessible on the web as *NCHRP Web-Only Document 82* at http://www4.trb.org/trb/onlinepubs.nsf. These appendixes are titled as follows:

Appendix A: Petrographic Analysis Results;
Appendix B: Laboratory HMA Mixture Design Results;
Appendix C: Aggregate Tests;
Appendix D: Test Section Construction and Control;
Appendix E: Moisture Susceptibility; and
Appendix F: Bibliography.

CONTENTS

SUMMARY

Aggregate Tests for Hot-Mix Asphalt Mixtures Used in Pavements

NCHRP Project 4-19, "Aggregate Tests Related to Asphalt Concrete Performance in Pavements," recommended a set of performance-related aggregate tests for evaluating aggregates for use in hot-mix asphalt (HMA) pavements. Performance indicators considered in the research included permanent deformation resulting from laboratory traffic loading (both with and without stripping), fatigue cracking, and surface defects (e.g., raveling, popouts, and potholes). The performance relationships were developed based on tests performed using the Superpave Shear Tester (SST) and the Georgia Loaded Wheel Tester (GLWT); however, the relationships were not validated.

As part of their results, the NCHRP 4-19 researchers recommended a follow-on experiment for additional research to achieve validation. The proposed research involved tests of both coarse and fine aggregate uncompacted voids as well as the flat or elongated particle test, 2:1 ratio (FOE21). These three tests were to be validated for their ability to predict HMA rutting and fatigue performances. Additionally, particle size analysis and methylene blue values (MBV) of the HMA mixture aggregate fraction smaller than the 0.075-mm sieve (p0.075) were to be tested to validate their ability to predict rutting in HMA mixtures. The researchers further suggested that the MBV of the fine aggregate be validated for ability to predict moisture susceptibility of HMA. Finally, the results of Micro-Deval (MDEV) and Magnesium Sulfate Soundness (MGSO4) tests on aggregates were to be evaluated for predicting HMA toughness and durability.

The object of this research was to use accelerated pavement testing techniques to conduct the rutting, fatigue, and moisture susceptibility validation experiments identified in NCHRP Project 4-19. For each aggregate test, a descriptive ranking indicating how well it relates to HMA performance is given. Also, an attempt has been made to suggest appropriate tests for given combinations of climatic conditions, materials, and traffic loads.

A literature review was completed first and was used to guide the research team in selecting five coarse and six fine aggregates for use in the study. The selected aggregates were tested and used in various combinations to produce five coarse-graded and six fine-graded mixtures that were then tested for rutting characteristics in the accelerated loading facility. The five coarse aggregates covered a wide array of aggregate types and properties; each was combined with a common natural sand to produce the five coarse-graded mixtures. The six fine aggregates also represented various aggregate types and properties; each of these was combined with a common coarse aggregate to produce the six fine-graded mixtures.

On completing the rutting tests, six of the original eleven mixtures were chosen for accelerated testing to determine their fatigue characteristics. The mixtures were chosen so as to represent a wide range of aggregate and mixture characteristics. Although the rutting testing proceeded well, problems were encountered with the fatigue testing. Construction of the conventional flexible pavement sections in the accelerated loading facility proved to be more difficult than anticipated. Lack of temperature control in the facility also made it difficult for the test slabs to exhibit fatigue signs during the test, at least two mixtures exhibited excessive rutting before showing signs of fatigue.

In addition to the rutting and fatigue tests, five additional HMA mixtures were designed using five of the six fine aggregates and one common coarse aggregate. These mixtures were placed in the accelerated loading facility and tested for rutting in the presence of moisture to determine if the aggregate tests predict moisture susceptibility in HMA mixtures.

Test results showed that the UVA of both fine and coarse aggregates reasonably predict rutting performance of HMA mixtures. The FOE21 test also appears to predict HMA rutting performance. These three tests also may show trends in relation to HMA fatigue performance, but the fatigue data are limited. A minimum coarse aggregate UVA of 40 percent is recommended for traffic less than 100,000 Equivalent Single Axle Loads (ESAL); a minimum coarse aggregate UVA of 45 percent is recommended for traffic of 100,000 ESAL and greater. A minimum fine aggregate UVA of 40 percent is recommended for traffic volumes less than 500,000 ESAL; a minimum fine aggregate UVA of 45 percent is recommended for traffic volumes above this level. An upper limit of 50 percent is recommended for the FOE21 value for all traffic levels.

The MDEV and MGSO4 tests also appear reasonably predictive of HMA performance. Maximum values of 15 and 20 percent for MDEV and MGSO4, respectively, are recommended.

Although the particle size analysis of the p0.075 material and the MBV tests appear to have some performance predictive ability, the relationships were weak. Neither of these tests is recommended for routine aggregate specifications.

Finally, research is suggested to gather additional information about the relationship between the recommended aggregates tests and HMA fatigue performance. Because the relationship between laboratory and in-service fatigue typically is a scaling factor, adequate information can be obtained from a laboratory experiment. Full-scale testing is not required.

CHAPTER 1

Introduction and Research Approach

Problem Statement and Research Objectives

Hot-mix asphalt (HMA) mixtures are complex materials composed of mineral aggregates and asphalt binder. Because about 95 percent by weight of the HMA mixture is aggregate, the coarse and fine aggregate properties influence pavement performance significantly. Studies have shown that HMA pavement rutting and stripping can be directly related to improper selection and use of aggregates (*1*).

Tests and associated criteria used by highway agencies to select aggregate for HMA mixtures are empirical. Often, they have not been related to pavement performance directly. Aggregate tests that provide clearer relationships with performance will provide better means for evaluating and selecting aggregates.

The completed NCHRP Project 4-19, "Aggregate Tests Related to Asphalt Concrete Performance in Pavements," recommended a set of performance-related aggregate tests for evaluating aggregates for use in HMA pavements. Pavement performance indicators assumed to be related to these laboratory aggregate tests were permanent deformation because of traffic loading (both with and without stripping), fatigue cracking, and surface defects (e.g., raveling, popouts, and potholes). The performance relationships were developed based on laboratory tests with the Superpave Shear Tester (SST) and the Georgia Loaded Wheel Tester (GLWT); however, these relationships were not validated with prototype-scale traffic tests; the NCHRP 4-19 researchers recommended additional research as shown in Table 1. The objective of the current research was to use accelerated pavement testing techniques to perform the rutting, fatigue, and moisture susceptibility validation experiments identified in NCHRP Project 4-19. Analysis was directed toward developing a descriptive ranking of each aggregate test indicating how well it related to HMA performance. Also, appropriate tests for given combinations of climatic conditions, materials, and traffic loads have been suggested.

Scope of Study

Research was conducted to document the ability of aggregate tests identified in NCHRP Project 4-19 to predict in-service performance of HMA pavements. Relationships between aggregate properties and HMA pavement performance were evaluated in full-scale accelerated loading conditions. Individual aggregate tests, as well as combinations of tests that related to HMA performance, were identified. Recommendations for use in HMA aggregate selection and mixture design procedures have been provided. Specifically, a practical set of performance-related aggregate tests has been recommended for inclusion in HMA mixture design systems. Future research to determine the ruggedness, precision, and bias of the test methods has been suggested.

Research Approach

The research was performed in two phases. Phase I included review of *NCHRP Report 405* and other relevant literature and the development of a research plan. Phase II included execution of the research plan established in Phase I and preparation of the final project report.

Relating results of the aggregate tests shown in Table 1 to the HMA distresses of rutting, moisture susceptibility, and fatigue served as the basis for the validation experiments. The research was conducted according to the plan, shown in Figure 1, which involved aggregate testing, identification of HMA mixture designs, and HMA mixture testing using accelerated pavement tests. The accelerated testing was completed in three series, each relating to one of three HMA distresses noted above.

Aggregate Testing

Aggregates were characterized using tests listed in Table 2. These include the tests identified in NCHRP Project 4-19,

Table 1. Validation experiments recommended by Kandhal and Parker [*1*].

Experiment	Validation Experiment	Performance
1	Uncompacted Void Content of Coarse Aggregate and Flat or Elongated Particles (2:1 ratio) in Coarse Aggregate	Rutting and Fatigue
2	Uncompacted Void Content of Fine Aggregate	Rutting and Fatigue
3	Methylene Blue Test of Fine Aggregate	Moisture Susceptibility
4	Particle Size Analysis and Methylene Blue of p0.075 Material	Rutting
5	Micro-Deval and Magnesium Sulfate Soundness Tests	Durability/ Toughness

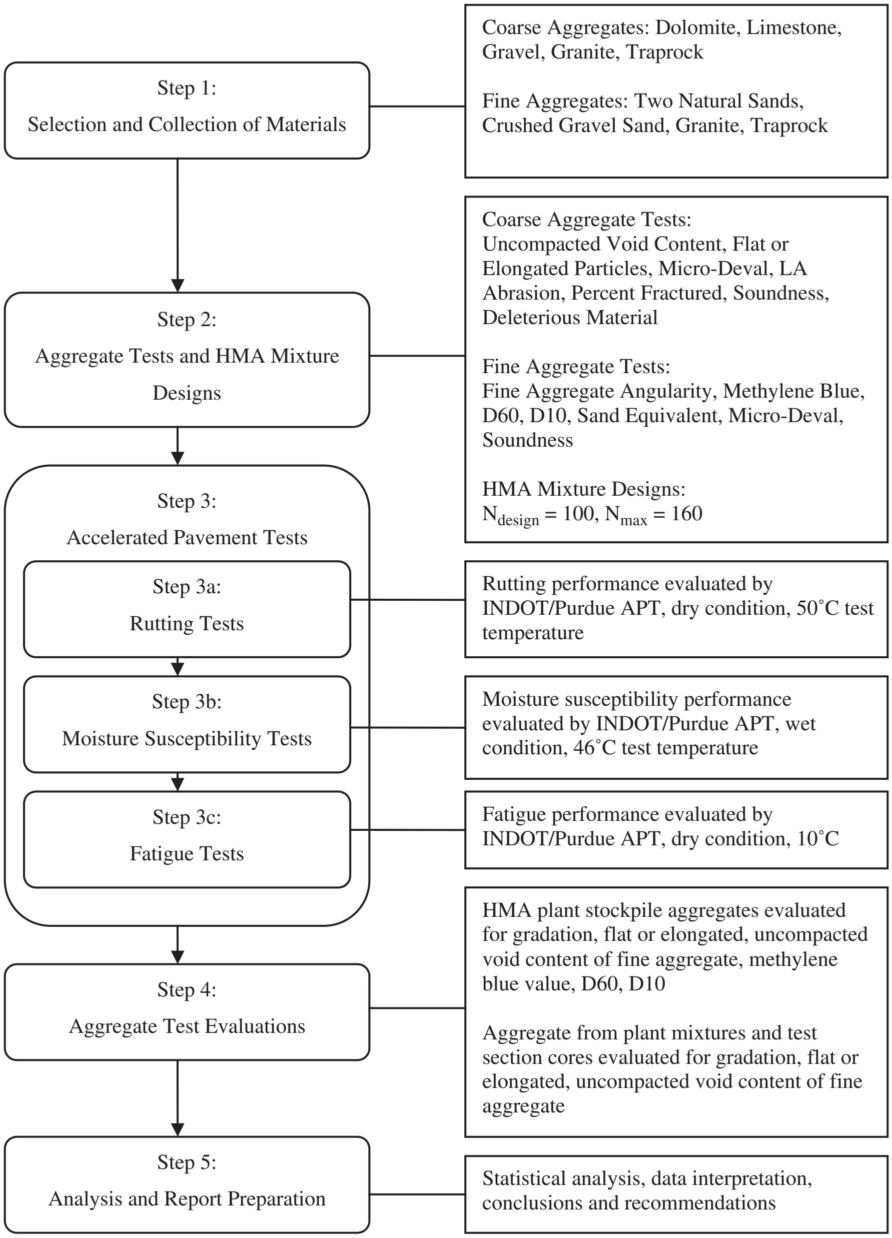


Figure 1. Research work flowchart.

Table 2. Aggregate characterization tests.

Test Method	Recommended by Kandhal and Parker	Superpave Requirement	Additional Test
Sieve Analysis for Determining Gradation and Size (AASHTO T11 & T27)	X	X	
Uncompacted Void Content of Coarse Aggregate, Method A (AASHTO TP56)	X		
Uncompacted Void Content of Coarse Aggregate, Method B (AASHTO TP56)			X
Flat *or* Elongated Particles in Coarse Aggregate (ASTM D4791)	X (2:1)	X (5:1)	X (3:1)
Flat *and* Elongated Particles in Coarse Aggregate (ASTM D4791)			X (3:1, 5:1)
Uncompacted Void Content of Fine Aggregate, Method A (ASTM C1252)	X	X	
Uncompacted Void Content of Fine Aggregate, Method B (ASTM C1252)			X
Virginia Test Method for Determining Percent Voids in Fine Aggregates (VTM5)			X
Methylene Blue Test for Fine Aggregate (AASHTO TP57)	X		
Particle Size Analysis of p0.075 Materials for Determining D60, D30, and D10 Sizes	X		
Methylene Blue Test for p0.075 Material (AASHTO TP57)	X		
Micro-Deval Test (AASHTO TP58)	X		
Magnesium Sulfate Soundness Test (AASHTO T104)	X		
Clay Content by Sand Equivalent (AASHTO T176)		X	
Clay Lumps and Friable Particle (AASHTO T112)		X	
Percent Fractured Particles in Coarse Aggregate (ASTM D5821)		X	
Los Angeles Abrasion Test (ASTM C96)		X	
Specific Gravity and Absorption of Aggregate (AASHTO T84 and T85)		X	

the aggregate tests specified by Superpave criteria, Uncompacted Void Content of Coarse Aggregate, Method B (AASHTO TP 56), and Virginia Test Method for Determining Percent Voids in Fine Aggregates (VTM5) tests.

Accelerated Testing Experiments

Rutting Experiment

The rutting experiment design is shown in Table 3. Coarse aggregate, fine aggregate, and particles smaller than the 0.075-mm sieve (p0.075) were evaluated for their effect on HMA rutting performance. For coarse-graded mixtures, a natural sand was used in combination with various coarse aggregates. For fine-graded mixtures, an uncrushed gravel was used as the coarse aggregate in combination with various fine aggregates. The effects of coarse and fine aggregate on HMA mixture performance were studied by constructing and testing 11 test sections in the Accelerated Pavement Tester (APT). Five of the test sections were coarse-graded HMA mixtures with gradations plotting below the maximum density line (MDL). The other six sections were fine-graded HMA mixtures with gradations plotting along or above the MDL.

Moisture Susceptibility Experiment

Five fine-graded HMA mixtures were used to investigate relationships between moisture susceptibility and fine aggregate properties as shown in Table 4. Performance as affected by moisture damage was assessed by the amount of rutting observed in the HMA mixtures. The AASHTO T 283 test was also performed on cores extracted from the APT test lanes before accelerated pavement testing. Stripping after traffic was also noted

Table 3. Rutting experiment design.

Aggregate Performance Test Category	Mix	Aggregate	
		Coarse	Fine
Coarse Aggregate Test Methods Evaluation (Coarse-graded Mixtures)	CA-1	Dolomite (IN)	Natural Sand A (IN)
	CA-2	Limestone (IN)	
	CA-3	Granite (NC)	
	CA-4	Gravel (IN)	
	CA-5	Traprock (VA)	
Fine Aggregate Test Methods Evaluation (Fine-graded Mixtures)	FA-1	Gravel (IN)	Dolomite (IN)
	FA-2		Granite (NC)
	FA-3		Traprock (VA)
	FA-4		Crushed Gravel Sand (IN)
	FA-5		Natural Sand A (IN)
	FA-6		Natural Sand B (OH)

Table 4. Moisture susceptibility experiment design.

Aggregate Performance Test Category	Mix	Aggregate	
		Coarse	Fine
Fine Aggregate Test Methods Evaluation (Fine-graded Mixtures)	FAM-1	Dolomite (IN)	Granite (NC)
	FAM-2		Traprock (VA)
	FAM-3		Crushed Gravel Sand (IN)
	FAM-4		Natural Sand A (IN)
	FAM-5		Natural Sand B (OH)

visually. After construction and before testing, water was pooled on the test lanes for 2 days with the pavement heating system turned on. During APT testing, the test sections were kept wet by adding water to the pavement surface.

Fatigue Experiment

Relationships between fatigue cracking and coarse and fine aggregate properties were evaluated through the construction and testing of six APT sections as indicated in Table 5. These mixtures were selected from the 11 mixtures used in the rutting experiment based on performance. Fatigue performance was characterized by percent fatigue cracking in the wheel path.

Analysis Methods

Experiments were designed to test the hypotheses that there are relationships between aggregate tests (properties) and HMA performance when full-scale accelerated loading is applied. Analysis of variance (ANOVA) was used to develop a descriptive ranking indicating how well each test related to performance. Subsequently, multivariable regression analyses were conducted to investigate whether a single test or a combination of aggregate tests best predicted HMA performance. This process provided a rational basis for recommending aggregate tests related to HMA performance.

The relative effect of traffic was determined through analysis of the APT test results. For example, APT traffic repetitions and rutting at different levels of one or more material characteristics (e.g., fine aggregate angularity) were plotted. An example of these relationships is shown in Figure 2. Alternatively, a level of distress could be selected (e.g., 10-mm rut depth) at which to compare the effect of the aggregate characteristic on performance. Figure 3 shows a relationship for FAA and a 10-mm rut depth distress level. This type of analysis was used to determine the aggregate characteristic's sensitivity to traffic level and also provide a method of developing traffic-related input for regression analysis targeted at determining the performance of HMA pavements at different traffic levels with the individual or multiple aggregate properties as input factors.

Table 5. Fatigue experiment design.

Aggregate Performance Test Category	Aggregate	
	Coarse	Fine
Coarse Aggregate Test Methods Evaluation (Coarse-graded Mixtures)	CA-2 (Limestone)	Natural Sand A (IN)
	CA-3 (Uncrushed Gravel)	
	CA-4 (Granite)	
Fine Aggregate Test Methods Evaluation (Fine-graded Mixtures)	Uncrushed Gravel (IN)	FA-1 (Natural Sand A)
		FA-3 (Natural Sand B)
		FA-4 (Granite)

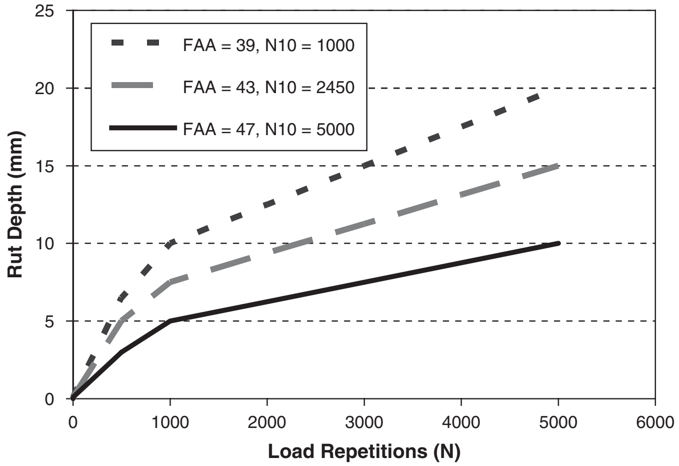


Figure 2. Effect of FAA on rut depth.

