EVALUATION OF THE EFFECTS OF MIXTURE PROPERTIES AND COMPACTION METHODS ON THE PREDICTED PERFORMANCE OF SUPERPAVE MIXTURES

by

N. Paul Khosla
and
S. Sadasivam

HWY-2001-03

FINAL REPORT
FHWA/NC/2002-030

in Cooperation with

North Carolina Department of Transportation

Department of Civil Engineering
North Carolina State University

August 2002

Technical Report Documentation Page

1. Report No. **FHWA/NC/2002-030**	2. Government Accession No.	3. Recipient's Catalog No:
4. Title and Subtitle **Evaluation of the Effects of Mixture Properties and Compaction Methods on the Predicted Performance of Superpave Mixtures**		5. Report Date **August 2002** 6. Performing Organization Code
7. Authors **N. Paul Khosla, S. Sadasivam**		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 2001- June 2002** 14. Sponsoring Agency Code **2001-03**
15. Supplementary Notes		

16.Abstract

The Superpave volumetric design method contains no strength or 'proof' test for quality control and quality assurance of mixtures. Accelerated wheel tracking systems, such as the Asphalt Pavement Analyzer (APA) and the NCSU Wheel Tracking Device (WTD) may fulfill the need for a relatively simple and inexpensive performance test. It is imperative that the predictability of these test systems should correlate with the field performance. Moreover, several compaction methods are used to fabricate specimens for performance testing in the laboratory. The compaction methods adopted in the laboratory are expected to simulate the properties of the pavement in the field. It is essential that the laboratory compaction of specimens should be a true indicator of field performance. So, the effects of different compaction methods on the performance of mixtures have been investigated in this study.

Laboratory compaction methods such as Superpave Gyratory Compaction (SGC) and Rolling Wheel Compaction (RWC) were compared with the field compaction. Four field sites had been selected for this purpose. The mixtures were identified as Auburn Coarse, Auburn Fine, Charlotte and Kinston. The Auburn mixtures were 12.5mm mixtures whereas the Charlotte and the Kinston mixtures were 9.5mm mixtures. The performance parameters of the mixtures include fatigue and rutting distresses. Various performance evaluation tests were conducted on the field cores and specimens fabricated using the Superpave Gyratory Compactor (SGC) and Rolling Wheel Compactor (RWC). Performance evaluation was done using test systems such as Shear tester, Asphalt Pavement Analyzer (APA) and NCSU Wheel Tracking Device.

The analysis of test results indicate that the laboratory compacted mixtures tend to be superior in their performance than the field cores. The mixtures compacted using the SGC and the RWC have higher stiffness values and lower shear strain values than the field cores. The Rolling Wheel Compaction (RWC) seems to simulate field compaction better than the SGC. The mixtures, which failed to satisfy the RSCH test criteria, had rut depths greater than 0.5 inch, as measured by the APA and NCSU WTD. The mixtures that passed the RSCH tests had rut depths less than 0.5 inch. The APA test and the NCSU WTD test can be used as a simulator to examine the rutting susceptibility of a mixture. It is suggested that a rut depth of 0.5 inch could be prescribed in the APA test and the NCSU WTD test as "pass/fail" or "go no-go" criteria.

17. Key Words	18. Distribution Statement
Superpave mixtures, Compaction methods, Asphalt Pavement Analyzer, NCSU Wheel Tracking Device, Rutting, Fatigue Cracking	

19.Security Classif.(of this report)	20.Security Classif.(of this page)	21.No. of Pages	22.Price
Unclassified	Unclassified	166	

Form DOT F 1700.7 (8-72)

DISCLAMIER

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.

EXECUTIVE SUMMARY

The Superpave volumetric design method contains no strength or 'proof' test for quality control and quality assurance of mixtures. Accelerated wheel tracking systems, such as the Asphalt Pavement Analyzer (APA) and the NCSU Wheel Tracking Device (WTD) may fulfill the need for a relatively simple and inexpensive performance test. It is imperative that the predictability of these test systems should correlate with the field performance.

Moreover, several compaction methods are used to fabricate specimens for performance testing in the laboratory. The compaction methods adopted in the laboratory are expected to simulate the properties of the pavement in the field. The physical properties of the specimens depend on the method of compaction used for fabrication. It is essential that the laboratory compaction of specimens should be a true indicator of field performance. So, the effects of different compaction methods on the performance of mixtures have been investigated in this study.

Laboratory compaction methods such as Superpave Gyratory Compaction (SGC) and Rolling Wheel Compaction (RWC) were compared with the field compaction. Four field sites had been selected for this purpose. The mixtures were identified as Auburn Coarse, Auburn Fine, Charlotte and Kinston. The Auburn mixtures were 12.5mm mixtures whereas the Charlotte and the Kinston mixtures were 9.5mm mixtures. The performance parameters of the mixtures include fatigue and rutting distresses. Various performance

evaluation tests were conducted on the field cores and specimens fabricated using the Superpave Gyratory Compactor (SGC) and Rolling Wheel Compactor (RWC). Performance evaluation was done using test systems such as Shear tester, Asphalt Pavement Analyzer (APA) and NCSU Wheel Tracking Device. The results of these test systems were compared and correlated. The compaction characteristics of the mixtures were studied using the Superpave Gyratory Compactor and the Gyratory Load-Cell Plate Assembly (GLPA).

The analysis of test results indicate that the laboratory compacted mixtures tend to be superior in their performance than the field cores. The mixtures compacted using the SGC and the RWC have higher stiffness values and lower shear strain values than the field cores. The Rolling Wheel Compaction (RWC) seems to simulate field compaction better than the SGC. There exists a good correlation among the results of the Repeated Shear tests at Constant Height tests, the APA tests and the NCSU WTD rut tests. The mixtures, which failed to satisfy the RSCH test criteria, had rut depths greater than 0.5 inch, as measured by the APA and NCSU WTD. The mixtures that passed the RSCH tests had rut depths less than 0.5 inch. The APA test and the NCSU WTD test can be used as a simulator to examine the rutting susceptibility of a mixture. It is suggested that a rut depth of 0.5 inch could be prescribed in the APA test and the NCSU WTD test as "pass/fail" or "go no-go" criteria.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

As asphalt concrete mixture design evolved from the conventional Marshall method to the new Superpave procedure, it became necessary to identify practical and relatively economical laboratory methods to predict the performance of mixtures on the roadway. Currently, the Superpave volumetric design method contains no strength or 'proof' test for quality control and quality assurance of mixtures. Test procedures that are used in the Superpave intermediate and complete procedures are designed to obtain input parameters for the Superpave computer model and require expensive and complex test equipment. Accelerated wheel tracking systems, such as the Asphalt Pavement Analyzer (APA), may fulfill the need for a relatively simple and inexpensive performance test. The APA is a thermostatically controlled device designed to predict the rutting susceptibility of the HMA under the wheel-path by applying linear repetitive loads. Several different laboratory compaction methods can be used to fabricate specimens for APA testing including the Superpave gyratory compactor (SGC), vibratory, static and rolling wheel. Each of these methods may produce specimens that have very different aggregate particle orientation, voids and corresponding estimated performance. For the APA to be used for performance testing, it is imperative that the specimens tested in this device be representative of the mixtures as they exist in the field.

As the use of Superpave mixtures increases, so will experience in their design and construction. It is thought that Superpave mixtures are generally more difficult to compact than Marshall mixtures in some cases. One possible reason for this is the wide range of properties and physical characteristics of the aggregates and binder types used in different geographic regions of the country. The compaction level and volumetric specifications in Superpave may be difficult to achieve or even unnecessary in some locations of the United States. It may be essential for state highway agencies to modify or amend the Superpave design specifications to cover the traffic levels, source material properties and observed performance in their jurisdictions. For instance, the design compaction level used by the SGC (as given by N_{des} and N_{max}) should be evaluated by observing how the designed mixtures compact in the field and perform in laboratory evaluation equipment.

With respect to the performance evaluation of Superpave mixtures used in North Carolina, several questions may be posed,

1. *How well do specimens fabricated used laboratory compaction methods simulate the properties of the pavements in the field ?*
2. *Can the densification curves generated by the SGC (N_{des} and N_{max}) during the mixture design process be compared to the field densities of the mixes ?*
3. *Can a performance evaluation device such as the APA be used to detect poorly performing Superpave mixtures ?*
4. *How does mixture performance as measured by the APA correlate with that of other performance evaluation procedures and devices ?*

The following sections describe the proposed objectives and approach that will be used to explore the answers to these questions.

1.1 Objectives and Scope of Study

In order to address the concerns and questions presented above, the primary objectives of this study are:

1. *Evaluate the effects of compaction type (rolling wheel and Superpave gyratory compactor) on a mixture's performance as measured by the APA, Wheel Tracking Device at NCSU and Repeated Shear Constant Height test (RSCH).*
2. *Evaluate how changes in aggregate and asphalt source affect mixture compaction and predicted performance in the test systems listed in 1 above by employing several Superpave mixtures from different field sites in North Carolina.*
3. *Compare the predicted performance, as measured by the test systems listed above, of test samples compacted in the field to the same mixtures compacted using the laboratory compaction systems listed in 1.*
4. *Evaluate and compare the densification characteristics of mixtures with varying degree of compaction (in terms of number of gyrations) in the Superpave Gyratory Compactor (SGC) and the Gyratory Load Cell Plate Assembly (GLPA).*

1.2 Research Methodology and Approach

The research plan consisted of three main tasks. First, the field sites were selected from which test samples were collected. Secondly, loose mixtures from these sites were compacted using Rolling Wheel Compactor (RWC) and Superpave Gyratory Compactor

(SGC). Lastly, the performance of these laboratory compacted mixtures was compared to the performance of the field cores and slabs obtained from the selected sites. A more detailed explanation of this work plan is given in Figure 1.1.

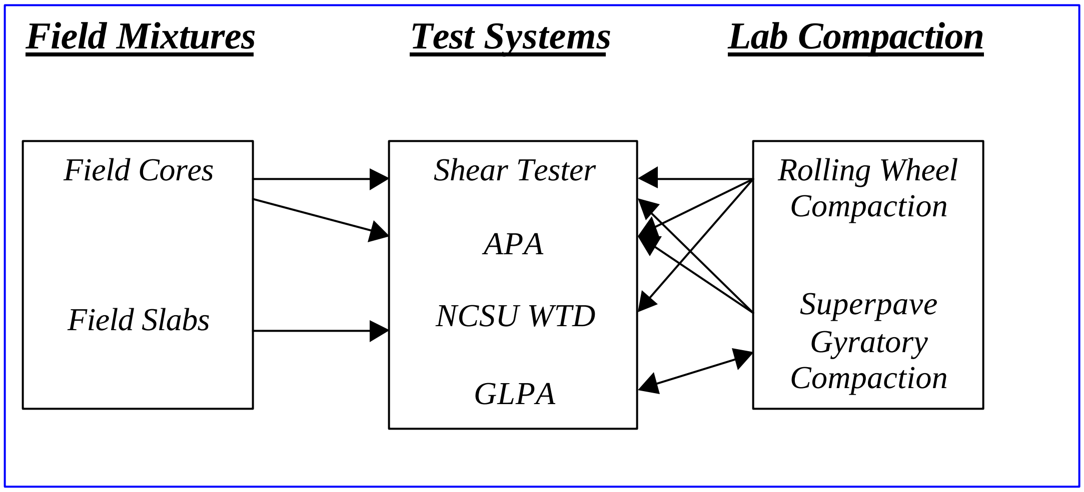

Figure 1.1 Research Plan

Task 1: Field Site Selection and Test Material Procurement

Since one of the objectives of this research was to evaluate how changes in aggregate and binder sources affect the performance evaluation of mixtures, typical mixtures were selected from different geographic regions in and out of North Carolina. Field specimens and loose mixtures were collected from these sites.

Task 1.1 Site Selection:

The location and the total number of test sites were selected after consultation with NCDOT. Four test sites were selected in such a way that each test site had a different type of aggregate gradation (coarse or fine) and a nominal maximum size of aggregate

(12.5mm or 9.5mm). The test sites were Auburn (NCAT research tracks), Kinston and Charlotte. NCDOT was the contractor for the North Carolina test sections in NCAT research tracks. The Kinston and the Charlotte mixtures were from Kinston and Matthews counties of North Carolina. The aggregate sources for all the four mixtures were from the quarries of North Carolina. The detailed information about the mixtures is provided in the following chapters. These sites were the pavements that contain SUPERPAVE volumetrically designed mixtures being used in either new or overlay construction.

Task 1.2 Test Sample Procurement:

After the number and location of test sites were selected, test samples were gathered from each site. Test samples included field cores, field slabs and loose mixtures. Loose mixtures were procured for the compaction of the mixtures using SGC and Rolling Wheel compactor. Field cores and loose mixtures were taken from all the four sites, whereas field slabs were available only for the Kinston and the Charlotte mixtures. Field cores were 150 mm in diameter with varied thickness. The thicknesses of field slabs were 75mm and 100mm for the Kinston and the Charlotte mixtures, respectively.

Task 2: Evaluation of Laboratory Compaction Methods

The central objective of this research was to evaluate how different compaction methods (RWC and SGC) differ from the field compaction in performance, say fatigue and rut life. The following subsections outline how each of these compaction methods was used to accomplish this phase of research.

Rolling Wheel Compaction using the NCSU Wheel Tracking Device:

The Wheel Tracking Device (WTD) at NCSU has the ability to compact large rectangular slab samples using a steel rolling wheel at various compaction pressures. The sample size used in the WTD is 520mm long, 430mm wide and up to a thickness of 300mm in 75mm lifts. Since the WTD rolling wheel compactor has been scaled and designed to match that of field compaction equipment, it is thought that it simulates field compaction better than any other laboratory compaction method currently in use.

Cylindrical test specimens were cored out from the RWC slabs for repeated shear tests and APA tests. The test results of RWC specimens were then compared with the corresponding results of field cores and SGC compacted specimens. The rutting performance of rolling wheel compacted mixtures was evaluated by using accelerated test facility in the WTD and the results were compared to those from the APA.

Superpave Gyratory Compactor:

The SGC was used to fabricate cylindrical test specimens, with densities similar to those of the field mixtures, for testing in the SST and the APA. The rutting performance of these samples were compared to the samples compacted by the other laboratory methods and field cores. In addition to the use of the SGC as a compaction method for testing in the SST and the APA, one of the objectives of this study was to compare how the compaction curve of the SGC compares to the actual field density of the mixtures. Since the gyratory compactor is used to fabricate mixtures in the SUPERPAVE volumetric design procedure, N_{des} should correspond to a mixture's field density after construction, while the %Gmm should be 96%. The level of relative compaction in the SGC can be verified or calibrated for the design of SUPERPAVE mixtures used in North Carolina. This is also another reason why the evaluation of field sites using the SUPERPAVE volumetrically designed mixtures in new or overlay construction would be beneficial to this study.

The compaction characteristics of the mixtures were studied and compared to the results from the Gyratory Load Plate Assembly (GLPA). The energy indices measured using the GLPA and the SGC better explains the compaction characteristics of the mixtures during construction and under traffic.

Task 3: Performance Evaluation

As discussed above, the relative rutting performance of samples fabricated using the laboratory compaction methods were compared to each other and to the rutting performance of the samples taken from the field. The objective being to determine which compaction method yields a sample that exhibits similar performance to that produced in the field. The last phase of research was to evaluate the APA itself in order to calibrate the rutting performance it predicts to that of two other rutting evaluation tests: the NCSU wheel tracking device and the simple shear tester.

Asphalt Pavement Analyzer:

The APA basically consists of three parallel steel wheels, rolling on a pressurized rubber tube, which applies loading to beam or cylindrical specimens in a linear track. The test specimens, loading tubes and wheels are all contained in a thermostatically controlled environmental chamber. The depth of rutting in the test specimens is measured after the application of 8000 loading cycles. The predicted rutting measured by the APA is the central facet of the study. As mentioned above, Task 2 was to evaluate how the performance of sample fabricated using different laboratory compaction methods compared to that of the field specimens. The results of the APA tests were compared with the results of the Simple Shear Tester and the WTD at NCSU.

Simple Shear Tester:

The SST is a closed-loop system that consists of four major components: the testing apparatus, the test control unit and data acquisition system, the environmental control chamber, and the hydraulic system. In this proposed study, repeated shear test at constant height and frequency sweep test at constant height was used to analyze the performance of HMA mixtures. A full description of the test procedures can be found in AASHTO TP7. The rutting and fatigue analyses were then conducted using the test results.

The frequency sweep test at constant height was used to analyze the permanent deformation and fatigue cracking. A repeated shearing load was applied to the specimen to achieve a controlled shearing strain of 0.045 percent. The specimen was tested 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 ϕ were determined by this test.

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 were applied to the specimen. The test specimens were subjected to load cycles of 5000 cycles or until the permanent strain reaches 0.045 percent that corresponds to the maximum allowable rut depth of 0.5 inch. 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.

NCSU Wheel Tracking Device:

In addition to providing a method to compact mixtures for further testing, the WTD is a sophisticated testing device to evaluate the rutting performance of mixtures. It has a rubber tire to apply a rolling pressure to a slab for a designed number of cycles. The amount of pressure applied by the wheel can be set constant or be variable, as can the wheel path itself (to simulate the effect of wandering traffic in the field). The rut depth is measured after a set number of cycles using a laser at predetermined points along the length of the slab. The test stops either at the set number of cycles or when the rut depth reaches a specified limit. The WTD not only ranks the performance of a mixture similar to the APA but also gives the rutting profile of the slab after every interval of rutting cycles.

Frictional Resistance by Gyratory Load Cell Plate Assembly:

A Gyratory Load Cell Plate Assembly (GLPA) was developed and initially tested at the University of Wisconsin – Madison. This device easily fits on most SGCs without modification and requires no deviation in the compaction procedure. The assembly consists of three load cells fixed between two parallel plates at an equal radial distance, 120^o apart. The force on the three load cells is continuously monitored, along with sample deflection and height, throughout the fabrication process. The corresponding resultant force and eccentricity acting on the plates are then calculated. Assuming that at any gyration the sample is fully constrained, and the energy due to surface traction is negligible, the energy balance for the sample can be written using the following:

$$W = U \tag{1.1}$$

Where

W = work of the external forces, and

U = total strain energy of the sample

Expanding the above equation yields the following:

$$\frac{1}{2} M\theta = \frac{1}{2} \tau\gamma V \tag{1.2}$$

where,

M = applied moment,

θ = tilt angle (radians)

τ = frictional resistance

γ = shear strain

V = sample volume at any cycle

The resulting moment M can be calculated by multiplying the ram force R by the eccentricity e for a given gyration cycle. The frictional resistance can be determined by simplifying the above equation into the form

$$\tau = FR = Re/Ah \qquad (1.3)$$

where,

A = sample cross section area

H = specimen height at any given gyration

The University of Wisconsin study found that asphalt content, aggregate gradation, aggregate angularity, air voids and compaction temperature all affected the frictional resistance of the specimen, and recommendations were made concerning the use of %Gmm with frictional resistance in the mixture design process. However, no correlations were made between frictional resistance, other mixture performance equipment or methods, and actual field performance. In view of the above discussion, GLPA was used in this study to determine the potential of such a device to provide a measure of stability of asphalt mixtures. Furthermore, it offered an opportunity to see if the frictional resistance in the laboratory evaluation had any relationship to field performance.

1.3 Summary

- Four types of mixtures were selected for this study from different geographic locations in and out of North Carolina to study the effects of aggregate and binder type on the compaction of mixtures. Field slabs, field cores, and loose mixtures were procured from these test sites. The mixture densification information of mixtures was obtained.

- The laboratory compaction methods included the WTD rolling wheel compactor and the Superpave Gyratory Compactor. The cylindrical specimens fabricated using these compactors were tested using the SST and the APA. The test results were compared to the test results of field cores. Similarly the WTD rut test results of rolling wheel compacted slabs were compared to those of field slabs. The densification information generated by the SGC and the energy indices developed using the SGC and GLPA explained the compaction characteristics of the mixtures.
- The relative rutting measurements obtained by the performance testing devices were also compared.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews the background literature that deals with the effect of different compaction methods, different types of accelerated laboratory wheel tracking devices and the performance of the Asphalt Pavement Analyzer (APA).

2.1 Evaluation of Laboratory Compaction Methods

The objective of a mix design system has always been to mix, compact, and test asphalt mixtures in the laboratory to determine its expected performance in service. The specimen prepared in the laboratory should be representative of a field-compacted specimen having the same properties as the prototype placed in the field and subjected to the compactive effects of traffic. So it is irrefutable that the laboratory compaction of specimens should be a true indicator of field performance. This section compares the various laboratory compaction methods and their ability to simulate field densification.

2.1.1 Compaction

Pavement density is a function of traffic and climate (temperature). For pavements to be designed correctly, traffic and climate must be simulated in the laboratory for mix design. The heart of all mixture design methods is the laboratory compaction method (1).

RILEM 152 PBM (2) identifies the type and degree of compaction as one of the five preparatory steps in the basic testing methodology of bituminous mixture design. Compaction of an asphalt concrete mixture is defined as “…a stage of construction, which transforms the mix from its very loose state into a more coherent mass, thereby permitting it to carry traffic loads”. The efficiency of the compactive effort will be a function of the internal resistance of the bituminous concrete. The resistance includes aggregate interlock, friction resistance, and viscous resistance. Another reason for compacting the asphalt pavement is to make it water tight and impermeable to air.

From the Hubbard Field method of mix design to the SHRP SUPERPAVE method, attempts have been made to select a compaction method that closely duplicates the properties of the actual road pavement. It is well established that method of compaction affects the physical properties of compacted asphalt concrete specimens. Factors such as particle orientation and aggregate interlock, void structure, and the number of interconnected voids should be considered in the selection of a compaction device (3).

2.1.2 Different Types of Compaction Methods

The four basic types of compaction methods are

1. Impact Compaction
2. Kneading Compaction
3. Gyratory Compaction
4. Rolling Wheel Compaction

Impact Compaction:

Impact compaction is the oldest method of laboratory compaction. In the 1920s, Hubbard and Field used a Procter hammer to compact asphalt mixtures. In 1930s, Marshall developed mechanical Marshall Hammer to simulate impact type compaction. The number of blows applied to each face of the specimen (35, 50 and 75 blows) was tied to general traffic levels. Higher energy levels (blows) were used for higher traffic levels. Unfortunately, different densities, because of the variability in Marshall hammers (mechanical, rotating, and manual hammers), will result when these compaction blows are applied (1).

Kneading Compaction:

The compaction method used by Hveem in his mix design procedure is kneading compaction. Kneading compaction applies forces through a roughly triangular-shaped foot that covers only a portion of the specimen face. Compacted forces by tamps are applied uniformly on the free face of specimen to achieve compaction. The partial face allows particles to move relative to each other, creating a kneading action that densifies the mix. There are different kneading compactors like California kneading compactor, Linear kneading compactor (LKC) and Arizona kneading compactor (1).

Gyratory Compaction:

Gyratory compaction was developed in the 1930s in Texas. Later this method of compaction was further developed and applied by the Army Cops of Engineers and the Central Laboratory for Bridges and Roads (LCPC) in France. One of the final product of Strategic Highway Research Program (SHRP) was Superpave Gyratory Compactor. Other types of gyratory compactors (4) are

- Texas Roots of Gyratory Compaction

- Corps of Engineers Gyratory Testing Machine
- LCPC French Gyratory Compaction

Gyratory process involves applying a vertical load while gyrating the mold in a back-and forth motion. Gyratory compaction produces a kneading action on the specimen.

Superpave Gyratory Compactor

The decision to use gyratory compaction as the Superpave compaction is based on NCHRP Study 9-5. NCHRP 9-5, which was designed to be a lead-in to the SHRP, focused on compaction methods and developed a preliminary mix design and analysis system using pre-SHRP performance related tests. Midway through the SHRP, as the Superpave method of mix design was being assembled, an evaluation of available gyratory compaction research was done.

An underlying premise of the gyratory protocol selection was that material property parameters were not expected to come from the compactor. The primary objective of SHRP was to develop and validate material properties, and test methods to measure the properties, which could be used to predict performance. Therefore, the need for fundamental or empirical engineering properties from a compactor did not exist. Hence, the material properties, which can be measured with the Gyratory Testing Machine, were not required.

The ability to evaluate the rate of densification was selected as a desirable characteristic. The constant angle and constant vertical pressure of the Texas 6 inch gyratory allowed the densification curves to be developed. Early testing showed that the high angle, five degrees, produced a very rapid rate of compaction and produced densification curves, which were difficult to measure. An angle of one degree was then selected which matched the LCPC protocol. Subsequent work indicated that the rate of densification was not sufficient; hence, the final angle selected for Superpave was 1.25 degrees.

In the SGC, a mix is subjected to two kinds of stresses during compaction: one is the constant vertical stress and other is a shearing stress. The shearing stress must overcome the shear strength of the mix to compact it.

Other compaction devices include

- Rolling Wheel Compactor
- APA Static and Vibratory Compactor
- French Plate Compactor

2.1.3 Studies on Different Compaction Methods

Early Research in Compaction:

In early 1950s, Vallerga was probably the early researcher to emphasize the importance of proper compaction. He made a comparative study on the influence of static load, impact and kneading compaction methods on bituminous mixtures. He observed that method of compacting or fabricating laboratory test specimens of bituminous paving mixtures has a profound influence on stability and cohesion values as measured by the Hveem's stabilometer and cohesiometer respectively. He found that different compaction methods gave different stability values even when the compacted mixes show the same density. This observation made him to conclude that different compaction methods yield different "orientation" or "arrangement" of particles that influence the stability or resistance to deformation of the mass rather than mere ascribe to the density or decrease in void ratio alone (5).

Studies by Von Quintus et al:

A NCHRP sponsored study evaluated the ability of five compaction devices to simulate field compaction (6). The compaction devices evaluated were selected on the basis of their availability, uniqueness in mechanical manipulation of mixture and potential for use by agencies responsible for asphalt mixture design. The devices evaluated are

- Mobile steel wheel simulator
- Texas gyratory compactor
- California kneading compactor
- Marshall impact hammer
- Arizona vibratory-kneading compactor

The ability of the five laboratory compaction devices to simulate field compaction is based on the similarity between engineering properties (resilient moduli, indirect tensile strengths and strain at failure, and tensile creep data) of laboratory-compacted samples and field cores. The test results show that although there is no single laboratory compaction method that always provided the best match with the results of the field compaction method, the Texas gyratory compactor demonstrated the ability to produce mixtures with engineering properties nearest those determined from field cores. The California kneading compactor and the mobile steel wheel simulator ranked second and third respectively, but with very little difference between the two. The Arizona vibratory kneading compactor and the Marshall impact hammer ranked as least effective in terms of their ability to produce mixtures with engineering properties similar to those from field cores.

An abstract of results are given in Table

Compaction Device	Percent of Cells with properties	
	Closest to Field Cores	Indifferent from the Field Cores
Texas Gyratory	45	63
Mobile steel wheel simulator	25	49
California kneading compactor	23	52
Arizona vibratory-kneading compactor	7	41
Marshall impact hammer	7	35

Studies by Joe Button et al

A similar study was carried out by Joe W. Button et al , as a part of the research project for SHRP program (7). Four types of compaction methods that were evaluated are

- Exxon Rolling Wheel
- Texas Gyratory compactor
- Rotating base Marshall hammer
- Elf linear kneading compactor

Laboratory-fabricated specimens from each compaction device were tested to characterize the material response of each mixture in tensile and compressive shear modes of loading. Test results were compared to corresponding results from field cores and statistically analyzed. Analyses indicated that the gyratory method most often produced specimens similar to pavement cores (73 percent of the tests performed). Exxon and Elf compactors had the same probability of producing specimens similar to pavement cores (64 percent of the tests performed). The Marshall rotating base compactor had the least probability of producing specimens similar to pavement cores (50 percent of the tests performed). He observed difficulties in using Exxon rolling wheel compactor in controlling air voids with the finished specimens than the other compaction methods. He concluded that the Texas gyratory compactor is more convenient for preparing laboratory specimens for routine mixture design and testing of asphalt concrete. From the above study, it seems to be rational to argue that gyratory method of compaction would provide better results than the other compaction methods.

Studies by UCB Research Group

As a part of SHRP A-003 research program at University of California, Berkeley, Sousa et al investigated gyratory (Texas type), kneading and rolling wheel compaction procedures (3).

The gyratory compactor was found to place excessive emphasis on the asphalt binder and to inaccurately portray the role of asphalt aggregate interaction in the performance of properly constructed pavements. Furthermore, the shape and dimension of specimens produced by gyratory compactors are limited. Although kneading compactor is more adaptable for producing a larger variety of sizes and shapes, it creates a more stable aggregate structure that is commonly developed by conventional construction practice, thereby failing to capture the role of the asphalt binder in properly performing pavements. Because the response of rolling wheel specimens to test loads is typically between that of gyratory and kneading specimens, rolling wheel compaction is best suited for preparing laboratory specimens. Among the methods investigated, it appears to duplicate field-compacted specimens quite well.

Accordingly, based on these studies as well as an evaluation of international experience, it is strongly recommended that rolling wheel compaction be used for the preparation of laboratory specimens of asphalt-aggregate mixes which are to be evaluated as a part of a comprehensive asphalt-aggregate mix analysis system.

Rolling-wheel compaction is intuitively appealing for its obvious similarity to field compaction process. Moreover, extensive studies have demonstrated that it produces uniform specimens with engineering properties similar to those of cores extracted from recently constructed pavements. Rolling Wheel compaction is a comparatively easy procedure to use and enables rapid fabrication of specimen in suitable numbers and shapes for a comprehensive mix design/analysis system. Because specimens produced by rolling wheel compaction are cored or sawed from a larger mass, all surfaces are cut. Cut surfaces are desirable because air voids can be more accurately measured, comparisons with specimens extracted from in-service pavements are more accurate, specimens are more homogeneous, and test results are likely to be less variable. Rolling-wheel compaction also has the advantage that specimens containing large-size aggregates can be produced without difficulty.

