RESEARCH & DEVELOPMENT

An Investigation of the Effect of Ndesign Values on Performance of Superpave Mixtures

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by

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16. Abstract

The Superpave design method requires that asphalt concrete mixtures satisfy various volumetric requirements at specific levels of compactive effort in the Superpave gyratory compactor. These levels are a function of climate and total traffic during the pavement service life, expressed in Equivalent Single Axle Loads (ESALs). Asphalt concrete mixtures for higher traffic levels are compacted to a higher number of design gyrations (Ndesign) as a mix that resists further compaction also resists rutting more effectively. This often negatively impacts the fatigue performance due to lower asphalt content in the mix. Therefore, a performance-oriented approach to determine Ndesign was developed that optimizes mixture performance with respect to both rutting and fatigue cracking.

Surface mixes in North Carolina are designated on the basis of nominal aggregate size (S9.5mm or S12.5mm) and traffic level (A, B, C and D). Asphalt concrete mixes were designed at Ndesign levels of 50, 75, 100 and 125 gyrations for six different surface mixes. Asphalt content was determined for each mix using the Superpave design method. Dynamic modulus specimens were prepared at the determined optimum asphalt contents and dynamic modulus (E*) was measured using the Asphalt Mixture Performance Tester (AMPT) device. The E* data and corresponding binder properties were used as input in the AASHTO Darwin-ME software to predict the rutting and fatigue performance of the mixtures by assuming a model pavement section and an appropriate traffic level.

The concept of relative performance was used to determine the optimum Ndesign such that performance of the mix is optimized with respect to both fatigue cracking and rutting. The recommended value of Ndesign for each type of surface mix was determined after comparing the calculated optimum gyrations with the existing North Carolina DOT specifications, as well as analyzing the relative performance characteristics of the mix.

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EXECUTIVE SUMMARY

Superpave design method requires that asphalt concrete mixtures satisfy various volumetric requirements at specific levels of compactive effort in the Superpave Gyratory Compactor. These levels are a function of climate and total traffic during the pavement service life, expressed in ESALs. Several state highway agencies in the US have adopted gyration values for designated mix types based on traffic levels. Asphalt concrete mixtures for higher traffic levels are compacted to a higher number of design gyrations (Ndesign) as a denser mix resists rutting more effectively. However, this negatively impacts the fatigue performance due to a lower asphalt content in the mix. Therefore, a performance-oriented approach to determine Ndesign was developed that optimizes mixture performance with respect to both rutting and fatigue cracking.

For a given mix, asphalt content using the Superpave mix design method is determined by compacting specimens to four percent air voids at Ndesign number of gyrations. As Ndesign increases, the asphalt content required to achieve the target density decreases. At lower Ndesign, the higher asphalt content results in better fatigue resistance and higher Ndesign results in better rutting resistance. Hence, the rutting and fatigue performance characteristics of asphalt mixtures should be well-characterized and relative performance at different gyration levels be analyzed in order to determine the optimum Ndesign.

Surface mixes in North Carolina are designated on the basis of nominal aggregate size (S9.5mm or S12.5mm) and traffic level (A, B, C and D). As part of the research activity, asphalt concrete mixes were designed at Ndesign levels of 50, 75, 100 and 125 gyrations for six different surface mixes. Asphalt content was determined for each mix using the Superpave design method. Dynamic modulus specimens were prepared at the determined optimum asphalt contents and dynamic modulus (E*) was measured using the Asphalt Mixture Performance Tester (AMPT) device. The E* data and corresponding binder properties were used as input in the AASHTO Darwin-ME software to predict the rutting and fatigue performance of the mixtures by assuming a model pavement section and an appropriate traffic level.

A relative performance indicator for a specific mix was defined as the ratio of number of ESALs to failure for a given distress at a particular Ndesign level to the maximum ESALs (at 50 gyrations for fatigue and 125 gyrations for rutting). Relative performance was plotted against the asphalt content to determine the optimum asphalt content, and Ndesign was calculated as the gyrations corresponding to the calculated optimum. The recommended value of Ndesign for each type of surface mix was determined after comparing the calculated optimum gyrations with the existing North Carolina DOT specifications, as well as analyzing the relative performance characteristics of the mix.

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1. INTRODUCTION

The Superpave mix design method was developed as part of the Strategic Highway Research Program's (SHRP) Asphalt Research Program, conducted from 1987 to 1993. The concept behind this method involves incorporating performance, environmental conditions, load factors, and material characterization in one design in order to improve the performance of asphalt pavement structures by reducing rutting, thermal cracking, and fatigue cracking. The Superpave method follows a volumetric approach where the optimum asphalt content and gradation are selected by analyzing the air void content and other volumetric properties of the mix. The main tool in the volumetric mix design is the Superpave Gyratory Compactor (SGC). A satisfactory mix design is one that meets rigorous volumetric requirements at an initial and design levels of gyrations ($N_{initial}$ and N_{design}, respectively). The initial and design levels, in turn, are determined by the total traffic, expressed in equivalent single axle loads or ESALs, expected on the pavement over its projected service life.

The advantages of this approach are that specification criteria can be established to judge the quality and control of asphalt mixtures during the manufacturing process and during the construction in the field. On the other hand, the disadvantages of this method are that the mix designer is restricted when the adjustments to the volumetric properties are desired, but more importantly, the performance of the mix is not explicitly considered as part of the design process. To overcome this flaw, state DOTs have incorporated performance related tests such as Hamburg Wheel Tracking Device (HWTD) and Asphalt Pavement Analyzer (APA), which NCDOT is currently using.

Many agencies that are currently designing and building Superpave mixes have observed that, in general, the rutting performance of Superpave mixes tends to be satisfactory. This adequate performance is expected because, based on the requirements of material and volumetric properties, Superpave asphalt mixes tend to have strong aggregate skeletons. In addition, the rutting performance is improved when the rutting depth measured using wheel tracking tests are specified to accept or reject asphalt mixes. However, to guarantee high rutting performance, asphalt mixtures are becoming drier causing fatigue cracking that has become a widespread problem especially in relatively new pavements, between 5 and 7 years old. To obtain an acceptable mixture, it is necessary to improve the fatigue cracking resistance. This improvement can be achieved in two ways based on the volumetric design procedure:

- **a.** Increasing the target relative density at a given number of design gyrations, increasing the binder content.
- **b.** Reducing the number of design gyrations while maintaining an air void level of 4%.

In this research study, the second approach will be used to optimize the rutting and fatigue performances because increasing the target relative density has the potential to generate performance problems, especially with soft binders.

There is a consensus among different agencies that the current N_{design} levels do not maximize field performance. Design levels of compaction were originally specified in what is known as the "N_{design} Tables" suggesting compaction efforts based on design traffic levels and average high air temperature. These tables were later evaluated, determining that the design gyratory compaction levels may be too high, and in 1999, the Superpave N_{design} table was consolidated to four levels, as shown in Table 1.1. This reduction in the compaction criteria was based on the sensitivity of mixture volumetric properties and mixture stiffness to N_{design}, and the climatic aspect of the criteria was eliminated since it is accounted for during the binder selection process. Even with this modification of the compaction levels, many studies showed that the proposed levels are still too high for many mixtures, and many agencies have adopted variations of the Ndesign table to suit their particular needs, including NCDOT.

Table 1.1 Ndesign levels recommended in NCHRP 9-9

Design ESALs (millions)	Number of Gyrations		
	$N_{initial}$	N_{design}	N_{max}
< 0.3	6	50	75
0.3 to < 3	7	75	115
3 to < 30	8	100	160
≥ 30	9	125	205

1.1 Research Objectives

The primary objectives of this study were to:

1. Evaluate the sensitivity of asphalt volumetric properties to different design levels.
2. Investigate the effect of changes in Ndesign values on mixture stiffness and performance characteristics in terms of fatigue and rutting potential.
3. Recommend Ndesign levels for different NCDOT mixtures for varying traffic and reliability levels.

1.2 Research Approach and Methodology

1.2.1 Task 1 – Materials and Superpave Mix Designs

Mix designs were conducted for all mixtures currently in the NCDOT specifications. These mixtures include 9.5A, 9.5B, 9.5C, 9.5D, 12.5C, and 12.5D surface mixtures. The mix designs were performed per the N_{design} values in the NCDOT specifications at the start of this study. The optimum asphalt content was determined based on volumetric properties with 4% air void content. The necessary materials, aggregates and binder, were provided by NCDOT.

1.2.2 Task 2 – Modification of Mix Designs

In order to examine the effect of the number of gyrations on pavement performance, test specimens were compacted and tested at different gyrations while maintaining an air void content of 4%, which requires varying the asphalt content. To determine the asphalt content at 50, 75, 100, and 125 gyrations for each mix, specimen heights that yield 4% air voids were back-calculated for a given %AC. This calculation is performed utilizing G_{mm}, %AC, and the mass. During the mix design, a measured value for G_{mm} was obtained at a given asphalt content, and this measured value is then used to approximate G_{mm} at different levels of %AC through the following equation:

$$G_{mm} = \frac{P_{mm}}{\frac{P_s}{G_{se}} + \frac{P_b}{G_b}}$$

where G_{mm} = maximum specific gravity of paving mixture

P_{mm} = percent by mass of total loose mixture = 100

P_S = aggregate content, percent by total mass of mixture

P_b = asphalt content, percent by total mass of mixture

G_{se} =effective specific gravity of aggregate

G_b = specific gravity of asphalt

Once G_{mm} values were obtained, the heights that yield 4% air voids can be calculated through the volume, mass, and height relationship:

$$Height = \frac{Mass}{\pi d^2/4 \times 0.96 \times G_{mm}}$$

where d = 150 mm, mass and G_{mm} vary by % AC. In order to have accurate units, the diameter is converted to centimeters and the equation becomes:

$$Height = \frac{Mass}{17.67 \times 0.96 \times G_{mm}}$$

Using this approach, multiple trials were performed to validate this method; initially, this operation began with %AC ranging from 4.5% to 7% with 0.5% increments to ensure that all the gyration levels needed are covered, but the results showed that the data points were far apart and the gyrations were exceeding the needed range. To obtain better data, the increments were reduced to 0.25%.

After the heights are calculated, the compactor is set to height mode; the specimens get compacted until they reach the specified height and the number of gyrations taken to reach this condition is recorded. These gyrations are then plotted against % AC. Once the number of gyrations is plotted versus asphalt content, the best fit line is used to determine a relationship and an equation that would allow the calculation of % AC for a given number gyrations.

1.2.3 Task 3 – Performance Based Testing

The mixtures were evaluated for their resistance to fatigue and rutting performances. The performance tests employed for this purpose were Dynamic Modulus and Flow Number testing performed on the Asphalt Mixture Performance Tester.

1.2.3.1 Task 3A – Dynamic Modulus Testing

Dynamic Modulus testing was conducted on the mixtures to evaluate their rutting and fatigue performances with the aid of the Asphalt Mixture Performance Tester (AMPT). During the Dynamic modulus test, a repeated load at varying frequencies is applied to a test specimen over a relatively short period of time and measure the specimen's recoverable strain and permanent deformation. The frequencies used in this study were 10 Hz, 1 Hz, and 0.1 Hz.

1.2.3.2 Task 3B – Flow Number Testing

The Flow Number test is also conducted using the AMPT device. The flow number is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain. This test is performed to estimate the rutting potential of the mixtures. In this test, a specimen conditioned at a specified temperature is subjected to a repeated haversine axial compressive load pulse of 0.1 sec every 1.0 sec. The flow numbers obtained were used to compare rutting performance of the mixtures as the number of gyrations is changed. In this study, an unconfined flow number test was conducted at a temperature of 54.4 C (130 F).

1.3 Task 4 – Analysis of Data

The dynamic modulus results obtained from the AMPT were used as an input parameter in the mechanistic-empirical software analysis tool to predict the fatigue and rutting performances of the mixtures. The analysis method of choice for this portion was DARWin-ME due to its widespread use by many highway agencies and organizations. As a first step, the master curves, as specified in AASHTO PP66 standard, were developed to estimate the modulus values for various frequencies and temperatures as required by DARWin-ME. Once all the input parameters were complete, the analysis was performed and the fatigue and rutting performances are determined as the number of trucks that correspond to 10 percent or more cracking in the pavement, and 0.75 inches deformation in the AC layer, respectively. In order to compare the rutting and fatigue values, the relative performance concept was used to develop a uniform scale for comparison. The relative performance values were then potted and the intersection point of the curves was determined as the number of gyrations that optimize the performance for that specific mixture. This new value was then compared to the original and current Ndesign values to quantify the effect of the optimum value and determine its effect on pavement performance.

2. LITERATURE REVIEW

Pavement performance is a function and byproduct of the mix design process; the purpose of a mix design to produce a mixture that performs adequately under the given environmental and loading conditions.

2.1 History and Background

Over the years, different mix design methods were developed to address various design criteria and performance requirements; the three common methods are Hveem, Marshall, and Superpave mix designs (11). The first method was developed in California in the early 1920s; it uses a kneading compactor to simulate field compaction and a stability test to measure the strength of the mix. While the Hveem compaction method is extremely similar to field compaction, the equipment is expensive and not portable. In addition to having a narrow range in stability measurements, these limitations restrict this method from being widely implemented (11). The Marshal mix design method, alternatively, was developed in the late 30s with the objective of selecting an asphalt content that meets certain stability and flow requirements (1). This approach focuses on strength, voids, and durability while using inexpensive equipment, but the drop hammer compaction and lack of shear strength testing in addition to stability and flow not being fundamental mechanistic properties (1) make this approach seem simplistic and inadequate to design long lasting mixtures. The need for a more practical mix design method led to the development of the Superpave mix design through the SHRP program in the early 1990s. This method considers environmental conditions, loading, and material characterization in designing a mix, and uses volumetric properties of the mixture to predict pavement field performance (1). The main equipment in the Superpave mix design is the Superpave Gyratory Compactor which is used to obtain volumetric data at specified levels of gyrations that are based on the expected total traffic on the pavement expressed in equivalent single axle loads (ESALs) (5). These levels of compaction are labeled $N_{initial}$, N_{design}, and N_{max}; Table 2.1 shows the compaction effort specification based on the total traffic as recommended in NCHRP project 9-9 (2).

