RESEARCH & DEVELOPMENT

VALIDATION OF APA DESIGN CRITERIA FOR FIELD SURFACE MIXTURES

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by

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Several test methods are in practice to assess the rutting potential of a mixture. The commonly used procedures are Diametral tests, Uniaxial test, Triaxial tests, Shear tests, Empirical tests, and Simulative tests. Of all these test methods, simulative test methods are relatively easier to use and ready for immediate adoption. The APA test is the most widely used simulative test. It is imperative that the rut depth criteria for the APA test should be developed for its employment. In a recent study conducted at NCSU, it was concluded that the APA could clearly detect poorly performing mixtures. With the limited availability of data, a reasonable correlation was observed between the APA tests and Repeated Shear at Constant Height (RSCH) tests.
A comprehensive research study was conducted on all surface mixtures of NCDOT. The rut depths measured from the APA test were compared with the corresponding shear strains of the RSCH test. From HWY-2005-13 project, regression models were developed to characterize the rutting behavior of each individual mix by considering effects of test temperature, aggregate types and traffic volumes. Validation of these models was done using the field cores obtained from NCDOT and further modified models were developed. In addition, the shear and APA tests were fine-tuned by addressing issues related to air voids, test temperatures and aggregate sources. Statistical analysis was performed on the test results as measured by the APA and the RSCH tests. This was used to characterize rut resistance of mixtures used in this study. The correlations estimated using the data obtained from the APA and Shear tests were used to develop rut depth criteria for the APA test. The developed rut depth criteria for the APA test could be adopted for immediate use in practice.</td></tr>
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CHAPTER 1: INTRODUCTION AND PROBLEM STATEMENT

Rutting is one of the main failure mechanisms for asphalt concrete pavements. Premature rutting of asphalt pavements is a serious concern experienced in recent years due to the increased traffic and wheel loads. Rutting is defined as the accumulation of small amounts of unrecoverable strain resulting from applied wheel loads to asphalt pavement. This deformation is caused by excessive traffic consolidation or plastic deformation due to insufficient mixture stability. Rutting is likely to be a failure that would occur in the early stages of a pavement's life. Rutting is a serious problem for a number of reasons; for example, rain can pond in the ruts, increasing the chance for vehicle hydroplaning and subsequent accidents. Excessive ruts can also reduce the effective thickness of a pavement, reducing the structural capacity of the pavement and increasing the likelihood of premature failure through fatigue cracking. Thus, rutting not only decreases the useful life of a pavement but also creates a safety hazard for the traveling public. Therefore, it is important to estimate the rutting potential of a mixture before construction.

Several test methods are in practice to assess the rutting potential of a mixture. The commonly used procedures are Diametral tests, Uniaxial tests, Triaxial tests, Shear tests, Empirical tests, and Simulative tests. Of all these test methods, simulative test methods are relatively easier to use and ready for immediate adoption. Loaded wheel testers (LWT) are becoming increasingly popular with transportation agencies as they seek to identify asphalt mixtures that may be prone to rutting. Of the different laboratory rut testers, the Asphalt Pavement Analyzer (APA) is the most widely used loaded wheel tester. The APA test is not a fundamental test for permanent deformation. It can be considered as a simulative test, which simulates the traffic loading and temperature effects on compacted asphalt mixtures. It is simple to perform and uses cylindrical specimens compacted using the Superpave gyratory compactor (SGC). Various studies have demonstrated the performance of the APA [1, 2, 3].

A recent research project conducted at NCSU (HWY-2005-13) compared the APA test results with the results for fundamental tests obtained on a large variety of asphalt mixtures. Two surface course mixtures (9.5 mm and 12.5 mm mixtures) and three aggregate sources: marine limestone from the Castle Hayne, NC, quarry, natural sand from the Emery pit, NC, and granite from Cabarrus, NC, were used to prepare mixtures. The APA and shear tests were conducted on surface course mixtures and correlations were developed between the results of the shear test and the APA tests. The APA tests were fine-tuned by considering different air voids, test temperatures and aggregate sources to quantify their effects on the predictability of the APA tests. The objective of this research was to establish a correlation between the rut depths measured by APA testing and shear testing, develop a statistical model to predict shear strain using the above correlation and develop the APA rut depth criteria for the mixtures used. The effects of test temperatures, different levels of traffic volumes and aggregate types were characterized to develop several repeated shear at constant height testing (RSCH)-APA regression models. Table 1.1 shows the regression models developed from this project.

Table 1-1: Regression Models for RSCH Shear Strain and APA Rut Depth @ 8000 Cycles

Mix Designation	Regression Model @ 58°C	Regression Model @ PG-High
Average Cycles		
S9.5B	*Predicted RSCH Shear Strain* = -0.0015 + 0.00314**APA Rut Depth*+ 0.00247*(*AGG_L*), R^2 = 0.80	*Predicted RSCH Shear Strain* = -0.00552 + 0.00321**APA Rut Depth*+ 0.00203*(*AGG_L*), R^2 = 0.86
S9.5C	*Predicted RSCH Shear Strain* = -0.0114 + 0.0105**APA Rut Depth*, R^2 = 0.82	*Predicted RSCH Shear Strain* = -0.0029 + 0.0045**APA Rut Depth*, R^2 = 0.62
S12.5C	*Predicted RSCH Shear Strain* = 0.00463 + 0.005**APA Rut Depth*- 0.00476*(*AGG_G*), R^2 = 0.79	*Predicted RSCH Shear Strain* = -0.00493 + 0.00331**APA Rut Depth*- 0.00433*(*AGG_G*), R^2 = 0.73
S12.5D	*Predicted RSCH Shear Strain* = -0.00296 + 0.00811**APA Rut Depth*+0.0027*(*AGG_G*), R^2 = 0.84	*Predicted RSCH Shear Strain* = 0.0016 + 0.0043**APA Rut*, R^2 = 0.88
Maximum Cycles		
S9.5B	*Predicted RSCH Shear Strain* = -0.0004148 + 0.00369**APA Rut Depth*+ 0.000318*(*AGG_L*), R^2 = 0.74	*Predicted RSCH Shear Strain* = -0.02184 + 0.00662**APA Rut Depth*+ 0.00634*(*AGG_L*), R^2 = 0.87
S9.5C	*Predicted RSCH Shear Strain* = -0.0155 + 0.0145**APA Rut Depth*, R^2 = 0.82	*Predicted RSCH Shear Strain* = -0.00949 + 0.0066**APA Rut Depth*, R^2 = 0.68
S12.5C	*Predicted RSCH Shear Strain* = 0.00579 + 0.00716**APA Rut Depth*- 0.00657*(*AGG_G*), R^2 = 0.81	*Predicted RSCH Shear Strain* = -0.00546 + 0.00495**APA Rut Depth*- 0.0057*(*AGG_G*), R^2 = 0.76
S12.5D	*Predicted RSCH Shear Strain* = -0.00347 + 0.00954**APA Rut Depth*+0.00319*(*AGG_G*), R^2 = 0.83	*Predicted RSCH Shear Strain* = 0.0049 + 0.0022**APA Rut*, R^2 = 0.83

These models were used to develop the APA rut depth criteria for different test/traffic conditions. The regression techniques developed in this research had characterized the rut-resistance of mixtures from ‘excellent’ to ‘fair’, when compared with the Asphalt Institute (AI) criteria for evaluating rut resistance using RSCH permanent shear strain. The rut depth criteria for the APA tests have been developed based on a multiple linear regression analysis of the APA test results at the end of 8000 cycles for samples with 7% air voids, the predicted values of RSCH shear strain for samples with 4% air voids for each aggregate type used in the mix. The APA rut depth criteria for the mixtures used in this study and developed for different test temperatures and range of traffic volumes are listed in Tables 1.2 and 1.3. The rutting criteria listed in Tables 1.2 and 1.3 are based on experimental data and the statistical analyses of the results of tests conducted on mixtures used in this study. It can be seen that the models have characterized the effects of aggregate type in a fairly uniform manner with more stringent criteria developed for mixtures containing limestone and granite mixed with natural sand than for those mixtures containing granite only. Table 1.4 lists simple and easy-to-use accept/reject criteria developed for the mixtures used in this research at different test temperatures and traffic volumes.

In spite of the good correlation between the APA and shear test results, there are plenty of other issues that need to be addressed. Earlier research conducted on the APA at NCSU showed that this test was sensitive to different compaction methods. The effect of field compaction method on the predictability of these test results should be addressed. For realistic and accurate relationships between laboratory performance and actual performance in the field, it is important to conduct laboratory tests using field cores. In addition to recommending a specific rut depth criteria for the acceptance/rejection of asphalt mixtures, there is a need to compare and validate model predictions by testing representative field cores from surface mixtures. **Such a validation will assist in formulating more meaningful APA rut depth criteria for design of asphalt mixtures and will be of great benefit for Quality control/Quality assurance purposes. Moreover, the results of HWY-**

2005-13 project show that the amount of rutting is relatively small, with a maximum of 5.5 mm for the granite with 7% natural sand, and all but one of the other combinations rutted less than 4 mm. These limitations could be overcome if reliable and dependable rut depth criteria for the APA test could be implemented by incorporating test results from field cores.

Table 1-2: APA Rut Depth Criteria (in mm) at 58°C for Average and Maximum Traffic Volume

Rut Resistance	APA Rut Depth Criteria (in mm) at 58°C for Average Traffic Volume											
	9.5C			**12.5D**			**9.5B**			**12.5C**		
	G	L	G+N	G	L	G+N	G	L	G+N	G	L	G+N
Excellent	<2.25	<2.25	<2.25	<1.5	<1.75	<1.75	<3.75	<3.0	<3.75	<2	<1	<1
Good	2.25-3	2.25-3	2.25-3	1.5-2.5	1.75-3	1.75-3	3.5-7	3.0-6.0	3.5-7	2 – 4	1-3	1-3
Fair	3-4	3-4	3-4	2.5-3.75	3-4	3-4	7 – 10	6.0-9.5	7 – 10	4-6	3-5	3-5
Poor	>4	>4	>4	>3.75	>4	>4	>10	>9.5	>10	>6	>5	>5
APA Rut Depth Criteria (in mm) at 58°C for Maximum Traffic Volume												
Rut Resistance	**9.5C**			**12.5D**			**9.5B**			**12.5C**		
	G	L	G+N	G	L	G+N	G	L	G+N	G	L	G+N
Excellent	<2	<2	<2	<1.25	<1.5	<1.5	<2.75	<1.75	<2.75	<1.5	<0.75	<0.75
Good	1.75-2.5	1.75-2.5	1.75-2.5	1.25-2.25	1.5-2.5	1.5-2.5	2.75 -5.5	1.75-4.5	2.75 - 5.5	1.5-3	0.75-2	0.75-2
Fair	2.5-3.5	2.5-3.5	2.5-3.5	2.25-3.25	2.5-3.5	2.5-3.5	4.5-8	4.5-7.5	4.5-8	3-4.5	2-3.5	2-3.5
Poor	>3.5	>3.5	>3.5	>3.25	>3.5	>3.5	>8	>7.5	>8	>4.5	>3.5	>3.5

G – Granite, L – Limestone, G+N- Granite + Natural Sand

Table 1-3: APA Rut Depth Criteria (in mm) at PG-High for Average and Maximum Traffic Volume

	APA Rut Depth Criteria (in mm) at PG-High for Average Traffic Volume											
Rut Resistance	**9.5C**			**12.5D**			**9.5B**			**12.5C**		
	G	L	G+N	G	L	G+N	G	L	G+N	G	L	G+N
Excellent	<3	<3	<3	<2	<2	<2	<4.75	<4.25	<4.75	<3	<1.75	<1.75
Good	3-5.25	3-5.25	3-5.25	2-4.5	2-4.5	2-4.5	4.75-8	4.25-7.25	4.75-8	3-6	1.75-4.75	1.75-4.75
Fair	5.25-7.5	5.25-7.5	5.25-7.5	4.5-6.75	4.5-6.75	4.5-6.75	8-11	7.25-10.5	8-11	6-9	4.75-7.75	4.75-7.75
Poor	>7.5	>7.5	>7.5	>6.75	>6.75	>6.75	>11	>10.5	>11	>9	>7.75	>7.75
APA Rut Depth Criteria (in mm) at PG-High for Maximum Traffic Volume												
Rut Resistance	**9.5C**			**12.5D**			**9.5B**			**12.5C**		
	G	L	G+N	G	L	G+N	G	L	G+N	G	L	G+N
Excellent	<2.5	<2.5	<2.5	<1.75	<1.75	<1.75	<4	<4	<5	<2.25	<1	<1
Good	2.5-4	2.5-4	2.5-4	1.75-4.5	1.75-4.5	1.75-4.5	4-5.5	4-5.5	5-6.5	2.25-4.25	1-3	1-3
Fair	4-5.5	4-5.5	4-5.5	4.5-5.75	4.5-5.75	4.5-5.75	5.5-7	5.5-7	6.5-8	4.25-6.25	3-5	3-5
Poor	>5.5	>5.5	>5.5	>5.75	>5.75	>5.75	>7	>7	>8	>6.25	>5	>5

G – Granite, L – Limestone, G+N- Granite + Natural Sand

Table 1-4: Accept/Reject APA Rut Depth Criteria (in mm)

Traffic Level(Test Temperature)	**9.5C**	**12.5D**	**9.5B**	**12.5C**
Average. Traffic (58°C)	5	4	10	6
Average. Traffic (PG-High)	8	7	11	8
Maximum Traffic (58°C)	4	3.5	8	4.5
Maximum Traffic (PG-High)	6	6	8	6

CHAPTER 2: LITERATURE REVIEW

The Asphalt Pavement Analyzer (APA) is a modification of the Georgia Loaded Wheel Tester (GLWT) and was first manufactured in 1996 by Pavement Technology, Inc. The APA is a multifunctional loaded wheel tester used for evaluating permanent deformation (rutting), fatigue cracking, and moisture susceptibility of both hot and cold asphalt mixes. The APA can test gyratory, vibratory, Marshall Specimens, field cores and roadway slabs in a temperature controlled chamber. A repeated load is applied to the test specimens in a dry or wet condition [4].

An earlier study conducted by Lai demonstrated the use of the GLWT. The rut depths of various mixtures measured using the GLWT were proportional to their Marshall's stability values [5]. A study conducted by the FHWA evaluated the ability of three LWT devices including the APA to predict or rank the field performance of WesTrack. Samples taken from 10 rehabilitated test sections at WesTrack were tested using the APA. The results were compared with WesTrack performance. The correlation (R^2=89.9%) was observed between the APA and WesTrack performance [6].

The Florida Department of Transportation conducted an investigation with the APA similar to the GLWT study described previously [7]. The authors observed that the APA ranked the mixtures according to their field performance ranking. They suggested that average values within the range of 7 to 8mm and of 8 to 9mm may be used as a performance limiting criteria at 8000 cycles for beam and gyratory samples, respectively.

Studies by Kandhal and Mallick observed that the APA is sensitive to aggregate gradation as the mixes with gravel and limestone aggregates generally had higher rutting than with granite [8]. The APA had a fair correlation (R^2=0.62) with the repeated shear constant height (RSCH) test conducted with the Simple Shear Tester. Based on very limited data, the authors suggested that the APA rut depth after 8000 passes should be less than 4.5 mm to minimize rutting in the field.

A study at NCAT assessed the available LWTs regarding specific considerations, such as simplicity, test time, cost of equipment, availability of data to support use, published test method, available criteria, and so on. The study recommended that the APA can be adopted for use in mix design and QC/QA. It recommended a criterion of 8mm for the APA rut test at the end of 8000 cycles [9].

2.1. Permanent Deformation

A major concern today in many parts of the United States is excessive permanent deformation (rutting) in heavy duty asphalt-concrete pavements resulting from frequent repetitions of heavy axle loads, many of which are operating with radial tires having pressures 20 to 25 psi higher than the bias-ply tires which they have replaced. Rutting gradually develops with increasing numbers of load applications and appears as longitudinal depressions in the wheel paths. Rutting is caused by a combination of densification (decrease in volume and, hence, increase in density) and shear deformation. However, shear deformation rather than densification is considered to be the primary cause of rutting in properly constructed pavements [1].

The current Superpave volumetric design criteria partially address the problem of rutting and durability of asphalt mixtures through the use of control points, which are developed to ensure the use of continuous gradations. In addition, the aggregates must satisfy the requirements for the aggregate consensus properties. These would be expected to result in mixes with high rut resistance by obtaining a good aggregate structure.

2.2. Effects of Mixture Characteristics on Rutting

Rutting in asphalt concrete pavements is significantly affected by mixture characteristics such as aggregate gradation, aggregate texture, asphalt content and viscosity. Dense aggregate gradation, rough aggregate texture, high values of binder viscosity and low binder content are some of the characteristics that are considered favorable to achieve rut-resistant mixtures [1]. The effect of binder performance grades on rutting characteristics is specific to the aggregate source; the same grade change can increase or decrease resistance to compaction or traffic, depending on aggregate source. The traffic densification index of a specific aggregate source can give a better insight into determining the efficacy of increasing binder performances grades. Higher values of Fine Aggregate Angularity (FAA) generally increase rut resistance of a mixture. Angular aggregates have better interlocking capability than rounded aggregates and thus offer more resistance to rutting. But, there are significant interactions between FAA and gradation that affect a mixture’s volumetric properties and shear resistance [14].

2.3. Superpave Specifications to Address Permanent Deformation

The Superpave volumetric mix design procedure specifies asphalt binder properties, aggregate properties and mixture properties. These performance-based properties control the behavior of asphalt binder and asphalt mixtures [5]. The Superpave specifications for asphalt binder use the rolling thin film oven test (RTFO) to simulate asphalt aging during construction. It requires a minimum value (2.2 kPa) for $G^*/\sin\delta$ for the RTFO aged residue as measured by the dynamic shear rheometer (DSR), which is performance based property for rutting. Asphalt binders with higher values of $G^*/\sin\delta$ are more resistant to permanent deformation. [6].

Specifications on aggregates to address permanent deformation include those on coarse aggregates and fine aggregates [7]. Superpave requires minimum values for the percentage of crushed faces for coarse aggregates and the angularity of fine aggregates to achieve rut resistance. Superpave suggests selection of Fine Aggregate Angularity (FAA) values based on traffic levels. But recent research has shown that there is significant interaction between FAA and gradation that affects a mixture's volumetric properties and shear resistance [14].Superpave has also specified acceptable values of G_{mm} at different levels of compaction and requirements on the values of voids in mineral aggregate (VMA) and voids filled with asphalt (VFA) [7].

2.4. Simple Shear Tester (SST)

The SST was developed during SHRP, a $50-million nationally coordinated research project completed in 1993 (11). SHRP was geared toward developing improved tests and specifications for asphalt paving materials.

2.4.1. Background of Simple Shear Tester

The SST was designed to perform a variety of performance-related tests on asphalt mixtures, including characterization of the Complex Modulus and Phase Angle, determination of the Bulk Modulus, and evaluation of various aspects of the nonlinear, plastic behavior typical of granular materials such as asphalt mixtures at high temperatures. Data gathered using the SST, along with a variety of other information, were in turn used as input to a computer program meant to provide performance predictions for a given pavement system as a function of time.

2.4.2. Frequency Sweep at Constant Height (FSCH) and Repeated Shear at Constant Height (RSCH) Tests

Two test procedures conducted using the SST that are widely used and that relate well to various aspects of pavement performance are:

(1) Frequency sweep at constant height (FSCH) test

(2) Repeated Shear at Constant Height (RSCH) test

The frequency sweep test is a technique for evaluating the complex shear modulus of asphalt mix. The shear modulus defines the relationship between shear stress and shear strain and is essential information in analyzing the behavior of a pavement system under traffic loading and during changes in temperature. The RSCH test is a repeated load test designed to characterize the resistance of an asphalt mixture to permanent deformation at high temperatures. Numerous studies have shown that the maximum permanent shear strain determined after the 5,000-cycle RSCH test is a good predictor of the rut resistance of asphalt mixtures [12, 13]. The magnitude of the complex modulus (|G*|) at high temperatures has also been related to rut resistance.

Both of these tests are described in AASHTO TP7-94: *Test Method for Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot Mix Asphalt (HMA)Using the Simple Shear Test (SST) Device*. The SST tests are usually performed on 50-mm-thick, 150-mm diameter specimens taken from a 115-mm-high standard specimen as produced by the Superpave gyratory compactor (SGC). Specimen preparation for the SST is complex and time-consuming, requiring careful sawing of the gyratory specimen, gluing platens onto the specimen, and, in some cases, fastening transducers onto the sides of the specimen.

2.5. Asphalt Pavement Analyzer (APA)

The APA, shown in Figure 2.1, is a modification of the Georgia Loaded Wheel Tester (GLWT) and was first manufactured in 1996 by Pavement Technology, Inc. The APA can be used to evaluate the rutting, fatigue, and moisture resistance of asphalt mixtures.

2.5.1. Background of the APA

The APA is the second generation of the GLWT and 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. 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. Typically, test temperatures for the APA have ranged from 40.6°C to 64°C (105°F to 147°F). However, for this study, the APA tests were carried at slightly higher temperatures as well.

Figure 2-1: Asphalt Pavement Analyzer (APA)

2.5.2. Potential of the APA to Predict Rutting of Asphalt Mixtures

Many transportation agencies and contractors use the APA to identify asphalt mixtures that may be susceptible to rutting as a supplement to their mix design procedure. Several studies have been carried out to evaluate the suitability of the APA for assessing the rutting potential of asphalt mixes. In a previous study conducted by Choubane, Page and Musselman for assessing the rutting potential of asphalt mixes in Florida, it was found that the APA may be an effective tool to rank asphalt mixtures in terms of their respective rut performance. The evaluation consisted of correlating the APA predicted rutting development with field measurements. Correlations were made with both beam and gyratory samples. The testing variability was also investigated. The APA test results were also compared with results from the Georgia loaded wheel tester. The findings indicate that average values within the ranges of 7 to 8 mm (0.28 to 0.31 in.) and of 8 to 9 mm (0.31 to 0.35 in.) may be used as performance limiting criteria at 8,000 cycles for beam and gyratory samples, respectively [9].

In another study carried out to evaluate the potential of the APA to predict rutting, the objectives were to find the sensitivity of the equipment to changes in aggregate type and gradation, performance grade (PG) of asphalt binder, and evaluate the equipment by comparing the test results with the test results from Simple Shear Tester (SST). Mixes from poor, fair and good performing pavements were also tested with the APA to develop a rut depth criterion for evaluation of mixes. The study indicated that the APA is sensitive to aggregate gradation, asphalt binder PG grade and asphalt film thickness. Mixtures with lower

PG grade binders showed a greater tendency to rut than those mixtures with higher PG grade binders. The study also established a fair correlation between the APA rut depths and repeated shear at constant height (RSCH) rut depths conducted with the Simple Shear Tester [3].

2.5.3. APA vs. Shear

Earlier studies have established a correlation between the APA rut depths and rut depths measured by repeated shear at constant height test conducted using the Simple Shear Tester. In a study done by Kandhal and Mallick to assess the potential of the APA to predict rutting of asphalt mixtures, a comparison of RSCH and the APA results yielded an R^2 value of 0.62. This indicates that RSCH and APA characterized mixes in a similar manner [3]. In yet another study, an R^2 value of 0.79 was observed between the APA and RSCH data [8].

2.5.4. Advantages of the APA

The APA is already being used widely by several transportation agencies to identify rutting susceptibility of asphalt mixtures. The APA simulates field traffic and temperature conditions and relatively simple to use. The APA can be used on both laboratory and field specimens. Tests can be conducted on multiple samples and on both cylindrical and beam samples. Elaborate guidelines and criteria for the use of the APA are available. Use of other rut testing devices such as the Hamburg Wheel Tracking device or the French Rutting Tester is limited in the USA and hence have less potential to be widely accepted [10].

CHAPTER 3: RESEARCH APPROACH AND METHODOLOGY

3.1. Research Objectives

The project has two parts

1. Laboratory part: Finished in the previous project HWY-2005-13 "Development of APA design criteria for field surface mixtures.
2. Field part: The field cores were obtained from NCDOT and the regression models developed in the project HWY-2005-13 were validated and further modifications to the regression models were done.

Laboratory Part

The primary objectives of this study were to develop the APA rut depth criteria that could be used to characterize the rut resistance of surface mixtures. The APA and shear tests were conducted on surface course mixtures used by NCDOT. Correlations were developed between the results of shear tests and APA tests. The APA tests were fine-tuned by considering different air voids, test temperatures and aggregate sources to quantify their effects on the predictability of the APA tests.

Field Part

The primary objectives of this research study were to:

- Conduct the APA and shear tests on all the field cores
- Modify the regression models correlating shear tests and the APA test data
- Develop and recommend the APA test criteria for evaluation of rutting potential of the mixtures.

3.2. Research Plan

3.2.1. Laboratory Part

Task 1 – Materials and Mix Designs

Currently, the NCDOT uses six surface course mixtures including four 9.5mm mixtures and two 12.5mm mixtures. In this study, we included four surface course mixtures and three aggregate sources – Limestone (A3), Granite (A1) and Granite (with Natural Sand, A4). Use of Gravel (A2) was a part of the initial research plan, but was removed subsequently after consultation with NCDOT.

Task 2 - Asphalt Pavement Analyzer (APA) Test

The rutting susceptibility of the mixtures is assessed by placing cylindrical samples under repetitive loads of a wheel-tracking device, known as the Asphalt Pavement Analyzer (APA). 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.

The APA tests were conducted on all surface mixtures. The tests were conducted at two different air voids (4% and 7%) and the following two different test temperatures:

1. High temperature of standard PG grade based upon the climate (T2).
2. Seven-day average high pavement temperature at 50-mm depth from pavement surface at 98% reliability (T1).

Task 3 – Shear Tests

The Simple Shear Tester (SST) was developed under SHRP as a way to measure the shear characteristics of asphalt mixtures. Six tests can be performed with the SST for measuring the mix performance characteristics: the Simple Shear, Frequency Sweep at Constant Height, Uniaxial Strain, Volumetric Shear, Repeated Shear at Constant Stress Ratio, and Repeated Shear at Constant Height tests measure properties that may be useful in calculating the resistance to permanent deformation and fatigue cracking.

Frequency Sweep at Constant Height (FSCH)

The frequency sweep test at constant height is used to analyze the permanent deformation and fatigue cracking. From the test results, dynamic shear modulus and phase angles for different frequencies are determined. The FSCH tests were performed on all the mixtures at both 4% and 7% air voids.

Repeated Shear at Constant Height (RSCH)

This test was performed to estimate the rutting potential of a mixture. 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 mixtures. This test was performed at the seven-day average high pavement temperature at 50-mm depth from pavement surface at 98% reliability.

Task 4 – Statistical Analysis of the APA and Shear Test Results

Statistical analysis was performed on the test results as measured by the APA and the SST. The primary analysis tool selected for developing the rut test criteria for the APA test was a correlation/regression analysis. The rut depths measured from the APA test were compared with the corresponding shear strains of the RSCH test. The Asphalt Institute Criteria was used to interpret the RSCH maximum permanent shear strain. Table 3.1 shows the mixture test matrix. Table 3.2 shows the Asphalt Institute (AI) criteria for evaluating rut resistance using RSCH permanent shear strain.

Table 3-1: Research Test Matrix (Lab Part)

Mixture Designation (PG Grade of Asphalt Binder)	Aggregate Source	Air Voids	No. of replicates for APA Test		No. of replicates for Shear Test	
			Temperature T1	Temperature T2	FSCH	RSCH
S12.5C (PG70-22)	A1	4%	4	4	4	4
	A1	7%	4	4	4	4
	A3	4%	4	4	4	4
	A3	7%	4	4	4	4
	A4(NS)	4%	4	4	4	4
	A4(NS)	7%	4	4	4	4
S12.5D (PG76-22)	*A1*	4%	4	4	4	4
	A1	7%	4	4	4	4
	A3	4%	4	4	4	4
	A3	7%	4	4	4	4
	A4(NS)	4%	4	4	4	4
	A4(NS)	7%	4	4	4	4
S9.5C (PG70-22)	*A1*	*4%*	4	4	4	4
	A1	*7%*	4	4	4	4
	A3	*4%*	4	4	4	4
	A3	*7%*	4	4	4	4
	A4(NS)	*4%*	4	4	4	4
	A4(NS)	7%	4	4	4	4
S9.5B (PG64-22)	*A1*	*4%*	4	4	4	4
	A1	*7%*	4	4	4	4
	A3	*4%*	4	4	4	4
	A3	*7%*	4	4	4	4
	A4(NS)	*4%*	4	4	4	4
	A4(NS)	*7%*	4	4	4	4

Table 3-2: AI Criteria for Evaluating Rut Resistance

RSCH permanent shear strain, %	Rut Resistance
< 1.0 Excellent	Excellent
to < 2.0	Good
to < 3.0	Fair
> 3.0	Poor

3.2.2. Field part

Task 1- Materials and Mix Designs

HWY-2005-13 research project used four surface course mixtures including two 9.5mm mixtures and two 12.5mm mixtures. In this study, we included all representative field cores of the same mixtures. The selection for the field cores was made in consultation with the NCDOT.

Task 2- Asphalt Pavement Analyzer (APA) Test

The APA tests were conducted on all the field cores. The tests were conducted at the following two different test temperatures:

1. High temperature of standard PG grade based upon the climate (T1)
2. Seven-day average high pavement temperature at 50-mm depth from pavement surface at 50% reliability (T2).