European experience has proven the practicality and superiority of rolling wheel compaction. It is recommended form of specimens preparation in France and is a major component of the LCPC mix design/evaluation methodology. Studies in the United Kingdom as well as the Royal Dutch Shell Laboratory, Amsterdam, also demonstrate the effectiveness of rolling wheel compaction.

2.1.4 Effect of Compaction on the Internal Structure

From the above discussions, it is evident that the method of compaction has profound influence on the measured mechanical properties on the compacted asphalt concrete specimens. Earlier research indicate that gyratory, rolling wheel, and kneading compaction produce specimens with significantly different permanent deformation responses to repeated shear loading. The effect of compaction procedure has been mainly attributed the difference in the internal structure of the compacted mixes.

Internal structure refers to the distribution of aggregates and their associated voids. The air void distribution constitutes the first phase of the internal structure. The Superpave volumetric mixture design procedure focuses on average percent air voids for specifying and designing AC mixtures. Two specimens with the same average percent air voids may have a different distribution of air voids and intuitively they are expected to respond differently under loading conditions. The next aspect of the internal structure of AC is aggregate distribution, orientation and contacts. Researchers have already established the relationship between the number of contacts and shear strength of granular assembly.

Two different research groups have studied the effect of compaction methods on internal structure of asphalt concrete specimens using image analysis. Digital Image Processing (DIP) consists of converting video pictures into a digital form and applying various mathematical procedures to extract significant information from the picture. It is fast becoming a versatile tool for characterizing the internal structure of materials. The research group at UCB and Danish National Roads Laboratory (DNRL) used image analysis of plane specimens compacted using UCB rolling wheel, Texas Gyratory and California kneading compactors (8). E.Masad et al used DIP to quantify the internal structure parameters of specimens compacted using Superpave gyratory compactor and linear kneading compactor (9).

Aggregate Orientation:

The results of the image analysis of Masad et al show that the aggregates have preferred orientation toward the horizontal direction in SGC and they appear to have more of a random distribution in Linear Kneading Compactor (LKC) specimens. The average angle of inclination was found to be smaller for specimens compacted with the SGC than those compacted with the LKC.

DRNL's image analysis confirms the hypothesis that a greater degree of aggregate orientation results from rolling wheel compaction as compared with that produced by the Texas gyratory compactor. These findings support the hypothesis that Texas gyratory specimens' lower resistance to permanent deformation under repetitive shear loads is at least partly related to the lack of a strong , oriented aggregate structure. On the other hand, the rolling wheel specimens' greater resistance is a result of aggregate orientation and inter particle contact caused by the forces induced by the rolling alone because unlike gyratory and kneading methods, rolling wheel compaction does not include any static leveling loading that might increase particle-to-particle contact by crushing aggregates together.

Contacts:

The results of the image analysis by E.Masad et al indicate that LKC specimens had more contacts (about 550 contact points on six sections) than the SGC specimens (about 450 contact points). It is interesting to note that several studies have indicated that specimens compacted by kneading action had significantly higher resistance to permanent deformation than specimens compacted by gyratory action. Evidently, the higher shear strength of kneading compacted specimens is associated with the high number of coarse aggregate contacts.

Air void distribution:

Asphalt aggregate mixes compacted in the field usually have increasing air void contents from the top of the lift to the bottom. The reason for air-void gradients can be easily explained by the distribution of forces under a field compaction wheel which decrease with depth. E.Masad et al studied the air void distribution in SGC and LKC compacted specimens using X-ray tomography. The middle of the SGC specimen was compacted more than the top and the bottom. For the materials studied, the air voids were found to be relatively uniform between 20 and 100mm. In the LKC specimens, air voids were more concentrated at the bottom (Fig.2.1-2.4).

Rolling wheel compacted specimens would be expected to have increasing air void contents from the top to the bottom of the lift, as do field specimens. Air void contents are expected to be fairly homogeneous in the horizontal plane of the rolling wheel. Gyratory specimens are subjected to a high axial compressive stress, a side-to-side shear stress, and a torsional shear stress. Under high axial compressive stresses and many gyrations, it is expected that the interior of the specimen become better compacted. The torsional shear stress, and the inability of aggregate to become oriented, is thought to reduce compaction near the vertical walls of the specimen. As-compacted Texas gyratory and kneading compacted specimens appear to have different aggregate and air void structure near the mold surface than in their interior.

The method of compaction has a profound influence on the engineering properties of asphalt concrete mixtures. Different methods of compaction yield different aggregate orientation and air void distribution. Conclusions of different studies indicate that gyratory method and rolling wheel compactions simulate properties that are closer to field compaction.

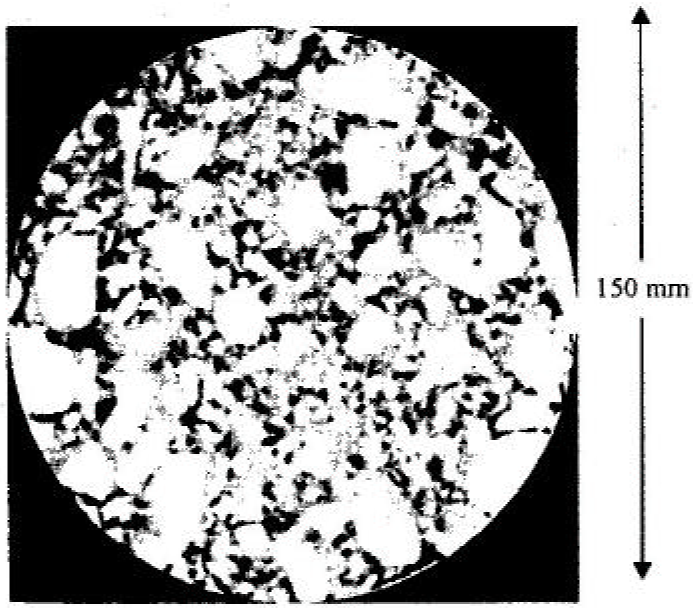

Figure 2.1 Horizontal X-ray Tomography Image of a SGC Specimen

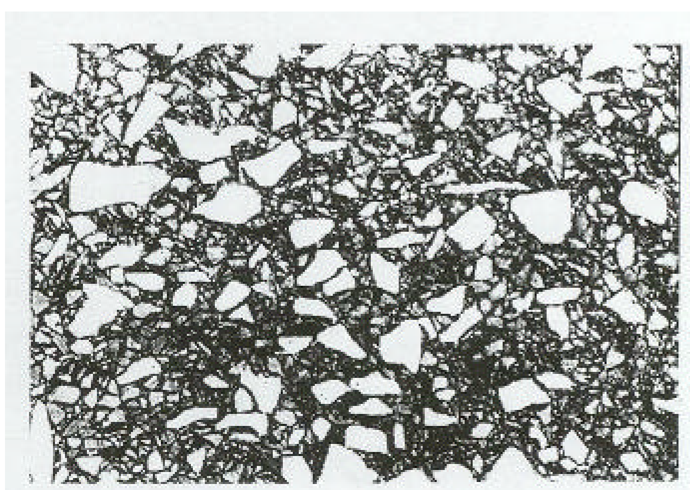

Figure 2.2 Optical Digital Camera Image of a Vertical Section of a SGC Specimen

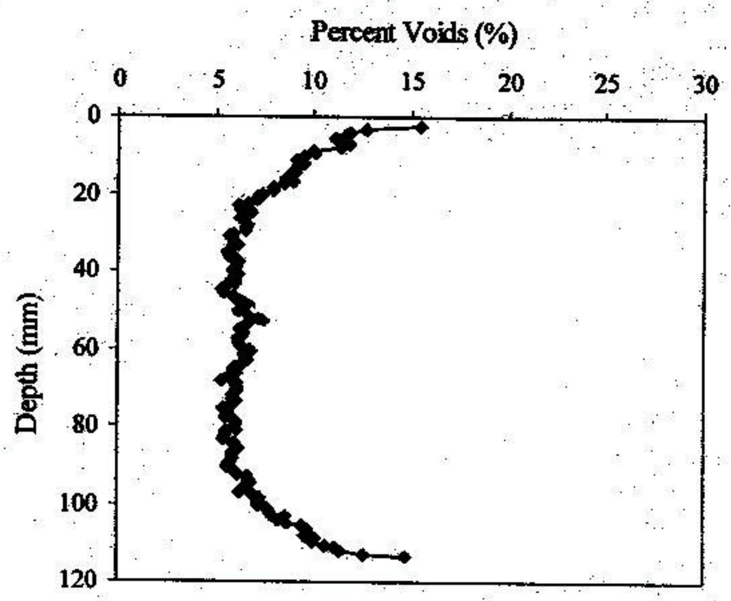

Figure 2.3 Void Distribution in a SGC Specimen

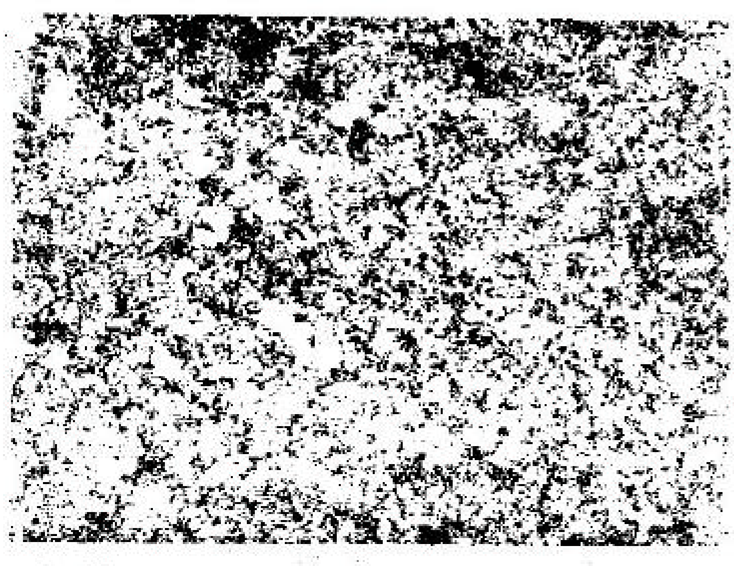

Figure 2.4 Projections of 3-D Images of Air Voids of a SGC Specimen

2.1.5 SGC Compaction Characteristics of Mixtures

A significant component of the Superpave Volumetric mix design protocol lies on the compaction process. The laboratory compaction process proceeds through three land marks: N_{ini} which corresponds to the state of the mixture as the breakdown roller makes its first few passes; N_{des} representing the anticipated state of density in the mixture after 3 to 5 years; and N_{max} which represents a "factor-of-safety" condition should the traffic projections be seriously underestimated or the climate hotter than the anticipated (10). The densification curve (%G_{mm} vs. log N) would accurately represent the state of the mixture at any point in the anticipated life of the mixture, i.e., during construction and subsequently under traffic. Hussain U.Bahia et al (11) introduced the concept of compaction energy indices by utilizing the SGC results to optimize the densification characteristics under construction and densification characteristics under traffic. The densification curves were separated into different regions to represent the construction compaction requirements and the traffic densification to selected air voids or to terminal densification. The compaction energy index (CEI) and the traffic densification index (TDI) are used as new measures to relate to construction and in-service performance of mixtures. But the rationality of the use of these indices is being questioned. Coree and Vander Horst (10) argue that the greater part of the compaction is achieved while the mixture is in excess of 115^{o}C. But the mixture temperature under operating conditions under traffic may range from -28^{o}C to 58^{o}C (as indicated by the grade of the binder, PG 58-28). Moreover they argue about the non-conformation of the SGC data to rutting models adopted by Superpave. The inability of the SGC compaction curve to highlight plastic instability is attributed to the fact that the mixture is so effectively contained within the relatively infinitely rigid walls of the mold and equally rigid top and bottom platens that the type of lateral flow observed in rutting pavement is totally prevented, even though the actual state of the mixture may be wholly plastic during laboratory compaction.

2.2 Accelerated Wheel Tracking Devices

Accelerated laboratory rutting prediction tests are needed for design as well as quality control/quality assurance purposes. Laboratory wheel tracking devices potentially could be used to to identify HMA mixtures that may be prone to rutting. Loaded wheel testers (LWT) are becoming increasingly popular with transportation agencies as they seek to identify hot mix asphalt mixtures that may be prone to rutting. The LWTs allow for an accelerated evaluation of rutting potential in the designed mixes (12)

2.2.1 Loaded Wheel Testers used in the United States

Several LWTs currently are being used in the United States. They include the Georgia Loaded Wheel Tester (GLWT), Asphalt Pavement Analyzer (APA), Hamburg Wheel Tracking Device (HWTD), LCPC (French) Wheel Tracker, Purdue University Laboratory Wheel Tracking Device (PURWheel), and one-third scale Model Mobile Load Simulator (MMLS3). Following are descriptions for each of these LWTs.

Georgia Loaded Wheel Tester

The GLWT was developed during the mid-1980s through a cooperative research study between the Georgia Department of Transportation and the Georgia Institute of

Technology. The primary purpose for developing the GLWT was to perform efficient, effective, and routine laboratory rut proof testing and field production quality control of HMA. The GLWT is capable of testing HMA beam or cylindrical specimens. Beam dimensions are generally 125 mm wide, 300 mm long, and 75 mm high (5 in x 12 in x 3in). Compaction of beam specimens for testing in the GLWT has varied greatly according to the literature. The original work by Lai (13) utilized a "loaded foot" kneading compactor. Heated HMA was "spooned" into a mold as a loaded foot assembly compacted the mixture. A sliding rack, onto which the mold was placed, was employed as the kneading compactor was stationary. West et al. utilized a static compressive load to compact specimens. Heated HMA was placed into a mold and a compressive force of 267 kN(60,000 lbs) was loaded across the top of the sample and then released.

This load sequence was performed a total of four times. In 1995, Lai and Shami described a new method of compacting beam samples. This method utilized a rolling wheel to compact beam specimens. Laboratories prepared cylindrical specimens are generally 150 mm in diameter and 75 mm high. Compaction methods for cylindrical specimens have included the "loaded foot" kneading compactor and a Superpave gyratory compactor. Both specimen types are most commonly compacted to either 4 or 7 percent air void content. However, some work has been accomplished in the GLWT at air void contents as low as 2 percent (14). Testing of samples within the GLWT generally consists of applying a 445-N (100-lb) load onto a pneumatic linear hose pressurized to 690 kPa (100 psi). The load is applied through an aluminum wheel onto the linear hose, which resides on the sample. Test specimens are tracked back and forth under the applied stationary loading. Testing is typically accomplished for a total of 8,000 loading cycles (one cycle is defined as the backward and forward movement over samples by the wheel). However, some researchers have suggested fewer loading cycles may suffice. Test temperatures for the GLWT have ranged from 35°C to 60°C (95°F to 140°F). Initial work by Lai was conducted at 35°C (95°F). This temperature was selected because it was Georgia's mean summer air temperature. Test temperatures within the literature subsequently tended to increase to 40.6°C (105°F), 46.1°C (115°F), 50°C (122°F) (3, 8), and 60°C (140°F) (8). At the conclusion of the 8,000-cycle loading, permanent deformation (rutting) is measured. Rut depths are obtained by determining the average difference in specimen surface profile before and after testing. A template with 7 slots that fits over the sample mold and a micrometer are typically used to measure rut depth.

Asphalt Pavement Analyzer

The APA, shown in Figure 2.5 and 2.6, is a modification of the GLWT and was first manufactured in 1996 by Pavement Technology, Inc. The APA has been used to evaluate the rutting, fatigue, and moisture resistance of HMA mixtures. Since the APA is the second generation of the GLWT, it follows the same rut testing procedure. A wheel is loaded onto a pressurized linear hose and tracked back and forth over a testing sample to induce rutting. Similar to the GLWT, most testing is carried out to 8,000 cycles. Unlike the GLWT, samples also can be tested while submerged in water. Testing specimens for the APA can be either beam or cylindrical. Currently, the most common method of compacting beam specimens is by the Asphalt Vibratory Compactor. However, some have used a linear kneading compactor for beams. The most common compactor for cylindrical specimens is the SGC (15). Beams are most often compacted to 7 percent air voids; cylindrical samples have been fabricated to both 4 and 7 percent air voids. Tests can also be performed on cores or slabs taken from an actual pavement. Test temperatures for the APA have ranged from 40.6°C to 64°C (105°F to 147°F). Wheel load and hose pressure have basically stayed the same as for the GLWT, 445N and 690 kPa (100 lb and 100 psi), respectively.

Figure 2.5 Model of APA

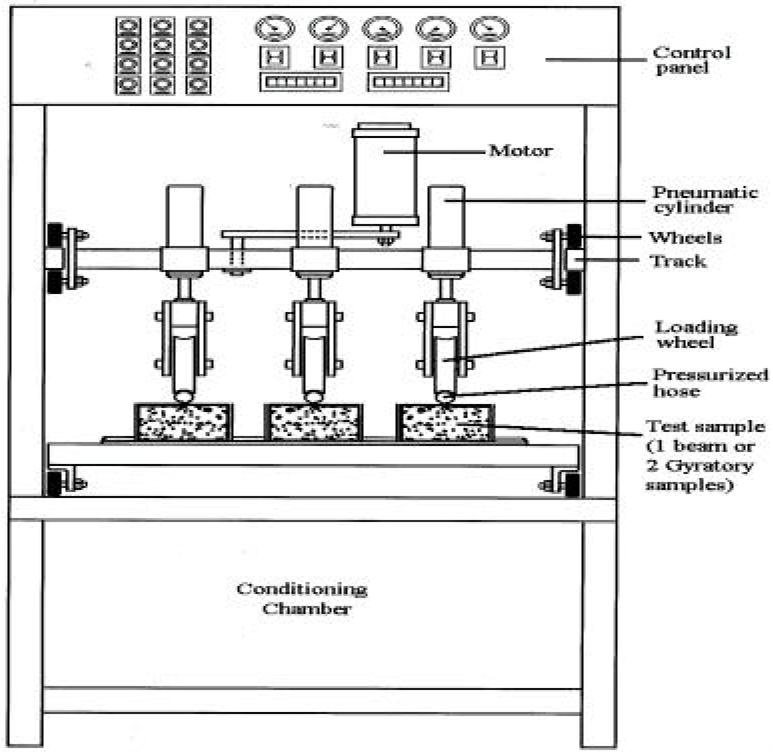

Figure 2.6 Schematic Drawing of the APA

NCSU Wheel Tracking Device (CS 6000)

The NSCU Wheel Tracking Device (CS6000) was designed by James Cox & Sons. The NCSU Linear Compaction and Wheel Tracking system was designed to simulate the field conditions of asphalt concrete pavements from construction to application. The system can compact a loose mixture to given density and then can quickly be configured to evaluate the compacted slab's rutting resistance. The NCSU WTD can also perform rutting analysis on slabs taken from field sections. A detailed explanation of the wheel tracking system is given in Chapter 5.

Hamburg Wheel-Tracking Device

The HWTD, as shown in Figure 2.7, was developed by Helmut-Wind Incorporated of Hamburg, Germany (16). It is used as a specification requirement for some of the most traveled roadways in Germany to evaluate rutting and stripping. Tests within the HWTD are conducted on a slab that is 260 mm wide, 320 mm long, and typically 40 mm high(10.2 in x 12.6 in x 1.6 in). These slabs are normally compacted to 7±1 percent air voids using a linear kneading compactor. Testing in the HWTD is conducted under water at temperatures ranging from 25°Cto 70°C (77°F to 158°F), with 50°C (122°F) being the most common temperature. Loading of samples in the HWTD is accomplished by applying a 705-N (158-lb) force onto a 47-mm-wide steel wheel. The steel wheel is then tracked back and forth over the slab sample. Test samples are loaded for 20,000 passes or until 20 mm of deformation occurs. The travel speed of the wheel is approximately 340 mm per second. The results obtained from the HWTD consist of rut depth, creep slope, stripping inflection point, and stripping slope. The creep slope is the inverse of the deformation rate within the linear region of the deformation curve after post compaction and prior to stripping (if stripping occurs). The stripping slope is the inverse of the deformation rate within the linear region of the deformation curve, after the onset of stripping. The stripping inflection point is the number of wheel passes corresponding to the intersection of the creep slope and the stripping slope. This value is used to estimate the relative resistance of the HMA sample to moisture-induced damage. A slight modification of the HWTD was made by the Superfos Construction, U.S.(previously Couch, Inc.). This device was referred to as the Superfos Construction Rut Tester (SCRT). The SCRT used slab specimens with similar dimensions as the HWTD. The primary difference between the two was the loading mechanism. The Superfos Construction Rut Tester. SCRT applied an 82.6-kg (180-lb) vertical load onto a solid rubber wheel with a diameter of 194 mm and width of 46 mm. This loading configuration resulted in a contact pressure of approximately 940 kPa (140 psi) and contact area of 8.26 cm^2(1.28 in2) which was applied at a speed of approximately 556 mm per second.Test temperatures ranging from 45°C to 60°C (113°F to 140°F) have been used with the SCRT. Recent research with the SCRT has used 60°C as the test temperature. An air void content of 6 percent was generally used for dense-graded HMA samples. Results from the SCRT are identical to those from the HWTD and include rut depth, creep slope, stripping slope, and stripping inflection point.

Another slight modification of the HWTD is the Evaluator of Rutting and Stripping (ERSA) equipment (17). This device was built by the Department of Civil Engineering at the University of Arkansas. Testing of cylindrical or beam samples in the ERSA can be conducted in either wet or dry conditions. A 47-mm wide steel wheel is used to load specimens with 705 N (160lb) for 20,000 cycles or a 20-mm rut depth, whichever occurs first.

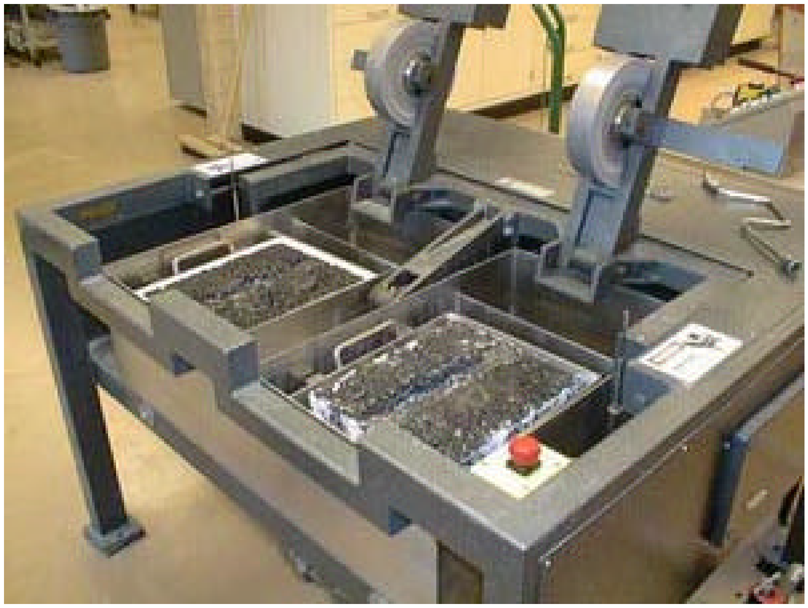

Figure 2.7 Model of HWTD

LCPC (French) Wheel Tracker

The Laboratoire Central des Ponts et Chausées (LCPC) wheel tracker [also known as the French Rutting Tester (FRT)] has been used in France for over 15 years to successfully prevent rutting in HMA pavements. In recent years, the FRT has been used in the United States, most notably in the state of Colorado and FHWA's Turner Fairbank Highway Research Center. The FRT is capable of simultaneously testing two HMA slabs. Slab dimensions are typically 180 mm wide, 50 mm long, and 20 to 100 mm thick (7.1 in x 19.7 in x 0.8 to 3.9in). Samples are generally compacted with a LCPC compactor with tires (18). Loading of samples is accomplished by applying a 5000-N (1124-lb) load onto a 400 x 8 Treb Smooth pneumatic tire inflated to 600 kPa (87 psi). During testing, the pneumatic tire passes over the center of the sample twice per second. Within France, test temperatures for FRT testing are generally 60°C (140°F) for surface courses and 50°C (122°F) for base courses. However, it has been suggested that temperatures lower than

60°C (140°F) can be used for colder regions within the United States. Rut depths within the FRT are defined by deformation expressed as a percentage of the original slab thickness. Deformation is defined as the average rut depth from a series of 15 measurements. These measurements consist of three measurements taken across the width of a specimen at five locations along the length of the slab. A "zero" rut depth is generally defined by loading a sample at ambient temperature for 1,000 cycles.

Figure 2.8 Model of LCPC

Purdue University Laboratory Wheel Tracking Device

As the name states, the PURWheel was developed at PurdueUniversity. PURWheel tests slab specimens that can either be cut from the roadway or compacted in the laboratory. Slab specimens are 290 mm wide by 310 mm long (11.4 in x12.2 in). Thickness of slab samples depends upon the type mixture being tested. For surface course mixes, a sample thickness of 38 mm (1.5 in) is used while binder and base course mixes are tested at thickness of 51 mm and 76 mm (2 in and 3 in), respectively.

Laboratory samples are compacted using a linear compactor also developed by Purdue University. This compactor was based upon a similar compactor owned by Koch Materials in preparing samples for the HWTD. The primary difference being that the Purdue version can compact larger specimens. Samples are compacted to an air void content range of 6 to 8 percent. PURWheel was designed to evaluate rutting potential and/or moisture sensitivity. Test samples can be tested in either dry or wet conditions. Moisture sensitivity is defined as the ratio of the number of cycles to 12.7 mm of rutting in a wet condition to the 12.7 mm of rutting in the dry condition. The 12.7-mm rut depth is used to differentiate between good and bad performing mixes with respect to rutting . Loading of test samples in PURWheel is conducted utilizing a pneumatic tire. A gross contact pressure of 620 kPa (90 psi) is applied to the sample. This is accomplished by applying a 175-kg (385-lb) load onto the wheel that is pressurized to 793 kPa (115 psi). A loading rate of 332 mm/sec is applied. Testing is conducted to 20,000 wheel passes or until 20 mm of rutting is developed. PURWheel is very similar to the HWTD. However, one interesting feature about PURWheel is that it can incorporate wheel wander into testing. This feature is unique among the LWTs common in the United States.

Model Mobile Load Simulator (MMLS3)

The one-third scale MMLS3 was developed recently in South Africa for testing HMA in either the laboratory or field. This prototype device is similar to the full-scale Texas Mobile Load Simulator (TxMLS) but scaled in size and load. The scaled load of 2.1-kN (472-lb) is approximately one-ninth (the scaling factor squared) of the load on a single tire of an equivalent single axle load carried on dual tires. The MMLS3 can be used for testing samples in dry or wet conditions. An environmental chamber surrounding the machine is recommended to control temperature. Temperatures of 50°C and 60°C have been used for dry tests, and wet tests have been conducted at 30°C. MMLS3 samples are 1.2 m (47 in) in length and 240 mm (9.5 in) in width, with the device applying approximately 7200 single-wheel loads per hour by means of a 300-mm (12-in) diameter, 80-mm (3-in) wide tire at inflation pressures up to 800 kPa(116 psi) with a typical value of 690 kPa (100 psi). Wander can be incorporated up to the full sample width of 240 mm. Performance monitoring during MMLS3 testing includes measuring rut depth from transverse profiles and determining Seismic Analysis of Surface Waves moduli to evaluate rutting potential and damage due to cracking or moisture, respectively. Rut depth criteria for acceptable performance are currently being developed (19). Currently there is no standard for laboratory specimen fabrication, although research is being proposed to the Texas Department of Transportation.

2.2.2 Effect of Test Parameters and Mixture Properties on LWT Results

As shown in the previous descriptions on LWTs, all have similar operating principles. Essentially, a load is tracked back and forth over a HMA test sample. Therefore, the effect of various test parameters and material constituents should be similar for each. Following are descriptions of how different test parameters and constituents can affect LWT results. Within the operating specifications for each of the LWTs, two test parameters are always specified: air voids and test temperature. This is primarily due to the fact that these two parameters have the most effect on test results; especially rut depths. As air voids increase, rut depths also increase. Likewise, as test temperature increases, rut depths also increase.

Air void contents for each of the LWTs are generally specified based upon two concepts. First, some believe that specimen air void contents should be approximately 7 percent, since this air void content represents typical as-constructed density. Others believe that test specimens should be compacted to 4 percent air voids, as actual shear failure of mixes usually takes place below approximately 3 percent. Another test parameter that can significantly affect test results is the type and compaction method of test samples. The two predominant "types" of test specimens are cylinders and beams/slabs. For rutting, the literature indicates that the two sample types do provide different rut depths; however, both types generally rank mixes similarly. The primary reason these two types of specimens do not produce the same rut depths is that they are generally compacted by different methods. For instance, cylindrical specimens are typically compacted using the Superpave gyratory compactor while beam samples are generally compacted with a vibratory or kneading compactor. The method of compaction influences the density (air void) gradients and aggregate orientation within samples.

Another test parameter that significantly affects test results is the magnitude of loading. A wide range of loadings are used in the different devices. Although a recent study indicated that small changes in the magnitude of loading may not affect LWT rut results, previous research has shown that significant differences in loadings can affect test results. For rutting, it has been shown that six hours at the test temperature is sufficient. If samples are not preheated sufficiently, low rut depths can be expected. Researchers have compared identical aggregates and gradations but using different binder grades in LWTs. When tested at similar temperatures, mixes containing stiffer grades of asphalt binder will provide lower rut depths. Rutting tends to follow the $G^*/\sin\delta$ of the binder when tested using the Dynamic Shear Rheometer. Another mixture characteristic that affects LWT results is nominal maximum aggregate size. For a given aggregate and binder type, mixes with larger nominal maximum aggregate size gradations tend to provide lower rut depths.