Table 2.1 Ndesign levels recommended in NCHRP 9-9

Design ESALs (millions)	Number of Gyrations		
	$N_{initial}$	N_{design}	N_{max}
< 0.3	6	50	75
0.3 to < 3	7	75	115
3 to < 30	8	100	160
≥ 30	9	125	205

The purpose of Project 9-9 was to verify the gyration levels and consolidate the N_{design} table, but the recommendation, as NCHRP 573 indicates, was based on the sensitivity of the volumetric properties and rutting performance tests to changes in the compaction level, and did not consider any field performance tests (2). As a result, there is a consensus among different agencies that the current compaction effort specifications do not maximize field performance. Prozzi et al. indicated that the current design gyrations yield pavements that perform well with regards to permanent deformation but do not adequately resist fatigue cracking (5). As an alternative to the N_{design} approach, several studies have suggested the concept of the locking point as a measure of compaction. Locking point is reached when further compaction results in little to no difference in the specimen's height thus only damaging the aggregate structure rather than increasing the strength of the mixture (3).

2.2 Flexible Pavement Distresses

2.2.1 Rutting

Rutting is a major pavement distress that occurs due to permanent deformation in the pavement, mainly in the wheel path (3). The problem with rutting is that water accumulates on the surface of the pavement causing hydroplaning and loss of skid resistance (5). Rutting has two types, the first is subgrade rutting in which the whole pavement structure deforms, and the second is mixture rutting which mix design attempts to minimize through different parameters (3). Mixture rutting can occur as a result of weak aggregate skeleton due to lack of interlocking or bonding between the aggregate particles. The presence of too much binder in the mix can also result in insufficient compaction and a weaker structure that has low rutting resistance (3). The cost and experience requirements necessary to obtain the shear tester to measure rutting prevented this test from being adopted by transportation agencies (9) which, instead, preferred to rely on volumetric data to estimate permanent deformation. Despite a lack of a mechanical test to assess potential field permanent deformation, a few tests such as the Asphalt Pavement Analyzer and the Hamburg Wheel-Tracking Device can be applied on a small scale in the lab to simulate field performance. These simulations produce results that are adequate enough to build a correlation with actual performance (2).

2.2.2 Fatigue Cracking

Fatigue cracking is the result of failure of materials due to cyclic loading. This distress begins in the form of small cracks that propagate and become connected to affect the roughness of the pavement surface (3) (6). According to SHRP A-003, factors affecting fatigue can be categorized into four criteria; the first is the fabrication method mainly compaction, then mode or history of loading, followed by mixture variables, and environmental and loading variables (6). The focus of this review is to investigate the effect of the fabrication method on this phenomenon. During this stage, certain mixture characteristics that contribute to fatigue life such as binder content, percent air voids, and compaction level (3) (6) can be optimized to increase fatigue resistance without sacrificing rutting performance. Achieving a balance between rutting and fatigue through manipulation of these characteristics has been the focus of numerous research projects yielding different combinations of approaches and recommendations. One of the common approaches is to reduce the compaction effort by 20 (3) or even 30 (2) gyrations to improve cracking resistance without compromising rutting performance (3). One of the limitations of Superpave is the lack of mechanistic performance tests and fatigue performance is no exception; however, there are laboratory simulative tests that can be used to predict field performance (3). These tests were evaluated by SHRP A-003 based on their accuracy and effectiveness and are ranked as follows: beam or third point loading test and direct tension test followed by indirect tensile test, then dissipated energy method and finally fracture mechanics tests (5).

2.3 Compaction Effort Modifications

Based on field observations and research, the general consensus is that the current N_{design} gyration levels used in mix design do not maximize field performance. Several studies have shown that Superpave mixes perform extremely well with regards to rutting but lack in fatigue resistance and durability (3) (2) (5). To overcome this performance deficiency, many researchers have identified the compaction aspect of the mix design process as the main controlling factor of this behavior and developed different methods and approaches to balance rutting and fatigue resistance. Two of the most commonly suggested approaches are the concept of locking point, which is the point at which the specimen height does not change for at least 2 gyrations (3), and N_{design} level reduction.

Air void content is a critical characteristic for any pavement as it connects pavement design, mix design and ultimately field performance. In a study sponsored by the Colorado DOT to determine the relationship between the number of gyrations and their resulting air voids and the ultimate field density, researchers found that the ultimate field density is reached within the first 3 years of the pavement life (10). Although results from pavement densification research have shown that ultimate density is reached between 2 and 10 years, the Colorado research monitored 22 projects from mix design until 6 years after construction with air voids measured every year, concluding that the most densification occurs within the first 3 years of service life. The results from this study indicate that the average in-place air voids after 6 years is 5.7% suggesting that the pavement target air void of 4% may never be reached, thus warranting a reduction in the compaction level (3, 10) and increasing the binder content without jeopardizing rutting performance (4).

The purpose of investigating the compaction effort is to determine a balance between opposite mixture properties: rutting and cracking. According to NCHRP report 567, rutting resistance increases by 15 to 25% with an increase of one level in the compactive effort, while at the same time decreasing the fatigue performance by roughly 20% (11).

2.3.1 Locking Point

The concept of locking point is the byproduct of an Illinois DOT study, where it was defined as the first occurrence of three consecutive gyrations with the same height after two consecutive equal heights known as locking point 3-2-2 (2). As other agencies adopted this concept, the definition varied to become the first instance of two consecutive gyrations yielding the same height, locking point 2, or the second occurrence of two consecutive gyrations resulting in the same sample height (locking point 2-2), and the third occurrence of two consecutive gyrations yielding the same specimen height (locking point 2-2-2) (2). In general, the locking point is the stage in the compaction where the aggregate particles have interlocked to provide maximum skeleton strength and any further compaction would result in structural degradation of the particles (3,2). In the NCHRP 573 report, locking point 3-2-2 was found to produce the best relationship with the ultimate field density out of all the locking point approaches, however this correlation was weak (R^2=0.47), thus determining that this concept is not dependent only on design traffic but it is also affected by the aggregate type, gradation, and angularity (2). A study for the Georgia DOT to verify the Superpave N_{design} values also investigated the locking point approach where the researchers evaluated the number of gyrations at which the specimen heights remained constant for two (LP2), three (LP3), and four (LP4) consecutive gyrations (3). Upon determining the number of gyration for the different mixes used in this study for each locking point definition, the averages were calculated and used to compact samples to determine the resulting air voids. These air voids were then compared to the in-place air void content which was 5.7% after 5 years of traffic (3). The researchers found that the LP3 locking point at 69 gyrations produced an air void content of 5.4% which compares closely to the 5 year in-place air voids (3). As a result of this study, GDOT changed its compaction requirement from traffic based N_{design} levels to a compaction level based on the 65 gyrations locking point (3).

2.4 Compactive Effort Modification

Throughout the years, Superpave mixes have performed extremely well in rutting resistance (2, 4) but pavement durability and fatigue resistance in particular was inadequate resulting in widespread of cracks that propagate and cause major serviceability issues. The unanimous opinion on this phenomenon is that the mixtures are over-compacted during mix design. This opinion was verified in a study by the Colorado DOT when 22 projects were monitored from preconstruction mix design until 6 years after opening to traffic. The in-place air voids were measured regularly to determine the pavement densification and compare it to the 4% target air voids set during mix design. Upon completion of this research, it was determined that the ultimate field density, with an average air void content 1.2% higher that the design value, is reached within the first 3 years of the pavement life and that any further compaction was statistically insignificant (10). Based on these findings any reduction, within reason, in the compactive effort was justified.

2.5 Verification of Superpave Ndesign Compaction Levels for Georgia

In conjunction with Georgia DOT Watson et al. conducted a study with a twofold purpose; the first objective was to compare the performance of Superpave mixes and Marshall mixes, and then evaluate the effect of the number of gyrations on rutting and durability. The results of the first phase confirmed the findings of the Colorado study, as it was found that after 5 years of traffic, Superpave mixes still have an average in-place air void of 5.7% further proving that the compaction effort is too high or the target air void is too low (3). Based on these conclusions, the next phase focused on reducing the compactive effort without a significant effect on rutting performance. Using 25 mm base course and 12.5 mm surface course as the experimental mixtures, the gyration levels evaluated were 35, 60, 85, and 110 along with the locking point approach discussed earlier.

Several samples were made for each level and tested for potential rutting using the asphalt pavement analyzer, for which GDOT set the rutting test limit at 5mm maximum. Fatigue life was also evaluated using the flexural beam test where failure is defined as the point when the strength reaches half of its original value (3). To determine the rutting susceptibility, the 12.5 mix was evaluated at 64^0C while the 25 mm mix was tested at 50^0C and 64^0C, but in order to reach the same rutting criteria at both temperatures, the asphalt content would need to increase by 0.75% or decrease the number of gyrations by 46 when testing at 50^0C (3). Based on the rutting criteria alone, the researchers determined that all the 25 mm mixes can be designed at an Ndesign level of 50 gyrations and still meet the requirements. The durability testing to estimate the fatigue failure was performed using 2 strain levels: 250µm and 500µm.Table 2.2 below shows the number of loading cycles to failure based on gyration levels.

Table 2.2 GDOT cycles to fatigue failure

Gyrations	250 µm	500µm
35	2305467	79564
60	1514725	57101
85	792721	40562
110	847496	30104

From these results it is clear that as the compactive effort increases, the fatigue life decreases, however, it is also evident that the strain level has a major effect on the fatigue performance. In addition to the number of gyrations and strain levels, the researchers also varied and monitored the effects of the type of aggregate on these results and concluded that while there is a relationship between fatigue life and the number of gyrations, the apparent and hidden effects of strain level and aggregate source on these performance tests prevent the relationship from being conclusive. As a result of these inconclusive results, this study recommended the use of the locking point gyrations in lieu of the traffic based N_{design} tables. Three different locking points, LP2, LP3, and LP4, we defined based on the frequency of the occurrence of the same height readings. Below are the locking point results based on the aggregate source.

Table 2.3 GDOT Locking Points

Aggregate Source	LP2 Gyrations	LP3 Gyrations	LP4 Gyrations
A	35	68	92
B	39	68	90
C	39	64	88
D	41	69	91
E	43	83	100
F	37	67	84
G	36	62	83
H	42	73	102
Average	39	69	91

Since the air void content is a common characteristic between mix design, pavement design, and performance (4) (10), researchers relied on it to make their recommendation. Several samples were made and compacted using the average locking point gyration number, and their respective air void contents were measured and compared to the in-place voids after 5 years of traffic, which was determined to be 5.7%. The results of this comparison showed that the LP3 method produced values most closely to those obtained in the field (3) with an average air void of 5.4% based on which, the study recommended that GDOT replace the N_{design} table with a single gyration level of 65 gyrations for all mix types (3).

2.6 Transitioning from TGC to SGC

In 2006, Button et al. of the Texas Transportation Institute conducted a study to evaluate the effect of replacing the Texas Gyratory Compactor with the Superpave Gyratory Compactor and propose compaction specifications using the SGC. Although the TGC produced excellent rutting resistant mixtures, TxDOT decided to switch compactors because the SGC allows better simulation of field mixtures, facilitates sample reproduction, and improves identification of weak aggregate structures (8).

The first stage of this study involved the calibration of Superpave gyratory compacted mixes to produce similar performance results as those compacted with the TGC. Since the gyration angle in the TSG is much higher than that of the SGC, 5.8 and 1.25 respectively, using the same number of gyrations would not produce identical samples due to the compactive effort difference. In order to achieve the same performance using the SGC, the researchers instead used the asphalt content as a comparison criterion and determined the number of gyrations that yield the same asphalt content as the original method to maintain good rutting resistance (8). The durability and fatigue resistance of the TGC mixtures, however, have been a concern for the TxDOT so to address this issue, the authors of this study requested to extend their research based on the studies and findings that link the compactive effort to field performance.

The objective of phase 2 of this study was to reduce the compactive effort to increase the durability without affecting the already established rutting performance (8). This experiment was performed with five mixtures; type A, B, C, D, and CMHB-C with type C and D being the most common surface courses used by the TxDOT. For type C and D three asphalt grades were used; PG 64-22, 70-22, and 76-22, whereas the remaining mixtures only PG 64-22 and 76-22 were used. for each mix type, two mixtures were designed using limestone and river gravel to quantify the effect of the aggregate source on the performance, and the testing gyration levels were set at 60, 90, and 120 gyrations for mixes A and B, and 80, 120, 140 for the other mix types. After the mix design process and specimen fabrication, the samples were tested using the Hamburg Wheel Tracking Device (HWTD) to measure rutting for which TxDOT set the termination criteria at either 12.5 mm rut depth or 20000 wheel passes whichever occurs first. The HWTD results are show in Table 2.4 and Table 2.5 below.