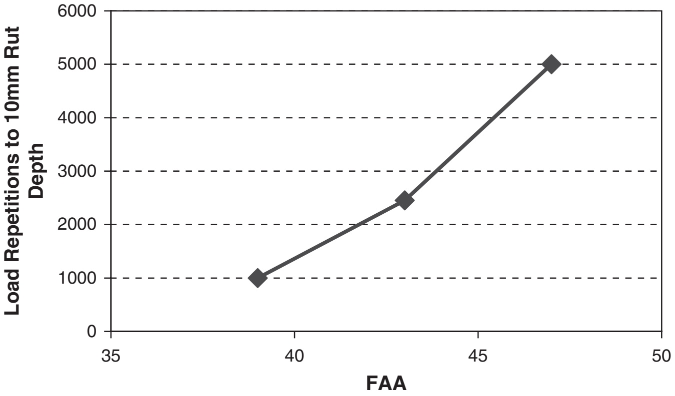


Figure 3. Effect of UVA on traffic.

CHAPTER 2

Findings

State-of-the-Art Summary

The summary focuses on literature published after *NCHRP Report 405*. Multiple databases were used; 46 papers were reviewed. This summary provides a synopsis of the literature in terms of the reported effects of aggregate properties on rutting, fatigue life, and durability of HMA pavements and organized by effect of gradation and nominal maximum size; particle shape, angularity, and surface texture; and properties of p0.075 materials.

Effects of Aggregate Gradation and Size

Selection of aggregate gradation for use in HMA pavement is important to pavement performance. Recent guidance for HMA gradation has been defined in terms of the Superpave restricted zone. This zone is located along the maximum density line between the 0.300-mm and 4.75- or 2.36-mm particle sizes (depending on the maximum nominal size of the aggregate). Avoiding this zone was intended to limit the amount of rounded natural sand that can contribute to mixture instability. Some research suggests that aggregate gradations plotting below this zone produce more rut-resistant mixtures. However, other studies have shown that gradations plotting above the restricted zone provide equal or even more rut-resistant mixtures (*2*).

Comparing HMA pavement performance based only on different aggregate gradations is not a simple matter. The interrelationships among aggregate gradation, aggregate characteristics, and HMA volumetric properties are complex. In general, dense-graded HMA mixtures with adequate Voids in the Mineral Aggregate (VMA) provide improved resistance to degradation and improved resistance against fatigue cracking when used in thick pavements (*1*). In a recent study, coarse-graded HMA mixtures were found to be more sensitive to variations in asphalt binder content and p0.075 material than were fine-graded mixtures (*3*).

The following observations concerning the effects of aggregate gradation and size on HMA mixture properties and performances were reported in the literature:

- HMA mixtures with gradations passing through the restricted zone exhibit higher bulk density and lower air voids than mixtures with gradation plotting below and above the zone (*4*);
- Fine-graded HMA mixtures have better fatigue performance than do more coarsely graded mixtures (*5*);
- HMA specifications that allow gradations to pass through the restricted zone produce the best performing pavements in Georgia (*6*);
- In accelerated loading tests, HMA mixtures with gradations above the restricted zone generally exhibit less rutting than those with gradations below and through the restricted zone (*7, 8*);
- Triaxial test results indicate that fine-graded HMA mixtures have greater shear strength than those with coarser gradations (*2*); and
- The SST indicated that an aggregate gradation passing through the restricted zone had no significant effect on HMA mixture performance (*4*).

HMA performance is also influenced by the maximum aggregate size. HMA mixtures with larger maximum aggregate sizes were reported to exhibit better rutting performance than those with smaller maximum aggregate sizes (*9, 10*). Khedaywi and Tons (*11*) also found that smaller coarse aggregate particles provided more aggregate interlocking and resulted in increased HMA shear strength.

Accelerated pavement testing seems to delineate the effect of maximum aggregate size on HMA performance much more effectively than do the laboratory methods. It was reported that differences between mixtures with different nominal maximum aggregate sizes (NMAS) that had shown significant performance differences when tested in the FHWA

Accelerated Loading Facility (ALF) could not be detected by laboratory methods (*9*). The following observations regarding aggregate size effects were reported in the literature:

- Increasing the maximum aggregate size in a gradation will improve the mixture quality with respect to creep performance, resilient modulus, and tensile strength, but will decrease the Marshall stability and flow (*10*);
- Pavement sections tested with the FHWA ALF indicated that mixtures with an NMAS of 37.5 mm perform better than those with a 19.0 mm NMAS (*9*); and
- A national pooled-fund study found that mixtures with a NMAS of 9.5 mm and 19.0 mm performed similarly when tested with the Purdue APT and the Purdue laboratory wheel tracking device (PurWheel) (*7*).

Particle Shape, Angularity, and Surface Texture

Generally, aggregate shape, angularity, and surface texture characteristics influence HMA performance; however, some state agencies and aggregate producers have expressed concerns with the validity and practicality of the specifications and methods used to determine these characteristics—generalizing these specifications to all types of aggregates may be inappropriate. For instance, HMA performance problems associated with some aggregate types (e.g., igneous aggregate) are usually not related to particle shape (*12*).

Numerous studies have been conducted on the effects of particle shape, angularity, and surface texture on HMA performance. Results of a study indicated uncompacted voids content of the coarse aggregate, often referred to as the coarse aggregate angularity (CAA), did not correlate with the actual observed performance of either the fine- or coarse-graded mixtures (*8, 13*). An accelerated pavement testing study revealed that the amount of crushed gravel in HMA mixtures affected rutting performance. Tests on two mixtures made with gravel aggregate showed a mixture with 40-percent crushed gravel was more sensitive to rutting than a mixture with 70-percent crushed gravel (*14*). Also, increasing the percentage of crushed particles in HMA mixtures increased the Marshall stability (*14*).

The particle shapes of coarse aggregates used in HMA mixtures have been found to affect both performance and workability of the mixtures. A study conducted using the Superpave Gyratory Compactor (SGC) showed that increasing the amount of flat and elongated particles increased the required compaction energy (*15*), indicating that HMA mixtures with high percentages of flat and elongated particles are less workable. In addition, increased amounts of flat and elongated particles in HMA mixtures result in more aggregate breakdown, thus exposing the aggregate surface and creating a potential durability problem. The VMA was also found to increase slightly with an increasing percentage of flat and elongated coarse aggregate particles.

The uncompacted voids content of fine aggregate or fine aggregate angularity (FAA), as affected by particle shape, angularity, and surface texture, is determined in accordance with ASTM C 1252 by measuring the voids ratio of loosely placed fine aggregate in a standard cylinder. In general, fine aggregates with high FAA values result in higher internal friction and stronger bonds with asphalt binder that leads to better stability and rut resistance of HMA mixtures.

Kandhal and Parker (*1*) indicated that FAA value is an important factor in HMA mixtures performance with aggregate gradations above the restricted zone. They concluded that the higher the FAA, the greater the resistance of HMA to permanent deformation. For coarse-graded mixtures, a study showed that FAA did not impact the HMA performance as measured by the Asphalt Pavement Analyzer (APA), Couch Wheel Tracker, and SST (*16*). However, studies conducted using the APT, PurWheel, and triaxial tests found that FAA of coarse-graded mixtures correlated well with HMA rutting performance. These results also indicated that very high FAA values do not necessarily provide better performance than do sands with more typical FAA values in the range of 40 to 45 (*7, 17*).

Stiady (*7*) reported that design asphalt binder content is affected by FAA; higher FAA is associated with increased resistance to compaction, higher VMA, and higher asphalt binder content. Higher asphalt binder content results from the fixed 4-percent air voids criteria. Very high FAA values also tend to indicate slivered particle shape and/or extremely rough texture. During mixture design compaction, slivered particles orient themselves randomly resulting in high VMA and asphalt binder content. When such a mixture is put into service, traffic breaks or turns the slivered particles flat and the original binder content becomes excessive. Rough aggregate such as slag resists both laboratory compaction and in-service traffic densification and thus maintains a higher VMA. This high VMA accommodates high design binder content.

Brown and Cross (*18*) conducted field studies of rutted HMA pavements in several states. They concluded that the initial air voids of HMA mixtures have a strong correlation with rutting. They also concluded that aggregate properties have little effect on the rutting rate for HMA mixtures with in-place voids below 2.5 percent. Sousa and Weisman (*19*) reported that, for HMA mixtures with air voids content below 2 to 3 percent, the binder acts as a lubricant between the aggregates and reduces point-to-point contact pressure.

Properties of Material Passing the 0.075-mm Sieve

Addition of mineral filler, material passing the 0.075-mm sieve, affects HMA mixture performance. Depending on the particle size, mineral filler can act as filler or as an extender of the binder. When the mineral filler functions as a binder extender, over-rich HMA mixtures can result and lead to flushing and/or rutting. Some p0.075 materials cause stiffening of the binder and/or HMA mixtures and thus increase fatigue cracking. The amount and characteristics of the p0.075 material can also contribute to HMA mixtures that become susceptible to moisture damage. This can lead to a loss of mixture integrity, lower shear strength, cracking, and increased rutting.

Kandhal and Parker (*1*) investigated the effect of mineral filler by examining filler-binder mortar stiffness of mortars with filler-binder ratios of 0.8 and 1.5 by weight. They found that the MBV of the p0.075 material was related to the filler-binder mortar stiffness. The higher the MBV value, the stiffer was the filler-binder mortar. They also found a strong relationship between the MBV of the p0.075 material and the stiffness parameters $|G^*|/\sin\delta$ and $|G^*|\times\sin\delta$, obtained from the SST tests. The G^* parameter is the complex modulus and δ is the phase angle of material tested under dynamic loading. The $|G^*|/\sin\delta$ parameter is a measure of HMA stiffness at high temperatures or slow loading rates. High $|G^*|/\sin\delta$ values indicate high stiffness HMA mixtures and high resistance against rutting at high temperature. The product $|G^*|\times\sin\delta$ is a measure of HMA stiffness at intermediate temperatures or high loading rates. High $|G^*|\times\sin\delta$ indicates high HMA mixture stiffness and thus low resistance to fatigue cracking.

Khedaywi and Tons (*11*) suggested introduction of a specific size of fine particles into the HMA mixtures could increase mixture shear strength. The surface characteristics of the coarse aggregate (rugosity) determines the size of fine particles that contribute the most to the interlocking mechanism between the coarse aggregate particles in an HMA mixture. It was suggested that, depending on the relative size of the fine particles and the size of coarse particle surface voids, the fine particles can be completely or partially lost in the surface voids of the larger particles. When completely lost inside the surface rugosities, fine particles do not participate in HMA shear resistance. When partially lost by rugosity, fine particles can either improve or reduce the interlock between the coarse aggregate particles. Increased interlock occurs when parts of the fine particles are embedded in surface voids of adjoining coarse particles. Reduction of interlock occurs when the average size of the fine particles is larger than the average size of the coarse aggregate surface voids. In this case, the fine particles act like roller bearings between the coarse aggregate particles. It was found that the higher the rugosity of the coarse aggregate, the larger the size of fine particles that result in higher HMA mixture shear strength.

The amount of mineral filler used in HMA mixtures does not seem to affect rutting performance adversely as measured by the Repeated Shear at Constant Height (RSCH) test. The RSCH test is performed by applying shear load pulses to a cylindrical HMA specimen and keeping the specimen height constant (AASHTO TP 7). Although increasing the amount of filler does not affect the test result, increasing the mineral filler content does lead to decreased optimum binder content. Ultimately, this can lead to durability and fatigue problems (*20*). Also, coarse-graded mixtures that have gradations plotting below the MDL have been found to be sensitive to the amount of p0.075 material (*3*).

Kandhal and Parker (*1*) indicated that decreasing the size of D60 (particle size at which 60 percent of the material passes) of the p0.075 increases the HMA mixture's stiffness and resistance to rutting. Logically, this increase in mixture stiffness would also reduce the mixture's resistance to fatigue cracking. The HMA mixtures tested consisted of coarse and fine limestone aggregates of sizes larger than the 0.075-mm sieve. Different types of p0.075 material were incorporated with the coarse and fine limestone to study the effects on rutting, fatigue, and stripping performance.

In addition to D60 (particle size at which 60 percent is smaller) of the p0.075 material, the MBV and D10 (particle size at which 10 percent is smaller) of the p0.075 material were also related to HMA mixture rutting performance. The higher the MBV, the stiffer was the HMA mixture. Increasing the D10 particle size was found to reduce the tensile strength ratio of HMA mixtures (*1*). These findings were based on the AASHTO T 283 test, the SST Frequency Sweep at Constant Height (FSCH), and Simple Shear at Constant Height (SSCH) tests (AASHTO TP 7). AASHTO T 283 determines the ratio between the tensile strength of unconditioned and moisture-conditioned specimens subjected to a freeze-thaw cycle. In the FSCH test, an HMA specimen is subjected to a sinusoidal shear strain applied at different frequencies while a vertical load is also applied to keep the specimen height constant. In this test, the stiffness of the specimen is determined as a function of frequency. In the SSCH test, a constant shear load is applied to an HMA specimen while keeping the specimen height constant.

Aggregate Test Results

Coarse Aggregate

Table 6 lists the type, source location, and properties of the coarse aggregates used in the study. Two traprock sources were evaluated, but only Traprock #88 was used in the performance

Table 6. Coarse aggregate description, location, and properties.

Aggregate Type		Dolomite	Limestone	Uncrushed Gravel	Granite	Traprock #78	Traprock #88
Designation		CA-1	CA-2	CA-3	CA-4	CA-5	CA-5b
Source Location		Indiana	Indiana	Indiana	North Carolina	Virginia	Virginia
Nominal Maximum Size (mm)		12.5	12.5	12.5	12.5	12.5	12.5
		Percent Passing					
Sieve Size (mm)	19.0					100	100.0
	12.5	100	100	100	100	89.0	100.0
	9.5	87.0	87.9	84.1	90.0	60.0	85.4
	4.75	25.0	24.7	18.1	23.0	7.0	11.2
	2.36	1.4	4.7	1.1	4.0	2.0	1.3
	1.18	0.4	2.0	0.2	3.0	0.6	0.6
	0.60	0.4	1.7	0.2	2.0	0.6	0.6
	0.30	0.3	1.5	0.2	1.0	0.6	0.6
	0.15	0.3	1.4	0.2	1.0	0.6	0.6
	0.075	0.2	1.3	0.2	0.5	0.6	0.6
Dry Bulk Specific Gravity (ASTM C127)		2.734	2.550	2.598	2.649	2.897	2.910
Apparent Specific Gravity (ASTM C127)		2.825	2.752	2.742	2.705	2.981	2.989
Water Absorption, % (ASTM C127)		1.2	2.9	2.0	0.8	0.7	0.9
Flat *or* Elongated Particles (ASTM D4791), %							
■ 2:1 Ratio		44.9	48.4	28.8	47.5	34.2	35.5
■ 3:1 Ratio		4.6	6.0	2.6	3.3	5.8	2.0
■ 5:1 Ratio		0.7	1.3	0.0	0.0	0.0	0
Flat *and* Elongated Particles (ASTM D4791), %							
■ 3:1 Ratio		21.7	28.0	13.2	20.1	18.6	11.6
■ 5:1 Ratio		6.3	8.1	1.8	2.7	2.3	2.7
Uncompacted Voids, %							
■ Method A – AASHTO TP56		51.2	48.2	42.2	48.9	46.8	48.0
■ Method B – AASHTO TP56		49.8	49.6	42.9	49.1	48.4	48.8
Micro-Deval (AASHTO TP58), %		7.0	10.9	8.8	5.5	5.1	4.6
LA Abrasion Test (Type C Gradation - ASTM C96), %		23.0	24.8	18.8	18.9	13.6	14.3
Percent Fractured Particles (ASTM D5821), %							
■ 1 or more than 1		100	100	15	100	100	100
■ 2 or more than 2		100	100	12	100	100	100
Clay Lumps and Friable Particles (AASHTO T112), %		0	0	0	0	0	0
Magnesium Sulfate Soundness Test, 5 cycles (AASHTO T104), %		0.8	6.3	6.6	0.4	0.9	1.0

tests. The research team was unable to produce an acceptable mixture design with the coarser traprock (#78).

Laboratory Sample Results

Before completing mixture designs, samples of each coarse aggregate were received in the laboratory from the aggregate manufacturers. These samples were tested for the various properties shown in Table 6.

Flat or elongated particle percentages were separately determined on two size fractions, 12.5 mm to 9.5 mm and 9.5 mm to 4.75 mm. The weighted averages reported were computed based on the amount of each size fraction in the actual coarse aggregate gradation. Determining the percentage of flat or elongated and flat and elongated particles at the 3:1 ratio was added during the course of the research.

The uncompacted voids of Method A (UVA) were measured on a standard coarse aggregate specimen consisting of 1,970 g of 12.5-mm to 9.5-mm and 3,030 g of 9.5-mm to 4.75-mm aggregate sizes. Uncompacted voids of Method B (UVB) were measured on two size fractions, 12.5 mm to 9.5 mm and 9.5 mm to 4.75 mm, separately. The void measurements on the two fractions were averaged and are reported as Method B values.

The Micro-Deval (AASHTO TP 58) tests were performed on a standard specimen consisting of 750 g of 12.5-mm to 9.5-mm, 375 g of 9.5-mm to 6.7-mm, and 375 g of 6.7-mm to 4.75-mm aggregate sizes. The total, combined specimen was placed in the Micro-Deval metal container and filled with approximately 2 liters of water. The sample was soaked for a minimum of 1 hour. After soaking, 5,000 g of steel balls were introduced into the container. The container was then placed on the Micro-Deval machine and rotated for 105 minutes. After this, the sample was washed over the 4.75-mm and 1.18-mm sieves, recombined, and oven dried. The loss is the amount of material passing the 1.18-mm sieve expressed as a percentage of the original sample mass.