2.2.3 LWT Results Versus Field Performance

Numerous studies have been conducted to compare results of LWT testing to actual field performance. Most of these studies have been to relate LWT rut depths to actual field rutting. In the development of the GLWT, the researchers used four mixes of known fieldrut performance from Georgia. Three of the four mixes had shown a tendency to rut in the field. Results of this work showed that the GLWT was capable of ranking mixtures similar to actual field performance. A similar study conducted in Florida used three mixes of known field performance. One of these mixes had very good rutting performance, one was poor, and the third had a moderate field history. Again, results from the GLWT were able to rank the mixtures similar to the actual field rutting performance. The University of Wyoming and Wyoming Department of Transportation participated in a study to evaluate the ability of the GLWT to predict rutting. For this study, 150-mm cores were obtained from 13 pavements that provided a range of rutting performance. Results showed that the GLWT correlated well with actual field rutting when project elevation and pavement surface types were considered. The effect of elevation on rut depths was most likely due to different climates at respective elevation intervals. The Florida Department of Transportation conducted an investigation with the APA similar to the GLWT study described previously. Again, three mixes of known field performance were tested in the APA. Within this study, however, beams and cylinders were both tested. Results showed that both sample types ranked the mixes similar to the field performance data. A good correlation was found between the APA and the GLWT test results. The authors recommended that the average values within the ranges of 7 to 8mm and of 8 to 9mm may be used as a performance limiting criteria at 8000 cycles for beams and gyratory compacted specimens, respectively. Therefore, the authors concluded that the APA had the capability to rank mixes according to their rutting potential. Studies by Prithvi S.Kandhal and Rajib B.Mallick (15) evaluated the APA for HMA mix design. They found that the APA had a fair correlation (R^2 = 0.62) with the repeated shear constant height test with the shear tester.

The tests on ERSA conducted by the University of Arkansas concluded that the gyratory compacted specimens exhibited significantly lower rut depths than that of the field compacted specimens. The specimen configuration (cylindrical versus prismatic beam) is not a significant factor in performing wheel tracking tests. The study recommended additional testing to establish and validate the relationship between the performance of gyratory compacted and field compacted specimens.

The Colorado Department of Transportation and the FHWA's Turner FairbankHighway Research Center participated in a research study to evaluate the FRT and actual field performance. A total of 33 pavements from throughout Colorado that showed a range of rutting performance were used. The research indicated that the French rutting specification (rut depth of less than 10 percent of slab thickness after 30,000 passes) was too severe for many of the pavements in Colorado. Eleven of 15 sites failed the criteria despite good pavement performance. However, no sites that passed the French specification rutted in the field, and the sites that rutted in the field failed the specification. By reducing the number of passes for low-volume roads and decreasing the test temperature for pavements located in moderate to high elevations (i.e., colder climates), the correlation between the FRT results and actual field rutting was greatly increased.

Another research study by the LCPC compared rut depths from the FRT and field rutting. Four mixtures were tested in the FRT and placed on a full-scale circular test track in Nantes, France. Results showed that the FRT can be used as a method of determining whether a mixture will have good rutting performance. The FHWA conducted a field pavement study at Turner-Fairbank Highway Research Center using an accelerated loading facility (ALF). HMA mixtures were produced and placed over an aggregate base on a linear test section. Three LWTs were used to test mixes placed on the ALF in order to compare LWT results with rutting accumulated under the ALF. The three LWTs were the FRT, GLWT, and HWTD. Based upon this study, the results from the LWTs did not always rank the mixtures similar to the ALF. A joint study by the FHWA and Virginia

Transportation Research Council evaluated the ability of three LWTs to predict rutting performance on mixtures placed at the full-scale pavement study WesTrack. The three LWTs were the APA, FRT, and HWTD. For this research, 10 test sections from WesTrack were used. The relationship between LWT and field rutting for all three LWTs was strong. The HWTD had the highest correlation (90.4%), followed by the APA (89.9%) and FRT (83.4%). Two important criteria were emphasized. The first criterion is the selection of an appropriate test temperature at which the pavement will be expected to perform. The second criterion is the assumption of laboratory compaction simulating field compaction. The authors quoted studies showing discrepancies between the field compaction and several laboratory compaction devices.

Three studies by the Texas Department of Transportation utilized the prototype MMLS3 to determine the relative performance of two rehabilitation processes and establish the predictive capability of this laboratory-scale device. For the first two studies, the MMLS3 tested eight full-scale pavement sections in the field adjacent to sections trafficked with the TxMLS. Field testing combined with additional laboratory testing indicated that one of the rehabilitation processes was more susceptible to moisture damage and less resistant to permanent deformation compared to the second process. This second process was less resistant to fatigue cracking. In addition, a comparison of pavement response under full-scale (TxMLS) and scaled (MMLS3) accelerated loading showed good correlation when actual loading and environmental conditions were considered. An ongoing third study aims to tie MMLS3 results with actual measured performance of four sections at WesTrack. A high testing temperature (60°C) was selected based on the critical temperature for permanent deformation during a 5-day trafficking period during which failure occurred for three of the four sections. Limited laboratory testing using the HWTD and the APA is also included in this study, but only the rankings from HWTD results show good correlation with actual performance. Results indicate that the MMLS3 is capable of correctly ranking performance of the four WesTrack sections.

Studies at NCAT (20) recommended the following tests and criteria for the use of LWT devices for evaluating rutting. The studies considered various factors such as availability of the equipment, cost, test time, applicability for QC/QA, performance data and ease of use.

Performance Tests	Recommended Criteria	Test Temperature
1st choice APA	8mm @ 8000 cycles	High temperature for selected PG grade
2nd choice HWTD	10mm @ 20000 cycles	50°C
3rd choice FRT	10mm @ 30000 cycles	60°C

Based upon review of the laboratory wheel tracking devices and the related literature detailing the laboratory and field research projects, the following observations are provided.

*Both cylindrical and beam specimens, depending upon the type of wheel tracking device, can be used to rank mixtures with respect to rutting.

*Results obtained from the wheel tracking devices seem to correlate reasonably well to actual field performance when the in-service loading and environmental conditions of that location are considered.

*The wheel tracking devices seem to reasonably differentiate between performance grades of binders.

*Wheel tracking devices, when properly correlated to a specific site's traffic and environmental conditions, have the potential to allow the user agency the option of a pass/fail or "go/no go" criteria. The ability of the wheel tracking devices to adequately predict the magnitude of the rutting for a particular pavement has not been determined at this time.

CHAPTER 3

MIXTURE INFORMATION

This chapter describes the mixtures used in this study. The mixture description includes the information about the field specimens and the loose mixtures and their properties used in this study. Four mixtures were used in this study. They were designated as Auburn Coarse, Auburn Fine, Charlotte and Kinston mixtures.

3.1 Field Specimens

The field specimens included field cores and field slabs. The location and the total number of test sites were selected after consultation with NCDOT. Four test sites were selected in such a way that each test site had a different type of aggregate gradation (coarse or fine) and a nominal maximum size of aggregate (12.5mm or 9.5mm). The pavement locations were Auburn NCAT research tracks (Auburn Coarse and Auburn Fine), Matthews county (Charlotte) and Kinston County (Kinston) in North Carolina. The aggregates used in these mixtures are from the quarries of North Carolina. These sites were the pavements that contained SUPERPAVE volumetrically designed mixtures being used in either new or overlay construction.

Field cores consisted of cylindrical specimens of 150mm diameter with varying heights. Field cores were taken from all four locations. The cores were catalogued as AC (Auburn Coarse), AF (Auburn Fine), C (Charlotte) and K (Kinston). The field cores were then used for shear tests and APA tests. The cores were sawed to a thickness of 50mm and

75mm for shear tests and APA tests, respectively. However, the thickness of field cores for Kinston mixtures was slightly lesser than 75mm. So 70mm thick field cores were used in APA tests only for the Kinston mixture. The bulk densities of the field cores were carefully measured using the conventional water displacement method. Table 3.1 shown below gives the average bulk specific gravity of field cores with their corresponding range of values.

Table 3.1 Bulk Specific Gravity

Mixture	Average BSG	Range
Auburn Coarse	2.362	2.336 to 2.365
Auburn Fine	2.374	2.363 to 2.385
Charlotte	2.369	2.347 to 2.415
Kinston	2.268	2.262 to 2.273

For a meaningful comparison of the effect of different compaction methods, the loose mixtures that were compacted using the laboratory compaction methods were compacted to the corresponding specific gravities given in Table 3.1.

Field slabs were available only from the Kinston and the Charlotte sites. Field slabs could not be obtained from the Auburn NCAT research tracks. The slab thickness was 100mm and 75mm for Charlotte and Kinston mixtures, respectively. The slabs were cut to the desired dimensions and were used for rut tests using NCSU Wheel Tracking Device.

3.2 Loose Mixtures

The mixtures from the test sites were provided as loose mixtures by NCDOT. The loose mixtures were used to fabricate specimens in laboratory for further evaluation. These mixtures were heated to the appropriate compaction temperatures for specimen fabrication. The Superpave Gyratory Compactor and the NCSU WTD rolling wheel compactor were used for fabricating cylindrical and slab specimens, respectively. The compaction of slabs using the NCSU WTD roller compactor is discussed in Chapter 5. Cylindrical specimens, cored from rolling wheel compacted slabs and as well as those fabricated using the SGC were used for shear tests and APA tests. The slabs were tested using NCSU WTD for evaluating the rutting characteristics. The loose mixtures were also used to evaluate the compaction characteristics using the SGC and the GLPA.

The maximum theoretical specific gravity was determined for all the four mixtures. The mixtures were compacted to the corresponding average bulk densities of the field cores. In addition to this, in order to rank the performance of individual mixtures, specimens were compacted to 4 percent air voids using the SGC for shear tests. Table 3.2 gives the information about the G_{mm} values and percent air voids for the mixtures compacted using the SGC and the NCSU WTD rolling wheel compactor.

Table 3.2 Target Bulk Densities and Air Voids of Mixtures

Mixture	G_{mm}	Target G_{mb}	Percent Air
Auburn Coarse	2.498	2.362	5.4
Auburn Fine	2.477	2.374	4.2
Charlotte	2.563	2.369	7.6
Kinston	2.419	2.268	6.2

3.3 Characteristics of Mixtures

The individual characteristics of mixtures are discussed in the following subsections. The information about the mixtures as provided by the NCDOT is also presented in here.

3.3.1 Auburn Coarse

This mixture was from the test tracks of NCAT, Auburn. The NCDOT was the contractor for the North Carolina test sections of this project. This was a surface mix with 12.5mm nominal maximum size of aggregates with a gradation below the restricted zone. The coarse gradation of this mixture is shown in Figure 3.1. The source of aggregates was from Martin Marietta, Jamestown, NC. The effective specific gravity of the aggregates was 2.709. The grade of asphalt binder used was PG 67-22 with a specific gravity of 1.029. This mixture was designed for a traffic level of 10 to 30 Million ESALs. Gyration levels used were 8/100/160. The compaction temperature of this mixture was 155^{o}C. Table 3.3 summarizes the characteristics of the mixture.

Table 3.3 Information about Auburn Coarse Mixture

% Asphalt Binder	5.3
G_{mb} @ Ndes	2.421
Max. Sp.Gr (G_{mm})	2.496
% Voids – Total Mix (VTM)	3.0
% Solids – Total Mix	97.0
% Effective AC content (P_{be})	4.8
Dust to AC Ratio ($P_{0.075}/P_{be}$)	0.90
% Voids in Mineral Agg. (VMA)	14.3
% Voids filled with AC (VFA)	79.0
$\%G_{mm}$ @ N_{ini} 8	89.2
$\%G_{mm}$ @ N_{des} 100	96.5
$\%G_{mm}$ @ N_{max} 160	97.0

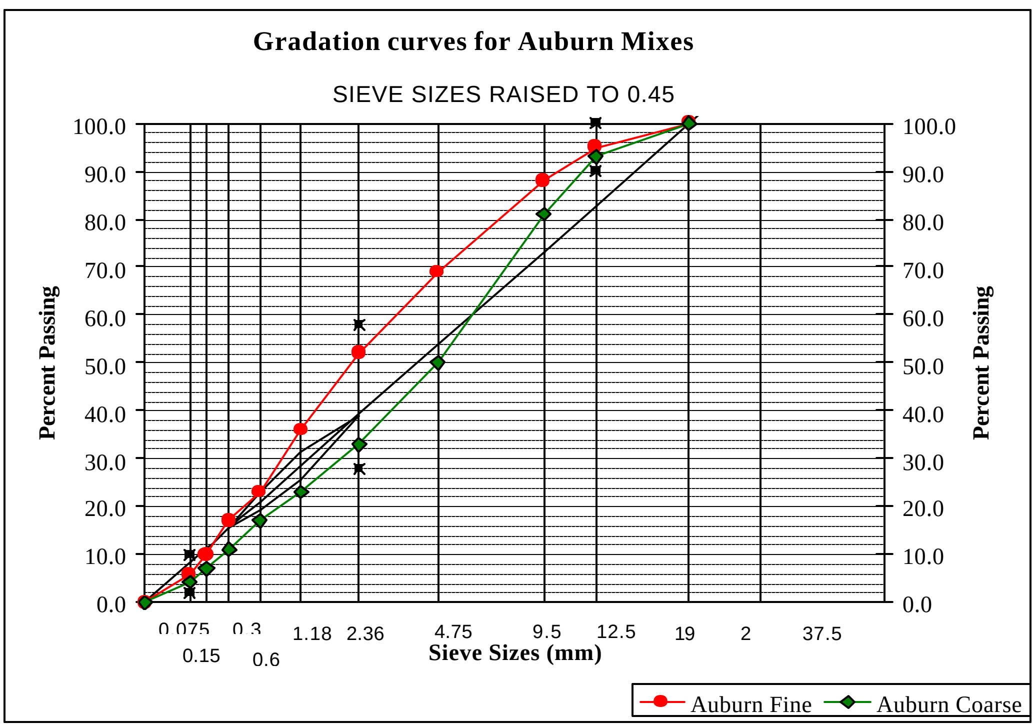

Figure 3.1 Gradation Curves for 12.5mm Auburn Mixtures

3.3.2 Auburn Fine

This mixture was also from the test tracks of NCAT, Auburn. This mixture was similar to Auburn Coarse mixture but with a finer gradation. This was a surface mix with 12.5mm nominal maximum size of aggregates with a gradation above the restricted zone. The fine gradation of this mixture is shown in Figure 3.1. The source of aggregates was from the Martin Marietta quarry, Jamestown, NC. The effective specific gravity of the aggregates was 2.713. The grade of asphalt binder used was PG 67-22 with a specific gravity of 1.029. This mixture was designed for a traffic level of 10 to 30 Million ESALs. Gyration levels used were 8/100/160. The compaction temperature for this mixture was 155^{o}C. Table 3.4 summarizes the characteristics of the mixture.

Table 3.4 Information about Auburn Fine Mixture

% Asphalt Binder	5.3
G_{mb} @ Ndes	2.421
Max. Sp.Gr (G_{mm})	2.508
% Voids – Total Mix (VTM)	4.0
% Solids – Total Mix	96.0
% Effective AC content (P_{be})	4.8
Dust to AC Ratio ($P_{0.075}/P_{be}$)	1.21
% Voids in Mineral Agg. (VMA)	14.6
% Voids filled with AC (VFA)	72.0
%G_{mm} @ N_{ini} 8	88.4
%G_{mm} @ N_{des} 100	96.0
%G_{mm} @ N_{max} 160	97.0

3.3.3 Charlotte

This mixture was from the pavement structures constructed in Matthews County of North Carolina. The Rea Construction Co was the contractor for this project. This was a surface mix with 9.5mm nominal maximum size of aggregates with a gradation below the restricted zone. The coarse gradation of this mixture is shown in Figure 3.2. The source of aggregates was from the Martin Marietta quarry, Matthews, NC. The effective specific gravity of the aggregates was 2.789. The grade of asphalt binder used was PG 64-22 with a specific gravity of 1.03. This mixture was designed for a traffic level less than 3 Million ESALs. Gyration levels used were 7/75/115. The compaction temperature for this mixture was 149^{o}C. Table 3.5 summarizes the characteristics of the mixture.

Table 3.5 Information about Charlotte Mixture

% Asphalt Binder	5.9
G_{mb} @ Ndes	2.433
Max. Sp.Gr (G_{mm})	2.534
% Voids – Total Mix (VTM)	4.0
% Solids – Total Mix	96.0
% Effective AC content (P_{be})	5.6
Dust to AC Ratio ($P_{0.075}/P_{be}$)	1.14
% Voids in Mineral Agg. (VMA)	17.1
% Voids filled with AC (VFA)	77.2
%G_{mm} @ N_{ini} 7	86.6
%G_{mm} @ N_{des} 75	96.0
%G_{mm} @ N_{max} 115	97.7

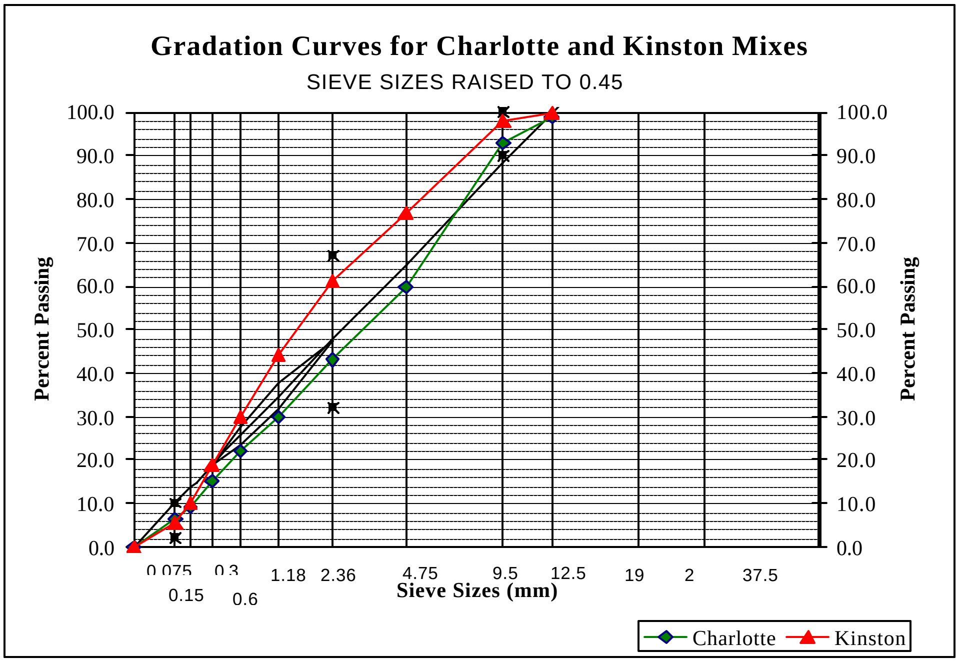

Figure 3.2: Gradation Curves for 9.5mm Mixtures (Charlotte and Kinston)

3.3.4 Kinston

This mixture was from the pavement structures constructed in Kinston County of North Carolina. The contractor of this project was APAC – Carolina (Barrus). This mixture was a surface mix with 9.5mm nominal maximum size of aggregates with a gradation above the restricted zone. The fine gradation of this mixture is shown in Figure 3.2. The sources of aggregates were from the Martin Marietta quarry, Fountain and Clarke, NC. The natural sand and baghouse fines were from Barrus, Whitfield .The effective specific gravity of the aggregates was 2.667. The grade of asphalt binder used was PG 64-22 with a specific gravity of 1.03. This mixture was designed for a traffic level less than 3 Million ESALs. Gyration levels used were 7/75/115. The compaction temperature for this mixture was 144^{o}C. Table 3.6 summarizes the characteristics of the mixture.

Table 3.6 Information about Kinston Mixture

% Asphalt Binder	6.1
G_{mb} @ Ndes	2.334
Max. Sp.Gr (G_{mm})	2.431
% Voids – Total Mix (VTM)	4.0
% Solids – Total Mix	96.0
% Effective AC content (P_{be})	5.3
Dust to AC Ratio ($P_{0.075}/P_{be}$)	1.06
% Voids in Mineral Agg. (VMA)	15.8
% Voids filled with AC (VFA)	76
%G_{mm} @ N_{ini} 7	89.0
%G_{mm} @ N_{des} 75	96.0
%G_{mm} @ N_{max} 115	97.2

The information provided in this chapter was furnished by the NCDOT. The mixtures were compacted in the laboratory using the SGC to verify the above information. The densification information and the compaction characteristics evaluated in the laboratory are discussed in Chapter 4.

CHAPTER 4

COMPACTION CHARACTERISTICS OF MIXTURES

The compactability of a mixture can be evaluated by the densification information generated using the Superpave Gyratory Compactor (SGC) and the Gyratory Load Cell Plate Assembly (GLPA). This section describes the compaction characteristics of all the four mixtures included in this study.

4.1 Superpave Gyratory Compactor

The primary device used in Superpave mix design is the Superpave Gyratory Compactor (SGC). The SGC is used to produce specimens for volumetric analysis, and it also records data to provide a measure of specimen density throughout the compaction procedure.

SHRP researchers had several goals in developing a laboratory compaction method (21). Most importantly, they wanted to realistically compact mix specimens to densities achieved under actual pavement climate and loading conditions. The compaction device needed to be capable of accommodating large aggregates. They also wanted the compactor to be able to measure compactability so that potential tender mix behavior and similar compaction problems could be identified. A high priority for SHRP researchers was a device portable enough for use in mixing facility for quality control operations. Since no existing compactor achieved all these goals, the SGC was developed.

The SGC consists of three components:

- reaction frame, rotating base, and motor
- loading system, loading ram, and pressure gauge
- height measuring and recording system
- mold and base plate

A loading mechanism presses against the reaction frame and applies a load to the loading ram to produce a 600 kPa compaction pressure on the specimen. A pressure gauge measures the ram loading to maintain constant pressure during compaction. The SGC mold has an inside diameter of 150mm and a base plate in the bottom of the mold provides confinement during compaction. The SGC base rotates at a constant 30 gyrations per minute during compaction with the mold positioned at a compaction angle of 1.25 degrees.

Specimen height measurement is an important function of the SGC. Specimen density can be estimated during compaction by knowing the mass of material placed in the mold, the inside diameter of the mold, and the specimen height. Height is measured by recording the position of the ram throughout the test. Using these measurements, a specimen's compaction characteristics are developed.

4.2 SGC Compaction of Mixtures

The loose mixtures were compacted in the laboratory not only to evaluate the compaction characteristics of the mixtures but also to establish the parameters such as "correction factors" for fabricating specimens at the average bulk densities of the respective field cores. The compacted specimens were used for shear tests and APA tests. The loose mixtures were heated and mixed thoroughly. The amount of mixture was sampled out for compaction of mixture specimens (approximately 4800g for one specimen). These were field mixtures and therefore they were aged before compacting. The mixtures were heated at their corresponding compaction temperatures. The mixtures were placed in the mold and compacted using the SGC. Compaction proceeded until Nmax had reached. Specimen height was continually monitored during compaction and a height measurement was recorded after each gyration. Table 4.1 gives the compaction temperature and desired levels of gyrations for each mixture.

Table 4.1 : Levels of Gyrations and Compaction Temperatures

Mixture	NMSA, mm	Gradation	Temperature	$\mathbf{N_{ini}}$	N_{des}	N_{max}
Auburn Coarse	12.5	Coarse	155 ^{o}C	8	100	160
Auburn Fine	12.5	Fine	155 ^{o}C	8	100	160
Charlotte	9.5	Coarse	149 ^{o}C	7	75	115
Kinston	9.5	Fine	144 ^{o}C	7	75	115

4.2.1 Compaction Characteristics

The compaction data was analyzed by computing percent G_{mm} values for each level of gyration. Percent G_{mm} values at different levels of gyrations (N_{ini}, N_{des} and N_{max}) were calculated. Superpave volumetric mix design characteristics such as VMA, VFA were determined. Table 4.2 gives the compaction summary of all the four mixtures.

Table 4.2: Compaction Summary

Mixture	%G_{mm}@ N_{des}	%Voids	%G_{mm}@ N_{ini}	%G_{mm}@ N_{max}	%VMA	%VFA
Auburn Coarse	96.67	3.03	88.36	98.01	14.44	72.29
Auburn Fine	97.38	2.62	90.23	98.33	14.88	73.12
Charlotte	93.68	6.32	86.24	94.75	17.76	77.48
Kinston	95.15	4.85	89.41	95.57	16.38	75.59

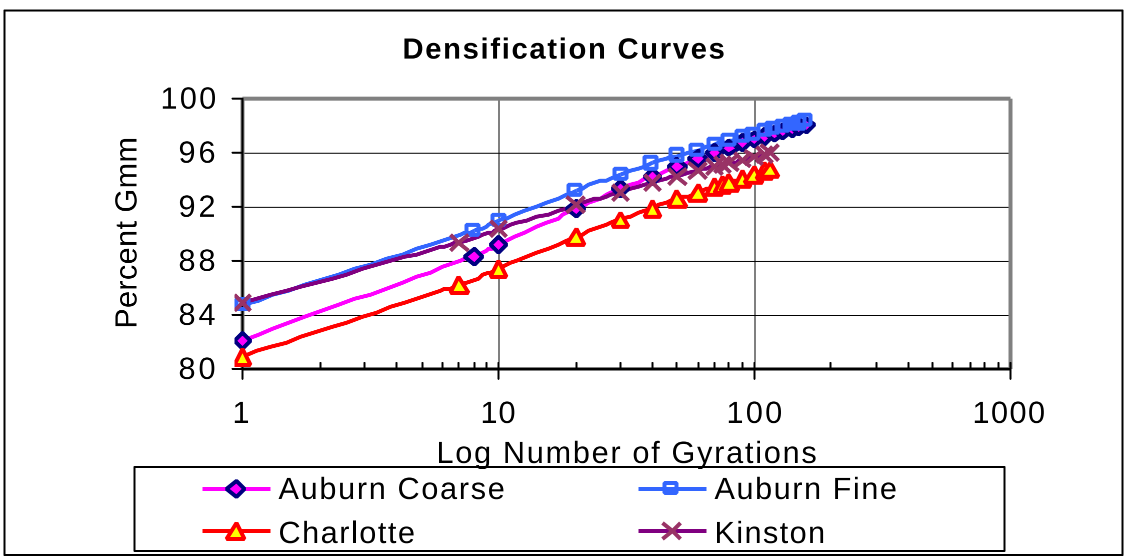

Figure 4.1 Densification Curves of Mixtures

Figure 4.1 shows the densification characteristics of each mixture. Percent G_{mm} values were plotted against the corresponding gyrations on a logarithmic scale. A logarithmic regression for percent G_{mm} was performed for each curve with number of gyration (N) as predictor variable. Table 4.3 shows the regression equation for each mixture with the corresponding R^2 values.

Table 4.3: Regression Equation of Compaction Curves

Mixture	Equation	R^2
Auburn Coarse	%Gmm = 3.2132 ln(N) + 82.104	0.9966
Auburn Fine	%Gmm = 2.7095 ln(N) + 84.899	0.9963
Charlotte	%Gmm = 2.9669 ln(N) + 80.816	0.9985
Kinston	%Gmm = 2.3514 ln(N) + 85.429	0.9986

It was found from the densification curves and compaction summary that none of the mixtures had the recommended 4 percent air voids at N_{des}. The air voids level was closer to 4 percent criterion for the Kinston mixture. The percent air values at N_{des} were only around 2 percent for the Auburn mixtures. The percent air at N_{des} was above 6 percent for the Charlotte mixtures. The compaction characteristics of the Auburn coarse and fine mixtures were almost similar. They seemed to be easier to compact than other mixtures. The Charlotte mixture was the most difficult mixture to compact among all the mixtures.

A noteworthy characteristic in the evaluation of Superpave mixtures is the slope of the compaction curve (k_{SGC}), percent G_{mm} versus log N(22). The compaction slope is an indication of an aggregate structure's resistance to compaction. Since the SGC operates as a gyratory shear compactor, the slope of the compaction curve might be considered related to the shear resistance of the aggregate structure. The slope of the compaction curve is calculated by considering the percent G_{mm} values between the gyrations 10 to 100. The values of k_{SGC} are given in Table 4.4.

Table 4.4 : Compaction Slope of Mixtures

Mixture	%G_{mm} @ N=10	%G_{mm} @ N=100	k_{SGC}
Auburn Coarse	89.22	96.97	7.75
Auburn Fine	90.97	97.38	6.41
Charlotte	87.32	94.16	6.84
Kinston	90.79	96.11	5.32

The Auburn Coarse mixture had the highest compaction slope whereas Kinston mixture had the lowest compaction slope. A mixture with higher compaction slope is expected to offer more resistance to compaction. The slopes of the Auburn Fine mixture and the Charlotte mixture are closer to each other. It appears that the Auburn Coarse mixture had the highest shear resistance and Kinston mixture had the lowest shear resistance among all the mixtures.

Another characteristic in the evaluation of Superpave mixture is the Gyration Ratio (GR) (23). The Gyration Ratio is the ratio of the number of gyrations by the SGC to achieve 95 percent G_{mm} to the number of gyrations to achieve 98 percent G_{mm}. This ratio actually gives an indication of the change of stiffness of the mixture between 5 and 2 percent air voids. Table 4.5 shows the values of GR for each mixture.