Table 2.4 Type A and B rutting results

Mix type	Aggregate	PG Grade	Rutting measurements (mm)		
			60	90	120
A	Limestone	64-22	11.18	6.97	9.33
		76-22	5.67	5.64	5.37
	River gravel	64-22	5.82	6.58	6.02
		76-22	6.1	5.68	6.32
B	Limestone	64-22	7.1	9.15	5.46
		76-22	5.46	6.09	5.25
	River gravel	64-22	9.08	8.07	6.41
		76-22	5.46	6.09	5.25

Table 2.5 Type C, D, and CH results

Mix type	Aggregate type	PG Grade	Rutting measurement (mm)		
			80	120	140
C	Limestone	64-22	12.47	13.35	8.21
		70-22	4.61	3.65	3.73
		76-22	7.8	10.52	10.55
	River gravel	64-22	8.83	8.83	4.02
		70-22	6.65	4.09	4.09
		76-22	3.8	2.66	4.09
D	Limestone	64-22	5.02	5.02	2.89
		70-22	6.28	8.16	3.39
		76-22	4.91	4.88	3.18
	River gravel	64-22	3.77	3.77	2.64
		70-22	2.91	3.07	2.3
		76-22	3.09	3.09	2.46
CMHB-C	Limestone	64-22	17.50	9.74	10.95
		76-22	7.44	5.96	8.47
	River gravel	64-22	7.09	5.62	5.38
		76-22	4.81	4.81	4.81

From the results above, the lowest gyration levels that did not cause significant rutting were selected as the N_{design} values for each mix type (8). The results of this study also confirmed that as the compactive effort decreases and asphalt content increases, the mixtures becomes more durable and their fatigue resistance improves (2) (4). As a part of the recommendation, the authors suggested that since some of the samples did not meet the required VMA specification due to the increase in asphalt content, this criterion needs to be investigated to determine its effect on the performance of the pavement. Table 2.6 below summarizes the results and recommendations of this study.

Table 2.6 Recommended Gyration Levels for TxDOT

Mix type	No. of SGC gyrations (phase1)	Recommended N_{design} SGC gyrations
A	100	90
B	110	90
C	160	120
D	160	120
CMHB-C	140	120

2.7 Effect of Compaction on Superpave Surface Course Materials

In his thesis research at West Virginia University, Nicholas Hornbeck evaluated the effect of compaction on the performance of Superpave mixes. Specifically, the objective of this research was to determine the effect of lowering the compaction effort on the rutting potential of the mixtures (3). In West Virginia, as in most of the country, Superpave mixtures were found to perform well with regards to rutting but durability and fatigue resistance needed some improvement. As it is well documented in the literature, reducing the compactive effort would increase the asphalt content which would improve the durability and fatigue life of pavements (2). Based on this literature evidence and the conclusions that suggest that the N_{design} values are too high, Mr. Hornbeck and his advisor decided to investigate the consequences of reducing the gyration levels on the performance and volumetric properties of the mixtures.

For this study, two common surface courses, 9.5 mm and 12.5 mm, were selected for the experiment. The 12.5 mix included a percentage of recycled asphalt whose initial asphalt content was measured and subtracted from the total binder to ensure that the specified binder contents were used (3). The specified design load for the study was 3 to 30 million ESALs requiring, based on current specifications, a compactive effort of 100 gyrations and PG 70-22 asphalt grade. All the materials were acquired through West Virginia Paving, who was responsible for performing the mix designs at 100 gyrations which produced asphalt contents of 6.5% and 5.9%

for the 9.5 and 12.5 mixes respectively. Using the same gradations, another mix design was performed in the lab to determine the binder contents that yield 4% air voids at a compaction level of 80 gyrations for each mix type, and the resulting contents were 7.1% for the 9.5 mm and 6.3% for the 12.5 mm mixture.

After the mix design process was complete and the asphalt contents were determined for each gyration level, 3 samples of each mix type were fabricated at 100 gyrations and 6 samples of each were made at 80 gyrations. These mixtures were then tested for susceptibility to permanent deformation using both the Asphalt Pavement Analyzer (APA) and the Indirect Tensile Test (IDT) (3). For APA testing; samples were compacted to a height of 75 mm and a target air void of 7.5±0.5 % to simulate newly constructed pavements. Each mix type had 3 replicates aged for one week then tested after conditioning for 4 hours at 60^0C, under a horse and wheel load pressure of 100±5 psi each and 8000 cycles. Measurements were taken prior to starting the test and immediately after at different locations on the sample and then averaged to determine the amount of rutting that occurred. The IDT testing on the other hand was performed on samples used to measure the air void content of each mix. After aging for 1 hour and 15 minutes, the samples were tested in the Marshall Stabilometer at a deformation rate of 50 mm/min and the results were then plotted in the form of load versus deformation (3). Table 2.7 and Table 2.8 display the APA and IDT results.

Table 2.7 APA rut depth measurements

Replication	9.5 mm 100 gyrations	9.5 mm 80 gyrations	12.5 mm 100 gyrations	12.5 mm 80 gyrations
1	5.85	6.45	5.2	6.67
2	3.25	5.05	4.45	5.03
3	4.35	4.5	5.7	6.17
4		5.62		5.28
5		6.55		4.69
6		7.54		6.31
Average	4.48	5.95	5.12	5.69

To determine the effect of lowering the compactive effort on the rutting performance based on the APA results, an analysis of variance was conducted to test whether the mean rutting value of the 100 gyration level is significantly different than the 80 gyration level with a 95% confidence level. The resulting p-values from this test indicated that there is not enough evidence to make such a conclusion, thus concluding that a 20% reduction in the compactive effort can be made without compromising the rutting resistance of Superpave mixtures.

Table 2.8 IDT Results

Mix type	Gyrations	Binder Content	Strength (psi)
9.5	100	6.5	16.3
	80	7.1	14.5
12.5	100	5.9	20.2
	80	6.3	21.5

For the 9.5 mm mix it is noted that as the binder content increases, the strength decreases, however, for the 12.5 mm mix the opposite is true. Since the strength variations are not statistically significant, the conclusion would be to reduce the N_{design} for this traffic level, and possibly all N_{design} values, by 20% based on these findings.

2.8 NCHRP Report 573

In a 2007 study sponsored by the National Cooperative Highway Research Program (NCHRP), Brian Prowell and Ray Brown investigated the accuracy and reliability of laboratory Superpave mixtures in predicting field performance. With 40 field observations in 16 states, this research had three objectives; evaluate the field densification of Superpave mix design pavements, verify the current N_{design} specifications, and evaluate the locking point concept as an alternative to N_{design} values (2).

The projects monitored for this research used Superpave mixtures with varying compactive efforts based on the expected traffic as recommended in the NCHRP 9-9 N_{design} table. One project with a compaction level of 50 gyrations was selected for this study, 12 with 75 gyrations, 18 with 100 gyrations, and 9 with 125 gyrations. These projects were monitored for four year after construction with data collection taking place during construction, after 3 months, 6 months, 1 year, 2 years, 3 years, and 4 years to measure field density and pavement condition. The researchers tested a total of 4085 SGC samples and 5670 cores. These results along with site traffic data were used to make the final recommendations for the N_{design} levels (2).

In-place density has a major effect on pavement performance; if the in-place air voids are too high, the pavement will be susceptible to cracking and if they are too low, permanent deformation becomes a concern. The average in-place density of the 40 projects at construction was 91.6% with 55% of the projects having less than 92% Gmm and 78% having less than 93% (2). As the gyration level increases, the percent Gmm decreases. The testing results showed that most densification occurs early in the pavement life with 63% occurring in the first 3 months. The 6 month density remained the same as the previous measurement, after 1 year it increased by 0.8 to 94.4% and after 2 years the density was only 94.6% (2). based on similar projects that claim that the ultimate densification occurs within the first 2 to 3 years after construction, the researchers tested this hypothesis by conducting an ANNOVA test comparing the 2 year and 4 year field densities concluding that there was no significant difference between the two, thus verifying that most of the densification does occur after 2 years. Although the traffic level is the most apparent cause of field densification, this study investigated other factors and concluded that high temperature PG grade and the construction month also play a role in the densification process. The researchers observed that mixes constructed between April and June compacted better than the average by about 1% whereas the pavements placed in September and October were 2-3% below the average (2). This variation in density can be attributed to the weather conditions during the early life of the pavement; the high temperatures in the summer, for example, keep the binder at elevated temperatures making the mixture easier to compact thus producing better densification than those compacted in the winter.

To evaluate the current compaction levels, the gyrations needed to achieve the 2 year in-place density were back calculated from a linear regression since the lab samples were compacted only with 100 and 160 gyrations. The predicted gyrations were then plotted against the ultimate in-place density, but the resulting relationship was too weak with excessive outliers hence not suitable to make any conclusions. As an alternative approach, in-place air voids after 2 years were compared to N_{design} compaction air voids. The observations from this comparison echoed the findings of previous studies and showed that, with the exception of very few projects, the average ultimate in-place air voids was 5.5%, 1.5% higher than the mix design air voids of 4%. The results of this comparison indicate that since the design density is not reached even after the ultimate densification is achieved, the compactive effort is too high, thus the N_{design} levels need to be modified to resemble in situ conditions. While evaluating the densification, it was observed that at gyration levels greater than 100, no significant compaction occurred beyond what was achieved at 100 gyrations, implying that N_{design} levels above 100 are pointless even with very high traffic levels.

The use of the locking point concept as an alternative to the N_{design} values was also evaluated using 4 different definitions; locking point 3-2-2, 2, 2-2, 2-2-2, where the numbers signify the frequency of consecutive equal height measurements. Comparing the calculated densities for each locking point to the 2 year in-place density showed that only the 3-2-2 locking point formed a relationship with the density, however this relationship was weaker that those obtained through design traffic and air voids comparison. An evaluation of this approach indicated that the locking point depends more on the gradation, aggregate type and angularity, and binder content than it does on the design traffic (2), therefore this concept does not fit the scope of this project and cannot be used as a solution.

Evaluation of the pavement condition at the end of the project indicated that very little rutting has occurred with an average rut depth of 1.7 mm. on the other hand, cracking, popouts and raveling were a common feature in most of the projects. This observation indicates that these mixtures had low asphalt content, therefore the compactive effort need to be reduced to minimize these distresses especially since the results of this study indicate that, at a 95% confidence interval, most mixes are very rut resistant (2).

The recommendations of this research are shown in Table 2.9. Since mixes containing PG76 grade or higher densified significantly less than those containing unmodified binders, the authors accounted for this difference by recommending compaction efforts for binders less than PG76 and those PG76 and greater. The authors also recommend eliminating the $N_{initial}$ and N_{max} criteria since the majority of mixes failed the $N_{initial}$ requirements and 40% failed the N_{max} requirements, but did not show excessive rutting after 4 years, therefore these criteria are not accurate measurements of performance and should be discarded.

Table 2.9 Recommended Ndesign levels

20 Year Design Traffic (ESALs)	2 Year Design Traffic (ESALs)	Ndesign for binders < PG 76-XX	Ndesign for binders >PG 76-XX or mixes placed >100mm from surface
< 300,000	< 30,000	50	NA
300,000 to 3,000,000	30,000 to 230,000	65	50
3,000,000 to 10,000,000	230,000 to 925,000	80	65
10,000,000 to 30,000,000	925,000 to 2,500,000	80	65
> 30,000,000	> 2,500,000	100	80

2.9 Optimum Number of Gyrations Based on Project Requirements

In Texas, as in most states that have adopted Superpave mix design, the pavements perform satisfactorily in resisting rutting but lag far behind in fatigue performance. To address this issue, Texas DOT (TxDOT) along with researchers at the University of Texas investigated the possibility of reducing the compaction levels to increase the binder content in mixtures and improve fatigue cracking resistance (5) (4). To determine an optimum number of gyrations based on the performance, rutting potential was measured with the Hamburg Wheel Tracking Device (HWTD), while the Indirect Tension Test measured cracking resistance along with the four point bending beam to measure fatigue resistance.

Mix designs were performed for several commonly used mixes to determine the optimum binder content. Based on these results, the asphalt contents were modified, while maintaining a target air void of 4%, to reach 50, 75, 100, and 125 gyrations. Samples were then compacted at these different gyrations and tested for rutting and cracking susceptibility (5). Since rutting is measured in millimeters and cracking is measured in terms of the number of cycles to failure, a direct comparison of the two characteristics is not possible. The concept of relative performance was developed to allow direct comparison by standardizing the results and quantifying the performance in a common unit. This concept is based on comparing the performance at each gyration level to a base performance which is defined as the performance at 125 gyrations for rutting and 50 gyrations for fatigue (5) because a high compactive effort yields better rutting resistance and low compaction is better for cracking resistance.

$$RP_{Fatigue} = \frac{P_{N_{Design}=i}}{P_{N_{Design}=50}}$$

$$RP_{Rutting} = \frac{P_{N_{Design}=i}}{P_{N_{Design}=125}}$$

Where RP is the relative performance, $P_{N_{Design}=i}$ is the performance at the chosen gyration level.

After calculating the relative performance results for each distress, they are plotted versus the N_{design} level to determine the optimum compactive effort as shown in Figure 2.1.