Los Angeles abrasion loss (ASTM C 96) was determined on a Type C specimen consisting of 2,500 g of 9.5-mm to 6.3-mm and 2,500 g of 6.3-mm to 4.75-mm size particles.

Magnesium sulfate soundness loss (AASHTO T 104) values were measured on material retained on the 9.5-mm and 4.75-mm sieves and are reported as the weighted average on the basis of the original gradations.

The bulk specific gravity and water absorption values of the coarse aggregates were determined according to the ASTM C 127 method.

Field Results

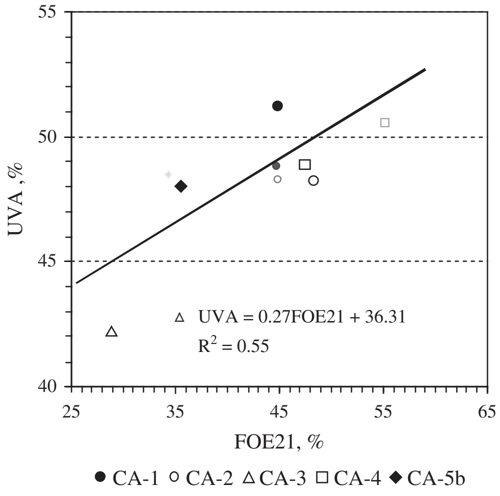
In addition to testing aggregate samples received from the producers for mixture design purposes, flat and/or elongated tests were conducted on aggregate samples taken from the HMA plant stockpiles, aggregate recovered from plant-produced mixtures, and aggregate recovered from APT test section cores after binder extractions. Table 7 lists the flat and/or elongated values of the coarse aggregates from these sources.

The data in Table 7 show that the 2:1 flat or elongated ratios (FOE21) are somewhat variable throughout the construction process. The FOE21 may show some changes in particle shape from the stockpiles through the HMA mixture production and construction process, but it is not conclusive. Some of the variability could result from coring because it is often difficult to discard all the aggregate pieces on the edge of the core that were cut by the core barrel during the coring procedure. As shown in Table 7, the uncompacted voids measured on samples taken from the HMA plant stockpiles indicated little change except for dolomite and granite.

Table 7. Coarse aggregate test data.

Flat *or* Elongated Particles, 2:1 Ratio						
Mixture		CA-1	CA-2	CA-3	CA-4	CA-5b
Coarse Aggregate		Dolomite	Limestone	Gravel	Granite	Traprock#88
Sample Source	Mixture Design	49	48	27	46	34
	HMA Plant Stockpile	45	45	35	55	34
	HMA Plant Mixture	41	50	29	38	34
	APT Cores	37	49	35	41	33
Flat *or* Elongated Particles 5:1 Ratio						
Mixture		CA-1	CA-2	CA-3	CA-4	CA-5b
Coarse Aggregate		Dolomite	Limestone	Gravel	Granite	Traprock#88
Sample Source	Mixture Design	1	1	0	0	0
	HMA Plant Stockpile	1	1	0	0	0
	HMA Plant Mixture	2	2	0	1	0
	APT Cores	1	0	0	0	0
Flat *and* Elongated Particles 5:1 Ratio						
Mixture		CA-1	CA-2	CA-3	CA-4	CA-5b
Coarse Aggregate		Dolomite	Limestone	Gravel	Granite	Traprock#88
Sample Source	Mixture Design	6	8	2	3	3
	HMA Plant Stockpile	6	8	1	7	3
	HMA Plant Mixture	8	8	1	4	2
	APT Cores	5	4	2	6	2
Uncompacted Voids Content, Method A, %						
Mixture		CA-1	CA-2	CA-3	CA-4	CA-5b
Coarse Aggregate		Dolomite	Limestone	Gravel	Granite	Traprock#88
Sample Source	Mixture Design Material	51.2	48.2	42.2	48.9	48.0
	HMA Plant Stockpile	48.8	48.3	42.7	50.6	48.5

Figure 4 shows the relationship between coarse aggregate UVA and FOE21. Data obtained during the HMA mixture design phase are shown by the larger symbols and those from HMA plant stockpiles are shown by the small symbols. There is a positive correlation between UVA and FOE21. As FOE21 increases, so does the UVA.



Note: Large symbols are data from mixture design phase. Small symbols are from HMA plant stockpiles.

Figure 4. Coarse aggregate UVA and FOE21 relationship.

Fine Aggregate

Description, source location, and properties of the fine aggregates used in the study are listed in Table 8. Initially, six fine aggregate types were used in the HMA mixture designs, but acceptable mixture designs could not be obtained using the FA-5 and FA-6 aggregates. As a remedy, different dolomite (FA-5b) and traprock (FA-6b) sands were used. Mixtures using these alternate sands produced desirable volumetric properties. Mixtures with the original dolomite (FA-5) and traprock (FA-6) fine aggregates were not used in the study.

Table 8. Fine aggregate description, location, and properties.

Aggregate Type		Natural Sand A	Crushed Gravel Sand	Natural Sand B	Granite Sand	Dolomite Sand[1]	Traprock #16[1]	Dolomite Sand[2]	Traprock #13[2]
Designation		FA-1	FA-2	FA-3	FA-4	FA-5	FA-6	FA-5b	FA-6b
Source Location		Indiana	Indiana	Ohio	North Carolina	Indiana	Virginia	Indiana	Virginia
		Percent Passing							
Sieve Size (mm)	9.5	100	100	100	100	100	100	100.0	100.0
	4.75	100	100	100	99.0	98.4	95.0	100.0	96.0
	2.36	89.9	81.8	85.3	83.0	71.6	57.0	81.3	70.1
	1.18	59.2	50.6	61.9	57.0	31.7	34.0	51.7	49.1
	0.60	30.4	30.8	37.5	40.0	15.0	20.0	33.4	35.6
	0.30	9.0	17.2	18.0	27.0	6.0	12.0	19.5	25.7
	0.15	1.6	7.3	6.1	19.0	1.7	6.0	10.5	16.8
	0.075	0.8	3.5	3.2	13.0	0.7	2.7	5.7	9.7
Dry Bulk Specific Gravity (ASTM C128)		2.585	2.660	2.586	2.639	2.665	2.911	2.634	2.892
Apparent Specific Gravity (ASTM C128)		2.714	2.782	2.735	2.689	2.830	3.003	2.820	3.007
Water Absorption, % (ASTM C128)		1.8	1.6	1.9	0.7	2.2	1.0	2.5	1.3
Particle Size of p0.075 Materials									
▪ D60, microns		20.2	14.3	12.2	13.4	17.9	11.6	18.4	10.9
▪ D30, microns		9.7	7.0	5.6	6.6	8.4	5.4	8.2	5.0
▪ D10, microns		2.8	2.2	2.0	2.8	2.7	2.0	2.5	1.8
Uncompacted Void Content, %									
▪ Method A - ASTM C1252		40.3	46.1	41.9	49.1	45.0	48.8	46.8	49.2
▪ Method B - ASTM C1252		43.1	50.4	46.4	53.0	49.9	53.6	50.9	53.6
▪ VTM5		44.0	51.6	47.3	54.4	51.4	55.0	51.9	55.1
Methylene Blue Value (AASHTO TP57)		3.3	1.3	5.0	8.0	0.5	6.8	2.8	5.1
Clay Content by Sand Equivalent (AASHTO T104), %		98	90	82	70	100	86	79	70
Magnesium Sulfate Soundness, 5 cycles (AASHTO T104), %		9	13	24	13	9	7	30	13
Micro-Deval (Ontario Test Method LS-619), %		10.0	17.0	20.4	10.6	5.8	12.1	18.1	14.5

[1] Used during the initial HMA mixture design

Laboratory Sample Results

Before completing mixture designs, samples of each of the fine aggregates were received in the laboratory from the aggregate producers. These samples were tested for the various properties shown in Table 8.

The fine aggregate test results in Table 8 show a wide range in test values. The uncompacted voids contents were measured by three methods, Methods A and B of ASTM C 1252, and the VTM5 method. Equipment for the VTM5 method is basically a larger scale of the ASTM C 1252 apparatus. In Method A, voids were determined using a standard fine aggregate specimen consisting of 44 g of 2.36- to 1.18-mm, 57 g of 1.18- to 0.60-mm, 72 g of 0.60- to 0.30-mm, and 17 g of 0.30- to 0.15-mm size fractions. In Method B, the voids of three individual size fractions were determined (i.e., 2.36 mm to 1.18 mm, 1.18 mm to 0.60 mm, and 0.60 mm to 0.30 mm). These three individual measurements were averaged and reported as the Method B value. The VTM5 procedure is similar to the ASTM C 1252, Method B, procedure. Three size fractions, 2.36 to 1.00 mm, 1.00 to 0.60 mm, and 0.60 to 0.30 mm, were used. Results indicate that using 1.00 or 1.18 mm as a size break was insignificant because sieving the 2.36- to 1.18-mm fraction on the 1.00-mm sieve produced a negligible number of particles.

Particle size analyses were conducted on the p0.075 material using a Horiba LA500 Particle Size Analyzer. The sizes at 60 (D60), 30 (D30), and 10 (D10) percent of the fraction smaller than 0.075 mm were determined.

The MBV test is used to determine the amount and nature of potentially harmful materials, such as clay and/or organic material, that may be present in the p0.075 fraction. The sand equivalent test is used to measure the relative amount of clay-sized particles in a fine aggregate. Tests were performed on material passing the 4.75-mm sieve.

Magnesium sulfate soundness of each material was determined for material passing the 4.75-mm sieve. Material retained on the 2.36-, 1.18-, 0.60-, and 0.30-mm sieves were tested separately. The sample mass of each size fraction was approximately 300 g. Each sample was soaked for 16 to 18 hours and oven dried for 6 to 8 hours. After five cycles of soaking and drying, each sample was washed over the same sieve on which it was retained before the test. Material loss of each size fraction was computed as the percentage of the original mass. Based on the individual fraction loss, the weighted averages were computed based on the percentage of each size fraction in the original fine aggregate gradations.

Micro-Deval tests were performed in accordance with the Ontario Test Method LS-619. A 500-g mass of each sample was prepared by combining six individual size fractions of material between the 4.75- and 0.075-mm sieves. The amount of material on each size fraction was designed such that the combined sample had a fineness modulus of 2.8. In the test, samples were placed into the Micro-Deval jars and approximately 750 mL of water was added. The samples were allowed to saturate for 24 hours. Approximately 1,250 g of steel balls were then put into the jars containing the sample and water. The jars were placed on the Micro-Deval machine and rotated for 15 minutes. Samples were then washed over the 0.075-mm sieve and losses computed as the amount of material passing the 0.075-mm sieve expressed as the percentage of the original sample mass.

The bulk specific gravity and absorption values of the fine aggregates were determined according to the ASTM C 128 method.

Field Results

In addition to testing laboratory samples received from aggregate producers, aggregate samples collected from the HMA plant stockpiles and recovered from plant-produced mixtures and APT cores were also tested. The fine aggregate UVA and MBV test results are listed in Table 9. For the UVA results, there is good agreement between the field results and those obtained from laboratory samples. Some degradation did occur during mixture production and placement.

Similarity of fine aggregate UVA test results obtained for the laboratory mixture design aggregate and the aggregate from the HMA plant stockpiles suggests that degradation during material handling and transportation was not significant; however, increased degradation did occur during HMA production. The UVA of fine aggregates extracted from the HMA plant mixtures were consistently lower than those from the HMA plant stockpiles. The difference between the UVA values for the HMA plant stockpiles and the HMA plant mixtures was divided by the initial UVA of the aggregate sampled from the HMA plant stockpiles. This index indicated the amount of relative degradation resulting from HMA mixture production for each aggregate. As shown in Figure 5, the degradation is correlated to the initial UVA values. Fine aggregates with initially high UVA values appear to degrade more than do those with initially low UVA values.

There is reasonable agreement between field MBV values and those obtained on laboratory samples, except for FA-1, FA-4, and FA-6b aggregates. According to the AASHTO TP 57 test method, the mixture design results (laboratory samples) for FA-1 and FA-6b indicate that the aggregates should have excellent performance while the stockpile results indicate they are marginally acceptable. However, for the FA-4 aggregates, the stockpile results indicated acceptable performance, but the mixture design results were marginally acceptable. For

Table 9. Fine aggregate uncompacted voids content (Method A) and methylene blue values.

	Mixture ID	FA-1	FA-2	FA-3	FA-4	FA-5b	FA-6b
	Aggregate Type	Natural Sand A	Crushed Gravel Sand	Natural Sand B	Granite Sand	Dolomite Sand	Traprock Sand
		Uncompacted Voids Content, %					
Sample Source	Mixture Design	40.3	46.1	41.9	49.1	46.8	49.2
	HMA Plant Stockpile	39.2	47.6	42.0	48.9	46.2	49.3
	HMA Plant Mixture	38.7	45.1	40.9	46.2	45.0	46.6
	APT Cores	38.3	44.7	41.0	45.5	45.1	46.4
		Methylene Blue Value					
	Mixture Design	3.3	1.3	4.9	11.1	2.8	5.1
	HMA Plant Stockpile	7.8	1.3	5.5	5.8	2.8	6.9

these three aggregates, the materials delivered to the hot-mix plant apparently had fines that were somewhat different from the materials used in the mixture design.

Mixture Designs

All mixtures were designed using the Superpave volumetric mixture design method outlined in the Asphalt Institute Manual, SP-2, *Superpave Level I Mix Design,* and subsequent addendum. The number of design gyrations, N_{des}, and maximum number of gyrations, N_{max}, used for all designs were 100 and 160, respectively. This compaction effort was selected based on a design Equivalent Single Axle Load (ESAL) level of 3 to 30 million. Before compaction, all mixtures were aged for 2 hours at the compaction temperature. Design binder contents were selected at 4-percent air voids using specimens compacted to the N_{des} value. Once the design binder content was selected, additional specimens were compacted to N_{max} to ensure that the mixture density at this point was less than 98 percent of the maximum theoretical density.

A 12.5-mm NMAS was used for all mixtures because of its wide use by highway agencies for HMA surface mixtures. A single, unmodified asphalt binder, PG 64-22, was used in all mixtures, because it represents a typical neat binder grade for much of the United States and is included in most specifications. The experiments were designed to assess aggregate contribution to HMA mixture performance. The complete binder and mixture design data are included in Appendix B, which is available in *NCHRP Web-Only Document 82*.

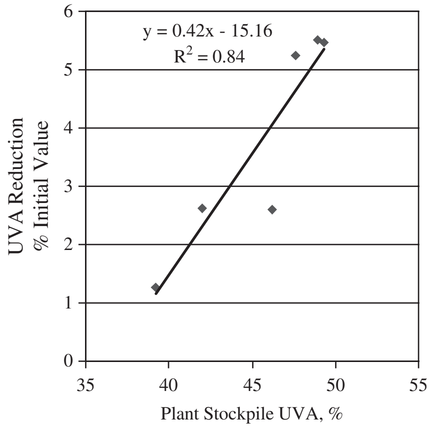


Figure 5. Fine aggregate degradation.

Coarse-Graded Mixtures

A natural sand with a UVA of 40.3 percent was used as the fine aggregate for all coarse HMA mixtures. The coarse-graded mixture design data are given in Table 10. Traprock #78 was initially used in the laboratory mixture design process. However, because of the low design binder content and VMA values, a different traprock stockpile (Traprock #88) was evaluated and a second mixture design conducted with this aggregate. This second mixture was used in APT testing.

Fine-Graded Mixtures

A natural uncrushed gravel with a UVA of 42.2 percent was used as the coarse aggregate for all fine-graded HMA mixtures

Table 10. Mixture design data (at 4 percent air voids).

Coarse-Graded Mixtures (Rutting and Fatigue)

Mix No.	P_b (P_{be})	G_{mm}	VMA		VFA		DP	%G_{mm}		G_{se}	G_{sb}
			N_{des}	N_{max}	N_{des}	N_{max}		N_{ini}	N_{max}		
CA-1	5.7 (4.7)	2.524	14.9	14.1	73.4	78.8	0.7	86.0	97.0	2.766	2.689
CA-2	6.1 (4.4)	2.447	14.0	13.2	71.5	76.7	0.9	85.4	96.9	2.688	2.566
CA-3	3.9 (2.9)	2.511	10.8	9.9	63.6	70.2	1.1	88.5	97.1	2.665	2.600
CA-4	5.8 (5.3)	2.461	16.0	15.1	75.1	80.8	0.7	87.0	97.1	2.691	2.652
CA-5[1]	3.7 (3.1)	2.664	11.4	10.3	66.2	75.1	1.2	89.1	97.4	2.838	2.786
CA-5b[2]	4.8 (4.3)	2.630	14.3	13.6	72.0	77.5	0.6	88.2	97.0	2.853	2.808

[1] Contained Traprock #78 and was not tested in the APT

[2] Contained Traprock #88 and was tested in the APT

Fine-Graded Mixtures (Rutting and Fatigue)

Mix No.	P_b (P_{be})	G_{mm}	VMA		VFA		DP	%G_{mm}		G_{se}	G_{sb}
			N_{des}	Req'd.	N_{des}	Req'd.		N_{ini}	N_{max}		
FA-1	6.0 (4.9)	2.438	15.3	14.0	74.0	65-75	0.4	90.8	96.7	2.671	2.594
FA-2	5.7 (5.3)	2.447	16.2		75.2		0.7	88.3	96.9	2.669	2.638
FA-3	5.8 (4.8)	2.444	15.0		73.6		0.8	88.9	97.1	2.672	2.602
FA-4	4.9 (4.5)	2.460	14.3		73.0		1.9	88.1	97.3	2.651	2.625
FA-5[3]	7.4 (5.7)	2.458	17.4		77.0		0.4	87.1	97.6	2.766	2.642
FA-6[3]	6.3 (5.8)	2.565	18.0		77.9		0.6	87.2	97.4	2.851	2.811
FA-5b[4]	6.3 (5.1)	2.454	15.8		74.7		0.7	87.5	97.4	2.705	2.620
FA-6b[4]	4.9 (4.3)	2.619	14.4		72.2		1.6	87.7	97.2	2.845	2.797

[3] Originally designed, but not tested in the APT

[4] Prepared using fine aggregates from different source or gradation and tested in the APT

Fine-Graded Mixtures (Moisture Susceptibility)

Mix No.	P_b	G_{mm}	VMA		VFA		DP	%G_{mm}		G_{se}	G_{sb}
			N_{des}	Req'd	N_{des}	Req'd		N_{ini}	N_{max}		
FAM-1	6.1	2.481	15.6	14.0	74.4	65-75	0.7	90.1	96.9	2.728	2.648
FAM-2	6.4	2.485	16.8		76.4		0.9	87.6	97.2	2.748	2.687
FAM-3	5.4	2.488	15.3		74.3		1.7	87.5	97.2	2.707	2.671
FAM-4[5]	6.5	2.588	18.3		78.4		0.8	86.8	97.3	2.894	2.848
FAM-4b[6]	5.3	2.650	15.0		73.3		1.4	86.7	97.3	2.904	2.835
FAM-5	6.1	2.469	15.9		74.8		0.7	88.9	96.8	2.715	2.650

[5] Originally designed, but not tested in the APT

[6] Prepared using fine aggregates from the same source, but different gradation and tested in the APT

in the rutting and fatigue studies. The mixture design data are shown in Table 10.

