PERFORMANCE EVALUATION OF FINE GRADED SUPERPAVE MIXTURES FOR SURFACE COURSES

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HWY-2000-06

FINAL REPORT
FHWA/NC/2002-005

in Cooperation with

North Carolina Department of Transportation

Department of Civil Engineering
North Carolina State University

August 2001

Technical Report Documentation Page

1. Report No. FHWA/NC/2002-005	2. Government Accession No.	3. Recipient's Catalog No:
4. Title and Subtitle Performance Evaluation of Fine Graded Superpave Mixtures for Surface Courses		5. Report Date August 2001
		6. Performing Organization Code
7. Authors N. Paul Khosla, S. Sadasivam, Glen Malpass		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil Engineering North Carolina State University Box 7908, Raleigh, NC, 27695-7908		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address NC Department of Transportation Research and Analysis Group 1 South Wilmington Street, Raleigh, NC 27601		13. Type of Report and Period Covered Final Report July 1999 – June 2001
		14. Sponsoring Agency Code 2000-06
15. Supplementary Notes		

16.Abstract

SHRP A407 recommends that aggregate gradations pass below the restricted zone as traffic level increases. The aggregate gradation curve of most of the SUPERPAVE mixes used today, especially in the Southeast region of the U.S., follows a typical "S" shape with fines lying slightly below the restricted zone. Such a gradation yields a relatively coarse mix; however, the use of gradation with fines slightly above the restricted zone is technically acceptable according to SHRP specifications. Since such a mix is similar to the I-I or I-2 surface mixture used by the NCDOT for surfacing of the secondary roads, it will be more economical as well as more amenable to acceptance by field engineers. The use of natural sand will reduce the build up of fines in the stone quarries and encourage the use of reclaimed asphalt pavement (RAP) material.

This study investigated the use of natural sand in the fine and coarse gradations for the surface course mixtures. The mixtures were designed using the SUPERPAVE mix design approach and were evaluated for their performance in terms of resistance to rutting, fatigue, and moisture damage. In addition, the accelerated performance of these mixtures was also evaluated using the Asphalt Pavement Analyzer (APA).

17. Key Words Superpave mixtures, natural sand, SHRP performance tests, rutting and fatigue life, Asphalt Pavement Analyzer.		18. Distribution Statement	
19.Security Classif.(of this report) Unclassified	20.Security Classif.(of this page) Unclassified	21.No. of Pages 81	22.Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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ACKNOWLEDGMENTS

The author expresses his sincere appreciation to the authorities of the North Carolina Department of Transportation for making available the funds needed for this research.

Sincere thanks go to Mr. Cecil Jones, Chairman, Technical Advisory Committee, for his interest and helpful suggestions through the course of this study. Equally, the appreciation is extended to other members of the committee, Mr. Jim Grady, Mr. Carson Clippard, Mr. Jack Cowsert, Mr. J. Travis, and Dr. Moy Biswas for their continuous support during this study.

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CHAPTER 1

INTRODUCTION

Because approximately 85% of the total volume of a hot-mix asphalt (HMA) mixture consists of aggregates, the mineral aggregate properties are important to asphalt mixture performance. One of the most important properties of the aggregate in the HMA mix is the gradation. Aggregate gradation for a SUPERPAVE mix design is bound by control points and a restricted zone on a 0.45 power chart that helps establish the gradation of the aggregate blends.

The control points serve the following purposes: maximum size of aggregate; relative proportion of coarse aggregate and fine aggregate; and amount of dust. In its aggregate gradation limit, the restricted zone is introduced to avoid mixtures that have a high proportion of fine sand relative to total sand. It is based on experience with "humped" gradations that are generally caused by excessive amounts of fine sand. It also avoids gradations that follow the maximum density, which do not have adequate voids in the mineral aggregate. This criterion ensures that the aggregate will develop a strong, stone skeleton to enhance resistance to permanent deformation while enhancing mixture durability.

SHRP A407 recommends that aggregate gradations pass below the restricted zone as traffic level increases. The aggregate gradation curve of most of the SUPERPAVE mixes used today, especially in the Southeast region of the U.S., follows a typical "S" shape with fines lying slightly below the restricted zone. Such a gradation yields a relatively coarse mix; however, the use of gradation with fines slightly above the restricted zone is technically acceptable according to SHRP specifications. Since such a mix is similar to the I-I or I-2 surface mixture used by the NCDOT for surfacing of the secondary roads, it will be more economical as well as more amenable to acceptance by field engineers. The use of natural sand will reduce the build up of fines in the stone quarries and encourage the use of reclaimed asphalt pavement (RAP) material.

1.1 Problem Statement

For the highway community, most of the experience with different types of aggregate gradations has been with either Marshall or Hveem compacted specimens. However, as each state and other highway agencies are preparing to switch over to the SUPERPAVE™ system, several questions remain unanswered. There is a need to evaluate the effect of the restricted zone on volumetric properties of fine graded mixtures and determine if these mixtures can be successfully designed by the SUPERPAVE mix design. More specifically, the following questions need to be answered:

1. *How does the gradation with fines slightly above the restricted-zone perform as compared to the gradation with fines lying slightly below the restricted zone?*
2. *What is the effectiveness of utilizing natural sands as fine aggregates?*
3. *What kinds of guidelines are needed for designing and producing fine aggregate blends for secondary roads?*
4. *What is the maximum amount of natural sand that can be allowed in a mixture to satisfy the SUPERPAVE mix design criteria?*

The scope of this proposal includes a background, explaining the aggregate gradation curves and the approach to the SUPERPAVE mix design process for fine graded mixtures containing natural sand. Current SUPERPAVE performance tests and the use of loaded wheel testing device are also discussed to evaluate the performance of asphalt mixtures. The objectives and scope are given followed by a research approach that will accomplish the goals of the study.

1.2 Objectives and Scope of Study

The following are the specific objectives of the proposed study:

1. *Study the aggregate gradation curves and investigate the use of natural sand in the fine and coarse gradations for the Surface Course mixtures.*
2. *Design the mixtures using the SUPERPAVE mix design approach and conduct testing of the selected asphalt mixtures, including the SUPERPAVE performance tests to evaluate their performance in terms of resistance to rutting, fatigue, and moisture damage.*

3. *Compare the accelerated performance test results of the selected asphalt mixtures using the Asphalt Pavement Analyzer (APA).*

1.3 Research Approach and Methodology

Prior to presenting the specific steps to be taken in the research portion of the study, it is appropriate to review the fundamentals of mineral aggregate in asphalt mixtures, especially in regards to the SHRP system. The theory of the SUPERPAVE gyratory compactor (SGC), SUPERPAVE Intermediate and Complete mix designs, and loaded wheel testing machine are presented in addition to factors affecting the aggregate gradation selection.

As stated earlier, one of the most important properties of the aggregate in an HMA mix is the gradation, since about 85% of its total volume consists of aggregates. The angularity, shape, and texture of the aggregate particles also have an effect on the performance of HMA mixtures by controlling the mixture's strength and rutting. By specifying coarse and fine aggregate angularity, the SUPERPAVE mix design seeks to achieve an HMA with a high degree of internal friction and high shear strength for rutting resistance.

To help specify a proper aggregate gradation, the SHRP suggested two additional features to the traditional 0.45 power chart: control points and a restricted zone. This is illustrated in Tables 1.1 and 1.2 and Figures 1.1 and 1.2, respectively. The control points perform as ranges through which gradations must pass. Their functions are: to maximize the size of aggregate; to balance the relative proportion of coarse aggregate and fine aggregate; and to control the amount of dust. The restricted zone is placed along the maximum density gradation between intermediate size and the 0.3mm size. It is introduced to avoid mixtures that have a high proportion of fine sand relative to the total sand. It also avoids gradations that follow the maximum density, which do not have adequate voids in the mineral aggregate. SHRP recommends that gradations pass outside the restricted zone in order to provide adequate VMA and to avoid excessive use of rounded sands. It also states that gradations that violate the restricted zone may possess a weak aggregate skeleton that depends too much on asphalt binder stiffness to achieve mixture shear strength. *However, in many instances, the restricted zone will discourage* *the use of fine natural sand in an aggregate blend and encourage the use of clean manufactured sand.*

Table 1.1 12.5mm Nominal Size Specifications

Sieve Size (mm)	Control Points		Restricted Zone Boundary	
	Minimum	Maximum	Minimum	Maximum
19		100.0		
12.5	90.0	100.0		
9.5		90.0		
4.75				
2.36	28.0	58.0	39.1	39.1
1.18			25.6	31.6
0.6			19.1	23.1
0.3			15.5	15.5
0.15				
0.075	2.0	10.0		

Table 1.2 9.5mm Nominal Size Specifications

Sieve Size (mm)	Control Points		Restricted Zone Boundary	
	Minimum	Maximum	Minimum	Maximum
12.5		100.0		
9.5	90.0	100.0		
4.75		90.0		
2.36	32.0	67.0	47.2	47.2
1.18			31.6	37.6
0.6			23.5	27.5
0.3			18.7	18.7
0.15				
0.075	2.0	10.0		

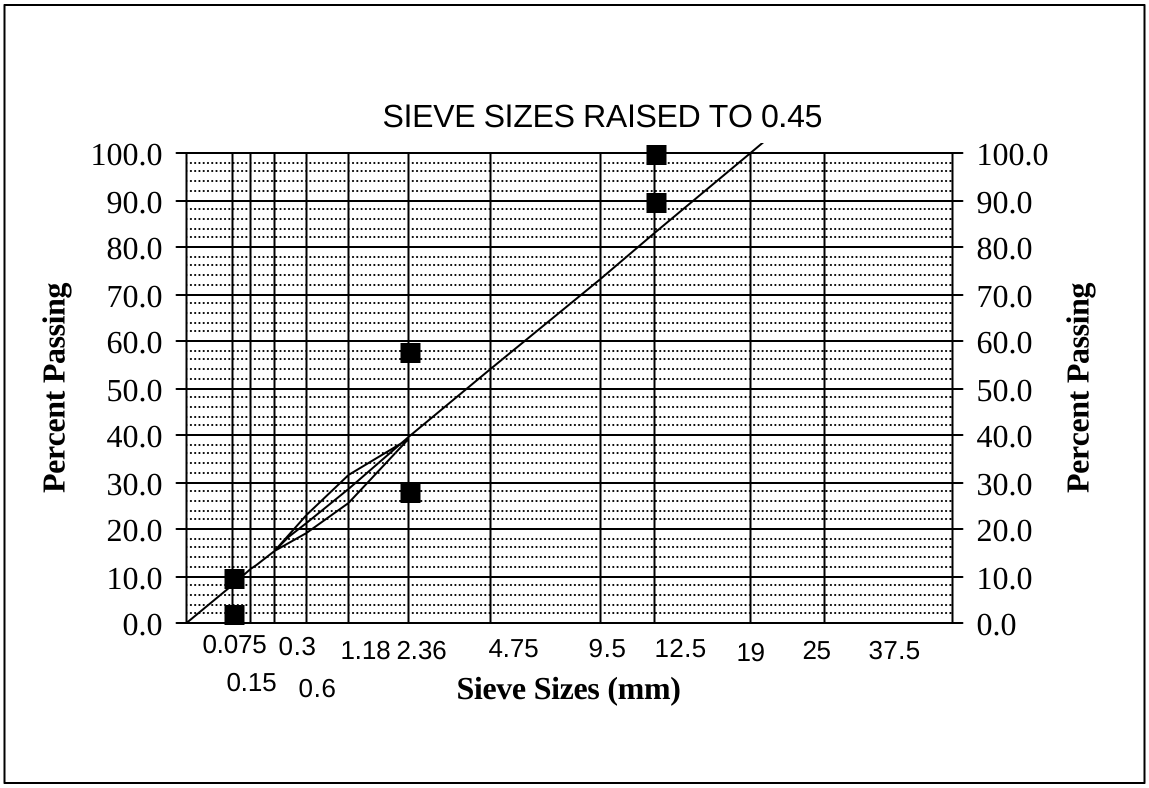


Figure 1.1 12.5mm Nominal Size Specifications

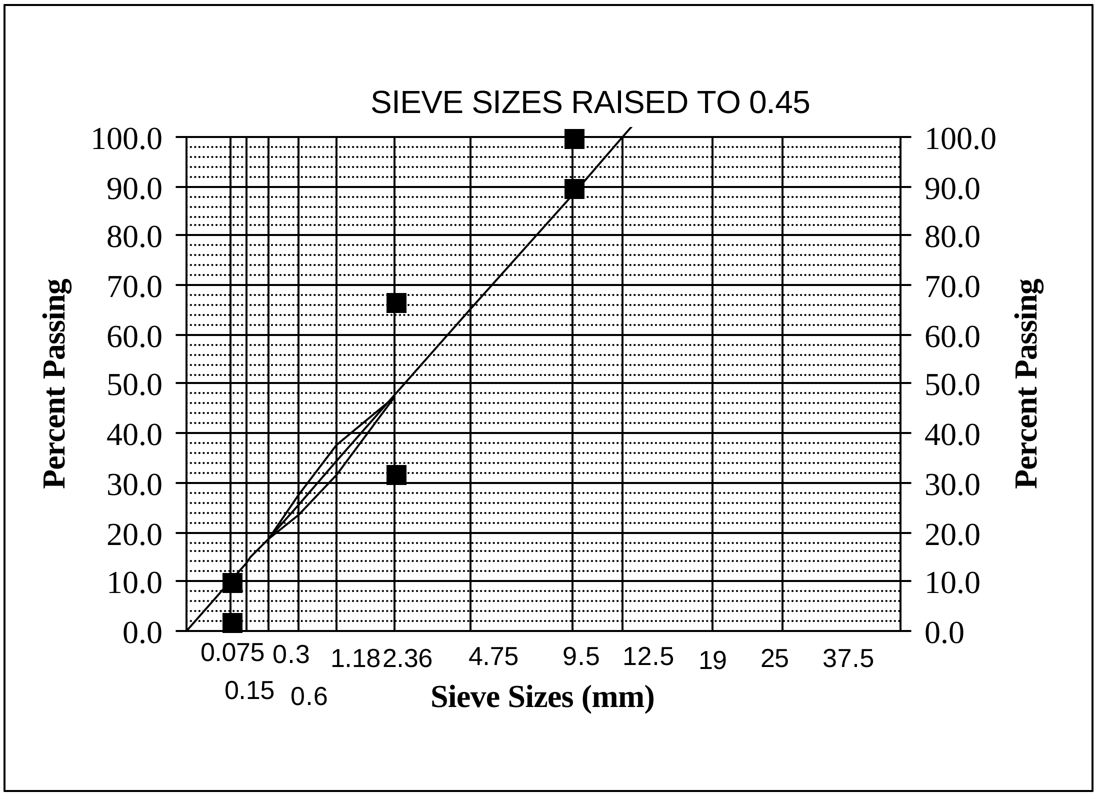
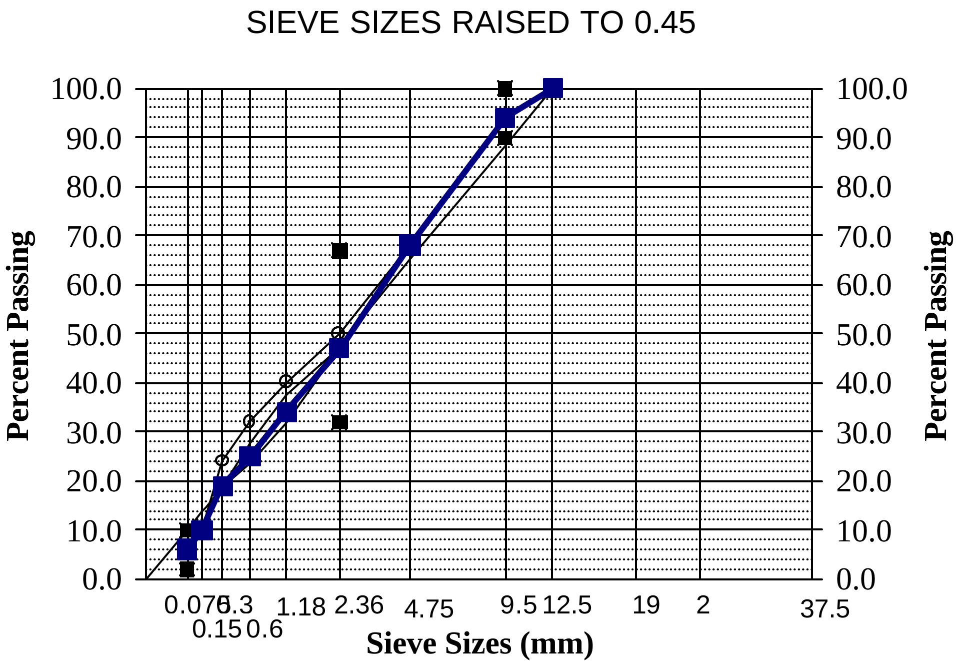


Figure 1.2 9.5mm Nominal Size Specifications

The amount of fines used in asphalt concrete mixtures and its shape and surface texture play a significant role in determining the workability, durability, and strength of asphalt concrete pavements. Angular and rough aggregate particles produced from crushing operations usually produce mixtures that are stronger and more resistant to permanent deformation than mixtures containing round and smooth aggregates from natural river sands. However, crushed fines are blended with natural sands to increase the workability of the mix.