The data acquisition system of the APA measures the rut depths at four points of these paired specimens and plots the average value, which is used as the final rut depth of that mixture. The rut depths of each individual specimen were measured.

Task 3- Shear Tests

In this study, Frequency Sweep Test at Constant Height and Repeated Shear Test at Constant Height were used to analyze the performance of asphalt mixtures.

Task 4- Statistical Analysis of the APA and Shear Test Results

The data obtained from the APA and shear tests on the field cores was pooled with the laboratory test data from the previous project (HWY-2005-13) and comprehensive statistical analysis was performed. The primary analysis tool selected for developing the rut test criteria for the APA test is the simple correlation/regression analysis. The rut depths measured from the APA test were compared with the corresponding shear strains of the RSCH test. The Asphalt Institute criteria were used to interpret the RSCH maximum permanent shear strain. The AI criteria for RSCH shear strain was used for categorizing the mixtures according to their performance. The rut depths estimated using the AI criteria were used in the development of APA-RSCH correlation. Using the AI criteria, the RSCH rut depths were estimated using the SHRP Rutting model. The RSCH rut depths, as calculated using the SHRP model, are 2.8mm, 5.6mm and 8.4mm at 1%, 2% and 3% shear strains, respectively. The corresponding APA rut depths at these shear strains were estimated. The mixtures were then categorized as excellent, good, fair or poor performing mixtures. Table 3.3 shows the Research Test Matrix for the field part of the project.

Table 3-3: Research Test Matrix (Field Part)

Mixture Designation	No: of replicates for APA Test	No: of replicates for Shear Test	
		FSCH	RSCH
RS 9.5B	4	4	4
RS 9.5B	4	4	4
RS 9.5C	4	4	4
RS 12.5D	4	4	4
RS 12.5C	4	4	4

CHAPTER 4: MATERIAL SELECTION AND EVALUATION

In this section, the source and properties of the aggregates and asphalt binders used for the laboratory part of this study are presented. The field cores were provided by the NCDOT, so material selection and evaluation will not be done for those.

4.1. Manufactured Aggregate Properties

Marine limestone from the Castle Hayne, NC, quarry, natural sand from the Emery pit, NC, and granite from Cabarrus, NC, were used to prepare mixtures in this research project. Both limestone and granite aggregates were sampled from the quarry's main #67, #78M, washed and unwashed screenings stockpiles and brought back to the laboratory where they were oven-dried, and sieved into individual size fractions. Materials retained on the 3/4", 1/2", 3/8", #4, #8, #16, #30, #50, #100 and #200 sieves and the material passing the #200 sieve were stored in separate containers so that any aggregate gradation used for the study could be batched from the individual size fractions. This method of aggregate blending allows for strict control and exact replication of a mixture's aggregate gradation. The specific gravity values of the manufactured aggregate as determined by AASHTO T84 ("*Specific Gravity and Absorption of Fine Aggregate*") and AASHTO T85 ("*Specific Gravity and Absorption of Coarse Aggregate*") for the aggregates are given below in Table 4.1. The fine aggregate angularity as determined by AASHTO T304 ("*Standard Test Method for Uncompacted Void Content of Coarse Aggregate*"), ASTM C1252 ("*Standard Test Method for Uncompacted Void Content of Fine Aggregate"*) are also given in Table 4.1.

Table 4-1: Manufactured Aggregate Properties

Property	Aggregate			
	Limestone		Granite	
	Coarse Aggregate	Fine Aggregate	Coarse Aggregate	Fine Aggregate
Bulk Specific Gravity	2.392	2.608	2.758	2.759
Flat and Elongated 3:1/5:1	0.3	-	2.8	-
Uncompacted Void Content of Fine Aggregates	-	47.9	-	46.5
Uncompacted Void Content of Coarse Aggregates	100/100	-	100/100	-

4.2. Asphalt Binder

The following three asphalt binders were used for mixtures in this research project,

- PG70-22, from the Citgo terminal in Wilmington, NC
- PG64-22, from the Citgo terminal in Wilmington, NC
- PG76-22, from the Citgo terminal in Savannah, GA

The specific gravities of the binders used in this study are given in Table 4.2.

Table 4-2: Values on Binder Specific Gravity

Binder	Specific Gravity
PG70-22	1.039
PG64-22	1.039
PG76-22	1.036

4.3. Natural Sand

Natural sand, when mixed with fines, increases the workability of the mix. Natural sand from Emery pit, NC was used for certain mixtures in this project. In these mixtures, natural sand forms 15% by weight of the total aggregate blend. Natural sand stockpiles were oven-dried and sieved into individual size fractions. Materials retained on #8, #16, #30, #50, #100, #200 and passing the #200 were stored in separate containers so that any aggregate gradation used for the study could be batched from the individual size fractions. The fine aggregate void content as determined by AASHTO T304 ("*Standard Test Method for Uncompacted Void Content of Coarse Aggregate*"), had a value of 41.9.

CHAPTER 5: EVALUATION OF JOB-MIX-FORMULA AND MIXTURE DESIGN

5.1. Introduction

The Job Mix Formulae (JMF) for some of the mixtures in the experimental plan were provided by NCDOT. Volumetric properties for such mixtures were evaluated and compared to NCDOT requirements and the results are summarized in this section. Superpave volumetric mixture design was performed for the rest of the mixtures. The results of the Superpave volumetric mixture design are presented in this section. The mixture design procedure is briefly described and the requirements and specifications are first presented, followed by the results in the mixture designs. In order to simplify the explanation and discussion of different mixtures, aggregate types and asphalt binders used in this study, the following notation will be used:

(AGG)-(NMSA)(PG)-(SAND)

Where,

AGG = aggregate type, limestone (L), granite (G)

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

PG = performance grade of binder, PG64-22 (B), PG70-22 (C), PG76-22 (D)

SAND = sand type, manufactured (M), natural (N)

Example 1. L-12.5C-M = 12.5mm NMSA mixture using 100% manufactured sand containing limestone aggregates and PG70-22 asphalt binder.

Example 2. G-9.5B-N = 9.5mm NMSA mixture using 85% manufactured sand and 15% natural sand containing granite aggregates and PG64-22 asphalt binder.

In order to simplify the explanation and discussion of different mixtures, mixtures for which JMF (Job Mix Formula) were provided by NCDOT will be referred to as Type A mixtures and those mixtures for which Superpave mixture designs were performed will be referred to as Type B mixtures. Table 5.1 provides a list of mixtures that are part of the experimental plan.

Table 5-1: Mixtures Included in this Study

Mixture Notation	JMF/Mixture Design	Mix Designation
G-12.5C-M	JMF provided by NCDOT	Type A
L-12.5C-M	Superpave mix design performed	Type B
G-12.5C-N	Superpave mix design performed	Type B
G-12.5D-M	Superpave mix design performed	Type B
L-12.5D-M	Superpave mix design performed	Type B
G-12.5D-N	Superpave mix design performed	Type B
G-9.5B-M	Superpave mix design performed	Type B
L-9.5B-M	Superpave mix design performed	Type B
G-9.5B-N	JMF provided by NCDOT	Type A
G-9.5C-M	JMF provided by NCDOT	Type A
L-9.5C-M	Superpave mix design performed	Type B
G-9.5C-N	JMF provided by NCDOT	Type A

5.2. Evaluation of Job Mix Formula

The JMF for all the TYPE A mixtures were evaluated to check for volumetric properties and to verify that the requirements of the Superpave mixture design were met.

5.2.1. Aggregate Gradation

As mentioned earlier, the aggregate stockpiles were sieved into individual size fractions and later used for aggregate blending. The aggregates were later batched according to the fractions specified in the JMF for each mixture. The gradations for the combined aggregate for all Type A mixtures as specified by the JMF have been included in APPENDIX A.

5.2.2. Evaluation of Volumetric Properties

The next step in this process was the evaluation of volumetric properties of the individual mixtures. A total of four batches were prepared, two of which were used for measurements of maximum specific gravity and the remaining two were used for measurement of bulk specific gravity and other volumetric properties. The design asphalt content for all Type A mixtures, as specified by the JMF, are given in Table 5.2. The same information can also be found in the JMF for each Type A mixture in APPENDIX B. The mixture ingredients were mixed at the optimum mixing temperature for the grade of the asphalt binder used in that mix. The optimum mixing temperatures for the asphalt binders used in this project, and as specified by NCDOT, are given in Table 5.3.

Table 5-2: Design Asphalt Contents of Type A Mixtures

Mixture Notation	Design Asphalt Content (%)
G-12.5C-M	5%
G-9.5B-N	6.7%
G-9.5C-M	5.2%
G-9.5C-N	5.5%

Table 5-3: Optimum Mixing Temperatures for Asphalt Binders

Asphalt Binder	Optimum Mixing Temperature
PG64-22	149°C
PG70-22	157°C
PG76-22	168 °C

After mixing, the maximum specific gravity was evaluated using the Rice specific gravity test. The results of the above test based on an average of two replicates, are given in Table 5.4.

Table 5-4: Maximum Specific Gravity (Gmm) Results for Type A Mixtures

Mixture Notation	Maximum Specific Gravity (Gmm)
G-12.5C-M	2.575
G-9.5B-N	2.483
G-9.5C-M	2.541
G-9.5C-N	2.525

The remaining batches of asphalt mixtures were then aged for four hours at 135°C in accordance with NCDOT specifications. They were then heated for two hours at the optimum temperature for compaction as suggested by NCDOT. The optimum compaction temperatures and the N_{ini} / N_{des} / N_{max} for the asphalt binders used in this study are given in Table 5.5.

Table 5-5: Optimum Compaction Temperatures for Asphalt Binders

Asphalt Binder	Optimum Compaction Temperature	Nini / Ndes / Nmax
PG64-22	149°C	7/75/115
PG70-22	155°C	8/100/160
PG76-22	162°C	9/125/205

The mix was then compacted using the Superpave Gyratory Compactor (SGC) for N_{max} gyrations. Bulk specific gravities were evaluated and volumetric properties were determined. Average results based on two replicates are shown in Tables 5.6, 5.7, 5.8 and 5.9.

Table 5-6: Volumetric Properties for G-12.5C-M Mixture

Description	Gmm	Va	% VMA	% VFA	%Gmm @ Nini	%Gmm @ Nmax	Dust Proportion
Laboratory Results	2.574	4.1%	14.9	71.8	88.9	96.6	1.00
JMF	2.575	4.3 %	15.1	70.9	89.1	96.6	1.00
NCDOT Requirements	-	4 %	14 % Min.	65 - 75	≤ 89	≤ 98	0.6-1.2

Table 5-7: Volumetric Properties for G-9.5B-N Mixture

Description	Gmm	Va	% VMA	% VFA	%Gmm @ Nini	%Gmm @ Nmax	Dust Proportion
Laboratory Results	2.480	4%	18.5	78.2	90.3	96.7	0.81
JMF	2.483	3.9 %	18.4	78.4	90.3	96.9	0.81
NCDOT Requirements	-	4 %	15 % Min.	65 - 78	≤ 90.5	≤ 98	0.6-1.2

Table 5-8: Volumetric Properties for G-9.5C-M Mixture

Description	Gmm	Va	% VMA	% VFA	%Gmm @ Nini	%Gmm @ Nmax	Dust Proportion
Laboratory Results	2.541	4.2 %	15.2	74.2	90	96.4	0.9
JMF	2.541	4.0 %	15.3	74.4	NA	NA	NA
NCDOT Requirements	-	4 %	14 % Min.	65 - 75	≤ 89	≤ 98	0.6-1.2

Table 5-9: Volumetric Properties for G-9.5C-N Mixture

Description	Gmm	Va	% VMA	% VFA	%Gmm @ Nini	%Gmm @ Nmax	Dust Proportion
Laboratory Results	2.525	4.1	15.4	74.5	90	96.5	0.86
JMF	2.525	4.0 %	15.9	74.8	90	96.7	0.86
NCDOT Requirements	-	4 %	14 % Min.	65 - 75	≤ 89	≤ 98	0.6-1.2

5.3. Mixture Design

As stated earlier, Type B mixtures are those for which Superpave mix designs were performed in the laboratory as JMF for the same were not provided.

5.3.1. Introduction

In a typical Superpave volumetric mixture design, trial aggregate gradations are selected that meet the requirements of that mixture's gradation control points, and compacted with a Superpave gyratory compactor to specified number of revolutions or gyrations (N_{max}) using a calculated trial asphalt content. The bulk specific gravities of the trial aggregate gradation samples are measured and calculations are performed to determine estimated optimum binder content and the corresponding volumetric properties at that binder content. The estimated volumetric properties of these trial aggregate gradations are evaluated for compliance with the Superpave specifications. The aggregate gradation that best satisfies the volumetric requirements of that mixture type is then used to fabricate specimens at varying asphalt binder contents and the volumetric properties of that design aggregate gradation are again evaluated over a range of binder contents. The binder content that satisfies the requirements of 4.0% air voids, and other Superpave specifications, is then the optimum design asphalt content for that mixture type.

5.3.2. Design of 12.5mm Mixtures Containing 100% Manufactured Sand

A final aggregate gradation was selected from three trial gradations in the process described earlier. The final aggregate gradations for all 12.5mm Type B mixtures (without natural sand) are shown in Figures 5.1, 5.2, 5.3 and Table 5.10.

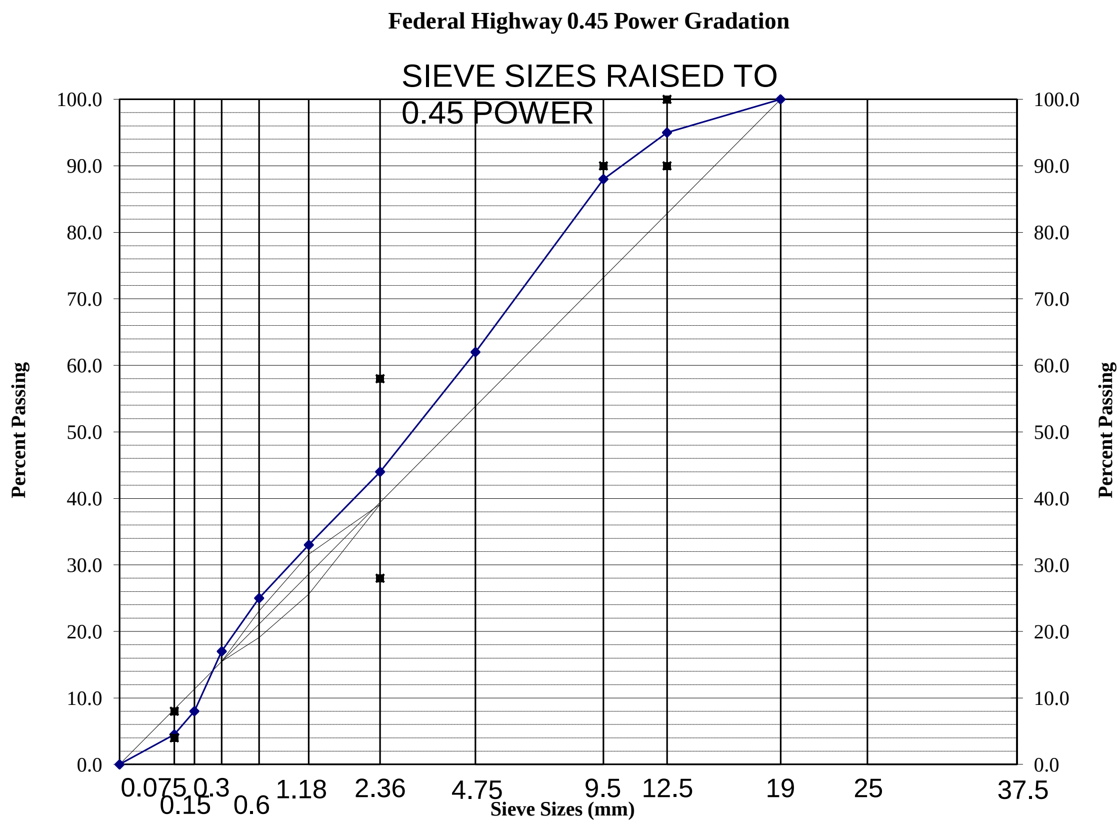

Figure 5-1: Selected Aggregate Blend for L-12.5C-M Mixture

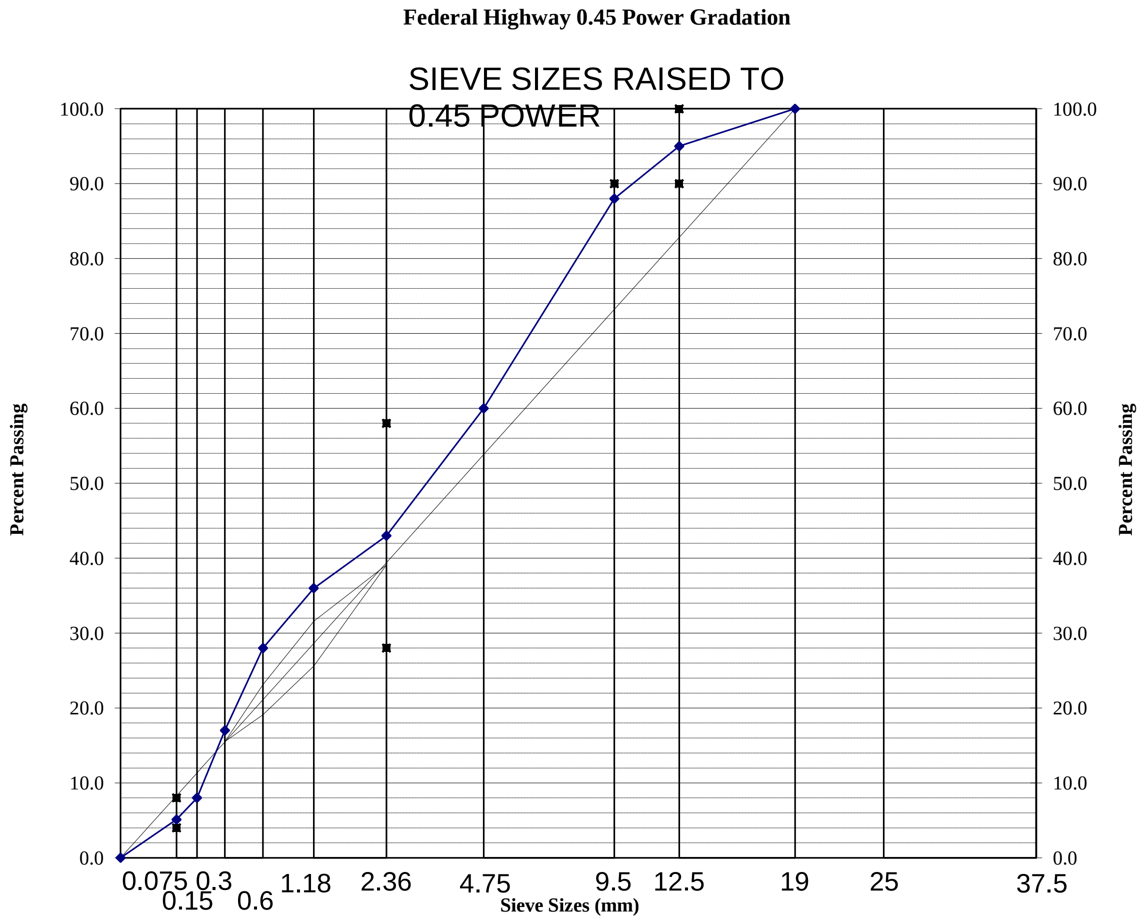

Figure 5-2: Selected Aggregate Blend for G-12.5D-M Mixture

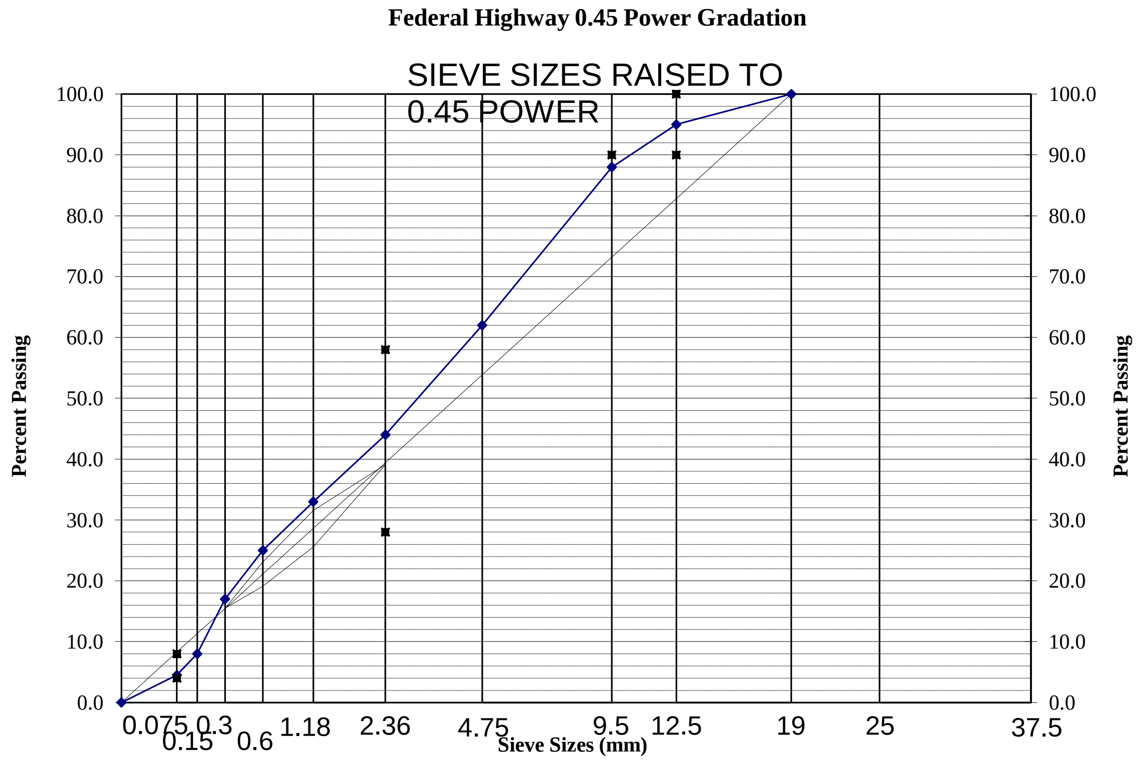

Figure 5-3: Selected Aggregate Blend for L-12.5D-M Mixture

Table 5-10: Aggregate Gradation for 12.5mm, Type B, Manufactured Sand Mixtures

Sieve Size (mm)	Percent Passing		
	L-12.5C-M	G-12.5D-M	L-12.5D-M
25	100	100	100
19	100	100	100
12.5	95	95	95
9.5	88	88	88
4.75	60	62	62
2.36	43	44	44
1.18	36	33	33
0.6	28	25	25
0.3	17	17	17
0.15	8	8	8
0.075	5.1	4.5	4.5
Pan	0	0	0

Once the design aggregate structure was selected, specimens were fabricated over a range of binder contents and the optimum binder content was selected that best met the mixture Superpave mixture requirements. Table 5.11 presents the maximum theoretical specific gravity of the mixtures and the bulk specific gravity of the aggregate blends. Table 5.12, 5.13 and 5.14 present the design information and the evaluated volumetric properties based on average values of two replicates.

Table 5-11: G_{mm} and G_{sb} Values for 12.5mm, Type B, Manufactured Sand Mixtures

Mixture	Asphalt Content %	Gmm	Gsb
L-12.5C-M	5	2.25946	2.521
G-12.5D-M	5	2.590373	2.757
L-12.5D-M	5.8	2.369046	2.521

Table 5-12: Mixture Design Properties for L-12.5C-M Mix

Description	Asphalt Content (%)	Air Voids (%)	VMA (%)	VFA (%)	%Gmm @ Nini	%Gmm @ Nmax
Mix Design Results	5	4.0	14.5	72.5	87	96.7
NCDOT Requirements	-	4.0	14 % Min.	65 – 75	≤ 89	≤ 98

Table 5-13: Mixture Design Properties for G-12.5D-M Mix

Description	Asphalt Content (%)	Air Voids (%)	VMA (%)	VFA (%)	%Gmm @ Nini	%Gmm @ Nmax
Mix Design Results	5	4.0	14.78	74	89.4	96.99
NCDOT Requirements	-	4.0	14 % Min.	65 – 75	≤ 89	≤ 98

Table 5-14: Mixture Design Properties for L-12.5D-M Mix

Description	Asphalt Content (%)	Air Voids (%)	VMA (%)	VFA (%)	%Gmm @ Nini	%Gmm @ Nmax
Mix Design Results	5.8	4.0	14.86	72	85.35	97.28
NCDOT Requirements	-	4.0	14 % Min.	65 – 75	≤ 89	≤ 98

It can be observed from Tables 5.12, 5.13 and 5.14 that all of the above mixtures satisfy the NCDOT requirements for evaluating volumetric properties of mixtures designed using the Superpave design guidelines.

5.3.3. Design of 9.5mm Mixtures Containing 100% Manufactured Sand

A final aggregate gradation was selected from three trial gradations in the process described earlier. The final aggregate gradations for all 9.5mm, Type B mixtures containing 100% manufactured sand are shown in Figures 5.4, 5.5, 5.6 and Table 5.15.