Mixtures FA-5 and FA-6 are dolomite and traprock fine-graded aggregate mixtures, respectively. The compacted HMA mixtures using the original dolomite (Mixture FA-5) and traprock (mixture FA-6) sands had high VMA values resulting in voids filled with asphalt (VFA) values above the maximum allowed by specification. To remedy this problem, different dolomite and traprock fine aggregate stockpiles were identified. These two new fine aggregates (FA-5b, FA-6b) had higher percentages of p0.075 material than the original materials (see Table 8). Mixture design results for these mixtures are shown in Table 10. Both have VFA values within the specification limits. Their dust proportions also increased considerably.

Moisture Susceptibility Mixtures

Five of the six fine aggregates used in the rutting study were selected for the moisture susceptibility experiment. Each fine aggregate was combined with a common, crushed dolomite coarse aggregate and mixture designs were completed; mixture design data are given in Table 10.

Accelerated Pavement Test Results

Accelerated pavement tests were conducted at the APT facility at the Indiana DOT Research Division in West Lafayette, Indiana. Up to four test lanes can be constructed in this facility at a time using conventional paving equipment. Details of the facility, test section construction, and data collection can be found in Appendix D, which is available in *NCHRP Web-Only Document 82*.

Rutting

Rutting was monitored by recording transverse surface profiles at increments of traffic applied with dual tires and without wander. These profiles were captured with software that automatically reduces and stores the data in a spreadsheet (*7*). An initial profile was recorded before traffic application and used as the baseline reference for determining rutting from subsequent profiles.

Each test lane was trafficked until a total rut depth of 20 mm was achieved or 20,000 wheel passes were applied, whichever occurred first. Profiles were recorded at nine locations over the length of a given test section; however, three consecutive sections nearest the center of the test section (Sections 4, 5, and 6, see Figure D.8) were averaged and used as a single result in the subsequent analyses. These three locations were used because the APT wheel carriage travels at a constant speed over this portion of the test lane.

Performance

Coarse-Graded Mixtures. Rutting in the APT as a function of wheel passes for the coarse-graded mixtures is shown in Figure 6. In addition to total rut depth, the rut rate was also computed. Rut rate is simply the slope of the regression line and has units of mm/log(N) where N is the number of wheel passes. Rutting data for mixtures CA-1, CA-2, CA-3, and CA-5b exhibited a bilinear trend; these data were fitted by two logarithmic functions. The rut rate during the early traffic stage is the slope of the first regression line while the rut rate during later traffic stage is the slope of the second regression line. The regression equations for all mixtures are given in Table 11.

Rutting performance parameters for coarse-graded mixtures are shown in Table 12. These parameters include total rut depth at 5,000 and 20,000 wheel passes as well as the rut rate during early and later traffic stages (early and late stages are defined by the N break point shown in the table). As an example, for mixture CA-2, early traffic is where N<200, while late traffic is N>200. For each of the rutting performance parameters, mixtures are ranked from 1 (best) to 5 (worst). The mixtures were ranked by four parameters; three of the mixtures were ranked the same by the four parameters; however, the early rut rate inverts 1 and 2, and 3 and 4. This would seem to indicate that after approximately 200 wheel passes are applied with the APT, one can obtain a good indication of the relative rutting rank of an HMA mixture.

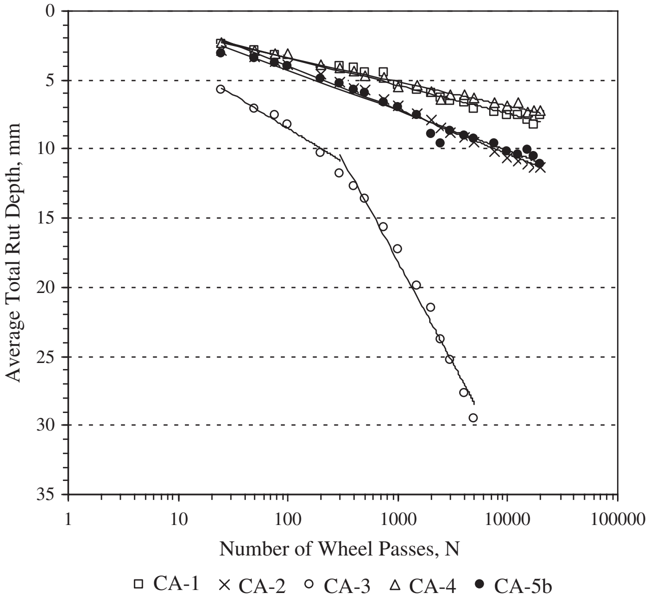


Figure 6. Coarse-graded mixture rut depth development.

Fine-Graded Mixtures. APT rutting of the fine-graded mixtures is shown in Figure 7. Testing on Mixture FA-1 (Natural Sand A) was terminated at 1,000 wheel passes because of excessive total rut depth. Testing on Mixture FA-2 was terminated inadvertently at 12,500 wheel passes; however, the trend for this mixture shows that it would have most likely accommodated additional passes with a minimal increase in rutting.

Rut development curves for fine-graded mixtures also appear to be bilinear. As above, the first regression line represents early traffic stage rutting and the second later traffic

Table 11. Coarse-graded mixture rutting regression equations.

Mixture ID	Regression Equation	Condition
CA-1	Total rut depth = 1.56 log(N) + 0.28	for N < 400
	Total rut depth = 2.25 log(N) -1.50	for N > 500
CA-2	Total rut depth = 1.89 log(N) + 0.17	for N < 200
	Total rut depth = 3.56 log(N) -3.74	for N > 200
CA-3	Total rut depth = 4.88 log(N) – 1.27	for N < 200
	Total rut depth = 14.72 log(N) – 26.02	for N > 200
CA-4	Total rut depth = 1.75 log(N) – 0.13	for all N
CA-5b	Total rut depth = 2.09 log(N) – 0.01	for N < 200
	Total rut depth = 3.27 log(N) – 2.66	for N > 200

Table 12. Coarse-graded mixture rutting performance.

Mixture ID	Total Rut Depth at 5,000 Passes		Total Rut Depth at 20,000 Passes		Total Rut Rate (mm/log(N))				Overall
	mm	Rank	mm	Rank	Early traffic	Rank	Later Traffic	Rank	Rank
CA-1	7.1	2	7.6	2	1.6	1	2.3	2	2
CA-2	9.5	4	11.3	4	1.9	3	3.6	4	4
CA-3	29.5	5	—[1]	—[1]	4.9	5	14.7	5	5
CA-4	6.3	1	7.2	1	1.8	2	1.8	1	1
CA-5b	9.2	3	11.1	3	2.1	4	3.3	3	3

[1] Tested to only 5,000 wheel passes.

stage rutting. Regression equations for the data are given in Table 13.

Table 14 lists total rut depths at 1,000; 5,000; and 20,000 wheel passes and rutting rates for both early and later traffic stages. These rutting parameters were used as the basis for ranking mixture performance from 1 (best) to 6 (worst). Overall rank is the rank appearing the most number of times for each mixture. Three of the parameters (rut depth at 5,000 and 20,000, and rut rate at later traffic) rank the mixtures the same. The remaining two parameters rank the mixtures the same, but have 3 and 4 inverted from the previous three parameters. Again, it appears that a good indication of the rut resistance can be gained after approximately 200 wheel passes of the APT.

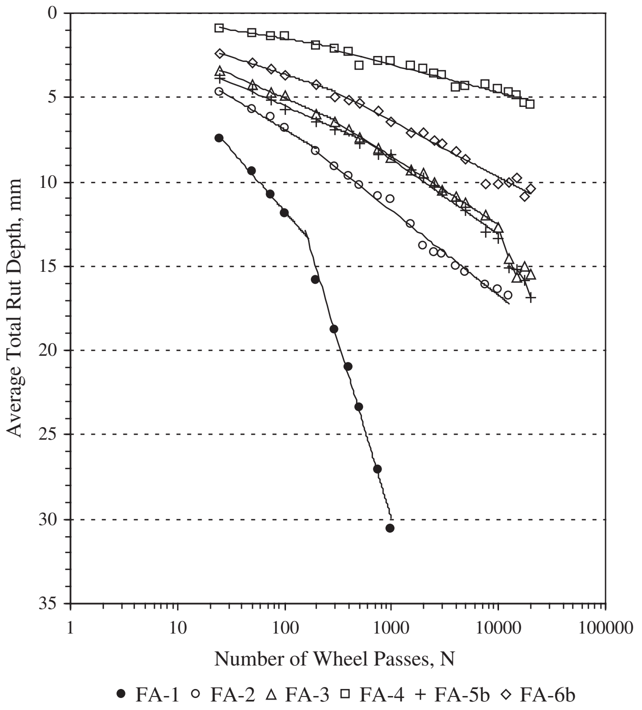


Figure 7. Fine-graded mixture rut depth development.

Moisture Susceptibility

Before APT testing, six cores were taken from each of the moisture susceptibility test lanes. In-place densities and air voids of the test lanes were determined from the cores, which were then used to test the plant-produced mixtures for moisture susceptibility in accordance with AASHTO T 283. In addition to moisture conditioning, the conditioned specimens were also subjected to one freeze/thaw cycle before being tested in indirect tension.

The AASHTO T 283 test results are shown in Table 15. Averages of VTM ranged from 7.1 to 9.9 percent. Degree of saturation for the conditioned specimens varied from 67.4 to 78.2 percent. The tensile strength ratio (TSR) [the ratio of the indirect tensile strength of conditioned specimens to that of dry (unconditioned) specimens] varied from 1.10 to 0.79. Some specimens were loaded until they cracked. The interior surfaces were then inspected for stripping and photographs were taken. Visual observation indicated that stripping occurred. Typically, conditioned specimens lost their glossy appearance and the interior surface exhibited a brownish tint (see Figures E.1 to E.5 in Appendix E provided in *NCHRP Web-Only Document 82*). Stripping in terms of lost binder film was also observed in specimens with dolomite coarse aggregate.

Performance

Rutting accumulation for all test lanes is shown in Figure 8. A 20-mm total rut depth criteria was adopted for traffic termination. Mixture FAM1 (Natural Sand A) was terminated at 1,000 wheel passes, while mixture FAM5 (Natural Sand B) reached the 20-mm total rut depth criteria and was terminated at 7,500 wheel passes. The FAM5 mixture exhibited a significant increase in rutting between 5,000 and 7,500 wheel passes. There was also an increase in rutting after 3,000 wheel passes on mixture FAM3 (Granite Sand). In general, this type of rutting does not occur in dry rutting tests and may be an indication of stripping. The rutting data for mixtures FAM1, FAM2, and FAM4 do not show a change in rate of rutting accumulation.

Table 13. Fine-graded mixture rutting regression equations.

Mix ID	Regression Equation	Condition
FA-1	Total rut depth = 7.26 log(N) - 2.78	for N < 100
	Total rut depth = 21.10 log(N) - 33.33	for N > 200
FA-2	Total rut depth = 3.81 log(N) – 0.74	for N < 200
	Total rut depth = 5.00 log(N) – 3.29	for N > 300
FA-3	Total rut depth = 2.78 log(N) – 0.52	for N < 200
	Total rut depth = 4.02 log(N) – 3.56	for N > 300
FA-4	Total rut depth = 1.06 log(N) – 0.61	for N < 200
	Total rut depth = 1.63 log(N) – 1.84	for N > 300
FA-5b	Total rut depth = 2.75 log(N) – 0.004	for N < 400
	Total rut depth = 4.45 log(N) – 4.70	for N > 500
FA-6b	Total rut depth = 2.10 log(N) – 0.57	for N < 200
	Total rut depth = 3.31 log(N) – 3.54	for N > 300

Table 14. Fine-graded mixture rutting performance.

Mix ID	Rut Depth at 1,000 Passes (mm)	Rank	Rut Depth at 5,000 Passes (mm)	Rank	Rut Depth at 20,000 Passes (mm)	Rank	Total Rut Rate (mm/log (N))				Overall Rank
							Early Traffic		Later Traffic		
								Rank		Rank	
FA-1	30.6	6	NA[1]		NA[1]		7.3	6	21.1	6	6
FA-2	11.1	5	15.4	5	18.1[2]	5	3.8	5	5.0	5	5
FA-3	8.6	4	11.3	3	15.5	3	2.8	4	4.0	3	3
FA-4	2.8	1	4.3	1	5.4	1	1.1	1	1.6	1	1
FA-5b	8.4	3	11.7	4	16.8	4	2.8	3	4.5	4	4
FA-6b	6.4	2	8.7	2	10.4	2	2.1	2	3.3	2	2

[1] Testing was terminated at 1,000 wheel passes because total rut depth was more than 20mm

[2] Testing was inadvertently terminated at 12,500 wheel passes; total rut depth at 20,000 wheel passes was predicted using the regression equation.

The rutting data were also plotted as a function of the log of the number of wheel passes (see Figure 9). This plot shows that the rutting of mixtures FAM1, FAM2, FAM3, and FAM5 appears to be bilinear. As a result, data for these mixtures were fitted with two logarithmic regression lines. The regression equations for all mixtures are shown in Table 16.

Table 17 shows total rut depths for 1,000; 5,000; and 20,000 wheel passes and total rutting rates for early and later traffic stages. These rutting parameters were used in ranking performance. Among these rutting parameters, only total rut depth at 1,000 wheel passes and total rutting rate are available for all mixtures. Based on these rutting parameters, the mixtures were ranked from 1 (best) to 5 (worst). Overall performance rank from best to worst are FAM2 (Crushed Gravel Sand), FAM3 (Granite Sand), FAM4 (Traprock Sand), FAM5 (Natural Sand B), and FAM1 (Natural Sand A).

Table 15. AASHTO T 283 and MBV test results.

Mixture ID	FAM1	FAM2	FAM3	FAM4	FAM5
Aggregate Type	Natural Sand A	Crushed Gravel Sand	Granite	Traprock	Natural Sand B
	Dry Specimens				
Tensile Strength, kPa	452.3	689.6	837.7	652.8	808.7
Average Air Voids, %	8.4	9.1	8.3	9.9	7.1
	Conditioned Specimens				
Tensile Strength, kPa	499.4	621.2	708.1	537.0	640.2
Average Air Voids, %	9.1	9.2	8.2	9.4	7.5
Degree of Saturation, %	70.9	78.2	67.4	69.2	71.4
TSR	1.10	0.90	0.85	0.82	0.79
Methylene Blue Value	3.3	1.3	8.0	5.1	5.0

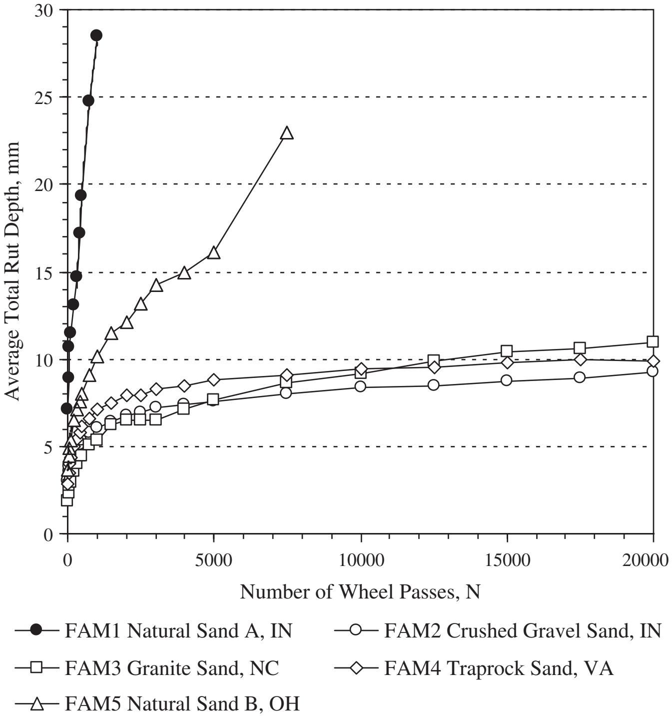


Figure 8. Rut depth development.

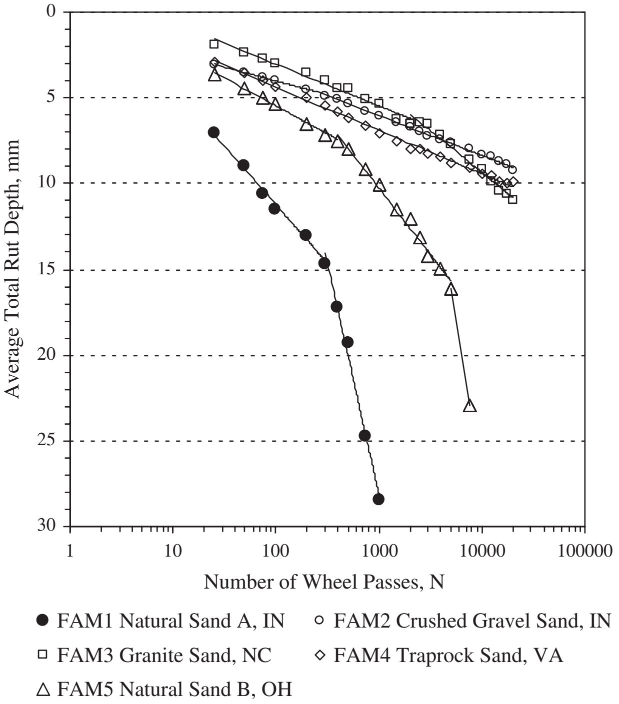


Figure 9. Rut depth development.

Table 16. Regression equations.