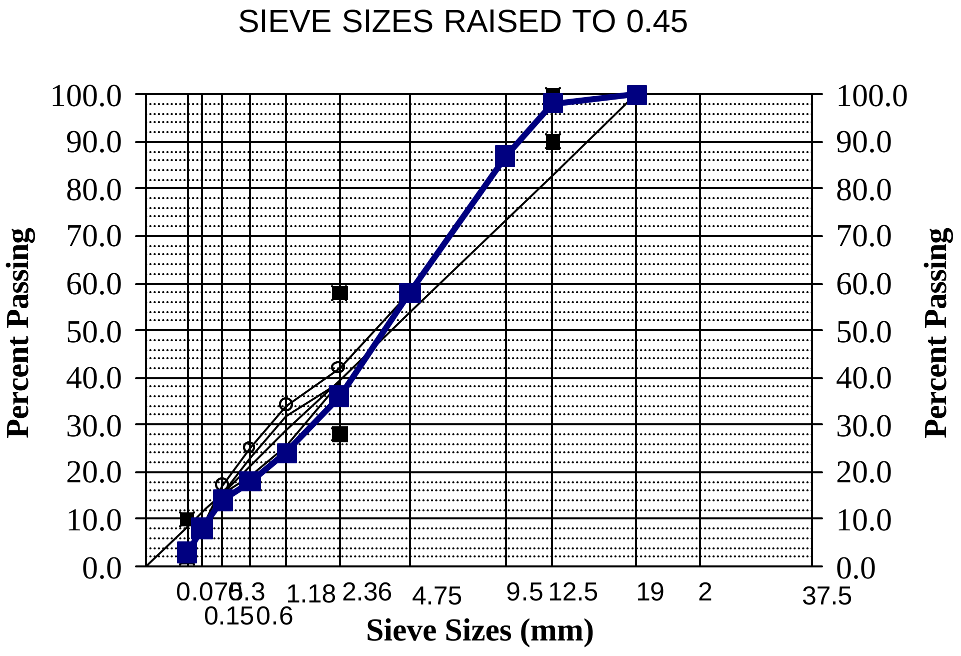
To study the different aggregate gradation curves, four different mixes will be evaluated. All of these mixes will consist of crushed granite aggregate available in NC with varying percentages of natural sand. The type of granite and sand will be selected in consultation with NCDOT. Two different sizes of aggregate blends will be used: 12.5 mm nominal size and 9.5 mm nominal size. For each type of aggregate blend, two different aggregate gradations will be utilized comparing finer and coarser gradations: (1) above restricted zone with 12.5mm NMSA, (2) below restricted zone with 12.5mm NMSA, (3) through restricted zone with 9.5mm NMSA, and (4) above restricted zone with 9.5mm NMSA. Sample gradations are shown in Figures 1.3 and 1.4. The aggregate gradations are different only around the restricted zone. A PG64-22 asphalt cement will be used for all the mixtures evaluated in this study.

A new, key feature in the SUPERPAVE mix design method is the laboratory compaction. Laboratory compaction is accomplished by the SGC. The SGC's unique feature is that it can provide information about the compactability of the particular mixture by capturing data during compaction. Specimen density is achieved in the gyratory compactor on the basis of three controls: vertical pressure, gyratory angle and number of gyrations. The compaction pressure is 600 kPa, and the SGC base rotates at constant 30 revolutions per minute during compaction with the mold positioned at a compaction angle of 1.25 degrees. A specimen height measurement is an important characteristic of the SGC since specimen density can be estimated during compaction by knowing the mass of material, the diameter of the mold, and the specimen height.



SIEVE SIZES RAISED TO 0.45

Figure 1.3 Sample 9.5mm Gradations



SIEVE SIZES RAISED TO 0.45

Figure 1.4 Sample 12.5mm Gradations

In SUPERPAVE system, the compaction is a function of the design number of gyrations, N_{des}. It is used to vary the compactive effort of the design mixture and is a function of climate and traffic level. The initial number of gyrations (N_{ini}) is used to determine an estimation of the compactability, and the specimen is compacted to the maximum number of gyrations (N_{max}).

The compaction data are analyzed by calculating the estimated bulk specific gravity, corrected bulk specific gravity, and corrected percentage of maximum theoretical specific gravity (%G_{mm}). From these data points, three graphs are generated: air voids, voids in mineral aggregate (VMA), and voids filled with asphalt (VFA) versus asphalt content. The criteria for the proper mixtures are as follows:

- The target air void should be 4 percent
- VMA values are a function of the nominal maximum size of aggregate
- VFA values depend on traffic level
- % G_{mm} at N_{ini} should be less than 89%
- % G_{mm}, at N_{max} should be less than 98%

In order to evaluate the effect of the restricted zone on volumetric properties of specimens compacted with the SGC the following questions are addressed:

1) *Are N_{ini}, N_{des}, and N_{max} affected by the different aggregate gradations, and if so how?*

2) *Do the different type of aggregate blends (crushed granite and granite with natural sand) affect the volumetric properties?*

In order to get 4% air void in an I-2 surface mixture used by the NCDOT, the asphalt cement content is increased to as high as 7%. Since the fine graded asphalt mixture is designed for a low traffic-volume road, producing an economical mixture is one of the main goals. Currently, the NCDOT uses the target air voids of 5 to 5.5% with Marshall mix design method; however, the SUPERPAVE™ system specifies that the target air void should be 4%. This criteria requires the following investigations of I-2 surface mixture:

1. *Is it reasonable to design I-2 surface mix by the SUPERPAVE mix design method?*
2. *Can it be produced easily and economically?*

The volumetric properties of the mixes at optimum asphalt content are compared as well as the compaction parameters for different mixes will be compared. In addition, the moisture sensitivity of the design mixture will be evaluated according to the AASHTO T283 to ensure the adequate performance of the mixes.

The performance based tests and performance prediction models are the products of the SHRP research. Outputs from these tests are used to make predictions of actual pavement performance. They are developed to estimate the performance life of a prospective HMA in terms of equivalent single axle loads (ESALs). Two new performance based testing procedures were developed by the SHRP: SUPERPAVE Shear Tester (SST) and the Indirect Tensile Tester IDT. The data from these tests are used to estimate actual pavement performance.

The SUPERPAVE Volumetric mix design entails compacting test specimens using the SGC and selecting asphalt content on the basis of volumetric design requirements. Intermediate mix design uses a volumetric mix design as a starting point and adds an array of SST and IDT tests to arrive at a series of performance predictions. It is used for traffic up to ten million ESALs and is anticipated to be the most predominant SUPERPAVE mix design used in typical highway applications. Complete mix design includes most of the facets of Volumetric and Intermediate mix designs. Complete designs offer a more reliable level of performance prediction. It is required for traffic levels exceeding ten million ESALs.

The performance testing and performance prediction models are important in designing and managing pavements. The SUPERPAVE™ performance prediction includes the following four components:

- material property model
- environmental effects model
- pavement response model
- pavement distress model

These models account for both the new asphalt mixture being designed and the characteristics of the in-place pavement.

The test results from the SST and IDT are used to determine non-linear elastic, visco-elastic, plastic, and fracture properties as the material property model. The environmental effects model calculates pavement temperature as a function of depth and material thermal characteristics. The pavement response model predicts stresses and strains using a two-dimensional, axisymmetric finite element approach from the output of the material property and environmental effects models. The pavement distress model estimates rutting and fatigue and low temperature cracking by using the pavement response and material property models. The major difference between the Intermediate and Complete mix designs is that Complete level testing provides a more reliable prediction of pavement performance because it involves performance testing over a wider range of temperatures as compared to Intermediate mix design. This allows use of the environmental effects model to more accurately predict pavement performance.

The SST is a closed-loop system that consists of four major components such as the testing apparatus, the test control unit and data acquisition system, the environmental control chamber, and the hydraulic system. Six tests can be performed using the SST, and they are as follows:

- volumetric test
- uniaxial strain test
- repeated shear test at constant stress ratio
- repeated shear test at constant height
- simple shear test at constant height
- frequency sweep test at constant height

The volumetric and uniaxial strain tests are performed only for the Complete mix design.

A full description of the test procedures can be found in AASHTO TP7. In this proposed study, repeated shear test at constant height and frequency sweep test at constant height will be used to analyze the performance of HMA mixtures. The rutting and fatigue analyses will then be conducted using the test results.

The repeated shear test at constant height is performed to identify an asphalt mixture that is prone to tertiary rutting. Tertiary rutting occurs at low air void contents and is the result of bulk mixture instability. In this test, repeated synchronized shear and axial load are applied to the specimen. The test specimens are subjected to load cycles of between 5,000 and 120,000 cycles depending on traffic and climate conditions, or until the permanent strain reaches five percent. One load cycle consists of 0.1 second load followed by 0.6 second rest period. The permanent shear strains are measured in this test.

The frequency sweep test at constant height is used to analyze the permanent deformation and fatigue cracking. A repeated shearing load is applied to the specimen to achieve a controlled shearing strain of 0.05 percent. One hundred cycles are used for the test at each of the following loading frequencies: 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02 and 0.01 Hz. The dynamic shear modulus (G*) and phase angle (δ) are determined by this test.

The IDT is used to measure the creep compliance and strength of asphalt mixtures using indirect tensile loading at intermediate to low temperatures. Two tests are performed using the IDT: Creep Compliance and Strength at Low Temperatures and Strength at Intermediate Temperatures. A full description of the test procedures can be found in AASHTO TP9. Although the IDT is a part of the SUPERPAVE Intermediate and Complete designs, it will not be included in this study.

The loaded wheel testing machine is a proof tester of HMA mixtures. A compacted asphalt concrete specimen is subjected to an elevated temperature in a loaded wheel system under repetitive loading, and the permanent deformation induced under the wheel path is measured. This test will simulate the actual field compaction, the traffic loading and the environmental conditions in a laboratory.

In addition to the SST and loaded wheel testing, an indirect tensile strength test will be conducted to develop a new and simple approach to ensure the performance of the mixes. The test will be conducted at 25 +/- 1.0 °C at the loading speed of 2 in./min. Then the tensile strength will be calculated by the following equation:

$$\mathbf{S_t = 2P/\pi tD}$$

Where,
S_t= tensile strength in psi
P = maximum load in lbs
t = specimen height before testing in inches.
D = diameter of specimen in inches.

In accordance with AASHTO T283, the moisture sensitivity of SUPERPAVE mixtures will be evaluated using the given equation for the indirect tensile strength. From the calculated tensile strengths, a tensile strength ratio will be determined for each aggregate blend. Currently, the NCDOT criterion for tensile strength ratio is a minimum of 0.85 or 85%.

In view of the detailed discussion in the preceding sections, the project objectives will be achieved through the following main tasks:

l) **Aggregate Gradation Selection:** All the mixes will consist of manufactured crushed granite aggregate and varying amount of natural sand with a maximum of 20 percent. Preliminary discussions with NCDOT have suggested 2 levels for the amount of natural sand. The selection of natural sand used will be made in consultation with NCDOT. Two different sizes of principal aggregate blends will be used: 12.5 mm and 9.5 mm nominal sizes. Four different gradations will be used to study all the possible adversative effects, if any, on mixes: **(1)** gradation above the restricted zone with 12.5mm NMSA, **(2)** gradation below the restricted zone with 12.5mm NMSA, **(3)** gradation through the restricted zone with 9.5mm NMSA, and **(4)** gradation above the restricted zone with 9.Smm NMSA. The aggregate gradations will be different only around the restricted zone. In order to ensure an acceptable level of performance for fine aggregate, AASHTO TP33 will be used to determine the particle shape and surface texture of the fine aggregates.

2) **Mixture Design:** It is proposed that the SUPERPAVE mix design is performed for all aggregate gradations and blends to determine the optimum asphalt contents. A PG64-22 asphalt cement will be used for all the mixtures. The mix design will be conducted for each of the mixes with the SUPERPAVE gyratory compactor for designing secondary roads in North Carolina. The values of N_{ini}, N_{des} and N_{max} of 6, 50, and 75, respectively, will be used for 9.5mm NMSA gradations and 7, 75, and 115 will be used for 12.5mm NMSA gradations. After the mix designs are completed, the volumetric properties of the mixes at optimum asphalt content will be evaluated, and the moisture sensitivity of the design mixture will be evaluated according to AASHTO T283.

3) **SUPERPAVE Performance Testing:** After the successful completion of the mix design, the following two SUPERPAVE performance prediction tests will be conducted: repeated shear test at constant height and frequency sweep test at constant height. As discussed earlier, these tests will evaluate the rutting and fatigue characteristics of fine graded mixes containing natural sand. As the low temperature cracking is not a prevalent mode of distress in pavements in North Carolina, especially in eastern part of the state, these evaluations will not be included in this study. *The positive results of performance evaluation will produce guidelines for designing and producing such mixes and will allow the NCDOT to develop and utilize a relatively economical SUPERPAVE™ surface course mixes for secondary roads. On the other hand, the negative results will prevent the NCDOT from using potentially troublesome mixes.*
4) **Indirect Tensile Strength Testing:** A study of mixtures by the indirect tensile testing device will be conducted to develop a simpler approach for evaluating the performance of mixes. This test will also help in producing guidelines for designing and producing fine graded SUPERPAVE™ surface course mixes.
5) **Loaded Wheel Testing:** The testing of mixtures by the loaded wheel testing device, known as Asphalt Pavement Analyzer (APA), will be conducted to screen the mixes. This will be used to determine the rut susceptibility of mixes under the wheel path. Such an approach will also help in producing guidelines for designing and producing fine graded SUPERPAVE surface course mixes.

The following sections will explain in detail the testing and characterization of the materials used in this study, give the results of the SUPERPAVE volumetric design of all study mixtures, and discuss the results of the mixture performance testing. The results of the moisture sensitivity and loaded wheel testing will also be presented and discussed.

CHAPTER 2
LITERATURE REVIEW

Mineral aggregates play an important role in the performance of asphalt mixtures. Aggregates constitute about 85% of total volume of asphalt mixtures. Various factors such as gradation and maximum size of the aggregate blend, angularity and surface texture of the aggregates influence the performance of the mixtures.

2.1 Superpave Specifications on Aggregates

Unlike the Marshall and Hveem mix design methods, Superpave mix design procedures incorporate aggregate criteria by refining the existing test methods. Two types of aggregate procedures are specified: consensus properties and source properties

The consensus properties are coarse aggregate angularity, fine aggregate angularity, flat and elongated particles and clay content (1). Angularity of the aggregates ensures a high degree of internal friction and shear resistance. Limiting elongated pieces ensures that the mixture will not be susceptible to aggregate breakage during handling and construction and under traffic. Limiting the amount of clay ensures the adhesive bond between asphalt binder and the aggregate. Source properties include toughness, soundness and deleterious materials. Those properties are source specific and are used to qualify local sources of aggregates.

2.1.1 Role of Aggregate Gradation

One of the most important properties of the aggregates in the asphalt mix is the gradation. To specify aggregate gradation, Superpave uses the 0.45 power gradation chart with control points and a restricted zone to develop a design aggregate structure. Control points function as master ranges between which gradation must pass. They are placed on the nominal maximum sieve, an intermediate sieve (2.36mm), and the smallest sieve (0.075mm).

The restricted zone, residing along the maximum density gradation between an intermediate sieve and the 0.3mm sieve, forms a band through the gradation cannot pass. Gradations that pass through the restricted zone have been called “humped gradations” because of their characteristic hump shape in this area. In most cases, a humped gradation indicates a high proportion of fine sand relative to total sand. This gradation poses compaction problems during construction and offers reduced resistance to permanent deformation during its performance life. The restricted zone also prevents the gradation from following the maximum density line in the fine aggregate sieves. Gradations that follow this maximum density gradation often have inadequate VMA to allow enough asphalt content for adequate durability. These gradations are every sensitive to asphalt content and can easily become plastic with even minor variations in asphalt content.

2.1.2 Air Void Considerations

The packing characteristics of asphalt-coated aggregate properties in an asphalt mixture are related to both aggregate surface characteristics and gradation. Aggregate surface characteristics include angularity and surface texture. Surface properties contribute to stability and skid resistance.

Sufficient voids are needed to develop adequately thick asphalt films for adhesion and durability. Aggregate gradation has a major influence in the formation of intergranular void space between the aggregate particles. The volume of this intergranular void space between the aggregate particles of a compacted paving mixture that includes the air voids and the effective asphalt content, expressed as a percent of total volume, is called the Voids in the Mineral Aggregate (VMA).

A gradation with maximum density has no or very little air voids. The addition of asphalt to this maximum density gradation only serves to separate the aggregate particles, which reduces the shear strength of the mix and increases the potential for lateral flow. Too much air voids makes the mixture highly permeable and thereby reduces the resistance to the action of air and water. High permeability to air causes embrittlement of the binder due to oxidation, causing the pavement to crack. High permeability to water encourages stripping of the asphalt from the aggregate particles, and endangering the subgrade layer and base course as well (2). Thus air voids in the compacted mixture play an important role in the durability of asphalt concrete. Therefore, the voids' content must be carefully chosen so that none of the important characteristics are sacrificed.

2.2 Natural Sands

Fine aggregate contributes more to VMA than coarse aggregate. The interaction of shape and texture of the fine aggregates on the packing characteristics of an asphalt mixture greatly influence the VMA of the mix. So rough textured and angular aggregates will have a high degree of interlock when a load is applied and will be more resistant to displacement by that load. Crushed aggregates or Manufactured aggregates are angular and have rough surface textures.

In practice, the use of natural sand is widely noticed. Natural sand can be defined as fine aggregate that are obtained from natural deposits, rather than those that are collected during aggregate crushing operations. The use of natural sand is attractive to contractors because it is generally less expensive than crushed fines (3).

Natural sands are fine, well rounded aggregates with smooth surface texture. Aggregates that are rounded are more easily moved or displaced by an applied load. Rounded materials tend to slide by each other when subjected to load. The particles with smooth surface textures will generally be more easily compacted than the aggregates with rough surface textures.

The presence of natural sand in asphalt concrete tends to lower the resistance of the mixture and makes more susceptible to permanent deformation, shoving, and bleeding than mixtures containing 100 percent manufactured fine aggregates(4). These effects of natural sands are attributable to their round shape and smooth surface texture, which facilitate to the rearrangement of larger aggregate particle under the influence of repeated loads.

Agencies like the Federal Highway Administration (FHWA) and the U.S. Army Corps of Engineers (USACE) have issued guidance that limits the contents of natural sand in pavement constructions. FHWA’s Technical Advisory T5040.27 provides the following recommendations regarding natural sands: “The quality of natural sand varies considerably from one location to another. Since most natural sands are rounded and often contain some undesirable materials, the amount of natural sand such as a general rule, should be limited to 15 to 20 percent for high volume pavements and 20 to 25 percent for medium and low volume pavements. These percentages may increase or decrease depending on the quality of the natural sand and the types of traffic to which the pavement will be subjected”. USACE limits the natural sand content of heavy-duty pavement mixtures to 15% by mass of all the aggregate.

However some natural sands have performed as well as manufactured fine aggregates. The shape of natural sands ranges from well round to angular, depending on their mineralogy and geologic history. The performance of an asphalt mixture can also depend on the quality of sand used.

2.3 Review of Past Work

Various papers have been published in the literature regarding the performance of natural and crushed aggregates in asphalt mixtures.