Table 4.5: Gyration Ratio of Mixtures

Mixture	N for 95%G_{mm}	N for 98%G_{mm}	GR
Auburn Coarse	50	160	3.20
Auburn Fine	37	132	3.56
Charlotte	119*	328*	2.76
Kinston	55	210*	3.82

* Extrapolated from the regression equation given in Table

The Charlotte mixture did not reach 95% G_{mm} at N_{max}. So it was assumed that the mixture would reach the above percent G_{mm} values at the extrapolated number of gyrations. The same was applied for Kinston mixture. It should be borne in mind that the extrapolated N values are based only on the logarithmic regression fit of the densification information obtained from the SGC. Based on the number of gyrations that a mixture took to reach the desired compaction level (95%Gmm or 98%Gmm), it was found that the Auburn mixtures were easier to compact and the Charlotte mixture was the difficult mixture to compact, followed by the Kinston mixture.

4.2.2 Compaction using Pine SGC

For computing the energy indices using the SGC and the GLPA, the compaction of the mixtures was done using Pine SGC and GLPA. In addition to the computation of energy indices, the percent G_{mm} values at initial, design and maximum levels of gyrations are calculated. Table 4.6 gives the values of percent G_{mm} at different levels of gyrations.

Table 4.6 Compaction Summary (Pine SGC)

Mixture	$\%G_{mm}@ N_{des}$	%Voids	$\%G_{mm}@ N_{ini}$	$\%G_{mm}@ N_{max}$
Auburn Coarse	97.06	2.94	88.20	98.16
Auburn Fine	96.92	3.08	89.36	97.92
Charlotte	93.68	6.32	87.71	94.60
Kinston	95.15	4.85	87.34	96.30

It should be noted that the compaction summary of the mixtures provided by the NCDOT does not agree with the compaction results obtained at NCSU. The compaction parameters of the mixtures measured using the Troxler SGC and the Pine SGC agreed with each other. Moreover through out this study, the specimens compacted at target air voids were found to be the same when the compaction parameters measured at NCSU were used for calculations. So it can be said that the compaction summary given in Table 4.2 is found to be accurate though it does not conform to the information provided by the NCDOT.

4.3 Gyratory Load Cell Plate Assembly

Measurement of mechanical properties 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 (24).

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.

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 from the energy spent in distortion. The distortion energy is believed to be related to the resistance of the mixture to rutting under traffic.

4.3.1 Description of GLPA

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 the 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 4.2

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.

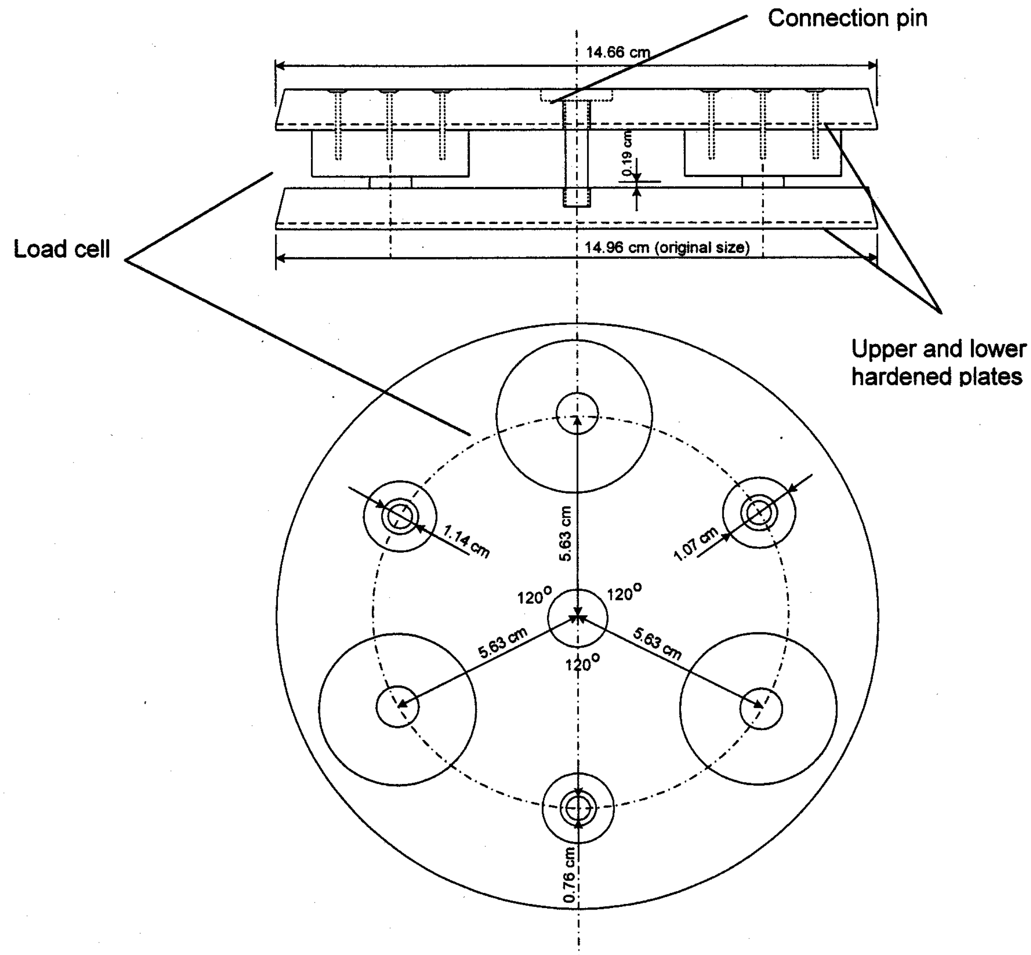

Figure 4.2 Gyratory Load Plate Assembly

4.4 Energy Indices

The performance of HMA can be divided into two parts, performance during construction and performance under traffic loading (25). 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. 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 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 areas under the densification curve between selected reference points are related to the actual field construction and in-service conditions as indicators of mixture suitability for construction and performance under traffic. The energy indices are calculated by integrating the area under the densification curve between any two given points.

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. This effort is the work applied by the pavers/rollers to compact the mix to the required density during construction. The initial in-place density behind the paver is not constant and depends on the characteristics of the mix. The initial density after the rolling operation (at the end the construction) is well defined at a certain air voids level. Many specifications require that the pavement be compacted to approximately 92 percent of Gmm for acceptance. The energy that the contractor must expend in compacting the mix from its initial density to the required density at the end of rolling is estimated by these indices. Mixes that require lower compaction energy are desirable.

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 4.3. These indices represent the total effort required to compact the mixture to a terminal density of 98 percent Gmm. The 98 percent Gmm is considered the critical density condition at which the mix is within the plastic failure zone. Mixtures with higher traffic indices are more desirable because they are expected to require more traffic to densify at that point. It should be noted that there exists a strong correlation within the two construction indices (CDI & CFI) and the two traffic indices (TDI & TFI). The Densification indices (CDI & TDI) are measured using the SGC and the Force indices (CFI & TFI) are measured using the GLPA.

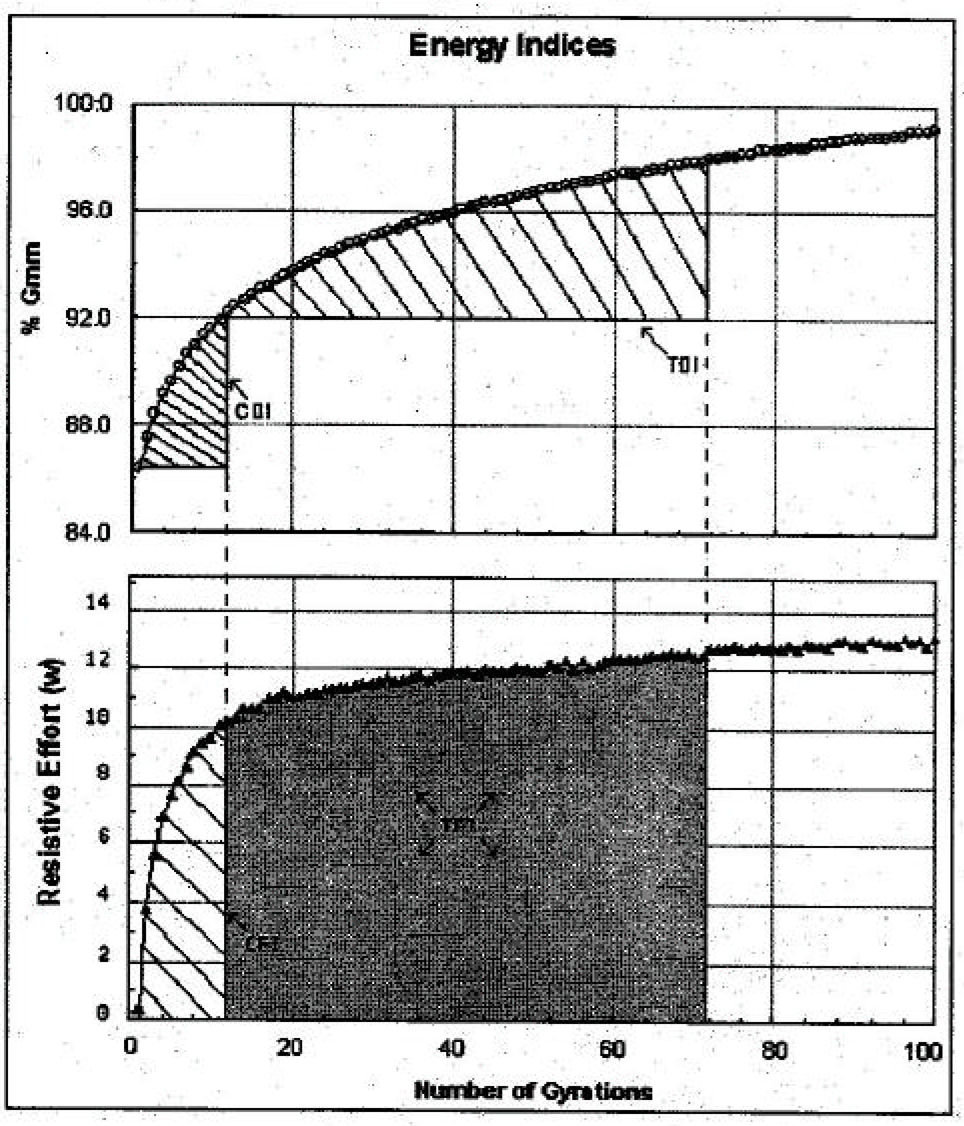

Figure 4.3 Energy Indices (CDI, CFI,TDI,TFI)

The resultant force, which is measured by the load cells, can be used to explain the behavior of the mixtures. The average values of the amplitude of the load carried by three load cells are shown in Figure 4.4. The plot shows the maximum and minimum load carried by the load cells for each of the mixtures. The maximum load cell amplitude of the mixtures is given in Table 4.7.

Table 4.7 Maximum Amplitude carried by the Load Cells

Mixture	Max. Amplitude (kN)
Auburn Coarse	7.64
Auburn Fine	7.33
Charlotte	7.38
Kinston	7.64

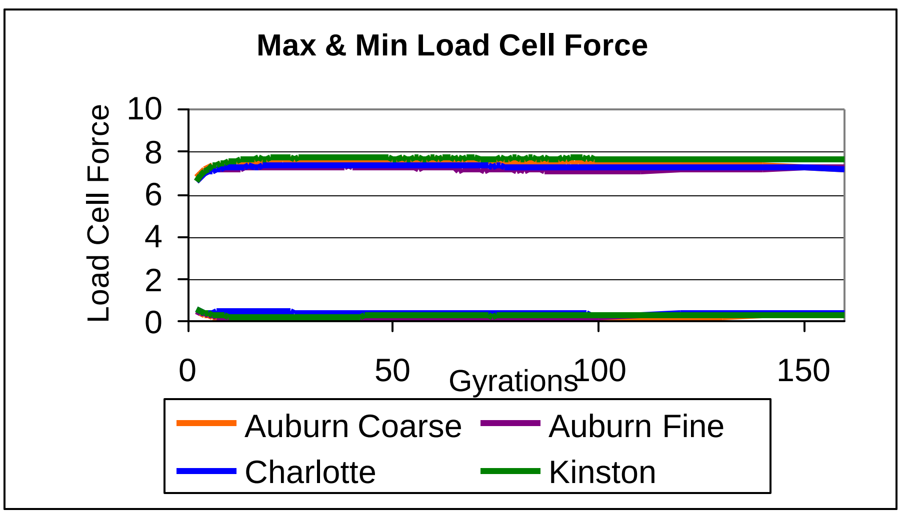

Figure 4.4 Maximum and Minimum Load Cell Amplitudes of Mixtures

The load cell amplitudes of all the mixtures were in a narrow range. Moreover, it was observed that the load cell force had a minor change with increasing gyrations. This indicates that the mixtures maintained this level of frictional resistance throughout the test. These trends indicated that no significant difference existed among mixtures as their maximum load cell force and the rate of change of load cell forces was almost the same. So it is believed that the GLPA is not sensitive enough to detect the difference among the mixtures when the aggregate sources were different.

Table 4.8 presents the energy indices for all the mixtures. Figures 4.5 and 4.6 present the comparison of construction indices and traffic indices.

Table 4.8 Energy Indices

Mixture	CDI	TDI	CFI	TFI
Auburn Coarse	163	550	257	1561
Auburn Fine	118	600	203	1331
Charlotte	270	2143*	439	7080*
Kinston	211	1078	333	3461

*Need to extrapolate the TEI and TFI to 98% Gmm since the mix never reached the final density after 600 gyrations.

The Charlotte mixture had the highest values for all the indices, followed by the Kinston mixture. Among the 12.5mm mixtures, the Auburn Coarse mixture had the lower TDI whereas the Auburn Fine had the higher TDI. Energy indices can be compared among mixtures only if the mixtures have the same aggregate source.

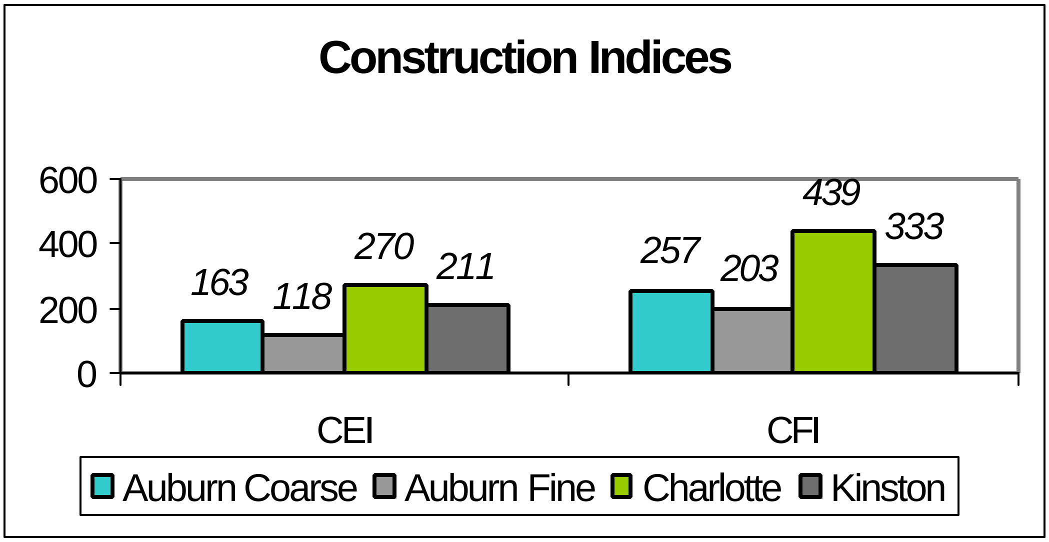

Figure 4.5: Construction Indices

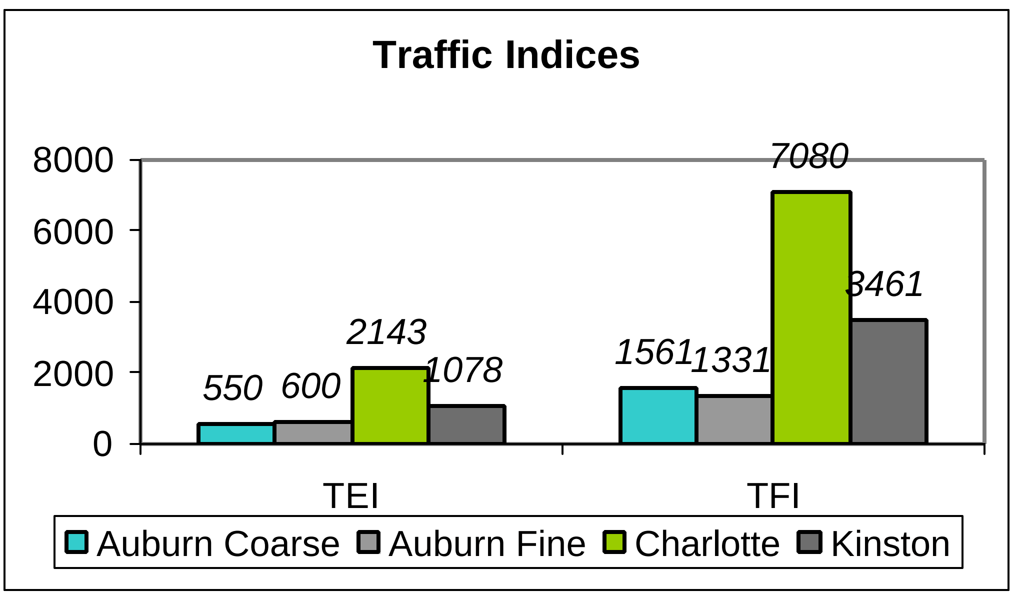

Figure 4.6: Traffic Indices

A review of the construction indices suggested that the Auburn Fine mixture would require less energy for compaction than other mixtures. The Auburn Fine mixture was the most desirable for compaction during construction, followed by the Auburn Coarse and the Kinston. The Charlotte mixture would require greater energy than the other mixtures.

Lower construction indices and higher traffic indices are desirable for selecting an optimum mixture for constructability and resistance to traffic. This trend is not seen in the Kinston and the Charlotte mixtures, as the sources of the aggregates used in the mixtures were not the same. However, the Auburn mixtures seemed to be comparable, as their sources of the aggregates remained the same. The Auburn Fine mixture had the lower CDI and higher TDI when compared to the Auburn Coarse mixture, which further indicated that the Auburn Fine mixture would perform better than the Auburn Coarse mixture.

Higher traffic indices indicate longer rut life as it is expected that the mixture would require more traffic to reach their terminal density (11). Before comparing these indices to evaluate the performance of the mixture under traffic, the explanation given in the succeeding paragraphs should be taken into account.

Auburn mixtures were compacted to 160 gyrations whereas the Charlotte and Kinston mixtures were compacted to 600 gyrations. As per the definition, the construction indices are the integration of the area under the densification curve between the first gyration and the 92% G_{mm}. On the other hand, the traffic indices are the integration of the area under the densification and resistive work curves between 92%G_{mm} and 98% G_{mm}.

Figure 4.7 shows the densification curves for the mixtures.

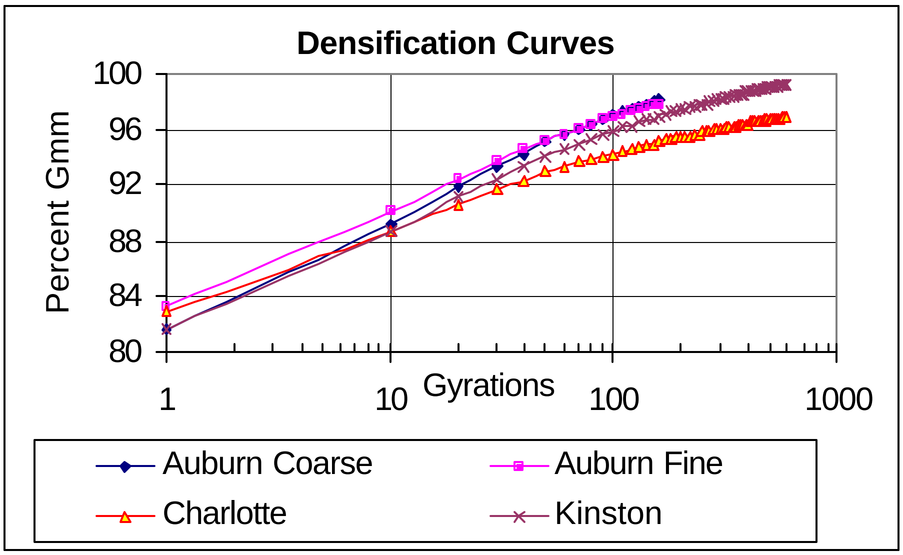

Figure 4.7 Densification Curves of Mixtures

It can be noted from the densification curves shown in Figure 4.7 that only the Auburn mixtures reached their 98 percent of maximum density in 160 gyrations. Charlotte and the Kinston mixtures did not reach their 98 percent of maximum density in Nmax (115 gyrations). So in order to make the mixtures reach the 98 percent of maximum density, these mixtures had been compacted to 600 gyrations. The Kinston mixture reached its 98 %Gmm around 270 gyrations. The Charlotte mixture did not reach its 98 % Gmm even after 600 gyrations. So the traffic indices were calculated by extrapolation. The reason for very high values of traffic indices for the Charlotte and the Kinston mixtures is that these mixtures took more number of gyrations than the Auburn mixtures.

Brian J.Coree and Kera VanDerHorst (10) argue that the resulting compaction curve cannot be considered to be fully representative of the compaction history of an in-service mixture. The temperature of the mixture is typically in the range of 80^{o}C to 200^{o}C during construction. The greater part of compaction is achieved while the asphalt mixture is in excess of 115^{o}C. The mixture never reaches such a high temperature in-service. Under operating conditions under traffic, the mixture temperature may reach in the range indicated by the PG X-Y grade of the binder. In the laboratory, mixtures are compacted at an equi-viscous temperature through out the compaction process.

Moreover, the lateral plastic flow developed in a pavement rutting is totally prevented during the compaction, as the walls of the mold are well confined and rigid. Thus the laboratory compaction is reasonable representation of the construction compaction conditions, but not of in-service conditions.

So these concerns about the traffic indices limit the evaluation of mixtures only to the constructability of the mixtures. In this study, the rutting characteristics of the mixtures are not inferred from the traffic indices. The rutting characteristics of the mixtures are discussed in Chapter 5.

CHAPTER 5

PERFORMANCE EVALUATION OF MIXTURES

The effect of different compaction methods on the performance of the mixtures was evaluated using the Simple Shear Tester, Asphalt Pavement Analyzer (APA), NCSU Wheel Tracking Device and GLPA. In addition, the results of the different test systems helped in evaluating accelerated test devices like the APA and the NCSU WTD in comparison with fundamental tests like Simple Shear tests.

5.1 Performance Evaluation using the Simple Shear Tester

Shear tests were performed in accordance with AASHTO TP7 Procedures E and F (26). The tests included Frequency Sweep test at Constant Height (FSCH) and Repeated Shear test at Constant Height (RSCH). These tests were conducted on the field cores (FC), Superpave gyratory compacted specimens (SGC), and rolling wheel compacted specimens (RWC). Field mixtures were compacted to the corresponding field densities and the tests were performed at the bulk densities of the field cores. The test results were then used to perform an analysis of a representative pavement structure to investigate the effect on the predicted field performance.

5.1.1 Specimen Preparation

The specimens prepared for FSCH and RSCH tests were 150mm (6-in.) in diameter. The specimens were sawed to a thickness of 50 mm (2-in.). The specific gravities of the specimens were measured. The specimens were then glued between the loading platens using the ‘DEVCON’ 5 minute plastic putty and were allowed to cure for several hours before testing.

5.1.2 Selection of Test Temperature for FSCH and RSCH

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 a mix to fatigue cracking is calculated based on the mix properties evaluated using FSCH at 20^{o}C.

The seven-day average high pavement temperature at 50-mm depth from pavement surface at 98% reliability was estimated using SHRPBIND version 2.0 software for three different locations - Auburn (AL), Charlotte (NC) and Kinston (NC). RSCH tests were conducted on field cores at these temperatures. The testing temperatures for each mixture are summarized in Table 5.1.

Table 5.1 Testing Temperatures

Mix	FSCH	RSCH
Auburn – Coarse	20	54.1
Auburn Fine	20	54.1
Charlotte	20	51.9
Kinston	20	50.8

5.1.3 Frequency Sweep Test at Constant Height

This test is performed to measure linear visco-elastic 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 order of frequencies is 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 are 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. Four mixtures viz, Auburn Coarse, Auburn Fine, Charlotte and Kinston were tested at a temperature of 20^{o}C. 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)

5.1.3.1 Analysis of FSCH Test Results

Figures 5.1 to 5.3 show the results of frequency sweep tests for all the mixtures. The figures show the dynamic shear modulus (G*) as a function of frequency at 20^{o}C. The figures are plotted for the mixtures according to their method of compaction. Tables 5.2

to 5.5 compare the G* values and the corresponding phase angles of different mixtures and compaction methods. Figure 4 shows a bar chart that compares the G* values of the compaction methods for all the four mixtures.

Table 5.2 Results of Frequency Sweep Tests – Auburn Coarse (12.5mm Below RZ)

Freq (Hz.)	**Average G* (Pa)/Phase Angle(Deg)**		
	Field Cores	**Rolling Wheel Compaction**	**Gyratory Compaction**
0.01	1.59E+08/48.95	2.13E+08/42.20	1.71E+08/42.60
0.02	2.28E+08/46.71	2.81E+08/39.57	2.31E+08/40.88
0.05	3.68E+08/42.61	4.01E+08/31.21	3.19E+08/34.36
0.1	5.10E+08/40.06	6.84E+08/35.72	5.68E+08/40.75
0.2	7.12E+08/35.63	9.18E+08/30.03	7.92E+08/36.26
0.5	9.82E+08/27.92	1.20E+09/24.86	1.06E+09/29.99
1	1.45E+09/22.25	1.54E+09/14.00	1.52E+09/22.09
2	1.76E+09/21.84	1.65E+09/18.58	1.62E+09/22.76
5	2.02E+09/18.76	2.18E+09/12.50	2.10E+09/18.98
10	2.30E+09/16.32	2.42E+09/8.95	2.39E+09/16.94

Table 5.3 Results of Frequency Sweep Tests – Auburn Fine (12.5mm Above RZ)

Freq (Hz.)	Average G* (Pa)/Phase Angle(Deg)		
	Field Cores	Rolling Wheel Compaction	Gyratory Compaction
0.01	1.55E+08/43.85	3.16E+08/34.73	1.69E+08/46.14
0.02	1.99E+08/41.98	4.08E+08/31.59	2.32E+08/44.85
0.05	2.81E+08/36.81	5.59E+08/26.25	3.59E+08/40.41
0.1	4.32E+08/40.84	7.91E+08/27.79	5.98E+08/42.09
0.2	5.89E+08/37.42	1.01E+09/23.98	9.18E+08/36.35
0.5	8.07E+08/30.30	1.23E+09/19.15	1.20E+09/27.02
1	1.13E+09/27.12	1.61E+09/14.38	2.04E+09/19.14
2	1.25E+09/23.62	1.86E+09/16.39	1.89E+09/21.46
5	1.69E+09/21.56	2.19E+09/11.74	2.66E+09/18.14
10	1.96E+09/18.73	2.40E+09/10.85	2.98E+09/13.27

Table 5.4 Results of Frequency Sweep Tests – Charlotte (9.5mm Below RZ)

Freq (Hz.)	Average G* (Pa)/Phase Angle(Deg)		
	Field Cores	Rolling Wheel Compaction	Gyratory Compaction
0.01	3.78E+07/46.27	7.13E+07/46.43	8.73E+07/41.46
0.02	4.86E+07/48.22	9.44E+07/44.83	1.11E+08/40.98
0.05	7.04E+07/48.12	1.36E+08/42.52	1.53E+08/36.54
0.1	1.04E+08/49.12	2.21E+08/43.53	2.58E+08/43.67
0.2	1.44E+08/48.14	2.98E+08/41.79	3.44E+08/42.00
0.5	2.31E+08/46.12	4.46E+08/37.90	5.09E+08/37.55
1	3.30E+08/45.25	5.97E+08/35.10	6.80E+08/34.28
2	4.66E+08/41.50	7.63E+08/29.94	8.67E+08/30.80
5	7.07E+08/37.36	1.07E+09/28.31	1.18E+09/27.38
10	9.45E+08/33.34	1.31E+09/25.03	1.44E+09/25.41

Table 5.5 Results of Frequency Sweep Tests – Kinston (9.5mm Above RZ)

Freq (Hz.)	Average G* (Pa)/Phase Angle(Deg)		
	Field Cores	**Rolling Wheel Compaction**	**Gyratory Compaction**
0.01	2.01E+07/51.32	6.57E+07/47.66	8.50E+07/43.24
0.02	2.81E+07/54.04	8.99E+07/45.80	1.12E+08/42.64
0.05	4.92E+07/55.93	1.34E+08/43.19	1.61E+08/39.87
0.1	5.92E+07/52.86	2.00E+08/43.96	2.33E+08/41.54
0.2	9.31E+07/55.77	2.71E+08/41.85	3.11E+08/39.60
0.5	1.49E+08/50.72	4.05E+08/36.16	4.56E+08/33.02
1	2.18E+08/50.09	5.45E+08/35.01	6.00E+08/32.54
2	3.16E+0846.46	7.13E+08/31.38	7.60E+08/29.01
5	4.88E+08/41.67	9.74E+08/28.31	1.01E+09/25.75
10	6.63E+08/37.51	1.21E+09/24.76	1.22E+09/23.07