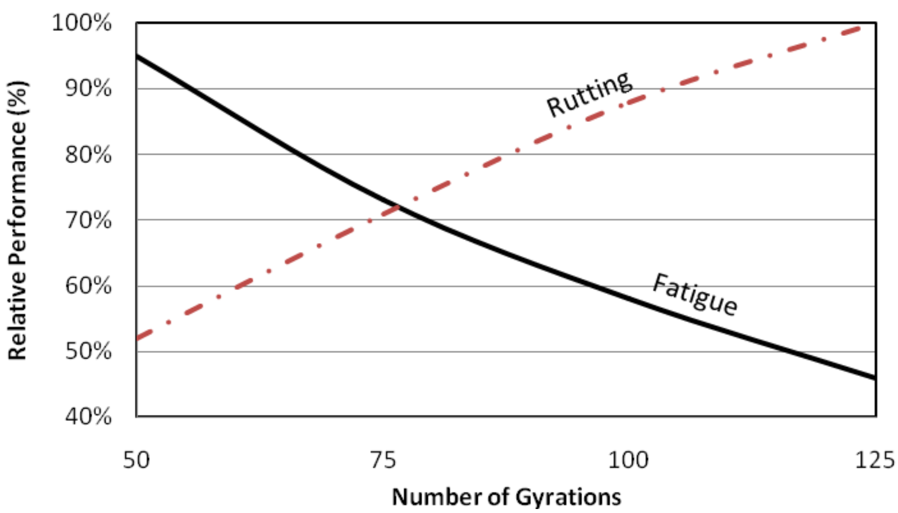

Figure 2.1 Relative performance concept

To analyze the results from this study, the authors developed two approaches to evaluate the effects of varying the compactive effort. The first method is based on the weighted combination of performance curves for rutting and fatigue allowing for a selection of an optimum number of gyrations by plotting the performance results versus the compaction levels. The second option uses confidence intervals to determine the effect of the degree of compaction on rutting and cracking results (5). After analyzing the average relative performance curves, the researchers concluded that the mix performance is optimized at a compaction effort between 75 and 85 gyrations on the SGC (5). A comparison of different factors showed that PG grade and binder content have the most effect on rutting performance which would not be significantly impacted even with a significant reduction in the compactive effort to increase mixture durability. In conclusion, the authors also noted that the current testing parameters of the HWTD and fatigue tests may not be good indicators of rutting and fatigue resistance due to the variability in their results and thus may underestimate these values.

The current N_{design} specifications and the target air voids of 4 % do not optimize field performance. As shown in many studies, the compaction levels can be reduced by as much as 25% to improve mixture durability and fatigue resistance without significantly impacting the rutting performance. This reduction can be achieved either by relating performance results to the compaction levels or by using the locking point concept. The first method is preferred as it was used in numerous studies that produced strong relationships and acceptable results. The locking point approach can also be used to improve performance as demonstrated by the Georgia DOT, however, the factors affecting this characteristic such as gradation, binder content, and aggregate type have not been thoroughly investigated to determine the extent of their influence. Reducing the compaction level and increasing the binder content will affect the volumetric properties such as VFA and VMA for which the specifications should be evaluated and modified to reflect these changes since the new mixtures will likely fail to meet the original volumetric requirements.

3. MATERIAL CHARACTERIZATION

Asphalt concrete is composed of asphalt cement and aggregates blended in proportions based on desired performance; the process of determining theses proportions is known as mix design. This chapter discuses the aggregate properties and mix deigns for the different mixture types used in this research.

3.1 Aggregate Properties

The type of aggregate used in the research was granite selected and provided by NCDOT due to its common use in most pavements in the state. After procurement of the aggregates, the specific gravity and percent absorption of the different stock piles were determined in compliance with AASHTO T84-88 "Specific Gravity and Absorption of Fine Aggregate" and AASHTO T85-88 "Specific Gravity and Absorption of Coarse Aggregate". The measured values are given in Table 3.1 below.

Table 3.1 Aggregate Specific Gravity

Aggregate Type	Bulk specific gravity	Apparent specific gravity	Percent absorption
Coarse	2.623	2.648	1.53%
Fine	2.684	2.705	0.30%

3.2 Asphalt Binder

Three asphalt binders, PG64-22, PG70-22, and PG76-22, were selected for this project and obtained by NCDOT from Nustar Energy.

3.3 Superpave Mix Design Procedure

To evaluate the current Ndesign levels, mix designs were performed for all the surface courses used in the state of North Carolina; these mixtures are S9.5A, S9.5B, S9.5C, S9.5D, S12.5C, and S12.5D. The first step in the mix design process is the selection of the design aggregate gradation. Initially, three trial blends were prepared and trial binder contents were estimated for each one based on the effective specific gravity and the fractions of the fine and coarse aggregates. For each trial gradation, two specimens were compacted to the appropriate number of gyrations and the heights were recorded during compaction, in addition to one pan of loose mixture with the same trial asphalt content for determining the theoretical maximum specific gravity (G_{mm}) of the mix. The Superpave compaction criteria for a mix design are based on three points throughout the compactive effort; an initial (N_{ini}), design (N_{des}), and maximum (N_{max}) number of gyrations. The gyrations levels were developed for in-service pavements with different traffic levels and temperatures. The initial, design, and maximum gyrations for each mixture according to the current NCDOT specifications are as follows:

- S9.5A: N_{ini} = 6 gyrations, N_{des} = 50 gyrations and N_{max} = 75 gyrations
- S9.5B: N_{ini} = 7 gyrations, N_{des} = 75 gyrations and N_{max} = 115 gyrations
- S9.5C and 12.5C: N_{ini} = 8 gyrations, N_{des} = 100 gyrations and N_{max} = 160 gyrations
- S9.5D and S12.5D: N_{ini} = 9 gyrations, N_{des} = 125 gyrations and N_{max} = 205 gyrations

Once the specimens were compacted, the trial gradations were then evaluated based on their volumetric properties and the one that meets the Superpave mix design criteria is selected as the design gradation. Table 3.2 displays the recommended Superpave mix design limits.

Table 3.2 Superpave Mix Design Criteria

Mix Type	% VMA	% VFA	% G_{mm} @ N_{ini}	Dust Proportion
S9.5A	16 (Min)	70-80	≤ 91.5	0.6-1.4
S9.5B	15 (Min)	65-80	≤ 90.5	0.6-1.4
S9.5C	15 (Min)	65-76	≤ 90.0	0.6-1.4
S9.5D	15 (Min)	65-76	≤ 90.0	0.6-1.4
S12.5C	14 (Min)	65-75	≤ 90.0	0.6-1.4
S12.5D	14 (Min)	65-75	≤ 90.0	0.6-1.4

Once the design gradation is selected, specimens were fabricated with asphalt contents of +/- 0.5% and + 1.0% of the trial asphalt content with two repetitions at each level at Ndesign gyrations for each mixture. Based on the maximum theoretical and bulk specific gravities of these specimens, volumetric properties including %VMA, %VFA, dust proportion, and air content are evaluated for all binder contents. These properties are then plotted against asphalt content, and the design asphalt content is determined at 4% air voids. The remaining design properties of the mixture are then evaluated from their corresponding plots at the design asphalt content, and checked against the criteria in Table 3.2 to ensure the acceptance of this design. The mix design results of the mixtures used in this research are presented in the subsequent sections.

3.3.1 S9.5A Mixture

As described in section 3.3, three trial blends are evaluated and the most promising blend is selected. Table 3.3 shows the selected gradation for the S9.5A mixture, and Figure 3.1 shows the percent passing plot for the aggregate gradation.

Table 3.3 S9.5A Design Aggregate Structure

	% Passing	
Sieve Size, mm	**Mix Gradation**	**Control Points**
12.5	100	100
9.5	91	90-100
4.75	66	< 90
2.36	61	60-70
1.18	40	
0.6	29	
0.3	20	
0.15	12	
0.075	4	4-8

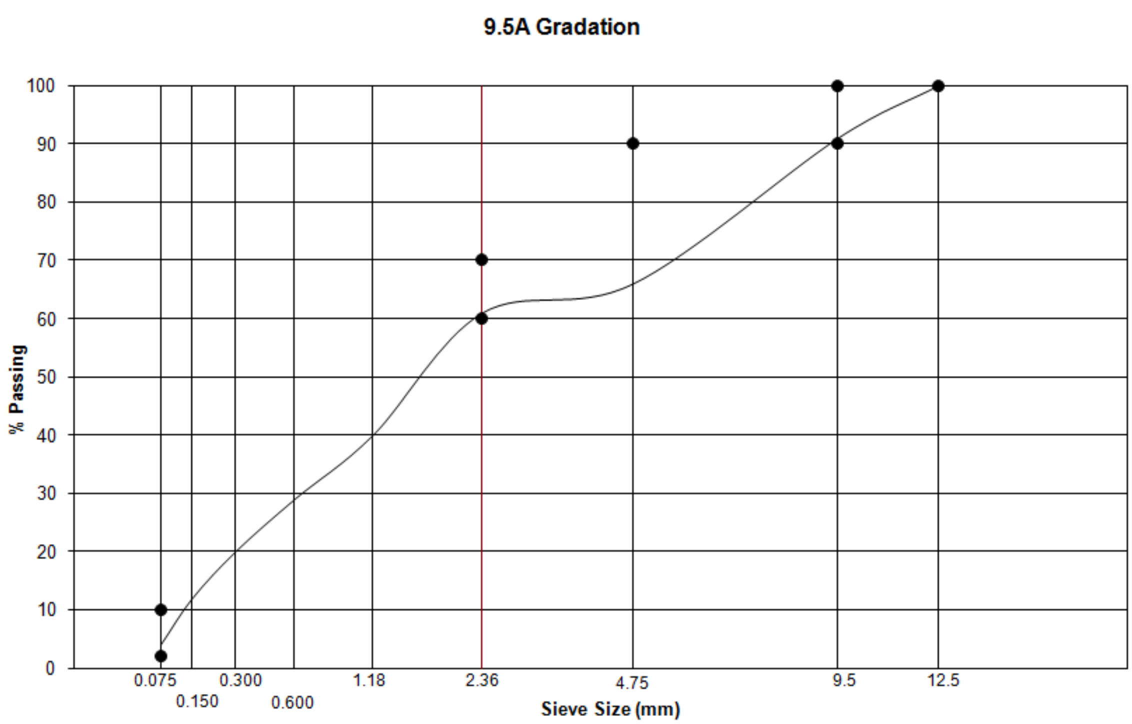

Figure 3.1 S9.5A Federal Highway 0.45 Power Gradation

With the selected gradation, the optimum binder content was calculated to be 6.0% at an air voids content of 4%. The mixture properties were checked at the design asphalt content to ensure that the Superpave criteria were met. nd the Superpave specifications for S9.5A mix. The Ndesign value in bold is the current NCDOT specification which was used as the base Ndesign value for Superpave mix design. The design asphalt contents at other gyration levels were back-calculated from the asphalt content at 50 gyrations for this mix.

Table 3.4 shows the observed mixture properties and the Superpave specifications for S9.5A mix. The Ndesign value in bold is the current NCDOT specification which was used as the base Ndesign value for Superpave mix design. The design asphalt contents at other gyration levels were back-calculated from the asphalt content at 50 gyrations for this mix.

Table 3.4 S9.5A Mixture Properties

Number of design gyrations	**50**	75	100	125	**Specification**
%Asphalt content - Total mix	6.0	5.77	5.56	5.4	-
Bulk Sp. Gravity, G_{mb}	2.326	2.345	2.356	2.357	-
Theoretical Max. Sp. Gravity, G_{mm}	2.429	2.437	2.445	2.450	-
% Air Voids - Total Mix	4.2	3.7	3.6	3.8	4%
%Voids in Mineral Aggregate	17.9	17.0	16.4	16.2	> 16%
%Voids Filled with Asphalt	77.6	76.5	75.6	75.4	70-80%

3.3.2 S9.5B Mixture

Similar to the first mixture, three trial blends are evaluated and the most promising blend is selected. Table 3.5 shows the selected gradation for the S9.5B mixture, and Figure 3.2 displays a graphical representation of the gradation.

Table 3.5 S9.5B Design Aggregate Structure

	% Passing	
Sieve Size, mm	**Mix Gradation**	**Control Points**
12.5	100	100
9.5	93	90-100
4.75	58	< 90
2.36	41	60-70
1.18	27	
0.6	18	
0.3	13	
0.15	8	
0.075	4	4-8

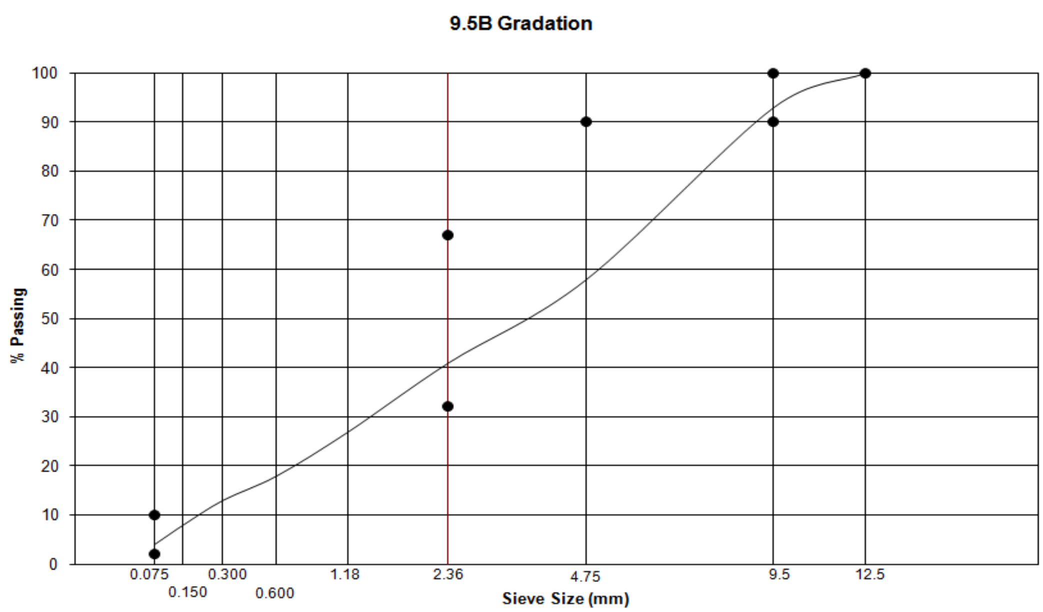

Figure 3.2 S9.5B Federal Highway 0.45 Power Gradation

With the selected gradation, the optimum binder content was determined to be 5.7% at an air voids content of 4%. The mixture properties were checked at the design asphalt content to ensure that the Superpave criteria.