JM Rice and WH Goetz (5) explored the possibility of using local Indiana dune, lake and gravel pit waste sands as aggregates for low cost sand bituminous pavement mixtures, particularly in areas where commercial aggregates are to be obtained only at a premium. Important characteristics of the sands, which influence the compressive strength of the mixtures, are the amount of the natural fine material, the surface texture of the sand grains and the gradation of the particle sizes. The Lake Michigan dune sands, because of their smooth surface texture, lack of natural fine material, and one sized gradation, are inferior to the lake sands in regard to compressive strength. The gravel-pit waste sands, unused products of the commercial gavel-pits, produced stronger mixtures. Similarly Paul and Rex (6) studied the possible problems encountered in the use of locally available materials in asphalt mixtures. They found that the mixtures containing natural aggregates produced inadequate compressive strengths. They recommended the use of crushed aggregates, which resulted in pronounced improvement in stability.

J.W. Button (7) et al studied the influence of fine aggregate on plastic deformation on laboratory prepared asphalt concrete mixtures when increasing amount of natural (uncrushed) aggregate particles are added to replace crushed particles. Tests on asphalt mixtures included unconfined compression, static and dynamic creep, and indirect tension. The particle index test was used on the aggregate. Particle indices increase as the amount of natural sand in the mix decreases. Some changes were observed with the replacement of natural sand particles by manufactured sand particles.

They are

- Increased asphalt content owing to greater specific surface area and greater absorption of asphalt by some manufactured particles.
- Increased air void content and VMA of compacted mixtures owing to the angular shape and surface texture of the manufactured particles

It was also observed that the manufactured sand mix is more resistant to compaction. Test results indicated that asphalt mixtures containing some natural sands plastically deform under static and dynamic loads much more readily than similarly graded mixtures containing only manufactured particles. They suggested that rutting can be successfully addressed by replacing most or all of natural sands with manufactured particles, using large top-size crushed aggregates, increasing the minimum allowable air voids in the laboratory compacted mixtures and limiting filler to bitumen ratio. They concluded that a properly designed asphalt paving mixture transmits loads through an interlocked aggregate framework. It does not depend on the asphalt or mastic for shear strength.

Kalcheff and Tunnicliff (8) studied the effects of crushed coarse and fine aggregates in asphalt concrete. They observed that the optimum asphalt content for properly designed asphalt paving mixtures is approximately the same for natural sand mixtures and manufactured sand mixtures containing sands of similar particle shape, but somewhat greater for mixtures containing manufactured sand having more angular particles. Test results indicated that the mixtures containing crushed coarse and fine aggregates are much more resistant to permanent deformation from repeated traffic loadings, and much less susceptible to the effects of temperature and high initial void content than comparable mixtures with natural sand. Also, tensile fatigue resistance is improved by using manufactured sand rather than natural sand. They concluded that manufactured sand resulted in improved mixture behavior in all cases.

Shklarsky and Livneh (9) made an extensive study of the difference between natural gravel and crushed-stone aggregates in combination with natural sand and crushed-stone fine aggregates. Several variables were studied including the Marshall stability and flow, angle of internal friction and cohesion as measured in triaxial shear, resistance to moving wheel loading, resistance to splitting, immersion-compression strengths, and permeability. They reported as follows: Replacement of the natural sand with crushed fines improves incomparably the properties of the product, increases its stability, reduces rutting, improves water resistance, reduces bitumen sensitivity, increases the void ratio, and brings the mixture of the quality level of one with crushed coarse and fine aggregate. On the other hand, replacement of the coarse material with crushed coarse aggregate entails no such decisive effect.

Moore and Welke (10) ran Marshall mix designs on 110 sands from throughout the state of Michigan in which the coarse aggregate, asphalt content, and mineral filler were held constant. Both the angularity of the fine aggregate and the gradation of the mixture are critical in acquiring higher stabilities. The more angular the fine aggregate, the higher the stability. As for gradation, the closer the gradation is to the Fuller curve for maximum density, the higher is the stability. Rounded sands of relatively uniform size result in lower stabilities. Moreover, manufactured sands have highly angular particle shapes and are made for extremely high stabilities.

Lottman and Goetz (11) have reported the effect of crushed gravel fine aggregate in improving the strength of dense-graded asphaltic surfacing mixtures.

2.3.1 Packing Volume Concepts and Rugosity

The behavior of natural and manufactured aggregates can be explained by the packing volume concepts developed by Tons and Goetz (12). The packing volume and rugosity concepts are the theoretical basis for understanding the bulk behavior and interlocking mechanisms of aggregate composites with and without a binder. Two aggregate factors that influence the behavior of a compacted asphalt mixture are particle geometry and particle volume. Particle geometry includes shape, angularity and surface texture of the aggregate particles. Generally angularity and texture are overlapped and are unified by the term “rugosity.” More angular the rock, the higher is the rugosity.

The particle volume is defined as the volume, which a rock particle occupies in a mass of mono volume particles. Since irregular particles usually touch one another at the peaks of the surface roughness, the packing volume encompasses not only the solids and the surface capillaries (micro surface voids), but also the volume of surface macro dips and valleys (macro surface voids). Macro surface voids are primarily a function of the rugosity of a surface. The packing volume can be visualized as the volume enclosed by a dimensionless membrane stretching along the peaks of surface roughness. For any arrangement of particles in bulk, this membrane partitions voids into interparticle voids and particle surface voids.

If all the aggregate particles were ideal, smooth and one-sized spheres and they were packed in a simple cubical arrangement, the voids in the mass, porosity, would be 47.6 percent. In the densest tetrahedral packing, porosity would be reduced to 26.0 percent. For randomly packed spheres and irregular particles, the porosities usually vary between the two extremes.

Ishai and Tons(13) proved experimentally that in bituminous mixtures, surface voids of large particles provide enough room not only for asphalt, but also for smaller particles. They explained conceptually using a container filled with one-size, coarse, smooth particles. To this container, a certain amount of one-size, fine, smooth particles were added. The average equivalent sphere diameters for coarse and fine particles were designated as dc and df respectively. If the diameter ratio df/dc is small enough, the fine particles will be able to filter between the coarse ones and will fill the interparticle voids. Thus, without changing the mass volume (volume of the container) the total packing volume of the blend will increase, while the amount of packing porosity will decrease. Under no dilation of coarse particles, the increase of the total packing volume is equal to the decrease of the volume of interparticle voids. When the diameter ratio df/dc increases, dilation will occur in the structure of coarse particles and the introduction of fine fraction will increase the mass volume. Under constant packing volume of the particles, any additional increase in the mass volume (dilation) will be equal to a change on the volume of interparticle voids. The models are additive in both cases.

The additivity and simplicity of the above models are distorted when aggregates with irregular and rough aggregate fractions are involved. In this case, some of the particles may penetrate through and under the imaginary packing volume membrane of coarse particles. They defined this interaction between coarse and fine aggregates as the fines lost by rugosity.

They further observed that less active fine particles will be located between the larger rough particles which will be packed closer together with thinner asphalt films between them exhibiting higher resistance to shear, tensile and compressive deformation. On the other hand, smooth textured particles will be simply pushed apart by the more active fines between them and show low strength. They found that aggregates with higher geometric irregularity possess lower packing VMA, while mixtures with smooth spherical aggregates possess higher packing VMA.

Khedaywi and Tons (14) studied the effect of aggregate rugosity and size on bituminous mixes. A hypothesis was tested which suggest that for each coarse aggregate type with different surface characteristics, there is a specific fine aggregate size that contributes to developing an interlocking mechanism between the surfaces of coarse aggregates when they are combined in a bituminous mix. For hypothesis testing, two types of coarse aggregates, limestone and rounded gravel, were used. They concluded that by matching the rugosity and the size of the fines properly, the strength of rounded gravel mixes could be made much closer to the strength of mixes using crushed limestone coarse aggregate.

CHAPTER 3

MATERIAL SELECTION AND EVALUATION

In this section the source and properties of the aggregate and asphalt binder used for this study are presented. The source and rheologic properties of the asphalt are presented first, followed by the gradation, specific gravity, angularity and source specific information for all mineral aggregates used in this study.

3.1 Asphalt Binder Properties

As mentioned in previous sections, it was decided that a PG64-22 binder would be used for all mixtures. The binder was obtained from Citgo Oil company's Savannah Georgia refinery. The properties of this binder, as tested by the supplier, are given below in Table 3.1.

Table 3.1 Asphalt Binder Properties

Test	Test Method	Specifications	Test Results
Unaged Binder			
Specific Gravity @ 15^{o}C(60^{o}F)	AASHTO T228	Report	1.034
Specific Gravity @ 25^{o}C(77^{o}F)	AASHTO T228	Report	1.028
API Gravity	Calculated	Report	5.3
Lbs./Gal.	ASTM Table 8	Report	8.615
Flash Point, ^{o}C	AASHTO T48	> 230^{o}C	278
Viscosity (Brookfield) @ 135^{o}C	ASTM D4402	< 3 Pa-S	0.410
Viscosity (Brookfield) @ 165^{o}C	ASTM D4402	Report	0.135
Phase Angle, degrees	AASHTO TP5	Report	84.8
Dynamic Shear, 10 rad/sec, $G^*/\sin\delta$ @ T^{o}C, in kPa	AASHTO TP5	> 1.00 kPa 64 ^{o}C	1.224
RTFO Aged Residue			
Mass Change, %	AASHTO T240	< 1.0 wt %	0.28
Dynamic Shear, 10 rad/sec, $G^*/\sin\delta$ @ T^{o}C, in kPa	AASHTO TP5	> 2.20 kPa 64 ^{o}C	2.525
PAV Aged Residue			
Dynamic Shear, 10 rad/sec, $G^*\sin\delta$ @ T^{o}C, in kPa	AASHTO TP5	< 5000 kPa 25 ^{o}C	2287
Creep Stiffness and m value, 60 sec @ T ^{o}C	AASHTO TP1	< 300 Mpa > 0.300	S = 145.9 m = 0.414
Mixing/Compaction T ^{o}C	160^{o}C / 150^{o}C		

3.2 Manufactured Aggregate Properties

The manufactured mineral aggregate used is this study was obtained from Martin Marietta's Garner N.C. quarry. This granite aggregate was selected for this study mainly because of the quarry's close proximity to the laboratory at NCSU. This aggregate's properties (specific gravity, angularity, etc.) are also known to be very consistent throughout the quarry. The aggregate was sampled from the quarry's main #67, #78M, washed and unwashed screening stockpiles and brought back to the laboratory where it was oven dried, and sieved into individual size fractions. Material retained on 19mm, 12.5mm, 9.5mm, #4, #8, #16, #30, #50, #100, #200 and passing the #200 was stored in separate containers so that any aggregate gradation used for the study could be batched from the individual size fractions. This method of aggregate blending, while somewhat time and labor intensive, allows for strict control and exact replication of a mixture's aggregate gradation. The specific gravity of the manufactured aggregate as determined by AASHTO T84-88 ("*Specific Gravity and Absorption of Fine Aggregate*") and AASHTO T85-88 ("*Specific Gravity and Absorption of Course Aggregate*") for the standard stockpile sizes are given below in Table 3.2. The aggregate angularity as determined by AASHTO TP56-99 ("*Standard Test Method for Uncompacted Void Content of Coarse Aggregate – As Influenced by Particle Shape, Surface Texture, and Grading*"), ASTM C1252 ("*Standard Test Method for Uncompacted Void Content of Fine Aggregate – As Influenced by Particle Shape, Surface Texture, and Grading*") and applicable sand equivalency values, by AASHTO T176-86 ("*Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test*"), are also given in Table 3.2.

3.3 Natural Sand Properties

The two natural sands used in this study were selected after consultation and input from the engineers in the Material and Tests Unit of the North Carolina Department of Transportation. Both sands, from the Ross and Snake pits, were obtained from the same supplier and are located in relatively close proximity to each other in the Lumberton area of southeastern North Carolina.

Table 3.2 Manufactured Aggregate Properties

Property	Stockpile Size Designation			
	#67	#78M	Washed Scns.	Dry Scns.
Bulk Specific Gravity	2.619	2.594	2.607	2.610
Apparent Specific Gravity	2.630	2.637	2.643	2.646
Aggregate Angularity % Voids	46.8	48.8	47.9	48.0
Flat and Elongated 3:1/5:1	15.5/0.5	22.5/2.4	N/A	N/A
Sand Equivalency	N/A	N/A	73	53

Table 3.3 and Figure 3.1 give the washed gradations of these two sands as determined by AASHTO T11-90 and T27-88 (“*Materials Finer Than 75mm (No.200) Sieve in Mineral Aggregates by Washing*” and “*Sieve Analysis of Fine and Coarse Aggregates*”). The specific gravity as determined by AASHTO T84-88 (“*Specific Gravity and Absorption of Fine Aggregate*”) and angularity values by ASTM C1252 (“*Standard Test Method for Uncompacted Void Content of Fine Aggregate – As Influenced by Particle Shape, Surface Texture, and Grading*”*)* of these sands are also presented in Table 3.3.

Table 3.3 Properties of Natural Sands

Sieve Size (mm)	**Ross Pit Sand**	**Snake Pit Sand**
	Percent Passing	
12.5	100	100
9.5	100	100
4.75	100	98
2.36	100	94
1.18	99	78
0.6	85	48
0.3	41	15
0.15	8	3
0.075	2	1
Bulk Specific Gravity	2.560	2.600
Apparent Specific Gravity	2.610	2.652
Aggregate Angularity % Voids	46	43

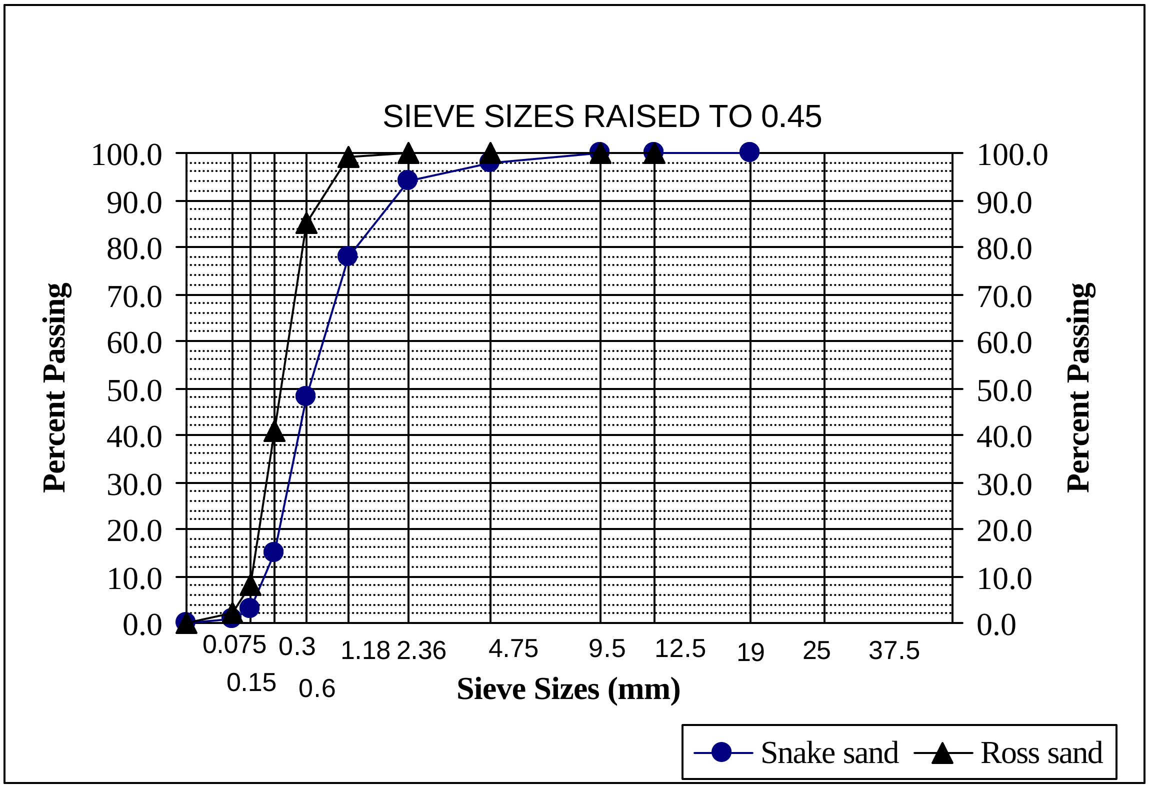


Figure 3.1 Natural Sand Gradations on 0.45 Power Chart

CHAPTER 4

MIXTURE DESIGN

In this section, the results of the SUPERPAVE volumetric mixture design are presented for all study mixtures. The mixture design procedure is briefly described and the requirements and specifications are first presented, followed by the results in the mixture designs for all study mixtures.

4.1 Mixture Design Procedure and Requirements

As mentioned in Chapter 1, it was decided that two different nominal maximum size aggregate (NMSA) gradations would be used in this study: 12.5mm and 9.5mm. The current NCDOT mixture requirements for a low volume pavement application were also used for both mixture types. Table 4.1 gives those mixture requirements and design parameters for a traffic level of less than 0.3 million equivalent single axle loads (ESALs) over the pavement's service life.

Table 4.1 NCDOT SUPERPAVE Mixture Design Criteria

Criteria or Specification	**S12.5B Mixture**	**S9.5A Mixture**
ESAL Range (millions)	<0.3	<0.3
Binder Grade	PG64-22	PG64-22
Gyrations at $N_{ini}\backslash N_{des}\backslash N_{max}$	7\75\115	6\50\75
%Air Voids	4.0	4.0
%Void in Mineral Aggregate (min.)	14.0	15.0
%Voids Filled with Asphalt	65-78	70-80
%G_{mm} at N_{ini} (max.)	90.5	91.5
%G_{mm} at N_{max} (max.)	98.0	98.0

In a typical SUPERPAVE volumetric mixture design, trial aggregate gradations are selected that meet the requirements of that mixture's gradation control points, and compacted with a SUPERPAVE gyratory compactor to specified number of revolutions or gyrations (N_{max}) using a calculated trial asphalt content. The bulk specific gravities of the trial aggregate gradation samples are measured and calculations are performed to determine an estimated optimum binder content and the corresponding volumetric properties at that binder content. The estimated volumetric properties of these trial aggregate gradations are evaluated for compliance to the specifications list in Table 4.1. The aggregate gradation that best satisfies the volumetric requirements of that mixture type is again used to fabricate specimens at varying asphalt binder contents and the volumetric properties of that design aggregate gradation are again evaluated over a range of binder contents. The binder content that satisfies the requirements of 4.0% air, and the additional requirements listed in Table 4.1, is then the optimum design for that mixture type. As mentioned in Chapter 1, one of the objectives of this study was to evaluate the gradation curves themselves and their effect on the design and performance of the mixtures. Upon consultation with NCDOT it was decided to concentrate on four general aggregate gradations for this study: 1) 12.5mm NMSA passing above the restricted zone, 2) 12.5mm passing below the restricted zone, 3) 9.5mm passing below through the restricted zone, and 4) 9.5mm passing above the restricted zone. These four gradations basically represent two different NMSA gradations, each one of those having a relatively coarser and finer portion of the fine aggregate fraction around the restricted zone. In order to simplify future explanation and discussion of the different mixtures and aggregate types used in this study, the following notation will be used:

(NMSA)(GRADATION)-(SAND)

where,

NMSA = nominal maximum size aggregate, either 9.5 or 12.5mm

SAND = sand type, manufactured (M), Ross pit (R) or Snake pit (S)

GRADATION = aggregate gradation with respect to the restricted zone, above (RA), below (RB), or through (RT).