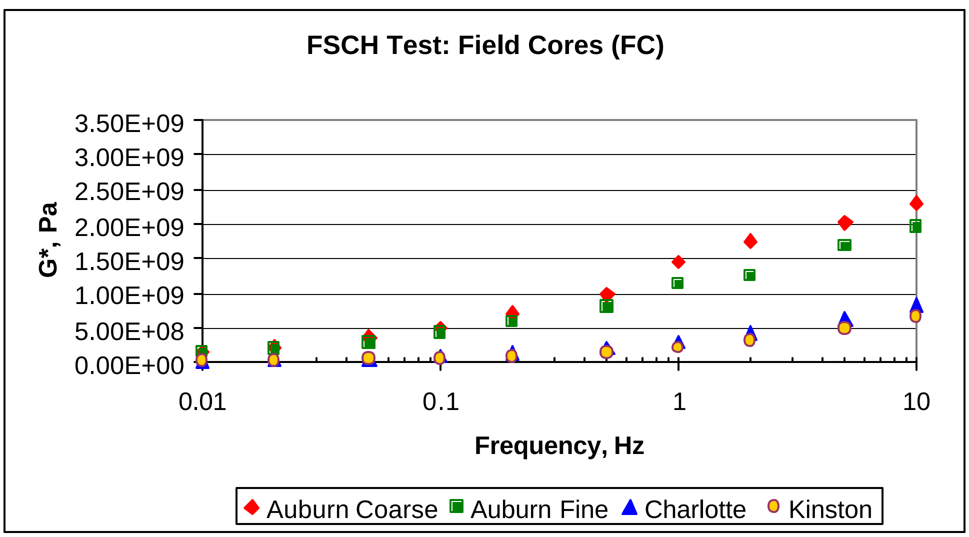

Figure 5.1 Frequency Sweep Test Results of Field Cores

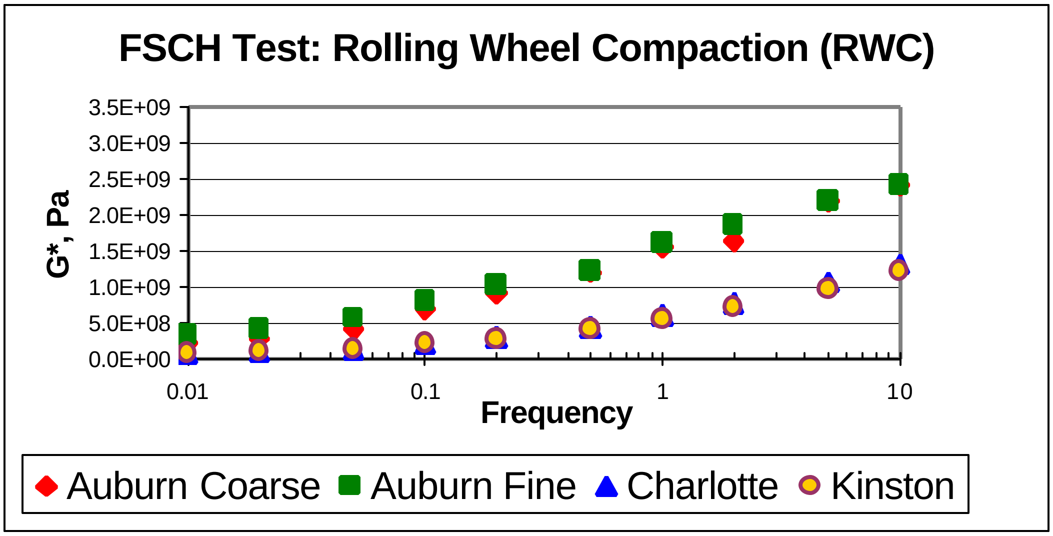

Figure 5.2 Frequency Sweep Test Results of RWC Specimens

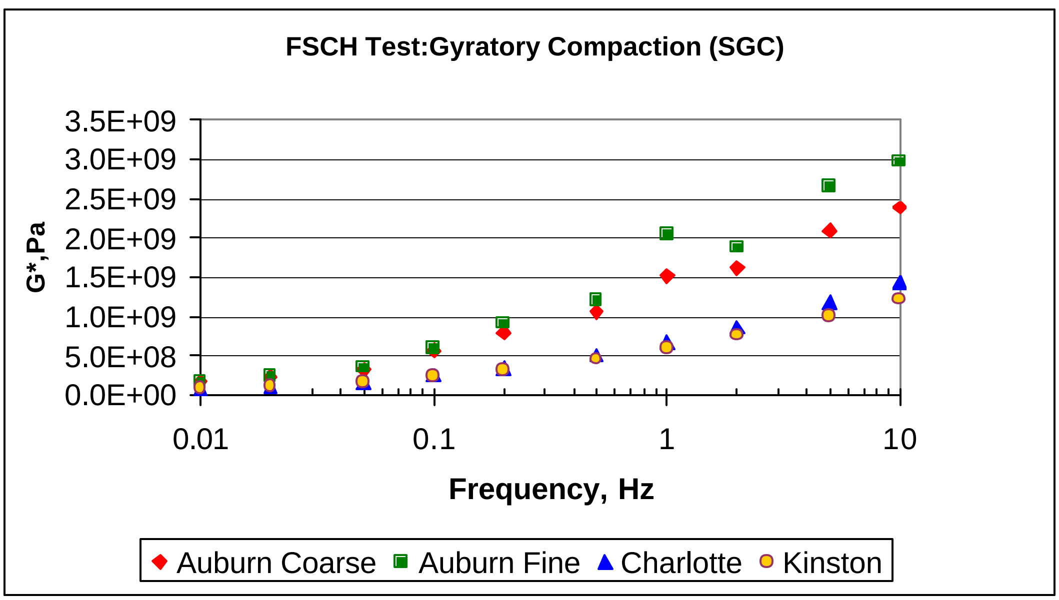

Figure 5.3 Frequency Sweep Test Results of SGC Specimens

The test results show that the G* values of the Auburn mixtures were almost twice that of the Charlotte and the Kinston mixtures. Similarly, the phase angles of the Auburn mixtures were half that of the other mixtures. In other words, the 12.5mm mixtures were stiffer than the 9.5mm mixtures. The same behavior was noticed for all the three methods of compaction. The Auburn Coarse mixture was the stiffest among the field cores and the RWC specimens, whereas the Auburn Fine mixture was the stiffest among the gyratory compacted specimens. The Kinston mixture had the lowest stiffness among all the mixtures and compaction methods.

For the Auburn Coarse mixture, the rolling wheel compaction provided the highest G* values and lowest phase angle than the other compaction methods. But there seemed to be very little difference between the G* values of the SGC mixtures and RWC mixtures. For the Auburn Fine mixtures, the gyratory compaction provided the highest G* values than the field cores and the rolling wheel compaction. The same trend was reflected in the Charlotte and the Kinston mixtures.

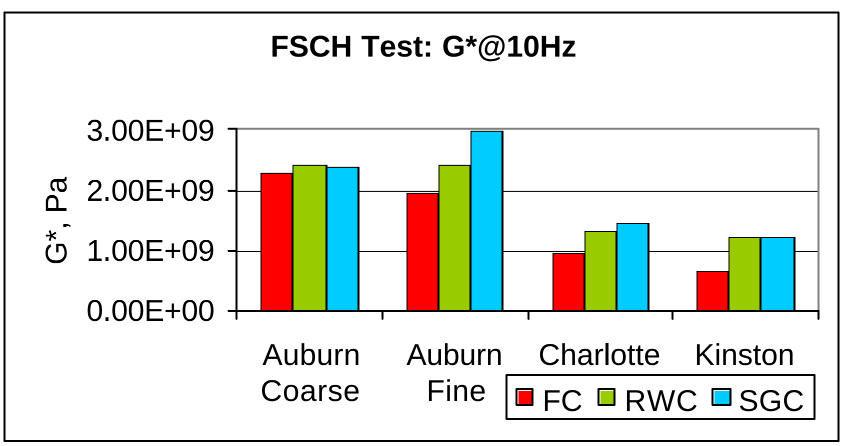

Figure 5.4 Comparison of G* @ 10 Hz

There was no definite trend in the phase angles of the mixtures. The phase angles of field cores were higher than the phase angles of RWC and SGC specimens for all of the mixtures. For the Charlotte and the Kinston mixtures, the phase angles of RWC and SGC specimens were almost equal; but for the Auburn mixtures, the phase angles of RWC specimens were lower than that of SGC specimens. The phase angles play a significant role in determining the viscous and elastic components of the mixture behavior and in estimating the fatigue life of the mixtures.

In general, it can be stated that the gyratory compaction provided the mixtures with higher stiffness than the field cores and the RWC mixtures. The field cores had the lowest stiffness among the three methods of compaction. The RWC mixtures have stiffness values in between the field cores and SGC mixtures. This indicates that laboratory compaction methods provide specimens that over estimate the stiffness properties of the field cores.

The results discussed above were the shear tests performed on four different types of mixtures at the corresponding densities of their respective field cores. The tests results furnished in Tables 5.2 to 5.5 can be used to compare the effect of different compaction methods on different mixtures.

One of the objectives of this study was to evaluate how changes in asphalt content and aggregate gradation affect mixture compaction and predicted performance. The mixtures used in this study had two different asphalt grades (PG 67 and PG 64), nominal maximum size of aggregates (12.5 and 9.5mm), aggregate gradations (above and below the restricted zone) and different sources of aggregates. In order to evaluate the effect of these differences, the bulk density of all the mixtures should be the same for their performance evaluation. The shear tests were conducted on specimens compacted at four-percent air voids using the Superpave Gyratory compactor. Table 5.6 and Figure 5.5 show the results of FSCH tests performed on mixtures compacted at four- percent air voids.

Table 5.6 Results of Frequency Sweep Tests – SGC Specimens at 4% Air Voids

Freq (Hz.)	Average G* (Pa)/Phase Angle(Deg)			
	Auburn Coarse	**Auburn Fine**	**Charlotte**	**Kinston**
0.01	4.03E+08/38.10	4.18E+08/35.73	2.61E+08/35.39	1.15E+08/44.57
0.02	5.23E+08/35.96	5.37E+08/33.31	3.32+08/34.31	1.53E+08/43.53
0.05	7.44E+08/31.06	7.33E+08/27.71	4.56E+08/30.48	2.27E+08/40.48
0.1	1.12E+09/32.30	1.08E+09/29.27	6.30E+08/32.85	3.17E+08/40.88
0.2	1.46E+09/28.96	1.41E+09/25.60	8.16E+08/29.87	4.27E+08/38.31
0.5	1.89E+09/25.68	1.68E+09/21.32	1.09E+09/25.84	6.28E+08/31.06
1	2.41E+09/18.36	2.34E+09/13.05	1.41E+09/21.74	8.32E+08/30.22
2	2.72E+09/23.39	2.48E+09/18.34	1.59E+09/22.07	1.02E+09/27.97
5	3.35E+09/18.93	3.10E+09/14.02	2.03E+09/18.35	1.36E+09/23.69
10	3.91E+09/18.64	3.46E+09/13.57	2.31E+09/17.13	1.61E+09/21.26

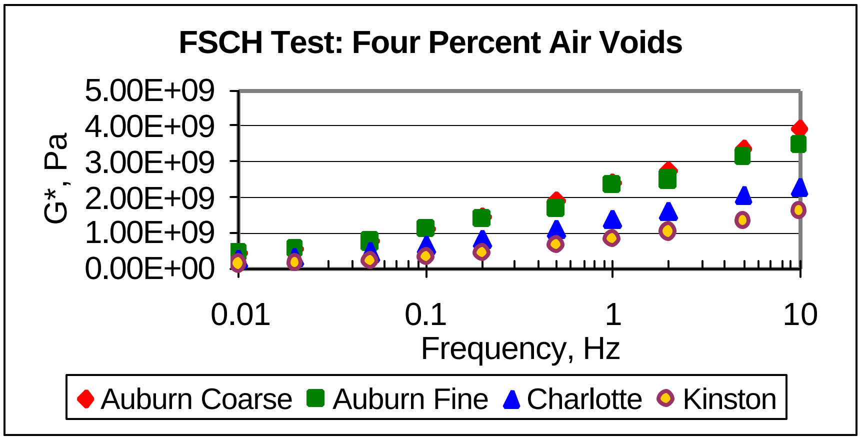

Figure 5.5 Frequency Sweep Test Results SGC Specimens at 4% Air Voids

The results of the frequency sweep tests show that mixtures of 12.5mm gradation (Auburn Coarse and Fine), had higher dynamic modulus values than the mixtures of 9.5mm gradation (Kinston and Charlotte). The stiffness values of Auburn mixtures were approximately twice those of the other mixtures. The Auburn Coarse mixture had the highest stiffness among all the mixtures followed by Auburn Fine, Charlotte and Kinston mixtures.

5.1.4 Repeated Shear Test at Constant Height

This test was performed to estimate the rutting potential of a mixture. The visco-elastic 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 actuator under control by the shear load cell applies haversine loads. The horizontal LVDT measures the difference in horizontal displacement between two points on the specimen separated by 37.5mm, thus away from the end effects and away from the deformation of the glue. 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 5,000 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). RSCH tests were performed on specimens of four mixtures and three compaction methods. The tests were conducted at their respective seven-day average high pavement temperature at 50-mm depth from the pavement surface.

5.1.4.1 Analysis of RSCH Test Results

The results of the RSCH tests are shown in Table 5.7 and Figures 5.6 to 5.8. Table 5.7 shows the shear strains and number of cycles for all the four mixtures compacted using three methods. Either the shear strain at the end of 5,000 cycles or the number of cycles to reach the limit of 5% strain is provided for each combination of mixture type and compaction method.

Table 5.7 Repeated Shear Test Results

Mixture	Field Cores		RWC		SGC	
	Cycles	Strain	Cycles	Strain	Cycles	Strain
Auburn –Coarse	5000	0.0270	5000	0.0163	5000	0.0132
Auburn –Fine	5000	0.0245	5000	0.0180	5000	0.0150
Charlotte	*802**	*limit*	5000	0.0210	5000	0.0129
Kinston	*677**	*limit*	*3300**	*limit*	5000	0.0283

* **Average number of cycles**

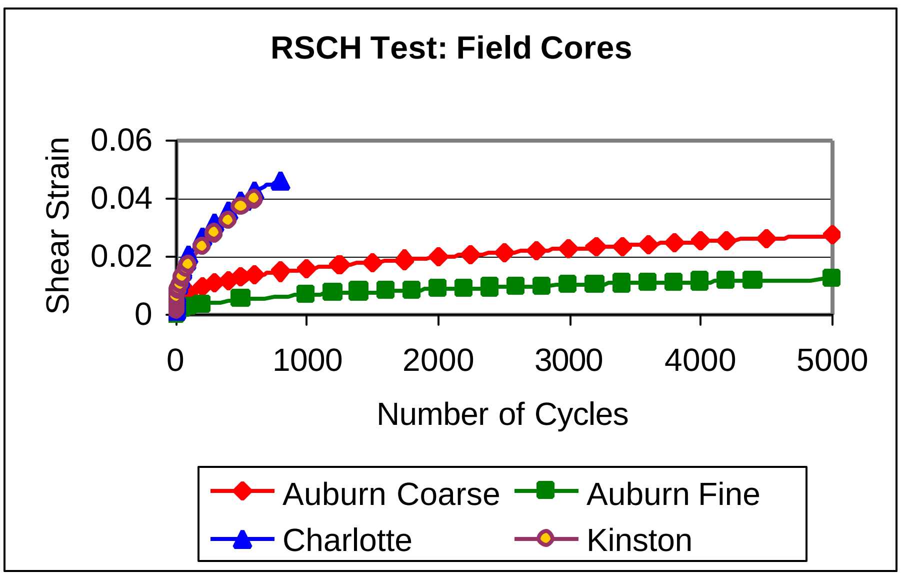

Figure 5.6 RSCH Test: Field Cores

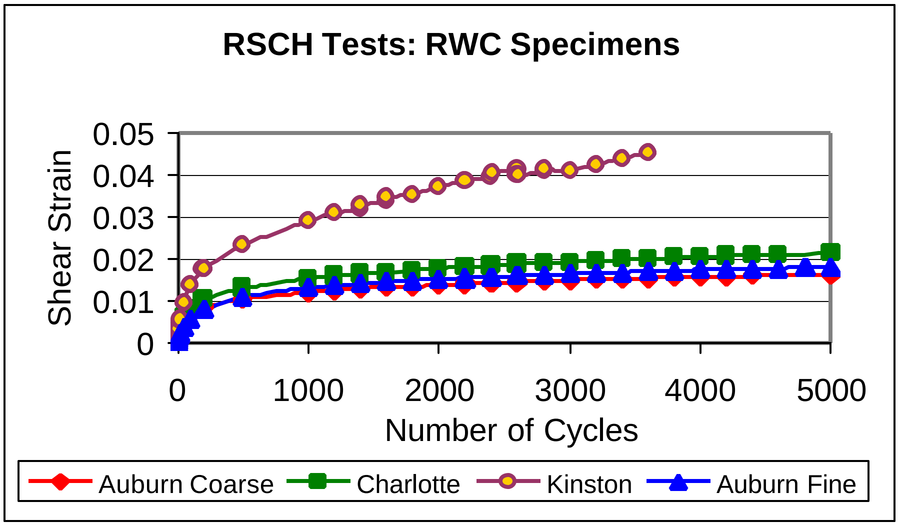

Figure 5.7 RSCH Test: RWC Specimens

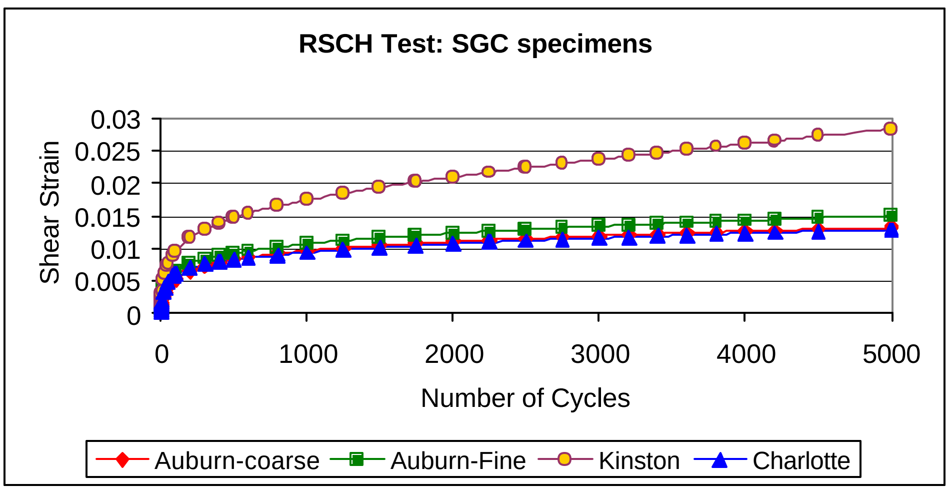

Figure 5.8 RSCH Test: SGC Specimens

The RSCH test results show that only the field cores of the Auburn mixtures reached the 5,000-cycle criterion. Field cores of the Charlotte and the Kinston mixtures failed below 1,000 cycles by reaching the maximum shear strain limit of 5 percent. All the mixtures compacted using the SGC passed their 5,000-cycle criteria. None of the mixtures reached the maximum shear strain limit. For the mixtures compacted using the rolling wheel, only the Kinston mixture reaches the maximum shear strain limit whereas all other mixtures passed the 5,000 cycle criterion.

The field cores had the lowest shear strength either in terms of the shear strain or the number of cycles to reach the strain limit. The SGC mixtures had the highest shear strength accompanied with lowest shear strains. The shear strains of the RWC mixtures were in between the shear strain values of the field cores and the SGC mixtures. In case of the SGC and the RWC mixtures, the shear strains of Auburn Coarse, Auburn Fine and Charlotte mixtures did not differ much whereas the shear strains of Kinston mixture were very high.

In general, the shear strains of field cores were higher than the shear strains of laboratory compacted specimens. The laboratory methods tend to under predict the rutting behavior. The rolling wheel compaction seems to simulate field compaction better than the gyratory compaction.

In order to evaluate the effect of changes in aggregate gradation and asphalt source, the SGC mixtures were compacted at four percent air voids and RSCH tests were conducted to determine the shear strains as shown in Table 5.8 and Figure 5.9. All the mixtures passed the 5,000 cycle criterion. The shear strains of the Auburn mixtures and the Charlotte were almost equal. The Kinston mixture had the highest shear strain among all the mixtures.

Table 5.8 Shear Strains of SGC Mixtures at 4% Air Voids

Mixture	Number of Cycles	Shear Strain
Auburn Coarse	5000	0.0127
Auburn Fine	5000	0.0122
Charlotte	5000	0.0121
Kinston	5000	0.0220

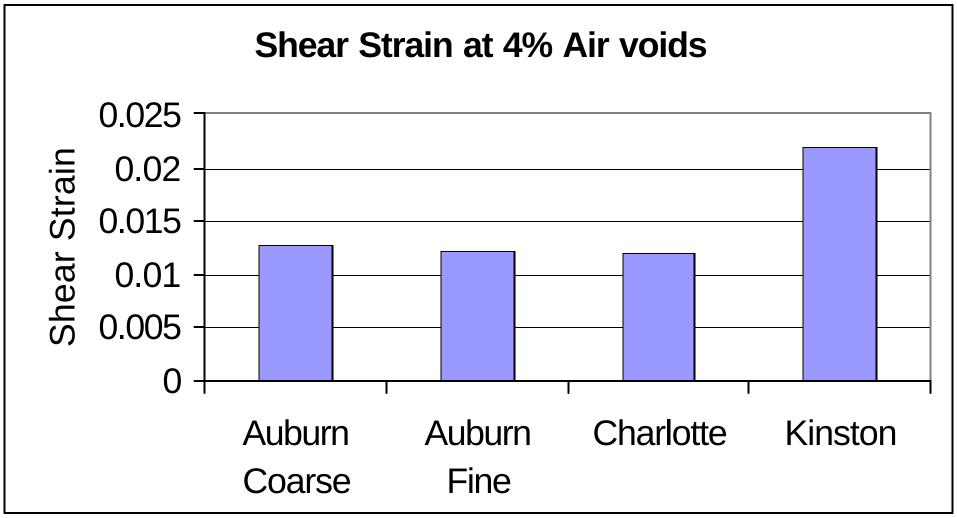

Figure 5.9 RSCH Test Results of Field Cores

5.2 Asphalt Pavement Analyzer for Rutting Susceptibility

The rutting susceptibility of the mixtures is assessed by placing rectangular or cylindrical samples under repetitive loads of a wheel-tracking device, known as the Asphalt Pavement Analyzer (APA). The 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 (cylindrical) specimens and beam specimens. Three beam or six gyratory samples can be tested simultaneously.

The theory behind a loaded wheel tester is to apply an appropriate cyclical loading to asphalt concrete specimens to best simulate actual traffic. This is accomplished 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 8,000 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.

In the APA testing, only rutting potential of the mixtures was investigated. The rutting tests were conducted on the field cores and compacted specimens of the loose mixtures. The air voids content of the field cores was estimated by calculating the density properties of the field cores. As the rutting potential of a mixture is a function of its air voids content, loose mixtures were compacted to the average bulk density of the field cores.

Cylindrical specimens were compacted using the Superpave Gyratory Compactor. The height of the specimen to be compacted was back calculated for each mixture using the correction factor for a given mass of a mixture. Loose mixtures were compacted to the required height to match the bulk density of the field cores. Similarly rectangular slabs were compacted using the rolling wheel compactor and cylindrical specimens were cored out of the slabs. The difference in the estimated air voids of field cores and compacted specimens for all the mixtures was within the acceptable range of $\pm$ 0.5 percent. The samples were sawed to a thickness of 75mm to fit in the APA molds. The samples of the Kinston mixtures were sawed to a thickness of 70mm as the thicknesses of the field cores were just slightly more than 70mm.

The APA is capable of controlling the temperature in the cabin. Duplicates of twelve sets of 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 8,000 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 cylindrical samples. The graphical software plots the average of four points for each cycle.

The results of the APA rutting tests are summarized in Table 5.9. The table shows the average rut depth of four points at the end of 8,000 cycles. Figures 5.10 to 5.12 show the change in rut depth with increasing number of cycles of field cores, the Superpave gyratory compacted (SGC) samples, and the rolling wheel compacted samples (RWC), respectively.

Table 5.9 APA Tests: Final Rut Depths

Mixture	Field Cores	RWC	SGC
Auburn Coarse	4.962	5.016	2.561
Auburn Fine	10.905	8.431	5.594
Charlotte	19.184	6.646	4.268
Kinston	15.93	12.169	12.122

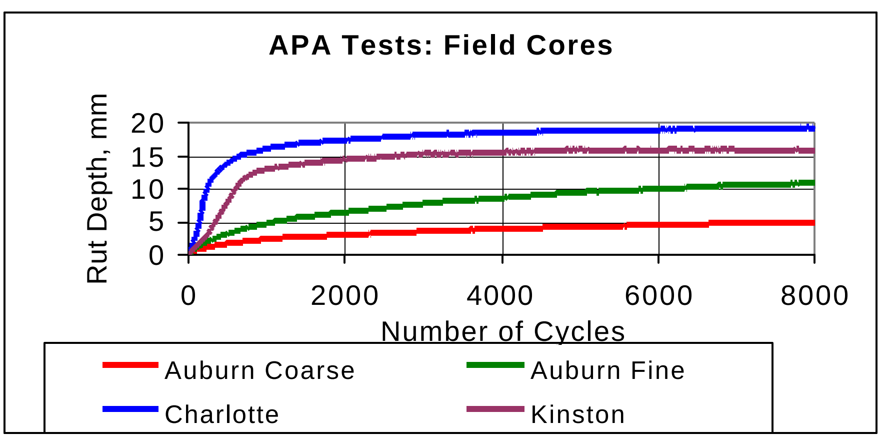

Figure 5.10: Rutting of Field Cores

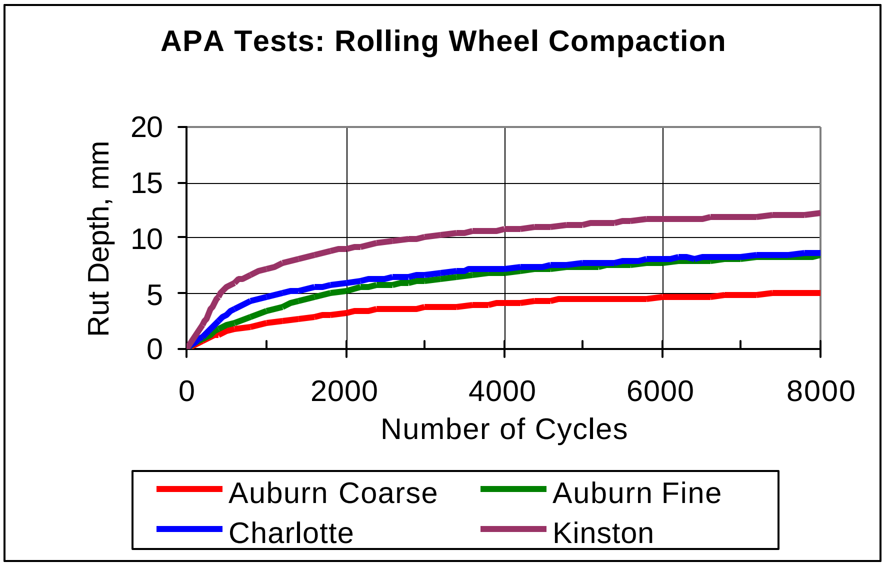

Figure 5.11: Rutting of Rolling Wheel Compacted Mixtures

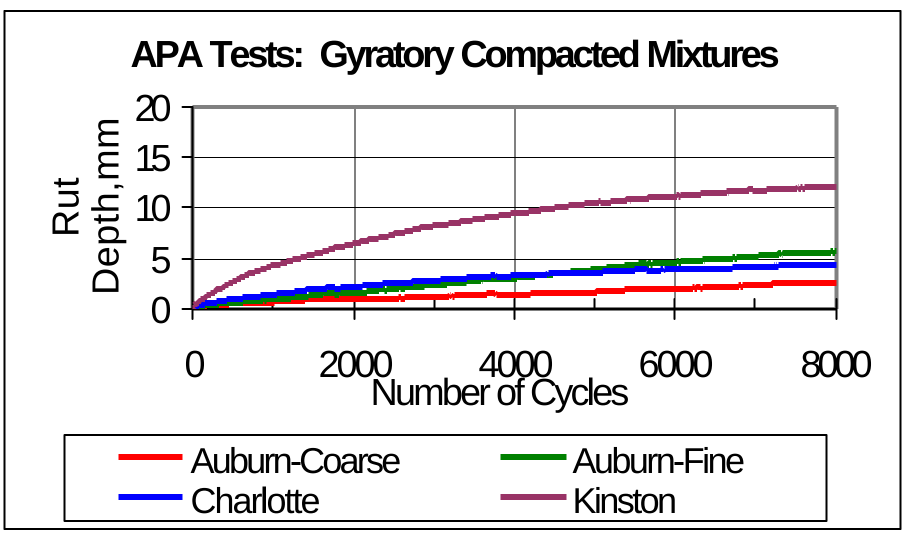

Figure 5.12: Rutting of SGC Compacted Mixtures

The results of the rutting tests show that the Auburn Coarse mixtures had the lowest rut depths among all the mixtures. The Kinston mixtures had the highest rut depths. For the Charlotte mixture, rut depth of the field specimens was much higher as compared to the rut depths of the SGC and RWC specimens. This behavior of the field cores of the Charlotte mixture was also reflected in the repeated shear tests. Rut depths of laboratory compacted specimens of the Auburn Fine mixture were closer to the corresponding rut depths of the Charlotte mixtures.

The mixtures could not be ranked based on these test results as these mixtures were tested at different air void contents. The performances of mixtures were compared to evaluate the effect of different compaction methods. The bar chart in Figure 5.13 compares the rut depths of respective mixtures for the three compaction methods.