Mix ID	Regression Equation	Condition
FAM1	Total rut depth = 6.82 log(N) - 2.40	for N < 200
	Total rut depth = 26.88 log(N) – 52.53	for N > 300
FAM2	Total rut depth = 1.62 log(N) + 0.77	for N < 200
	Total rut depth = 2.31 log(N) – 0.89	for N > 300
FAM3	Total rut depth = 2.18 log(N) – 1.32	for N < 1000
	Total rut depth = 4.88 log(N) – 10.16	for N > 2000
FAM4	Total rut depth = 2.53 log(N) – 0.69	for all N
FAM5	Total rut depth = 3.31 log(N) – 1.14	for N < 400
	Total rut depth = 8.03 log(N) – 13.94	for N > 500

When APT traffic application was complete, cores were collected and split open to determine visually if stripping had occurred. Photographs of the split surfaces are shown in Figures E.6 through E.10 (Appendix E). Visual inspection revealed no stripping of FAM1, FAM2, and FAM4 cores. There was a loss of glossiness on the split surfaces of FAM3 (Granite Sand) and FAM5 (Natural Sand B). These two mixtures also exhibited signs of stripping in their rutting data. Signs of stripping were observed on the bottom of cores taken from all of the test lanes.

Fatigue

Relationships between fatigue cracking and coarse and fine aggregate properties were evaluated through construction and testing of six mixtures in the APT as indicated in Table 18. Fatigue performance was characterized by percentage of fatigue cracking in the wheel path. The experiment is similar to the rutting experiment, with the exception that a conventional flexible pavement was installed consisting of 100 mm of HMA and 200 mm of a crushed stone on a subgrade. An attempt was made to control the pavement test temperature at approximately 10 to 20°C. However, because of the unavailability of a cooling system, this temperature range was exceeded for the tests conducted in June and July.

The six experimental fatigue mixtures listed in Table 18 were selected based on the earlier APT rutting performance and aggregate quality. Mixtures were selected to have as wide a range in both rutting performance and aggregate quality as possible. Of the six mixtures, three were coarse-graded and three were fine-graded. Mixture FA-1 (Natural Sand A) had the poorest aggregate qualities and exhibited the worst rutting performance. The mixture was included, even though such a mixture probably would be replaced in the field before failing in fatigue. Testing mixtures with the greatest range of aggregate quality, as determined by the aggregate test methods, were expected to provide the most useful information for determining the strength of the relationships between the aggregate properties and fatigue performance.

Table 17. Moisture susceptibility rutting performance.

Mix ID	Total Rut Depth at 1000 Passes (mm)	Rank	Total Rut Depth at 5000 Passes (mm)	Rank	Total Rut Depth at 20000 Passes (mm)	Rank	Total Rut Rate (mm/log(N))				Overall Rank
							Early Traffic	Rank	Late Traffic	Rank	
FAM1	28.5	5	—[1]		—[1]		6.8	5	26.9	5	5
FAM2	6.1	2	7.6	1	9.2	1	1.6	1	2.3	1	1
FAM3	5.4	1	7.7	2	11.0	2	2.2	2	4.9	3	2
FAM4	7.1	3	8.8	3	9.9	3	2.5	3	2.5	2	3
FAM5	10.1	4	16.1	4	—[2]		3.3	4	8.0	4	4

[1] Testing terminated at 1,000 wheel passes; 20 mm rut depth reached.

[2] Testing terminated at 7,500 wheel passes; 20 mm rut depth reached.

Based on rutting performance from best to worst, the fine-graded mixtures selected for the fatigue study were FA-4 (Granite), FA-3 (Natural Sand B), and FA-1 (Natural Sand A). Likewise, coarse-graded mixtures were CA-4 (Granite), CA-2 (Limestone), and CA-3 (Uncrushed Gravel).

Test Section Construction

The first step in constructing the fatigue test sections involved removing the previous rutting test sections. The underlying Portland concrete cement (PCC) slabs were then removed, along with the underlying pea gravel fill. Subsequently, a subgrade soil was installed and compacted to a depth of 1.5 m. Moisture was added to the soil, and the two were mixed using two motorized tillers. Compaction was accomplished using vibrating plate compactors. The Proctor curve for the soil is shown in Figure 10. An attempt was made to compact the soil on the wet side of optimum in order to render the soil more plastic and thereby aid the pavement fatigue process. The optimum moisture content is approximately 15 percent and the soil was compacted at 18- to 20-percent moisture. As can be seen from Figure 11, the California bearing ratio (CBR) value for moisture content in the desired range was approximately 2. The result was a "springy" subgrade that was indeed plastic. In fact, the subgrade was so "springy" that construction was made difficult. It was later discovered that the drain for the APT pit was clogged and that excess moisture could not be drained from the soil. Once the drain was repaired, the excess moisture drained and the soil became stiffer.

Table 18. Fatigue experiment design.

Aggregate Performance Tests Category	Aggregate Type	
	Coarse Aggregate	Fine Aggregate
Coarse Aggregate Test Methods Evaluation (Coarse-Graded Mixtures)	CA-2 (Limestone)	Natural Sand A
	CA-3 (Uncrushed Gravel)	
	CA-4 (Granite)	
Fine Aggregate Test Methods Evaluation (Fine-Graded Mixtures)	Uncrushed Gravel	FA-1 (Natural Sand A)
		FA-3 (Natural Sand B)
		FA-4 (Granite)

After subgrade compaction, a geotextile fabric was placed on the subgrade and an unbound, crushed stone base course was placed and compacted such that the finished base course was 200 mm in depth. The 100-mm deep HMA test section mixtures were then constructed on the base course using conventional HMA construction techniques as described in Appendix D (available in *NCHRP Web-Only Document 82*).

Fatigue Testing

Performance data were collected throughout the loading process, including transverse profiles when needed. Longitudinal and fatigue cracking were measured by counting the number of cracks that developed during loading. The frequency of measurement varied with test section and depended on how quickly the cracking occurred. From a fatigue standpoint, the criterion was established that a test

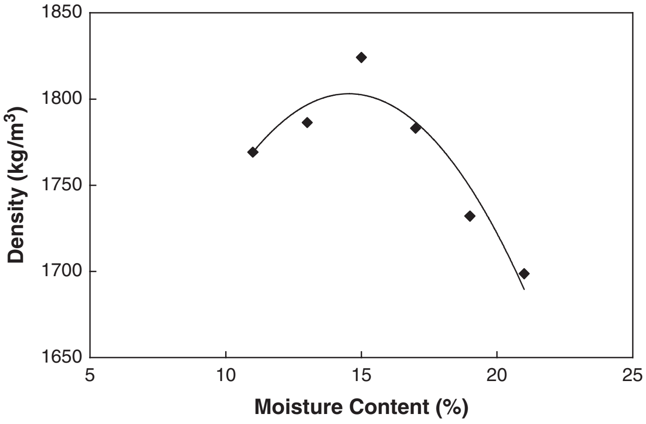


Figure 10. Subgrade Proctor curve.

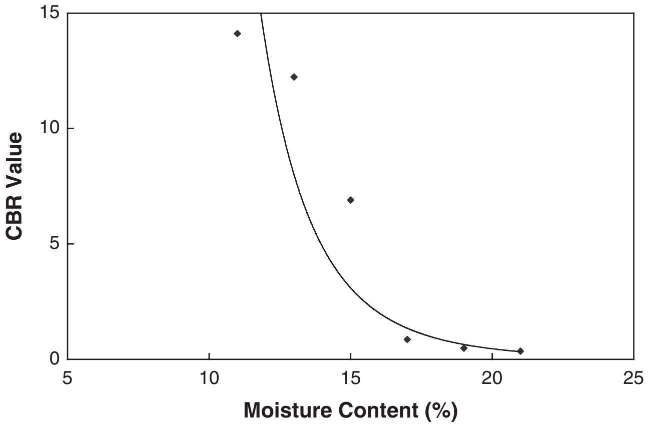


Figure 11. Soil CBR values.

section was considered to have failed when the center one-third of the test section had exhibited fatigue cracking exceeding 10 percent of the area. This center area of the test lane was chosen because it was expected to have the most uniform mixture properties. Random wheel wander was also incorporated during testing to help avoid rutting; it was done by a random number generator within the APT control program. The fatigue results are shown in Table 19.

The first test section to be trafficked in the fatigue experiment was the CA-3 (Uncrushed Gravel) mixture. Loading consisted of a 40 kN load on dual wheels with a tire pressure of 690 kPa. The section deformed quickly and failed after only 1,000 passes. The failure is shown in Figure 12. Three to four cracks appear in the center one-third of the test lane; however, inspection of the failure revealed that the subgrade failed before the fatigue properties of the mixture could be fully tested.

Testing began on the next test section, CA-2 (Limestone), with a reduced load of 26.7 kN applied to the dual wheels and the tire pressure reduced to 620 kPa. After 8,000 passes, no signs of cracking were observed, so the load was increased to 33.3 kN and an additional 12,000 passes were applied. The load was then increased to 40 kN and the tire pressure increased to 690 kPa. Testing was stopped at 80,000 wheel passes because the section showed signs of subgrade failure near the edge of the test pit. Minor fatigue cracking developed in the section during application of the last 60,000 wheel passes as shown in Figure 13. Subgrade failure was repaired and traffic continued; however, damage at the edge continued to accumulate and it was necessary to discontinue trafficking of the section to avoid damage to the APT equipment.

The third mixture to undergo fatigue testing was the FA-1 mixture produced using Natural Sand A. This test section proved difficult to compact during construction because of mixture tenderness and the resiliency of the section against which it was being compacted. As a result, numerous cracks occurred during compaction. These "roller" cracks were painted with a lime-water solution so as to appear white to distinguish them from cracks caused by APT loading. The existence of these cracks from the outset of the testing most certainly influenced the fatigue results of the section. The section before traffic is

Table 19. Fatigue results.

Test Mixture	Percent Cracking	Average Total Rut Depth (mm)	Number of Wheel Passes
CA-2	1	None	80,000
CA-3	30	None	1,000
CA-4	None	40.0	20,000
FA-1	25	None	2,000
FA-3	None	33.6	20,000
FA-4	None	43.8	20,000

Figure 12. CA-3 test section after 1,000 wheel passes.

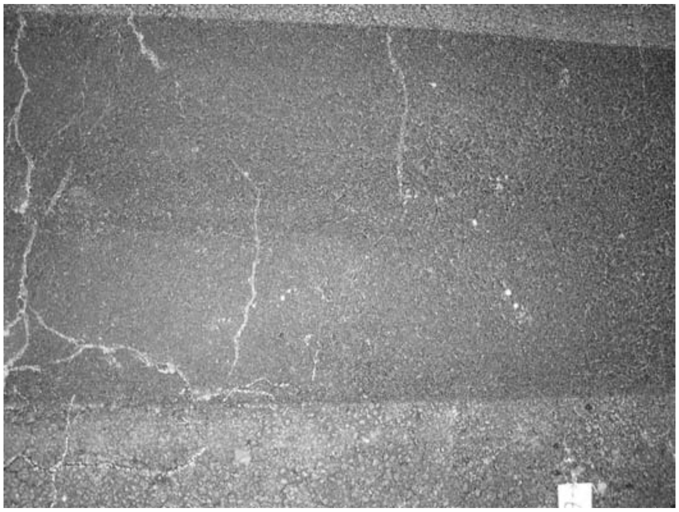


Figure 13. CA-2 test section after 80,000 wheel passes.

Figure 14. Initial FA-1 test section.

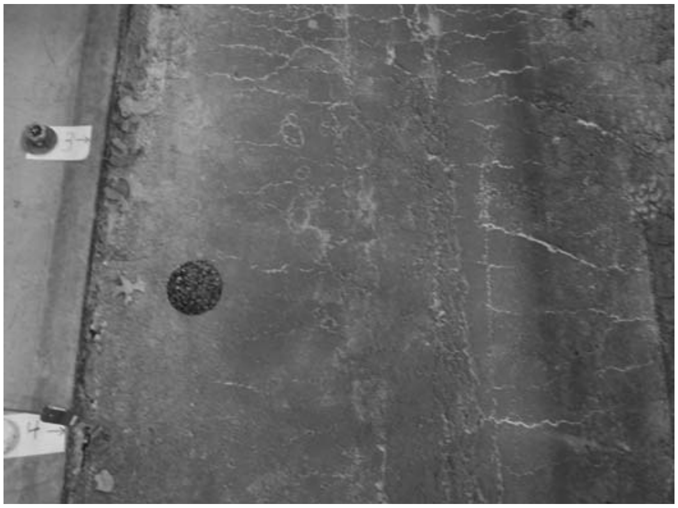


Figure 15. FA-1 test section after 2,000 wheel passes.

shown in Figure 14. Trafficking of this test section began with an applied load of 31.1 kN and tire pressure of 690 kPa. As shown in Figure 15, the section exhibited substantial fatigue cracking when the testing was stopped after 2,000 passes.

Fatigue testing of mixtures CA-2, CA-3, and FA-1 was finally completed in June 2003, and subsequently, the test sections were removed. In July 2003, test sections of mixtures FA-3 (Natural Sand B), FA-4 (Granite), and CA-4 (Granite) were placed in the APT facility. Testing immediately began on the FA-3 mixture; rutting began to develop with no sign of fatigue cracking. Without the ability to control temperature in the APT facility, the test pavement temperatures were well over the desired temperature range of 10 to 20°C. This affected the fatigue results of the last three APT test sections. Finally, in August 2003, trafficking was discontinued because 20,000 passes were applied on each section with no evidence of significant fatigue cracking; however, each section did show rutting. The FA-3 mixture (Natural Sand B) had an average rut depth of 33.6 mm, while the FA-4 (Granite) and CA-4 (Granite) mixtures had average rut depths of 43.8 and 40.0 mm, respectively. Recently, cooling capabilities have been installed in the APT building and fatigue tests have been conducted. These tests indicate that, had the desired temperature range been maintained during the testing of the FA-3, FA-4, and CA-4 mixtures, these mixtures probably would have sustained 80,000 to 100,000 APT wheel passes before failing in fatigue.

CHAPTER 3

Interpretation, Appraisal, and Application

The primary objective of NCHRP Project 4-19(2) was to validate performance-related aggregate tests recommended by Kandhal and Parker (*1*). A discussion of the relationships of these aggregate test methods to mixture performance and aggregate properties follows.

Coarse-Graded Mixtures

Kandhal and Parker recommended the coarse aggregate UVA (AASHTO TP 56) and the FOE21 as the first and second best coarse aggregate tests related to rutting, respectively. They also found that FOE51 was an important variable, but it was not recommended because of the narrow range in results and did not provide a clear measure of a coarse aggregate's performance.

The regression equations developed by Kandhal and Parker (*1*) suggested that as UVA increases, both rutting and rate of rutting decrease. An increase in FOE21 causes a reduction of mixture stiffness and an increase in the rate of rutting. In summary, Kandhal and Parker (*1*) suggested that high coarse aggregate UVA and low FOE21 values are desirable for improved pavement performance. The current research also found a strong correlation between FOE21 and coarse aggregate UVA ($r = 0.786$, $p\text{-value} = 0.064$). The correlation suggests that the FOE21 value significantly influences the orientation and structure of coarse aggregate as reflected by the UVA values.

Because the two variables, coarse aggregate UVA and FOE21, are highly correlated, it is not appropriate to use both as independent variables in a statistical model. Moreover, the conclusion drawn by Kandhal and Parker (*1*) about the effect of FOE21 on pavement permanent deformation can become unrealistic. In fact, a high percentage of FOE21 aggregate particles are desirable for HMA pavements.

For the current study, a correlation matrix was developed for eight of the coarse aggregate tests and three rutting parameters. The total rut depth at 20,000 wheel passes was not included because the CA-3 (Uncrushed Gravel) mixture has no data at that point. The matrix is shown in Table 20. The correlations between the rutting parameters and the coarse aggregate UVA and UVB are significant. Each of the test methods was assigned a descriptive ranking as shown in Table 20. The ranking was determined by assigning a value from 0 to 9 depending on the correlation coefficient between the given test method and the rutting parameters. For example, if the correlation coefficient for a given test was higher than 0.80, but less than 0.90, the descriptive ranking was assigned as 8. The ranking for a given test method was then averaged for the rutting parameters used. Thus the higher the ranking number, the better the aggregate test relates to HMA rutting performance in the APT. Table 20 shows that the coarse aggregate UVA and UVB have the highest descriptive rankings, 9.0, while the FOE21 has the next closest at 8.0. The remaining aggregate tests have much lower rankings.

Plots of the three permanent deformation parameters and the coarse aggregate UVA values are shown in Figures 16 through 18. These figures suggest that higher coarse aggregate UVA values result in greater resistance to permanent deformation. The plots also indicate that continued increase in rut resistance becomes negligible for UVA values higher than approximately 50 percent.

Although the flat or elongated and flat and elongated values at the 3:1 ratio (FOE31and F&E31) were expected to correlate positively with FOE21, the data shown in Table 20 indicated that neither of the 3:1 ratios correlates well to the rutting parameters. The relationships between rutting and FOE31 or F&E31 suggest that factors other than particle shape contribute to explaining rut resistance. Coarse aggregate UVA appears to successfully capture the effect of particle shape, surface characteristics, or mineralogy on rutting performance of the HMA mixtures tested in this research.

To further investigate interaction of aggregate tests, multiple regression analyses were performed between rutting parameters and coarse aggregate test data. The response variables included total rut depth at 5,000 wheel passes and total rut rate

Table 20. Correlation matrix of coarse aggregate properties and rutting parameter.

Coarse Aggregate Property	Rutting Parameter			
	Total Rut Depth @ 5000 Passes	Early Rut Rate	Later Rut Rate	Descriptive Ranking
UVA	-0.947 0.015	-0.963 0.008	-0.945 0.015	9.0
UVB	-0.983 0.003	-0.995 0.0004	-0.983 0.003	9.0
LALOSS	-0.161 0.796	-0.242 0.695	-0.151 0.809	1.0
MDEV	0.364 0.547	0.291 0.635	0.372 0.537	2.7
FOE21	-0.826 0.086	-0.845 0.071	-0.819 0.090	8.0
FOE31	-0.360 0.552	-0.436 0.463	-0.351 0.563	3.3
F&E31	-0.476 0.418	-0.534 0.354	-0.467 0.428	4.3
F&E51	-0.468 0.426	-0.550 0.337	-0.462 0.434	4.3

for both early and late traffic. The results, shown in Table 21, indicate that the coarse aggregate UVA is a good indicator of HMA mixture rutting performance. When the results from other aggregate properties such as FOE21 were combined with UVA, the R^2 does not change significantly. This finding indicates that the coarse aggregate UVA alone is a sufficient predictor of HMA mixture rutting performance. However, it should be recognized that these data were developed for coarse-graded mixtures using a few coarse aggregate types.