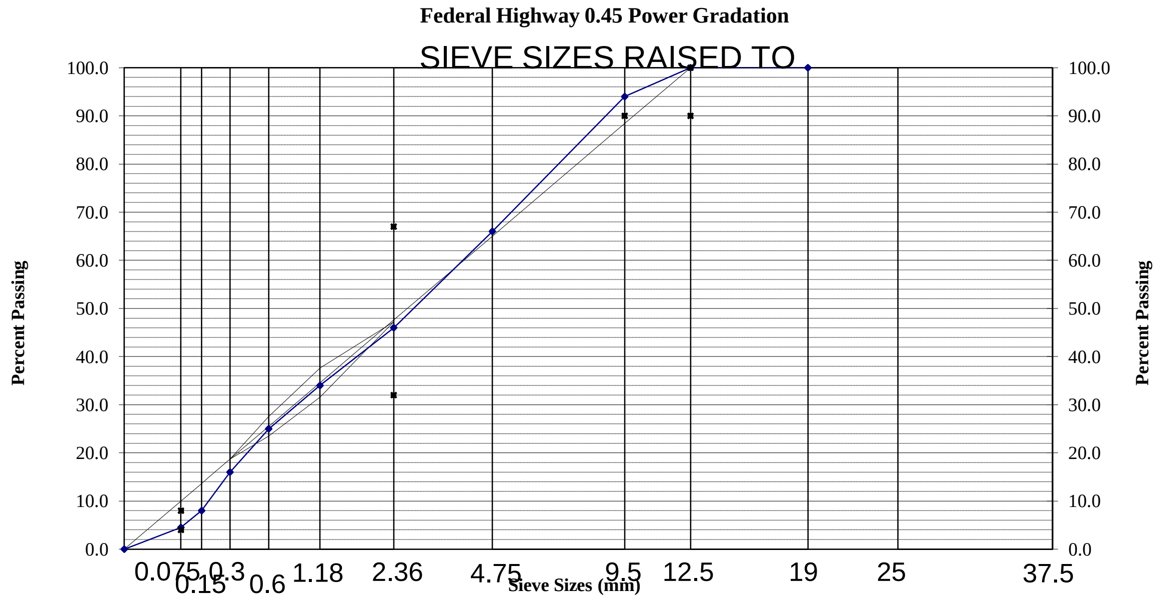

Figure 5-4: Selected Aggregate Blend for G-9.5B-M Mixture

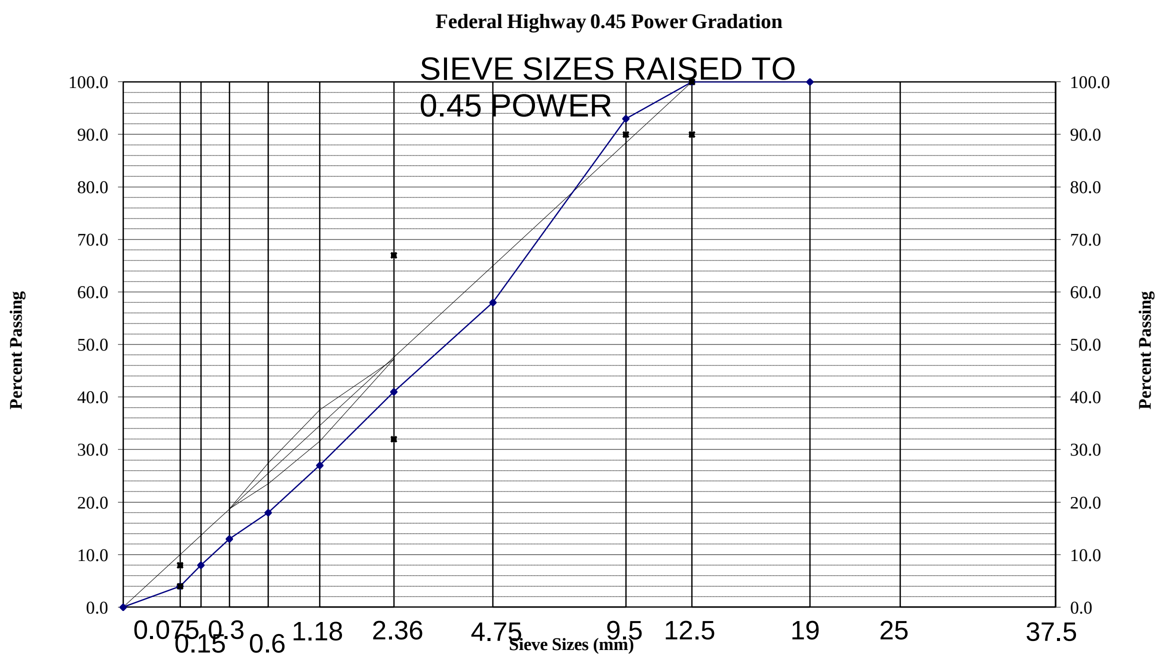

Figure 5-5: Selected Aggregate Blend for L-9.5B-M Mixture

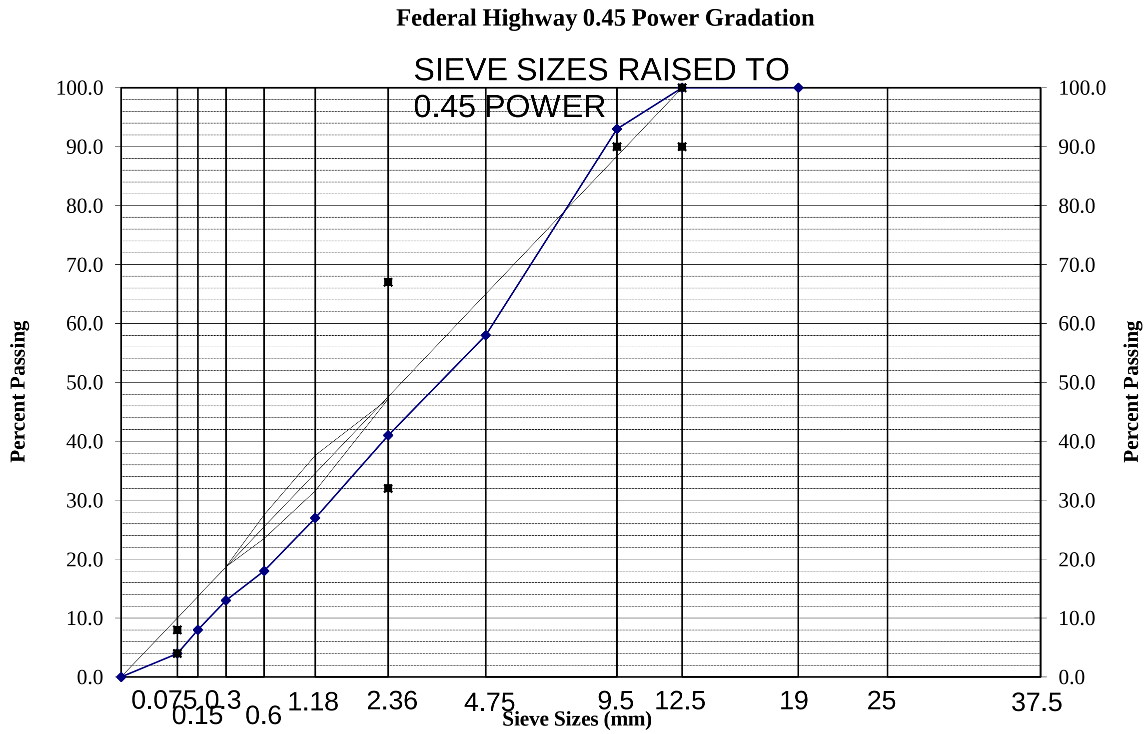

Figure 5-6: Selected Aggregate Blend for L-9.5C-M Mixture

Table 5-15: Aggregate Gradation for 9.5mm, Type B, Manufactured Sand Mixtures

Sieve Size	Percent Passing		
	G-9.5B-M	L-9.5B-M	L-9.5C-M
25	100	100	100
19	100	100	100
12.5	100	100	100
9.5	94	93	93
4.75	66	58	58
2.36	46	41	41
1.18	34	27	27
0.6	25	18	18
0.3	16	13	13
0.15	8	8	8
0.075	4.5	4	4
Pan	0	0	0

Once the design aggregate structure was selected, specimens were fabricated over a range of binder contents and the optimum binder content was selected that best met the mixture Superpave mixture requirements. Table 5.16 presents the maximum theoretical specific gravity of the mixtures and the bulk specific gravity of the aggregate blends. Table 5.17, 5.18 and 5.19 present the design information and the evaluated volumetric properties based on average values of two replicates.

Table 5-16: G_{mm} and G_{sb} Values for 9.5mm, Type B, Manufactured Sand Mixtures

Mixture	Asphalt Content %	Gmm	Gsb
G-9.5B-M	6.6	2.570622	2.741
L-9.5B-M	6.7	2.3588	2.434
L-9.5C-M	6.0	2.4196	2.434

Table 5-17: Mixture Design Properties for G-9.5B-M Mix

Description	Asphalt Content (%)	Air Voids (%)	VMA (%)	VFA (%)	%Gmm @ Nini	%Gmm @ Nmax
Mix Design Results	6.6	4.0	15.3	74.6	89.6	96.7
NCDOT Requirements	-	4.0	14 % Min.	65 – 78	≤ 90.5	≤ 98

Table 5-18: Mixture Design Properties for L-9.5B-M Mix

Description	Asphalt Content (%)	Air Voids (%)	VMA (%)	VFA (%)	%Gmm @ Nini	%Gmm @ Nmax
Mix Design Results	6.7	4.0	15.94	74.8	87.8	96.5
NCDOT Requirements	-	4.0	14 % Min.	65 – 78	≤ 90.5	≤ 98

Table 5-19: Mixture Design Properties for L-9.5C-M Mix

Description	Asphalt Content (%)	Air Voids (%)	VMA (%)	VFA (%)	%Gmm @ Nini	%Gmm @ Nmax
Mix Design Results	6	4.0	16	76	88	97.3
NCDOT Requirements	-	4.0	15 % Min.	73 – 76	≤ 89	≤ 98

It can be observed from Tables 5.17, 5.18 and 5.19 that all of the above mixtures satisfy the NCDOT requirements for evaluating volumetric properties of mixtures designed using the Superpave design guidelines.

5.3.4. Design of 12.5mm Mixtures Containing 85% Manufactured Sand and 15% Natural Sand

A final aggregate gradation was selected from three trial gradations in the process described earlier. The final aggregate gradations for all 12.5mm, Type B mixtures containing 15% manufactured sand are shown in Figures 5.7, 5.8 and Table 5.20.

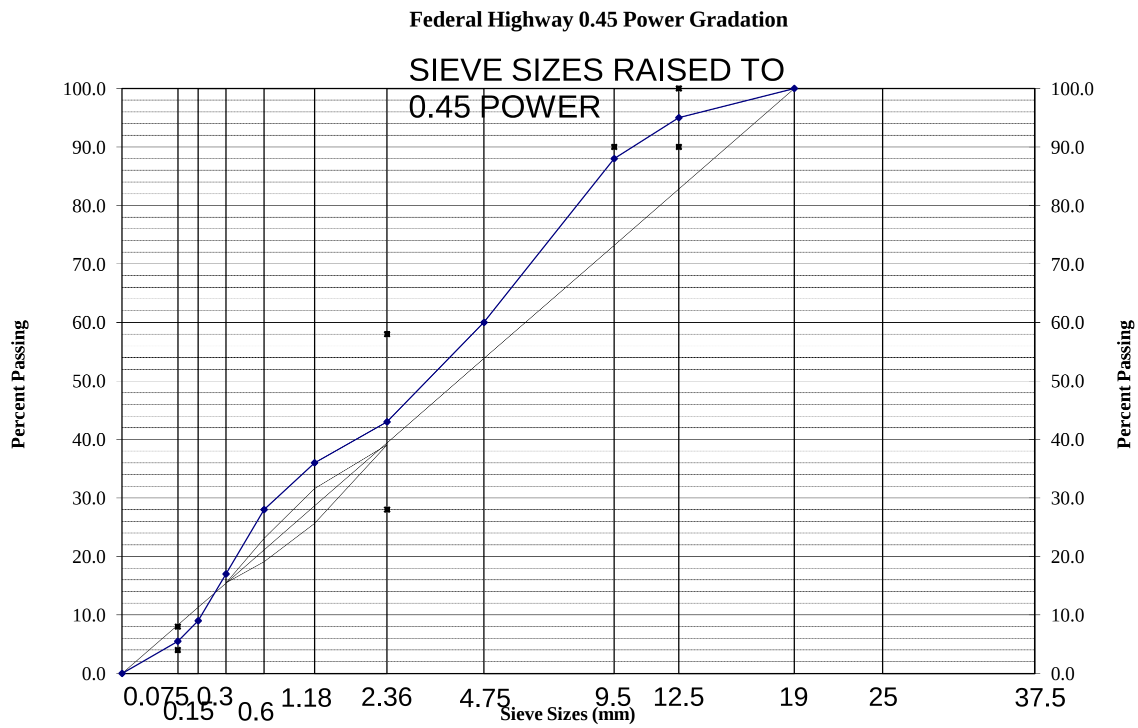

Figure 5-7: Selected Aggregate Blend for G-12.5C-N Mixture

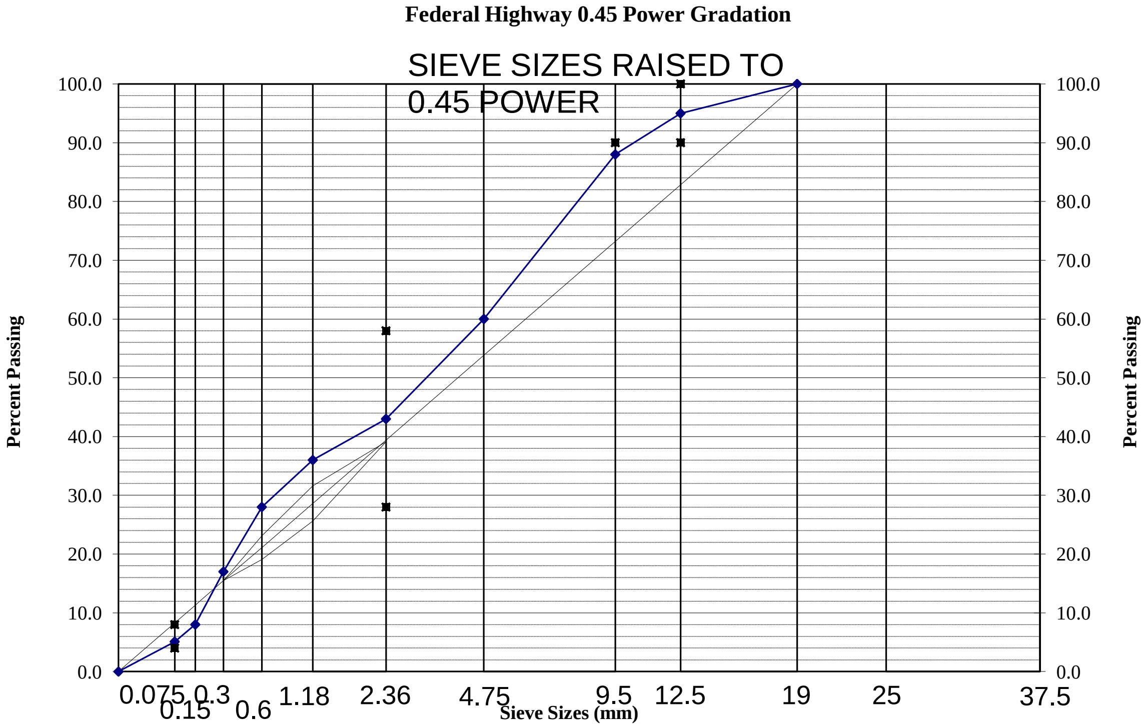

Figure 5-8: Selected Aggregate Blend for G-12.5D-N Mixture

Table 5-20: Aggregate Gradation for 12.5mm, Type B, Natural Sand Mixtures

Sieve Size	Percent Passing	
	G-12.5C-N	G-12.5D-N
25	100	100
19	100	100
12.5	95	95
9.5	88	88
4.75	60	60
2.36	43	43
1.18	36	36
0.6	28	28
0.3	17	17
0.15	9	8
0.075	5.5	5.1
Pan	0	0

Once the design aggregate structure was selected, specimens were fabricated over a range of binder contents and the optimum binder content was selected that best met the mixture Superpave mixture requirements. Table 5.21 presents the maximum theoretical specific gravity of the mixtures and the bulk specific gravity of the aggregate blends. Table 5.22 and 5.23 present the design information and the evaluated volumetric properties based on average values of two replicates.

Table 5-21: G_{mm} and G_{sb} Values for 12.5mm, Type B, Natural Sand Mixtures

Mixture	Asphalt Content %	Gmm	Gsb
G-12.5C-N	5.0	2.575	2.738
G-12.5D-N	4.9	2.57	2.738

Table 5-22: Mixture Design Properties for G-12.5C-N Mix

Description	Asphalt Content (%)	Air Voids (%)	VMA (%)	VFA (%)	%Gmm @ Nini	%Gmm @ Nmax
Mix Design Results	5.0	4.0	15.3	74.6	89.6	96.7
NCDOT Requirements	-	4.0	14 % Min.	65 – 78	≤ 90.5	≤ 98

Table 5-23: Mixture Design Properties for G-12.5D-N Mix

Description	Asphalt Content (%)	Air Voids (%)	VMA (%)	VFA (%)	%Gmm @ Nini	%Gmm @ Nmax
Mix Design Results	4.9	4.0	16	73	90	96.9
NCDOT Requirements	-	4.0	14 % Min.	65 – 78	≤ 90.5	≤ 98

CHAPTER 6: PERFORMANCE EVALUATION OF MIXTURES

The rutting susceptibility of mixtures were evaluated by using the Simple Shear Tester (SST) and the Asphalt Pavement Analyzer (APA)

6.1. Performance Evaluation Using Simple Shear Tester

Shear tests were performed in accordance with AASHTO TP7 Procedures E and F (22). The tests included Frequency Sweep test at Constant Height (FSCH) and Repeated Shear test at Constant Height (RSCH). These tests were conducted on specimens compacted using the Superpave Gyratory Compactor (SGC).

6.1.1. 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 'DEVCON' 5-minute plastic putty and were allowed to cure for several hours before testing.

6.1.2. 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°C throughout the year. The resistance of a mix to fatigue cracking is calculated based on the mix properties evaluated using FSCH at 20°C. The seven-day average high pavement temperature at 50-mm depth from the pavement surface at 50% reliability was estimated using SHRPBIND version 2.0 software for Raleigh, NC at 58°C.

6.1.3. Frequency Sweep Test at Constant Height

This test is performed to measure linear visco-elastic properties of asphalt concrete for rutting 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 at a temperature of 20°C. Twelve mixtures were tested at a temperature of 20°C. Four replicates of each of these mixtures were prepared at two air void contents: 4% and 7%, and used for the test. These mixtures, discussed in detail in Chapter 5, are summarized in Table 6.1. The mixtures used in the field part of this project are summarized in Table 6.2.

Table 6-1: Mixtures Used For FSCH Test (Lab Part)

Mixture Notation	Mixture Details – Aggregate, Binder
G-12.5C-M	Granite, PG70-22
L-12.5C-M	Limestone, PG70-22
G-12.5C-N	Granite + Natural Sand, PG70-22
G-12.5D-M	Granite, PG76-22
L-12.5D-M	Limestone, PG76-22
G-12.5D-N	Granite + Natural Sand, PG76-22
G-9.5B-M	Granite, PG64-22
L-9.5B-M	Limestone, PG64-22
G-9.5B-N	Granite + Natural Sand, PG64-22
G-9.5C-M	Granite, PG70-22
L-9.5C-M	Limestone, PG70-22
G-9.5C-N	Granite + Natural Sand, PG70-22

Table 6-2: Mixtures Used For FSCH Test (Field Part)

Mixture Notation	Mixture Details – Aggregate, Binder
RS 9.5B	#78M, PG64-22
RS 9.5C	#78M, PG 70-22
RS 12.5D	#78M, PG76-22
RS 12.5C	#57,#78M, PG64-22

Dynamic Shear Modulus and Phase angle was measured at each frequency for each mixture. The ratio of the stress response of the test specimen to the applied shear strain is used to compute a complex modulus for a given frequency. The delay in the response of the material is measured as phase angle. From the test results, the following graphs are generated to evaluate the mix properties:

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

Analysis of FSCH Test Results (Lab part)

Figures 6.1 to 6.4 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°C. The figures are plotted for the mixtures according to the mix type. Tables 6.3 to 6.6 compare the G* values and the corresponding phase angles of different mixtures according to the mixture type.

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)

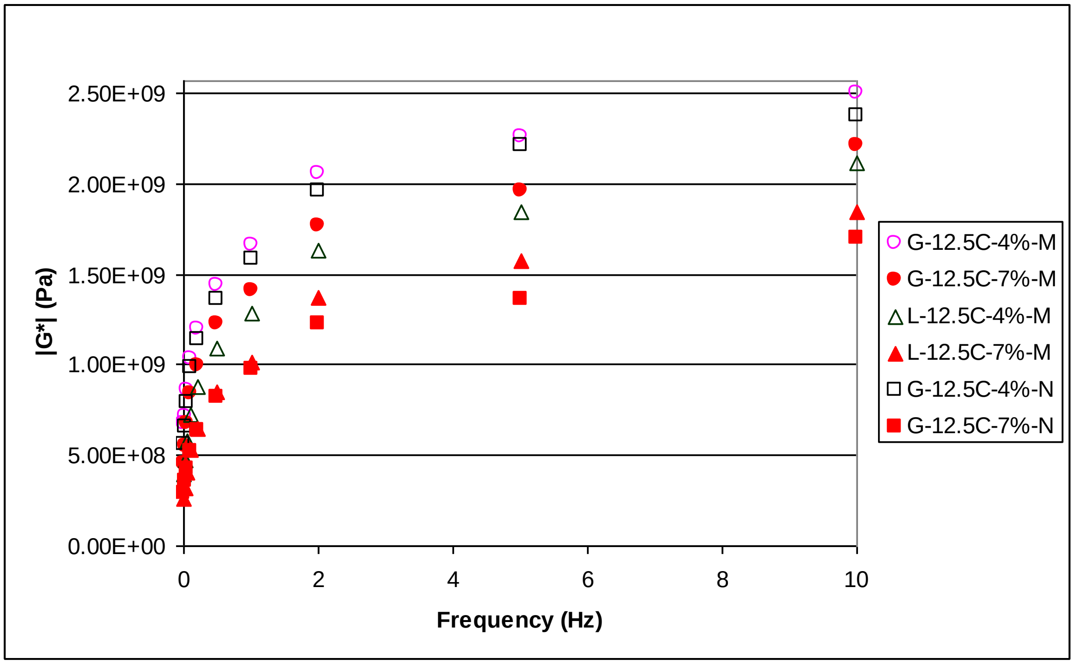

Figure 6-1: FSCH Tests of SGC Specimens for 12.5C Mix

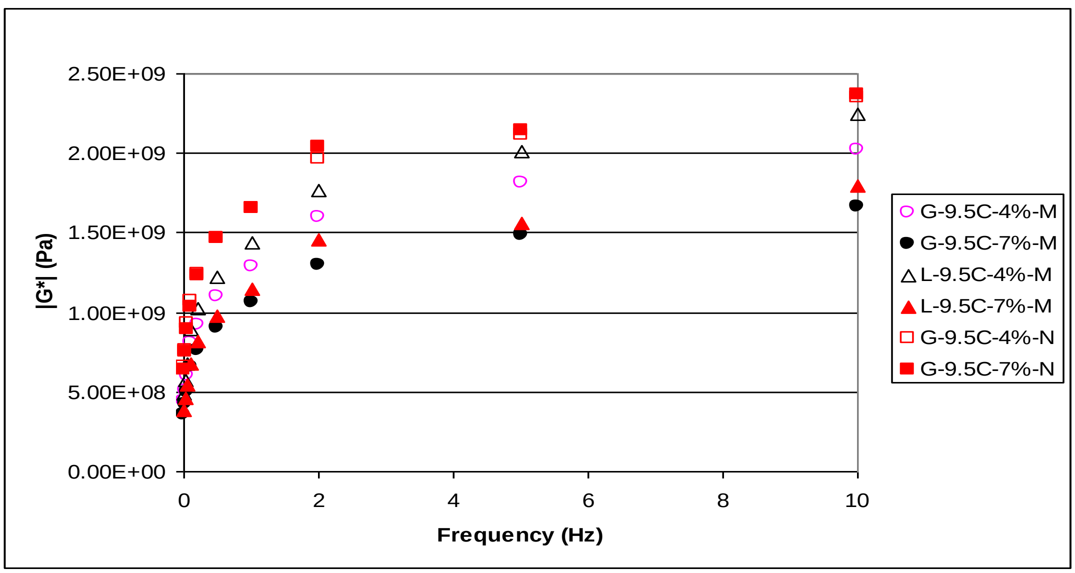

Figure 6-2: FSCH Tests of SGC Specimens for 9.5C Mix

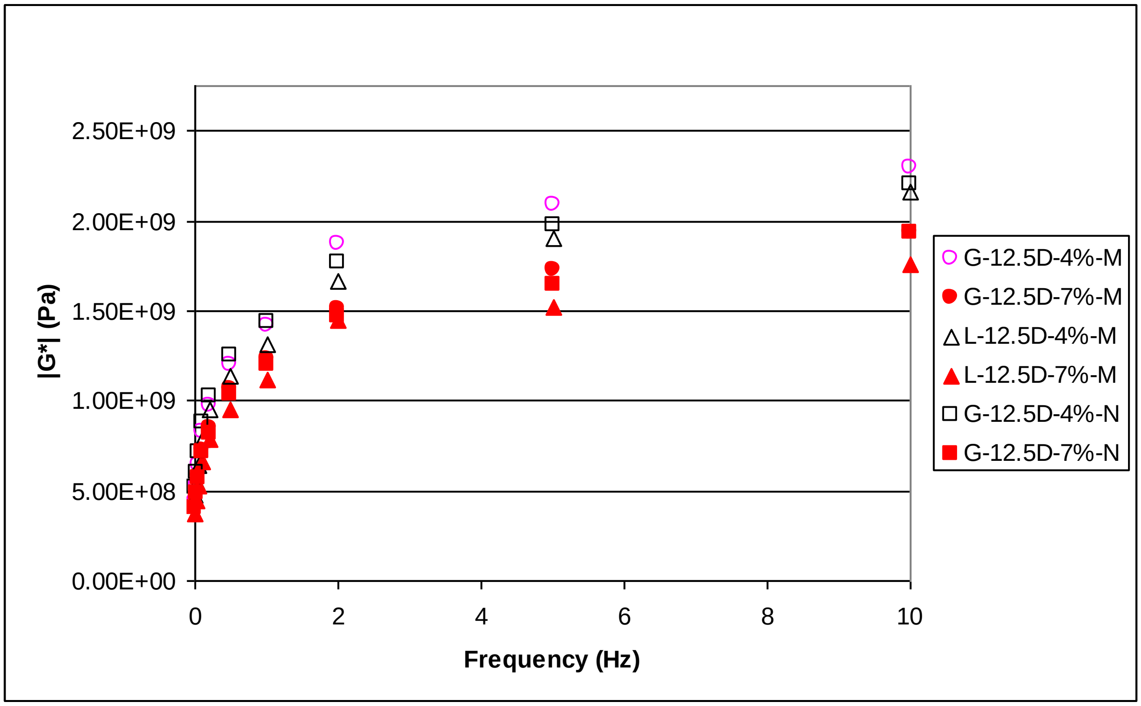

Figure 6-3: FSCH Tests of SGC Specimens for 12.5D Mix

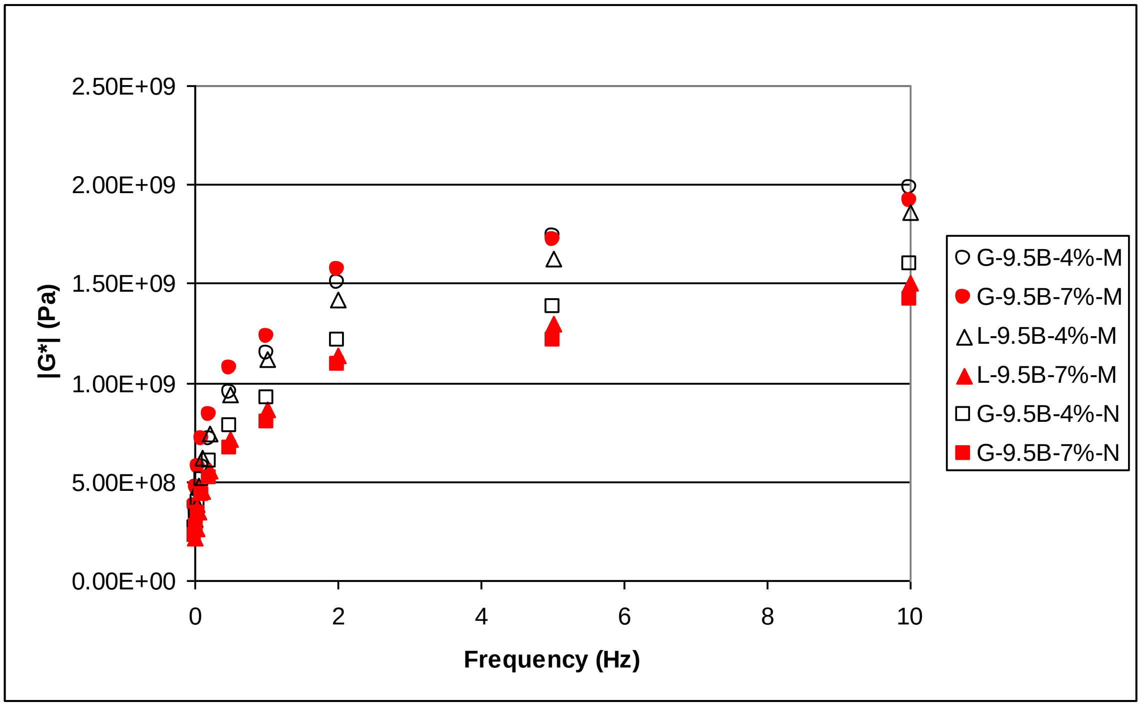

Figure 6-4: FSCH Tests of SGC Specimens for 9.5B Mix

Table 6-3: Results of FSCH Tests on 12.5C Mix

Frequency (Hz)	12.5C											
	Granite				Limestone				Granite + Natural Sand			
	4%		7%		4%		7%		4%		7%	
	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle
0.01	6.78E+08	29.35	4.51E+08	33.10	3.97E+08	32.39	2.61E+08	27.50	5.61E+08	30.40	2.90E+08	32.14
0.02	7.17E+08	28.88	5.47E+08	33.00	4.70E+08	31.94	3.22E+08	28.15	6.54E+08	29.88	3.56E+08	32.85
0.05	8.57E+08	26.34	6.79E+08	30.09	5.82E+08	30.47	4.08E+08	26.76	7.97E+08	27.45	4.26E+08	28.96
0.1	1.04E+09	25.51	8.44E+08	28.91	7.25E+08	29.81	5.29E+08	26.88	9.89E+08	25.49	5.24E+08	30.20
0.2	1.20E+09	23.75	9.97E+08	26.64	8.83E+08	28.51	6.47E+08	25.72	1.14E+09	24.25	6.40E+08	29.09
0.5	1.44E+09	21.38	1.22E+09	24.89	1.09E+09	26.24	8.55E+08	24.23	1.36E+09	22.17	8.25E+08	26.71
1	1.66E+09	19.86	1.41E+09	23.06	1.28E+09	25.01	1.01E+09	23.62	1.58E+09	20.08	9.78E+08	24.98
2	2.06E+09	19.95	1.77E+09	19.52	1.64E+09	21.67	1.37E+09	20.47	1.96E+09	17.10	1.22E+09	23.46
5	2.26E+09	16.54	1.96E+09	18.34	1.85E+09	20.59	1.58E+09	18.70	2.21E+09	15.31	1.37E+09	20.13
10	2.51E+09	17.27	2.21E+09	17.96	2.12E+09	19.36	1.85E+09	17.49	2.38E+09	15.87	1.70E+09	21.96