Example 12.5RA-M = 12.5mm NMSA mixture using 100% manufactured sand passing above the restricted zone.

4.2 Design of Mixtures Containing 100% Manufactured Sand

Given the fact that the objective of the study had fixed the aggregate gradations to some extent, the design of these mixtures did not include the typical selection of the design aggregate structure procedure. The gradations were selected first and, through a few trials using an asphalt content of 5.0%, were modified slightly until they yielded a design that met all the requirements of those mixture types listed in Table 4.1. Figures 4.1,4.2 and Table 4.2 show the final aggregate gradations that were selected for use in this study. Once the design aggregate structure was selected, specimens were fabricated over a range of binder contents and the optimum binder content was selected that best met the mixture requirements given in Table 4.1. Table 4.3 presents the maximum theoretical specific gravity of the mixtures and the bulk specific gravity of the aggregate blends. Table 4.4 below presents the design information and properties of the optimum mixtures containing 100% manufactured aggregate.

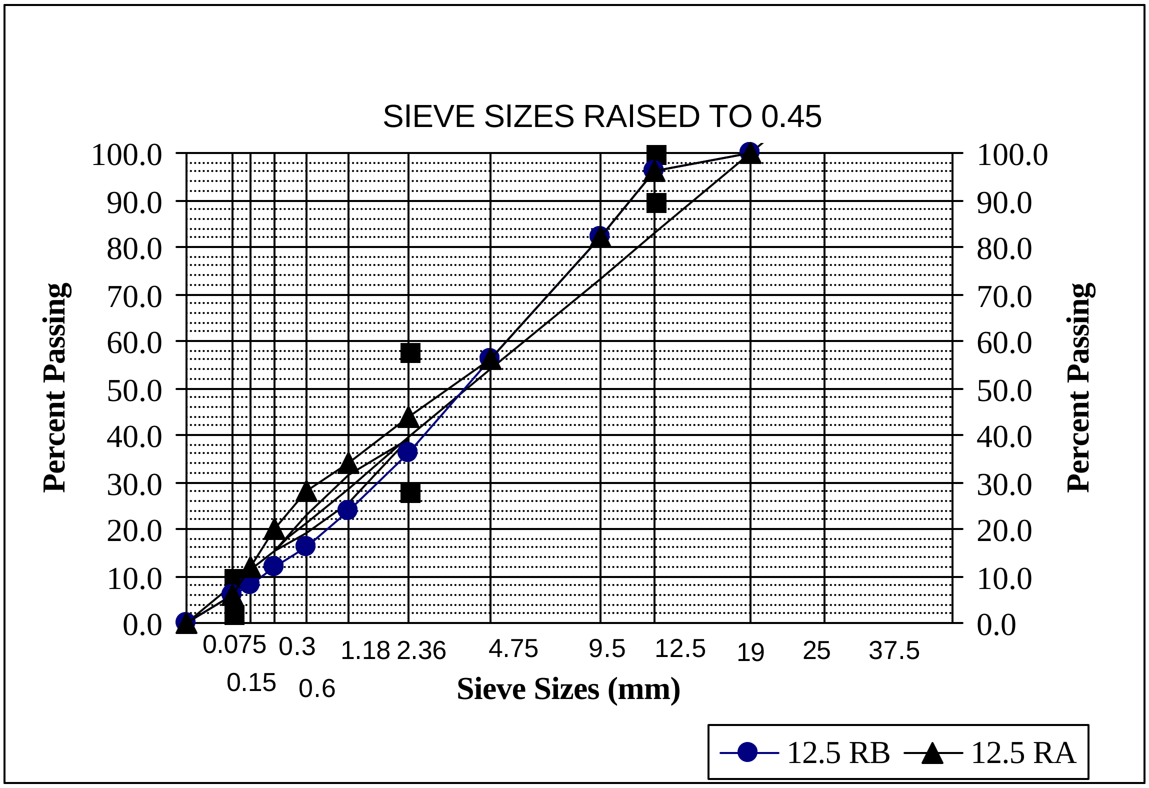


Figure 4.1 12.5mm Design Aggregate Gradations

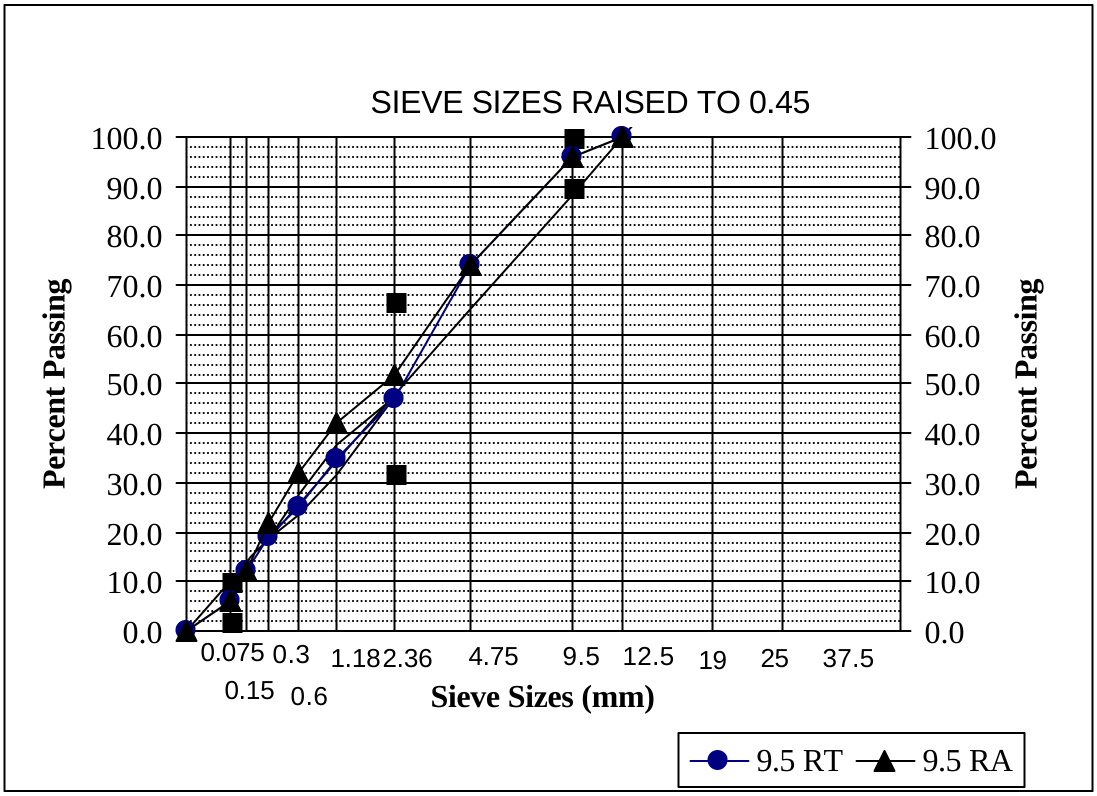


Figure 4.2 9.5mm Design Aggregate Gradations

Table 4.2 Aggregate Gradation for Manufactured Sand Mixtures

Sieve Size	Percent Passing			
	12.5RA-M	12.5RB-M	9.5RA-M	9.5RT-M
25	100	100	100	100
19	100	100	100	100
12.5	100	96	100	100
9.5	100	82	96	96
4.75	100	56	74	74
2.36	99.9	36	52	47
1.18	98.7	24	42	35
0.6	85.2	16	32	25
0.3	41.3	12	22	19
0.15	8	8	12	12
0.075	1.6	6	6	6
Pan	0	0	0	0

Table 4.3 Gmm and Gsb value of Manufactured Sand Mixtures

Mixture	Asphalt Content %	Gmm	Gsb
12.5RA-M	4.8	2.455	2.607
12.5RB-M	5.1	2.427	2.605
9.5RA-M	6.1	2.398	2.600
9.5RT-M	5.3	2.419	2.598

Table 4.4 Mixture Design Properties – 100% Manufactured Aggregate

Mixture ID	Asphalt Content (%)	Air Voids (%)	VMA (%)	VFA (%)	%Gmm@ Nini	%Gmm@ Nmax
12.5RA-M	4.8	4.0	14.9	73.1	89.3	97.1
12.5RB-M	5.1	4.0	15.2	73.7	89.9	97.2
9.5RA-M	6.1	4.0	17.8	77.6	90.8	97.6
9.5RT-M	5.3	4.0	15.3	73.8	90.1	97.4

4.3 Design of Mixtures Containing Natural Sand

Before mixture designs were initiated on the aggregate gradations containing natural sand, an analysis was preformed to determine the percentage of natural sand that could be blended with the manufactured aggregate. The percentage of the natural sands that can be substituted into the already fixed aggregate gradations will of course be dependent on the gradations of the natural sands themselves, but practical field limitations were also considered in the selection process. For instance, it was decided that a minimum of 10% natural sand should be considered, as any amount less than this would probably not be practical to blend during asphalt plant operations. The upper limit of the natural sand used in the aggregate gradations could also be limited not only by particle size specifications, but also fine aggregate angularity requirements. The fine aggregate angularity for the natural sands was determined in accordance with ASTM C1252 and the results were given in Table 3.3. For the assumed traffic level and nominal maximum size aggregate used in this study (shown in Table 4.1), NCDOT specifications require a minimum 40% uncompacted void content. Therefore, it can be concluded that the fine aggregate angularity alone will not limit the amount of natural sand that can be incorporated into the four aggregate gradations.

For the determination of a percent or range of feasible natural sand contents that can be substituted into the four aggregate gradations, the aggregate particle size distributions for the standard aggregate sizes (#67, 78M, manufactured sands) and natural sands were blended using a trial and error spreadsheet procedure. Figures 4.3 through 4.10 show the best possible material blends and how they compare to the target aggregate gradations. Figure 4.3 shows that the 12.5mm target aggregate gradation passing above the restricted zone can be met by substituting up to 20% Ross sand into the blend. However, it was determined that the addition of Ross sand in amounts greater than 10% caused the resulting gradation to deviate significantly from the target 12.5mm gradation passing below the restricted zone. Figure 4.4 shows that 12.5mm gradation passing below the restricted zone can be matched closely without the addition of any Ross sand. The same trend can be seen in the 9.5mm gradations (Figures 4.4 and 4.5) with 20% Ross sand being added to pass above the restricted zone, and no Ross sand being needed to achieve a gradation through the restricted zone. The Snake natural sand is much more flexible for use in the chosen aggregate gradations. It can be added in percentages ranging from 10 to 22% to meet the 12.5 and 9.5mm gradations passing above, below and through the restricted zone. From this analysis it was decided that the Snake sand would be used for the design of all four gradations, but the Ross sand should only be used to evaluate the 12.5 and 9.5mm gradations passing above the restricted zone.