To determine sensitivity of coarse aggregate UVA to traffic levels, the effect of coarse aggregate UVA on the number of APT wheel passes to reach total rut depths of 3.5 and 7.0 mm was examined; results are shown in Figures 19 and 20, respectively. The 7.0-mm total rut depth was selected because it was the minimum total rut depth exhibited at 20,000 wheel passes during the APT tests; the 3.5-mm total rut was arbitrarily chosen as one-half of the 7.0-mm rut depth.

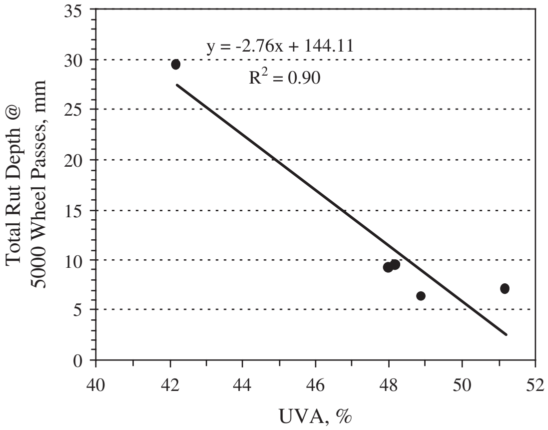


Figure 16. Rut depth/coarse aaggregate UVA relationship.

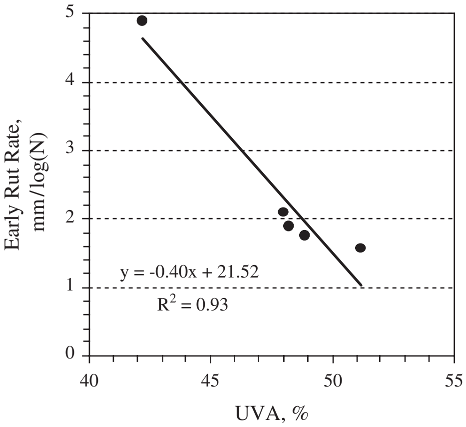


Figure 17. Early rut rate/coarse aggregate UVA relationship.

The relationships between coarse aggregate UVA and APT traffic to reach 3.5- and 7.0-mm rut depths appear to be exponential and significant. The regression equation shown in Figure 19 indicates the number of APT wheel passes to reach a 3.5-mm total rut depth increases by approximately 53 passes for an increase in coarse aggregate UVA from 45 to 50 percent. Figure 20 shows the number of wheel passes increases by approximately 3,715 to reach a 7.0-mm total rut depth for the same 5 percent increase in coarse aggregate UVA. The exponential relationship would seem logical up to a point. For example, for coarse aggregate UVA values between 35 and 40 percent, the number of wheel passes to reach a given rut depth increases very little. However, the increase is significant for coarse aggregate UVA values between 45 and 50 percent. In practice, most crushed aggregates appear to have coarse aggregate UVA values less than approximately 50 percent.

Figure 21 presents the APT rut depths as a function of the number of wheel passes for each of the coarse aggregates used in the study. The coarse aggregate UVA values are somewhat

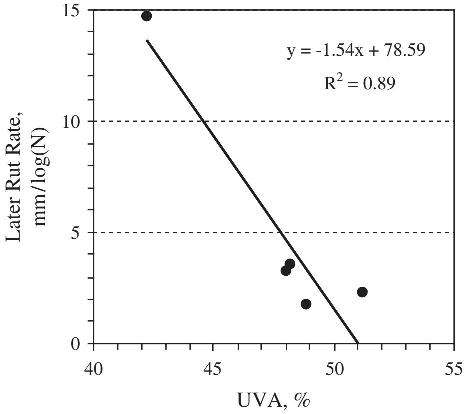


Figure 18. Late rut rate/coarse aggregate UVA relationship.

Table 21. Regression analyses between rutting parameters and coarse aggregate UVA.

Response Variable	Predictor Variable	Regression Equation	R^2	p-value
Total Rut Depth at 5,000 Wheel Passes	UVA	164.54 – 3.19 UVA	0.96	0.004
Early Rut Rate	UVA	23.6277 – 0.44 UVA	0.95	0.005
Later Rut Rate	UVA	90.14 – 1.78 UVA	0.96	0.004

grouped. The coarse aggregates with UVA values of 49 and 51 percent resulted in a rut depth of approximately 6 mm at 20,000 APT wheel passes; the two coarse aggregates with UVA values of 48 percent resulted in a total rut depth of about 10 mm after 20,000 passes; and the rounded gravel with a coarse aggregate UVA of 42 percent resulted in a rut of 30 mm at 5,000 wheel passes. These data suggest that a minimum coarse aggregate UVA value of 45 percent would be desirable.

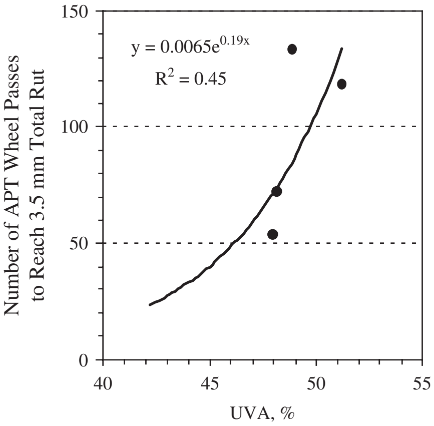


Figure 19. Effect of coarse aggregate UVA on traffic (3.5 mm).

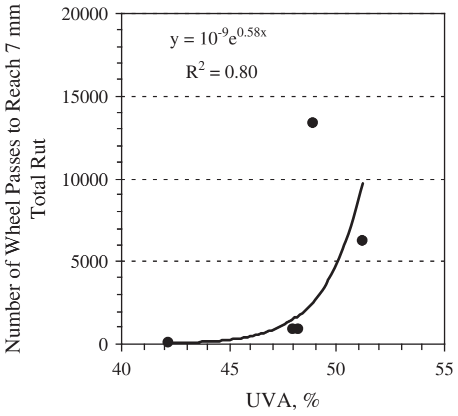


Figure 20. Effect of coarse aggregate UVA on traffic (7 mm).

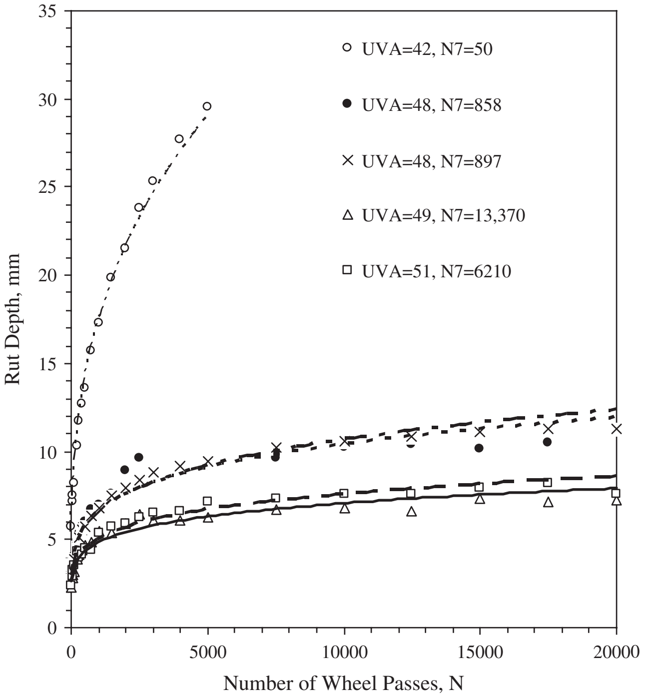


Figure 21. Effect of coarse aggregate UVA on rut depth.

Fine-Graded Mixtures

In *NCHRP Report 405*, correlations between fine aggregate properties and SST results were found to be poor; only the GLWT results were used for recommending fine aggregate UVA as a predictor of mixture rutting performance. In the current study, HMA aggregates were tested using ASTM C 1252, Methods A and B, as well as VTM5. These three tests are significantly correlated and give similar correlations with APT permanent deformation results.

Rutting parameters used to evaluate fine-graded HMA mixtures' rutting potential were rut depths at 1,000; 5,000; and 20,000 APT wheel passes, and early and late traffic rutting rates. Correlation analyses were conducted between the rutting parameters and the fine aggregate test results. In addition to the UVA, UVB, and VTM5 tests, other aggregate tests incorporated in the analysis were Micro-Deval (MDEV); magnesium sulfate soundness (MGSO4); and D60, D30, and

Table 22. Correlation matrix between fine aggregate properties and rutting parameters.

		UVA	UVB	VTM5	MDEV	MGSO4	D60	D30	D10
Total rut depth	1,000 passes	-0.809 0.051	-0.847 0.033	-0.838 0.037	-0.393 0.441	-0.393 0.441	0.736 0.096	0.773 0.071	0.393 0.441
	5,000 passes	-0.372 0.538	-0.511 0.379	-0.517 0.372	0.765 0.132	0.272 0.659	0.315 0.606	0.292 0.634	0.412 0.490
	20,000 passes	-0.715 0.286	-0.666 0.334	-0.685 0.315	0.948 0.052	0.906 0.094	0.466 0.534	0.312 0.688	0.360 0.641
Early Rut Rate		-0.793 0.0599	-0.846 0.034	-0.839 0.037	-0.287 0.581	-0.354 0.492	0.727 0.102	0.762 0.078	0.326 0.529
Later Rut Rate		-0.795 0.059	-0.822 0.045	-0.812 0.0499	-0.483 0.332	-0.419 0.409	0.746 0.088	0.785 0.064	0.459 0.360
Descriptive Ranking		6.4	7.0	7.0	5.0	4.2	5.6	5.2	3.4

D10 of the p0.075 fraction. The results are shown in Table 22. Only UVA, UVB, and VTM5 produce consistent correlations with the rutting parameters, although the MDEV and MGSO4 show good correlations with rut depth at 20,000 wheel passes. Plots of the rutting parameters as a function of fine aggregate UVA are shown in Figures 22 through 26.

Similar to the procedure used for the coarse-graded mixtures, each of the fine aggregate test methods was assigned a descriptive ranking as shown in Table 22. The ranking was determined in the manner described for the coarse-graded mixtures. Table 22 shows that fine aggregate UVB and VTM5 have the highest descriptive rankings at 7.0; the fine aggregate UVA is only slightly less at 6.4. The D60, D30, and MDEV rankings are the next closest at 5.6, 5.2, and 5.0, respectively.

Regression analyses were performed to develop equations relating rutting parameters and aggregate test results. The primary independent variables were UVA, UVB, and VTM5. The response variables were rut depths at 1,000; 5,000; and 20,000 APT wheel passes; and early and late traffic rutting rates.

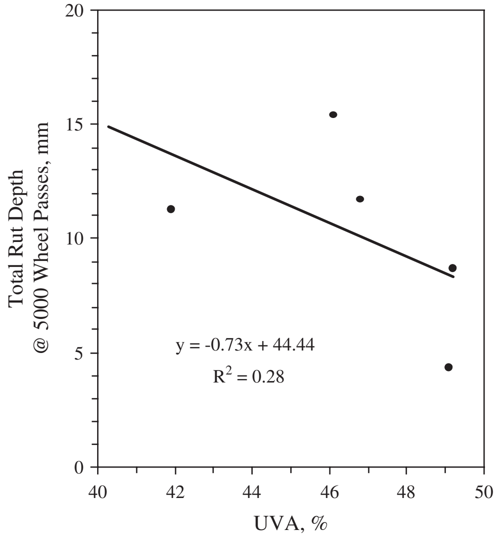


Figure 23. Rut depth/fine aggregate UVA relationship (5,000 passes).

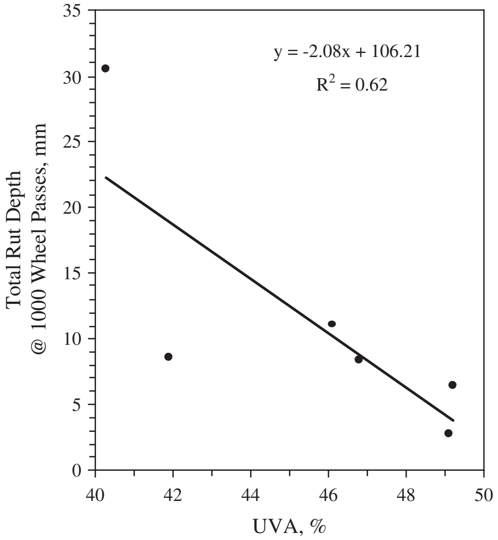


Figure 22. Rut depth/fine aggregate UVA relationship (1,000 passes).

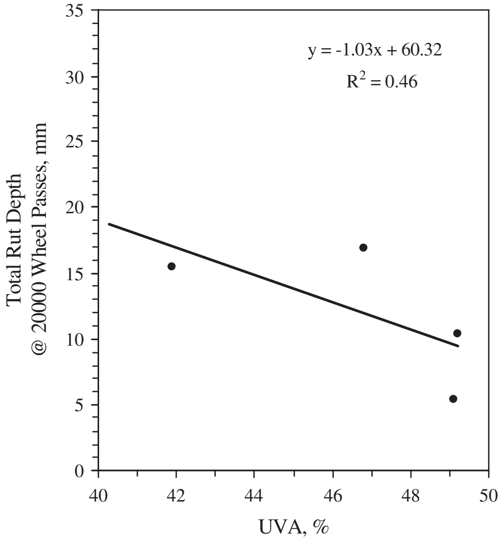


Figure 24. Rut depth/fine aggregate UVA relationship (20,000 passes).

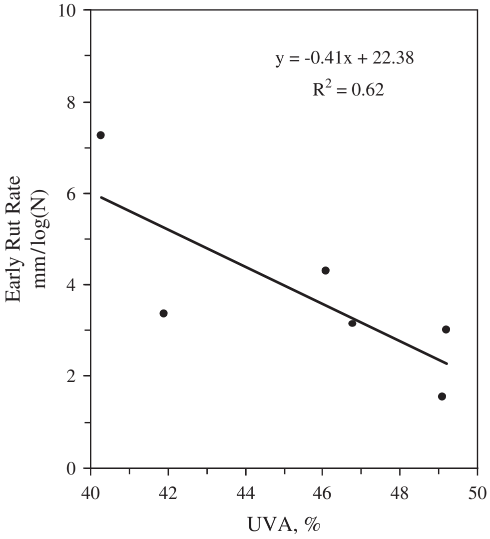


Figure 25. Early rut rate/fine aggregate UVA relationship.

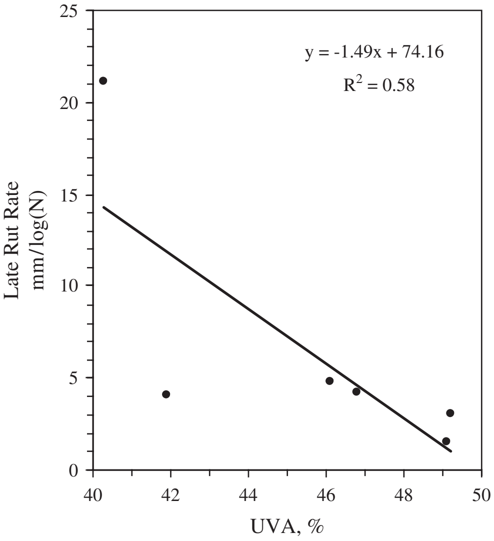


Figure 26. Late rut rate/fine aggregate UVA relationship.

Results of the regression analyses are given in Table 23. The relationships between total rut depth at 1,000 wheel passes and early and late traffic rutting rates and UVA, UVB, or VTM5 are good/fair and significant. These are the three rutting parameters that made use of all six fine aggregates. Not all six fine aggregates were used for rut depth analysis because no rut depth data were obtained for the FA-1 mixture at 5,000 and 20,000 APT wheel passes and for the FA-2 mixture at 20,000 wheel passes. Additional fine aggregate properties such as MDEV and MGSO4 were included in the regression analyses using stepwise regression, but these additions failed to improve the R^2 values. These results show that as fine aggregate UVA, UVB, or VTM5 values increase, the rutting resistance of an HMA mixture also increases; however, UVA may be preferable to UVB or VTM5 because the UVA test requires less material and time.

Table 23. Regression analyses between rutting parameters and fine aggregate UVA.

Response Variable	Predictor Variable	Model Equation	R^2	p-value
Rut Depth @ 1,000 passes[1]	UVA	100.26 – 1.95 UVA	0.65	0.051
	UVB	112.98 – 2.05 UVB	0.72	0.033
	VTM5	108.88 – 1.92 VTM5	0.70	0.037
Rut Depth @ 5,000 passes[2]	UVA	34.52 – 0.52 UVA	0.14	0.538
	UVB	47.88 – 0.74 UVB	0.26	0.379
	VTM5	46.34 – 0.69 VTM5	0.27	0.372
Rut depth @ 20,000 passes[3]	UVA	63.67 – 1.11 UVA	0.51	0.286
	UVB	66.29 – 1.06 UVB	0.44	0.334
	VTM5	64.84 – 1.01 VTM5	0.47	0.315
Early Rut Rate[1]	UVA	22.29 – 0.42 UVA	0.63	0.060
	UVB	25.40 – 0.45 UVB	0.72	0.034
	VTM5	24.56 – 0.42 VTM5	0.70	0.037
Later Rut Rate[1]	UVA	70.66 – 1.41 UVA	0.63	0.059
	UVB	78.86 – 1.46 UVB	0.68	0.045
	VTM5	75.82 – 1.36 VTM5	0.66	0.0499

[1] All mixtures are included
[2] FA-1 (Natural Sand A) is not included
[3] FA-1 (Natural Sand A) and FA-2 (Crushed Gravel Sand) are not included

Total rut depths at 5,000 and 20,000 wheel passes have poor correlations with fine aggregate UVA, UVB, and VTM5 (see Table 23). Although the correlations are poor, the plots indicate the effect of fine aggregate UVA, UVB, and VTM5 on rutting performance. Close examination suggests increasing fine aggregate UVA from 42 to approximately 47 percent does not appear to improve HMA rutting resistance; however, rutting resistance increases significantly for fine aggregate UVA values above 47 percent. Kandhal and Parker (*1*) reported similar results. Based on their GLWT data, mixture rutting susceptibility does not change much for fine aggregate UVA values of approximately 45 to 46 percent, but mixtures become less susceptible to rutting for fine aggregate UVA values above 46 percent. Furthermore, at UVA values of around 39 to 40 percent, HMA mixtures tested in both the GLWT and APT exhibited significant increases in rut depths.