Table 6-4: Results of FSCH Tests on 9.5C Mix

Frequency (Hz)	9.5C											
	Granite				Limestone				Granite + Natural Sand			
	4%		7%		4%		7%		4%		7%	
	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle
0.01	4.40E+08	30.41	3.62E+08	36.74	4.89E+08	35.82	3.86E+08	33.55	6.60E+08	28.08	6.37E+08	28.20
0.02	5.12E+08	32.21	4.20E+08	38.91	5.69E+08	37.94	4.58E+08	32.87	7.64E+08	26.27	7.53E+08	26.37
0.05	6.06E+08	29.64	4.99E+08	35.80	6.73E+08	34.91	5.41E+08	30.99	9.28E+08	23.43	8.96E+08	21.68
0.1	8.04E+08	28.49	6.62E+08	34.41	8.94E+08	33.56	6.81E+08	29.78	1.07E+09	20.59	1.03E+09	25.47
0.2	9.24E+08	25.70	7.60E+08	31.04	1.02E+09	30.27	8.22E+08	27.94	1.24E+09	20.83	1.23E+09	22.56
0.5	1.10E+09	24.29	9.01E+08	29.33	1.22E+09	28.61	9.73E+08	25.94	1.47E+09	19.47	1.47E+09	19.69
1	1.29E+09	22.74	1.06E+09	27.42	1.43E+09	26.74	1.14E+09	24.00	1.65E+09	18.20	1.66E+09	18.37
2	1.59E+09	14.81	1.30E+09	17.85	1.77E+09	17.41	1.46E+09	20.85	1.97E+09	15.62	2.04E+09	16.77
5	1.81E+09	16.71	1.49E+09	20.15	2.01E+09	19.65	1.56E+09	18.49	2.12E+09	14.60	2.14E+09	14.76
10	2.02E+09	15.91	1.66E+09	19.18	2.25E+09	18.71	1.80E+09	17.78	2.35E+09	14.00	2.37E+09	15.63

Table 6-5: Results of FSCH Tests on 12.5D Mix

Frequency	12.5D											
	Granite				Limestone				Granite + Natural Sand			
	4%		7%		4%		7%		4%		7%	
	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle
0.01	4.32E+08	33.51	4.01E+08	31.35	4.72E+08	29.62	3.75E+08	33.06	5.12E+08	28.76	4.02E+08	31.71
0.02	5.26E+08	32.96	4.78E+08	30.78	5.49E+08	28.78	4.47E+08	31.85	5.97E+08	27.15	4.87E+08	30.80
0.05	6.45E+08	33.12	5.83E+08	28.94	6.42E+08	28.11	5.29E+08	29.72	7.13E+08	25.29	5.72E+08	27.82
0.1	8.30E+08	29.96	7.19E+08	28.42	7.82E+08	27.96	6.65E+08	28.73	8.80E+08	23.54	7.17E+08	26.57
0.2	9.73E+08	27.93	8.48E+08	27.13	9.48E+08	26.48	7.89E+08	27.51	1.03E+09	24.36	8.21E+08	26.31
0.5	1.20E+09	25.96	1.07E+09	24.89	1.14E+09	24.91	9.50E+08	25.23	1.25E+09	21.42	1.04E+09	24.75
1	1.41E+09	23.69	1.23E+09	22.83	1.32E+09	23.74	1.11E+09	23.43	1.44E+09	19.78	1.20E+09	23.13
2	1.87E+09	17.91	1.51E+09	20.59	1.67E+09	21.77	1.44E+09	23.21	1.76E+09	18.50	1.46E+09	21.40
5	2.09E+09	19.52	1.72E+09	18.77	1.90E+09	19.29	1.52E+09	18.59	1.97E+09	16.30	1.65E+09	19.01
10	2.30E+09	18.77	1.93E+09	17.90	2.16E+09	18.56	1.75E+09	18.08	2.20E+09	15.78	1.93E+09	19.20

Table 6-6: Results of FSCH Tests on 9.5B Mix

Frequency	9.5B											
	Granite				Limestone				Granite + Natural Sand			
	4%		7%		4%		7%		4%		7%	
	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle	Complex Modulus	Phase Angle
0.01	2.69E+08	38.75	3.80E+08	35.56	3.14E+08	35.62	2.12E+08	38.71	2.63E+08	33.83	2.24E+08	34.04
0.02	3.36E+08	37.84	4.72E+08	35.10	3.84E+08	34.73	2.66E+08	38.32	3.18E+08	34.04	2.69E+08	34.33
0.05	4.49E+08	34.50	5.76E+08	32.71	4.82E+08	32.72	3.44E+08	36.45	3.97E+08	32.31	3.35E+08	32.72
0.1	5.69E+08	36.18	7.14E+08	32.42	6.21E+08	31.83	4.56E+08	35.36	5.04E+08	32.19	4.28E+08	32.60
0.2	7.15E+08	34.28	8.34E+08	30.19	7.46E+08	30.17	5.56E+08	33.09	6.06E+08	30.87	5.17E+08	31.64
0.5	9.49E+08	31.08	1.07E+09	26.65	9.43E+08	27.52	7.17E+08	30.78	7.76E+08	28.93	6.64E+08	29.84
1	1.15E+09	28.85	1.23E+09	24.98	1.12E+09	25.93	8.64E+08	28.87	9.17E+08	27.98	8.03E+08	28.58
2	1.51E+09	26.58	1.57E+09	22.14	1.42E+09	24.56	1.14E+09	26.92	1.22E+09	24.85	1.09E+09	19.36
5	1.74E+09	22.44	1.72E+09	20.44	1.62E+09	20.91	1.30E+09	22.70	1.38E+09	22.52	1.21E+09	23.21
10	1.99E+09	21.35	1.92E+09	18.86	1.86E+09	19.64	1.50E+09	21.22	1.60E+09	21.17	1.42E+09	22.28

Analysis of FSCH Test Results (Field part)

Figures 6.5 to 6.9 show the results of frequency sweep tests for the different mixes. The figures show the dynamic shear modulus (G*) as a function of frequency at 20°C. Tables 6.7 to 6.11 compare the G* values and the corresponding phase angles of the 9.5B mix for different specimens.

Figures 6.5 to 6.9 show the results of frequency sweep tests for all the Mixes.

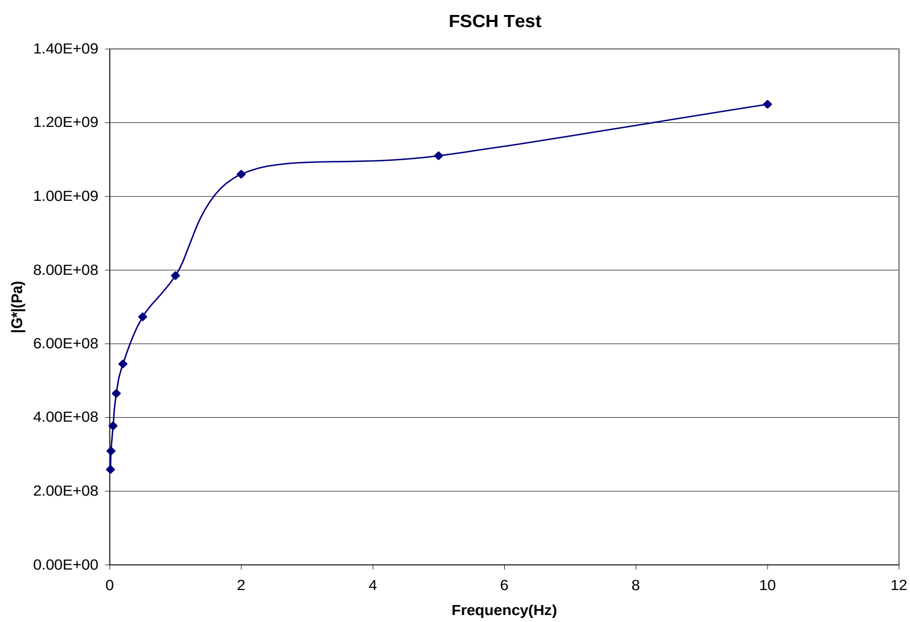

Figure 6-5: FSCH Test Result for 9.5B Mix (Field)

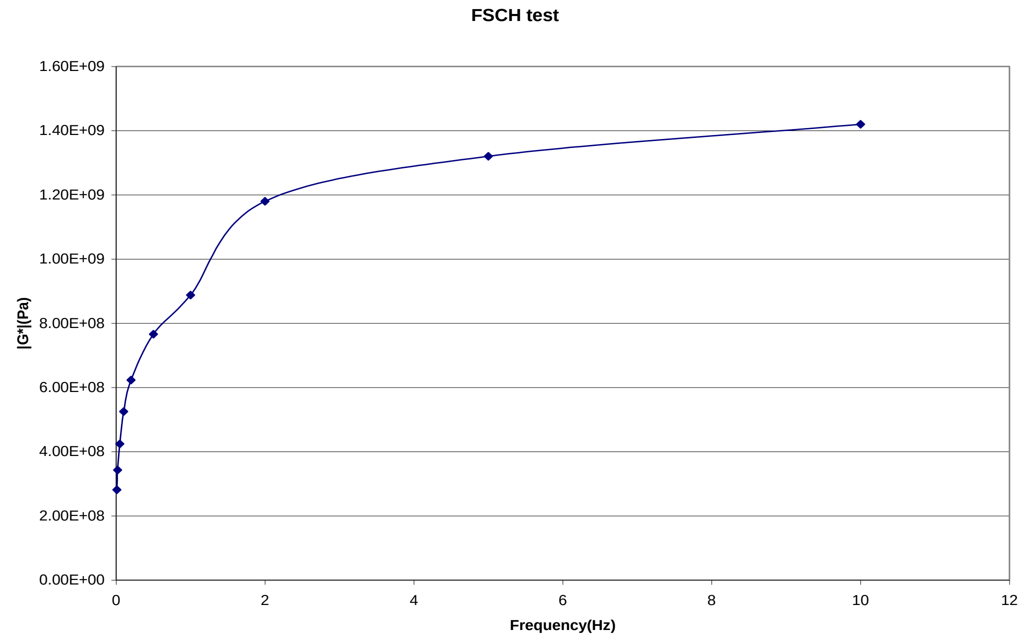

Figure 6-6: FSCH Test Result for Set 2 (9.5B Mix-Field)

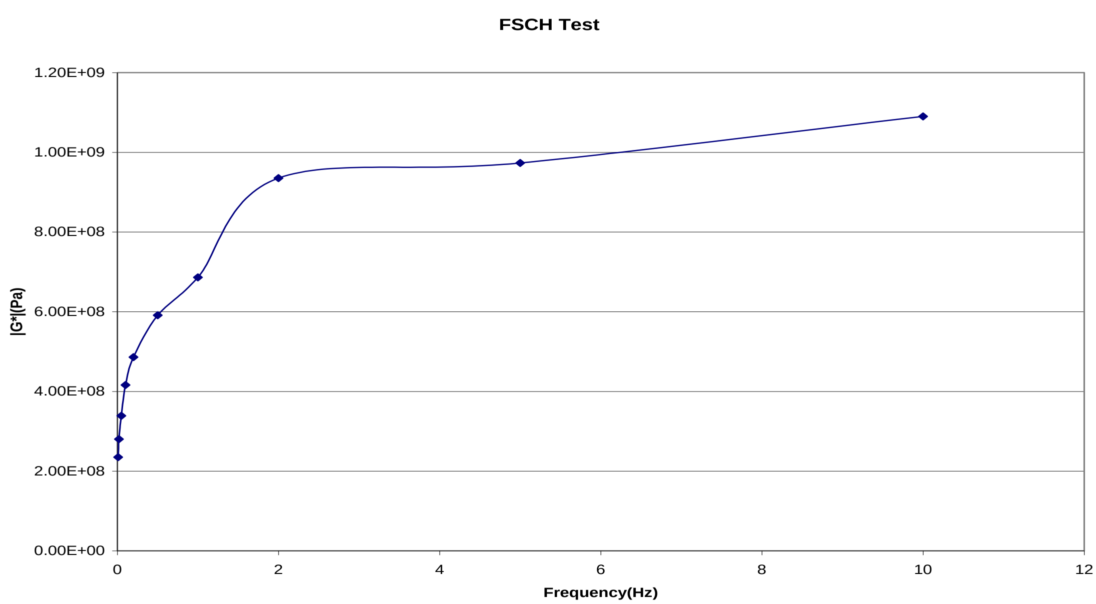

Figure 6-7: FSCH Test Result for 9.5C Mix (Field)

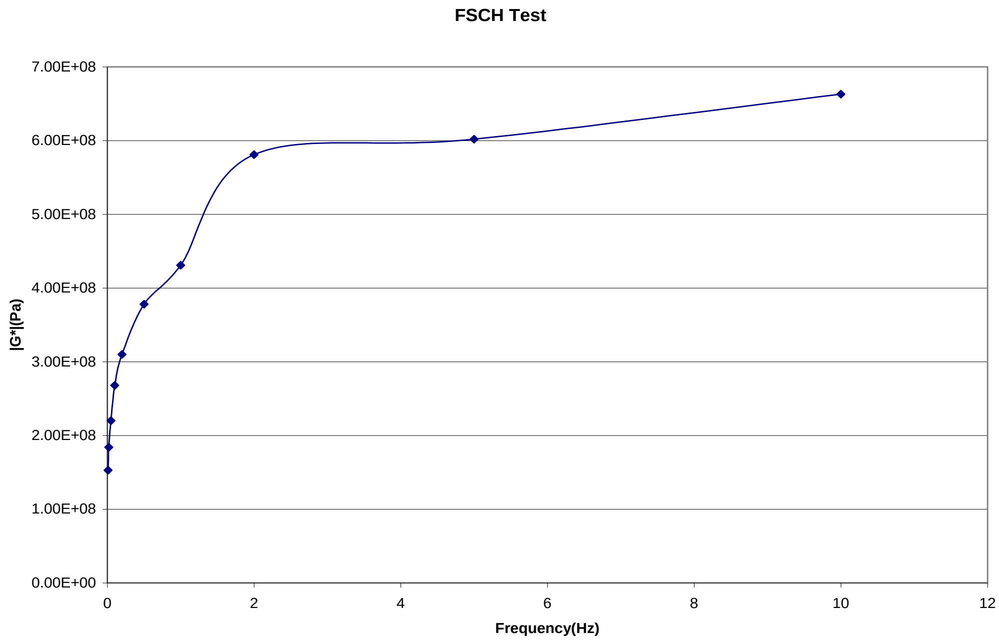

Figure 6-8: FSCH Test Result for 12.5D Mix (Field)

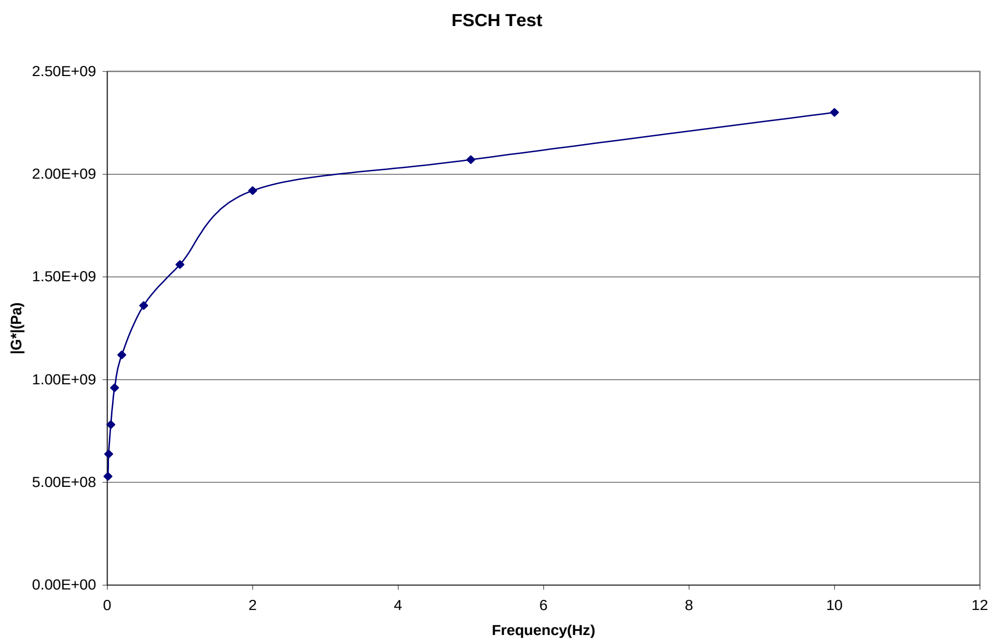

Figure 6-9: FSCH Test Result for 12.5C Mix (Field)

Tables 6.7 to 6.11 compare the G*(Complex Modulus) values and the corresponding phase angles of different specimens.

Table 6-7: Results of FSCH Tests for 9.5B Mix

Frequency(Hz)	Complex Modulus (Pa)	Phase Angle
0.01	2.35E+08	34.8755
0.02	2.80E+08	33.4613
0.05	3.39E+08	31.4249
0.1	4.16E+08	30.0911
0.2	4.86E+08	28.5267
0.5	5.91E+08	26.7159
1	6.86E+08	25.6615
2	9.35E+08	22.1026
5	9.73E+08	20.2207
10	1.09E+09	20.7025

Table 6-8: Results of FSCH Tests on Set 2 (9.5B Mix)

Frequency (Hz)	Complex Modulus (Pa)	Phase Angle
0.01	2.81E+08	35.065
0.02	3.43E+08	33.4384
0.05	4.24E+08	30.4061
0.1	5.25E+08	29.6166
0.2	6.23E+08	28.0085
0.5	7.66E+08	25.6507
1	8.88E+08	24.645
2	1.18E+09	21.5762
5	1.32E+09	21.941
10	1.42E+09	18.076

Table 6-9: Results of FSCH Tests on 9.5C Mix

Frequency(Hz)	Complex Modulus (Pa)	Phase Angle
0.01	2.35E+08	34.8755
0.02	2.80E+08	33.4613
0.05	3.39E+08	31.4249
0.1	4.16E+08	30.0911
0.2	4.86E+08	28.5267
0.5	5.91E+08	26.7159
1	6.86E+08	25.6615
2	9.35E+08	22.1026
5	9.73E+08	20.2207
10	1.09E+09	20.7025

Table 6-10: Results of FSCH Tests on 12.5D Mix

Frequency(Hz)	Complex Modulus (Pa)	Phase Angle
0.01	4.00E+08	34.2728
0.02	4.85E+08	32.1394
0.05	5.97E+08	28.6208
0.1	7.45E+08	27.4543
0.2	8.72E+08	25.4159
0.5	1.06E+09	22.9871
1	1.22E+09	21.2319
2	1.51E+09	19.8555
5	1.63E+09	17.6681
10	1.81E+09	16.9289

Table 6-11: Results of FSCH Tests on 12.5C Mix

Frequency(Hz)	Complex Modulus (Pa)	Phase Angle
0.01	5.29E+08	32.1583
0.02	6.38E+08	30.1096
0.05	7.81E+08	26.6711
0.1	9.60E+08	25.722
0.2	1.12E+09	23.6024
0.5	1.36E+09	21.2044
1	1.56E+09	19.132
2	1.92E+09	19.3711
5	2.07E+09	14.1265
10	2.30E+09	15.3527

6.1.4. 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 an indication of the mixtures 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 mixtures specified in Table 6.1. The tests were conducted at the seven-day average high pavement temperature at 50-mm depth from the pavement surface for Raleigh, NC, which is 58°C.

Analysis of RSCH Test Results (Lab Part)

The results of the RSCH tests are shown in Tables 6.12 to 6.15 and Figures 6.10 to 6.13. 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 air voids.

Table 6-12: Results of RSCH Tests on 12.5C Mix

12.5C											
Granite				Limestone				Granite + Natural Sand			
4%		7%		4%		7%		4%		7%	
Cycles	Strain	Cycles	Strain	Cycles	Strain	Cycles	Strain	Cycles	Strain	Cycles	Strain
5000	0.0036	5000	0.0049	5000	0.00467	5000	0.00656	5000	0.00826	5000	0.0093

Table 6-13: Results of RSCH Tests on 12.5D Mix

12.5D											
Granite				Limestone				Granite + Natural Sand			
4%		7%		4%		7%		4%		7%	
Cycles	Strain	Cycles	Strain	Cycles	Strain	Cycles	Strain	Cycles	Strain	Cycles	Strain
5000	0.0031	5000	0.0049	5000	0.00354	5000	0.00543	5000	0.00355	5000	0.0067

Table 6-14: Results of RSCH Tests on 9.5B Mix

9.5B											
Granite				Limestone				Granite + Natural Sand			
4%		7%		4%		7%		4%		7%	
Cycles	Strain	Cycles	Strain	Cycles	Strain	Cycles	Strain	Cycles	Strain	Cycles	Strain
5000	0.01193	5000	0.018	5000	0.0159	5000	0.0217	5000	0.0152	5000	0.0243

Table 6-15: Results of RSCH Tests on 9.5C Mix

9.5C											
Granite				Limestone				Granite + Natural Sand			
4%		7%		4%		7%		4%		7%	
Cycles	Strain	Cycles	Strain	Cycles	Strain	Cycles	Strain	Cycles	Strain	Cycles	Strain
5000	0.0044	5000	0.00461	5000	0.0046	5000	0.0047	5000	0.0056	5000	0.0074

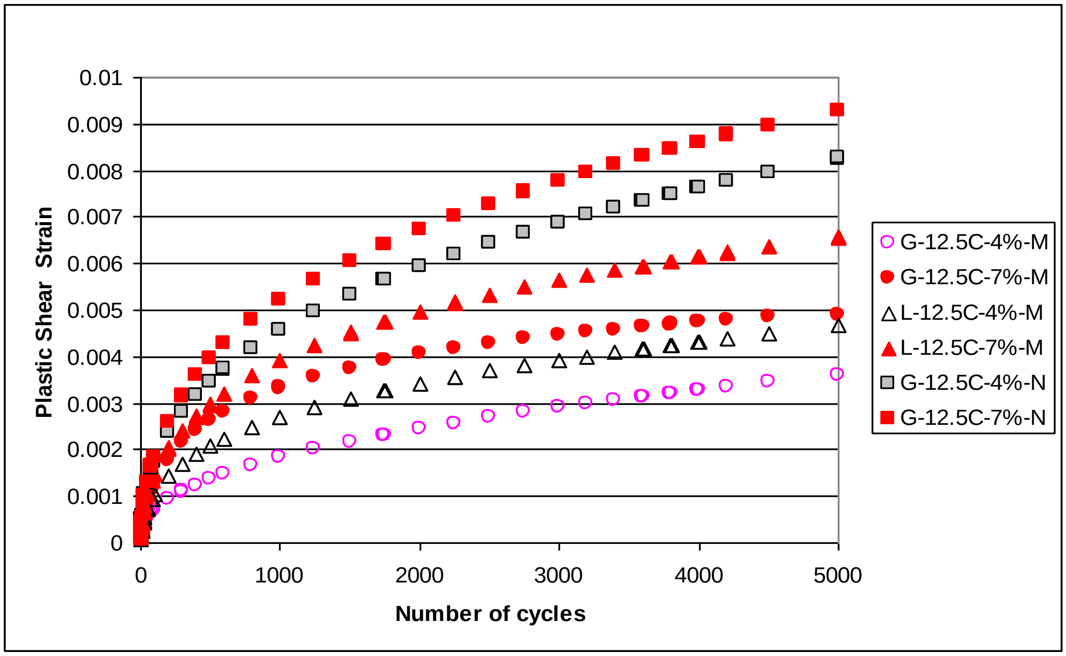

Figure 6-10: Results of RSCH Tests on SGC Specimens for 12.5C Mix

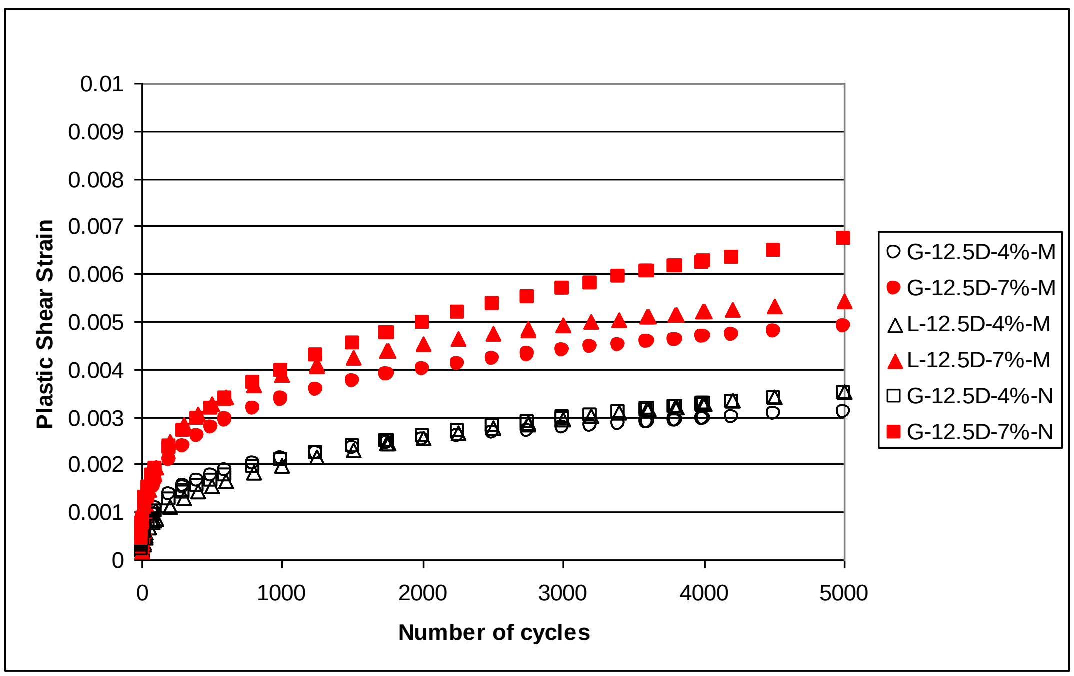

Figure 6-11: Results of RSCH Tests on SGC Specimens for 12.5D Mix

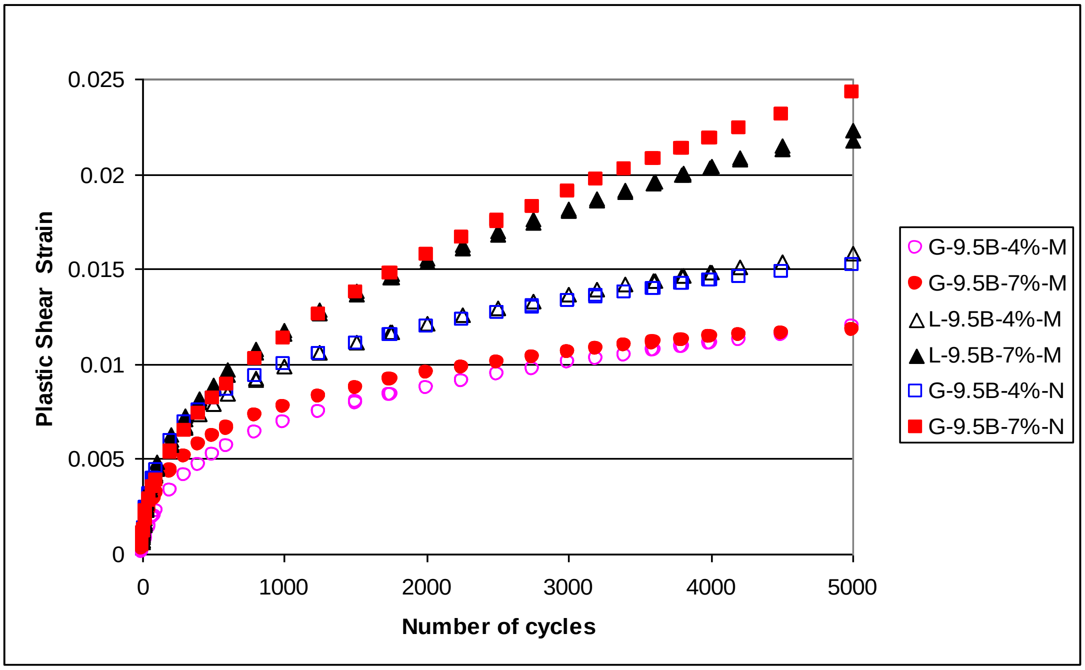

Figure 6-12: Results of RSCH Tests on SGC Specimens for 9.5B Mix

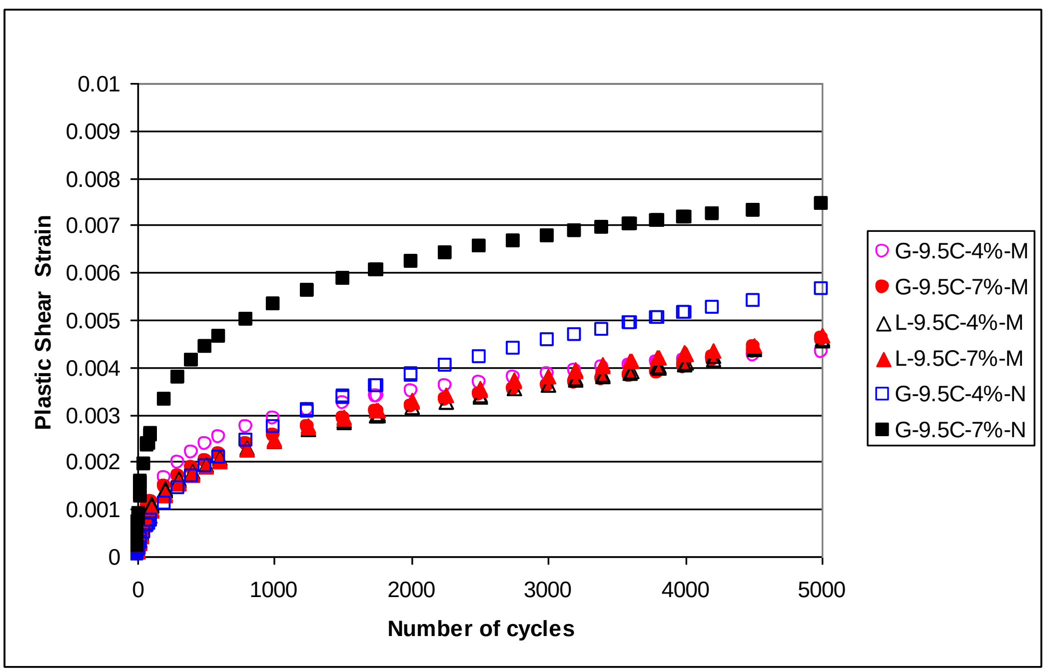

Figure 6-13: Results of RSCH Tests on SGC Specimens for 9.5C Mix

Figures 6.10 to 6.13 indicate that the shear strain accumulates in a rapid fashion for approximately the first 1000 cycles. Thereafter, the shear strain accumulation occurs in a fairly linear and non-rapid manner. This trend indicates the visco-elastic behavior of asphalt concrete. All of the above mixtures passed the 5000-cycle criteria. None of the mixtures reached the maximum strain limit. It can also be seen that for the same mix, samples with 4% air voids have lower shear strain accumulation than for samples with 7% air voids. This is consistent with the fact that the lower the air voids, the greater the stiffness, hence the lower the shear strain accumulation. In general, it can also be seen that mixtures with 9.5mm NMSA show higher shear strain accumulation than mixtures with 12.5mm NMSA. For the same NMSA-binder combination, mixtures containing natural sand have higher plastic shear strains than mixtures containing manufactured sand only. This is probably due to the fact that addition of natural sand decreases the average angularity of the aggregates, thus reducing its stiffness and resistance to shear deformation. Also, for the same NMSA-binder combination, mixtures containing granite tend to have higher shear strain accumulation compared to those containing limestone. In general, 9.5B type mixtures show the highest shear strain deformations and 12.5D type mixtures exhibit the lowest shear strain deformations. This observation can be explained by the fact that 12.5mm mixtures are stiffer than 9.5mm mixtures due to the presence of higher percentage of coarse aggregates and higher NMSA. Also, PG64-22 binder has the lowest stiffness and PG76-22 has the highest stiffness among all the binders use in this study. Higher binder stiffness results in lower shear deformation.