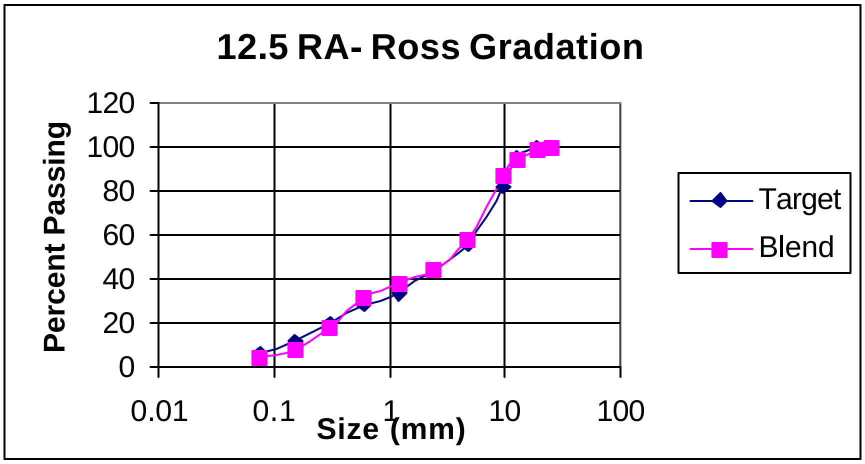


Figure 4.3 20% Ross Sand 12.5mm Gradation Above Restricted Zone

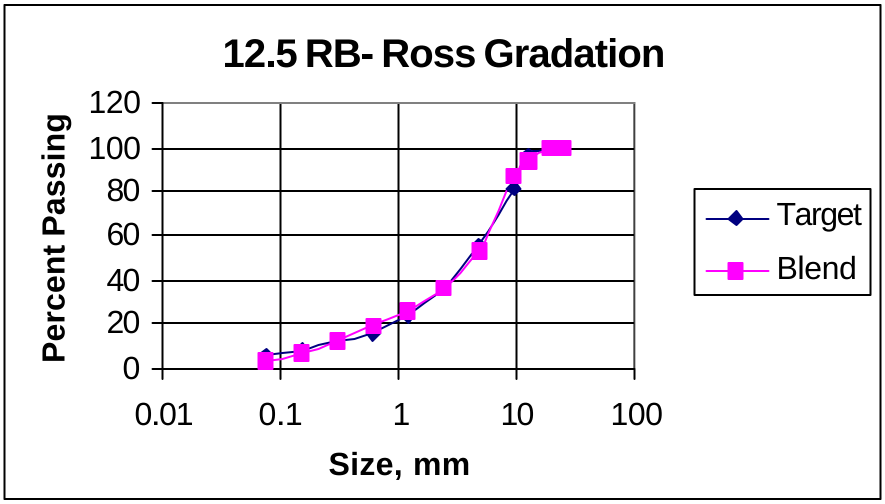


Figure 4.4 0% Ross Sand 12.5mm Gradation Below Restricted Zone

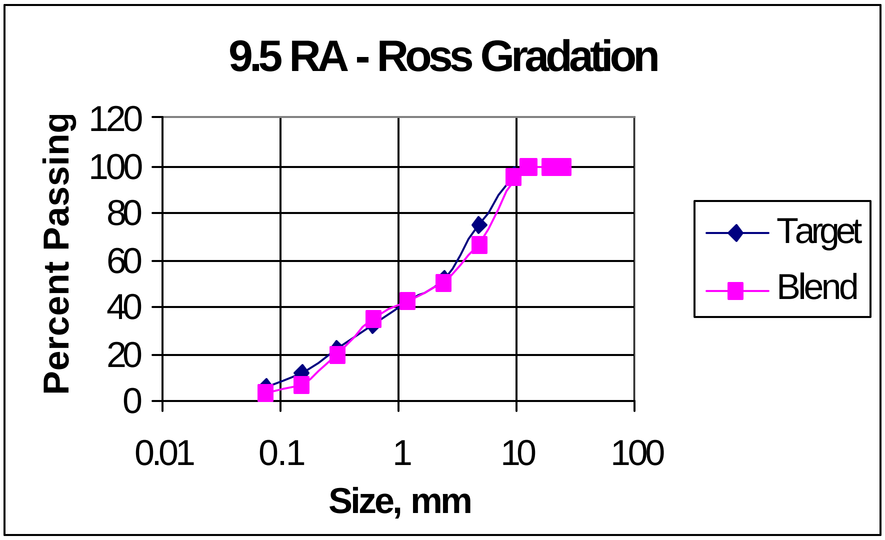


Figure 4.5 20% Ross Sand 9.5mm Gradation Above Restricted Zone

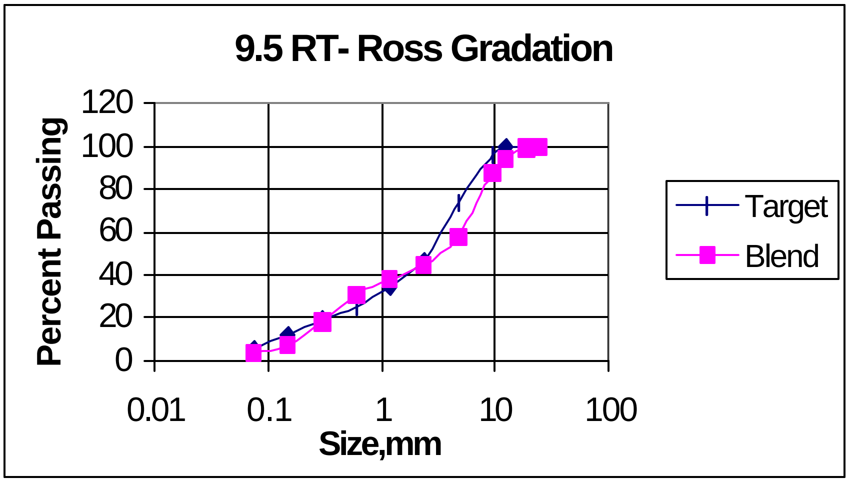


Figure 4.6 0% Ross Sand 9.5mm Gradation Through Restricted Zone

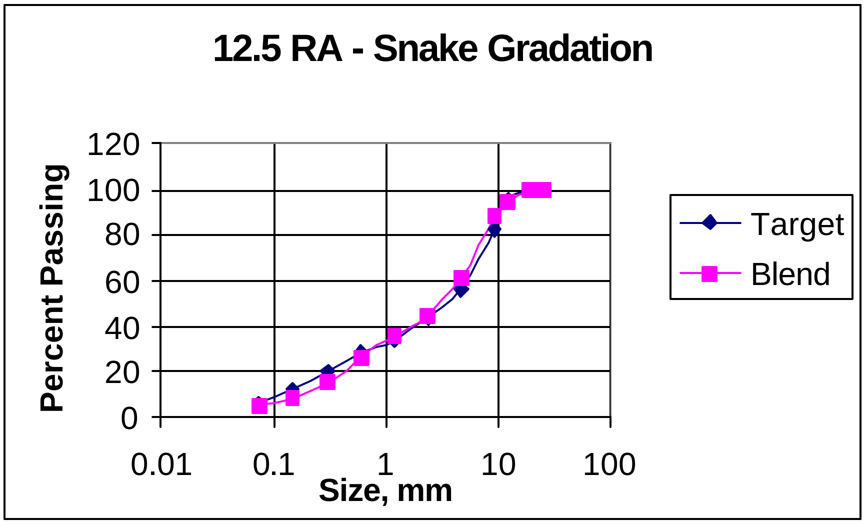


Figure 4.7 12% Snake Sand 12.5mm Gradation Above Restricted Zone

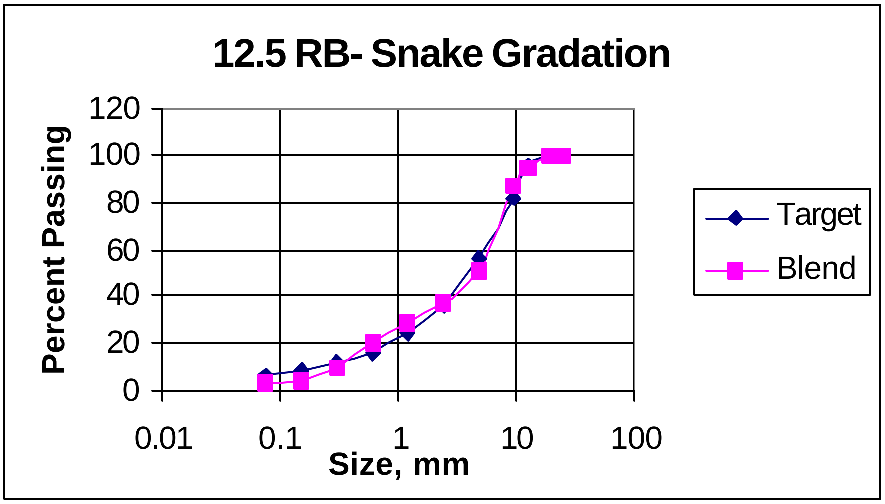


Figure 4.8 20% Snake Sand 12.5mm Gradation Below Restricted Zone

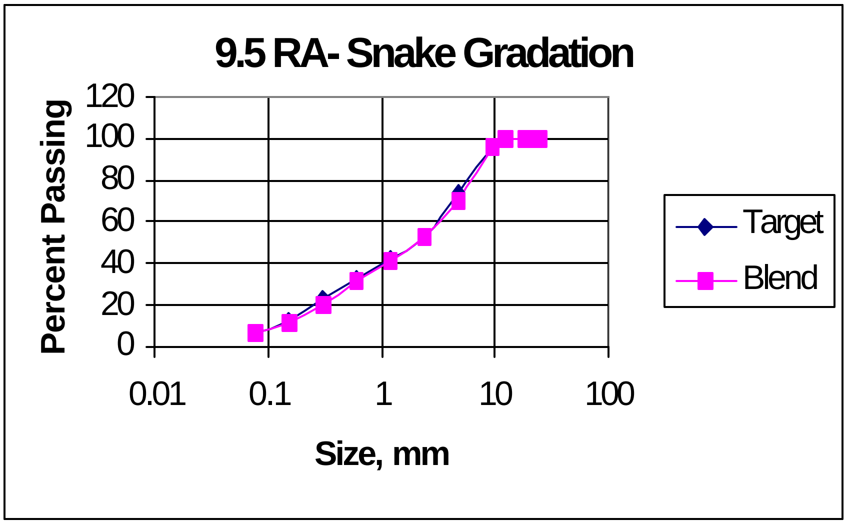


Figure 4.9 12% Snake Sand 9.5mm Gradation Above Restricted Zone

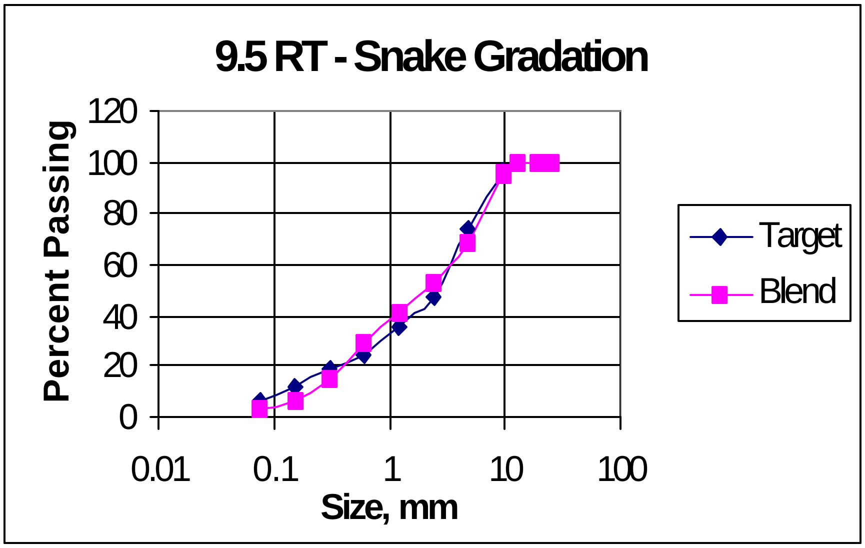


Figure 4.10 22% Snake Sand 9.5mm Gradation Through Restricted Zone

After the allowable percentage of natural sand for each gradation was determined, the mixture design process for the mixtures containing natural sand was performed exactly in the same manner as that for the mixtures containing 100% manufactured sand. Each aggregate gradation and natural sand combination listed above was used to fabricate specimens with a range of asphalt contents. Those mixtures that met the criteria in Table 4.1 were selected as the optimum designs. Table 4.3 below shows a summary of the volumetric properties at optimum asphalt content for mixtures containing natural sands. From Table 4.5 it can be seen that the 12.5RA-S mixture fails to meet the criteria for VMA (min 14.0) and the 9.5RA-S mixture fails to meet the criteria for dust proportion (0.6-1.2). Therefore, these mixtures were excluded from further study and leaving a total of four mixtures that contain natural sand for further evaluation in the performance testing and evaluation phase of the study.

Table 4.5 Volumetric Properties of Mixtures Containing Natural Sand

Mix ID	Sand Content (%)	Asphalt Content (%)	Air Voids (%)	VMA (%)	VFA (%)	Dust Pro-Portion (%)	% Gmm @ Nini	% Gmm @ Nmax
12.5RA-R	20	4.8	4.0	14.3	74.0	0.8	90.3	96.7
9.5RA-R	20	5.8	4.0	16.2	78.0	0.7	91.0	97.0
12.5RA-S	12	5.0	4.0	**13.8**	71.0	0.7	89.6	96.9
12.5RB-S	20	4.8	4.0	14.2	72.0	0.8	89.2	96.8
9.5RA-S	12	5.4	4.0	15.6	74.3	**1.4**	89.4	97.0
9.5RT-S	22	6.2	4.0	17.0	78.0	0.7	90.6	96.9

Table 4.6 presents the maximum theoretical specific gravity of the selected mixtures and bulk specific gravity of the aggregate blends. Tables 4.7 and 4.8 present the aggregate gradation of the selected mixtures containing Ross and Snake sands, respectively. Percent passing on each sieve size of manufactured sands as well as natural sands are given in these tables.

Table 4.6 Gmm and Gsb value of Mixtures containing Natural Sands

Mixture	Asphalt Content %	Gmm	Gsb
12.5RA-R	4.8	2.435	2.597
12.5RB-S	4.8	2.436	2.604
9.5RA-R	5.8	2.418	2.592
9.5RT-S	6.2	2.395	2.598

Table 4.7 Aggregate Gradation for Ross Sand Mixtures

Sieve Size	Percent Passing			
	12.5RA-R		9.5RA-R	
	Manufactured sand	Ross sand	Manufactured sand	Ross sand
25	100	100	100	100
19	99	100	100	100
12.5	94	100	100	100
9.5	88	100	95	100
4.75	58	100	66	100
2.36	44	100	51	100
1.18	38	100	43	100
0.6	34	97	37	97
0.3	30	88	31	88
0.15	26	82	26	82
0.075	23	80	23	80
Pan	20	80	20	80

Table 4.8 Aggregate Gradation for Snake Sand Mixtures

Sieve Size	Percent Passing			
	12.5RB-S		9.5RT-S	
	Manufactured sand	Snake sand	Manufactured sand	Snake sand
25	100	100	100	100
19	99	100	100	100
12.5	94	100	100	100
9.5	87	100	95	100
4.75	52	100	69	100
2.36	38	99	54	99
1.18	33	96	46	95
0.6	30	90	40	89
0.3	27	83	34	81
0.15	24	81	28	79
0.075	22	80	25	78
Pan	20	80	22	78

CHAPTER 5

MIXTURE EVALUATION

This chapter deals with the Superpave performance tests that were conducted to predict the performance of asphalt mixtures to fatigue cracking and rutting. Tests that were conducted using Simple Shear Tester, Asphalt Pavement Analyzer, Gyratory Load Plate Assembly and Indirect Tensile Strength Tests.

5.1 Simple Shear Tests

Using the Superpave Shear Tester (SST), the following tests were conducted:

- Frequency Sweep Test at Constant Height (FSCH)
- Repeated Shear Test at Constant Height (RSCH)

The test results were then used to perform an analysis of a representative pavement structure to investigate the effect on the predicted field performance.

Specimen Preparation

The specimens prepared for FSCH and RSCH tests were 150mm (6 inch) diameter specimens compacted to Ndesign level of gyrations using the SGC. Eight different types of mixtures with three replicates for each were prepared. Each specimen was sawed to a thickness of 50mm (2 inch). The bulk specific gravities (G_{mb}) of the compacted specimens were measured before testing. The specimens were glued between the loading platens using the adhesives.

Selection of Test Temperature

In the abridged fatigue analysis (SHRP A-003A) procedure, the pavement temperature is assumed to be 20^{o}C through out the year. The resistance of the mix to fatigue cracking is calculated based on the mix properties evaluated using FSCH at 20^{o}C temperature. The mixes are intended to be used for pavement construction in Cumberland county, North Carolina. The seven-day average high pavement temperature at 20-mm depth from the pavement surface was estimated using SHRPBIND Version 2.0 software. At 50% reliability, the temperature was 54.2^{o}C and at 98% reliability, the temperature was 57.4^{o}C. As the main objective of this study was to compare the performance of different mixes, and not to calculate actual pavement life, a test temperature of 54.2^{o}C was used.

5.1.1 Frequency Sweep Test at Constant Height

This test is used to measure linear viscoelastic properties of asphalt concrete for rutting and fatigue cracking analysis. This test uses a dynamic type of loading and is a strain controlled test with the maximum shear strain limited to ± 0.005 percent (maximum peak to peak of 0.0001 mm/mm). This test is conducted at a constant height requiring the vertical actuator to be controlled by the vertical LVDT. The specimen is preconditioned by applying a sinusoidal horizontal shear strain with amplitude of approximately 0.0001 mm/mm at a frequency of 10 Hz for 100 cycles. After preconditioning the specimen, a series of 10 tests are conducted in descending order of frequency. The following frequencies are used: 10,5,2,1,0.5,0.2,0.1,0.05,0.02 and 0.01 Hz. A specific number of cycles between 4 and 50 is applied. During the test, axial and shear loads and deformations are measured and recorded.

This test was conducted according to AASHTO TP-7 Procedure E. Eight mixtures, four for manufactured sands and four for natural sands, with three replicates each, were tested at a temperature of 20^{o}C (15). Dynamic Shear Modulus and Phase angle was measured at each frequency for each mixture. The ratio of the stress response of the test specimen to the applied shear strain is used to compute a complex modulus for a given frequency. The delay in the response of the material is measured as phase angle. From the test results, the following graphs are generated to evaluate the mix properties:

- Dynamic Shear Modulus ($|G^*|$) vs frequency (on log scale)
- Phase angle vs frequency (on log scale)

Analysis of FSCH Test Results

Table 5.1 shows the values of complex modulus and phase angles for all mixtures. Figure 5.1 shows the complex modulus as a function of frequency at 20 ^{o}C. Figure 5.2 shows the change in phase angles with changing frequency. As the stiffness of the material is a function of frequency of load applied, G* values are found to be increasing with increasing frequency. The test results show that the 9.5mm mixture above the restricted zone and manufactured sand (9.5RA-M) has the highest G* value, indicating it as the stiffest mixture among all mixtures. The mixture made with Snake sand and 9.5mm through the restricted zone (9.5RT-S) has the lowest G* value and the difference is considerably high when compared with other mixtures. The average phase angles of mixtures with manufactured sands are lower than that of the mixtures with natural sands indicating the better performance of mixtures made with manufactured sands. In general, finer mixtures are stiffer than other mixtures.

Table 5.1 Results of Frequency Sweep Tests

Freq (Hz.)	Average G* (MPa)/Phase Angle(Deg)							
	12.5RA-M	12.5 RB-M	9.5RA-M	9.5RT-M	12.5RB-S	9.5RT-S	12.5RA-R	9.5 RA-R
0.01	276/37	173/39	250/32	364/27	185/45	84/51	259/35	174/46
0.02	362/35	219/38	316/32	440/26	251/44	119/51	329/34	232/44
0.05	480/28	281/31	409/26	543/23	393/40	185/47	445/29	322/36
0.1	719/34	525/43	660/35	848/29	569/41	276/49	676/35	556/43
0.2	929/31	697/40	879/33	1050/27	779/37	383/45	905/32	785/38
0.5	1203/35	996/35	1130/28	1330/24	1135/29	591/38	1180/27	1124/32
1	1503/19	1346/29	1730/20	1680/19	1610/25	803/36	1690/20	1610/26
2	1683/20	1606/28	1960/21	1870/19	1805/25	1046/31	1770/21	1740/26
5	2003/16	2060/23	2560/16	2280/17	2265/22	1395/27	2270/18	2260/22
10	2220/16	2410/21	2970/14	2570/15	2650/21	1675/24	2560/15	2660/20

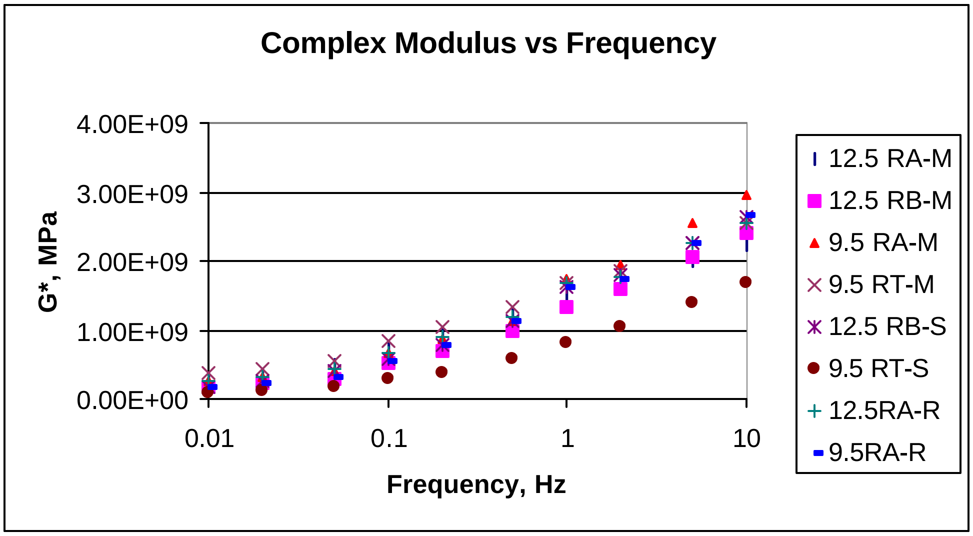


Figure 5.1 FSCH Test: Complex Modulus vs Frequency

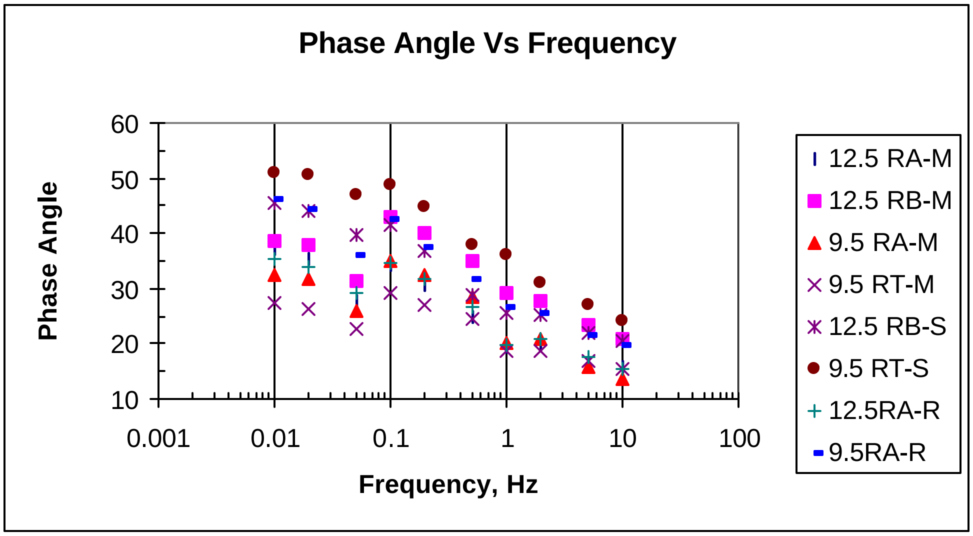


Figure 5.2 FSCH Test: Phase Angle vs Frequency

5.1.2 Repeated Shear Test at Constant Height

This test was performed to estimate the rut depth of a mixture. The viscoelastic properties of an asphalt mixture at high temperatures are related to its permanent deformation characteristics. The accumulation of plastic shear strain in a mixture under repeated loading can give some indication about the mixture's resistance to permanent deformation. The repeated shear testing at constant height was selected to evaluate the accumulated shear strain and permanent deformation characteristics of the mixture.

The RSCH test is a stress-controlled test with the feedback to the vertical load actuator from the magnitude of the shear load. The test is conducted at constant height, requiring the vertical actuator to be controlled by the vertical LVDT. The horizontal LVDT measures the difference in horizontal displacement between two points on the specimen separated by 37.5mm. It preconditions the specimen by applying a haversine load corresponding to a 7-kPa shear stress for 100 cycles. The 0.7-second load cycle consists of a 0.1-second shear load followed by 0.6-second rest period. After preconditioning the specimen, it applies a 68 ± 5 kPa haversine shear pulse for 5000 cycles or until 5% shear strain is reached. This corresponds to a frequency of approximately 1.43 Hz. During the test, axial and shear loads and deformations are measured and recorded. This test was conducted according to AASHTO TP-7 Procedure F (15). Eight mixtures, four for manufactured sands and four for natural sands were tested at a temperature of 54.2^{o}C. Three replicates were tested for each mixture.