Based on results in this research and those reported by Kandhal and Parker, it appears that fine aggregate UVA is a good predictor variable of HMA rutting performance. However, it should be recognized that in-place properties of HMA pavements, such as pavement density, also affect pavement performance. Furthermore, it is recommended that natural sands with fine aggregate UVA values below 40 percent be avoided, unless they are combined with a higher UVA fine aggregate and/or pass a performance test. Fine-graded HMA mixtures with fine aggregates having UVA values between 42 and 47 percent tend to exhibit similar rutting performance. Mixtures with fine aggregate UVA values above 47 percent appear to exhibit better rutting performance. However, experience has shown that an HMA mixture with a high fine aggregate UVA can produce a mixture with high voids in the mineral aggregate (VMA). Such mixtures require a high binder content to meet air voids criteria, which can lead to over-asphalting and poor mixture rutting performance.

Sensitivity of the fine aggregate UVA to APT traffic levels was analyzed at the 7.5-mm and 10-mm total rut depths. Figures 27 and 28 show the relationships between fine aggregate UVA and the number of APT wheel passes required to reach a 7.5- and 10-mm total rut depth, respectively. Both relationships appear to be exponential and significant. The exponential regression equation shown in Figure 27 indicates the number of APT wheel passes required to reach a 7.5-mm total rut depth increases by approximately 950 for an increase in fine aggregate UVA from 45 to 50 percent. For this same 5-percent increase in fine aggregate UVA, the equation shows the number of APT wheel passes increases by approximately 6,600 to reach a 10-mm total rut depth. These relationships seem logical up to a point. For example, for fine aggregate UVA values between 35 and 40 percent, the number of wheel passes applied before reaching a given rut depth increases very little. However, the increase is much larger for fine aggregate UVA values between 45 and 50 percent. The practical limit to the relationship is that many fine aggregates have UVA values of no more than approximately 50 percent.

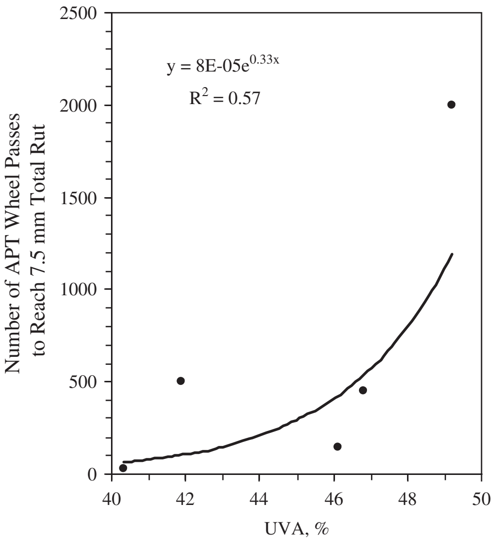


Figure 27. Effect of fine aggregate UVA on traffic (7.5 mm).

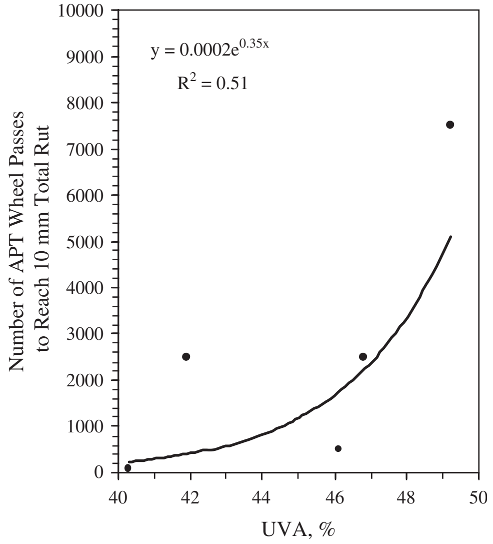


Figure 28. Effect of fine aggregate UVA on traffic (10 mm).

Figure 29 presents the APT rut depths as a function of the number of wheel passes for each of the fine aggregates used in the study. Unlike the coarse aggregate results, the fine aggregate UVA values are not grouped. Two of the fine aggregates have UVA values of 49 percent, but the granite outperformed the traprock; the former yielding approximately a 5-mm rut depth at 20,000 wheel passes and the latter an 11-mm rut depth at 20,000 wheel passes. Natural Sand B with a UVA of 42 percent performed as well as the dolomite sand with a UVA of 47 percent; both exhibited

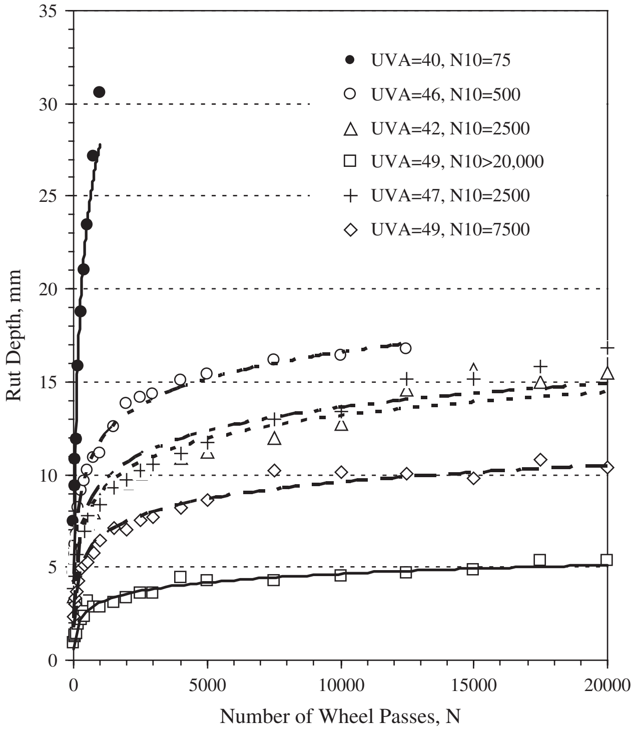


Figure 29. Effect of fine aggregate UVA on rut depth.

approximately a 15-mm rut depth at 20,000 wheel passes. Natural Sand A is the poorest fine aggregate-yielding in excess of 30 mm of rutting after approximately 1,000 APT wheel passes.

Moisture Susceptibility Mixtures

In *NCHRP Report 405*, Kandhal and Parker recommended the methylene blue value of the p0.075 fraction of the fine aggregates as the best predictor for the stripping potential of fine-graded HMA pavements. They used AASHTO T 283 and the GLWT tracking device to investigate the influence of fines in fine aggregate on stripping. The GLWT test was conducted under water maintained at 50°C and an inflection point on a plot of rutting versus number of passes was used as the parameter for evaluating mixture stripping performance. In the current study, only mixture FAM5 (Natural Sand B) had an obvious inflection point, which was presumably caused by stripping initiation. All other mixtures tested did not exhibit an obvious inflection point. Mixture FAM3 (Granite Sand) exhibited a slight change in slope that is possibly an indication of stripping.

Methylene Blue Test

The tensile strength ratio (TSR) determined in the AASHTO T 283 test was used to study the effect of the fine aggregate on the moisture susceptibility of the HMA mixtures. Kandhal and Parker (*1*) suggested that the moisture susceptibility of fine-graded HMA mixtures was related to the MBV of fine aggregates. The goal of the current study was to validate the effect of fine aggregate properties on HMA moisture susceptibility.

The correlation between TSR and the MBV of the fine aggregates was investigated, but no significant correlation was found. A plot of TSR as a function of MBV is shown in Figure 30. The TSR value of 100 percent for the FAM1 (Natural Sand A) mixture seems out of place given the MBV of 3.3. Further investigation revealed that the FAM1 mixture also had the least p0.075 material (3.0 percent). This amount may be low enough that the poor quality of fines did not affect its tensile strength; however, the figure suggests some trend in the data. Given the variability of the AASHTO T 283 test results, a clear relationship between HMA moisture susceptibility as measured by the test and the MBV test is not readily apparent.

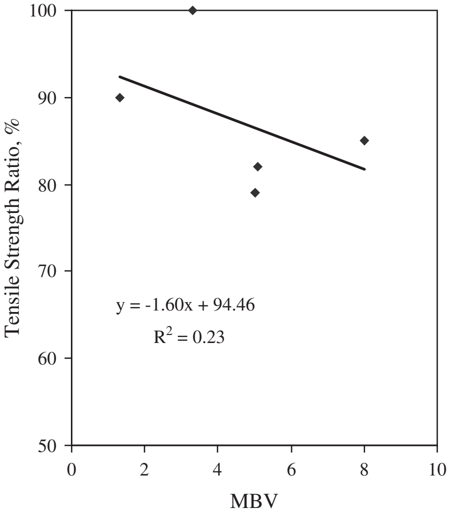


Figure 30. TSR/MBV relationship.

Rutting

Given that only one mixture exhibited an obvious inflection point, rutting parameters were also used to evaluate the effect of moisture on HMA performance. Parameters evaluated included rut depths at 1,000 and 5,000 APT wheel passes and rutting rates for both early and late traffic. The results are shown in Table 24. Rutting data for mixture FAM1 (Natural Sand A) was not available for 5,000 wheel passes. It can be seen that none of the correlations are significant at a level of 5 percent. Data from fine aggregate UVA, UVB, and VTM5 tests have good correlations with the rutting parameters, but again are not significant. The MBV values have poor/fair positive correlations with the rutting parameters. Particle size parameters have poor correlations with the rutting parameters. The relationships between each of these rutting parameters and fine aggregate UVA are shown in Figures 31 through 34.

A descriptive ranking was assigned to each test method as shown in Table 24. The table shows that fine aggregate UVA has the highest ranking of 8.3 followed closely by fine aggregate UVB and VTM5 tests at 8.0. The MBV has a ranking of 4.5 and the remaining tests have rankings of 3 or less. The rankings would seem to confirm that the fine aggregate UVA is the best test for predicting HMA mixture performance.

Regression analyses were performed to determine if combinations of aggregate test variables would provide an improved relationship with rutting parameters. The independent variables were fine aggregate UVA, UVB, and VTM5;

Table 24. Correlation matrix for rutting parameters and fine aggregate properties (moisture susceptibility tests).

	UVA	UVB	VTM5	MBV	D60	D30	D10
Rut depth at 1,000 Passes	-0.858 0.063	-0.856 0.064	-0.847 0.070	0.555 0.332	-0.293 0.632	-0.235 0.704	-0.462 0.434
Rut depth at 5,000 Passes	-0.948 0.052	-0.860 0.140	-0.858 0.142	0.257 0.743	-0.601 0.399	-0.453 0.547	-0.281 0.719
Early Rut Rate	-0.867 0.057	-0.842 0.073	-0.834 0.079	0.666 0.220	-0.308 0.614	-0.277 0.652	-0.452 0.444
Late Rut Rate	-0.867 0.057	-0.859 0.062	-0.851 0.068	0.572 0.313	-0.179 0.773	-0.119 0.850	-0.330 0.588
Descriptive Ranking	8.3	8.0	8.0	4.5	3.0	2.3	3.3

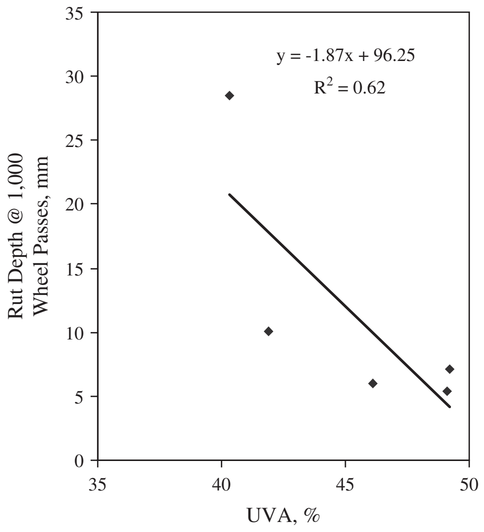


Figure 31. Rut depth/fine aggregate UVA relationship (moisture tests) (1,000 passes).

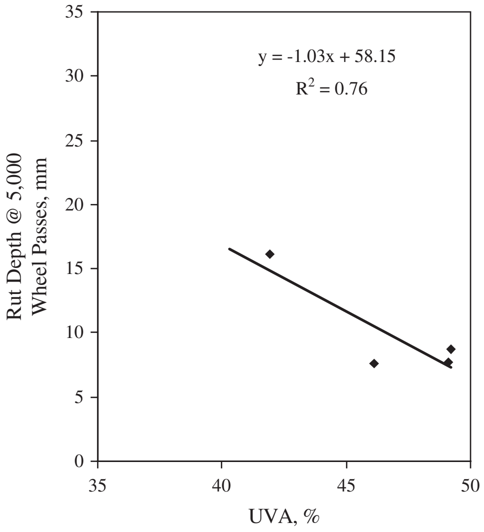


Figure 32. Rut depth/fine aggregate UVA relationship (moisture tests) (5,000 passes).

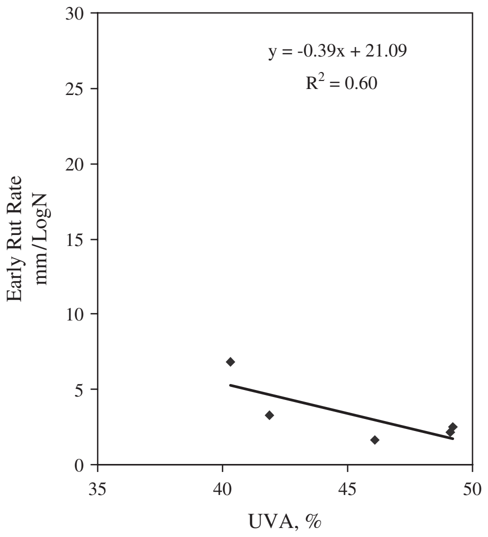


Figure 33. Early rut rate/fine aggregate UVA relationship (moisture tests).

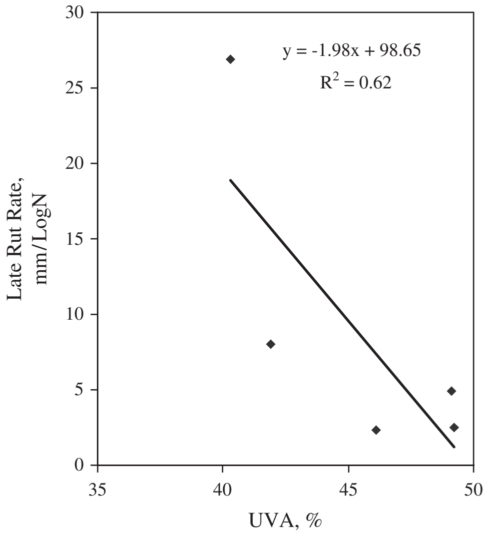


Figure 34. Late rut rate/fine aggregate UVA relationship (moisture tests).

MBV; D60; D30; and D10. Response variables were rut depths at 1,000 and 5,000 wheel passes, and the rut rate for both early and late traffic. The regression results are shown in Table 25; no combination was found significant at a 5-percent significance level.

The regression equations indicate fine aggregate UVA, UVB, and VTM5 are good predictors of the rutting performance of the fine-graded mixtures when tested in wet conditions. Only mixture FAM5 (Natural Sand B) showed an inflection point at approximately 5,000 APT wheel passes, which was presumably initiated by stripping. Based on the regression equations in Table 25, HMA rutting performance improves as the fine aggregate UVA increases.

Sensitivity of fine aggregate UVA to APT traffic levels in the presence of moisture was analyzed at the 4.5-mm and 9-mm total rut depths. Again, 9 mm was chosen because it is the maximum amount of rutting experienced. Figures 35 and 36 show relationships between fine aggregate UVA and the number of APT wheel passes in the presence of moisture required to reach 4.5- and 9-mm total rut depths, respectively. Both relationships appear to be exponential and significant. The exponential regression equation shown in Figure 35 indicates

Table 25. Regression analyses for rutting parameters and fine aggregate UVA (moisture susceptibility tests).

Response Variable	Predictor Variable	Model Equation	R^2	p-value
Rut Depth @ 1,000 Wheel Passes[1]	UVA	94.86 – 1.84 UVA	0.74	0.063
	UVB	102.95 – 1.86 UVB	0.73	0.064
	VTM5	98.97 – 1.73 VTM5	0.72	0.0699
Rut Depth @ 5,000 Wheel Passes[2]	UVA	63.78 – 1.14 UVA	0.90	0.052
	UVB	64.50 – 1.07 UVB	0.74	0.140
	VTM5	61.54 – 0.99 VTM5	0.74	0.142
Early Rut Rate[1]	UVA	21.27 – 0.39 UVA	0.75	0.057
	UVB	22.44 – 0.39 UVB	0.71	0.073
	VTM5	21.61 – 0.36 VTM5	0.70	0.079
Late Rut Rate[1]	UVA	98.26 – 1.97 UVA	0.75	0.057
	UVB	106.30 – 1.98 UVB	0.74	0.062
	VTM5	102.15 – 1.85 VTM5	0.72	0.068

[1] All mixtures included

[2] FAM1 (Natural Sand A) rut data is not available

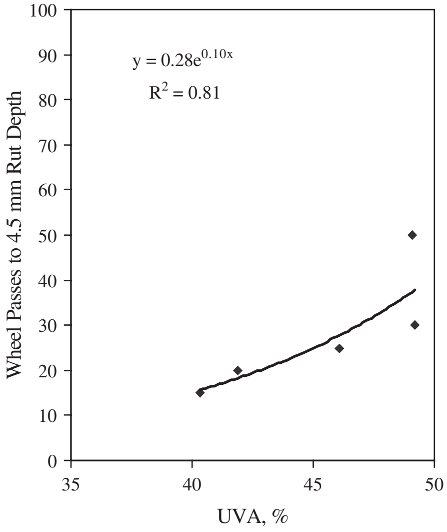


Figure 35. Effect of fine aggregate UVA on traffic (moisture susceptibility) (4.5-mm rut depth).

the number of APT wheel passes required to reach a 4.5-mm total rut depth increases by approximately 16 for an increase in fine aggregate UVA from 45 to 50 percent. For this same 5-percent increase in fine aggregate UVA, the equation shown in Figure 36 indicates the number of APT wheel passes increases by approximately 55,500 to reach a 9-mm total rut depth. Again, at the lower rut depth, the change in fine aggregate UVA makes very little difference in the number of APT wheel passes; however, at the 9-mm rut depth, slight changes in the fine aggregate UVA appear to make a very large difference in the number of wheel passes.