Table 3.6 shows the observed mixture properties and the Superpave specifications for S9.5B mix. The Ndesign value in bold is the current NCDOT specification which was used as the base Ndesign value for Superpave mix design. The design asphalt contents at other gyration levels were back-calculated from the asphalt content at 65 gyrations for this mix.

Table 3.6 S9.5B Mixture Properties

Number of design gyrations	50	**65**	75	100	125	**Spec.**
%Asphalt content - Total mix	6.13	5.70	5.72	5.43	5.21	-
Bulk Sp. Gravity, G_{mb}	2.333	2.345	2.356	2.360	2.365	-
Theoretical Max. Sp. Gravity, G_{mm}	2.428	2.435	2.443	2.453	2.461	-
% Air Voids - Total Mix	4.0	3.7	3.6	3.9	3.7	4%
%Voids in Mineral Aggregate	17.6	16.9	16.5	16.0	15.7	> 15%
%Voids Filled with Asphalt	77.3	76.4	75.7	75.1	74.5	65-80%

3.3.3 S9.5C Mixture

As discussed in Section 3.3, three trial blends are evaluated and the most promising blend is selected. Table 3.7 shows the selected gradation for the S9.5C mixture, and Figure 3.3 displays a graphical representation of the gradation.

Table 3.7 S9.5B Design Aggregate Structure

	% Passing	
Sieve Size, mm	**Mix Gradation**	**Control Points**
12.5	100	100
9.5	93	90-100
4.75	58	< 90
2.36	41	60-70
1.18	27	
0.6	18	
0.3	13	
0.15	8	
0.075	4	4-8

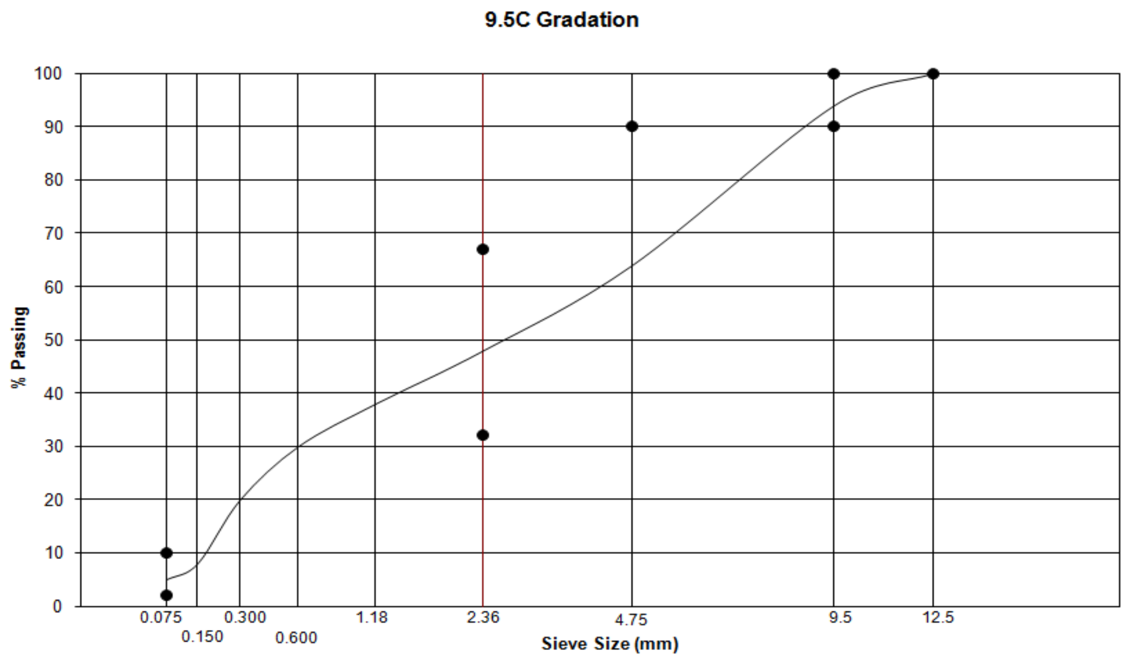

Figure 3.3 S9.5C Federal Highway 0.45 Power Gradation

With the selected gradation, an optimum binder content of 5.4% was obtained at an air voids content of 4%. The mixture properties were verified at the design asphalt content to ensure that the Superpave criteria. Table 3.8 shows the observed mixture properties and the Superpave specifications for S9.5C mix. The Ndesign value in bold is the current NCDOT specification which was used as the base Ndesign value for Superpave mix design. The design asphalt contents at other gyration levels were back-calculated from the asphalt content at 75 gyrations for this mix.

Table 3.8 S9.5C Mixture Properties

Number of design gyrations	50	**75**	100	125	**Specification**
%Asphalt content - Total mix	5.95	5.61	5.37	5.18	-
Bulk Sp. Gravity, G_{mb}	2.333	2.346	2.353	2.357	-
Theoretical Max. Sp. Gravity, G_{mm}	2.429	2.435	2.449	2.450	-
% Air Voids - Total Mix	4.0	3.6	3.8	4.1	4%
%Voids in Mineral Aggregate	17.5	16.8	16.3	16.0	> 15%
%Voids Filled with Asphalt	77.2	76.2	75.5	75.1	65-76%

3.3.4 S9.5D Mixture

Out of the three trial blends that were evaluated, the most promising blend was selected as the design gradation. Table 3.9 shows the selected gradation for the S9.5D mixture, and Figure 3.4 displays a graphical representation of the gradation.

Table 3.9 S9.5D Design Aggregate Structure

	% Passing	
Sieve Size, mm	**Mix Gradation**	**Control Points**
12.5	100	100
9.5	91	90-100
4.75	67	< 90
2.36	55	60-70
1.18	43	
0.6	31	
0.3	22	
0.15	10	
0.075	6	4-8

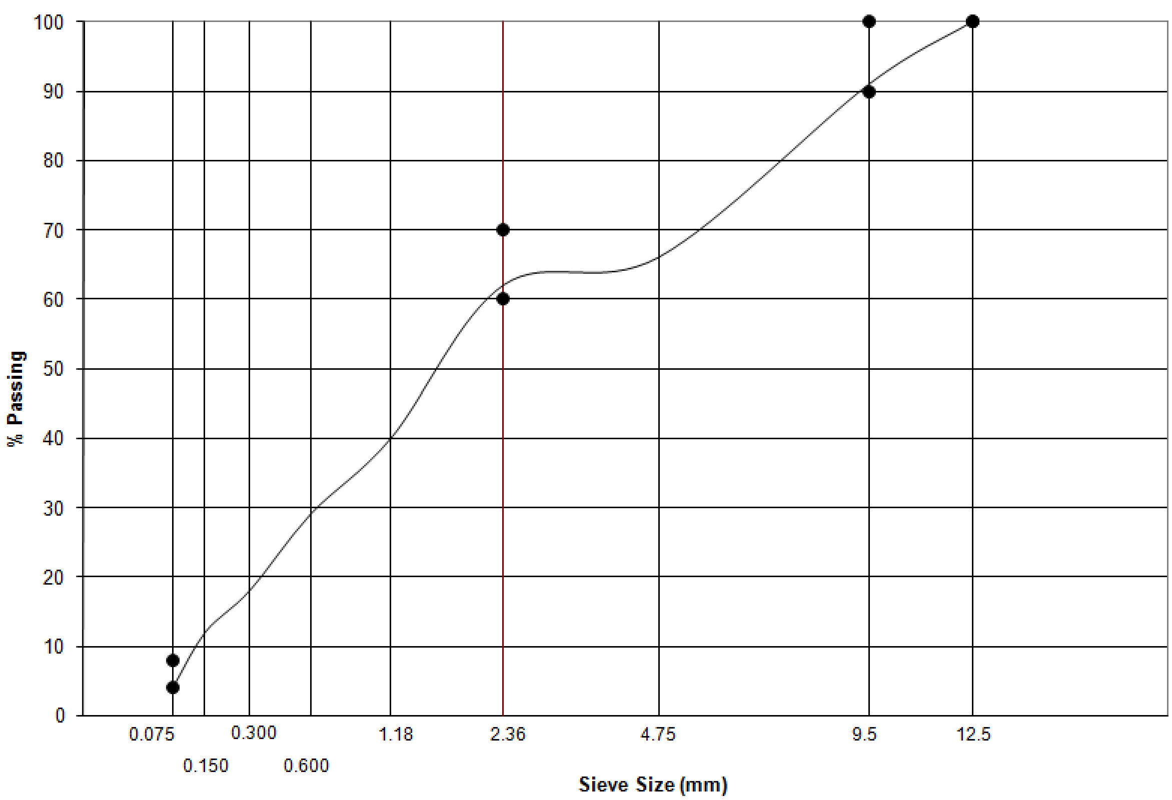

Figure 3.4 S9.5D Federal Highway 0.45 Power Gradation

With the selected gradation, an optimum binder content of 5.3% was obtained at an air voids content of 4%. The mixture properties were checked at the design asphalt content to ensure that the Superpave criteria. Table 3.10 shows the observed mixture properties and the Superpave specifications for S9.5D mix. The design asphalt contents at other gyration levels were back-calculated from the asphalt content at 100 gyrations for this mix.

Table 3.10 S9.5D Mixture Properties

Number of design gyrations	50	75	**100**	125	**Specification**
%Asphalt content - Total mix	5.90	5.60	5.40	5.23	-
Bulk Sp. Gravity, G_{mb}	2.333	2.350	2.347	2.365	-
Theoretical Max. Sp. Gravity, G_{mm}	2.432	2.442	2.449	2.455	-
% Air Voids - Total Mix	4.1	3.9	4.0	3.8	4%
%Voids in Mineral Aggregate	17.6	16.7	16.6	15.9	> 15%
%Voids Filled with Asphalt	77.3	76.0	76.0	74.5	65-76%

3.3.5 S12.5C Mixture

Similar to the previous mixtures, three trial blends are evaluated and the most promising blend is selected. Table 3.11 shows the selected gradation for the S12.5C mixture, and Figure 3.5 displays a graphical representation of the gradation.

Table 3.11 S12.5C Design Aggregate Structure

	% Passing	
Sieve Size, mm	**Mix Gradation**	**Control Points**
19	100	100
12.5	93	90-100
9.5	75	<90
4.75	59	
2.36	50	28-58
1.18	41	
0.6	28	
0.3	19	
0.15	8	
0.075	5	4-8

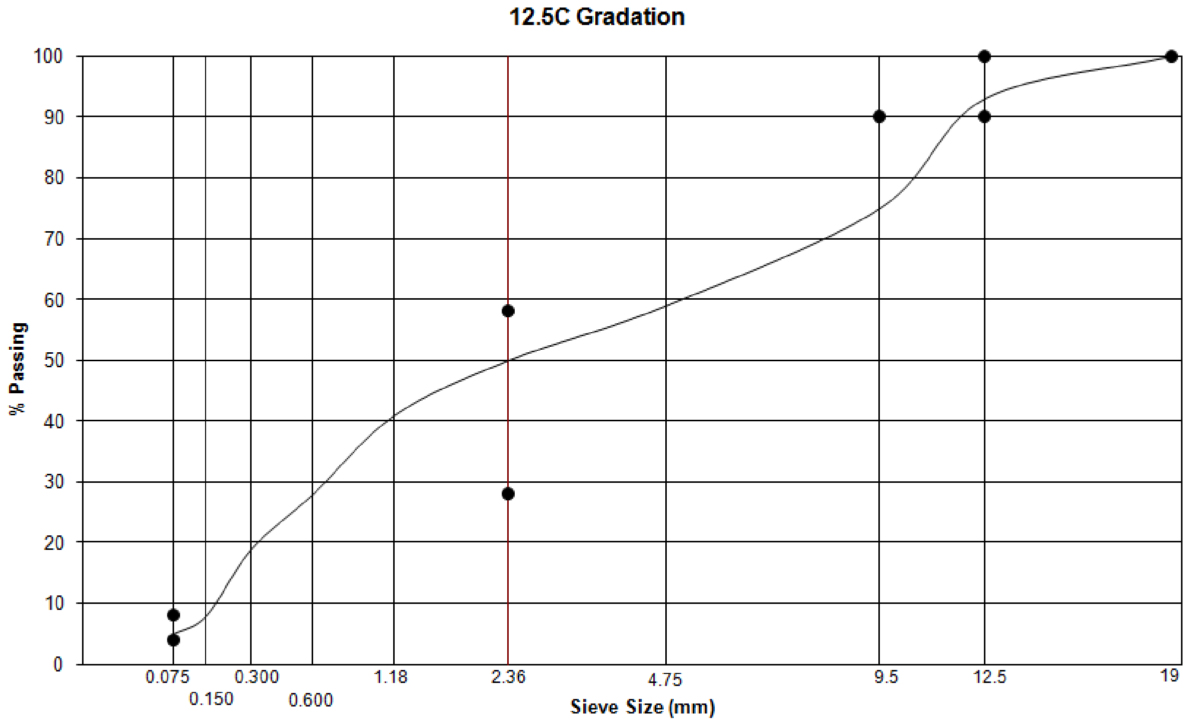

Figure 3.5 S12.5C Federal Highway 0.45 Power Gradation

With the selected gradation, an optimum binder content of 5.2% was obtained at an air voids content of 4%. The mixture properties were checked at the design asphalt content to ensure that the Superpave criteria. Table 3.12 shows the observed mixture properties and the Superpave specifications for S12.5C mix. The design asphalt contents at other gyration levels were back-calculated from the asphalt content at 75 gyrations for this mix.