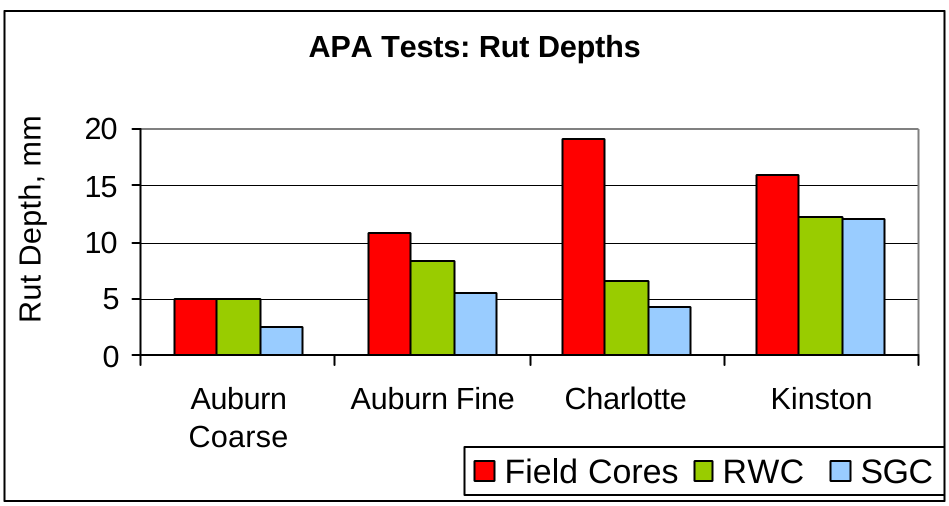

Figure 5.13 : Comparison of Final Rut Depths

It is evident that the SGC specimens performed better than the field cores and the RWC specimens for all the four mixtures. The rut depths of field cores were highest among the rut depths of specimens for all three compaction methods. The performance of the RWC specimens is in between the field cores and the SGC specimens.

Figures 5.10 to 5.12 show that the initial rate of deformation (within the first 1,000 cycles) was higher than the final rate of deformation. After approximately 1,000 cycles, the rate of deformation gradually decreased. It would be interesting to investigate the rut depths of all the mixtures at the end of 1,000 cycles. Table 5.10 shows the rut depths at the end of 1,000 cycles of all the four mixtures. The results show that the rut depths of the 9.5mm mixtures (Charlotte and Kinston) were higher than the rut depths of the 12.5mm mixtures (Auburn mixtures).

Table 5.10 APA Tests: Rut Depths after 1000 cycles

Mixture	Field Cores	RWC	SGC
Auburn Coarse	2.407	2.268	0.604
Auburn Fine	4.754	3.382	0.841
Charlotte	16.082	4.722	1.353
Kinston	13.083	7.227	4.271

The ratio of the rut depth after 1,000 cycles to the rut depth after 8,000 cycles, expressed as percentage, is called as "*Initial Rut Ratio*". The initial rut ratio is a measure of the deformation characteristics of a mixture. This ratio gives an indication about the amount of rutting that would take place in earlier stages of service. Table 5.11 gives the values of the initial rut ratio for all mixtures. Figure 5.14 compares these values for the mixtures of the three compaction methods.

Table 5.11 Initial Rut Ratio

Mixture	Field Cores	RWC	SGC
Auburn Coarse	48.5	45.2	23.6
Auburn Fine	43.6	40.1	15.0
Charlotte	83.8	71.1	31.7
Kinston	82.1	59.4	35.2

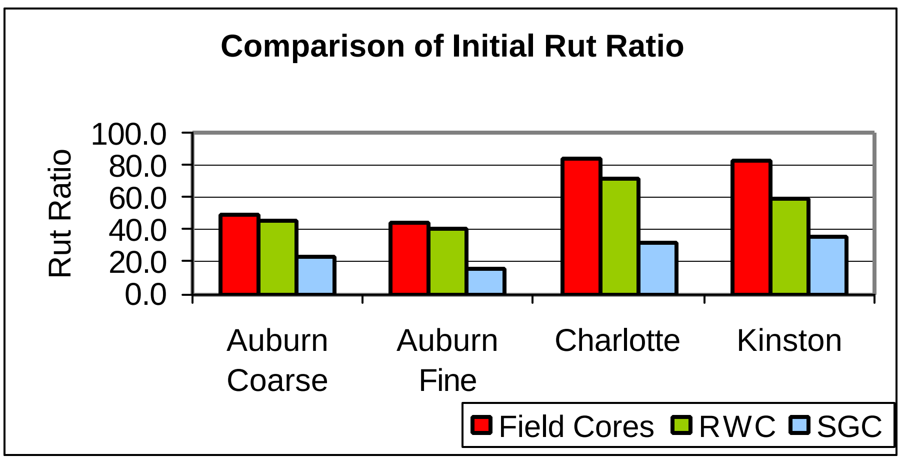

Figure 5.14 Comparison of Initial Rut Ratio

The initial rut ratio seemed to be influenced by the maximum size of the aggregate and the type of compaction method. In general, the 12.5mm mixtures had lower initial rut rates than the 9.5mm mixtures. The field cores had the highest initial rut ratios whereas the SGC samples had the lowest initial rut ratios. For the field cores, the Auburn mixtures reached about 50% of their final rut depth at the end of 1,000 cycles. The field cores of the Charlotte and the Kinston mixtures reached about 80% of their final rut depth at the end of 1,000 cycles. For the SGC samples, the Auburn mixtures reached only about 20% of their final rut depth whereas the Charlotte and the Kinston mixtures reached about 35% of their final rut depth at the end of 1,000 cycles. For the RWC samples, the initial rut ratios were found in between the initial rut ratios of field cores and SGC samples.

5.2.1 Viscoelastic Models

Rutting is an accumulation of plastic strain in Hot Mix Asphalt or lower layers due to repeated loading. In this study, the rut depths were analyzed to compare the rutting potential of HMA mixes. Then, viscoelastic parameters were determined for several mixes, and the effect of mix components on the viscoelastic parameters was evaluated (27). A discussion of viscoelastic models used for characterization of HMA is presented.

For the elastic behavior of materials, the strain of an elastic material stays constant and disappears immediately upon the removal of stress. If the stresses are too high, the response is no longer elastic, but plastic. Rutting under the wheel loads may results from lateral plastic flow. One of the primary causes of lateral plastic flow is the loss of internal friction due to an excessive amount of asphalt binder.

The stress whose response is no longer elastic is the yield stress. The permanent strain remains after the load is removed and is known as plastic strain (ε_p). The viscoelastic behavior of materials exhibits elastic action upon loading followed by as slow and continuous increase of strain at a decreasing rate. When stress is removed, at first there is an initial elastic recovery followed by a continuously decreasing strain. Materials are influenced by rate of stress – the longer the time to reach the final value of stress, the higher (or larger) is the strain. Viscoelastic materials (such as HMA) are also known as "time-dependent" materials. The creep (time dependent loading) phenomenon is a behavior of HMA under stress for a longer period of time. Creep strain rate determines viscosity.

Total Strain, ε = elastic + creep, $\varepsilon = \varepsilon_e + \varepsilon_c$

Where

ε_e = independent of time

ε_c = dependent on time, for the strain rate

$$e = \left(\frac{de}{de}\right) = \frac{de_c}{dt}$$

If the load is removed, the elastic strain will be reversed. A portion of the creep strain is also be recovered at a continuously decreasing rate. The amount of time dependent recoverable strain during recovery is generally a small part of time dependent creep strain for materials. A part of the creep strain is recoverable, while the elastic strain is fully recoverable. Permanent strain is the difference between total strain and recovered strain. Rutting is permanent strain. The instantaneous elastic, creep under constant stress, instantaneous recovery, delayed recovery and permanent strain are the phenomena commonly seen in viscoelastic materials such as asphalt concrete.

Asphalt materials can be characterized into 3 types such as sol, gel and gel-sol. “Sol” behaves as Newtonian fluids. The constant of proportionality between applied shear stress and time rate of shearing deformation, that is the strain rate, $K = \frac{ShearStress}{ShearRate}$, is also known as coefficient of viscosity or simply viscosity .

Viscosity is also defined as resistance to deformation or internal friction of a fluid. “Gel” is a plastic material that exhibits definite yield value when stressed, and above yield value flow becomes Newtonian in nature. Typical “gel” material is asphalt shingles. “Sol- Gel” materials exhibit viscoelastic behavior and non-Newtonian flow – viscosity as well as elasticity.

For mathematical models, “Hookean” spring and “Newtonian” dashpot elements represent elasticity and viscosity, respectively.

E = Linear Spring constant “Young Modulus”

E is the simplest parameter used in applied mechanics. It is defined only when the material is purely elastic. It does not adequately define a viscoelastic material.

Newtonian dashpot will be deformed continuously at a constant rate when it is subjected to a constant stress.

$\delta = \eta\varepsilon$

where η = coefficient of viscosity

Kelvin Model (Delayed Elasticity)

Kelvin Model introduces the characteristic of delayed recovery or delayed elasticity and is a model in which Hookean element (linear spring) and a Newtonian element (dashpot) are connected in parallel.

σεη

$\sigma_1 = R\ \varepsilon$ or $E\ \varepsilon$

$\sigma_2 = \eta\ \varepsilon$

$\sigma = \sigma_1 + \sigma_2$

By eliminating (σ_1, σ_2),

$$e + \left(\frac{R}{h}\right)e = \left(\frac{s}{h}\right)$$

Solution for ε is (for a constant stress σ_0 applied at t= 0)

$$e = \left(\frac{s_0}{R}\right)\left(1 - e^{-Rt/h}\right)$$

Strain rate,

$$e = \left(\frac{d_0}{R}\right)\left(e^{-Rt/h}\right)$$

Initial strain rate at t = 0+ is finite, $\varepsilon(0+) = (\sigma_0 / \eta)$ and $\varepsilon(\alpha) = 0$ when $t \rightarrow \infty$. If the strains were to increase at its initial rate (σ_0/η), it will cross the asymptotic value (σ_0/R) at time $t_c = (\eta/R)$ (t_c is called the retardation time). Most of the total strain (σ_0/R) occurs within the retardation time period since, $e^{-Rt/\eta}$ converge towards the asymptotic value rapidly for $t < t_c$.

At $t = t_c$,

$$\varepsilon = \left(\frac{\sigma_0}{R}\right)\left(1 - \frac{1}{e}\right) = 0.63\left(\frac{\sigma_0}{R}\right)$$

Thus, only (1-0.63) = 37% of asymptotic strain remain to be accomplished after t = tc.

If the stress is recovered at time t_1, the strain following stress removal can be determined by the superposition principle. The strain ε resulting from δ_0 applied at t = 0 is

$$\varepsilon_a = \left(\frac{\sigma_0}{R}\right)\left(1 - e^{-Rt/\eta}\right)$$

Then, strain ε_b resulting from applying $(-\sigma 0)$ independently at $t = t_1$ is,

$$\varepsilon_b = -\left(\frac{\sigma_0}{R}\right)\left(1 - e^{-R(t-t_1)/\eta}\right)$$

Hence, if the stress is applied at t = 0 and recovered at $-t = t_1(-\sigma_0$ added) the superposition principle yield the strain ε for $t > t_1$ during the recovery

$\varepsilon = \varepsilon_a + \varepsilon_b$

$$\varepsilon_a = \left(\frac{\sigma_0}{R}\right)\left(e^{-Rt/\eta}\right)\left[e^{Rt/\eta} - 1\right] \quad t > t_1$$

(when, $t \to \propto$, recovery tends towards zero).

One of the characteristics of Kelvin Model is that the strain increases with a decreasing rate. In addition, the stress at first is carried entirely by the viscous element and, under continued stress, viscous element deforms and is compelled to transfer a greater and greater portion of load to the elastic element. Finally the entire stress is carried by the elastic element – a phenomenon called as delayed elasticity. The Kelvin model is selected for analysis in this study, because the viscoelastic parameters used in the Kelvin model are relatively simple and can be determined from the results of tests with the Asphalt Pavement Analyzer.

Determination of E, h and Initial Strain Rate

Using the Kelvin's model and the results of APA rut tests, the parameters E and η values for each mix were determined. The steps involved in determining the above parameters are explained below.

1. Determination of Strain (ε)

Each cycle vs times(s) was calculated by considering APA mold compacted depth and average deformation (rut) depth. The original mold compacted depth was 75mm and average rut depth was different with samples, times and cycles.

$$\text{Strain } (e) = \frac{AverageRutDepth}{CompactedDepth}$$

2. Stress was 690 kPa (standard pressure) at the APA
3. Determination of Elastic Modulus E

   From Kelvin Model, $\sigma_0/E = \varepsilon$ at $t \rightarrow \propto$

   Considering the strain at the end of 8000 cycles to be the asymptotic value,

   $E = \sigma_0/\varepsilon$

4. Determination of Retardation time t_c

The retardation time, t_c, is the time at which 63 % of the total strain occurs.

5. Determination of Initial Strain Rate

Initial Strain Rate = Total Strain / Retardation time

6. Determination of Coefficient of Viscosity, η

$\eta = \sigma_0 * t_c / \varepsilon$

Figure 5.15 demonstrates the steps to calculate the viscoelastic parameters graphically.

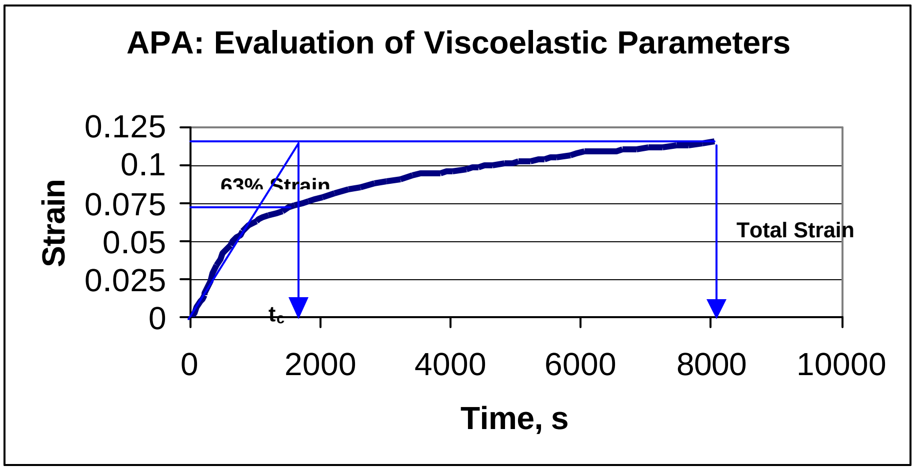

Figure 5.15 Typical Calculation of E, h and t_c

The values of E, η, t_c and initial strain rates are given in Table 5.12

Table 5.12 Summary of Viscoelastic Parameters

Mixture	Rut Depth, mm	Strain ε	E kPa	Retardation Time, t_c , s	η kPas	Initial Strain Rate
FC-AC	4.962	0.066	10429.3	2125	2.22E+07	3.11E-05
FC-AF	10.905	0.145	4745.5	2275.5	1.08E+07	6.39E-05
FC-C	19.184	0.256	2697.6	333	8.98E+05	7.68E-04
FC-K	15.93	0.212	3248.6	603	1.96E+06	3.52E-04
SGC-AC	2.561	0.034	20207.0	5074.6	1.03E+08	6.73E-06
SGC-AF	5.594	0.075	9251.0	4677	4.33E+07	1.59E-05
SGC-C	4.268	0.057	12125.1	2910	3.53E+07	1.96E-05
SGC-K	12.122	0.162	4269.1	2715	1.16E+07	5.95E-05
RWC-AC	4.986	0.066	10379.9	1917.5	1.99E+07	3.47E-05
RWC-AF	8.372	0.112	6181.0	2057	1.27E+07	5.43E-05
RWC-C	8.609	0.115	6011.2	1538.5	9.25E+06	7.46E-05
RWC-K	12.139	0.162	4263.3	1198.67	5.11E+06	1.35E-04

It can be found from the above Table 5.12 that rut depth increases with decreasing values of E and η. This may be due to the fact that rutting resistance of the mixture improves with stiffness of asphalt concrete mixture. The final rut depth increases with increasing initial strain rate. There is no definite trend between rut depth and retardation time but the retardation time seems to decrease exponentially with increasing rut depth.

The retardation times for gyratory compacted (SGC) samples are greater than the retardation times for the mixture of other compaction methods. The retardation times for rolling wheel compacted (RWC) samples are greater than those of field cores (FC). Retardation times of 12.5mm mixtures (AC &AF) are greater than the retardation times of 9.5-mm mixtures. This trend is seen in mixtures of all three compaction methods.

5.3 Wheel Tracking Test

The wheel-tracking test was carried out to estimate the permanent deformation or rutting in HMA pavements. The wheel-tracking test is performed using the NCSU Wheel Tracking Device (WTD). The WTD allows for an accelerated evaluation of rutting potential in the designed mixtures. The rut test using the WTD can be conducted on field slabs or on rolling wheel compacted slabs.

5.3.1 Description of NCSU WTD

As described earlier, the NCSU Linear Compaction and Wheel Tracking system was designed to simulate the field conditions of asphalt concrete pavements, from construction to application. The NCSU WTD can be used to compact loose mixtures into slabs at a desired air void content. The NCSU WTD can also perform rutting tests on laboratory compacted slabs and field slabs. The simple Windows based control software requires minimal user input and attention during testing. The system offers field simulation and mixture performance measurement with full automation and precision. Figure 5.16 shows a picture of the NCSU wheel tracking system.

Figure 5.16 NCSU Wheel Tracking System

The entire wheel tracking system is surrounded by environmental chamber with a temperature range of –4^{o}C to 65^{o}C. The chamber itself contains 2.5inches of dense rigid insulation sandwiched between 16 gauge stainless steel on the inside and 16 gauge stainless steel on the outside to reduce the amount of thermal energy loss. The system is computer controlled to within 1.0^{o}C of the set point temperature.

The NCSU WTD compacts specimen slabs 540mm long by 430mm wide and in 75mm lifts. Total pavement cross sections up to 300mm thick can be constructed in the system by stacking up to four specimen molds. Bound and unbound materials can be compacted to specified densities. And the data acquisition and control system is able to compact specimens in either deformation or load control modes. The number of compaction roller passes can be pre-programmed or system can monitor specimen height and stop compaction when a target deformation is reached. Given the maximum specific gravity of a mixture, the system can be programmed to stop compaction when a calculated bulk density (%Gmm) is reached. During the compaction process, all applied loads, deformations, temperatures, and wheel passes are recorded by the data acquisition system. The specimen height, air content and Gmb can be plotted against the compaction passes so that the required compaction energy required for different mixtures can be compared. The steel compaction wheel and specimen support table can be heated up to 150^{o}C to aid in the compaction process. The specimen molds can be quickly clamped and removed from the support table and each other for fast specimen fabrication. The molds themselves are fabricated such that they can be taken apart to ease in specimen removal and equipment clean up.

The wheel tracking system of CS6000 is flexible yet simple to use. The wheel pressure (up to 150psi), speed (up to 1Hz), track (uniform, random, outside edge) and direction (unidirectional and bi-directional) can all be set by the user. Rutting cycles can be set initially or deformation limits can also be set.

One unique feature of the NCSU WTD is the method it utilizes to measure the rutting deformation of the tested specimen. A class III laser measures the distance of the slab surface from a datum point and transforms these distances into a rut depth profile. The laser measurement can measure the variation in depth with an accuracy of 0.001inch. The number of wheel tracking cycles between laser measurements, as well as the number and location of measurement points are preset by the user. The measurement system stores the raw distance data in tabular format for analysis. A complete three-dimensional representation of the specimen can be generated to show how the rutting progresses over time.

The Wheel Tracking Device has a specimen support table on top of a rigid base. The rigid base supports the bottom plate and assemblies. The thickness of the test slab can be altered with the removable assemblies, which confine the slab in all four directions. The specimen support table can move upwards/downwards (Z-direction) and inwards/outwards (Y-direction). The specimen support table is stationary in X-direction. The movement of the specimen support table with slab and assemblies is controlled. The specimen support table can be heated up to a temperature of 95^{o}C.

The compaction foot is a semi-circular rigid foot for compacting slabs. The length of the foot segment is exactly the length of the slab. The width of the compaction foot is exactly half the width of the slab. The compaction foot can be heated up to a temperature of 95^{o}C. The compaction foot rolls rightwards/leftwards (X- direction). During the compaction of the slab, the specimen support table can be moved in Y and Z directions. The speed of rolling of the compaction foot can be varied. Figure 5.17 shows a semi-circular steel compaction foot and a rubber tire resting on a compacting slab. Figure 5.18 shows the schematic diagram of the wheel and specimen support table.

Figure 5.17 Compaction Foot and Rubber Tire Resting on a Slab

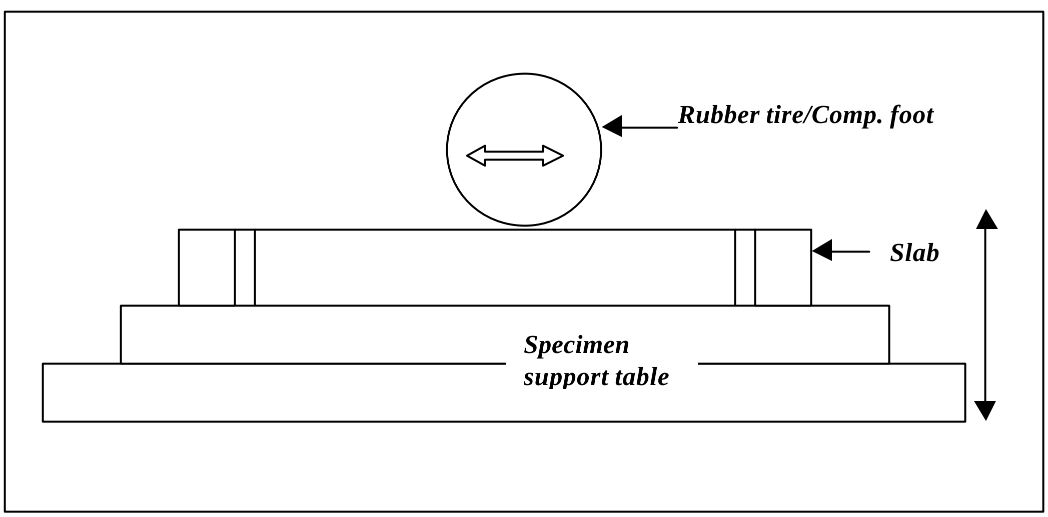

Figure 5.18 Schematic Diagram of the Wheel and Specimen support table

The compaction of the slab is carried out with the compaction foot. For the rut test, the compaction foot is replaced with the rubber tire. The process of compaction and rut tests are discussed in the following sections.

5.3.2 Rolling Wheel Compaction of Slabs

Rolling Wheel Compaction of the asphalt mixture is done using the WTD instead of a conventional roller. The WTD facilitates the rolling of slabs for wheel tracking rut tests. Cylindrical specimens can also be cored out of the slab for shear tests and APA tests.

The rolling was done using the compaction foot with manual hydraulics control. The bottom plate and the assemblies were fixed on the rigid base and the specimen support table. The whole set up was heated to a temperature of 95^{o}C. The compaction foot was also heated to a temperature of 95^{o}C. Foot and the bottom plate were greased to avoid sticking of the mixture.

The mixture was heated in the oven at its compaction temperatures as shown in Tables 3.3 to 3.6 in Chapter 3. The amount of the material that is required for the compaction was calculated using the volume – density calculations for the target air voids. It was learnt that the exact mass calculations gave incorrect densities with the resulting air voids less than the target air voids. The density of the center portion of the slab was higher than the target density. So, the following empirical relationship was developed based on a trial and error procedure.

$$Mass\ (corrected) = Mass\ (exact)/\ C_{SGC}*1.01$$

where

Mass (corrected) = Required Mass of the mixture for compaction

Mass(exact) = Numerically calculated mass of the mixture for achieving target air voids

C_{SGC} = Correction factor of the mixture when compacted using the SGC

The typical values of C_{SGC} would range from 1.01 to 1.02. Mass calculated using this relationship achieved the desired air void contents with a an acceptable range of ±.0.5%.

The mixture was compacted to a thickness of 75mm in three lifts. For the first lift, the mixture was compacted to half the total thickness. For the subsequent lifts, the mixture was compacted in two one-fourth of the remaining thickness. The slab was compacted in more than two lifts to minimize gradient in the distribution of air voids. After each lift, the surface of the compacted layer was scratched to prevent de-lamination of layers. During the compaction process, the specimen support table was moved vertically with slow and controlled movement to predetermined points. Predetermined heights (Z points) are attributed to the thickness or top surface of the slab. The resistance offered by compaction foot varies with the compactability of the mixture. The specimen support table was moved in Y direction to compact the rear portion of the slab. To achieve a uniform surface, the specimen support table was straddled across to prevent shoving of the mixture on the other side of the slab. After compaction, the slab is allowed to cool down. Nuclear gauge readings were then taken. For shear tests and APA tests, the cylindrical specimens were cored out. Four specimens can be cored out from one slab.

The density of the specimens was measured using the water-displacement method for verifying the target air voids.

5.3.3 Rutting Tests using the WTD

The rut tests were done on the RWC slabs and field slabs. RWC slabs were compacted for all the mixtures whereas the field slabs were only available for the Charlotte and the Kinston mixtures. The rut tests were performed at 60^{o}C.

The top surface of the test slab was painted with water-soluble white traffic paint. The surface was painted to prevent the effect of black surface that would cause interference with laser measurement system at high temperatures. The compaction foot was replaced with the rubber tire. The chamber was heated to a temperature of 60^{o}C. Figure 5.19 shows a typical rut test being done on a test slab on a 75mm thick slab. The figure also shows the rubber tire and the laser measurement system.

Figure 5.19 Typical Rut Test Using the NCSU WTD

The rut test was programmed to stop at a specific number of cycles or after the rut depth reached its limit. The number of cycles selected for the test was 10,000 and the rut limit was 1.5 inches. This rut limit includes the initial tire squeeze. Tire squeeze would gradually decrease when the test proceeds. The profile of the slab was measured before the commencement of the test and after every 1000 cycles. Laser measurement system measures the depth at 180 points every time. Measurement was taken at 5 points lengthwise and 36 points widthwise. Figure 5.20 shows the position of the measurement points in both X and Y directions. A compressive load of 1000 lbs was applied against the tire. The speed of the tire was selected as 30 passes/minute in one direction. The tire movement was bi-directional and the effective tire speed was 60 passes/minute.

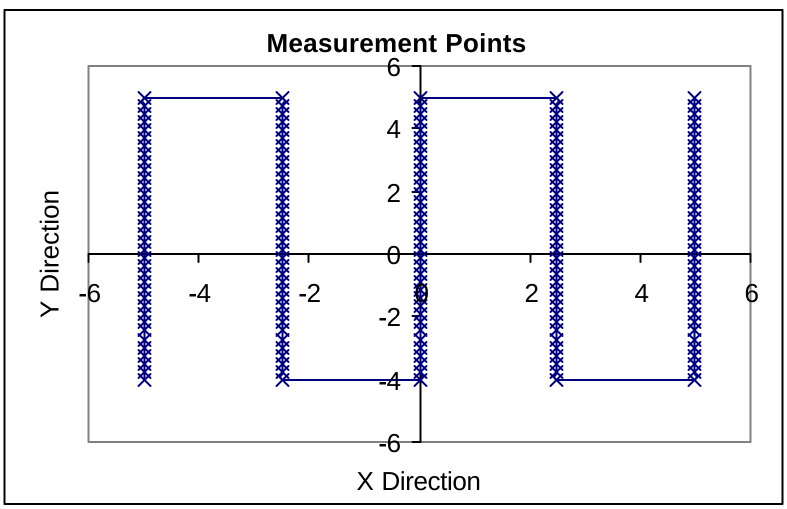

Figure 5.20 Laser Measurement Points on a Typical Slab

The rut tests were performed on RWC slabs for all the mixtures and field slabs for the Charlotte and the Kinston mixtures. The rut depths measured at different points of the slab were then analyzed. All the mixtures passed 10,000 cycles of loading without reaching the rut limit of 1.5 inches. A few of the mixture specimens had rut depths above 0.5 inch as shown in Table 5.13. It would be interesting to know the number of cycles that each mixture takes to reach 0.5 inch. So the number of cycles were interpolated from the rut data as the measurements were taken only after every 1,000 cycles. Table 5.13 furnishes the final rut depth values at the end of 10,000 cycles. The rut depth values are the average of profiles taken at 5 different sections of the slab in the X- direction. The values in the parenthesis indicate the number of cycles required to reach a rut depth of 0.5 inch. Figure 5.21 compares the rut depth of different mixtures.

Table 5.13 Wheel Tracking Tests: Rut Depth

Mixture	RWC Slabs, inch	Field Slabs, inch
Auburn Coarse	0.174	N.A
Auburn Fine	0.199	N.A
Charlotte	0.171	0.607 (2300)
Kinston	1.069 (2400)	0.983 (700)

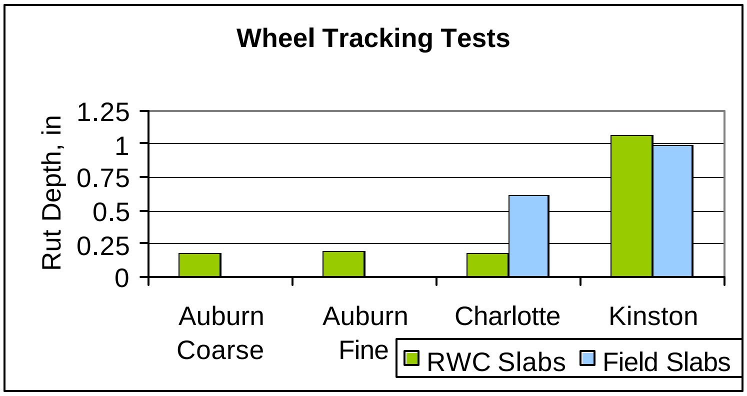

Figure 5.21 Comparison of Rut Depths

The rut test data shows that the Kinston mixtures had the highest rut depths for RWC slabs as well as for the field slabs. The Charlotte mixture of RWC slab had the lowest rut depth, followed by the Auburn Coarse and the Auburn Fine mixtures. The rut depths of these mixtures did not differ much compared to the Kinston mixture. For the Charlotte mixture, the rut depth of field slab was higher than the rut depth of RWC slab. For the Kinston mixture, rut depth of the field slab was lesser than the rut depth of RWC slab. But the fact that the RWC slab tolerated greater number of cycles than the field slab should be taken into account. It indicated that the field slabs rutted at a faster rate than the RWC slabs.