Analysis of RSCH Test Results

Figure 5.3 shows plastic shear strain of all mixtures as a function of number of cycles. All the mixtures have passed the 5000 cycle criterion indicating that no mixture has reached the maximum strain limit. Table 5.2 shows the maximum shear strain for all mixtures and percent difference in strain values with 12.5mm above mixture. From the graph, it can be found that the mixture with Ross sand and 9.5mm NMSA aggregates (9.5RA-R) has the highest plastic shear strain of 0.0226. The mixture with Ross sand and 12.5mm NMSA aggregates (12.5RA-R) has the lowest plastic shear strain of 0.0079. The shear strains of all other mixtures range between these two extremes. The results indicate that the mixture 12.5RA-R has the highest shear resistance among all the mixtures.

Table 5.3 Maximum Shear Strain of the Mixtures

Mixture	Maximum Shear Strain	Percent difference with 12.5mm above
12.5 RA-M	0.0149	0.0
12.5 RB-M	0.0166	11.7
9.5 RA-M	0.0135	-9.0
9.5 RT-M	0.0097	-35.0
12.5 RB-S	0.0147	-1.2
9.5RT-S	0.0112	-24.9
12.5RA-R	0.0080	-46.2
9.5RA-R	0.0226	52.3

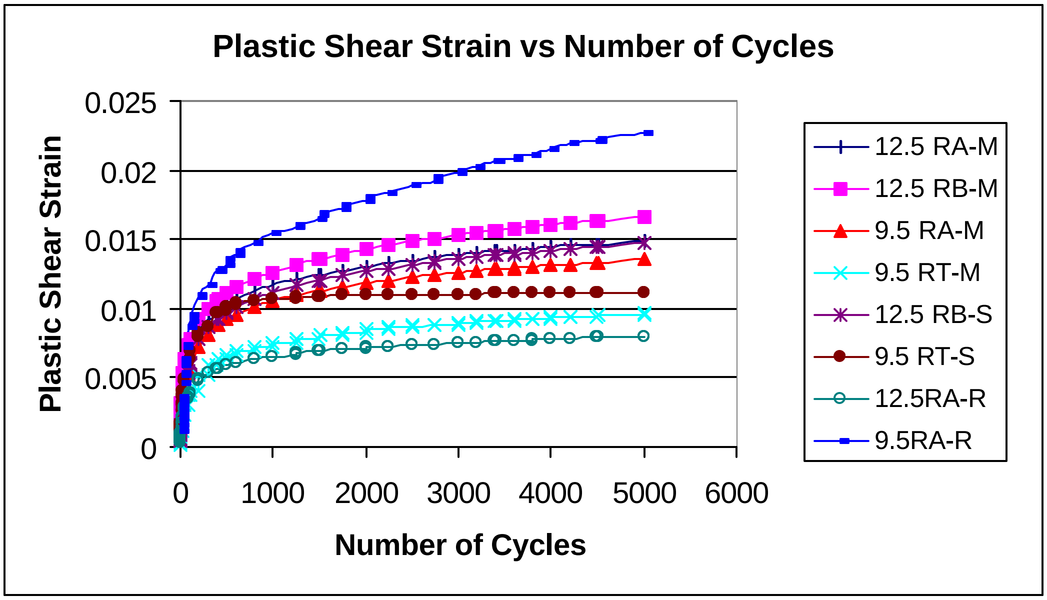


Figure 5.3 RSCH Test: Plastic Shear Strain vs Number of Cycles

5.2 Gyratory Load Plate Assembly

Measurement of mechanical property to evaluate mixture performance is not a new concept. One of the most important criticisms of the Superpave volumetric design procedure is the lack of a direct measure of mechanical properties of asphalt mixtures and the reliance on the control of densification characteristics. Gyratory Load Plate Assembly (GLPA) was developed to apply a two dimensional distribution of shear resistance as measured on the top of the specimen (16).

The plate includes 3 load cells equally spaced on the perimeter of a double-plate assembly, which can be inserted on the sample of the HMA in a typical gyratory mold. The load cells allow measuring the variation in distribution of force on top of the sample during the gyrations such that the position of the resultant force on top of the sample during the gyrations such that the position of the resultant force from the gyratory compactor can be determined in real time. The two dimensional distribution of the eccentricity of the resultant load can be used to calculate the effective moment required to overcome the shear resistance of mixtures and tilt the mold to conform to the 1.25 degree angle.

Description of GLPA

It is believed that this effective moment is a direct measure of the resistance of asphalt mixtures to distortion and to densification. Because the densification is being measured by the compactor, the measured moment can be used to separate the energy spent in densification form the energy spent in distortion. The distortion energy is believed to be related to the resistance of the mixture to rutting under traffic.

The main components of the GLPA are three 9kN load cells, two hardened steel plates that can fit into the compaction mold and a computer for data acquisition from both GLPA and SGC device. The load cells are placed on the upper plate of the assembly at a common radial distance, 120^{o} apart. Each load cell is attached by three screws so that the load pins of each load cell have a small contact point on the lower plate which is in contact with the hot mixture during he compaction. The load cells are designed for high temperature applications and were calibrated by the manufacturer at the level of typical compaction temperatures. Three connecting pins hold the steel plates together and maintain the alignment of the plates. The upper plate is slightly smaller in radius than the lower plate to allow for tilting of the plate assembly in the mold. The plate assembly can be easily placed on top of the mixture sample within the mold using a suction cup. The load cells are simply connected to the data acquisition system by a cable that extends from the top plate to the gyratory ram. During the compaction process, readings are taken at a rate of 50 readings per gyration from each load cell using signal conditioning and acquisition hardware controlled by the graphical programming language LabVIEW®. Deflection readings can also be recorded in real time by the system through the serial communication port of the SGC device. A schematic diagram is given in Figure 5.4

Based on the readings from the load cells, the two components of eccentricity of the total load relative to the center of the plate (e_x and e_y) can be calculated for each of the 50 points collected during each gyration. The calculations are done using general moment equilibrium equations along two perpendicular axes passing through the center of one of the load cells. The total resultant force, R, is simply calculated by the summation of the load cell forces at any instance of the gyration. The e_x and e_y values represent the location of the resultant force exerted by the gyratory ram at an instance of compaction.

Energy Indices

The performance of HMA can be divided into two parts, performance during construction and performance under traffic loading. In both parts, there are two basic characteristics that control performance: (a) resistance to densification, or volume change, and (b) resistance to distortion, also called shear resistance or stability (17). During the construction part, less resistance to densification and to distortion are considered favorable because it implies less compaction energy is required to achieve required density. In the second part, performance under traffic, more resistance to densification and to distortion is considered favorable because it implies that mixture can tolerate more traffic before reaching a certain level of rutting. Although densification and distortion are

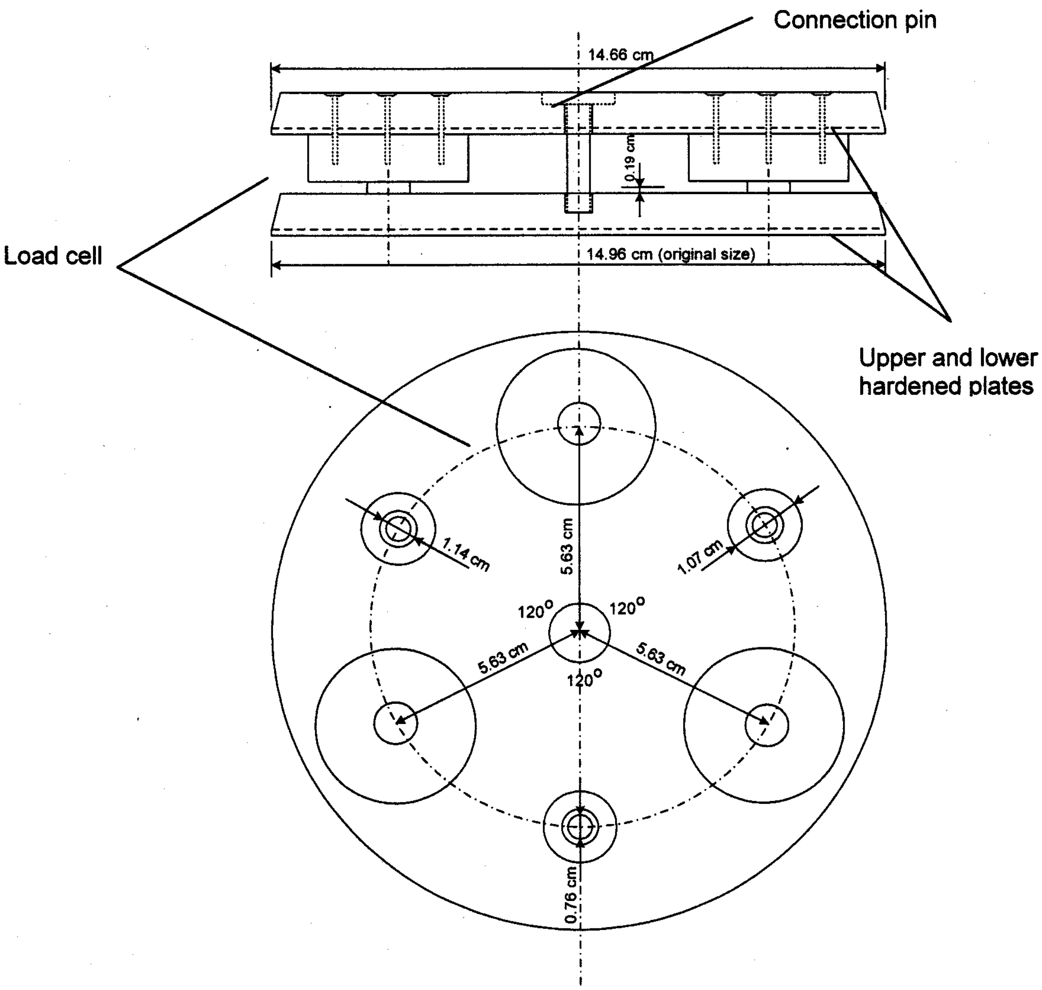


Figure 5.4 Gyratory Load Plate Assembly

not necessarily independent properties, they need to be measured independently because distortion could be measured at a constant volume (no densification).

The researchers of the University of Wisconsin Madison developed energy indices as measures of densification and distortion under construction and under traffic. The Compaction Densification Index (CDI) and Compaction Force Index (CFI) are used to evaluate the performance of mixtures during construction. CDI is measured by integration of the area under the densification curve measured by the SGC between the first gyration and the 92% G_{mm}. The 92% G_{mm} is assumed to be the target density at the end of construction. The CFI is the integration of the area under the resistive work curve measured with the GLPA between the same reference points. To measure the mixture resistance to traffic, the Traffic Densification Index (TDI) and Traffic Force Index (TFI) are used. TDI and TFI are estimated by integration of the area under the densification and resistive work curves between 92% G_{mm} and 98% G_{mm} as shown in Figure 5.5.

Table 5.4 shows the energy indices measured using the Superpave Gyratory Compactor and GLPA. The samples were gyrated to 300 cycles.

Table 5.4 Energy Indices

Mixture	CEI	TEI	CFI	TFI	%Gmm @ Nini	%Gmm @ Ndes	%Gmm @ Nmax	VMA
12.5RA-M	104	754	193	2162	89.3	96.1	97.0	13.9
12.5RA-R	125	1116	237	3858	89.2	95.2	96.0	15.0
12.5RB-M	110	274	167	904	88.8	97.7	98.8	13.7
12.5RB-S	98	474	177	1607	89.4	96.7	97.7	13.9
9.5RA-M	30	207	74	623	91.2	97.7	98.5	15.4
9.5RA-R	73	722	148	2194	89.8	95.5	96.3	16.0
9.5RT-M	56	246	117	804	90.1	97.2	98.2	14.3
9.5RT-S	28	273	77	821	91.2	97.2	98.1	15.9

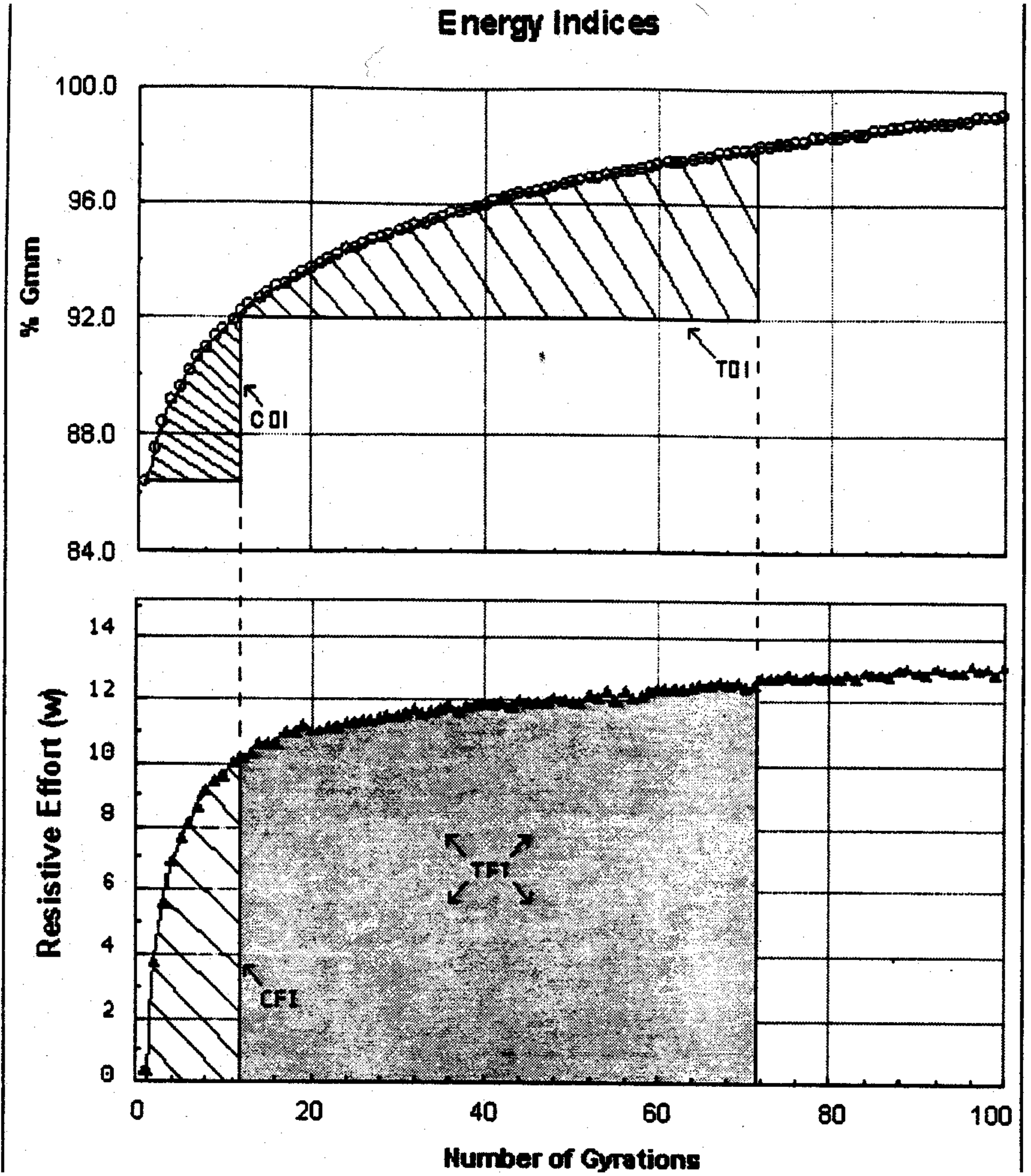


Figure 5.5 Energy Indices (CDI, CFI,TDI,TFI)

It is observed from the data in Table 5.4 that mixtures with 12.5mm NMSA have, in general, performed better than mixtures with 9.5mm NMSA for both types of sand. Ross sand mixtures (12.5 RAR and 9.5 RAR) have the highest energy indices among all the mixtures indicating that the mixtures offer the highest resistance to rutting. Th overall performance of mixtures with 12.5mm NMSA is good. The percent air voids at Ndesign is about 4.8% for 12.5 RA-R mixture while it is less than 3% for Snake sand mixtures. This analysis indicates that a strong aggregate skeleton will dissipate more energy in friction and therefore less energy will be available for densification during each cycle (18). The strong skeleton will be more resistance to densification and less deflection will be measured under each cycle. More cycles will be required to achieve density. Therefore more total energy will dissipate less energy in shear, and therefore more energy will be available for vertical densification. More vertical deflection will be seen for each cycle, compared to the strong skeleton. This indicates that less total energy will be required. Thus mixtures with higher energy indices have higher shear resistance.

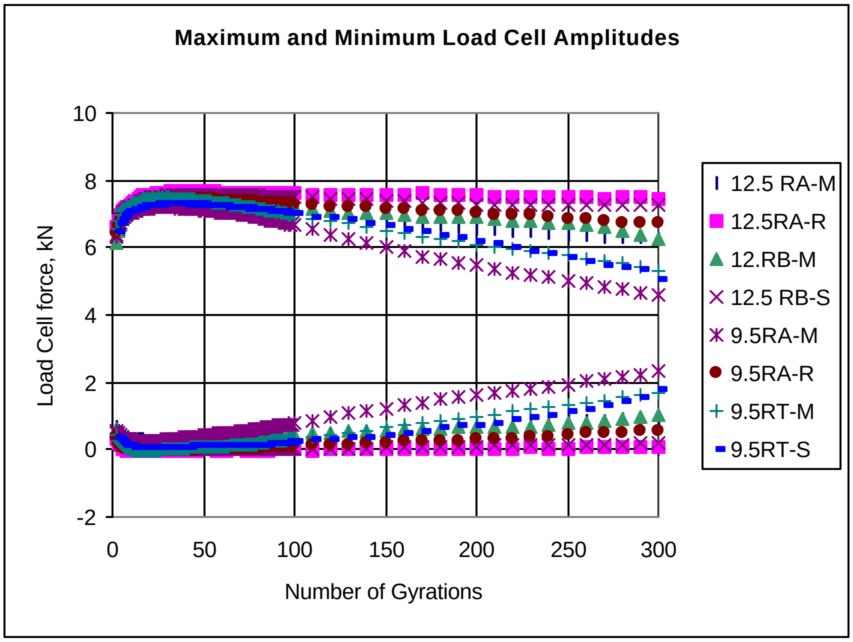


Figure 5.6 Maximum and Minimum Load Cell Amplitudes

Figure 5.6 shows the maximum and minimum load amplitudes carried by the load cell of GLPA during each of the 300 gyrations. The load amplitudes of 12.5mm mixtures start decreasing slowly whereas the 9.5mm mixtures (except 9.5RAR) start decreasing rapidly. The rapid rate of decrease indicates that the mixtures start losing the frictional resistance with increased number of gyrations. These trends are important because they could be related to observations in the field where rutting is observed for some mixtures after increased number of traffic load applications.