Table 3.12 S12.5C Mixture Properties

Number of design gyrations	50	**75**	100	125	**Specification**
%Asphalt content - Total mix	5.71	5.41	5.20	5.03	-
Bulk Sp. Gravity, G_{mb}	2.358	2.463	2.458	2.451	-
Theoretical Max. Sp. Gravity, G_{mm}	2.451	2.458	2.463	2.469	-
% Air Voids - Total Mix	3.8	4.3	3.7	4.3	4%
%Voids in Mineral Aggregate	16.4	16.3	15.5	15.6	> 14%
%Voids Filled with Asphalt	76.9	73.8	75.8	72.4	65-75%

3.3.6 S12.5D Mixture

As discussed in section 3.3, three trial blends are evaluated and the most promising blend is selected. Table 3.13 shows the selected gradation for the S12.5D mixture, and Figure 3.6 displays a graphical representation of the gradation.

Table 3.13 S12.5D Design Aggregate Structure

	% Passing	
Sieve Size, mm	**Mix Gradation**	**Control Points**
19	100	100
12.5	93	90-100
9.5	77	<90
4.75	61	
2.36	50	28-58
1.18	41	
0.6	30	
0.3	21	
0.15	11	
0.075	5	4-8

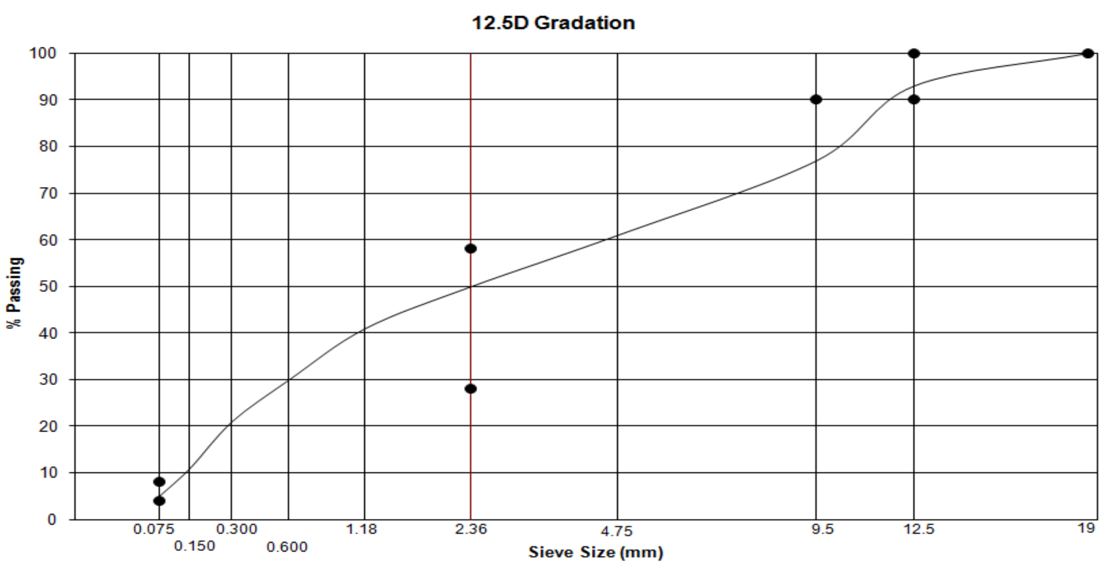

Figure 3.6 S12.5D Federal Highway 0.45 Power Gradation

Using the selected gradation, an optimum binder content of 4.9% was obtained at an air voids content of 4%. The mixture properties were checked at the design asphalt content to ensure that the Superpave criteria. Table 3.14 shows the observed mixture properties and the Superpave specifications for S12.5D mix. The design asphalt contents at other gyration levels were back-calculated from the asphalt content at 100 gyrations for this mix.

Table 3.14 S12.5D Mixture Properties

Number of design gyrations	50	75	**100**	125	**Specification**
%Asphalt content - Total mix	5.47	5.18	4.97	4.81	-
Bulk Sp. Gravity, G_{mb}	2.432	2.442	2.449	2.455	-
Theoretical Max. Sp. Gravity, G_{mm}	2.432	2.442	2.449	2.455	-
% Air Voids - Total Mix	4.3	4.1	4.2	4.1	4%
%Voids in Mineral Aggregate	17.2	16.5	16.2	15.7	> 14%
%Voids Filled with Asphalt	75.2	75.2	73.9	74.1	65-75%

3.4 Mixture Performance Evaluation

Performance evaluation and testing of the mixtures were conducted on the Asphalt Mixture Performance Tester, AMPT. AMPT testing was performed to determine two properties of the mixtures - Dynamic Modulus and Flow Number. The AMPT device, shown below in Figure 3.7, is a computer–controlled hydraulic testing machine capable of subjecting a compacted asphalt mixture specimen to cyclic loading over a range of temperatures (4 to 60^{o}C) and frequencies. The device does not directly measure the distress potential of the mixture, but measures the dynamic modulus at different temperatures and frequencies. Dynamic modulus of a mix is an important input for mechanistic-empirical pavement design and performance prediction procedure to predict fatigue cracking potential of the mixtures. Flow number test, which can also be performed on the device can be used to compare the rutting potential of asphalt mixtures.

Laboratory prepared loose mixture in accordance with AASHTO T312, *Preparation of Compacted Specimens of Modified and Unmodified Hot Mix Asphalt by Means of the SHRP Gyratory,* and conditioned per AASHTO R30, *Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA),* was used to prepare samples to test dynamic modulus and flow number as specified in AASHTO TP79-09. The samples were compacted to a diameter of 150 mm and a height of 178 mm. The compacted samples were cored and sawed to obtain a test specimen of 150 mm tall and 100 mm in diameter with around 4% ±0.5 air voids.

Figure 3.7 Asphalt Mixture Performance Tester (AMPT) Device

The samples were cored at the center using a diamond studded core bit to obtain a diameter of 100 mm (4in). The cored samples were sawed from the ends to obtain a height of 150 mm (6 in). Sawing operations were carefully performed to endure the ends of the specimen were parallel to the extent of using PVC piping sections to stabilize the sample in the sawing fixture. The cored and sawed samples were washed to eliminate all loose debris. The bulk specific gravities and air void content of each test sample were measured in accordance with AASHTO T-269, *Percent Air Voids in Compacted Dense and Open Asphalt Mixtures*. If any specimen was outside the required range of air voids, it was discarded and a new one was fabricated. Once the specimens were prepared, they were stored at room temperature until testing.

3.4.1 Dynamic Modulus Testing

Prior to testing, the specimens were checked for end parallelism and flatness to ensure that they are suitable for testing per AASHTO TP 79-09 requirements. The procedure for testing asphalt concrete specimens to measure dynamic modulus in the AMPT is as follows:

- Attach six targets to the specimen using epoxy. The distance of two targets should satisfy that the measure gauge length is around 70 mm and the angle between each set of two targets is 120 degrees. Wait for around 30 minutes to let the epoxy consolidate and then move to next step.

- Place one rubber membrane on each end of the specimen, and place the spherical stainless steel ball at the center and on top of the top platens.
- Place LVDTs on the specimen, and adjusts them to allow the full range of the LVDTs to be available for the measurement of deformation.
- Place the sample in the AES chamber to condition for the required time depending on the testing temperature.
- Move the specimen and the platens inside the AMPT environmental chamber on the loading pedestal; make sure that the loading cell is in line with the axis of the end platen and the specimen is in the center.
- Set the AMPT chamber temperature to the specific testing temperature, and allow the specimen to be conditioned for around 30 minutes to offset any temperature changes that may occur in the moving process.
- Run the test.
- Each dynamic modulus sample was tested under three frequencies (10, 1, and 0.1Hz) and three temperatures (4, 20, and 40^0C).

3.4.2 Flow Number Testing

Flow number was conducted in accordance with AASHTO TP 79-09, and the testing procedure was similar to dynamic modulus with the exception of the first two steps since no on-specimen LVDTs were used. The procedure was as follows:

- Place one rubber membrane on each end of the specimen, and place the spherical stainless steel ball at the center and on top of the top platens.
- Place the sample in the AES conditioning chamber for the required time depending on the testing temperature.
- Turn on the AMPT and set the chamber temperature to the specific testing temperature and allow it to equilibrate for at least 1 hour.

- Move the specimen and the platens inside the testing chamber and place them on the loading pedestal; make sure that the loading cell is in line with the axis of the end platen and the specimen is in the center.
- Close the testing chamber and allow the specimen to be conditioned for around 30 minutes to offset any temperature changes that may occur in the moving process.
- Run the test.
- Each flow number sample was subjected to a compressive load in haversine form with a loading time of 0.1 seconds and a rest duration of 0.9 seconds for a maximum of 10,000 cycles or until a deformation of 50,000 microstrains is reached. A deviatory stress of 600 kPa was applied to the specimen until the flow point is reached. Flow number testing was performed at 0 kPa confining pressure state and a temperature of 54^0C.

4. RESULTS

The objectives of this study as stated in the research plan were achieved by employing the AMPT to conduct dynamic modulus testing, and the results were used as input in the mechanistic-empirical design guide software, DARWin-ME, to estimate the fatigue and rutting potential of all the six mixtures being investigated. In addition, flow number testing was conducted to provide confirmation and quantify the effect of the recommended Ndesign values on rutting performance.

4.1 Dynamic Modulus Test Results

Dynamic modulus testing was conducted for all the asphalt mixtures on specimens prepared at an air void level of 4% and varying asphalt contents. Three replicate samples were tested at each asphalt content to verify the repeatability of the results. The tests were performed in accordance with AASHTO TP 79 "Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)", at three temperatures, 4^{o}C, 20^{o}C, and 40^{o}C, and three frequencies, 0.1Hz, 1Hz, and 10Hz.

The dynamic modulus test results for all the six mixtures are presented below in Table 4.1 through Table 4.6. The AMPT device measures the dynamic modulus in MPa at the specified frequencies and temperatures. However, DARWin-ME requires dynamic modulus data over a wider range of temperature and frequency values in units of psi, that cannot be directly obtained from the AMPT. To obtain the required E* data for use in the software, master curves are developed based on AASHTO PP66 to estimate the necessary values.

The test results show that the mixture stiffness increases with an increase in asphalt binder grade from PG 64-22 to PG 76-22. The expected trends in the measurement of dynamic modulus for different mixtures should reflect an increase in the E* with:

- an increase in asphalt binder stiffness
- an increase in test temperature from 4^{0}C to 20^{0}C
- an increase in loading frequency from 0.1Hz to 10Hz

The dynamic modulus data obtained from AMPT testing followed the expected trends with respect to all the above three variables.

Table 4.1 Dynamic Modulus Test Results for S9.5A Mix (MPa)

Test Temperature (^{0}C)		50 gyrations	75 gyrations	100 gyrations	125 gyrations
4	10 Hz	17586	17965	19158	19685
	1 Hz	13649	14131	14967	15291
	0.1 Hz	9870	10346	10936	10693
20	10 Hz	8086	8527	8990	9288
	1 Hz	4829	5225	5435	5611
	0.1 Hz	2603	2888	2970	3065
40	10 Hz	2111	2437	2673	3005
	1 Hz	926	1087	1247	1335
	0.1 Hz	433	511	563	639

Table 4.2 Dynamic Modulus Test Results for S9.5B Mix (MPa)

Test Temperature (^{0}C)		50 gyrations	75 gyrations	100 gyrations	125 gyrations
4	10 Hz	18449	18927	19402	19875
	1 Hz	13994	14406	14996	15374
	0.1 Hz	9683	10062	10723	11043
20	10 Hz	7952	8800	9590	9619
	1 Hz	4564	5184	5810	6065
	0.1 Hz	2216	2723	3148	3388
40	10 Hz	1991	2320	2699	2765
	1 Hz	840	1030	1182	1317
	0.1 Hz	387	509	548	660

Table 4.3 Dynamic Modulus Test Results for S9.5C Mix (MPa)

Test Temperature (^{0}C)		50 gyrations	75 gyrations	100 gyrations	125 gyrations
4	10 Hz	19126	20340	22394	24350
	1 Hz	15321	16043	18343	19840
	0.1 Hz	11529	12553	14121	15176
20	10 Hz	9751	10517	12084	13100
	1 Hz	6198	6848	8184	8838
	0.1 Hz	3545	4057	5039	5460
40	10 Hz	2787	3229	4107	4406
	1 Hz	1277	1572	2047	2302
	0.1 Hz	590	767	1045	1277

Table 4.4 Dynamic Modulus Test Results for S9.5D Mix (MPa)

Test Temperature (^{0}C)		50 gyrations	75 gyrations	100 gyrations	125 gyrations
4	10 Hz	17281	19369	20019	20796
	1 Hz	13593	15510	16013	16598
	0.1 Hz	10126	11835	12159	12488
20	10 Hz	8429	9556	9633	10022
	1 Hz	5297	6115	6155	6358
	0.1 Hz	3066	3592	3573	3700
40	10 Hz	2306	2733	2642	2728
	1 Hz	1074	1269	1224	1249
	0.1 Hz	558	633	620	612.5

Table 4.5 Dynamic Modulus Test Results for S12.5C Mix (MPa)

Test Temperature (^{0}C)		50 gyrations	75 gyrations	100 gyrations	125 gyrations
4	10 Hz	18169	19648	20577	21836
	1 Hz	14101	16147	17019	17815
	0.1 Hz	10130	12382	13278	13694
20	10 Hz	8465	10051	11102	11619
	1 Hz	5098	6502	7390	7546
	0.1 Hz	2682	3771	4451	4424
40	10 Hz	2261	2994	3463	3516
	1 Hz	987	1390	1617	1655
	0.1 Hz	475	668	767	807

Table 4.6 Dynamic Modulus Test Results for S12.5C Mix (MPa)

Test Temperature (^{0}C)		50 gyrations	75 gyrations	100 gyrations	125 gyrations
4	10 Hz	18384	19015	19623	20506
	1 Hz	14570	15346	15733	16382
	0.1 Hz	10768	11685	11833	12367
20	10 Hz	8771	9617	9647	10064
	1 Hz	5406	6189	6218	6477
	0.1 Hz	3051	3555	3691	3836
40	10 Hz	2329	2083	2942	3012
	1 Hz	1060	1302	1386	1479
	0.1 Hz	554	696	670	815

The effect of frequency on dynamic modulus can be explained in terms of loading duration - frequency is the inverse of loading time, therefore, as the frequency is decreased, the duration of loading is increased causing a reduction in the measured E*. Similarly, as the temperature increases, the asphalt concrete specimen begins to lose its structural integrity and the stiffness is reduced, thus the observed trend with respect to temperature. In order to maintain a constant air void level with the same gradation and lower asphalt content, the compaction effort needs to be increased, thus resulting in a specimen with improved bonding and aggregate interlocking which translates into increased stiffness. Since the measured E* values are a direct input in the DARWin-ME software, these trends are expected to be carried in the master curve building process and into the analysis and distress evaluation phase.