Analysis of RSCH Test Results (Field Part)

The results of the RSCH tests are shown in Table 6.16 and Figures 6.14 to 6.18. 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 different mixtures.

Table 6-16: Results of RSCH Tests on the Field Cores

Mixture	Cycles	Plastic Shear Strain
RS 9.5B	5000	0.0137973
RS 9.5B (set2)	5000	0.00811792
RS 9.5C	5000	0.00909332
RS 12.5D	5000	0.006418
RS 12.5C	5000	0.014809

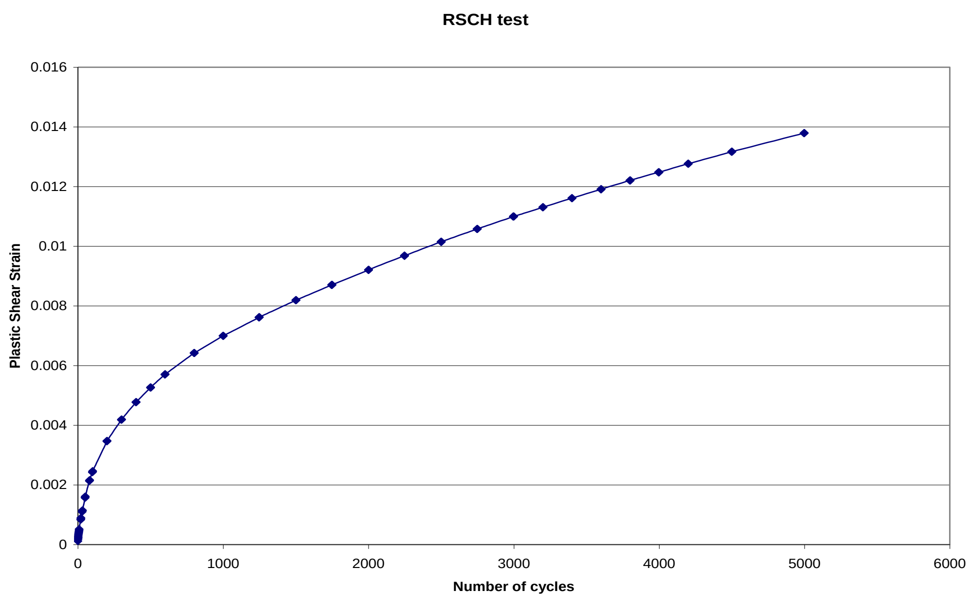

Figure 6-14: RSCH Test Result on 9.5B Mix (Field)

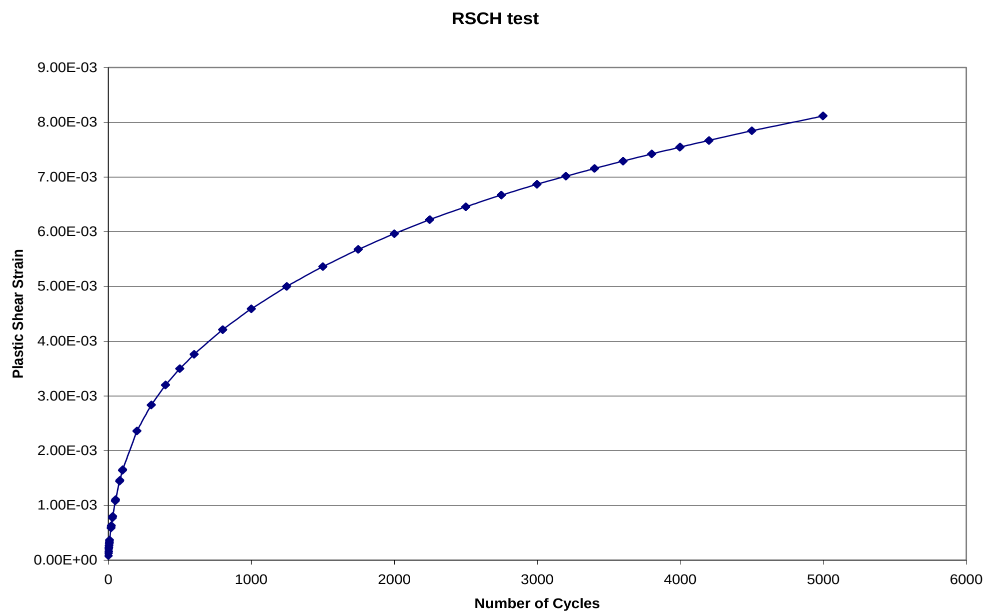

Figure 6-15: RSCH Test Result on Set 2 (9.5B Mix-Field)

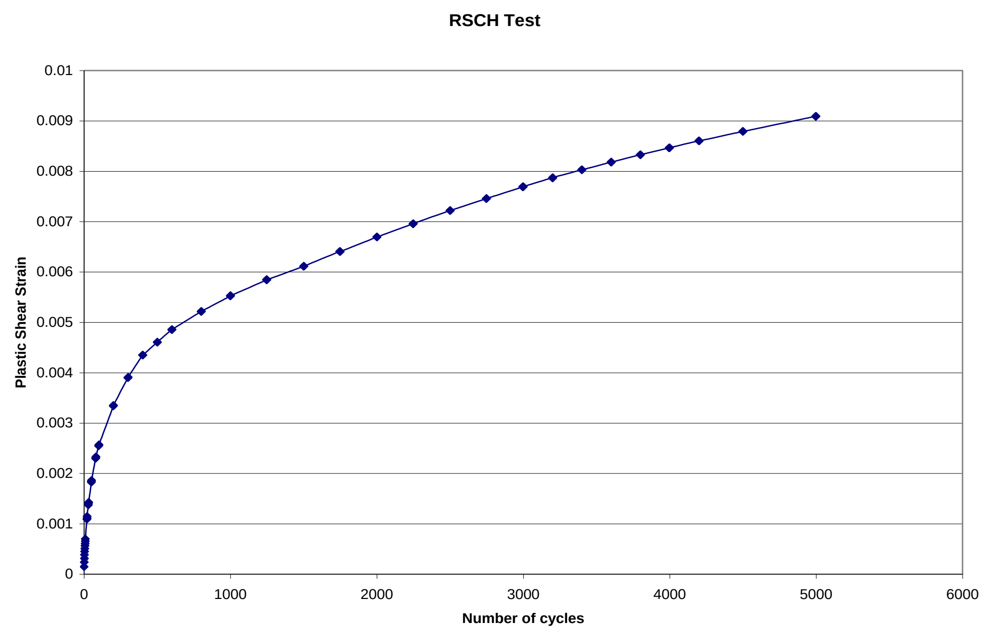

Figure 6-16: RSCH Test Result on 9.5C Mix (Field)

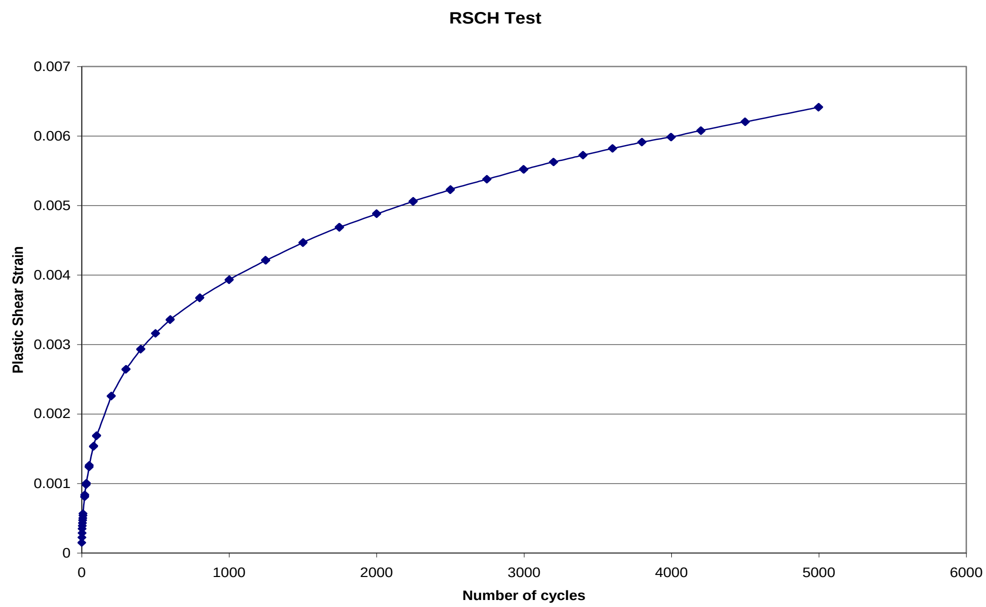

Figure 6-17: RSCH Test Result on 12.5D Mix (Field)

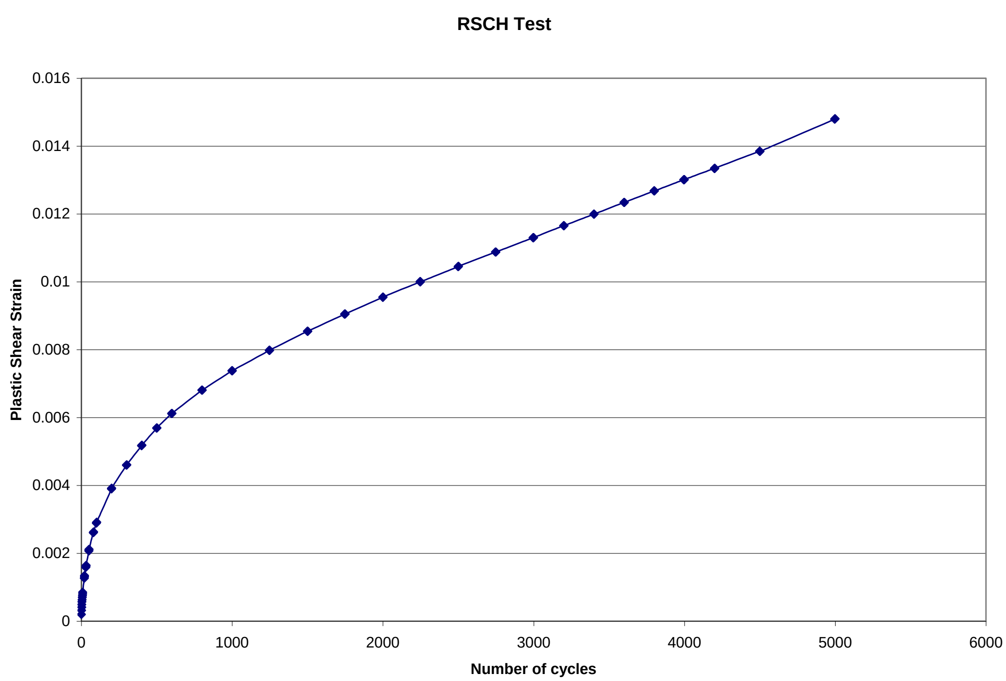

Figure 6-18: RSCH Test Result on 12.5C Mix (Field)

Figures 6.14 to 6.18 indicate that the shear strain accumulates in a rapid fashion for approximately the first 1000 cycles. Thereafter, the shear strain accumulation occurs in a fairly linear and non-rapid manner. This trend indicates the visco-elastic behavior of asphalt concrete. All of the above mixtures passed the 5000-cycle criteria. None of the mixtures reached the maximum strain limit. In general, it can also be seen that mixtures with 9.5mm NMSA show higher shear strain accumulation than mixtures with 12.5mm NMSA. In general, 9.5B type mixtures show the highest shear strain deformations and 12.5D type mixtures exhibit the lowest shear strain deformations. This observation can be explained by the fact that 12.5mm mixtures are stiffer than 9.5mm mixtures due to the presence of higher percentage of coarse aggregates and higher NMSA.

6.2. Performance Evaluation Using Asphalt Pavement Analyzer

The rutting susceptibility of the mixtures was assessed by placing samples under repetitive loads of a wheel-tracking device, called the Asphalt Pavement Analyzer (APA).

Duplicates of all the twelve mixtures used for SST were prepared. The cylindrical samples were compacted to an air void contents of 4% and 7%, using the Superpave Gyratory Compactor. The samples were checked to ensure they fell within the acceptable range of air voids. A tolerance of ±0.5 % change in air voids level was accepted. The samples were compacted to a thickness of 75mm to fit in the APA molds. The APA is capable of controlling the temperature in the cabin. Duplicates of twelve mixtures were tested at two temperatures, as specified earlier in chapter 3. The samples are kept inside the cabin at the required test temperature for two hours before testing. The number of cycles is selected as

8000 cycles (typical) from the control panel. The change in the rut depth is measured using a data acquisition system that measures at four points for gyratory samples. The graphical software plots the average of four points for each cycle. Tables 6.17 to 6.20 furnish experimental data for the APA rut depths of all mixtures after 8000 cycles.

Table 6-17: APA Rut Depth (in mm) for 12.5C Mix

12.5C											
Granite				Limestone				Granite + Natural Sand			
4%		7%		4%		7%		4%		7%	
58°C	70°C	58°C	70°C	58°C	70°C	58°C	70°C	58°C	70°C	58°C	70°C
1.768	1.988	2.428	3.115	1.718	1.73	2.238	3.623	1.913	2.665	2.588	3.719

Table 6-18: APA Rut Depth (in mm) for 12.5D Mix

12.5D											
Granite				Limestone				Granite + Natural Sand			
4%		7%		4%		7%		4%		7%	
58°C	76°C	58°C	76°C	58°C	76°C	58°C	76°C	58°C	76°C	58°C	76°C
0.994	1.021	1.176	1.748	0.886	1.172	1.398	1.482	1.175	1.637	2.441	4.559

Table 6-19: APA Rut Depth (in mm) for 9.5B Mix

9.5B											
Granite				Limestone				Granite + Natural Sand			
4%		7%		4%		7%		4%		7%	
58°C	64°C	58°C	64°C	58°C	64°C	58°C	64°C	58°C	64°C	58°C	64°C
2.136	2.636	2.902	4.068	2.414	2.783	3.315	3.784	3.67	3.761	4.97	5.5

Table 6-20: APA Rut Depth (in mm) for 9.5C Mix

9.5C											
Granite				Limestone				Granite + Natural Sand			
4%		7%		4%		7%		4%		7%	
58°C	70°C	58°C	70°C	58°C	70°C	58°C	70°C	58°C	70°C	58°C	70°C
1.856	2.185	2.368	3.754	1.54	2.01	2.12	2.65	1.67	2.27	2.53	4.53

It can be observed that, in general, mixtures with manufactured sand performed better than natural sand. For the same mix type-aggregate-PG Grade-air void combination, samples tested at PG-High temperature had more rutting than corresponding samples tested at 58°C. This observation is consistent with the fact that rutting increases with an increase in temperature. For the same mix type-aggregate-PG Grade-test temperature combination, samples with 4% air voids had lesser rutting than corresponding samples with 7% air voids. This observation is also consistent with the fact that since stiffness increases with a decrease in air voids content, rutting increases with an increase in air voids content. In general, 9.5B type mix shows the highest rutting among all the mix types. This observation is consistent with the findings of RSCH tests, where 9.5B type mixtures showed higher plastic shear strains than other mixtures.

Table 6.21 furnishes experimental data for the APA rut depths of all the field mixtures after 8000 cycles.

Table 6-21: APA Rut Depth (in mm) for Field Mixtures

Mixture Designation	Temperature(F)	APA Rut Depth(mm)
RS 9.5B	64	10.2
RS 9.5B (set2)	64	10.1
RS 9.5C	64	8.9
RS 12.5D	64	7.3
RS 12.5C	64	8.3

CHAPTER 7: STATISTICAL MODELING AND ANALYSIS OF RESULTS

7.1. Introduction

The objectives of this study were to (i) establish a correlation between the rut depth measured by APA testing and accumulated permanent shear strain measured by RSCH testing and (ii) to develop the APA rut depth criteria. Further, the aim was to develop a regression model to predict RSCH shear strains using the above correlation and with the effects of factors such as test temperatures, traffic volumes, and aggregate types. The strength of the correlation was measured using the coefficient of multiple determination (R^2). The RSCH shear strains were analyzed and interpreted to represent the effects of mix type and different traffic levels using the Superpave rutting model.

7.2. Statistical Modeling

Statistical modeling for this study was conducted by performing a regression analysis.

A general version of the regression model is as follows:

$$y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + \ldots + a_nx_n$$

where,

y = RSCH shear strain predicted by the model (dependent variable)

a_0 = intercept of the regression equation; n = Number of independent variables

$x_1, x_2, x_3 \ldots x_n$ = regression variables (independent variables)

$a_1, a_2, a_3 \ldots a_n$ = parameter estimates of the regression variables

When there is only one independent variable in the model, it becomes a simple linear regression between RSCH shear strain and the APA rut depth. With the inclusion of other independent variables such as mixture design parameters, FSCH test results and aggregate properties into the model, it becomes a multiple linear regression. Table 7.1 is a list of statistical parameters that were used in this study and their explanations.

Table 7-1: Explanation of Statistical Parameters

Parameter	Explanation
Degrees of Freedom (DF)	It is a measure of the number of independent pieces of information on which a parameter estimate is based
Sum of Squares	It is the sum of squares about the mean.
Mean Square	Sum of squares divided by the degrees of freedom
F Value	Value of F-statistic for testing the hypothesis that all slope statistics are zero
Prob>F	p-value for the above test. Lower p-value mean the variable is more significant
t-value for parameter estimate	value of t-statistic for the null hypothesis that parameter = 0
Prob>|t|	p-value for the above test

7.3. Full Model

The multiple linear regression model characterizes the effects of APA rut depths, air voids, mixture design parameters, binder viscosity, aggregate characteristics and FSCH test results among other variables to model the rutting behavior of the mixtures used in this study. The aim of this model is to predict RSCH permanent shear strain using the above mentioned variables.

7.3.1. Variable Selection

The following variables were short-listed as potential candidates for predicting RSCH shear strains:

1. **1.** RSCHSTRAIN (dependent variable) – RSCH shear strain predicted by regression model
2. **2.** APARD – Rut depth as measured by the APA test
3. **3.** NMSA – Nominal maximum aggregate size used in mixture design. This is a predictor variable that assumes a value of ‘zero’ for an NMSA value of 9.5mm and ‘one’ for an NMSA value of 12.5mm.
4. **4.** GSTAR – Complex modulus measured by FSCH test at 10Hz. Stiffer mixtures offer more rut resistance.
5. **5.** AV – An average value of the RSCH and APA test specimen air voids. Higher air voids cause more rutting.
6. **6.** PANGLE – Phase angle measured by FSCH test at 10Hz.
7. **7.** VMA – Voids in mineral aggregates of the mixture. Higher VMA has been shown to decrease rutting.
8. **8.** DUSTTOAC – Dust to binder content ratio. An increase in dust to binder content ratio will generally decrease the VMA. Due to the relationship between particle diameter and surface area, increasing the amount of material passing through the 0.075mm sieve will result in a greater total surface area of the aggregate blend. This

results in a thinner average film thickness, lower effective asphalt content, and could lower the VMA.

9. FAA – Fine aggregate angularity (FAA). Superpave specifies a minimum value of Fine Aggregate Angularity to achieve an acceptable rut resistant mixture. Angular aggregates have better interlocking capability than rounded aggregates and thus offer more resistance to rutting.

10. NDES – Number of N_{des} gyrations. This factor introduces the effects of traffic volume into the regression model.

11. PASSING3BY8 – Percentage of aggregates passing through 3/8” sieve. This factor introduces the effect of aggregate blending into the model. Higher percentage of aggregates passing through 3/8” sieve causes the mix to be stiffer and thus, increases rut resistance.

12. PASSING4 - Percentage of aggregates passing through #4 sieve. Higher percentage of aggregates passing through #4 sieve causes the mix to be stiffer and thus, increases rut resistance.

13. GMM – Rice specific gravity of the mixture. This factor introduces the effect of mixture design into the model.

14. VISCOSITY – Viscosity of binder at test temperature determined by the ASTM viscosity-temperature relationship [15]. This relationship is discussed later in this chapter. A stiffer binder, especially at higher temperatures, results in a higher rut resistance. Binder viscosities are given in Table 7.3.

15. Aggregate Type (categorical variable) – AGG_L, assumes a value 1 if the aggregate is limestone, AGG_G, assumes a value 1 if the aggregate is granite, if both values are zero, the aggregate type is Granite with natural sand. Earlier research has shown that aggregate type significantly affects rutting potential of a mix.

7.3.2. Binder Viscosity Values

The binder viscosity values used in this study were developed using the ASTM viscosity-temperature relationship [15], given by the following relationship:

$$\log \log \ \eta = A + VTS^{*}\log T_R$$

where,

η = viscosity (c_p)

T_R = test temperature, Rankine

A = regression intercept

VTS = regression slope of viscosity temperature susceptibility

The values of A and VTS parameters for the binders used in this study can be obtained from Table 7.2. The values of viscosity for the binders and test temperatures relevant to this study are listed in Table 7.3.

Table 7-2: Values of A and VTS Parameters Based on Asphalt Grade

High Temperature Grade	Low Temperature Grade (-22)	
	A	**VTS**
64	10.98	-3.68
70	10.29	-3.42
76	9.715	-3.20

Table 7-3: Binder Viscosities Determined by ASTM Viscosity-Temperature Relationship

Binder Grade	Test Temperature	Viscosity (Poise)
PG64-22	58°C	7024.83
PG70-22	58°C	15058.01
PG76-22	58°C	30482.48
PG64-22	64°C	2970.15
PG70-22	70°C	2941.03
PG76-22	76°C	2961.14

7.3.3. Full Model Results

This model includes all of the variables listed earlier. Table 7.4 shows the parameters estimates for this model.

Table 7-4: Parameter Estimates for Full Model

Variable	Standard error	T value	Estimate	Pr > |t|
Intercept	569.04	1.91	1086.9	0.05
NMSA	29.61	-1.91	-56.55	0.05
GSTAR	1.214E-10	-1.49	-1.81E-10	0.08
AV	0.00793	0.38	0.003	0.70
PANGLE	0.0076	-0.57	-0.004	0.57
VMA	0.1192	0.39	0.046	0.69
DUSTTOAC	27.97	-1.42	-39.71	0.15
FAA	0.65	-1.04	-0.68	0.29
NDES	0.024	-8.28	-0.19	<.0001
PASSING3BY8	5.61	-1.89	-10.60	0.05
PASSING4	0.23	3.36	0.77	0.001
GMM	0.22	0.15	0.03	0.88
VISCOSITY	0.0000089	3.03	2.7E-05	0.003
AGG_L	0	-	-	-
AGG_G	0.02	0.05	0.001	0.96
APARD	0.22	7.69	1.69	<0.0001

Note: The variable AGG_L has a parameter estimate of zero since it is a linear combination of other variables.

The full model looks as follows:

RSCHSTRAIN = 1086.9 -56.55**NMSA* -1.814E-10**GSTAR* + 0.003**AV* -0.004**PANGLE* +0.046**VMA* -39.71**DUSTTOAC* -0.68**FAA* -0.19**NDES* -10.60**PASSING3BY8* + 0.77**PASSING4* +0.03**GMM* + 2.7E-05**VISCOSITY* +0.001**AGG_G* + 1.69**APARD*

Full Model Critique

The full model yielded an R^2 value of 0.77. The RSCH shear strain predicted by the above model corresponds to a sample with similar mixture design characteristics. In this model, variables with negative parameter estimates are indirectly proportional to the dependent variable (RSCHSTRAIN). The values of probability indicate the significance of the effect of the corresponding variable on the model. Variables with probability values less than 0.0001 are highly significant and those with values greater than 0.1 are considered insignificant. It can be seen that GSTAR, AV, NDES, PASSING4, VISCOSITY and APARD are the only variables that are statistically significant to the model. Hence, the analysis was performed again to develop a modified model by selecting those variables that show the expected trend and are also significant at the 0.1 level of significance.

7.4. Modified Model

The modified model was developed by manually choosing variables that exhibit a significant relationship with the dependent variable. Table 7.5 shows the parameters estimates for this model.

Table 7-5: Parameter Estimates for Modified Model

Variable	Std. Error	Estimate	Pr > |t|	T-Value
Intercept	39.34	135.72	0.0007	3.45
NMSA	0.34	-0.75	0.02	-2.20
GSTAR	9.1826E-10	-1.25E-09	0.10	-1.36
AV	0.019	0.02	0.10	1.052
VMA	0.44	-1.34	0.002	3.04
DUSTTOAC	10.61	41.06	0.0001	3.86
FAA	1.21	-4.62	0.0002	3.818
NDES	0.0234	-0.20	<0.0001	8.54
PASSING4	0.15	0.52	0.0007	3.466
GMM	2.708	9.50	0.0006	3.508
APARD	0.19	1.31	<0.0001	6.89

The variables that were eliminated from the final model were PANGLE, RETAIN3BY8, VISCOSITY and the predictor variables AGG_G and AGG_L that represented aggregate types. These variables were eliminated either because they were not significant to the model or were exhibiting a trend different from what was expected.

7.4.1. Application of Modified Model on the Field Cores

RSCHSTRAIN= 135.72 -0.75 NMSA -1.25E-09 GSTAR +0.02 AV -1.34VMA +41.06 DUSTTOAC-4.62 FAA-0.20 NDES +0.52 PASSING4 +9.50 GMM +1.31 APARD

Table 7.6 presents the parameter estimates for the modified model.

Table 7-6: Parameter Estimates for Modified Model

Variable	Standard error	Estimate	Pr > |t|	T-Value
Intercept	39.34	135.72	0.0007	3.45
NMSA	0.34	-0.75	0.02	-2.20
GSTAR	9.1826E-10	-1.25E-09	0.10	-1.36
AV	0.019	0.02	0.10	1.052
VMA	0.44	-1.34	0.002	3.04
DUSTTOAC	10.61	41.06	0.0001	3.86
FAA	1.21	-4.62	0.0002	3.818
NDES	0.0234	-0.20	<0.0001	8.54
PASSING4	0.15	0.52	0.0007	3.466
GMM	2.708	9.50	0.0006	3.508
APARD	0.19	1.31	<0.0001	6.89

Table 7.7 presents the results of the modified model applied on the field cores where the RSCH strain predicted and RSCH strain observed are listed and the percentage error is calculated.

Table 7-7: Results of Modified Model Used on the Field Cores

Mixture	RSCH strain predicted	RSCH strain observed	% Error
RS 9.5B	0.02354	0.01197	96.6
RS 9.5B (set2)	0.026	0.0326	14.11
RS 9.5C	0.0450	0.0511	11.9
RS 12.5D	0.00568	0.006418	11.49
RS 12.5C	0.02626	0.014809	77.32

7.4.2. Model Created Using the Results from Set 1 (9.5B Mix)

RSCHSTRAIN= -4.82-1.45E-09*GSTAR+0.06*PANGLE -0.0653*VMA

+36.23*DUSTTOAC -3.56*FAA-0.35 *NDES +1.43 *APARD

R square value= 0.88

Table 7.8 presents the parameter estimates for the model developed using the data from the 9.5B mix.