Figure 5.22 shows the rutting profile at a typical cross-section of the field slab of Kinston mixture. It shows the rutting profile before rutting and after 10,000 cycles. The initial profile is almost horizontal, as no rutting has occurred at this point. A slight unevenness in the surface profile of the slab is clearly realized and detected by the laser measurements. The profile after every 1,000 cycles indicates the decrease in the depth of the slab i.e., rutting has occurred. The heaps on right and left ends of the profile indicate the lateral flow of the mixture when rutting has occurred.

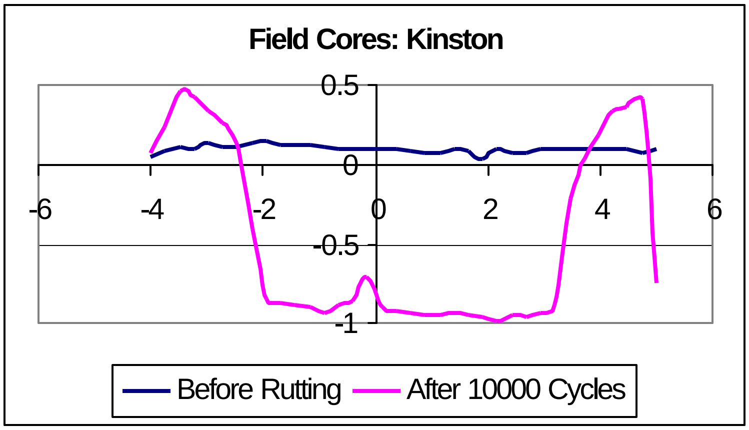

Figure 5.22 A Typical Rutting Profile

In each of the 5 cross sections of the slab, points were selected at which maximum rutting had occurred. The average of the change in rut depths after every 1,000 cycles at those points was determined. Figures 5.23 to 5.28 show the rut depths of each mixture with varying cycles of loading.

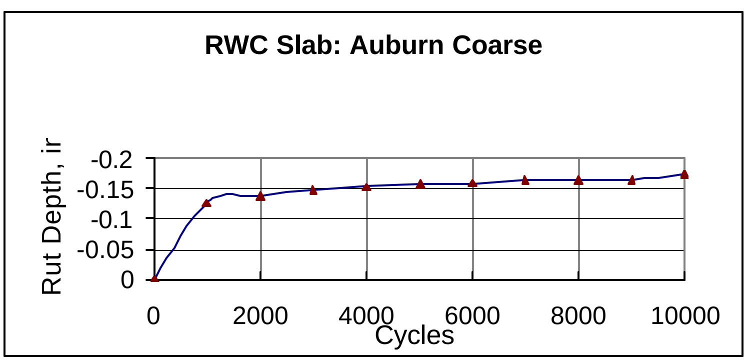

Figure 5.23: Rutting in Auburn Coarse Mixture (RWC slab)

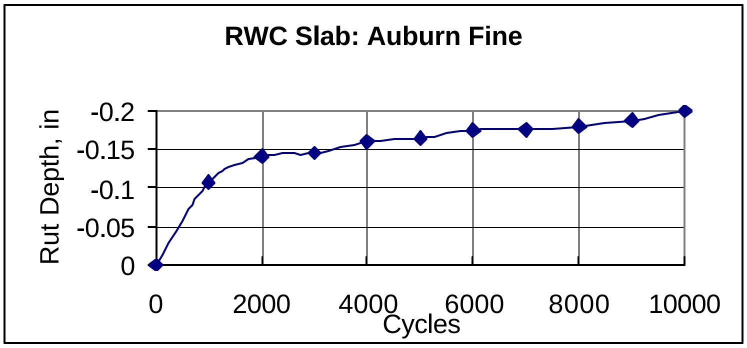

Figure 5.24: Rutting in Auburn Fine Mixture (RWC slab)

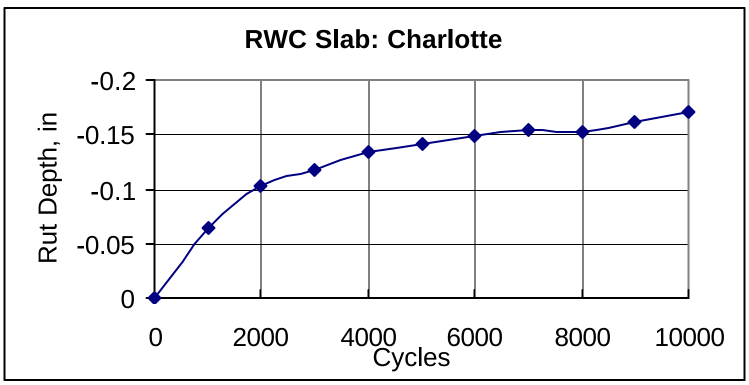

Figure 5.25: Rutting in Charlotte Mixture (RWC slab)

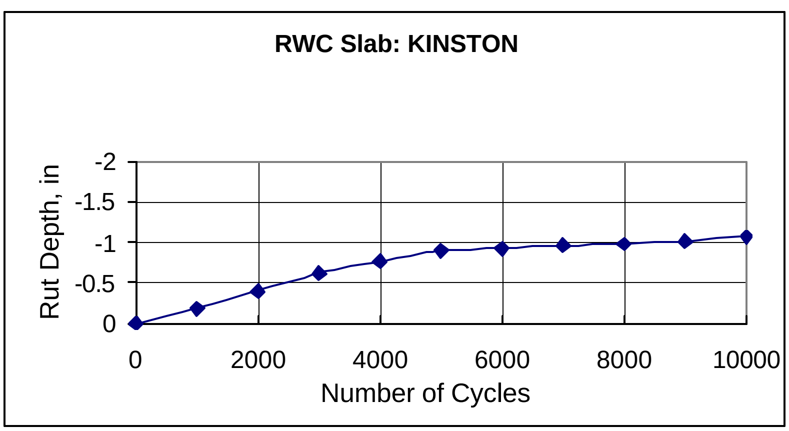

Figure 5.26: Rutting in Kinston Mixture (RWC slab)

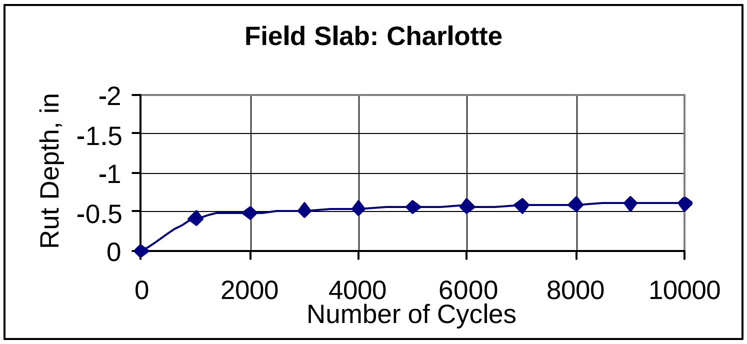

Figure 5.27: Rutting in Charlotte Mixture (Field slab)

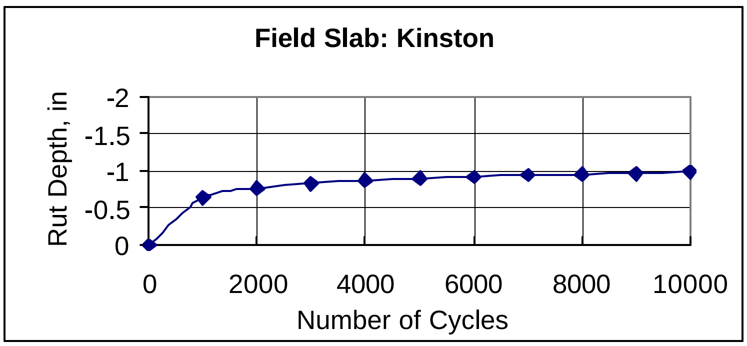

Figure 5.28 : Rutting in Kinston Mixture (Field slab)

The curves show that the rate of rutting was faster in the initial stages. For almost all of mixtures, the rutting rate was faster in first 2,000 cycles, which gradually decreased thereafter. The average rut depths at the end of 2,000 cycles are summarized in Table 5.14. Figure 5.29 shows the comparison of rut depths at the end of 2,000 cycles.

Table 5.14 Rut Depths after 2000 Cycles

Mixture	RWC Slabs, inch	Field Slabs, inch
Auburn Coarse	0.139	N.A
Auburn Fine	0.140	N.A
Charlotte	0.103	0.420
Kinston	0.396	0.640

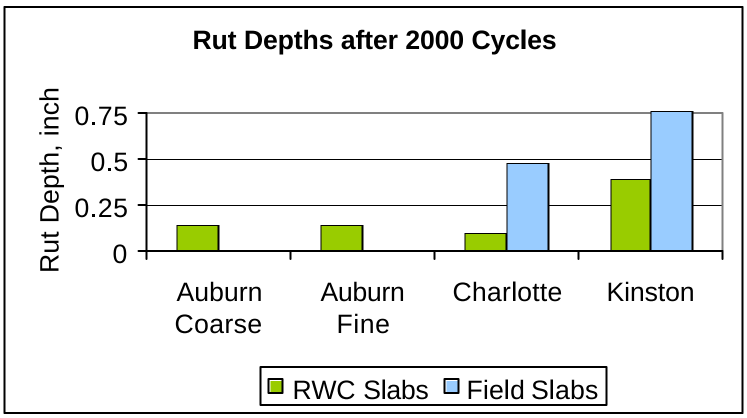

Figure 5.29: Rut Depths after 2000 Cycles

At the end of 2000 cycles, the field slabs had higher rut depths than the RWC slabs. It can be noticed that the field slabs reached almost 0.5-inch rut depth around 2,000 cycles. The ratio of rut depth after 2,000 cycles and the rut depth after 10,000 cycles of loading is calculated. The ratio is defined as the *Initial Rut Ratio,* expressed in percentage. Table 5.15 shows the initial rut ratios for the WTD rut tests.

Table 5.15 Initial Rut Ratio

Mixture	RWC Slabs	Field Slabs
Auburn Coarse	79.9	N.A
Auburn Fine	70.4	N.A
Charlotte	60.2	80.1
Kinston	37.0	77.3

Initial rut ratios show that almost 70 – 80% of the rutting occurred in the first 2,000 cycles for most of the mixtures. The Kinston mixture of RWC type, which had the lowest percentage, reached 0.5 inch rut depth around 2,400 cycles. This suggests that the terminal number of cycles for the WTD rut test can be decreased from 10,000 cycles.

The rut depths show that the rolling wheel compaction provides mixtures with superior performance as compared to the field slabs. The results of the wheel tracking tests are compared with the APA tests and the repeated shear tests in Chapter 6.

CHAPTER 6

MIXTURE PERFORMANCE ANALYSIS

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. In this, chapter, the effects of the different compaction methods are studied in terms of its performance to fatigue and rutting.

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. The resistance of a mix to fatigue cracking depends on the material properties such as initial flexural loss stiffness and voids filled with asphalt (VFA) and the pavement structural property, horizontal tensile strain at the bottom of the asphalt concrete layer. 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. For this purpose, 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 in this analysis.

Three different pavement structures are considered for the analysis. The Auburn mixtures were taken from the NCAT test tracks. The Charlotte and the Kinston mixtures were taken from locations with different pavement structures. For the Auburn mixtures, each surface layer is 3 inches thick, placed in 2-1.5 inches lift. Below these mixtures is approximately 19" of base.

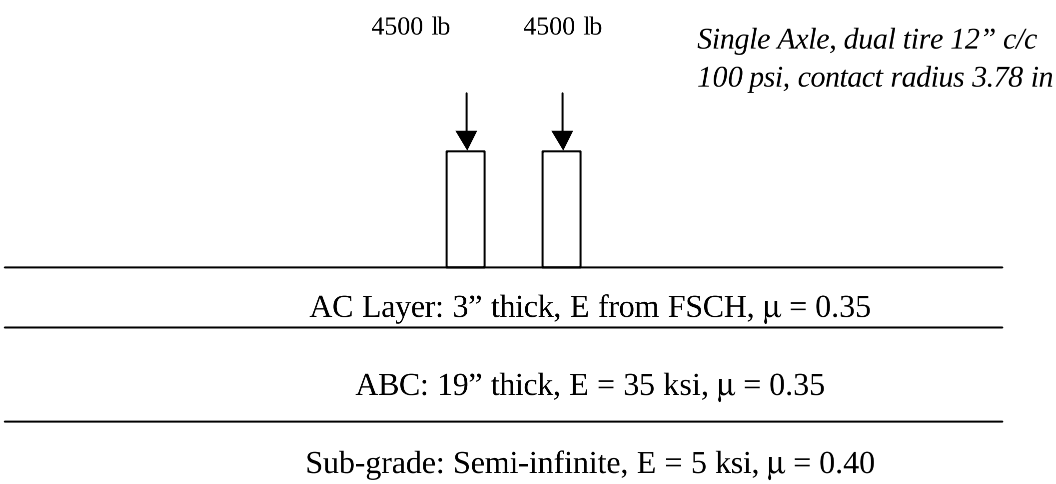

Figure 6.1 Typical Pavement Structure and Loading for Auburn Mixtures

For the Charlotte mixtures, the surface layer is 2.4" thick (60mm) and below that is a structural layer of 3.6" thick (90mm) with I19.0B. The ABC is 8" (200mm) thick.

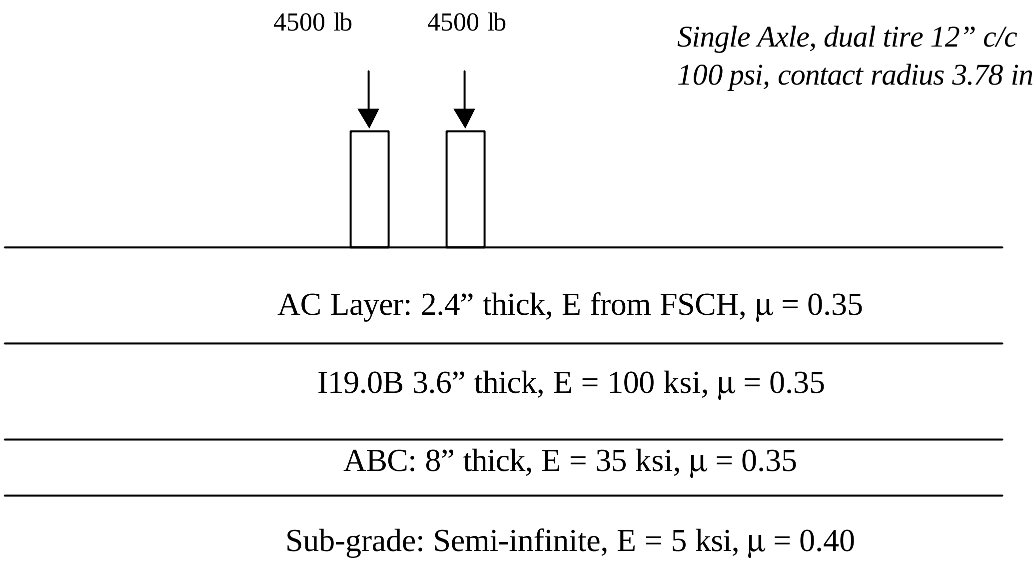

Figure 6.2 Typical Pavement Structure and Loading for Charlotte Mixtures

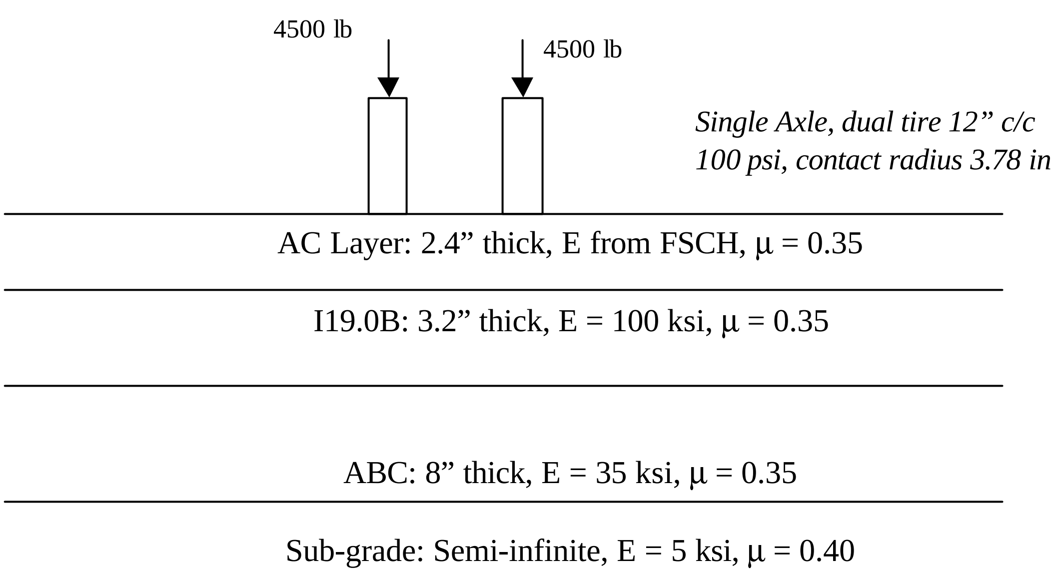

Figure 6.3 Typical Pavement Structure and Loading for Kinston Mixtures

For the Kinston mixtures, the pavement has 8" (200 mm) of ABC, 3.2" (80 mm) of I19.0B, and 2.4" (60 mm) of surface mix.

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

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

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

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

Mixture	Compaction	|G*| psi	Phase Angle	Go' psi	Go"	So'	So"
Auburn Coarse	Field Cores	2.30E+09	16.32	3.20E+05	9.37E+04	9.10E+05	3.26E+05
	RWC	2.42E+09	8.95	3.47E+05	5.46E+04	9.78E+05	2.21E+05
	SGC	2.39E+09	16.94	3.32E+05	1.01E+05	9.39E+05	3.45E+05
Auburn Fine	Field Cores	1.96E+09	18.73	2.69E+05	9.13E+04	7.77E+05	3.20E+05
	RWC	2.40E+09	10.85	3.42E+05	6.55E+04	9.66E+05	2.52E+05
	SGC	2.98E+09	13.27	4.21E+05	9.92E+04	1.17E+06	3.40E+05
Charlotte	Field Cores	9.45E+08	33.34	1.14E+05	7.53E+04	3.56E+05	2.79E+05
	RWC	1.31E+09	25.03	1.72E+05	8.04E+04	5.16E+05	2.92E+05
	SGC	1.44E+09	25.41	1.89E+05	8.96E+04	5.61E+05	3.16E+05
Kinston	Field Cores	6.63E+08	37.51	7.63E+04	5.85E+04	2.46E+05	2.32E+05
	RWC	1.21E+09	24.76	1.59E+05	7.35E+04	4.81E+05	2.74E+05
	SGC	1.22E+09	23.07	1.63E+05	6.93E+04	4.91E+05	2.62E+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.

The results are summarized in Table 6.2 and compared in Figure 6.4.

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

Mixture	Compaction	So"	VFA	Strain	Nsupply	Difference
Auburn Coarse	Field Cores	3.26E+05	72.29	0.000154	4.75E+06	-
	RWC	2.21E+05		0.000148	1.59E+07	234 %
	SGC	3.45E+05		0.000151	4.36E+06	-8%
Auburn Fine	***Field Cores***	3.20E+05	73.12	0.000167	3.93E+06	-
	RWC	2.52E+05		0.000149	1.15E+07	193 %
	SGC	3.40E+05		0.000134	7.43E+06	89%
Charlotte	Field Cores	2.79E+05	77.48	0.000139	1.59E+07	-
	RWC	2.92E+05		0.00014	1.34E+07	-16%
	SGC	3.16E+05		0.00014	1.10E+07	-31%
Kinston	Field Cores	2.32E+05	75.59	0.000132	2.69E+07	-
	RWC	2.74E+05		0.000145	1.21E+07	-55%
	SGC	2.62E+05		0.000145	1.36E+07	-49%

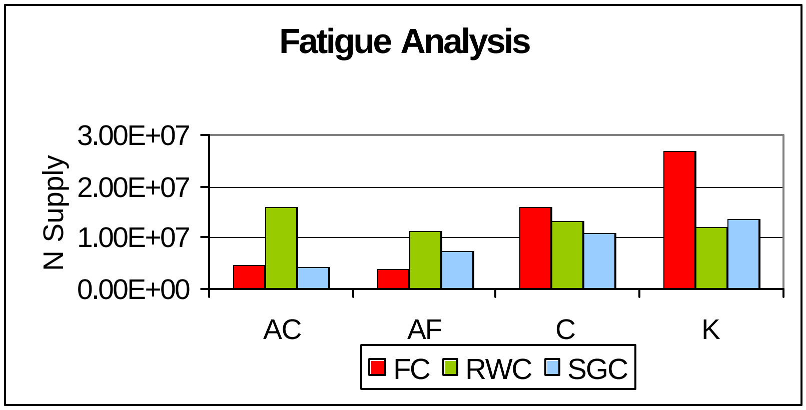

Figure 6.4 Comparison of Fatigue Life

For 12.5mm mixtures, RWC specimens had the longest fatigue life whereas for the 9.5mm mixtures, field cores had the longest fatigue life. Unlike the frequency sweep test results, the results of fatigue analysis did not give a definite trend. The higher Nsupply values of RWC specimens for the Auburn mixtures can be attributed to smaller phase angles, which in turn decreased the flexural loss stiffness. The fatigue life of field cores and SGC specimens of Auburn mixture were almost equal as were their corresponding phase angles. For the 9.5mm mixtures, the fatigue life of field cores was longer than those of laboratory compacted specimens. This behavior is attributed to the smaller flexural loss stiffness values of field cores.

The shear stiffness values of the 12.5mm mixtures were almost double that of the 9.5mm mixtures. Despite their higher stiffness values, the 12.5mm mixtures had shorter fatigue life than the 9.5 mixtures due to their lower VFA values. Given the fact that each mixture had different pavement structure, the ranking of mixtures in terms of their fatigue lives would be inappropriate.

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.

$$N_f = 0.00796 * \varepsilon_t^{-3.291} * E_1^{-0.854} \tag{6-4}$$

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)

Mixture	Compaction	Strain	So'	Nsupply
Auburn Coarse	Field Cores	1.54E-04	9.10E+05	2.30E+05
	RWC	1.48E-04	9.78E+05	2.46E+05
	SGC	1.51E-04	9.39E+05	2.36E+05
Auburn Fine	Field Cores	1.67E-04	7.77E+05	2.00E+05
	RWC	1.49E-04	9.66E+05	2.43E+05
	SGC	1.34E-04	1.17E+06	2.91E+05
Charlotte	Field Cores	1.39E-04	3.56E+05	7.22E+05
	RWC	1.40E-04	5.16E+05	5.04E+05
	SGC	1.40E-04	5.61E+05	4.77E+05
Kinston	Field Cores	1.32E-04	2.46E+05	1.16E+06
	RWC	1.45E-04	4.81E+05	4.75E+05
	SGC	1.45E-04	4.91E+05	4.68E+05

The AI method of fatigue analysis indicated that field cores of the Charlotte and the Kinston mixtures had longer fatigue life than the laboratory compacted specimens. For 12.5 mixtures, there was no significant difference among the three methods of compaction. SHRP fatigue model considers tensile strain, loss flexural modulus and voids filled with asphalt whereas the AI model considers only the tensile strain and the modulus of elasticity. So SHRP fatigue model provides more dependable results than the AI model.

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.

Rut depth (in.) = 11 * Maximum permanent shear strain *(6-5)*

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 (3) 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 true 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 and compared in Figure 6.5

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

Mixture	Compaction	Shear Strain	Rut Depth	Cycles	NSupply
Auburn Coarse	Field Cores	0.0270	0.30	5000	> 3156232
	RWC	0.0163	0.18	5000	> 3156232
	SGC	0.0132	0.15	5000	> 3156232
Auburn Fine	Field Cores	0.0245	0.27	5000	> 3156232
	RWC	0.0180	0.20	5000	> 3156232
	SGC	0.0150	0.17	5000	> 3156232
Charlotte	Field Cores	0.0455	0.50	802	721440
	RWC	0.0210	0.23	5000	> 3156232
	SGC	0.0129	0.14	5000	> 3156232
Kinston	Field Cores	0.0455	0.50	677	629306
	RWC	0.0455	0.50	3300	2257563
	SGC	0.0283	0.31	5000	> 3156232

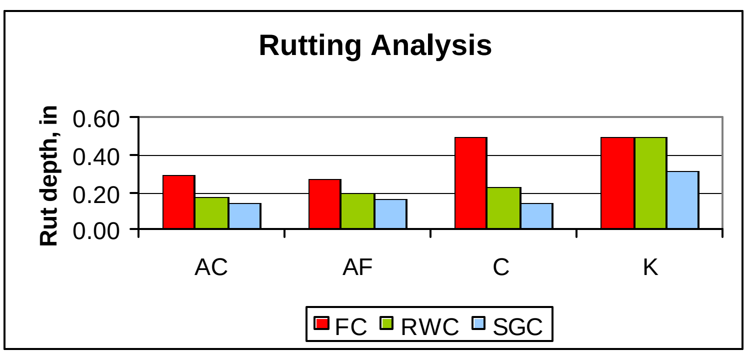

Figure 6.5 Comparison of Rut Depths

The results of rutting analysis clearly showed that the rut susceptibility of field cores was generally higher than RWC specimens and SGC specimens. The rut depths of RWC specimens were higher than the rut depths of SGC specimens. This trend is noticed in all mixtures, irrespective of the nominal maximum size of aggregate or gradation. In other words, it is evident that SGC specimens provided lower rut depths as compared to field cores. It should be borne in mind that there is no difference in air voids among the different methods of compaction as the laboratory specimens were compacted at the corresponding average densities of field cores for different mixtures. The rolling wheel compacted specimens seemed to better simulate the field conditions than the Superpave Gyratory Compactor.

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 was 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)

Mixture	Compaction	Shear Strain	***Nd***
Auburn Coarse	Field Cores	4.70E-04	1079545
	RWC	4.66E-04	1123575
	SGC	4.68E-04	1098346
Auburn Fine	Field Cores	4.79E-04	992807
	RWC	4.67E-04	1115408
	SGC	4.55E-04	1247194
Charlotte	Field Cores	8.90E-04	62180
	RWC	8.50E-04	76270
	SGC	8.42E-04	79569
Kinston	Field Cores	9.75E-04	41244
	RWC	9.02E-04	58435
	SGC	9.00E-04	59019

The analysis show that the SGC specimens tolerated higher number of load repetitions than the field cores. There seemed to be no significant difference between the results of SGC and RWC specimens. The AI method of rutting analysis utilizes only the flexural modulus of mixtures. 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 layer primarily dictate the rutting behavior of a given pavement. As this study involved the evaluation of the mixtures with respect to their rutting potential, the SHRP rutting model was employed for this purpose

6.3 Correlation of APA Test Results

Permanent deformation or rutting in asphalt concrete pavements can be measured using different performance evaluation procedures. The commonly used procedures, as indicated by the literature (20) are as follows:

- Diametral tests
- Uniaxial tests
- Triaxial tests
- Shear tests
- Empirical tests (Marshall test, Hveem test etc)
- Simulative tests (APA, PurWheel, HWTD, MMLS etc)

Among these, shear tests, empirical tests and simulative tests are more common. Shear tests, though fundamental, are very expensive, complicated and unreasonable for QC testing. Empirical tests such as Marshall test, Hveem test etc have been used for years with limited success. Simulative tests such as APA are simple, easy to perform. Literature shows reasonable correlation between the test results and field performance.

One of the objectives of this study was to investigate how the mixture performance as measured by the APA correlates with that of the other performance evaluation procedures and devices. The tests results as measured by the APA were compared with the RSCH test results and NCSU WTD test results. The NCSU WTD rut test is an accelerated wheel tracking tests that falls in the category of simulative tests. The WTD device has certain advantages over other simulative tests. The device uses rolling wheel compacted slabs and field slabs. The load is applied to through a rubber tire similar to a pneumatic tire used in vehicles.

Table 6.7 summarizes the test data as measured by the APA, RCSH and WTD rut tests. The data are converted into same scale (inches), as these test systems measure in different units such as mm and inch. Rut depths of APA measured in mm are converted to inches.

Table 6.7 Rut Depths (inches)

Mixture	Field Compaction			RWC			SGC	
	Shear	APA	WTD	Shear	APA	WTD	Shear	APA
Auburn Coarse	0.30	0.195	N.A	0.18	0.197	0.174	0.15	0.101
Auburn Fine	0.27	0.429	N.A	0.20	0.332	0.199	0.17	0.220
Charlotte	0.50*	0.755	0.607	0.23	0.262	0.171	0.14	0.168
Kinston	0.50*	0.627	0.983	0.50*	0.479	1.069	0.31	0.477

(*) Mixture reaches the limit and further test is stopped

The mixtures that reached the limit in shear tests were the Charlotte (FC), the Kinston (FC) and the Kinston (RWC). These mixtures had experienced the maximum allowable rut depth of 0.5 inch. The mixtures failed at different number of cycles (below 5000) which triggered the termination of the test. The corresponding rut depths of failed mixtures, measured using the APA or WTD, had either crossed 0.5 inch or almost reached 0.5 inch of rutting. None of the mixtures that passed the repeated shear tests had reached 0.5 inch of rutting. This fact explains the good correlation among the different test systems. Therefore, it seems that like the shear tests, the simulative tests such as the NCSU WTD or the APA can also effectively detect poorly performing mixtures.