The increasing trend in E* with increase in the number of design gyrations can be identified by plotting the E* master curves at different gyration levels at a reference temperature. Figure 4.1 through Figure 4.6 show sample plots of the master curves at a specified temperatures for the mixtures involved in this study. As the number of gyrations increase, the E* values increase, however this trend cannot be vividly discerned from the plots due to the range of the dynamic modulus values. The numerical values of dynamic modulus used to plot the master curves, presented in Appendix B of the report provide a better explanation of the observed trends.

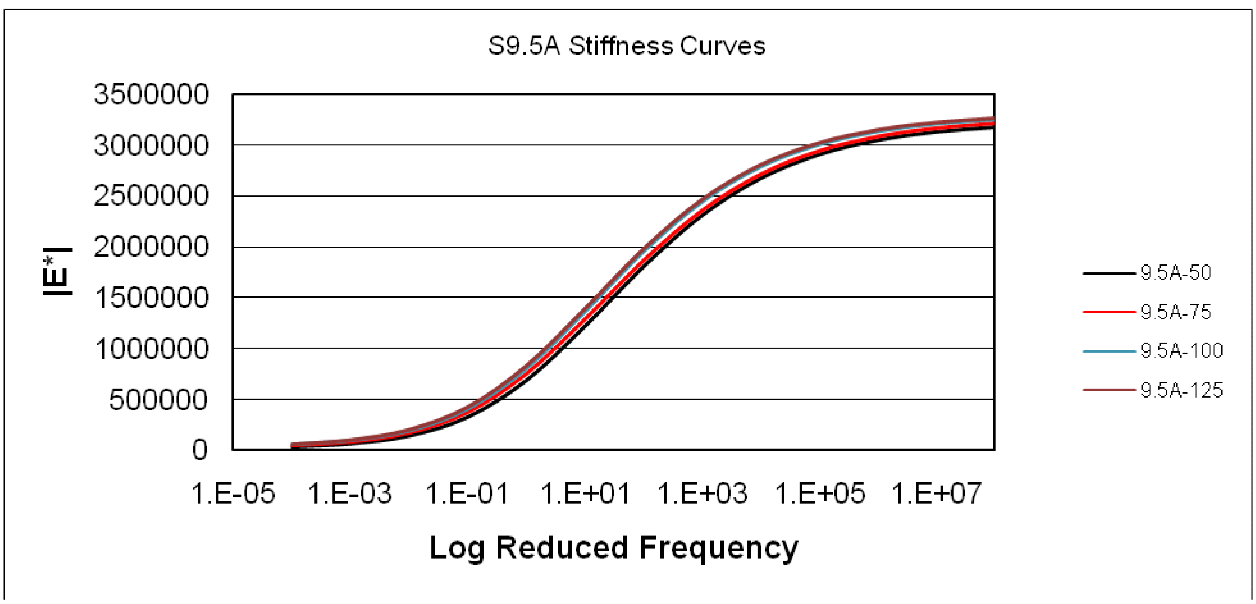

Figure 4.1 E* Master Curves at Different Gyration Levels for S9.5A Mix at 70^{0}F

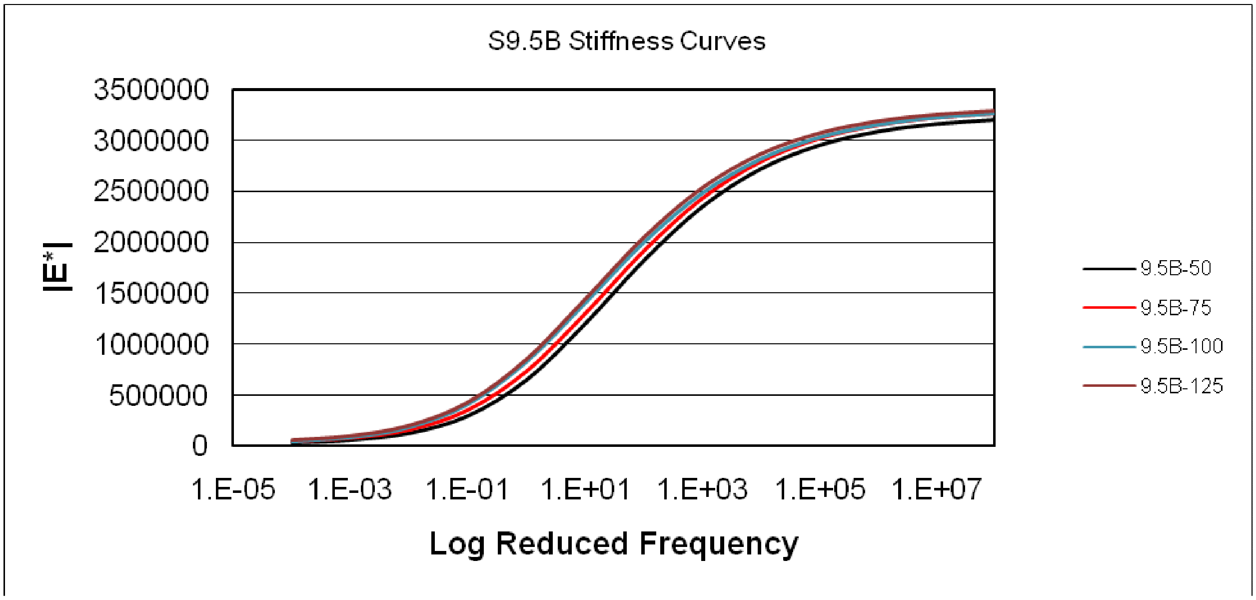

Figure 4.2 E* Master Curves at Different Gyration Levels for S9.5B Mix at 70^0F

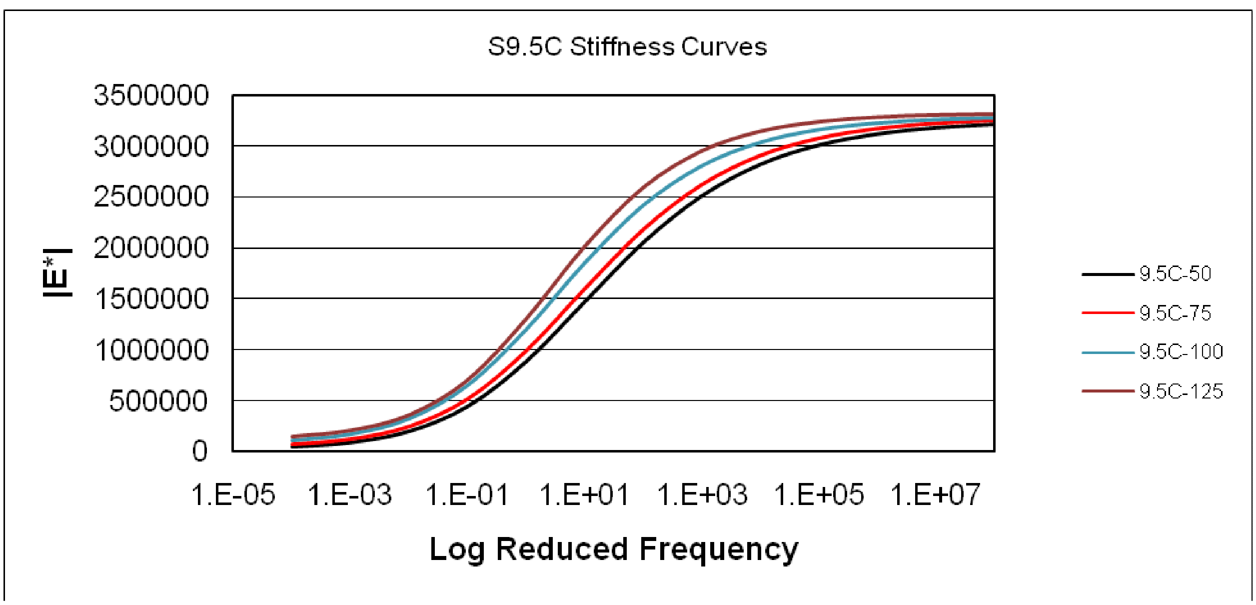

Figure 4.3 E* Master Curves at Different Gyration Levels for S9.5C Mix at 70^0F

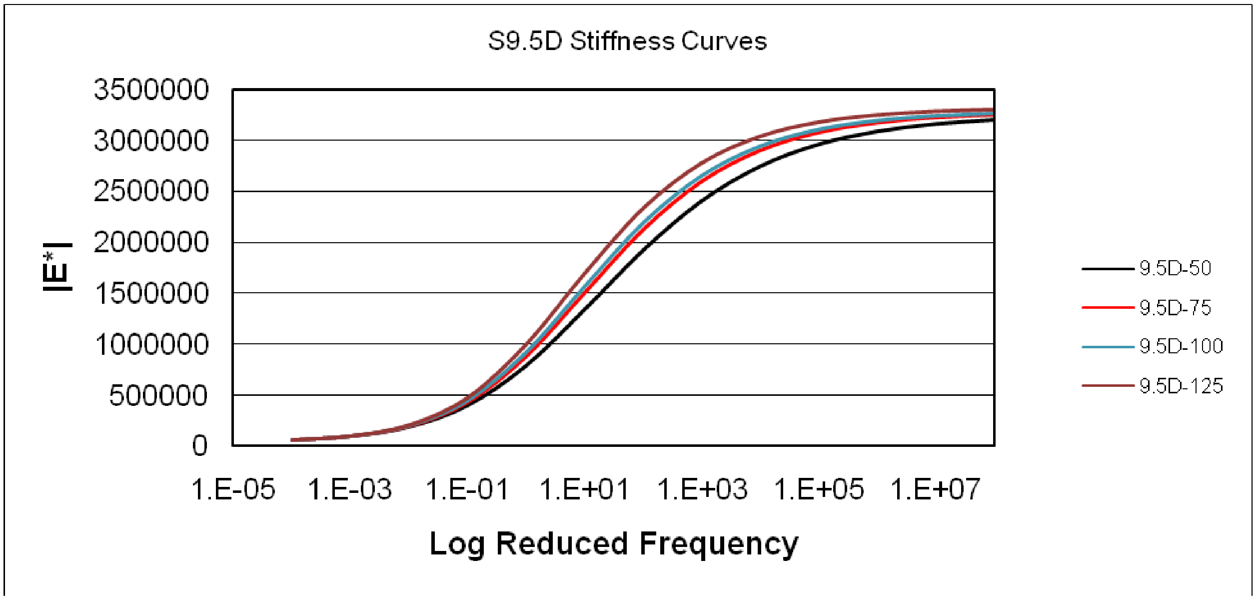

Figure 4.4 E* Master Curves at Different Gyration Levels for S9.5D Mix at 70^{0}F