Table 7-8: Parameter Estimates for the Model Using Set 1 (9.5B)

Variable	Standard Error	Estimate	Pr > |t|	t-value
Intercept	1.5643	-4.82	0.0003	-3.08
GSTAR	4.778E-10	-1.45E-09	0.10	3.03
PANGLE	0.04568	0.06	0.10	1.31
VMA	0.0565	-0.0653	0.002	-1.155
DUSTTOAC	3.2569	36.23	0.0001	11.12
FAA	0.1811	-3.56	0.0002	-19.65
NDES	0.017	-0.35	<0.0001	-20.59
APARD	0.16731	1.43	<0.0001	8.54

7.4.3. Model Created Using the Results from Set 2 (9.5B Mix)

RSCHSTRAIN= -3.67-1.21E-09*GSTAR+0.03*PANGLE + 34.32*DUSTTOAC -0.29 *NDES +1.26 *APARD

Table 7.9 presents the parameter estimates for the model created using the data from set 2 (9.5 B Mix)

Table 7-9: Parameter Estimates for the Model Using Set 2 (9.5B)

Variable	Std. Error	Estimate	Pr > |t|	t- value
Intercept	1.3567	-3.67	0.0006	-2.705
GSTAR	3.673E-10	-1.21E-09	0.23	3.29
PANGLE	0.0367	0.03	0.16	0.817
DUSTTOAC	3.245	34.32	0.0001	10.57
NDES	0.00654	-0.29	<0.0001	-44.3
APARD	0.2342	1.26	<0.0001	5.38

7.4.4. Model Created Using the Results from the 9.5C Mix.

RSCHstrain= -4.69-1.62E-09*GSTAR+0.043*PANGLE + 27.85*DUSTTOAC -0.16 *NDES +1.59 *APARD

Table 7.10 presents the parameter estimates for the model created using the data from the 9.5C Mix.

Table 7-10: Parameter Estimates for the Model Using Set 3 (9.5C)

Variable	Std. Error	Estimate	Pr > |t|	t-value
Intercept	1.5149	-4.69	0.0004	-3.09
GSTAR	4.9428E-10	-1.62E-09	0.57	-3.27
PANGLE	0.0491	0.043	0.23	0.875
DUSTTOAC	5.429	27.85	0.0001	5.129
NDES	0.00439	-0.16	<0.0001	-36.44
APARD	0.3274	1.59	<0.0001	4.856

7.5. Superpave Rutting Model Analysis (Lab Part)

The permanent deformation system of SHRP A-003A uses the following relation to convert the number of RSCH test cycles to ESALs.

$$\log(cycles) = -4.36 + 1.24 \log(ESALs)$$

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 corresponds to 3.156 million ESALs. According to the above relationship, the number of RSCH test cycles depends on the traffic level for which a mix is designed. The traffic levels corresponding to the mixtures used in this study are given in Table 7.11.

Table 7-11: Traffic Levels for Different Mixtures

Mixture Designation	Traffic Level (million ESALs)
S9.5B	0.3 – 3
S9.5C	3 – 30
S12.5C	3 – 30
S12.5D	> 30

Since the mixtures used in this study have been designed for different traffic levels, the number of RSCH test cycles would have to be different for different mixtures. This number can be calculated using the relationship mentioned earlier between RSCH test cycles and ESALs. Since each mix corresponds to a range of traffic volumes, we can either use the average traffic volume or the maximum traffic volume corresponding to a mix type for our analysis. Table 7.12 lists the calculated number of RSCH test cycles (AVG. CYCLES) corresponding to the average traffic volume that each mix used in this study is designed for. Table 7.13 lists the calculated number of RSCH test cycles (MAX. CYCLES) corresponding to the maximum traffic volume that each mix used in this study is designed for.

Table 7-12: RSCH Test Cycles Calculated for Average Traffic Volumes

Mixture Designation	Traffic Level (million ESALs)	Average Traffic (million ESALs)	RSCH Test Cycles (AVG. CYCLES)
S9.5B	0.3 – 3	1.65	2,238
S9.5C	3 – 30	16.5	38,876
S12.5C	3 – 30	16.5	38,876
S12.5D	> 30	30	81,589

Table 7-13: RSCH Test Cycles Calculated for Maximum Traffic Volumes

Mixture Designation	Traffic Level (million ESALs)	Maximum Traffic (million ESALs)	RSCH Test Cycles (MAX CYCLES)
S9.5B	0.3 – 3	3	4,695
S9.5C	3 – 30	30	81,589
S12.5C	3 – 30	30	81,589
S12.5D	> 30	45	1,34,892

In theory, an RSCH test would have to continue up to 38876 cycles in order to calculate the accumulated permanent shear strain at the end of 16.5 million ESALs for an S9.5C mix. The other numbers in Tables 7.12 and 7.13 can be interpreted in a similar manner. However, it is more practical and feasible to conduct an RSCH test up to 5000 cycles. The strain graph, so obtained, can be statistically modeled to predict the shear strain corresponding to any number of cycles. However, the assumption made here is that shear failure does not occur before reaching the specified number of RSCH test cycles for any mix. Figure 7.1 represents a typical laboratory RSCH strain curve and a typical strain curve predicted by a model representing the same curve. A typical model representing the strain graph is as follows:

$$y = aN^b$$

where,

y = Estimated RSCH Strain

a,b = Model Constants

N = Number of Cycles

The power regression law, represented by the above equation has been used in earlier studies as well [4]. The RSCH laboratory strain graphs of all the replicates with 4% air voids for each mix used in this study were modeled separately. The models yielded R^2 values in the range of 0.95 to 0.98. These models were used to predict shear strains at the number of cycles calculated using the relationship between RSCH test cycles and ESALs, specified in Tables 7.12 and 7.13.

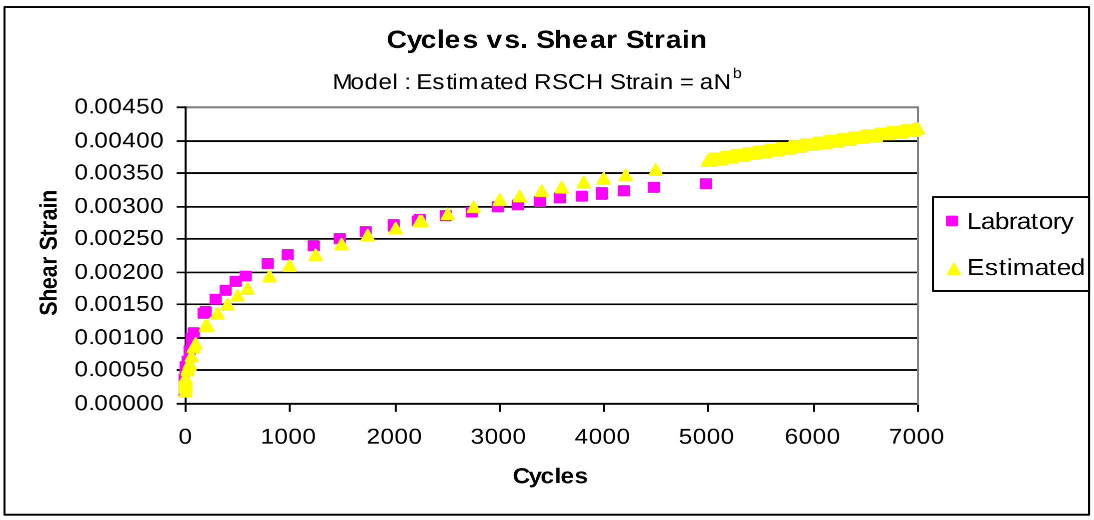

Figure 7-1: RSCH Laboratory Strain Curve vs. Predicted Strain Curve

Table 7.14 lists the average values of RSCH shear strains for four replicates prepared at 4% air voids at 5000 cycles and values of 'AVG CYCLES' and ' MAX CYCLES' for 9.5B mix type. Tables 7.15 to 7.17 compare the average values of predicted RSCH shear strains for four replicates and the observed RSCH shear strains for 9.5C, 12.5C and 12.5D mix types, respectively.

Table 7-14: RSCH Strain Values for 9.5B Mix

9.5B								
Granite			Limestone			Granite + Natural Sand		
4%			4%			4%		
Observed RSCH Strain @ 5000 cycles	Observed RSCH Strain @ 'AVG CYCLES'	Observed RSCH Strain @ 'MAX CYCLES'	Observed RSCH Strain @ 5000 cycles	Observed RSCH Strain @ 'AVG CYCLES'	Observed RSCH Strain @ 'MAX CYCLES'	Observed RSCH Strain @ 5000 cycles	Observed RSCH Strain @ 'AVG CYCLES'	Observed RSCH Strain @ 'MAX CYCLES'
0.01152	0.0009954	0.012829	0.01985	0.0144	0.019357	0.0152	0.01327	0.0148

Table 7-15: Predicted vs. Observed Results of RSCH Tests on 9.5C Mix

9.5C											
Granite				Limestone				Granite + Natural Sand			
4%				4%				4%			
Observed RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 'AVG CYCLES'	Predicted RSCH Strain @ 'MAX CYCLES'	Observed RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 'AVG CYCLES'	Predicted RSCH Strain @ 'MAX CYCLES'	Observed RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 'AVG CYCLES'	Predicted RSCH Strain @ 'MAX CYCLES'
0.0044	0.004911	0.01257	0.01767	0.00459	0.00488	0.01402	0.02054	0.00513	0.00667	0.01802	0.0258

Table 7-16: Predicted vs. Observed Results of RSCH Tests on 12.5C Mix

12.5C											
Granite				Limestone				Granite + Natural Sand			
4%				4%				4%			
Observed RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 'AVG CYCLES'	Predicted RSCH Strain @ 'MAX CYCLES'	Observed RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 'AVG CYCLES'	Predicted RSCH Strain @ 'MAX CYCLES'	Observed RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 'AVG CYCLES'	Predicted RSCH Strain @ 'MAX CYCLES'
0.00567	0.006256	0.01517	0.0209	0.00387	0.0041	0.00966	0.01316	0.00542	0.00575	0.01613	0.02344

Table 7-17: Predicted vs. Observed Results of RSCH Tests on 12.5D Mix

12.5D											
Granite				Limestone				Granite + Natural Sand			
4%				4%				4%			
Observed RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 'AVG CYCLES'	Predicted RSCH Strain @ 'MAX CYCLES'	Observed RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 'AVG CYCLES'	Predicted RSCH Strain @ 'MAX CYCLES'	Observed RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 5000 cycles	Predicted RSCH Strain @ 'AVG CYCLES'	Predicted RSCH Strain @ 'MAX CYCLES'
0.00307	0.0037	0.009971	0.01192	0.00337	0.00355	0.009451	0.011273	0.00355	0.0037	0.0122	0.01518

7.5.1. Rutting Model Analysis (Field Part)

Table 7.18 lists the average values of RSCH shear strains for four replicates at 5000 cycles and values of 'AVG CYCLES' and 'MAX CYCLES' for RS 9.5B mix type.

Tables 7.19 to 7.20 compare the average values of predicted RSCH shear strains for four replicates and the observed RSCH shear strains for RS 9.5C, 12.5D and 12.5C mix types, respectively.

Table 7-18: RSCH Strain Values for 9.5B Mixes (Field Part)

Observed RSCH strain @ 5000 Cycles	Observed RSCH strain @avg cycles	Observed RSCH strain @ max cycles
0.01197	0.0007896	0.01893

Table 7-19: Predicted vs Observed Results of RSCH Tests on 9.5C Mix

Observed RSCH strain @ 5000 cycles	Predicted RSCH strain @ 5000 cycles	Predicted RSCH strain @ Avg cycles	Predicted RSCH strain @ max cycles
0.00511	0.00532	0.01348	0.01859

Table 7-20: Predicted vs Observed Results of RSCH Tests on 12.5D Mix

Observed RSCH strain @ 5000 cycles	Predicted RSCH strain @ 5000 cycles	Predicted RSCH strain @ Avg cycles	Predicted RSCH strain @ max cycles
0.006418	0.00432	0.00953	0.01153

Table 7-21: Predicted vs Observed Results of RSCH Tests on 12.5C Mix

Observed RSCH strain @ 5000 cycles	Predicted RSCH strain @ 5000 cycles	Predicted RSCH strain @ Avg cycles	Predicted RSCH strain @ max cycles
0.00511	0.00483	0.00968	0.01482

7.6. APA Rut Depth Criteria (Lab Part)

The rut depth criteria for the APA test have been developed based on a multiple linear regression analysis of the APA test results at the end of 8000 cycles for samples with 7% air voids, the predicted values of RSCH shear strain for samples with 4% air voids which have been discussed in the earlier section and aggregate type used in a mix. This model is developed separately for each mix type. Further, since the APA tests were conducted at two temperatures for each mix type, there will be a separate model for each test temperature. The results of a multiple linear regression analysis using the backward elimination technique between predicted values of RSCH shear strains at ‘MAX. CYCLES’ (maximum traffic) and the APA rut depths at the end of 8000 cycles for each mix type are illustrated in Figures 7.2 to 7.9 and in APPENDIX C. These models include those dependent variables which are significant at the 0.1 level of significance.

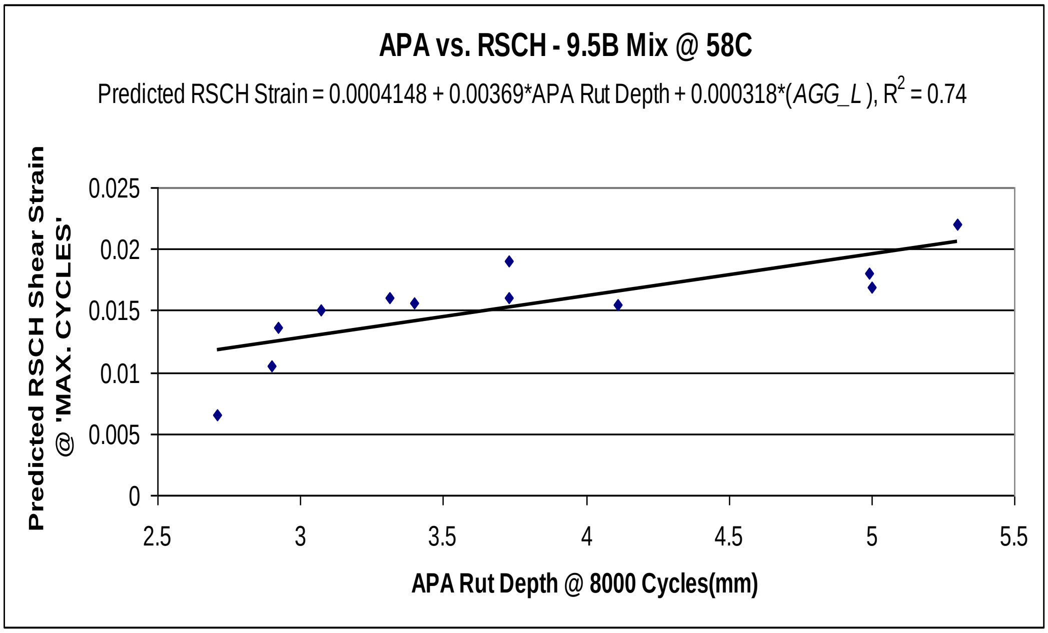

Figure 7-2: Correlation between RSCH Shear Strain @ MAX CYCLES and APA Rut Depth @ 8000 Cycles for 9.5B Mix (58°C)

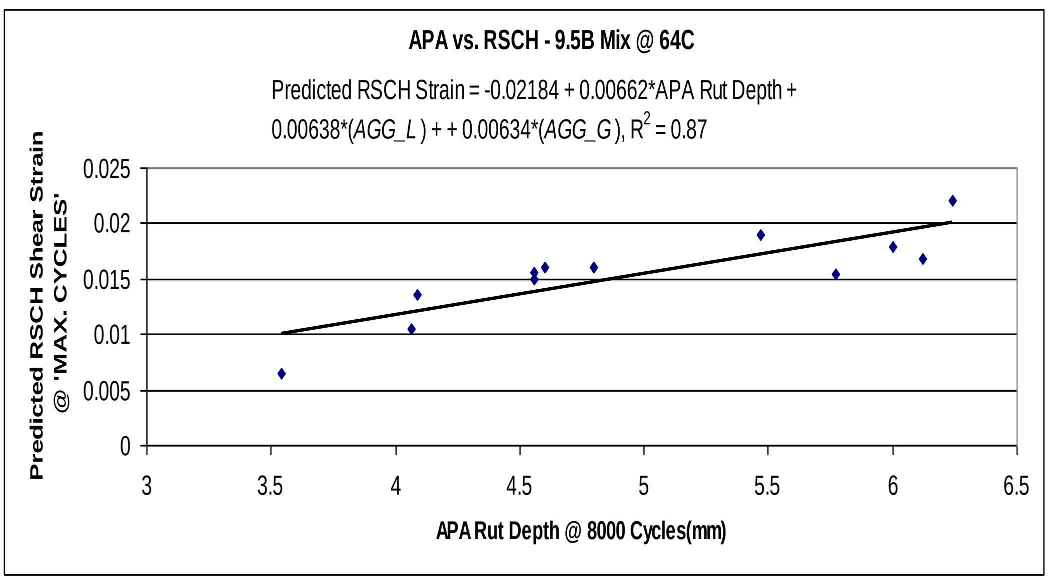

Figure 7-3: Correlation between RSCH Shear Strain @ MAX CYCLES and APA Rut Depth @ 8000 Cycles for 9.5B Mix (64°C)

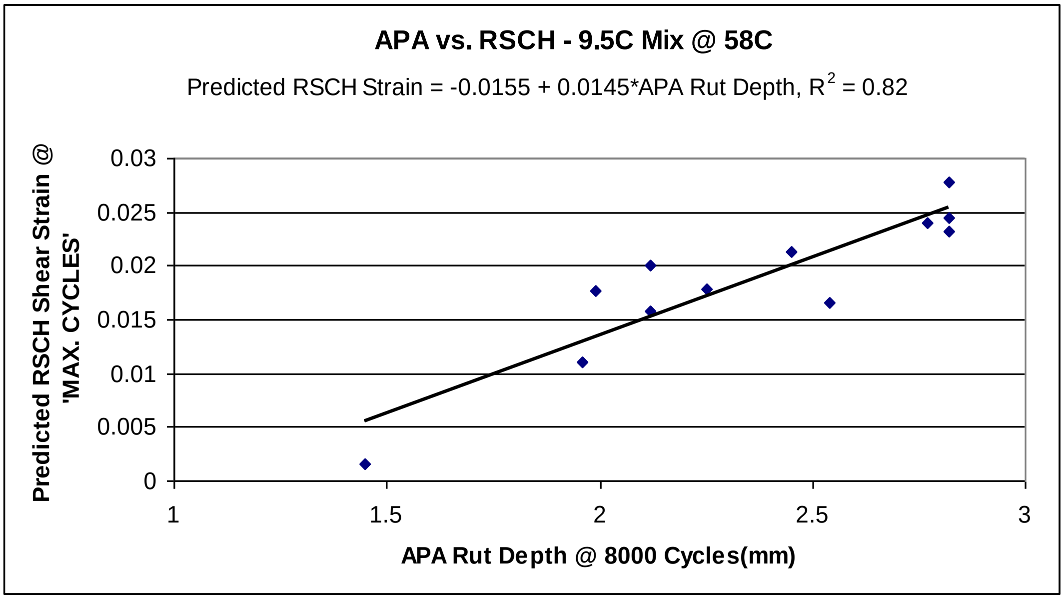

Figure 7-4: Correlation between RSCH Shear Strain @ MAX CYCLES and APA Rut Depth @ 8000 Cycles for 9.5C Mix (58°C)

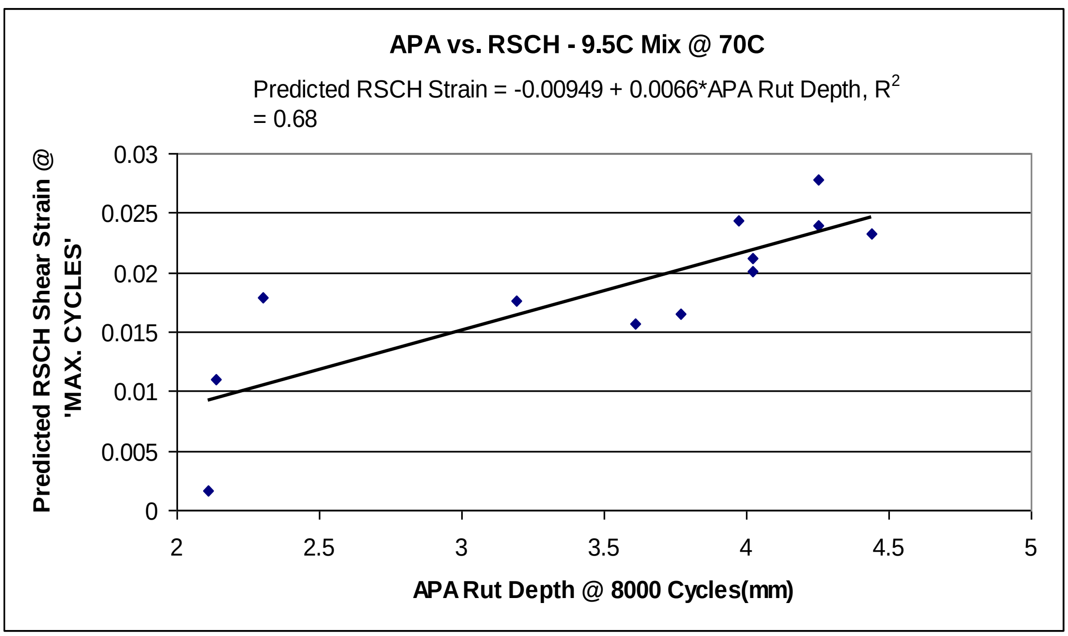

Figure 7-5: Correlation between RSCH Shear Strain @ MAX CYCLES and APA Rut Depth @ 8000 Cycles for 9.5C Mix (70°C)

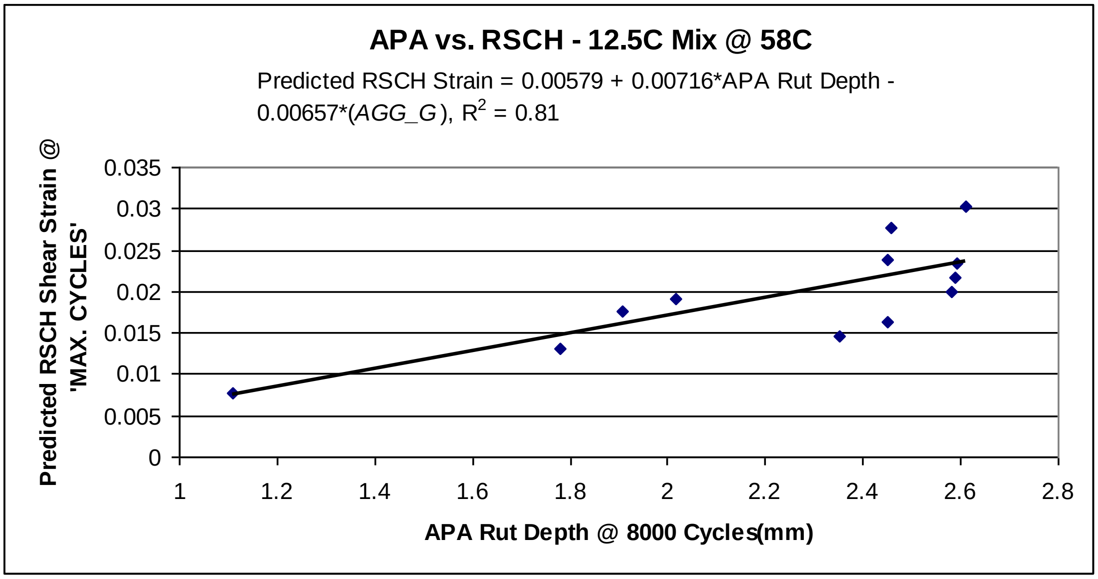

Figure 7-6: Correlation between RSCH Shear Strain @ MAX CYCLES and APA Rut Depth @ 8000 Cycles for 12.5C Mix (58°C)

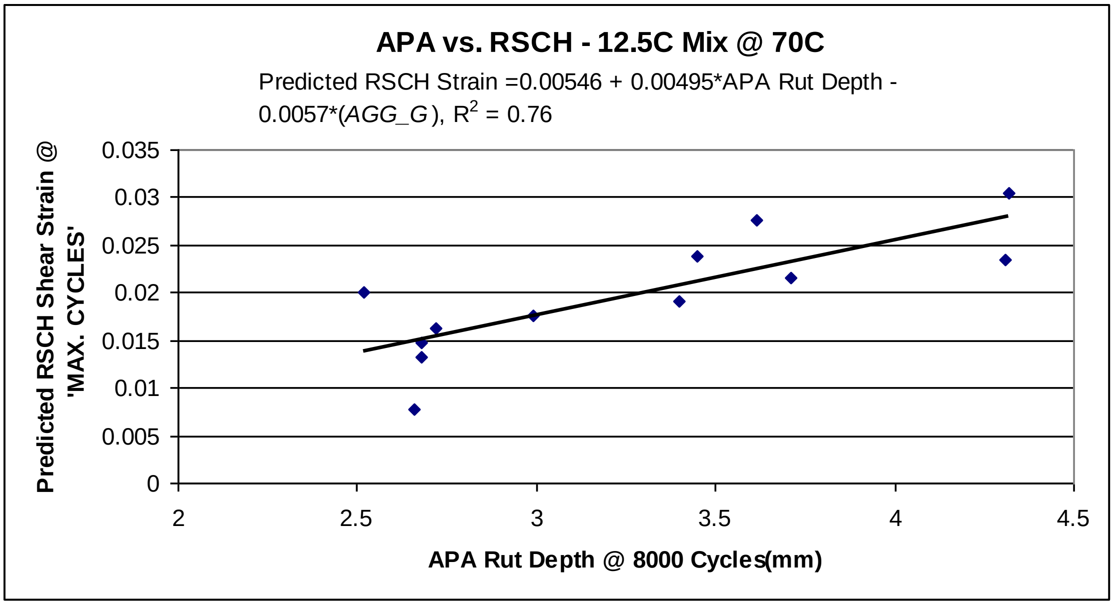

Figure 7-7: Correlation between RSCH Shear Strain @ MAX CYCLES and APA Rut Depth @ 8000 Cycles for 12.5C Mix (70°C)

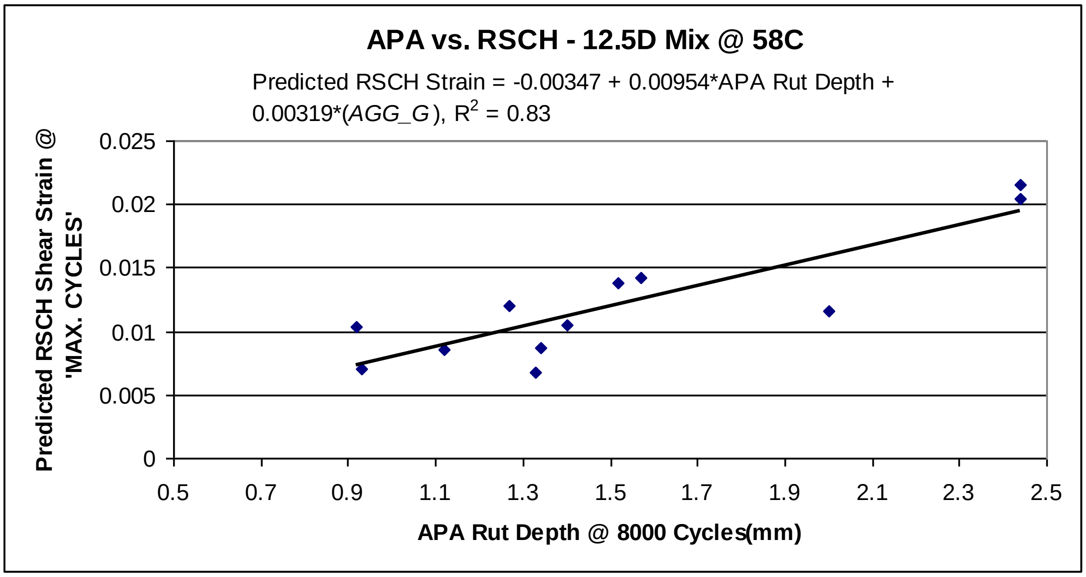

Figure 7-8: Correlation Between RSCH Shear Strain @ MAX CYCLES and APA Rut Depth @ 8000 Cycles for 12.5D Mix (58°C)

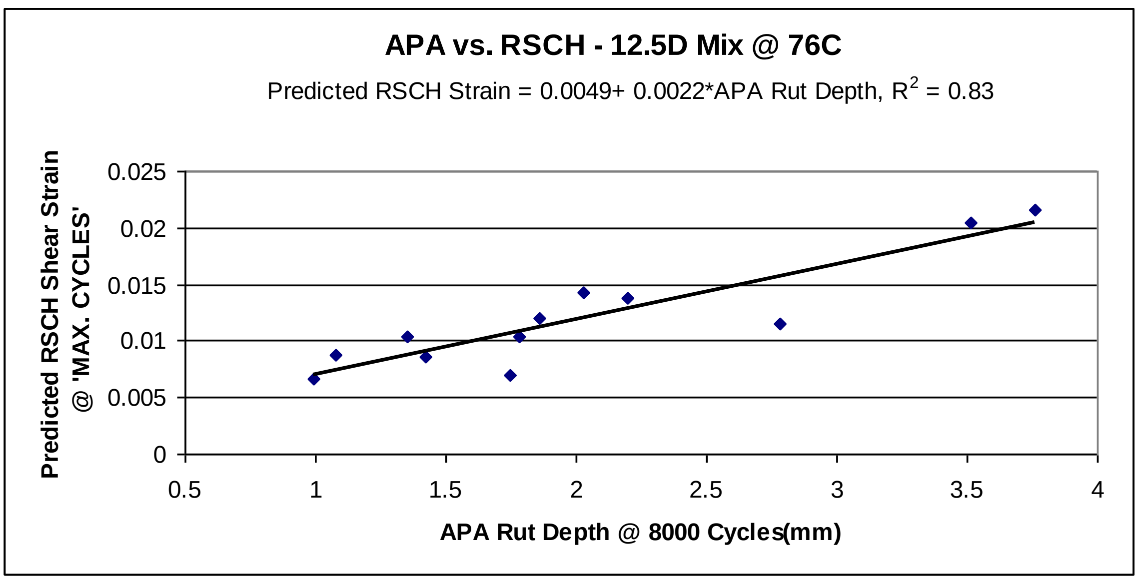

Figure 7-9: Correlation Between RSCH Shear Strain @ MAX CYCLES and APA Rut Depth @ 8000 Cycles for 12.5D Mix (76°C)

The results of a multiple linear regression analysis using the backward elimination technique between predicted values of RSCH shear strains at 'AVG. CYCLES' (average traffic) and the APA rut depths at the end of 8000 cycles for each mix type are summarized in Table 7.22 and in APPENDIX C.