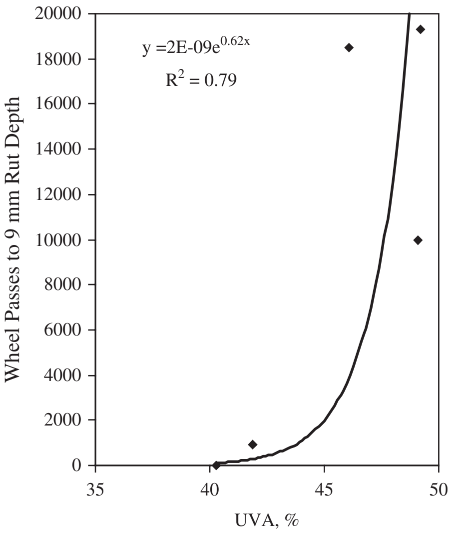


Figure 36. Effect of fine aggregate UVA on traffic (moisture susceptibility) (9-mm rut depth).

Figure 37 presents the APT rut depths as a function of the number of wheel passes for each of the fine aggregates used in the moisture susceptibility portion of the study. The fine aggregates with lower UVA values of 40, 42 percent show much poorer performance than the fine aggregates that have UVA values of 46 through 49 percent. The three mixtures with high UVA have comparable performances in the APT in the presence of moisture. These results suggest a minimum fine aggregate UVA value of approximately 45 percent may

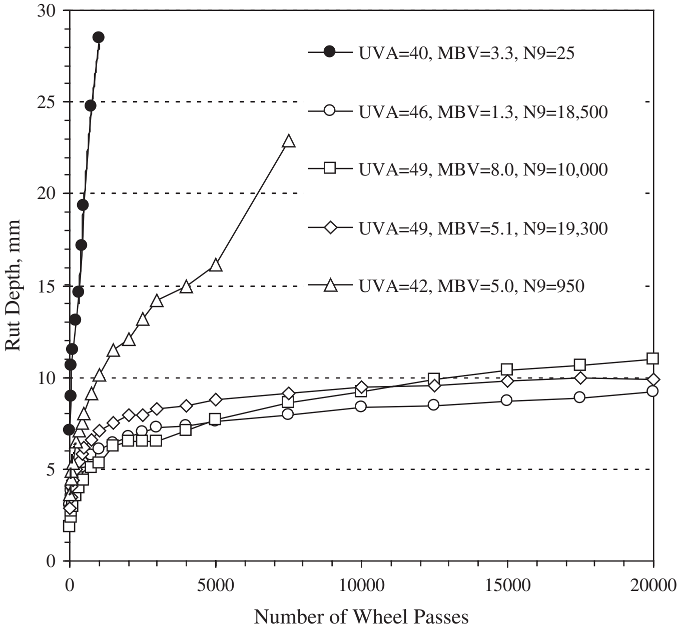


Figure 37. Effect of fine aggregate UVA on rut depth (moisture susceptibility).

help decrease rutting when the HMA mixture is exposed to moisture. The MBV for each mixture is also shown on the figure. There does not appear to be any pattern to the rutting as a function of the MBV. Indeed the three mixtures showing the least amount of rutting have MBV ranging from 1.3 to 8.0.

Fatigue Mixtures

These tests were the research team's attempt to produce fatigue cracking in the APT facility and the results were somewhat mixed. Three of the HMA mixtures exhibited fatigue cracking; the other three mixtures never developed fatigue cracking due to the inability to control temperature in the APT facility. However, considering the limitations of the data, some general conclusions can be drawn from the fatigue testing portion of the experiment.

The percent fatigue cracking (i.e., the percentage of cracked area to total area) as a function of the coarse aggregate UVA and FOE21, shown in Figures 38 and 39, respectively, indicates a trend in the data. As UVA or FOE21 increase, so do the number of APT wheel passes required to fatigue HMA mixtures. Figures 38 and 39 also show best fit lines, equations of the lines, and R^2 values. These are presented for informational purposes only. With three data points an excellent fit can nearly always be obtained. However, the trends appear valid and indicate that an HMA mixture containing coarse aggregates with UVA and/or FOE21 values in the 45- to 50-percent range would much better resist fatigue cracking than mixtures with UVA and/or FOE21 values below 45 percent.

Figure 40 is a plot of the percent fatigue cracking as a function of fine aggregate UVA for the three fine-graded mixtures. The data are obviously scattered because the FA-3 and FA-4 mixtures never exhibited fatigue cracking because of the inability to control ambient temperature. Both mixtures received 20,000 passes before testing was discontinued due to rutting. Recent fatigue testing in the APT with temperature control suggests that these mixtures may have sustained additional passes (up to approximately 100,000) before failing in fatigue. From the data available, it is not possible to draw conclusions on the trend in the fatigue cracking as a function of the fine aggregate UVA relationship.

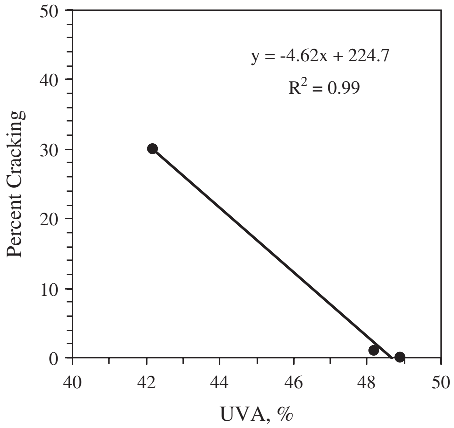


Figure 38. Fatigue cracking/coarse aggregate UVA relationship.

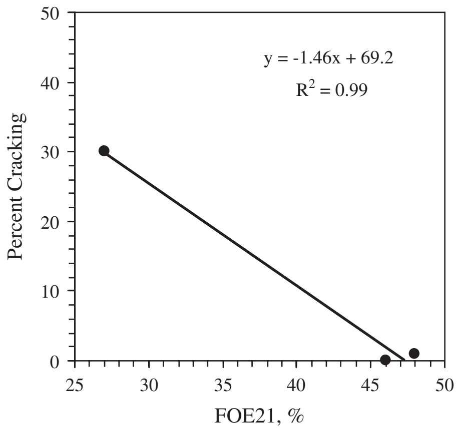


Figure 39. Fatigue cracking/flat or elongated relationship.

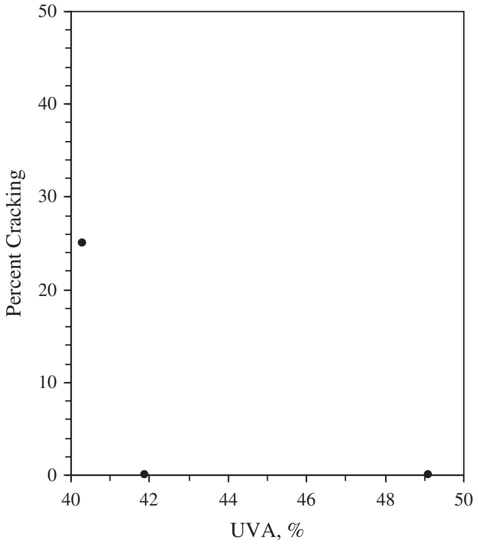


Figure 40. Fatigue cracking/fine aggregate UVA relationship.

CHAPTER 4

Conclusions and Suggested Research

The objective of this research was to use accelerated pavement testing techniques to conduct the rutting, fatigue, and moisture susceptibility validation experiments identified in NCHRP Project 4-19 by Kandhal and Parker (*1*) as shown in Table 1. The validation effort involved subjecting HMA mixtures prepared with various aggregates to full-scale accelerated pavement testing and measuring their performance according to one of three HMA failure modes: (1) rutting; (2) moisture susceptibility; and (3) fatigue. The results are discussed below and are summarized in Table 26.

Coarse Aggregate Uncompacted Voids Content

Rutting

The coarse aggregate UVA was found to be the best single predictor of rutting performance of the coarse-graded mixtures as indicated by the descriptive ranking. The test appears to capture information related to particle shape and texture and rutting decreases as the coarse aggregate UVA increases. As discussed in Chapter 3, the coarse aggregate UVA appears to be less important at lower traffic levels. The number of APT wheel passes to reach a rut depth of 3.5 mm covers a range of approximately 100. The coarse aggregate UVA is more sensitive at higher traffic levels where the number of wheel passes to reach a 7-mm rut depth covers a range of approximately 14,000. In both cases, the relationship between traffic and coarse aggregate UVA seems less sensitive for UVA values in the range of 40 to 45 percent. The relationship becomes stronger in the coarse aggregate UVA range of 45 to 50 percent. Previous testing in the APT has indicated that one APT pass is equivalent to approximately 2,500 ESAL. Applying this equivalency factor to the coarse aggregate UVA/wheel pass data, a performance limit occurs at 100,000 ESAL. For expected traffic below 100,000 ESAL, a minimum coarse aggregate UVA of 40 percent would be required. A coarse aggregate UVA of at least 45 percent would be required for traffic above 100,000 ESAL.

The preceding discussion of coarse aggregate UVA applies to the coarse aggregate UVB as well. The UVB test results had a high descriptive ranking as did the UVA test results. Thus, either test can be used to specify coarse aggregates used in HMA mixtures.

Fatigue

The research shows the trend that, as the coarse aggregate UVA increases, HMA mixture resistance to fatigue cracking increases. Although this trend can easily be seen in the data and appears logical, it is based on only three data points and other factors contribute to HMA mixture fatigue performance, such as initial mixture density, binder type, and pavement cross section. Nevertheless, there is no logical reason to discard the coarse aggregate UVA test as being unrelated to mixture fatigue performance.

Flat or Elongated Particles

Rutting

The percentage of flat or elongated particles, 2:1 ratio, does exhibit a predictive relationship with HMA mixture rutting performance. Rutting increases with increasing FOE21. The FOE21 has a descriptive ranking only slightly lower than coarse aggregate UVA. In fact, FOE21 was found to be positively correlated with UVA (i.e., as FOE21 increases, so does UVA). The two tests seem to predict HMA mixture rutting equally well. However, when the two descriptors are combined, they do not improve rutting prediction. If only one of the two tests is to be used, the coarse aggregate UVA seems preferable because it is typically less time consuming than the FOE21 test. However, given that the FOE21 and coarse aggregate UVA results are positively correlated, it would be good

Table 26. Test recommendations and proposed specification limits.

Test	Recommended for Specification Use	Proposed Specification	
		Traffic (ESAL)	Limit
Uncompacted Void Content of Coarse Aggregate, Method A (AASHTO TP56)[1]	Yes	Less Than 100,000	40%, Minimum
		100,000 and above	45%, Minimum
Flat or Elongated Particles in Coarse Aggregate (ASTM D4791)	Yes	All	50%, Maximum
Uncompacted Void Content of Fine Aggregate, Method A (ASTM C1252)[2]	Yes	Less Than 500,000	40%, Minimum
		500,000 and above	45%, Minimum
Methylene Blue Test for Fine Aggregate (AASHTO TP57)	No	—	—
Methylene Blue Test for p0.075 Material (AASHTO TP57)	No	—	—
Particle Size Analysis of p0.075 Materials for Determining D60, D30, and D10 Sizes	No	—	—
Micro-Deval Test (AASHTO TP58)	Yes	All	15%, Maximum
Magnesium Sulfate Soundness Test (AASHTO T104)	Yes	All	20%, Maximum

[1] Same recommendation and proposed specification applies to Method B as well.

[2] Same recommendation and proposed specification applies to Method B and Virginia Test Method for Determining Percent Voids in Fine Aggregate (VTM5) as well.

practice to include both tests when specifying coarse aggregates for use in HMA. If the coarse aggregate UVA test is used alone, aggregates with very high FOE21 values could be used because they would also have high UVA values. Aggregates with extremely high FOE21 values could cause problems in HMA mixtures.

Most coarse aggregates used in this research have FOE21 values between 35 and 50 percent. The FOE21 value of 50 percent appears to be a reasonable upper limit for specification purposes.

Fatigue

The research shows that as FOE21 increases, HMA mixture resistance to fatigue cracking increases. It should be recognized that this trend is based on only three data points and that many other factors contribute to the fatigue performance of an HMA mixture. Nevertheless, there is no logical reason to discard the FOE21 test as an aggregate test related to fatigue performance.

Fine Aggregate Uncompacted Void Content

Rutting

Rutting performance of fine-graded HMA mixtures is related to fine aggregate UVA. The HMA mixture rutting resistance increases with increasing fine aggregate UVA. Both fine aggregate UVB and VTM5 test results have slightly higher descriptive rankings than the UVA results. As a result, the following discussion of fine aggregate UVA applies to both fine aggregate UVB and VTM5 methods. It seems appropriate to recommend that any of the three tests can be used for specification purposes for fine aggregates used in HMA mixtures; the choice can be left to the specifying agency.

Similar to the coarse aggregate, the relationship between traffic and fine aggregate UVA appears to be less sensitive at lower traffic levels than at higher levels. In the case of fine aggregate UVA, the value of approximately 45 percent seems to be a logical break point. HMA performance is markedly improved with fine aggregate UVA values above 45 percent compared to HMA with fine aggregate UVA values below 45 percent. Using the APT equivalency factor of 2,500 ESAL per pass, it might be appropriate to allow the use of fine aggregate UVA as low as 40 percent for traffic levels below 500,000 ESAL and 45 percent or higher for traffic levels of 500,000 ESAL or higher.

The results of APT moisture susceptibility tests indicate that, in the presence of moisture, fine aggregate UVA is a better predictor of rutting performance than any other test; rutting decreases with increasing fine aggregate UVA. The sensitivity discussion previously applied to dry APT testing appears to be true of tests in the presence of moisture as well.

Fatigue

Data indicate a relationship between HMA mixture fatigue performance and fine aggregate UVA might exist. As the fine aggregate UVA increases, HMA mixture fatigue cracking decreases. The trend, if it does exist would seem logical. However, with the limited data obtained in the research (three data points) and given that two of the mixtures never exhibited fatigue cracking, the fine aggregate UVA cannot be recommended as an aggregate test related to fatigue performance. A relationship may exist, but additional testing is needed before a conclusive recommendation can be made.

Methylene Blue Test

Based on the AASHTO T 283 tests of cores taken from the APT test lanes, the MBV appears to be somewhat related to the TSR values. The higher the MBV, the lower the TSR value or the more susceptible the HMA mixtures are to moisture. However, the relationship does not seem strong and appears to be affected by the amount of p0.075 material in the mixture. For example, mixture FAM1 had a high MBV, but low p0.075 content. Despite the high MBV, the mixture had a high retained tensile strength after being subjected to one freeze-thaw cycle. Furthermore, research covered in the literature review indicates a high MBV does not always indicate the presence of harmful material in the aggregate blend.

Research results suggest the MBV test is not a good predictor of HMA performance and should therefore not be used to specify HMA mixture fine aggregates.

Particle Size Analysis

The effect of the p0.075 fraction on fine-graded mixtures was investigated using the APT. Overall, the D60 and D30 values show a fair correlation with rutting performance. HMA mixture total rut depth increases as the amount of D60 or D30 material increases. When used in conjunction with the fine aggregate UVA, neither the D60 nor D30 parameters improve the fine aggregate UVA prediction of HMA mixture rutting. The D10 parameter does not appear to correlate at all with HMA mixture rutting performance. Considering the effort that goes into completing the particle size analysis of the p0.075 fraction and its fair ability to predict mixture performance, particle size analysis of the p0.075 fraction is not recommended for routine aggregate specification testing.

Micro-Deval and Magnesium Sulfate Soundness

Kandhal and Parker (*1*) recommended MDEV and MGSO4 tests to address aggregate durability and toughness when used in HMA mixtures. The MDEV for both coarse and fine aggregates and the MGSO4 for fine aggregates were determined and correlations were made with rutting performance. The MDEV descriptive rankings for coarse and fine aggregates were 2.7 and 5, respectively. The descriptive ranking for the fine aggregate MGSO4 was 4.2. Coarse aggregate MDEV has little correlation to mixture rutting performance. The fine aggregate MDEV and MGSO4 have fair correlations with mixture rutting performance. If only data at 20,000 APT wheel passes is considered, the correlation between rutting performance and the fine aggregate MDEV and MGSO4 are excellent. The amount of rutting at 20,000 APT passes increases as the fine aggregate MDEV and/or MGSO4 values increase. However, the opposite trend exists at 1,000 passes. Nonetheless, there does appear to be a good enough correlation between fine aggregate MDEV and MGSO4 to recommend their use to specify aggregates used in HMA mixtures. A maximum value of 15 and 20 percent for MDEV and MGSO4, respectively, would limit rutting at 20,000 wheel passes to 12.5 mm.

Summary

The research has shown that for coarse aggregates, both UVA (UVB) and FOE21 are good predictors of HMA mixture performance. It is recommended the tests be used in all climates and for all materials. For traffic above 100,000 ESAL, a coarse aggregate UVA of 45 percent or greater is recommended. A minimum UVA of 40 percent is recommended for traffic below this level. The FOE21 value should be a maximum of 50 percent for all traffic levels.

For fine aggregates, UVA, UVB, or VTM5 tests can be used to control HMA rutting performance. The MDEV and MGSO4 tests on fine aggregates can also be used to control HMA mixture rutting performance. The UVA (UVB, VTM5) should be used in all climates and for all materials. For expected traffic of less than 500,000 ESAL, the minimum recommended UVA (UVB, VTM5) value is 40 percent; a minimum UVA (UVB, VTM5) of 45 percent is recommended for expected traffic greater than 500,000 ESAL.

The MDEV and MGSO4 tests should be used in all climates and for all materials. These tests may be important in high moisture climates. A maximum value of 15 and 20 percent for MDEV and MGSO4, respectively, are recommended for all traffic levels.

Recommended Research

Problems were encountered in the fatigue testing portion of the experiment because of the lack of temperature control. Also, only limited fatigue tests could be incorporated in the study because of budget and time constraints. As a result, performance relations in the study are not as strong as they need to be. Although it is true that fatigue performance depends on coarse and fine aggregates, other factors contribute to the performance, including gradation, binder type and volume, temperature, initial mixture density, pavement thickness, applied loads, tire pressures, and traffic speed and volume. Gradation, binder volume, and binder grade and type are likely the most significant factors related to fatigue performance. The other items are of only slightly less importance.

A comprehensive laboratory study was undertaken in NCHRP Project 4-19 to screen aggregate properties and tests related to HMA mixture rutting and moisture effects. The current study built on the experience of that research to produce positive results. It is recommended that a laboratory fatigue study be conducted with a goal of screening aggregate characteristics and tests affecting HMA fatigue performance. Normally, the difference between laboratory and in-service fatigue performance is a matter of using a scaling factor. For this reason, the research team believes that adequate information can be collected without the need for further full-scale testing.

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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