These test results indicate that mixtures with 12.5 mm NMSA perform better than mixtures made with 9.5mm NMSA. Energy index of mixtures made with natural sands does not vary much with the index of the corresponding mixtures made with manufactured sands.

5.3 Evaluation of Moisture Sensitivity

Moisture Damage in the AC layer occurs due to loss of adhesion between asphalt and aggregate and or loss of cohesion. A reduction in cohesion results in a reduction in strength and stiffness. The loss of adhesion is the physical separation of the asphalt cement and aggregate, primarily caused by moisture. The stripping of the asphalt from aggregate results in a reduction in the stiffness and strength of an asphalt mixture. Such reduction in stiffness may contribute to premature pavement deterioration.

Moisture susceptibility of a mixture can be evaluated by calculation of a tensile strength ratio using Modified Lottman test. This test was performed in accordance with AASHTO T 283 (19). A sample is conditioned by saturation and immersion to simulate a mixture's moisture exposure. The indirect tensile strengths of the unconditioned and conditioned sets are compared to evaluate the moisture damage induced by conditioning. This damage, loss of cohesion and adhesion, manifests itself in a loss of tensile strength of the mix.

Indirect tensile tests were performed on the three aggregates in accordance with AASHTO T 283 (*Resistance of Compacted Bituminous Mixture to Moisture Induced*

Damage). Three mixtures 12.5mm above with 100 percent manufactured sand, 12.5mm above with Ross sand and 12.5mm below with Snake pit sand, were prepared. A sample set of 4 specimens with 6 inches in diameter and 4 inches in thickness were prepared. One subset was tested dry and another subset was preconditioned before testing. The dry subset was stored at room temperature until testing. The specimens were then placed in a 77 F water bath for 2 hours and then tested. For preconditioning, the specimens were saturated in a vacuum container for a degree of saturation that ranges from 65% to 80%. The saturated specimens were then placed a water bath at 140 F for 24 hours. The specimens were removed and placed in a water bath at 77 F for 2 hours before testing. The specimens were removed from the water bath and tested using a Geotest loading frame equipped with a chart recorder. The specimens were loaded at a constant rate of 2 inches per minute. The loading was continued until a vertical crack appeared. The maximum load for each specimen was determined. Anti-stripping agents were not used in any of these mixtures.

The indirect tensile strength of each specimen was computed as follows:

$$S_t = 2P/\pi tD$$

where

S_t = tensile strength, psi

P = maximum load, lbs

t = specimen thickness, inches and

D = specimen diameter, inches

The tensile strength ratio (TSR) was calculated as follows:

$$TSR = S_2/S_1$$

where

S_1 = average tensile strength of unconditioned subset

S_2 = average tensile strength of conditioned subset

The objective of TSR tests was to evaluate the water sensitivity of the mixtures containing manufactured and natural sands included in this study. Therefore, as is evident, only TSR test results of 12.5mm mixtures are included in Table 5.5

The results of indirect tensile strength for conditioned and unconditioned specimens are given in Table 5.5

Table 5.5 Indirect Tensile Strength Tests

Mixture	Tensile Strength, psi		TSR percent
	Unconditioned	Conditioned	
12.5 RA-M	141.37	131.96	93.3
12.5 RA-R	133.41	115.15	86.3
12.5 RB- S	105.97	90.93	85.8

It is seen that there is a difference in tensile strength of about 6.7% between conditioned and unconditioned specimens for mixtures made with manufactured sands. This difference increases with the inclusion of natural sands. The reduction in tensile strength is about 13.7 % and 14.2% for mixtures containing Ross and Snake pit sands respectively.

The mixtures containing manufactured and natural sands met the minimum value of 85 for TSR. However, the results of the TSR tests show that manufactured sand performs better than natural sands. The addition of natural sand to asphalt mixtures could reduce the mechanical adhesion between the aggregates. Mechanical adhesion depends primarily on the physical properties of the aggregate such as surface texture, surface area etc. Also natural sands might contain fine clays which in turn would emulsify the asphalt in the presence of water. This might increase the probability of an asphalt mix to strip prematurely.

5.4 Asphalt Pavement Analyzer for Rutting Susceptibility

The rutting susceptibility of the mixtures was assessed by placing samples under repetitive loads of a wheel-tracking device, known as Asphalt Pavement Analyzer (APA). APA is the new generation of the Georgia Loaded Wheel Tester (GLWT). The APA has additional features that include a water storage tank and is capable of testing both gyratory and beam specimens. Three beam or six gyratory samples can be tested simultaneously (20).

The theory behind a loaded wheel tester is to apply an appropriate cyclical loading to asphalt to best simulate actual traffic. This is accomplished in this apparatus by air pressurized hoses laying across samples with a loaded wheel coming in contact with the hose and applying a predetermined load to the hose and thus the specimens. The wheel roles back and forth up to 8000 times or cycles and the rut depth is then measured.

Wheel loads are applied on test samples by means of three pneumatic cylinders, each equipped with an aluminum wheel. The magnitude of the load applied on each sample is regulated by air pressure supplied to each pneumatic cylinder. The load from each moving wheel is transferred to a test sample through a stiff pressurized rubber hose mounted along the top of the specimen. The pressure in the three hoses is regulated by a common pressure regulator so that the pressure in the three hoses should always be the same. The equipment is designed to evaluate not only the rutting potential of an asphalt mixture, but also its moisture susceptibility and fatigue cracking under service conditions. A model and schematic diagram of the APA is given in Figure. 5.7 and 5.8

In the APA testing, only rutting potential of the mixtures was investigated. Duplicates of all the eight mixtures were prepared. The cylindrical samples were compacted to an air void contents of 7 percent, using the Superpave Gyratory Compactor. Then the samples were checked whether they fell within the acceptable range of air voids. A tolerance of 0.5 % change in air voids level was accepted. The 7 percent air voids level was selected to simulate the typical field density achieved in the field. It is the average air voids that are specified for most HMA pavements immediately at the end of

Figure 5.7 Model of APA

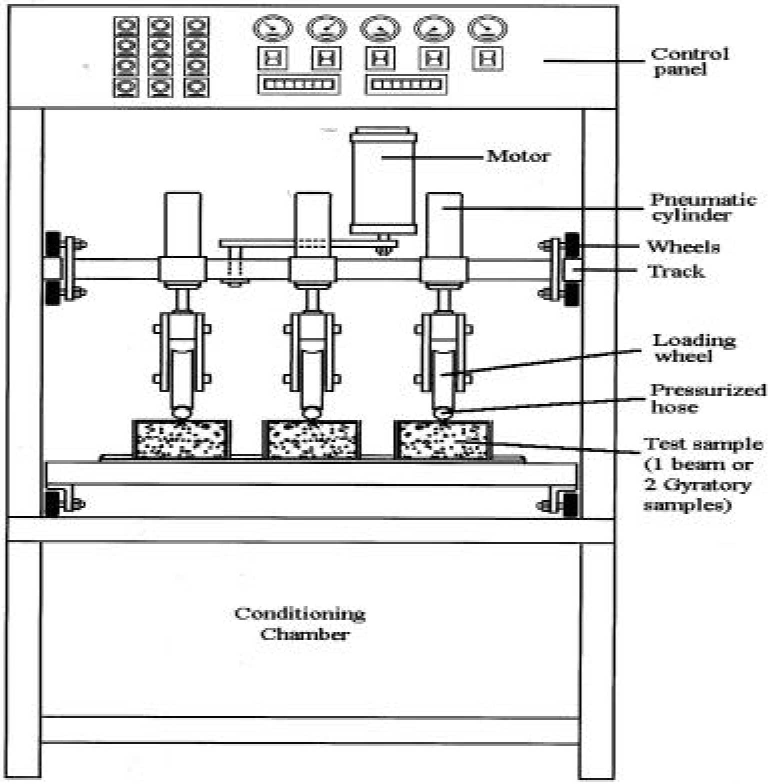


Figure 5.8 Schematic Drawing of the APA

construction. The samples were compacted to a thickness of 75mm to fit in the APA molds.

The APA is capable of controlling the temperature in the cabin. Duplicates of eight mixtures were tested at a temperature of 64^{o}C. The samples are kept inside the cabin at this temperature for two hours before testing. The number of cycles is selected as 8000 cycles (typical) from the control panel. The change in the rut depth is measured using a data acquisition system that measures at four points for gyratory samples. The graphical software plots the average of four points for each cycle. Table 5.6 furnishes the rut depth of each mixture after 8000 cycles.

Table 5.6 Rut Depth measured using APA

Mixture	Rut Depth, mm
12.5RA-M	10.08
12.5 RA-R	12.21
12.5 RB-M	9.03
12.5RB-S	7.85
9.5RA-M	12.12
9.5RA-R	15.23
9.5RT-M	9.29
9.5RT-S	15.37

It can be observed that, in general, mixtures with manufactured sand perform better than the mixtures with the natural sands. It is also observed that 12.5-mm mixtures perform better than 9.5-mm mixtures and coarse mixtures perform better than the fine mixtures. Mixtures with 12.5 NMSA and gradation below the restricted zone have the lowest rut depth amongst all the mixtures. The 12.5RB-S mixture has the lowest rut depth whereas 9.5 RT-S has the highest rut depth. It can, therefore, be concluded that the maximum size of the aggregate and the gradation influence the performance of mixtures with natural sands.

From the APA tests, it is observed that the deformation rate changes with the number of passes. Initial deformation rate within the first 1000 passes plays an important role in predicting the final rut depth of the mixture. The variation of initial deformation rates among the mixtures is large and so are their final rut depths. The mixtures reach nearly half of their final rut depth within 1000 cycles. The deformation rates gradually slow down beyond 1000 cycles and, for the most of the mixtures, the final deformation rates are nearly equal. This can be attributed to the reorientation of the aggregates, which is influenced by the maximum size, gradation and the aggregate type.

CHAPTER 6

MIXTURE PERFORMANCE EVALUATION

Analysis of Service Life of Pavement

The resulting parameters of FSCH and RSCH tests are the material responses that can be used to predict the pavement's performance under service for distresses such as fatigue cracking and rutting. Fatigue and Rutting analysis are performed using surrogate models developed by SHRP 003-A project and distress models of Asphalt Institute. Fatigue analysis of SHRP model considers material properties as well as pavement structural layer thickness whereas rutting analysis considers only the material properties.

6. 1 SUPERPAVE Fatigue Model Analysis

The abridged fatigue analysis system from SHRP A-003A predicts the resistance of mix to fatigue distress for a pavement structure under a given traffic load (21). The resistance of a mix to fatigue cracking depends on the horizontal tensile strain, initial flexural loss stiffness and voids filled with asphalt (VFA). Shear stiffness of the mixture is measured from the FSCH tests at 10 Hz at 20^{o}C. The critical tensile strain is a function of the pavement thickness.

Multi-layer elastic analysis is used to determine the design strain, the maximum principal tensile strain at the bottom of the asphalt concrete layer, under the standard AASHTO axle load of 18 kips. Therefore, a pavement structure was assumed to conduct this analysis. The pavement structure and loading are given in Figure 6.1. A standard 18-kip single axle load with dual tires inflated to 100 psi was used. The horizontal tensile strains at the bottom of AC layer are estimated at outer edge, center, inner edge, and center of dual tires using *EVERSTRESS* software for multilayer elastic analysis of pavement sections. The critical tensile strain is used as the design strain.

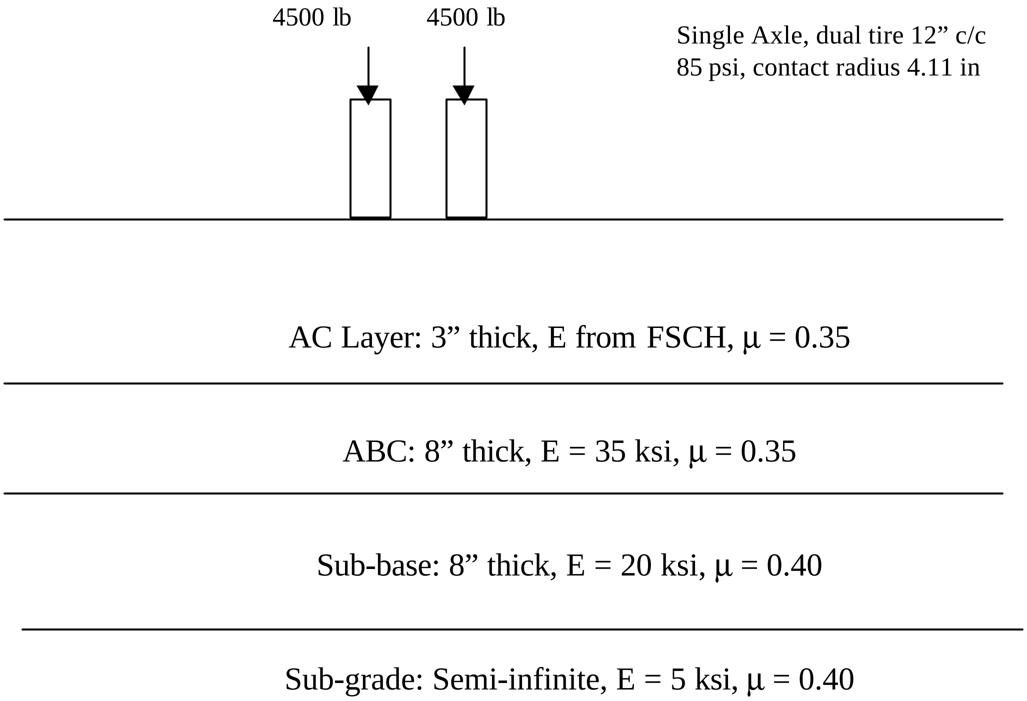


Figure 6.1 Typical Pavement Structure and Loading

The flexural properties of the mix are estimated using the following regression equations.

$$S_o = 8.56 * (G_o)^{0.913} \qquad R^2 = 0.712 \qquad \text{(6-1)}$$

$$S_o'' = 81.125 * (G_o'')^{0.725} \qquad R^2 = 0.512 \qquad \text{(6-2)}$$

where

S_o = initial flexural stiffness at 50th loading cycle is psi

G_o = shear stiffness at 10 Hz in psi

S_o” = initial flexural loss stiffness at 50th loading cycle is psi

G_o” = shear loss stiffness at 10 Hz in psi

A summary of material properties are given in Table 6.1

Table 6.1 Summary of Estimated Material Properties for Various Mixes

Gradation	Sand	|G*| psi	Phase	Go' psi	Go"	So'	So"
12.5mm above	Manufactured	3.22E+05	15.63	3.10E+05	8.68E+04	8.83E+05	3.09E+05
	Ross	3.71E+05	15.46	3.58E+05	9.89E+04	1.01E+06	3.39E+05
12.5mm below	Manufactured	3.50E+05	21.01	3.26E+05	1.25E+05	9.26E+05	4.03E+05
	Snake	3.84E+05	20.60	3.60E+05	1.35E+05	1.01E+06	4.26E+05
9.5mm above	Manufactured	4.31E+05	13.62	4.19E+05	1.01E+05	1.16E+06	3.46E+05
	Ross	3.86E+05	19.78	3.63E+05	1.31E+05	1.02E+06	4.15E+05
9.5mm through	Manufactured	3.72E+05	15.40	3.59E+05	9.88E+04	1.01E+06	3.39E+05
	Snake	2.43E+05	24.16	2.22E+05	9.94E+04	6.50E+05	3.41E+05

The fatigue resistance of a mix is then estimated from the following strain-dependent surrogate model.

$$N_{supply} = 2.738E5 * e^{0.077VFB} * e_0^{-3.624} * S_0''^{-2.72} \qquad (6\text{-}3)$$

where

Nsupply = estimated fatigue life of the given pavement section in ESALs

VFB = voids filled with asphalt

ε_0 = critical tensile strain at the bottom of AC layer

The coefficient of determination for the surrogate model for fatigue analysis is 0.79 with a coefficient of variation of 90 percent (21).

The results are summarized in Table 6.2. The results show that the 9.5mm mixtures with manufactured sand have the highest resistance to fatigue cracking. Mixtures made with Snake sand have lower fatigue life than other mixtures. 12.5mm mixture with Snake sand has the lowest fatigue life.

It is also found that the difference between the fatigue lives of mixtures of manufactured sand and natural sand is more than 30% for 9.5mm NMSA aggregate gradations whereas the difference is only around 10% for mixtures with 12.5mm NMSA aggregate gradations.

Table 6.2 Summary of Fatigue Analysis Results (SHRP Surrogate Model)

Gradation	Sand	So"	VFA	Strain	Nsupply	% Difference with Nsupply of Manf. sand	% Difference with N supply of 12.5 RA-M
12.5mm above	Manufactured	3.09E+05	73.1	2.35E-04	1.27E+06	-	-
	Ross	3.39E+05	74	2.21E-04	1.30E+06	2.69	2.69
12.5mm below	Manufactured	4.03E+05	73.68	2.30E-04	6.93E+05	-	-45.41
	Snake	4.26E+05	72	2.21E-04	6.05E+05	-12.78	-52.39
9.5mm above	Manufactured	3.46E+05	77.6	2.07E-04	2.07E+06	-	62.76
	Ross	4.15E+05	78	2.20E-04	1.04E+06	-49.47	-17.76
9.5 mm through	Manufactured	3.39E+05	73.8	2.21E-04	1.29E+06	-	1.38
	Snake	3.41E+05	78	2.66E-04	8.97E+05	-30.35	-29.39

The fatigue life values in Table 6.2 are estimated for asphalt layer of 3 inch thick. The lowest fatigue life observed among all the mixtures is about 600,000 ESALs for 12.5 mm mixture with Snake sand (12.5 RB-S). Poor fatigue life of mixtures observed in Table 6.2 is purely a function of design thickness of AC layer. This is demonstrated by estimating the fatigue life of the 12.5 RB-S mixture for varying thickness of AC layer, as shown in Table 6.3 and Figure 6.2.