Table 7-22: Regression Models for RSCH Shear Strain @ AVG. CYCLES and APA Rut Depth @ 8000 Cycles

Mix Designation	Regression Model @ 58°C	Regression Model @ PG-High
S9.5B	*Predicted RSCH Shear Strain* = -0.0015 + 0.00314**APA Rut Depth*+ 0.00247*(*AGG_L*), R^2 = 0.80	*Predicted RSCH Shear Strain* = -0.00552 + 0.00321**APA Rut Depth*+ 0.00203*(*AGG_L*), R^2 = 0.86
S9.5C	*Predicted RSCH Shear Strain* = -0.0114 + 0.0105**APA Rut Depth*, R^2 = 0.82	*Predicted RSCH Shear Strain* = -0.0029 + 0.0045**APA Rut Depth*, R^2 = 0.62
S12.5C	*Predicted RSCH Shear Strain* = 0.00463 + 0.005**APA Rut Depth*- 0.00476*(*AGG_G*), R^2 = 0.79	*Predicted RSCH Shear Strain* = -0.00493 + 0.00331**APA Rut Depth*-0.00433*(*AGG_G*), R^2 = 0.73
S12.5D	*Predicted RSCH Shear Strain* = -0.00296 + 0.00811**APA Rut Depth*+0.0027*(*AGG_G*), R^2 = 0.84	*Predicted RSCH Shear Strain* = 0.0016 + 0.0043**APA Rut*, R^2 = 0.88

The regression models developed in this section were further used to develop APA rut depth criteria. The rut depth criteria for evaluating rut resistance of mixtures will be based on the AI criteria for evaluating rut resistance, given in Table 7.23. The AI criteria are for RSCH tests conducted at 4% air voids.

Table 7-23: AI Criteria for Evaluating Rut Resistance

RSCH permanent shear strain, %	**Rut Resistance**
< 1.0 Excellent	Excellent
to < 2.0	Good
to < 3.0	Fair
> 3.0	Poor

The APA rut depth criteria for the mixtures used in this study and developed for different test temperatures and range of traffic volumes are listed in Tables 7.24 to 7.27.

Table 7-24: APA Rut Depth Criteria (in mm) at 58°C for Average Traffic Volume

Rut Resistance	9.5B			9.5C			12.5C			12.5D		
	G	L	G+N	G	L	G+N	G	L	G+N	G	L	G+N
Excellent	<3.75	<3.0	<3.75	<2.25	<2.25	<2.25	<2	<1	<1	<1.5	<1.75	<1.75
Good	3.5-7	3.0-6.0	3.5-7	2.25-3	2.25-3	2.25-3	2 – 4	1-3	1-3	1.5-2.5	1.75-3	1.75-3
Fair	7 – 10	6.0-9.5	7 – 10	3-4	3-4	3-4	4-6	3-5	3-5	2.5-3.75	3-4	3-4
Poor	>10	>9.5	>10	>4	>4	>4	>6	>5	>5	>3.75	>4	>4

G – Granite, L – Limestone, G+N- Granite + Natural Sand

Table 7-25: APA Rut Depth Criteria (in mm) at 58°C for Maximum Traffic Volume

Rut Resistance	9.5B			9.5C			12.5C			12.5D		
	G	L	G+N	G	L	G+N	G	L	G+N	G	L	G+N
Excellent	<2.75	<1.75	<2.75	<2	<2	<2	<1.5	<0.75	<0.75	<1.25	<1.5	<1.5
Good	2.75 - 5.5	1.75-4.5	2.75 - 5.5	1.75-2.5	1.75-2.5	1.75-2.5	1.5-3	0.75-2	0.75-2	1.25-2.25	1.5-2.5	1.5-2.5
Fair	4.5-8	4.5-7.5	4.5-8	2.5-3.5	2.5-3.5	2.5-3.5	3-4.5	2-3.5	2-3.5	2.25-3.25	2.5-3.5	2.5-3.5
Poor	>8	>7.5	>8	>3.5	>3.5	>3.5	>4.5	>3.5	>3.5	>3.25	>3.5	>3.5

G – Granite, L – Limestone, G+N- Granite + Natural Sand

Table 7-26: APA Rut Depth Criteria (in mm) at PG-High for Average Traffic Volume

Rut Resistance	9.5B			9.5C			12.5C			12.5D		
	G	L	G+N	G	L	G+N	G	L	G+N	G	L	G+N
Excellent	<4.75	<4.25	<4.75	<3	<3	<3	<3	<1.75	<1.75	<2	<2	<2
Good	4.75-8	4.25-7.25	4.75-8	3-5.25	3-5.25	3-5.25	3-6	1.75-4.75	1.75-4.75	2-4.5	2-4.5	2-4.5
Fair	8-11	7.25-10.5	8-11	5.25-7.5	5.25-7.5	5.25-7.5	6-9	4.75-7.75	4.75-7.75	4.5-6.75	4.5-6.75	4.5-6.75
Poor	>11	>10.5	>11	>7.5	>7.5	>7.5	>9	>7.75	>7.75	>6.75	>6.75	>6.75

G – Granite, L – Limestone, G+N- Granite + Natural Sand

Table 7-27: APA Rut Depth Criteria (in mm) at PG-High for Maximum Traffic Volume

Rut Resistance	9.5B			9.5C			12.5C			12.5D		
	G	L	G+N	G	L	G+N	G	L	G+N	G	L	G+N
Excellent	<4	<4	<5	<2.5	<2.5	<2.5	<2.25	<1	<1	<1.75	<1.75	<1.75
Good	4-5.5	4-5.5	5-6.5	2.5-4	2.5-4	2.5-4	2.25-4.25	1-3	1-3	1.75-4.5	1.75-4.5	1.75-4.5
Fair	5.5-7	5.5-7	6.5-8	4-5.5	4-5.5	4-5.5	4.25-6.25	3-5	3-5	4.5-5.75	4.5-5.75	4.5-5.75
Poor	>7	>7	>8	>5.5	>5.5	>5.5	>6.25	>5	>5	>5.75	>5.75	>5.75

G – Granite, L – Limestone, G+N- Granite + Natural Sand

The rutting criteria listed in Tables 7.24 to 7.27 are based purely on experimental data and the statistical analyses of the results of tests conducted on mixtures used in this study. In general, the models discussed earlier, could not characterize the effects of aggregate type on rutting criteria. It can be seen that for the same mix type-aggregate type combination, a higher rut criteria is recommended for a PG-High test temperature than for a test temperature of 58°C. This is due to the fact that a mix tends to rut more at higher temperatures. Also, for the same mix-aggregate type-test temperature combination, the rut criteria are more stringent for 'MAX.CYCLES' than for 'AVG. CYCLES'. This makes sense because, if a mix is expected to perform well for higher traffic volumes, it is expected to rut less. The same argument applies for lower rut criteria developed in case of 12.5D mix as compared to 9.5B mix. It can also be seen that the models have characterized the effects of aggregate type in a fairly uniform manner with more stringent criteria developed for mixtures containing limestone and granite mixed with natural sand than for those mixtures containing granite only. This is again consistent with the findings of RSCH and APA tests, where, mixtures containing granite only performed better than the other mixtures. Also, criteria for 9.5C mix are mostly similar to those developed for 12.5C mix. This is acceptable because both mixes are designed for the same traffic volumes. In general, the models used to develop the APA rut depth criteria have characterized the effects of aggregate types, test temperatures, mix types and traffic volumes in a fairly uniform and expected manner. Table 7.28 lists simple and easy-to-use accept/reject criteria for the mixtures used in this study at different test temperatures and traffic volumes. In general, the models discussed earlier, could not characterize the effects of aggregate type on rutting criteria. Hence, these criteria do not distinguish between aggregate types used in a particular mix.

Table 7-28: Accept/Reject APA Rut Depth Criteria (in mm)

Traffic Level(Test Temperature)	9.5B	9.5C	12.5C	12.5D
Average. Traffic (58°C)	10	5	6	4
Average. Traffic (PG-High)	11	8	8	7
Maximum Traffic (58°C)	8	4	4.5	3.5
Maximum Traffic (PG-High)	8	6	6	6

It is common for the APA tests to be conducted at 64°C in certain states. Since, the APA tests in this study were not conducted at this temperature it may not be possible to develop the APA rut criteria for this temperature. However, under the assumption that under identical test conditions, APA rutting increases linearly with test temperature, tentative rut depth criteria for a test temperature of 64°C can be developed. Table 7.29 lists tentative APA rut depth criteria for a test temperature of 64°C.

Table 7-29: Accept/Reject APA Rut Depth Criteria (in mm) for 64°C

Traffic Level(Test Temperature)	9.5B	9.5C	12.5C	12.5D
Average. Traffic	10.5	7	7	5
Maximum. Traffic	8	5	5	5

7.6.1. APA Rut Depth Criteria (Field Part)

The rut depth criteria for the APA test have been developed based on a multiple linear regression analysis of the APA test results at the end of 8000 cycles. This model is developed separately for each mix type.

Table 7.30 presents the regression models for RSCH shear strain @ AVG cycles and APA rut depth @ 8000 cycles for all the mixes.

Table 7-30: Regression Models for RSCH Shear Strain @ AVG Cycles and APA Rut Depth @ 8000 Cycles

Mix Designation	Regression Model
RS 9.5 B	Predicted RSCH shear strain= -0.0032+0.00285 * APA Rut depth, R square=0.79
RS 9.5 C	Predicted RSCH shear strain= -0.02361+0.0286 * APA rut depth, R square=0.82
RS 12.5D	Predicted RSCH shear strain= 0.0029+0.06538*APA Rut depth, R square=0.78
RS 12.5C	Predicted RSCH shear strain= -0.00632+0.00461*APA Rut depth, R square=0.75

Table 7.31 lists the AI criteria for evaluating rut resistance.

Table 7-31: AI Criteria for Evaluating Rut Resistance

RSCH Permanent Shear Strain %	Rut Resistance
<1.0 Excellent	Excellent
to < 2.0	Good
to <3.0	Fair
>3.0	Poor

Tables 7.32 and 7.33 present the APA rut depth criteria at PG-High for Average and Maximum Traffic volume

Table 7-32: APA Rut Depth Criteria (in mm) at PG-High for Average Traffic Volume

Rut Resistance	9.5B Mix	9.5C Mix	12.5D Mix	12.5C Mix
Excellent	<4.75	<3.25	<2.25	<2.0
Good	4.75-8.50	3.25-5.5	2.25-4.75	2.0-4.75
Fair	8.50-11.25	5.5-8.75	4.75-6.75	4.75-7.50
Poor	>11.25	>8.75	>6.75	>7.50

Table 7-33: APA Rut depth Criteria (in mm) at PG-High for Maximum Traffic Volume

Rut Resistance	9.5B Mix	9.5C Mix	12.5D Mix	12.5C Mix
Excellent	<4.25	<2.25	<2.0	<1.50
Good	4.25-5.0	2.25-3.75	2.0-4.75	1.50-3.25
Fair	5.0-7.75	3.75-6.25	4.75-6.0	3.25-5.25
Poor	>7.75	>6.25	>6.0	>5.25

7.6.2. Application of Modified Model for the Lab Data

The models created using the data from the field cores is applied to the cores prepared in the lab and the results are summarized in this section.

9.5 B mix

Model created using the results from set 2

RSCHstrain= -3.67-1.21E-09*GSTAR+0.03*PANGLE + 34.32*DUSTTOAC -0.29 *NDES +1.26 *APARD

Table 7.34 presents the parameter estimates for the model used for the 9.5B Mix

Table 7-34: Parameter estimates for the Model Used for 9.5B Mix

Variable	Std. Error	Estimate	Pr > |t|	t-value
Intercept	1.3567	-3.67	0.0006	-2.70
GSTAR	3.673E-10	-1.21E-09	0.23	-3.29
PANGLE	0.0367	0.03	0.16	0.817
DUSTTOAC	3.245	34.32	0.0001	10.57
NDES	0.00654	-0.29	<0.0001	-44.34
APARD	0.2342	1.26	<0.0001	5.38

RSCH shear strain predicted= 0.0176

RSCH shear strain observed (L) = 0.0159

% error=10.69%

9.5C mix

Model created using the results from set 3

RSCHstrain= - 4.69-1.62E-09*GSTAR+0.043*PANGLE + 27.85*DUSTTOAC -0.16 *NDES +1.59 *APARD

Table 7.35 presents the parameter estimates for the model for 9.5C Mix.

Table 7-35: Parameter Estimates for the Model for Set 3 (9.5C)

Variable	Std. Error	Estimate	Pr > |t|	t-value
Intercept	1.5149	-4.69	0.0004	-3.09
GSTAR	4.9428E-10	-1.62E-09	0.57	-3.27
PANGLE	0.0491	0.043	0.23	0.875
DUSTTOAC	5.429	27.85	0.0001	5.129
NDES	0.00439	-0.16	<0.0001	-36.44
APARD	0.3274	1.59	<0.0001	4.856

RSCH shear strain predicted=0.0019

RSCH shear strain observed (L) = 0.0046

% error= 58.69 %

Modified model

RSCHstrain= -3.62-1.42E-09*GSTAR+ 24.52*DUSTTOAC -0.12 *NDES +1.24 *APARD

Table 7.36 presents the parameter estimates for the modified model created by using the data from the 9.5C Mix.

Table 7-36: Parameter Estimates for the Modified Model Created Using the Results from 9.5C Mix

Variable	Std. Error	Estimate	Pr > |t|	t-value
Intercept	1.6234	-3.62	0.0002	-2.22
GSTAR	5.234E-10	-1.42E-09	0.62	-2.715
DUSTTOAC	4.572	24.52	0.0001	5.36
NDES	0.00482	-0.12	<0.0001	-24.89
APARD	0.2561	1.24	<0.0001	4.84

RSCH shear strain predicted= 0.0056

RSCH shear strain observed=0.0046

% error=21.7%

7.6.3. Combined Data of Field and Lab Cores

In this section the models created using the data from field cores are used to predict RSCH shear strain for the combined lab and field cores.

9.5 B mix

Model created using the results from set 2

RSCHstrain= -3.67-1.21E-09*GSTAR+0.03*PANGLE + 34.32*DUSTTOAC -0.29 *NDES +1.26 *APARD

Table 7.37 presents the parameter estimates for the model created using the results from set2 (9.5B Mix)

Table 7-37: Parameter Estimates for the Model Created Using the Results from Set 2 (9.5B Mix) (Combined Data)

Variable	Std. Error	Estimate	Pr > |t|	t-value
Intercept	1.3567	-3.67	0.0006	-2.70
GSTAR	3.673E-10	-1.21E-09	0.23	-3.29
PANGLE	0.0367	0.03	0.16	0.8174
DUSTTOAC	3.245	34.32	0.0001	10.57
NDES	0.00654	-0.29	<0.0001	-44.342
APARD	0.2342	1.26	<0.0001	5.38

RSCH shear strain predicted= 0.02347

RSCH shear strain observed=0.02425

% error= 3.21%

9.5 C Mix

Model created using the results from set 3

RSCHstrain= -4.69-1.62E-09*GSTAR+0.043*PANGLE + 27.85*DUSTTOAC -0.16*NDES +1.59 *APARD

Table 7.38 presents the parameter estimates for the model created using the results from 9.5C Mix (combined)

Table 7-38: Parameter Estimates for the Model Created Using the Results from 9.5C Mix (Combined)

Variable	Std.Error	Estimate	Pr > |t|	t-value
Intercept	1.5149	-4.69	0.0004	-3.09
GSTAR	4.9428E-10	-1.62E-09	0.57	-3.27
PANGLE	0.0491	0.043	0.23	0.875
DUSTTOAC	5.429	27.85	0.0001	5.129
NDES	0.00439	-0.16	<0.0001	-36.44
APARD	0.3274	1.59	<0.0001	4.856

RSCH shear strain predicted=0.04642

RSCH shear strain observed=0.04855

% error=4.38%

12.5 D Mix

Model created using the results from set 5

RSCHstrain= -9.31-1.34E-09*GSTAR+0.048*PANGLE + 38.54*DUSTTOAC -0.28 *NDES +1.74*APARD

Table 7.39 presents the parameter estimates for the model created using the results from 12.5C Mix (combined)

Table 7-39: Parameter Estimates for the Model Created Using the Results from 12.5C Mix (Combined)

Variable	Std. Error	Estimate	Pr > |t|	t-value
Intercept	1.638	-9.31	0.00038	-5.68
GSTAR	2.983E-10	-1.34E-09	0.78	-4.50
PANGLE	0.0328	0.048	0.29	1.4634
DUSTTOAC	5.942	38.54	0.0001	6.48
NDES	0.0227	-0.28	<0.0001	-12.33
APARD	0.3798	1.74	<0.0001	4.58

RSCH shear strain predicted=0.00368

RSCH shear strain observed=0.00329

% error= 11.8%

12.5C Mix

Model created using the results from set 4

RSCHstrain= -8.25-1.27E-09*GSTAR+0.039*PANGLE + 32.41*DUSTTOAC -0.15 *NDES +1.42 *APARD

Table 7.40 presents the parameter estimates for the model created using the results from 12.5C Mix (combined)

Table 7-40: Parameter Estimates for the Model Created Using the Results from 12.5C Mix (Combined)

Variable	Std. Error	Estimate	Pr > |t|	t-value
Intercept	1.549	-8.25	0.00032	-5.32
GSTAR	2.820E-10	-1.27E-09	0.73	-4.50
PANGLE	0.0231	0.039	0.27	1.688
DUSTTOAC	5.467	32.41	0.0001	5.92
NDES	0.00239	-0.15	<0.0001	-62.76
APARD	0.3408	1.42	<0.0001	4.16

RSCH shar strain predicted=0.00523

RSCH shear strain observed=0.00438

% error= 19.40%

Table 7.41 lists the average values of RSCH shear strains for four replicates prepared at 5000 cycles and values of 'AVG CYCLES' and 'MAX CYCLES' for 9.5B mix type. Tables 7.42 to 7.44 compare the average values of predicted RSCH shear strains for four replicates and the observed RSCH shear strains for 9.5C, 12.5D and 12.5C mix types, respectively.

Table 7-41: RSCH Strain Values for 9.5B Mixes (Combined)

Observed RSCH strain @ 5000 Cycles	Observed RSCH strain @avg cycles	Observed RSCH strain @ max cycles
0.02425	0.000643	0.01983

Table 7-42: Predicted vs Observed Results of RSCH Tests on 9.5C Mix (Combined)

Observed RSCH strain @ 5000 cycles	Predicted RSCH strain @ 5000 cycles	Predicted RSCH strain @ Avg cycles	Predicted RSCH strain @ max cycles
0.04855	0.04642	0.06862	0.06984

Table 7-43: Predicted vs Observed Results of RSCH Tests on 12.5D Mix (Combined)

Observed RSCH strain @ 5000 cycles	Predicted RSCH strain @ 5000 cycles	Predicted RSCH strain @ Avg cycles	Predicted RSCH strain @ max cycles
0.00329	0.00368	0.00396	0.00417

Table 7-44: Predicted vs Observed Results of RSCH Tests on 12.5C Mix (Combined)

Observed RSCH strain @ 5000 cycles	Predicted RSCH strain @ 5000 cycles	Predicted RSCH strain @ Avg cycles	Predicted RSCH strain @ max cycles
0.00438	0.00523	0.00568	0.059

7.7. APA Correlation (Combined Lab and Field Data)

Figures 7.10 -7.13 show the APA-RSCH correlation for the different mixes of combined lab and the field data.

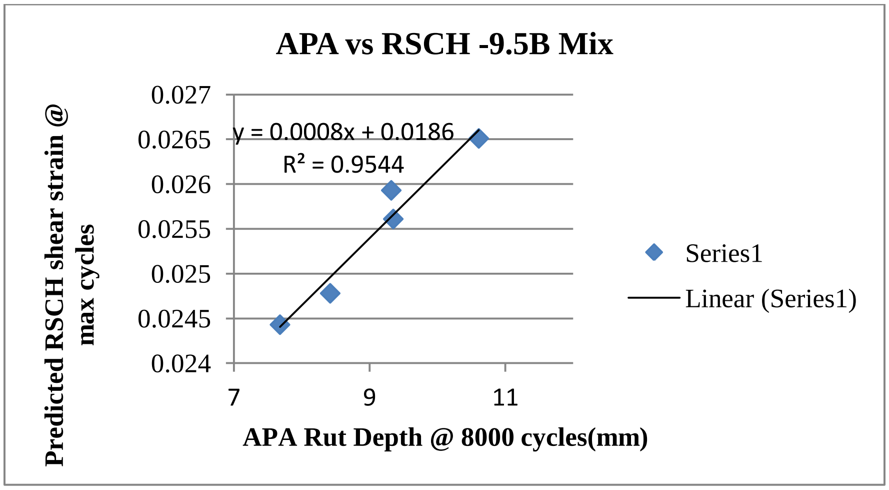

Figure 7-10: Correlation between RSCH Shear Strain @ MAX CYCLES and APA Rut Depth @ 8000 Cycles for 9.5B Mix

Predicted shear strain=0.0008* APA rut depth+0.0186, R square=0.95

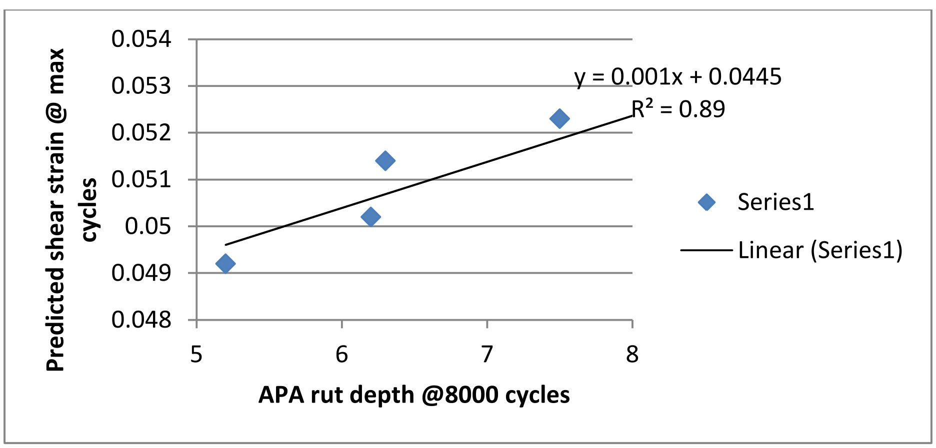

Figure 7-11: Correlation between RSCH Shear Strain @ MAX CYCLES and APA Rut Depth @ 8000 Cycles for 9.5C Mix

Predicted shear strain= 0.001* APA rut depth+ 0.0445,   R square=0.89

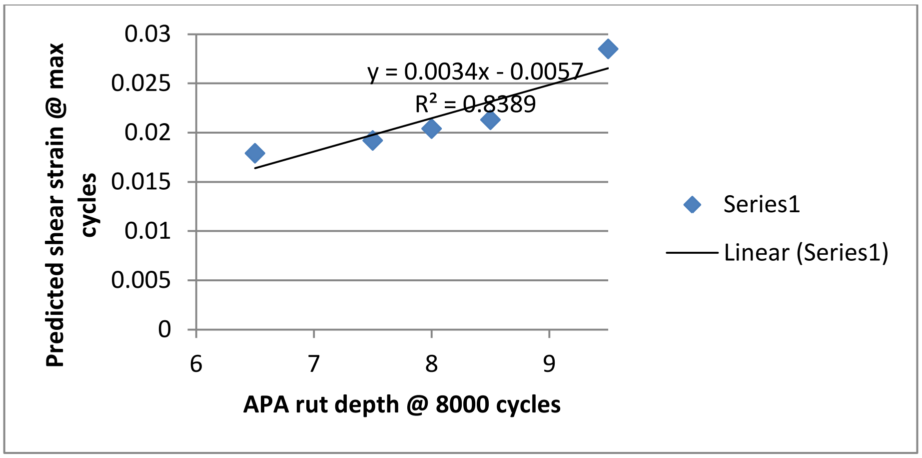

Figure 7-12: Correlation between RSCH Shear Strain @ MAX CYCLES and APA Rut Depth @ 8000 Cycles for 12.5D Mix (Combined)

Predicted shear strain= 0.0034* APA rut depth -0.0057,   R square=0.84

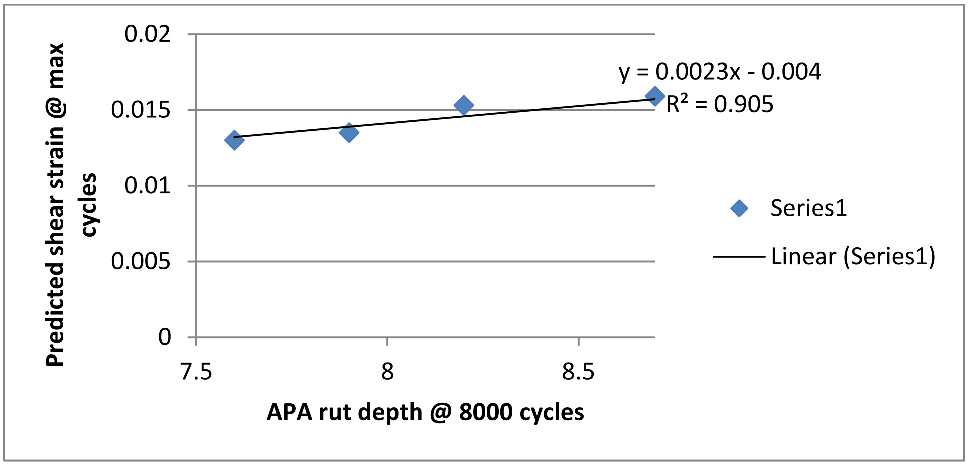

Figure 7-13: Correlation between RSCH Shear Strain @ MAX CYCLES and APA Rut Depth @ 8000 Cycles for 12.5C Mix (Combined)

Predicted shear strain= 0.0023* APA rut depth-0.004, R square=0.91

7.8. APA Rut Depth Criteria

Tables 7.45 and 7.46 present the APA rut depth criteria at PG-High for Average and Maximum traffic volume based on the combined lab and field cores data for all the mixtures.

Table 7-45: APA Rut Depth Criteria (in mm) at PG-High for Average Traffic Volume

Rut Resistance	9.5B Mix	9.5C Mix	12.5D	12.5C
Excellent	<4.0	<2.50	<2.0	<1.75
Good	4.0-7.00	2.50-5.0	2.0-4.25	1.75-3.75
Fair	7.00-10.0	5.0-7.0	4.25-6.50	3.75-7.0
Poor	>10.0	>7.0	>6.50	>7.0

Table 7-46: APA Rut Depth Criteria (in mm) at PG-High for Maximum Traffic Volume

Rut Resistance	9.5B Mix	9.5C Mix	12.5D	12.5C
Excellent	<2.75	<2.25	<1.75	<1.00
Good	2.75-4.0	2.25-3.0	1.75-4.25	1.00-2.75
Fair	4.0-6.75	3.0-5.50	4.25-5.50	2.75-4.75
Poor	>6.75	>5.50	>5.50	>4.75

7.9. Final Model

From all the models created using the combined lab and field cores one final model was developed which would predict shear strain for any mixture. In this model an additional parameter NMSA was introduced which includes the effect of size of the aggregate in the mixture.

Table 7.47 shows the parameter estimates for the final model developed for all the mixtures.