Different parameters established using the test systems in this study were correlated with each other. The strength of the correlation is measured using the coefficient of multiple determination (R^2). The corresponding data of two parameters were plotted on a scatter plot and the regression equation of the relationship was also determined.

The rut depths measured using the APA tests are related with the rut depths estimated using the shear test data. The rut depth calculated using the SHRP Surrogate models is a simple multiplication of the corresponding shear strain by 11. Figure 6.6 shows the scatter plot between the rut depths as measured using the APA and shear tester.

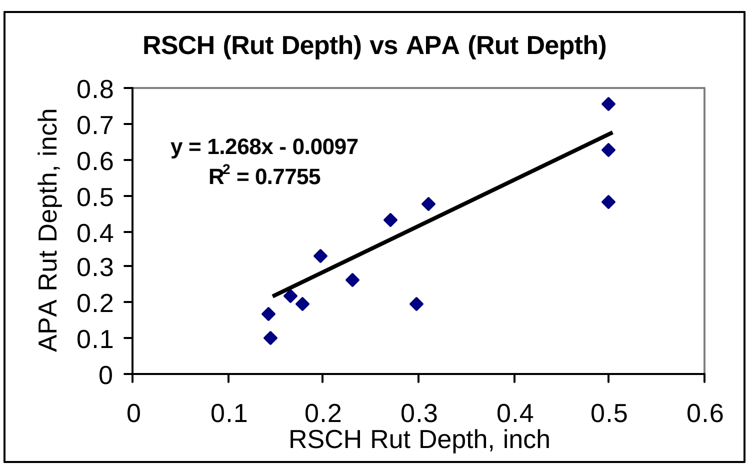

Figure 6.6 Correlation of RSCH Rut Depth and APA Final Rut Depth

It should be borne in mind that the RSCH rut depths of failed mixtures remain at 0.5 inch, though the mixtures failed at different number of cycles. In spite of the above fact, the R^2 value of 0.78 indicates a reasonably strong correlation between APA tests and shear tests.

It was observed from the APA tests that the initial rate of deformation was higher than the final rate of deformation. The rut depth after 1000 cycles was taken into account along with the final rut depth after 8000 cycles. The rut depth after 1000 cycles as measured by the APA were correlated with the rut depths estimated by the shear tests. Figure 6.7 shows the scatter plot between the rut depths after 1000 cycles with rut depths of shear test data.

The correlation between the APA rut depths after 1000 cycles and rut depths of shear tests are strong. The R^2 value of this relationship is about 0.78, almost equal to that of the final rut depth after 8000 cycles.

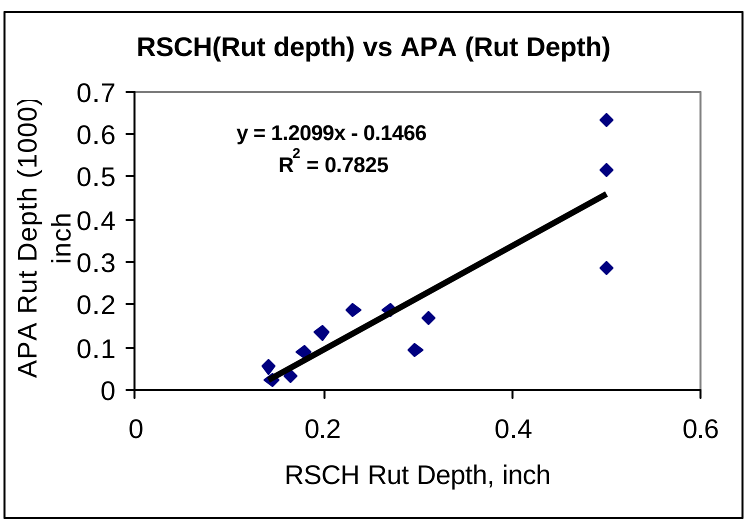

Figure 6.7 Correlation of RSCH Rut Depth and APA Initial Rut Depth

The mixtures of RWC type were tested using the APA and the NCSU Wheel Tracking Device. Though the limited number of data points, the rut depths of APA and WTD were correlated. Figure 6.8 shows this correlation in terms of the scatter plot between the APA final rut depth and WTD final rut depth. The R^2 value of the relationship was 0.81. This indicates a reasonale correlation between the predictability of the APA and the NCSU WTD.

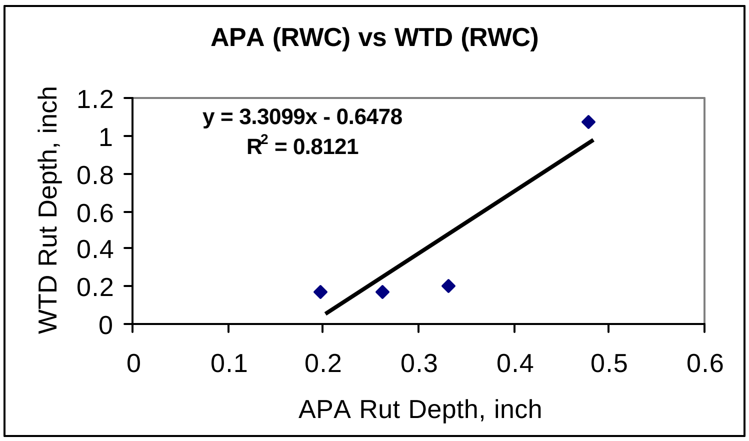

Figure 6.8 Correlation of WTD and APA Final Rut Depth of RWC

It was observed from the NCSU WTD test data that about 80% of the total rutting occurs in the first 2000 cycles. The rut depths after 2000 cycles were measured by the NCSU WTD were correlated with the APA rut depths after 1000 cycles. Figure 6.9 shows the scatter plot between the initial rut depths of APA and NCSU WTD. The R^2 value of 0.79 indicates a strong correlation between the initial rut depths of the APA and the NCSU WTD.

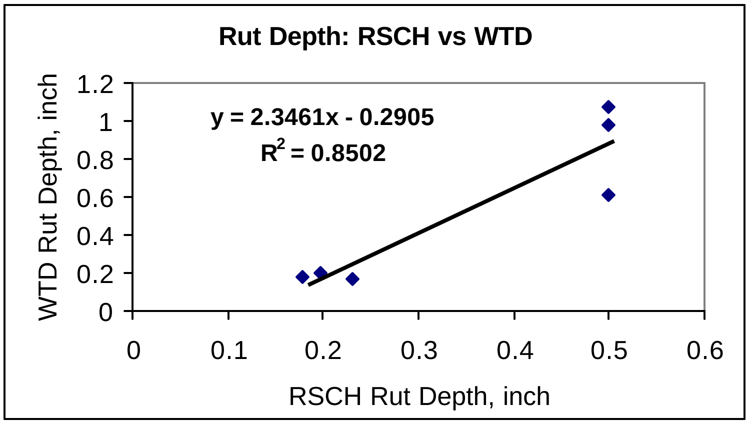

Figure 6.9 Correlation of Initial Rut Depths of APA and WTD

The WTD rut depths for the field slabs as well as the RWC slabs were correlated with the rut depths estimated using the shear test data. Figure 6.10 shows the scatter plot between the rut depths of WTD and Shear tester. The R^2 value of the above correlation is 0.85, which also indicates the existence of a reasonable correlation between the two test systems.

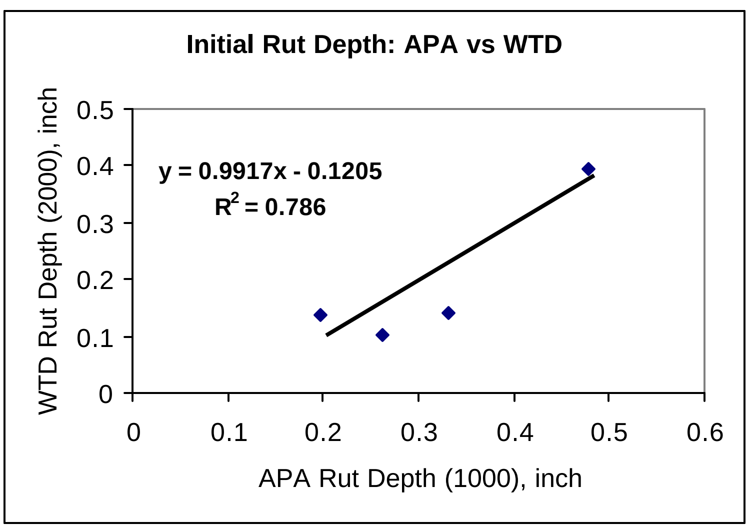

Figure 6.10 Correlation of RSCH Rut Depth and WTD Final Rut Depth

The R^2 values of all the relationships are above 0.75. This indicates that a strong correlation exists among the test results as measured by the Shear tester, the APA and the NCSU WTD. This supports the fact that simulative tests such as APA and the NCSU WTD can be used to detect poorly performing mixtures as effectively as the shear tests.

CHAPTER 7

SUMMARY OF RESULTS AND CONCLUSIONS

A laboratory mix design system aids in predicting the in-service performance of the asphalt mixtures through various performance evaluation tests. The compaction methods adopted in the laboratory for specimen fabrication are expected to simulate the properties of the pavement in the field. The physical properties of the specimens depend on the method of compaction used for fabrication. It is desirable that the laboratory compaction of specimens should be a true indicator of field performance. The effects of different compaction methods on the performance of mixtures have been investigated in this study.

The central objective of this study was to evaluate as to how the different compaction methods affect the performance of the mixtures. Laboratory compaction methods such as Superpave Gyratory Compaction (SGC) and Rolling Wheel Compaction (RWC) were compared with the field compaction. Four field mixtures had been selected for this purpose. Loose mixtures from the test sites were utilized for laboratory compaction of mixtures. The mixtures were identified as Auburn Coarse, Auburn Fine, Charlotte and Kinston. The Auburn mixtures were 12.5mm mixtures whereas the Charlotte and the Kinston mixtures were 9.5mm mixtures.

The performance parameters of the mixtures include fatigue and rutting distresses. Permanent deformation or rutting in hot mix asphalt pavements is caused by the consolidation or lateral movement, or both, of the HMA under traffic. The rutting susceptibility of the mixtures was investigated using fundamental test method such as Shear test and simulative tests using the APA and the NCSU WTD. The results of these test systems were compared and correlated.

Compaction characteristics of the individual mixtures were studied using the Superpave Gyratory Compactor and the Gyratory Load-Cell Plate Assembly (GLPA). Densification of mixtures obtained from the SGC revealed that no mixture had four percent air voids at design number of gyrations. Percent Air at N_{des} was around 3% for the Auburn mixtures, whereas the percent air values were 6.3% and 4.9% for the Charlotte and the Kinston mixtures, respectively. The Charlotte mixture did not reach four- percent voids even at its maximum number of gyrations. The slopes of the compaction curves of the mixtures were computed. The compaction slope is an indication of an aggregate structure's resistance to compaction. Since the SGC operates as a gyratory shear compactor, the slope of the compaction curve might be considered related to the shear resistance of the aggregate structure. In this regard, the Auburn Coarse mixture had the highest compaction slope whereas the Kinston mixture had the lowest compaction slope. The slopes of the Auburn Fine mixture and the Charlotte mixture were similar to each other. The compaction slopes seemed to suggest that the Auburn Coarse mixture had the highest shear resistance and the Kinston mixture had the lowest shear resistance among all the mixtures.

The mixtures were compacted using the SGC and the GLPA for the computation of energy indices. The volumetric properties estimated using the Pine SGC agreed with those properties estimated using the Troxler SGC. The Auburn mixtures were gyrated to 160 gyrations while the Charlotte and the Kinston mixtures were gyrated to 600 gyrations. The Charlotte mixture did not reach 98 percent of its maximum theoretical density even after 600 gyrations.

The energy indices, Construction indices and Traffic indices, are the measures of densification and distortion under construction and under traffic. As per the definition, the construction indices are the integration of the area under the densification curve between the first gyration and the 92% G_{mm}. On the other hand, the traffic indices are the integration of the area under the densification and resistive work curves between 92%G_{mm} and 98% G_{mm}.

The Compaction Densification Index (CDI) and Compaction Force Index (CFI) are used to evaluate the performance of mixtures during construction. This effort is the work applied by the pavers/rollers to compact the mix to the required density during construction. Mixes that require lower compaction energy are desirable. The compaction indices indicate that the Charlotte mixture is the harshest mixture to compact. The Kinston mixture follows next. The Auburn mixtures have lower indices than other mixtures. The Auburn Fine is the most desirable mixture for compaction followed by the Auburn Coarse.

The Traffic Densification Index (TDI) and Traffic Force Index (TFI) are used to evaluate the performance of mixtures during traffic. Higher traffic indices indicate that the mixture would require more traffic to reach their terminal density and, in other terms, longer rut life. The traffic indices show very high values for the Charlotte and the Kinston mixtures and very low values for the Auburn mixtures. A possible explanation could be that the Charlotte and the Kinston mixtures being harsh took more number of gyrations to reach 98 percent of their maximum theoretical density. Obviously, the Auburn mixtures were easier to compact given that the mixtures reached their 98 percent Gmm in fewer gyrations. The compactability of the mixtures severely influenced the values of traffic indices. However, the traffic indices (TDI and TFI) do not adequately explain the rutting potential of the mixtures with different sources of aggregates. Therefore, the reverse trend between the construction indices and traffic indices was not observed, as the aggregate sources of these mixtures remained different. The interpretation of rutting characteristics of mixtures from their traffic indices was not attempted due to these discrepancies.

In order to evaluate the effect of different compaction methods, various performance evaluation tests were conducted on the field cores and specimens fabricated using the SGC and RWC. Performance evaluation was done using test systems such as Shear tester, APA and NCSU WTD. The results of FSCH and RSCH tests were then analyzed using the SHRP A 003-A surrogate models and the Asphalt Institute (AI) method. The AI method considers only the mixture stiffness; on the other hand, surrogate models use various mixture properties such as shear strain, flexural stiffness and voids filled with asphalt. Therefore, the results of SHRP surrogate models are considered more dependable and are given more credence for the purpose of this discussion.

The FSCH test measured dynamic modulus and phase angles at 20^{o}C and at various frequencies. The values of dynamic modulus (G*) at 10Hz showed that the 12.5mm mixtures were stiffer than the 9.5mm mixtures. The same behavior was noticed for all the three methods of compaction. The gyratory compacted mixtures had the highest stiffness followed by the rolling wheel compacted mixtures. The field cores had lowest stiffness values for all four mixtures. The estimates of fatigue life do not agree with the trend shown by the dynamic modulus. The RWC mixtures had the longest fatigue life for the Auburn mixtures and on the other hand, the field cores had the longest fatigue life for the Charlotte and the Kinston mixtures. For the Auburn mixtures, the fatigue lives of field cores and SGC mixtures were almost equal. For the Charlotte and the Kinston mixtures, the fatigue lives of RWC and SGC mixtures were almost equal. The reason for the above mixed trend can be attributed to the trend of phase angles. For the Auburn mixtures, the phase angles of RWC were the lowest. For the Charlotte and the Kinston mixtures, the phase angles of RWC and SGC were almost the same, whereas the phase angles of the field cores were the highest. Higher phase angles increase the loss flexural modulus of the mixtures and the critical tensile strain at the bottom of the AC layer. This, in turn, decreases the fatigue life of the mixtures. Thus the phase angles attributed to the mixed trend of fatigue life of the mixtures.

The shear strains were measured using the RSCH test. The rut depths were estimated using the SHRP Rutting model. The Auburn mixture specimens prepared with all of the compaction types passed the 5000-cycle criteria. The field cores and RWC specimens of the Kinston mixtures failed at 677 and 3300 cycles of loading, respectively. For the

Charlotte mixtures, the field cores failed early at 802 cycles of loading while the laboratory compacted specimens passed the shear tests and their shear strains were very low. The shear strain of the SGC specimens was the lowest among the three-compaction methods for all the mixtures. The shear strains of RWC specimens are higher than those of SGC specimens. The field cores had the highest shear strain of all the mixtures. The results of the RSCH test show that specimens fabricated using the SGC tend to provide superior performance. The rolling wheel compaction, whose results are in between the SGC and field cores, seems to simulate field conditions better than the SGC.

Rutting characteristics of the mixtures were also measured using the Asphalt Pavement Analyzer (APA). The rut depths were measured at the end of 8000 cycles. The results of the APA tests showed that the SGC specimens had the lowest rut depths. The rut depths of the field cores were higher than the rut depths of the RWC specimens. The field cores of the Charlotte mixture rutted more severely than the RWC and SGC specimens. These results seemed to be in agreement with the RSCH test results.

As the initial rate of deformation was higher than the final rate of deformation in the APA tests, the rut depths at the end of 1000 cycles were determined which demonstrated the initial rutting behavior of the mixtures. The results show that the rut depths of SGC specimens had the lowest rut depths, followed by the RWC specimens. Field cores exhibited very high rut depths at the end of 1000 cycles. The Initial Rut Ratio, the ratio of the rut depth after 1000 cycles to the rut depth after 8000 cycles, was calculated for all the mixtures. The initial rut ratio seems to be influenced by the maximum size of the aggregate and the type of compaction method. In general, the 12.5mm mixtures have lower initial rut ratios than the 9.5mm mixtures. Field cores have the highest initial rut ratios whereas the SGC samples have the lowest initial rut ratios. For RWC samples, the initial rut ratios are found in between the initial rut ratios of field cores and SGC samples. This ratio could be a measure of the initial rutting resistance offered primarily by the aggregate skeleton of a mixture.

The results of the APA tests were used to estimate the viscoelastic parameters such as E and viscosity (η) using the Kelvin model. The estimated E value is not the real modulus of elasticity but could be considered as a "pseudo" modulus. The retardation time, t_c, at which 63 % of the total strain occurs, was also calculated. The retardation times of the SGC mixtures were greater than the retardation times of RWC specimens and field cores.

The results of the APA tests showed that the field cores had the higher rutting potential than the RWC specimens and the SGC specimens for all mixtures. The same trend was seen in the results and the estimates of the APA tests and the RSCH tests. The gyratory compaction provides specimens that tend to overestimate the field performance. The rolling wheel compaction of specimens seems to simulate field conditions better than the SGC.

The NCSU WTD rut tests were performed on RWC slabs of all mixtures and field slabs of the Charlotte and the Kinston mixtures. Field slabs of these mixtures produced deeper ruts than the RWC slabs at the end of 10000 cycles. Initial rut depths at the end of 2000 cycles produced a similar trend. Initial rut ratios showed that field slabs rutted faster than roller compacted slabs.

In general, the results of the rutting tests evaluated using the RSCH, APA and NCSU WTD indicated the same trend. The specimens fabricated using the SGC had lowest rut depths, followed by the RWC. The field specimens not only had highest rut depths but also rutted faster than the laboratory fabricated specimens. The Superpave Gyratory Compaction (SGC) tends to provide better performance and under predicts the field rutting potential. The Rolling Wheel Compaction (RWC) seems to simulate more realistic field compaction and produce field conditions better than the SGC. It is evident that the method of compaction has a profound influence on the performance of the mixtures. This fact could be possibly due to the difference in the internal structure of the compacted mixes, as explained in the literature. The differences in the distribution of air voids and aggregates orientation inside the mixture are referred to as the internal structure. Rolling wheel compacted specimens would be expected to have increasing air void contents from top to bottom of the lift, as do field specimens (8). Air void contents are expected to be fairly homogeneous in the horizontal plane of the rolling wheel. However for the SGC, the middle of the SGC specimen is compacted more than the top and the bottom, and the interior of the specimen is expected to become better compacted than the exterior (9).

The accelerated performance tests are simple, inexpensive and require less expertise than the fundamental tests such as the Shear tests. One objective of this study was to find whether performance evaluation devices such as APA could clearly detect poorly performing mixtures. The results of the APA tests were correlated with the results of the RSCH test and the NCSU WTD. When the results of all the test systems were converted to a same scale of inches and summarized, the comparison reveals that the mixtures that had failed in the RSCH test had rut depths greater than 0.5 inch in APA and NCSU WTD. Interestingly, none of the mixtures that passed the RSCH test had rut depths greater than 0.5 inch in other test systems either. These observations strongly suggest that the rut depth of 0.5 inch could be opted as “pass/fail” or “go-no go” criteria for APA tests.

The results of the APA and RSCH tests were correlated. The R^2 value of 0.78 indicates a reasonably strong correlation between the two tests despite the fact that the RSCH test uses 0.5 inch as rut depth for all failed mixtures. During the RSCH test, a mixture fails when it reaches the maximum shear strain. The failure occurs at different number of cycles for different mixtures. However, the SHRP rutting model estimates a rut depth of 0.5 for all failed mixtures even though the mixtures had failed at different cycles of loading. If the failed mixtures are allowed to 5000 cycles of loading, the shear strains as well as the rut depths would be much higher and a better correlation can be expected.

The results of APA and NCSU WTD tests on RWC specimens were also correlated. The R^2 value of the relationship was 0.81. This again, indicates a strong correlation between the predictability of the APA and the NCSU WTD. This correlation was done with limited availability of test data. The correlations among the different test parameters of RSCH, NCSU WTD and APA strongly support the premise that the predictability of the accelerated tests is as appealing as the fundamental tests like Shear tests. The APA can also detect poorly performing mixtures as one of the performance evaluation devices.

The performance evaluation tests were conducted at the densities of the field cores. The laboratory-fabricated specimens were compacted to the average density of the field cores. The air voids of the individual mixtures were different. One of the objectives of this study was to evaluate how changes in aggregate and asphalt source would affect the performance of the mixtures. For this purpose the mixtures were compacted to 4 percent air voids using the SGC, so that a meaningful comparison could be done. The Auburn Coarse mixture has the highest G* among all the mixtures followed by the Auburn Fine, the Charlotte and the Kinston mixtures. The RSCH test results show that the Kinston mixture had the highest shear strain among all the mixtures. The shear strains of the Auburn mixtures and the Charlotte did not differ significantly at four percent air voids.

Conclusions

In summary, the following principal conclusions can be drawn.

1. The laboratory compacted mixtures tend to be superior in their performance than the field cores. In other words, the laboratory compaction by SGC results in under prediction of the field rutting potential of the mixtures. The mixtures compacted using the SGC and the RWC have higher stiffness values and lower shear strain values than the field cores. The Rolling Wheel Compaction (RWC) seems to simulate field compaction better than the SGC.

2. There exists a good correlation among the results of the RSCH tests, the APA tests and the NCSU WTD rut tests. The mixtures, which failed to satisfy the RSCH test criteria, had rut depths greater than 0.5 inch, as measured by the APA and NCSU WTD. The mixtures that passed the RSCH tests had rut depths less than 0.5 inch.
3. The APA test can detect poorly performing mixtures as well as some of the other performance evaluation devices. It is suggested that a rut depth of 0.5 inch could be prescribed in the APA test as “pass/fail” or “go-no go” criteria. This suggested value of 0.5 inch is based on the test data of the four mixtures included in this study. However, more mixtures should be involved for this evaluation to get a better estimate of limiting value of rutting.
4. The NCSU WTD test can also be used as a simulator to examine the rutting susceptibility of a mixture. It seems that the same criterion of 0.5-inch rut depth is suitable for the NCSU WTD also.
5. When the mixtures were examined at four percent air voids, the test results indicated that the Auburn mixtures (12.5-ARZ and 12.5-BRZ) had higher G* values at 10 Hz than the Charlotte (9.5-BRZ) and the Kinston mixtures (9.5-ARZ). The RSCH test results indicated that the Kinston mixture had the highest rutting potential among all the mixtures. The rutting characteristics of other mixtures were almost similar.
6. Construction indices, as measured by the SGC and the GLPA, showed that the Auburn mixtures were more desirable from construction standpoint as these mixtures appeared to be easy to compact. The Charlotte mixture was the most difficult mixture to compact followed by the Kinston mixtures. The performance evaluation of the mixtures using the traffic indices was not attempted in this study.

REFERENCES

1. Philip B. Blankenship et al, “Rational Method for Laboratory Compaction of Hot-Mix Asphalt”, *Transportation Research Record 1454*, pp 144-153.
2. M.N Partl and L.Francken, “Basic Elements of a Testing Methodology for Bituminous Materials and significant features for testing”, *Bitumious Binders and Mixes*, Report of RILEM Techinical Committee 152 PBM, pp 1-10.
3. Carl. M. Monismith, “Asphalt Concrete: An Extraordinary Material for Engineering Applications”, *Thirtieth Henry M. Shaw Lecture*, North Carolina State University.
4. Gerald A. Huber, “Development of the Superpave Gyratory Compactor”, http://www.utexas.edu/research/superpave/articles/gyr_hist.html
5. B.A. Vallerga, “Recent Laboratory Compaction Studies of Bituminous Paving Mixtures”, *Proc. Association of Asphalt Paving Technologists*, Vol 21, 1951, pp.117-153
6. Von Quintus et al, “Comparative Evaluation of Laboratory Compaction Devices Based on Their Ability to Produce Mixtures with Engineering Properties similar to those produced in the Field,” *Transportation Research Record 1228*, pp 80-87.
7. Joe W. Button et al, “Correlation of Selected Laboratory Compaction Methods with Field Compaction”, *Transportation Research Record 1454*, pp 193-201
8. John Harvey et al, “Effects of Laboratory Specimen Preparation on Aggregate-Asphalt Structure, Air-Void Content Measurement, and Repetitive Simple Shear Test Results,” *Transportation Research Record 1454*, pp 113-122.
9. Eyad Masad, “Quantifying Laboratory Compaction Effects on the Internal Structure of Asphalt Concrete”, *Transportation Research Record 1681*, pp 179-185.

10. Brian J Coree and Kera VanDerHorst, ‘Superpave Compaction”, Crossroads 2000, Tranportation Conference Proceedings, pp 264-267 http://www.ctre.iastate.edu/pubs/crossroads/264superpave.pdf

11. Bahia, H., Friemel, Timothy, Peterson, Pehr and Russell, Jeffrey. Optimization of Constructability and Resistance to Traffic: A New Design Approach for HMA Using the Superpave Compactor. Proc., Association of Asphalt Paving Technologists, Vol 67, 1998, p 189

12. L.A. Cooley Jr., P.S. Kandhal, M.S. Buchanan, F. Fee, & A. Epps, “Loaded Wheel Testers In the United States: State of the Practice”, NCAT Report No 2001-04, Transportation Research E-Circular E-C016, July, 2000. http://www.nas.edu/trb/publications/circulars/ec016.pdf.

13. Lai, J. S. “Evaluation of Rutting Characteristics of Asphalt Mixes Using Loaded Wheel Tester”. Project No. 8609, Georgia Department of Transportation, Dec. 1986.

14. Collins, R., H. Shami, and J. S. Lai. “Use of Georgia Loaded Wheel Tester To Evaluate Rutting of Asphalt Samples Prepared by Superpave Gyratory Compactor”, Transportation Research Record 1545, TRB, National Research Council, Washington, D.C., Nov. 1996, pp. 161-168.

15. Kandhal, P. S., and R. B. Mallick. “Evaluation of Asphalt Pavement Analyzer for HMA Mix Design.” NCAT Report No. 99-4, National Center for Asphalt Technology, June1999.

16. Aschenbrener, T. “Evaluation of Hamburg Wheel-Tracking Device to Predict Moisture Damage in Hot Mix Asphalt”, Transportation Research Record 1492,TRB, National Research Council, Washington, D.C., July 1995, pp. 193-201.

17. Hall, K. D. and S. G. Williams, "Effects of Specimen Configuration andCompaction Method on Performance in Asphalt Concrete Wheel-Tracking Tests", Presented to the Canadian Technical Asphalt Association, June 1, 1999.

18. Bonnot, J. “Asphalt Aggregate Mixtures”, Transportation Research Record 1096, TRB, National Research Council, Washington, D.C., 1986, pp. 42-51.

19. Epps, A., T. Ahmed, M. Mikhail, and F. Hugo, “Performance Prediction with the MMLS3 WesTrack” Paper to be submitted for publication in the Journal of the Association of Asphalt Paving Technologists, March 19-21, 2001.

20. Brown, E.R., Kandhal, P.S., Jingna Zhang, “Performance Testing for Hot Mix Asphalt (Executive Summary), NCAT Report No 2001-05 A, Nov 2001 http://www.eng.auburn.edu/center/ncat/reports/rep01-05A.pdf

21. Superpave Level 1 Mix Design, Superpave Series No.2 (SP-2), Asphalt Institute, Lexington.

22. R. Michael Anderson and Hussian U. Bahia, “Evaluation of Aggregate Gradation for Asphalt Mixtures,” Transportation Research Record 1583,TRB, National Research Council, Washington, D.C., 1997, pp. 91-97

23. Rajib B.Mallick, “Use of Superpave Gyratory Compactor to Characterize HMA”, Transportation Research Record 1681,TRB, National Research Council, Washington, D.C., 1999, pp. 86-96

24. Guler, M, Bahia, HU, Bosscher, PJ., and Plesha, ME., “Device for Measuring Shear Resistance of Hot-Mix Asphalt in Gyratory Compactor”, Transportation Research Record 1723, 2000, pp 116-124.

25. Stakson A.D., Bushek, J.J. and Hussian U. Bahia, “Effect of Fine Aggregate Angularity (FAA) on Compaction and Shearing Resistance of Asphalt Mixtures,” (Unpublished).

26. Standard Method for Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot Mix Asphalt using the Simple Shear Test Device, AASHTO TP-7, American Association of State Highways and Transportation Officials, Washington, D.C., 1996

27. Hla Kyi and Rajib B. Mallick “Evaluation of Rutting Potential and Viscoelastic Properties of HMA with the APA” (Unpublished).