Table 6.3 Fatigue Life of 12.5 RB-S Mixture

Thickness of AC layer, inch	Tensile Strain ε_o	So"	**VFA**	**Nsupply**
2	2.66E-04	4.26E+05	72	3.11E+05
3	2.21E-04	4.26E+05	72	6.05E+05
4	1.79E-04	4.26E+05	72	1.29E+06
5	1.46E-04	4.26E+05	72	2.70E+06
6	1.21E-04	4.26E+05	72	5.42E+06

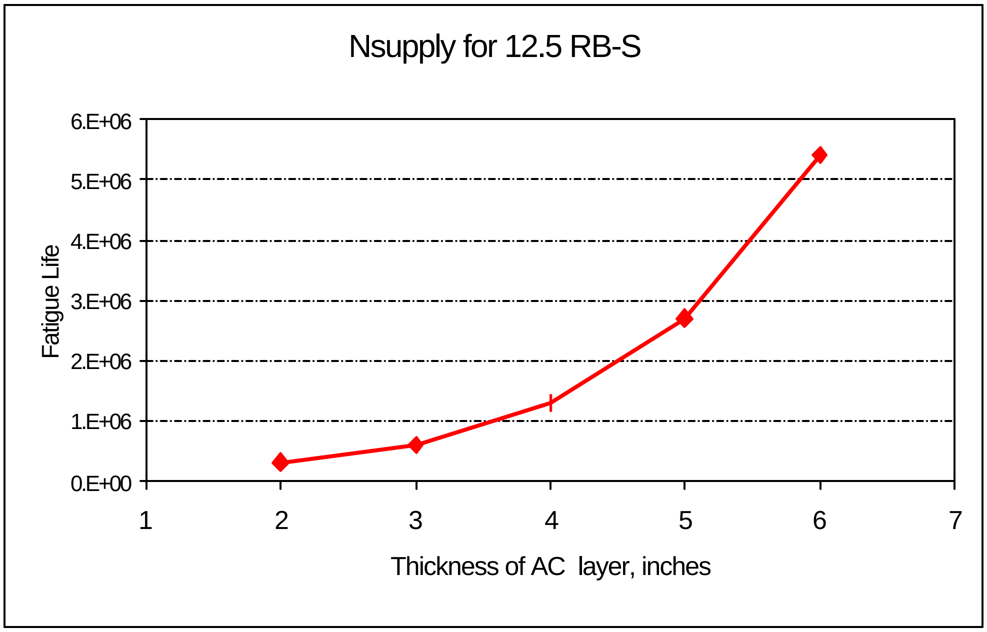


Figure 6.2 Fatigue Life of 12.5 RB-S Mixture

It is observed from the data in Table 6.3 that fatigue life of the 12.5RB-S mixture increases with increasing thickness of AC layer. Critical tensile strain decreases considerably with increasing thickness even with the material properties such as stiffness and VFB remaining the same and thereby increasing the Nsupply. The fatigue life of 4 inches thick layer of the worst performing mixture is approximately 1 million ESALs and if the thickness of AC layer is increased to 6 inches, the fatigue life increases to 5.4 million ESALs. Same trend is expected for better performing mixtures. Therefore, it is evident that poor fatigue life observed in Table 6.2 is due to the thickness of AC layer assumed for the analysis.

The number of cycles to failure under fatigue cracking is also estimated using Asphalt Institute model. The allowable number of load repetitions is related to the tensile strain at the bottom of the asphalt later, as indicated in the following equation.

$$N_f = 0.00796 * \varepsilon_t^{-3.291} * E_1^{-0.854} \qquad (6\text{-}4)$$

where,

N_f = allowable number of load repetitions to prevent fatigue cracking (20% of area of crack)

ε_t = tensile strain at the bottom of asphalt later

E_1 = elastic modulus of asphalt layer

The results are tabulated in Table 6.4

Table 6.4 Summary of Fatigue Analysis Results (AI Method)

Gradation	Sand	Tensile Strain	Elastic Modulus	N_f	Percent Difference
12.5mm above	Manufactured	2.35E-04	8.83E+05	5.86E+05	8.53
	Ross	2.21E-04	1.01E+06	6.36E+05	
12.5mm below	Manufactured	2.30E-04	9.25E+05	6.03E+05	4.29
	Snake	2.21E-04	1.03E+06	6.28E+05	
9.5mm above	Manufactured	2.07E-04	1.16E+06	6.98E+05	-8.30
	Ross	2.20E-04	1.02E+06	6.40E+05	
9.5 mm through	Manufactured	2.21E-04	1.01E+06	6.35E+05	-20.99
	Snake	2.66E-04	6.51E+05	5.02E+05	

The results of AI fatigue cracking model show that the mixtures made with natural sand have almost the same resistance to fatigue cracking as the mixtures made with manufactured sand.

6.2 SUPERPAVE Rutting Model Analysis

The permanent deformation system of SHRP A-003A estimates rut depth from the maximum permanent shear strain obtained from RSCH test using the following relation.

$$\text{Rut depth (in.)} = 11 * \text{Maximum permanent shear strain} \qquad (6\text{-}5)$$

If rutting in millimeters is desired, the coefficient of the above equation is about 275. The above relationship is obtained for a tire pressure of 100psi and asphalt layer thickness of 15inch. Studies performed for the similar pavement structure at 200psi and 500psi suggest that this relationship is independent of the tire pressure. But the same is not reflected in the case of pavement thickness. The coefficient is expected to decrease with a decrease in asphalt layer thickness.

The conversion of the number of RSCH test cycles to ESALs is determined by the following equation:

$$\log(\text{cycles}) = -4.36 + 1.24 \log(\text{ESALs}) \qquad (6\text{-}6)$$

where,
cycles = number of cycles obtained from the RSCH test
ESALs = equivalent 18-kip single axle load

According to the above relationship, 5000 cycles of the RSCH test correspond to 3.156 million ESALs. The summary of the results are given in Table 6.5

Table 6.5 Summary of Rutting Analysis Results (SHRP Surrogate Model)

Gradation	Sand	Shear Strain	Rut depth, in	% Difference with Rut depth of Manf. sand	% Difference with rut depth of 12.5 RA-M
12.5mm above	Manufactured	0.015	0.164	--	--
	Ross	0.008	0.088	-46.2	-46.2
12.5mm below	Manufactured	0.017	0.183	--	+11.7
	Snake	0.015	0.162	-11.5	-1.2
9.5mm above	Manufactured	0.014	0.149	--	-9.0
	Ross	0.023	0.249	+67.3	+52.29
9.5mm through	Manufactured	0.010	0.106	--	-35.0
	Snake	0.011	0.123	+15.6	-24.9

From the results, it can be seen that the 9.5m mixture with Ross sand has the highest rut depth. On the other hand, the 12.5mm mixture with the same Ross sand has lowest rut depth. The resistance to rutting for 12.5-mm gradation is greater for a mix with natural sand as compared to that of a mix with manufactured sand. But for 9.5-mm gradations, mixtures with natural sand show a reduced performance than the same mixtures containing manufactured sand. Test results indicate that a complex interaction exists among the maximum size of aggregate, the type of fine aggregate and design asphalt content, which most likely influences the shear resistance of the mix.

In addition, the rutting model of Asphalt Institute was utilized for investigating the rutting resistance of the mixtures since the rutting distress model developed by the SHRP program depends only on the mixture properties. In the AI distress model, the allowable number of load repetitions (N_d) to limit rutting (0.5 inch) is related to the vertical compressive strain at the top of subgrade (ε_c) by the following relationship:

$$N_d = 1.365 \times 10^{-09} * \varepsilon_c^{-4.477} \qquad (6\text{-}7)$$

The vertical compressive strain at the top of subgrade is estimated using EVERSTRESS pavement analysis software. The estimated number of cycles to failure under rutting for all mixtures are given in Table 6.6

Table 6.6 Summary of Rutting Analysis Results (AI Method)

Gradation	Sand	Shear Strain	N_d	Percent Difference
12.5mm above	Manufactured	6.50E-04	2.53E+05	9.79
	Ross	6.37E-04	2.78E+05	
12.5mm below	Manufactured	6.46E-04	2.61E+05	6.26
	Snake	6.37E-04	2.78E+05	
9.5mm above	Manufactured	6.23E-04	3.07E+05	-9.06
	Ross	6.36E-04	2.80E+05	
9.5mm through	Manufactured	6.37E-04	2.78E+05	-24.99
	Snake	6.79E-04	2.08E+05	

The results of SHRP model and AI model exhibit similar trend in that the 12.5 mixtures made with natural sand have almost the same shear resistance as those made with manufactured sand. A relative inferior performance of natural sands in the 9.5mm mixtures is reflected in both models.

It should be borne in mind that even though there are some relative differences in rutting potential, the maximum rut depth according to SHRP Rut Model in Table 6.5 is about 0.25 inch. Furthermore, the rut depths are calculated for 5000 cycles of RSCH test. This corresponds to 3 million ESALs. In other words, all the mixtures included in this study will perform well up to at least 3 million ESALs of traffic.

The analysis using the AI model is based on the elastic analysis of the pavement structure and the rutting is governed by the compressive strain at the top of the subgrade. In other words, the AI model is predicated on the assumption that rutting is controlled by the deformation of the subgrade. On the other hand, the SHRP model assumes that rutting is more pronounced in the surface layers and, therefore, the mixture properties of the surface later primarily dictate the rutting behavior of a given pavement.

In view of the above reasoning and for the objective of relative evaluation of mixture performance for rutting, SHRP model should be given more credence.

CHAPTER 7

SUMMARY OF RESULTS AND CONCLUSIONS

The performance of the asphalt concrete mixtures is judged based on the ability of the mixture to resist fatigue and rutting distresses. Tests were carried out to evaluate the performance of the mixtures containing manufactured and natural sands in terms of fatigue and permanent deformation. Tests were conducted using Simple Shear Tester, Asphalt Pavement Analyzer, GLPA and Superpave Gyratory Compactor.

The results of FSTCH and RSTCH were then analyzed using the Asphalt Institute (AI) method and SHRP A 003-A Surrogate models. The AI method considers the mixture stiffness, the only material parameter used in its analysis. On the other hand, surrogate models use various mixture properties such as shear strain, flexural stiffness and VFA. Therefore, the results of SHRP surrogate models are given preference in this discussion.

The estimates of fatigue life show that for mixtures of 12.5mm gradation, natural sands have performed at par with 100 percent manufactured sand. The performance of the mixtures differs within a range of ± 10 %. This difference is not statistically significant. For mixtures of 9.5mm gradations, the fatigue life of mixtures containing natural sand is almost half as compared to the mixtures containing manufactured sand. This significant difference indicates the inferior performance of natural sands in the 9.5mm mixtures. The same trend is reflected in the results obtained by the AI method.

The results show that the fatigue life of the mixture is influenced by the maximum size of the aggregate and the gradation as well as the type of sand to be used. The 9.5mm mixture with the gradation above the restricted zone and manufactured sand (9.5RA-M), the finest among all the four gradations, has the highest fatigue life whereas the 12.5mm mixture with the gradation below the restricted zone and Snake sand (12.5RB-S), the coarsest among all the four gradations, has the lowest fatigue life. Though the fatigue life of 12.5mm mixtures with the gradation below the restricted zone is nearly half of the12.5mm mixtures with the gradation above the restricted zone, the addition of natural sands did not significantly affect the performance of these mixtures. On the other hand, though the fatigue life of the 9.5mm mixtures with 100 percent manufactured sand performed better than the 12.5mm mixtures, the addition of natural sands reduced their fatigue life by 30% to 50%. Therefore, it can be concluded that natural sands perform equally well as compared with manufactured sand for mixtures of 12.5mm gradation while the addition of natural sand results in the reduction of fatigue life for mixtures of 9.5mm gradation.

As is evident from the analysis of the data in Chapter 6, the 9.5mm mixture with Ross sand had the highest rut depth. On the other hand, the 12.5 mm mixture made with the same Ross sand had the lowest rut depth. The resistance to rutting for 12.5mm gradation was greater for a mix with natural sand as compared to that of a mix with manufactured sand. But for 9.5mm gradations, mixtures with natural sand showed a reduced performance than the same mixtures containing manufactured sand. It is evident that a complex interaction exists among the maximum size of the aggregate, the type of fine aggregate and design asphalt content, which most likely influences the shear resistance of the mix and rutting potential. However, the estimates of rutting indicate that the range of rut depths for 5000 cycles (3 million ESALs) in the shear testing is from 0.09 to 0.25 inch. In other words, certain amount of natural sand can be used in these mixtures without any significant effect on the rutting potential

The TSR test results reveal that mixtures with natural sands are relatively more moisture susceptible. The TSR values for mixtures with Ross and Snake sands are 86.3% and 85.8%, respectively. These values pass the NCDOT criteria of a minimum value of 85%. There is a difference in tensile strength of about 6.7% between conditioned and unconditioned specimens for mixtures made with manufactured sands. This difference increases with the inclusion of natural sands. The reduction in tensile strength is about 13.7 % and 14.2% for mixtures containing Ross and Snake pit sands, respectively. This might increase the probability of an asphalt mix to strip prematurely.

The energy indices measured by SGC and GLPA show that 12.5mm mixtures perform better than 9.5mm mixtures with an exception to 9.5 mm mixture containing Ross sand. It is also observed that there is not much difference in CEI and CFI values of coarser gradations and finer gradations of 12.5mm mixture. But TEI and TFI values of finer gradations are greater than those of the coarser gradations. These observations contradict with the notion that coarser gradations have better rutting resistance under heavy traffic loads. The same trend was observed by Bahia et al (18). The authors explain that coarser gradations are less desirable for construction and in-service traffic densification, assuming that SGC is truly representing field conditions. They postulate that in a fine blend, more individual particles result in more contact points. This increased number of stone to stone contact points increases the frictional resistance of the mix and its resistance to deformation. So finer mixtures tend to have a lower, more distributed void content, which is explained by the higher CEI. On the other hand, coarser mixtures have much more void space and fewer friction points allowing a relatively amount of energy to move the aggregate particles past one another under the extended kneaded action. The lower TDI can be explained by this increased space for movement of the particles. The same has been observed with the indices of GLPA. The results of GLPA show that finer mixtures have better frictional resistance, a measure of mix stability, than coarse mixture. However this concept of interparticle contacts has not been widely accepted or validated with the actual field performance. Furthermore, one of the major deficiencies of the GLPA test is that it is conducted at the compaction temperature of about 155^{o}C at which the behavior of the mixtures could be quite different from a maximum service temperature of about 60^{o}C.

The results of the APA test show that mixtures with 12.5mm aggregates and gradation below the restricted zone perform well irrespective of the presence of natural sand. It is observed that coarser gradation with 12.5mm aggregate and manufactured sand mixtures exhibit lower rut depth. These results once again emphasize the role of size of maximum aggregate and type of gradation in predicting the performance of natural sands. The behavior of mixtures below 1000 passes seems to be an area of interest as it gives nearly half of the final rut depth. Some of the studies show that rut depth of APA testing correlates well with the field performance ranking but this study involved a limited number of samples. Due to lack of sufficient amount of data, APA results are still remain to be validated with the data obtained from other studies at NCSU. Standard protocols call for APA tests to be conducted on specimens compacted to approximately 7% air voids and at maximum temperature of the performance graded asphalt, while the shear tests are conducted on specimens compacted to Ndes and at 54^oC. The discrepancy in these test conditions may cloud a meaningful comparison of the performance of mixtures as evaluated by these tests.

It is viewed that the performance of natural sand is greatly influenced by the maximum size of aggregate. As the aggregate size decreases, VMA of the mix increases. Higher VMA results in the reduction of stability and tensile strength. Studies by E.R.Brown (22) show that there is an increase in the resilent modulus of the mixture with increased aggregate size, and therefore, increased stiffness will result in the reduction of stresses in the underlying layers. Also, when the diameter ratio of fine and coarse particle fractions (d_f/d_c) increases, dilation will occur in the coarse particle structure and the introduction of the fine fraction will increase the mass volume (13).

The rutting test results indicates that the minimum service life of all the mixtures included in this research study is about 3 million ESALs, while the minimum fatigue life is to the tune of about 1 million ESALs. Therefore, it is quite evident that even 9.5mm mixtures containing natural sand can adequately serve the low volume secondary roads.

It can be concluded from the test results that

1. Maximum size of aggregate and type of gradation influence the performance of mixtures containing natural sand
2. The performance of 12.5mm mixtures, in terms of fatigue and rutting, is not adversely affected by incorporation of natural sand in the mixture gradation.
3. The rutting performance of 9.5mm mixtures is not affected by the addition of natural sand, while the fatigue life of these mixtures is adversely affected. The 9.5mm

mixtures containing natural sand have 50% to 70% of fatigue life of the mixtures made with manufactured sand.

4. The rutting test results indicate that the minimum service life of all the mixtures is about 3 million ESALs, while the minimum fatigue life is to the tune of approximately 1 million ESALs. Therefore, it is quite evident that even 9.5mm mixtures containing natural sand can adequately serve as a surface course for the low volume secondary roads.
5. The fatigue life of a given pavement structure is a function of the thickness of the asphalt concrete layer; thicker the asphalt concrete layer, higher the fatigue life. Therefore, an increase in thickness of 9.5mm mixtures containing natural sand may improve the fatigue life to a desired level.
6. The mixtures containing natural sand exhibit relatively higher moisture susceptibility.
7. The GLPA test is conducted at the compaction temperature (approximately 150^oC) at which the behavior of the mixtures could be significantly different from the behavior at the maximum service temperature of 60^oC. Furthermore, standard protocols call for APA tests to be conducted on specimens compacted to approximately 7% air voids and at maximum service temperature of the performance graded asphalt, i.e. 64^oC. On the other hand, the shear tests are conducted on specimens compacted to Ndes and at 54^oC. The discrepancy in these test conditions may obscure a meaningful comparison of the performance of mixtures as evaluated by these tests.

IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

This study has provided an objective evaluation of the Superpave mix design for mixtures containing natural sand. The results provide guidelines for designing such mixes and allow NCDOT to develop and utilize relatively economical Superpave surface course mixes for secondary roads.

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