RSCHstrain= -7.62-1.23*NMSA + 29.53*DUSTTOAC -0.13 *NDES +1.51 *APARD

Table 7-47: Final Model Developed

Variable	Std. error	Estimate	Pr > |t|	t-value
Intercept	1.783	-7.62	0.00028	-4.27
NMSA	0.43	-1.23	0.05	-2.86
DUSTTOAC	6.249	29.53	0.0001	4.72
NDES	0.00192	-0.13	<0.0001	-67.71
APARD	0.4201	1.51	<0.0001	3.59

7.10. Mixture Characterization

The RSCH shear strains predicted by the models used to develop the APA rut depth criteria were compared with the Asphalt Institute (AI) criteria for evaluating rut resistance using RSCH permanent shear to characterize the rut resistance of the mixtures in this study. Table 7.48 summarizes the way in which the models used to develop the APA rut criteria have characterized the rut resistance of the mixtures used in this study.

Table 7-48: Rutting Resistance of Mixtures as Characterized by Regression Models

Mixture Designation(PG Grade of Asphalt Binder)	Aggregate Source	Traffic Level	Rut Resistance	
			T1-58C	T2-PG High
S12.5C (PG70-22)	G	AVG	Excellent	Good
	G	MAX	Good	Good
	L	AVG	Good	Good
	L	MAX	Good	Good
	G+N	AVG	Good	Good
	G+N	MAX	Fair	Fair
S12.5D (PG76-22)	G	AVG	Excellent	Excellent
	G	MAX	Excellent	Good
	L	AVG	Good	Good
	L	MAX	Good	Good
	G+N	AVG	Good	Good
	G+N	MAX	Fair	Fair
S9.5C (PG70-22)	G	AVG	Excellent	Good
	G	MAX	Good	Good
	L	AVG	Good	Good
	L	MAX	Good	Good
	G+N	AVG	Good	Good
	G+N	MAX	Fair	Fair
S9.5B (PG64-22)	G	AVG	Excellent	Excellent
	G	MAX	Good	Good
	L	AVG	Good	Good
	L	MAX	Good	Good
	G+N	AVG	Good	Good
	G+N	MAX	Fair	Fair

G- Granite, L-Limestone, G+N- Granite + Natural Sand

It can be seen from Table 7.48 that statistical models used to develop the APA rut criteria have characterized the rut-resistance of the various mixtures used in this study from 'excellent' to 'fair'. None of the mixtures have 'poor' rut resistance for any level of traffic or the APA test temperature. In general, mixtures with granite aggregate (without natural sand) are more rut resistant than others. Mixtures containing limestone aggregate also perform well under both levels of traffic. The presence of natural sand in a mixture, in general, makes a mixture more prone to rutting. The test temperature does not seem to affect the rutting characteristics of the mixtures in a significant way.

7.11. Initial to Final APA Rut Ratio

For a typical APA test, most of the rutting occurs in the first 1000 cycles of loading. This initial rutting could indicate susceptibility to early rutting. The initial to final APA rut depth ratio was computed to investigate if this ratio could identify poorly performing mixtures. Table 7.49 lists the initial to final rut depth ratio for all the mixtures used in this study.

Table 7-49: APA Initial to Final Rut Depth Ratios

Mixture Designation(PG Grade of Asphalt Binder)	Aggregate Source	Air Voids	APA Initial (1000 cycles) to Final (8000 cycles) Rut Depth Ratio @ T1 (58C)	APA Initial (1000 cycles) to Final (8000 cycles) Rut Depth Ratio @ T2 (PG HIGH)
S12.5C (PG70-22)	A1	4%	0.4	0.48
	A1	7%	0.47	0.42
	A3	4%	0.62	0.61
	A3	7%	0.66	0.39
	A4(NS)	4%	0.52	0.53
	A4(NS)	7%	0.46	0.51
S12.5D (PG76-22)	*A1*	4%	0.8	0.64
	A1	7%	0.64	0.51
	A3	4%	0.45	0.68
	A3	7%	0.61	0.59
	A4(NS)	4%	0.54	0.43
	A4(NS)	7%	0.45	0.71
S9.5C (PG70-22)	*A1*	*4%*	0.92	0.42
	A1	*7%*	0.47	0.53
	A3	*4%*	0.75	0.74
	A3	*7%*	0.55	0.5
	A4(NS)	*4%*	0.43	0.49
	A4(NS)	*7%*	0.63	0.52
S9.5B (PG64-22)	*A1*	*4%*	0.51	0.42
	A1	*7%*	0.52	0.44
	A3	*4%*	0.58	0.57
	A3	*7%*	0.51	0.57
	A4(NS)	*4%*	0.44	0.48
	A4(NS)	*7%*	0.37	0.4

An attempt was made to identify any possible relationship between APA initial to final rut ratios and the rutting resistance of mixtures as characterized by the various techniques. From

Table 7.49, it can be seen that, in general, 40% to 60% of the rutting occurs within the first 1000 cycles. But, no definite relationship can be drawn between the rutting characterization and rutting ratios at this point.

CHAPTER 8: SUMMARY AND CONCLUSIONS

8.1. Summary

The objective of this study was to establish a correlation between the rut depths measured by the APA testing and RSCH testing, develop a statistical model to predict RSCH shear strain using the above correlation and develop the APA rut depth criteria for the mixtures used in this study. The effects of test temperatures, different levels of traffic volumes and aggregate types were characterized to develop several RSCH-APA regression models. These models were used to develop the APA rut depth criteria for different test/traffic conditions. The regression techniques developed in this study have characterized the rut-resistance of mixtures from 'excellent' to 'fair', when compared with the Asphalt Institute (AI) criteria for evaluating rut resistance using RSCH permanent shear strain.

8.2. Conclusions

- Good correlations were observed between results of the APA and RSCH tests conducted on mixtures used in this study. These correlations were used to develop regression models.
- The regression models were fine-tuned to characterize the rutting behavior of each individual mix by considering effects of test temperatures, aggregate types and traffic volumes.
- The APA rut depth criteria were developed for a test temperature of 58°C and PG-High temperatures of the binders used in this study and for average and maximum

traffic levels of mixtures used in this study. The regression models used to develop these criteria have characterized the effects of the test temperature and traffic volumes in a uniform and expected manner.

- It was observed that presence of natural sand increases the rutting potential of a mixture. Granite aggregate was slightly more rut resistant than limestone aggregate in case of mixtures not containing any natural sand. The models used to develop rut depth criteria characterize the effects of aggregate type accordingly.

8.2.1. Conclusions (Field Part)

- The APA rut depth criteria developed using the combined lab and field cores data was more stringent compared to the criteria based on the lab data. This is due to the fact that the field cores have been procured from the field and hence the APA rut depth values for them were higher compared to the lab cores.
- The regression models, when applied on the combined lab and field data, were able to predict the RSCH shear strain in a better way. (% error range being 3.21% to 19.40%).
- The APA-RSCH correlations from combined lab and field data showed a higher R^2 (coefficient of determination) value compared to the correlations developed from the lab data which means a better prediction of RSCH shear strain can be done using this model.
- The final model developed from the combined lab and field data can predict RSCH shear strain for cores irrespective of whether it’s a lab or a field core.

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IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

The products of this research are the APA rut depth criteria for surface mixtures in North Carolina that can be used to assess the rutting resistance of a given asphalt mixture by conducting the simulative type laboratory APA test.

These criteria can be used by the materials and testing division of the NCDOT for categorizing various asphalt mixtures based on the rut depths observed after testing each mixture on the APA.

For the implementation of this product, there is no additional training needed as the research product is the rut depth criteria for the APA tests. The NCDOT personnel are already trained for the method and procedure for conducting the APA tests.

APPENDIX A: JMF COMBINED GRADATIONS FOR TYPE A MIXTURES

Table A-1: JMF Combined Gradation for G-12.5C-M

Sieve Size	% PASSING
19.0 mm	100
12.5 mm	95
9.5 mm	88
4.75 mm	62
2.36 mm	44
1.18 mm	33
0.6 mm	25
0.3 mm	17
0.15 mm	8
0.075 mm	4.5

Table A-2: JMF Combined Gradation for G-9.5B-N

Sieve Size	% PASSING
19.0 mm	100
12.5 mm	100
9.5 mm	95
4.75 mm	76
2.36 mm	60
1.18 mm	49
0.6 mm	37
0.3 mm	23
0.15 mm	10
0.075 mm	5.1

Table A-3: JMF Combined Gradation for G-9.5C-M

Sieve Size	% PASSING
19.0 mm	100
12.5 mm	95
9.5 mm	94
4.75 mm	66
2.36 mm	46
1.18 mm	34
0.6 mm	25
0.3 mm	16
0.15 mm	8
0.075 mm	4.5

Table A-4: JMF Combined Gradation for G-9.5C-N

Sieve Size	% PASSING
19.0 mm	100
12.5 mm	95
9.5 mm	93
4.75 mm	68
2.36 mm	50
1.18 mm	40
0.6 mm	31
0.3 mm	18
0.15 mm	8
0.075 mm	4.4

APPENDIX B: JMF FOR TYPE A MIXTURES

Page 1 of 1

North Carolina Department of Transportation

HOT MIX ASPHALT JOB MIX FORMULA (SUPERPAVE)

Contractor: Blythe Construction, Inc. Concord (Poplar Tent)

Plant Location: Concord, NC

Plant ID: AS53

County: Cabarrus

Material: Asphalt Concrete Surface Course, Type S 12.5C

Asphalt Type: HMAC - Hot-Mix Asphalt Concrete

AMD: 02-0240 JMF: 02-0240-151

Effective Date: 05/02/2002 (Approved)

Contract: WBS:

AGGREGATE SOURCES AND BLEND PERCENTAGES

APPROVED SUPPLIER	OTHER SUPPLIER	MATERIAL	BLEND %
Vulcan Materials Co. Cabarrus Quarry - Concord		Coarse Aggregate, #78M	48.0
Vulcan Materials Co. Cabarrus Quarry - Concord		Coarse Aggregate, #67	8.0
Vulcan Materials Co. Cabarrus Quarry		Screenings, Washed	44.0
		TOTAL	100.0

JMF COMBINED GRADATION

SIEVE SIZE	% PASSING
50.0 mm	100
37.5 mm	100
25.0 mm	100
19.0 mm	100
12.5 mm	95
9.5 mm	88
4.75 mm	62
2.36 mm	44
1.18 mm	33
0.600 mm	25
0.300 mm	17
0.150 mm	8
0.075 mm	4.5

Total Binder %:	5.0
Asphalt Binder Grade:	PG 70 -22
Asphalt Pay Binder Grade:	PG 70 -22
Gmm meas (Rice):	2.575
Gmb Ndes:	2.472
Gsb:	2.757
Gse:	2.792
Gsa:	2.803
Binder Specific Gravity:	.000
% AC Absorption:	.47
VTM Ndes:	4.0
VMA Ndes:	14.9
VFA Ndes:	71.8
Mix Temperature °F:	315
Minimum Compaction %:	92.0
Rut Depth:	
Anti-Strip Additive %:	.50
Modifier %:	.00
Nini/Ndes/Nmax:	8/100/160
Add'l Binder %:	5.0
% Binder from RAP:	.0
Other Binder %:	.0
Blend Ratio:	.0 / .0 / .0
% AC in RAP:	.0
% AC in RAS:	.0

Binder Supplier: Axeon SP - Binder Wilmington, NC (#31)

Anti-Strip Supplier: Arr-Maz Products Winter Haven, FL

Comment: This mix meets 1999 Specs. for S 12.5D(99).

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Approved By: Asphalt Design Engineer

Charles R. Colgate

Charles R. Colgate

Figure B-1: **JMF for A1-12.5C-M Mixture**

North Carolina Department of Transportation

HOT MIX ASPHALT JOB MIX FORMULA (SUPERPAVE)

Contractor: Blythe Construction, Inc. Concord (Poplar Tent)

Plant Location: Concord, NC

Plant ID: AS53

County: Cabarrus

Material: Asphalt Concrete Surface Course, Type S 9.5B

Asphalt Type: HMAC - Hot-Mix Asphalt Concrete

AMD: 03-0650 JMF: 03-0650-171

Effective Date: 09/16/2003 (Approved)

Contract: WBS:

AGGREGATE SOURCES AND BLEND PERCENTAGES

APPROVED SUPPLIER	OTHER SUPPLIER	MATERIAL	BLEND %
Vulcan Materials Co. Cabarrus Quarry - Concord		Coarse Aggregate, #78M	38.0
G.S. Materials Emery Pit		Sand, Asphalt	15.0
Vulcan Materials Co. Cabarrus Quarry		Screenings, Washed	47.0
		TOTAL	100.0

JMF COMBINED GRADATION

SIEVE SIZE	% PASSING
50.0 mm	100
37.5 mm	100
25.0 mm	100
19.0 mm	100
12.5 mm	100
9.5 mm	95
4.75 mm	76
2.36 mm	60
1.18 mm	49
0.600 mm	37
0.300 mm	23
0.150 mm	10
0.075 mm	5.1

Total Binder %:	6.7
Asphalt Binder Grade:	PG 64 -22
Asphalt Pay Binder Grade:	PG 64 -22
Gmm meas (Rice):	2.483
Gmb Ndes:	2.384
Gsb:	2.729
Gse:	2.760
Gsa:	2.775
Binder Specific Gravity:	.000
% AC Absorption:	.40
VTM Ndes:	4.0
VMA Ndes:	18.4
VFA Ndes:	.0
Mix Temperature °F:	300
Minimum Compaction %:	92.0
Rut Depth:	
Anti-Strip Additive %:	.75
Modifier %:	.00
Nini/Ndes/Nmax:	7/75/115
Add'l Binder %:	6.7
% Binder from RAP:	.0
Other Binder %:	.0
Blend Ratio:	.0 / .0 / 100.0
% AC in RAP:	.0
% AC in RAS:	.0

Binder Supplier: Axeon SP - Binder Wilmington, NC (#31)

Anti-Strip Supplier: Arr-Maz Products Winter Haven, FL

Anti-Strip Product: Ad-Here LOF 6500

Comment:

Approved By: Asphalt Design Engineer

Charles R. Colgate

Charles R. Colgate

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Figure B-2: **JMF for A1-9.5B-N Mixture**

North Carolina Department of Transportation

HOT MIX ASPHALT JOB MIX FORMULA (SUPERPAVE)

Contractor:	APAC-Atlantic - Thompson-Arthur Poplar Tent	Material:	Asphalt Concrete Surface Course, Type S 9.5C
Plant Location:	Concord, NC	Asphalt Type:	HMAC - Hot-Mix Asphalt Concrete
		AMD:	02-0733 JMF: 02-0733-151
Plant ID:	AS6	Effective Date:	10/14/2003 (Void)
County:	Cabarrus	Contract:	WBS:

AGGREGATE SOURCES AND BLEND PERCENTAGES

APPROVED SUPPLIER	OTHER SUPPLIER	MATERIAL	BLEND %
Vulcan Materials Co. Cabarrus Quarry - Concord		Coarse Aggregate, #78M	48.0
Vulcan Materials Co. Cabarrus Quarry		Screenings, Washed	52.0
		TOTAL	100.0

JMF COMBINED GRADATION

SIEVE SIZE	% PASSING
50.0 mm	100
37.5 mm	100
25.0 mm	100
19.0 mm	100
12.5 mm	100
9.5 mm	94
4.75 mm	66
2.36 mm	46
1.18 mm	34
0.600 mm	25
0.300 mm	16
0.150 mm	8
0.075 mm	4.5

Total Binder %:	5.2
Asphalt Binder Grade:	PG 70 -22
Asphalt Pay Binder Grade:	PG 70 -22
Gmm meas (Rice):	2.541
Gmb Ndes:	2.439
Gsb:	2.741
Gse:	2.760
Gsa:	2.839
Binder Specific Gravity:	.000
% AC Absorption:	.30
VTM Ndes:	4.0
VMA Ndes:	45.6
VFA Ndes:	74.4
Mix Temperature °F:	315
Minimum Compaction %:	92.0
Rut Depth:	
Anti-Strip Additive %:	.50
Modifier %:	.00
Nini/Ndes/Nmax:	8/100/160
Add'l Binder %:	5.2
% Binder from RAP:	.0
Other Binder %:	.0
Blend Ratio:	.0 / .0 / 100.0
% AC in RAP:	.0
% AC in RAS:	.0

Binder Supplier: Associated Asphalt Salisbury, NC (#12)

Anti-Strip Supplier: Arr-Maz Products Winter Haven, FL

Anti-Strip Product: Ad-Here LOF 6500

Comment: JMF revised to delete contract no. reference. Jmf cannot be used as final surface layer.

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Approved By: Asphalt Design Engineer

Charles R. Colgate

Charles R. Colgate

Figure B-3: JMF for A1-9.5C-M Mixture

North Carolina Department of Transportation

HOT MIX ASPHALT JOB MIX FORMULA (SUPERPAVE)

Contractor:	Blythe Construction, Inc. Concord (Poplar Tent)	Material:	Asphalt Concrete Surface Course, Type S 9.5C
Plant Location:	Concord, NC	Asphalt Type:	HMAC - Hot-Mix Asphalt Concrete
Plant ID:	AS53	AMD:	03-0651 JMF: 03-0651-171
		Effective Date:	09/16/2003 (Approved)
County:	Cabarrus	Contract:	WBS:

AGGREGATE SOURCES AND BLEND PERCENTAGES

APPROVED SUPPLIER	OTHER SUPPLIER	MATERIAL	BLEND %
Vulcan Materials Co. Cabarrus Quarry - Concord		Coarse Aggregate, #78M	51.0
G.S. Materials Emery Pit		Sand, Asphalt	15.0
Vulcan Materials Co. Cabarrus Quarry		Screenings, Washed	34.0
		TOTAL	100.0

JMF COMBINED GRADATION

SIEVE SIZE	% PASSING
50.0 mm	100
37.5 mm	100
25.0 mm	100
19.0 mm	100
12.5 mm	100
9.5 mm	93
4.75 mm	68
2.36 mm	50
1.18 mm	40
0.600 mm	31
0.300 mm	18
0.150 mm	8
0.075 mm	4.4

Total Binder %:	5.5
Asphalt Binder Grade:	PG 70 -22
Asphalt Pay Binder Grade:	PG 70 -22
Gmm meas (Rice):	2.525
Gmb Ndes:	2.424
Gsb:	2.725
Gse:	2.754
Gsa:	2.769
Binder Specific Gravity:	.000
% AC Absorption:	.40
VTM Ndes:	4.0
VMA Ndes:	15.9
VFA Ndes:	74.5
Mix Temperature °F:	315
Minimum Compaction %:	92.0
Rut Depth:	
Anti-Strip Additive %:	.75
Modifier %:	.00
Nini/Ndes/Nmax:	8/100/160
Add'l Binder %:	5.5
% Binder from RAP:	.0
Other Binder %:	.0
Blend Ratio:	.0 / .0 / 100.0
% AC in RAP:	.0
% AC in RAS:	.0

Binder Supplier: Axeon SP - Binder Wilmington, NC (#31)

Anti-Strip Supplier: Arr-Maz Products Winter Haven, FL

Anti-Strip Product: Ad-Here LOF 6500

Comment:

Information contained herein may have been designated or indicated as "confidential" or as a "trade secret" at the time of its initial disclosure to the Department of Transportation. This information is intended for use by the Department and shall not be revealed to others without the approval of the Pavement Construction Engineer.

Approved By: Asphalt Design Engineer

Charles R. Colgate

Charles R. Colgate

Figure B-4: JMF for A1-9.5C-N Mixture

APPENDIX C: RESULTS OF MULTIPLE LINEAR REGRESSION ANALYSIS

Table C-1: Backward Elimination Regression Results for RSCH Shear Strain @ AVG. CYCLES and APA Rut Depth @ 8000 Cycles for 9.5B Mix (58°C)

Variable	Parameter Estimate	Std. Error	F Value	Pr>F
Intercept	-0.00150	0.00221	0.47	0.5123
APARD	0.00314	0.00054	32.66	0.0003
AGG_L	0.00247	0.00100	6.03	0.0364

Table C-2: Summary of Backward Elimination for AVG. CYCLES-9.5B-58°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_G	2	0.0224	0.7942	0.98	0.3522

Table C-3: Backward Elimination Regression Results for RSCH Shear Strain @ MAX. CYCLES and APA Rut Depth @ 8000 Cycles for 9.5B Mix (58°C)

Variable	Parameter Estimate	Std. Error	F Value	Pr>F
Intercept	0.00041	0.00310	0.02	0.8964
APARD	0.00369	0.00077	22.89	0.0010
AGG_L	0.00318	0.00141	5.08	0.0506

Table C-4: Summary of Backward Elimination for MAX. CYCLES-9.5B-58°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_G	2	0.0260	0.7343	0.87	0.3789

Table C-5: Backward Elimination Regression Results for RSCH Shear Strain @ AVG. CYCLES and APA Rut Depth @ 8000 Cycles for 9.5B Mix (64°C)

Variable	Parameter Estimate	Std. Error	F Value	Pr>F
Intercept	**-0.00552**	**0.00234**	**5.57**	**0.0427**
APARD	**0.00321**	**0.00045**	**50.01**	**<.0001**
AGG_L	**0.00203**	**0.000834**	**5.95**	**0.0374**

Table C-6: Summary of Backward Elimination for AVG. CYCLES-9.5B-64°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_G	2	0.0438	0.8547	3.45	0.1002

Table C-7: Backward Elimination Regression Results for RSCH Shear Strain @ MAX. CYCLES and APA Rut Depth @ 8000 Cycles for 9.5B Mix (64°C)

Variable	Parameter Estimate	Std. Error	F Value	Pr>F
Intercept	**-0.02184**	**0.00939**	**5.40**	**0.0486**
APARD	**0.00662**	**0.00155**	**18.20**	**0.0027**
AGG_G	**0.00634**	**0.00218**	**8.61**	**0.0189**
AGG_L	**0.00638**	**0.00218**	**8.61**	**0.0189**

Table C-8: Summary of Backward Elimination for MAX. CYCLES-9.5B-64°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
-	3	-	0.87	-	-

Table C-9: Backward Elimination Regression Results for RSCH Shear Strain @ AVG. CYCLES and APA Rut Depth @ 8000 Cycles for 9.5C Mix (58°C)

Variable	Parameter Estimate	Std. Error	F Value	Pr>F
Intercept	**-0.01141**	**0.00374**	**9.30**	**0.0123**
APARD	**0.01045**	**0.00157**	**44.19**	**<.0001**

Table C-10: Summary of Backward Elimination for AVG. CYCLES-9.5C-58°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_G	2	0.0141	0.8268	0.71	0.4240
AGG_L	1	0.0113	0.8155	0.59	0.4627

Table C-11: Backward Elimination Regression Results for RSCH Shear Strain @ MAX. CYCLES and APA Rut Depth @ 8000 Cycles for 9.5C Mix (58°C)

Variable	Parameter Estimate	Std. Error	F Value	Pr>F
Intercept	**-0.01552**	**0.00514**	**9.13**	**0.0128**
APARD	**0.01449**	**0.00216**	**45.10**	**<.0001**

Table C-12: Summary of Backward Elimination for MAX. CYCLES-9.5C-58°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_G	2	0.0271	0.8466	1.72	0.2261
AGG_L	1	0.0281	0.8185	1.65	0.2310

Table C-13: Backward Elimination Regression Results for RSCH Shear Strain @ AVG. CYCLES and APA Rut Depth @ 8000 Cycles for 9.5C Mix (70°C)

Variable	Parameter Estimate	Std. Error	F Value	Pr>F
Intercept	**-0.00288**	**0.00420**	**0.47**	**0.5085**
APARD	**0.00455**	**0.00117**	**15.24**	**0.0029**

Table C-14: Summary of Backward Elimination for AVG. CYCLES-9.5C-70°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_G	2	0.0050	0.6515	0.12	0.7412
AGG_L	1	0.0477	0.6038	1.23	0.2961

Table C-15: Backward Elimination Regression Results for RSCH Shear Strain @ MAX. CYCLES and APA Rut Depth @ 8000 Cycles for 9.5C Mix (70°C)

Variable	**Parameter Estimate**	**Std. Error**	**F Value**	**Pr>F**
Intercept	**-0.00487**	**0.00528**	**0.85**	**0.3787**
APARD	**0.00664**	**0.00147**	**20.51**	**0.0011**

Table C-16: Summary of Backward Elimination for MAX. CYCLES-9.5C-70°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_G	2	0.0086	0.7091	0.24	0.6352
AGG_L	1	0.0368	0.6722	1.14	0.3135

Table C-17: Backward Elimination Regression Results for RSCH Shear Strain @ AVG. CYCLES and APA Rut Depth @ 8000 Cycles for 12.5C Mix (58°C)

Variable	**Parameter Estimate**	**Std. Error**	**F Value**	**Pr>F**
Intercept	**-0.00463**	**0.00434**	**1.14**	**0.3134**
APARD	**0.00500**	**0.00177**	**7.94**	**0.0201**
AGG_G	**-0.00476**	**0.00165**	**8.37**	**0.0178**

Table C-18: Summary of Backward Elimination for AVG. CYCLES-12.5C-58°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_L	2	0.0249	0.7889	1.07	0.3312

Table C-19: Backward Elimination Regression Results for RSCH Shear Strain @ MAX. CYCLES and APA Rut Depth @ 8000 Cycles for 12.5C Mix (58°C)

Variable	**Parameter Estimate**	**Std. Error**	**F Value**	**Pr>F**
Intercept	**0.00579**	**0.00587**	**0.97**	**0.3496**
APARD	**0.00716**	**0.00240**	**8.90**	**0.0154**
AGG_G	**-0.00657**	**0.00223**	**8.72**	**0.0162**

Table C-20: Summary of Backward Elimination for MAX. CYCLES-12.5C-58°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_L	2	0.0049	0.8015	0.20	0.6661

Table C-21: Backward Elimination Regression Results for RSCH Shear Strain @ AVG. CYCLES and APA Rut Depth @ 8000 Cycles for 12.5C Mix (70°C)

Variable	**Parameter Estimate**	**Std. Error**	**F Value**	**Pr>F**
Intercept	**0.00493**	**0.00580**	**0.72**	**0.4174**
APARD	**0.00331**	**0.00162**	**4.18**	**0.0712**
AGG_G	**-0.00433**	**0.00211**	**4.19**	**0.0710**

Table C-22: Summary of Backward Elimination for AVG. CYCLES-12.5C-70°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_L	2	0.0056	0.7287	0.17	0.6929

Table C-23: Backward Elimination Regression Results for RSCH Shear Strain @ MAX. CYCLES and APA Rut Depth @ 8000 Cycles for 12.5C Mix (70°C)

Variable	Parameter Estimate	Std. Error	F Value	Pr>F
Intercept	**0.00546**	**0.00776**	**0.50**	**0.4994**
APARD	**0.00495**	**0.00216**	**5.23**	**0.0481**
AGG_G	**-0.00577**	**0.00283**	**4.16**	**0.0719**

Table C-24: Summary of Backward Elimination for MAX. CYCLES-12.5C-70°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_L	2	0.0000	0.7502	0.00	0.9730

Table C-25: Backward Elimination Regression Results for RSCH Shear Strain @ AVG. CYCLES and APA Rut Depth @ 8000 Cycles for 12.5D Mix (58°C)

Variable	Parameter Estimate	Std. Error	F Value	Pr>F
Intercept	**-0.00296**	**0.00221**	**1.79**	**0.2137**
APARD	**0.00811**	**0.00124**	**42.50**	**0.0001**
AGG_G	**0.00270**	**0.00131**	**4.27**	**0.0687**

Table C-26: Summary of Backward Elimination for AVG. CYCLES-12.5D-58°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_L	2	0.0000	0.8315	0.00	0.9739

Table C-27: Backward Elimination Regression Results for RSCH Shear Strain @ MAX. CYCLES and APA Rut Depth @ 8000 Cycles for 12.5D Mix (58°C)

Variable	Parameter Estimate	Std. Error	F Value	Pr>F
Intercept	**-0.00347**	**0.00262**	**1.75**	**0.2179**
APARD	**0.00954**	**0.00147**	**41.87**	**0.0001**
AGG_G	**0.00319**	**0.00155**	**4.25**	**0.0693**

Table C-28: Summary of Backward Elimination for MAX. CYCLES-12.5D-58°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_L	2	0.0001	0.8293	0.01	0.9360

Table C-29: Backward Elimination Regression Results for RSCH Shear Strain @ AVG. CYCLES and APA Rut Depth @ 8000 Cycles for 12.5D Mix (76°C)

Variable	Parameter Estimate	Std. Error	F Value	Pr>F
Intercept	**0.00157**	**0.00111**	**2.01**	**0.1864**
APARD	**0.00427**	**0.00050**	**72.42**	**<.0001**

Table C-30: Summary of Backward Elimination for MAX. CYCLES-12.5D-76°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_G	2	0.0163	0.8840	1.31	0.2859
AGG_L	1	0.0053	0.8787	0.41	0.5365

Table C-31: Backward Elimination Regression Results for RSCH Shear Strain @ MAX. CYCLES and APA Rut Depth @ 8000 Cycles for 12.5D Mix (76°C)

Variable	Parameter Estimate	Std. Error	F Value	Pr>F
Intercept	**0.00218**	**0.00157**	**1.92**	**0.1960**
APARD	**0.00487**	**0.00071**	**46.82**	**<.0001**

Table C-32: Summary of Backward Elimination for MAX. CYCLES-12.5D-76°C

Variable Removed	No. of Variables in	Partial R-square	Model R-square	F Value	Pr>F
AGG_G	2	0.0123	0.8281	0.62	0.4554
AGG_L	1	0.0041	0.8240	0.21	0.6560