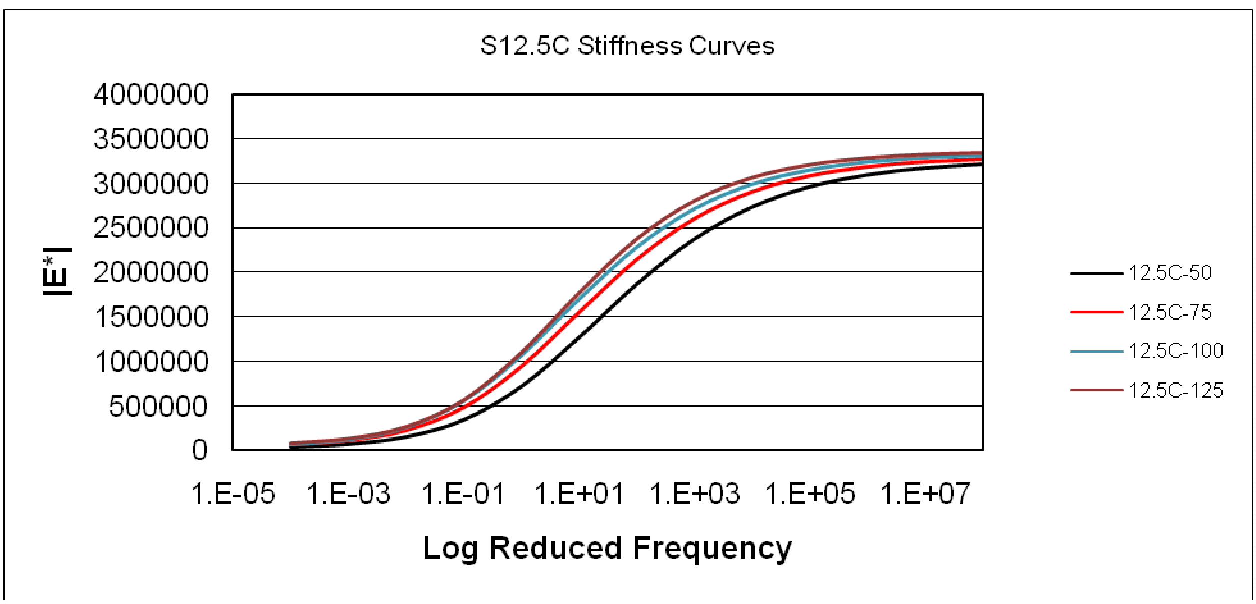

Figure 4.5 E* Master Curves at Different Gyration Levels for S12.5C Mix at 70^{0}F

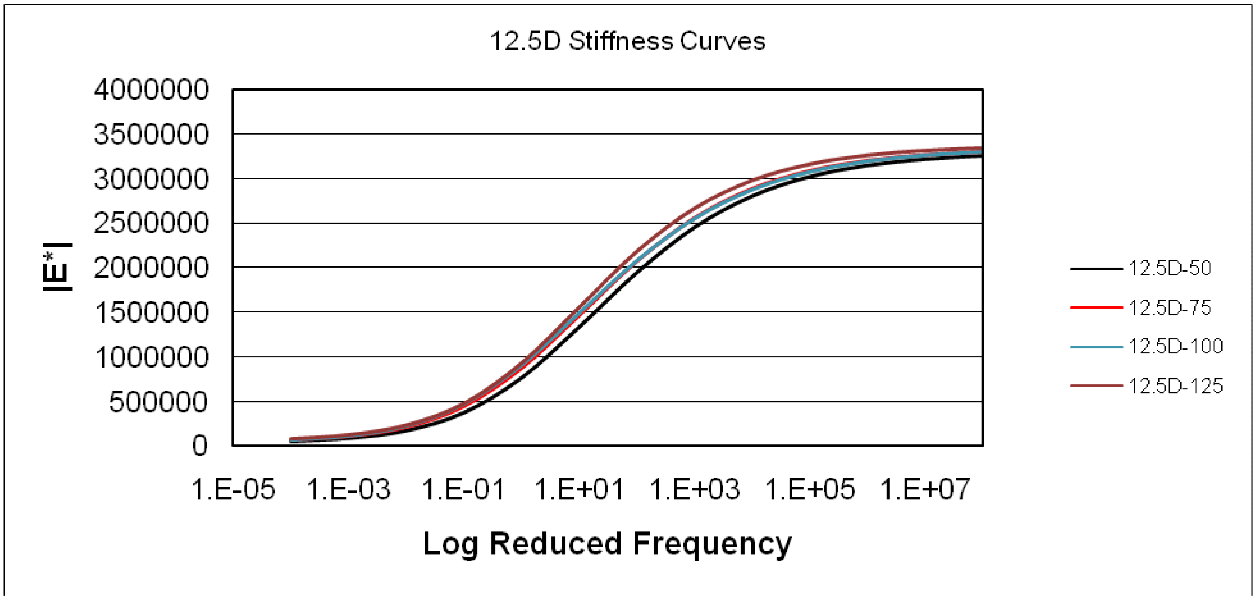

Figure 4.6 E* Master Curves at Different Gyration Levels for S9.5B Mix at 70^{0}F

4.2 Flow Number Results

Flow number testing was also performed as specified in AASHTO TP 79 and the results were compared to the rutting performance of the mixtures predicted using DARWin-ME. Two replicate samples with an air void content of 4% were prepared and tested for each mix type to verify the repeatability of the results. The tests were conducted at a temperature of 54 ^{0}C and the results are displayed in Table 4.7.

Table 4.7 Flow Number Test Results for All Surface Mixtures

No. of Gyrations	S9.5 A	S9.5B	S9.5C	S9.5D	S12.5C	S12.5D
50	205	304	661	1895	629	1169
75	296	525	784	3163	1082	4554
100	453	644	930	4765	2325	7502
125	600	783	1066	6456	2702	8973

Flow number testing was performed to characterize the mixtures and quantify their susceptibility to permanent deformation. As observed from the experimental results, the flow number values increase as the compaction effort is increased. It was also observed that as the binder grade increases the flow number values increase. Increasing the number of gyrations improves the stiffness of the specimen through better bonding and aggregate interlocking, thus the permanent deformation is reduced. In addition, as the high-temperature PG grade increases, the stiffness of the binder, and consequently the stiffness of the asphalt concrete specimen is improved resulting is reduced rutting of the mix. These results reinforce the observed trends in the variation of predicted rutting performance of the mixtures.

Apart from the trends in the measured flow numbers, the magnitude of flow number results for mixes S9.5D and S12.5D were observed to be significantly higher than those of the other mixtures. This is due to the use of PG 76-22 binder which resists rutting much better than the lower PG binder grades used in other types of surface mixes. Therefore, relative performance with respect to rutting and fatigue can be optimized such that fatigue resistance is improved by reducing the Ndesign value while still maintaining the rutting potential of the mix. This factor was also considered while developing recommendations for optimum Ndesign value for D-level mixes.

4.3 DARWin-ME Analysis Results

Dynamic modulus (E*) is a fundamental material property used to characterize an asphalt concrete mixture and is incorporated into the mechanistic-empirical pavement design procedure as a key parameter that correlates material properties to fatigue cracking and rutting performance. DARWin-ME design guide, which has recently been adopted by the industry as the primary tool for pavement design and performance prediction, was used in this research to investigate the fatigue and rutting performances of the mixtures involved in this study. Table 4.8 displays the fatigue and rutting performances of all the mixtures. The performances are defined as the number of truck to reach failure with respect to a particular distress, where the failure limits are defined as 10% cracking of the total area for fatigue and 0.75” permanent deformation in the AC layer for rutting.

Table 4.8 Average Fatigue and Rutting Performance of All Mixtures (in Number of Trucks to Failure)

Mix Type	No. of Gyrations	% Asphalt Content (by weight of mix)	Fatigue Performance	Rutting Performance
S9.5A	50	6.0	1662830	1556010
	75	5.77	1539390	1726000
	100	5.56	1451160	1858550
	125	5.4	1363790	1928600
S9.5B	50	6.13	2892910	2494240
	75	5.72	2511410	2892910
	100	5.43	2275750	3288750
	125	5.21	2029510	3417750
S9.5C	50	5.95	2749150	2155250
	75	5.61	2448840	2406540
	100	5.37	2448840	2814300
	125	5.18	2321950	3056330
S9.5D	50	5.9	4898700	7739820
	75	5.6	4703320	9747720
	100	5.4	4313830	9967750
	125	5.25	4122280	10187800
S12.5C	50	5.71	2258920	1766980
	75	5.41	2175980	2258920
	100	5.2	2093040	2533440
	125	5.03	1949530	2641290
S12.5D	50	5.47	3990000	3490000
	75	5.18	3550000	3930000
	100	4.97	3240000	3990000
	125	4.81	2860000	4190000

The predicted fatigue and rutting life for different mixes show that there is a high degree of variability in the magnitude of trucks to failure. In order to optimize the rutting and fatigue performance simultaneously, it is necessary that the predicted performance data should be in similar order of magnitude. In that case, the optimum performance can be identified as the intersection point of the prediction performance curves for fatigue and rutting plotted versus the number of gyrations. However, due to the difference in magnitude of the predicted performance values, additional parameters called "Relative Performance (RP)" were defined for both distresses and the calculated relative performance values were used to conduct further analysis, as explained in Section 5.

5. ANALYSIS

Superpave mix design is the most commonly used method for design of asphalt concrete mixtures to achieve the desired performance in the field. This approach involves the selection of an aggregate gradation and binder content that meet rigorous volumetric requirements based on the mix type, binder grade, and the expected traffic load which relates the compaction effort in terms of the number of gyrations. After selection of the aggregate gradation that satisfy the required volumetric criteria at a trial asphalt content, specimens are prepared at various asphalt contents by compacting them to the appropriate number of gyrations; the air voids are then measured and plotted versus the binder content. From this plot, the asphalt content that corresponds to 4% air voids when the mix is compacted to Ndesign gyrations is determined as the optimum binder content. The concept of design gyrations, Ndesign, was developed in the early 1990s as part of the SHRP program; however, more recent studies have raised concerns that these values do not optimize pavement performance. As performance with respect to field distresses is not explicitly considered in the design process, performance testing is necessary to evaluate the asphalt concrete mix.

Pavement performance evaluation can be done in many ways, and the appropriate approach is chosen depending on the objective and expected outcome of a project. To evaluate mixture performance for this project, dynamic modulus $|E^*|$, which is a fundamental mix property was selected as the input for analysis. Dynamic Modulus is one of the primary input parameters of mechanistic-empirical flexible pavement design procedures such as DARWin-ME software used by many agencies including NCDOT. $|E^*|$ is used to characterize the material properties of asphalt mixtures and determine the stress strain responses of a pavement at different loading and environmental conditions. Also, it is a direct input parameter in several pavement performance models to estimate the fatigue cracking and rutting performances of field mixtures.

Mixture stiffness is an extremely important aspect of pavement design; it depends on the air void and asphalt contents of the mix, and it has a significant effect on the fatigue performance of the pavement. Mixes with higher asphalt content exhibit lower fatigue cracking compared to those with lower asphalt content due to improved flexibility imparted by excess binder in the mix. To improve the durability of a pavement in terms of fatigue, it is necessary to enhance the flexibility to allow it to withstand more loading, which can be achieved by increasing the asphalt content while keeping other volumetric properties constant. This method was utilized to investigate the effect of reducing compaction levels on pavement performance. In this study, Superpave mix design was conducted for six different surface mixes (S9.5A, S9.5B, S9.5C, S9.5D, S12.5C, and S12.5D) using Ndesign levels of 50, 75,100 and 125 and the optimum asphalt content was determined for each mixture at every Ndesign level. Dynamic modulus specimens were then prepared at the optimum asphalt content, using a constant gradation for each mix to an air void content of 4% and tested using the Asphalt Mixture Performance Tested (AMPT) device to obtain the dynamic modulus values. With asphalt content in the mix being the only variable, the E* master curves for specimens compacted to different Ndesign levels are expected to follow the trend as shown in Figure 5.1.

Figure 5.1 Expected Trend of Dynamic Modulus Curve at Different Ndesign Levels

As the asphalt content increases, or equivalently, as the number of design gyrations on the SGC decreases, the asphalt mixtures may exhibit more rutting but the fatigue resistance of the asphalt mixture will increase. Rutting is generally measured in millimeters (or inches) and fatigue cracking is measured as a percentage of the total pavement area cracked. Hence, rutting and fatigue cracking should be expressed in terms of a parameter suitable for comparing the two distresses. The ultimate goal is to identify an optimum number of design gyrations such that the resulting asphalt mixture exhibits optimum performance with respect to both rutting and fatigue cracking.

Therefore, two new performance indicators to measure the Relative Performance (RP) for rutting and fatigue are defined as follows:

$$RP = \frac{P_{Ndesign=i}}{P_{Ndesign=ControlLimit}}$$

Where,

RP= Relative Performance for a specific distress

$P_{Ndesign=i}$ is the performance at *i* Ndesign gyrations

$P_{Ndesign=Control\ Limit}$ is the performance at a specific base Ndesign gyrations. The base Ndesign is selected as the value at which the mixture exhibits the best performance with respect to that distress

The performance of the mix at *i* Ndesign gyrations with respect to fatigue cracking or rutting is the number of cycles to failure with respect to that distress. The values of *i* in this equation are the gyration levels used as Ndesign values for specimen preparation, i.e. *i* = 50, 75, 100 and 125.

The control limit or "base" number of design gyrations is defined as 50 for fatigue resistance because the asphalt mixtures compacted at Ndesign = 50 gyrations contain the highest asphalt binder and thus, exhibit the highest fatigue resistance. The relative performance equation for fatigue cracking therefore becomes:

$$RP_{Fatigue} = \frac{P_{Ndesign=i}}{P_{Ndesign=50}}$$

For rutting, the "base" number of design gyrations is set as 125 because the asphalt mixtures compacted at Ndesign = 125 gyrations result in the highest rutting resistance. Therefore, the relative performance equation for rutting can be written as:

$$RP_{Rutting} = \frac{P_{Ndesign=i}}{P_{Ndesign=125}}$$

After establishing standardized performance indicators which allow comparison between rutting and fatigue cracking, relative performance curves - plots of relative performance with respect to both rutting and fatigue versus the number of design gyrations were plotted. The relative performance with respect to fatigue cracking ($RP_{Fatigue}$) is equal to 1 at an Ndesign value of 50 gyrations and decreases with an increase in the Ndesign value. On the contrary, the relative performance with respect to rutting ($RP_{Rutting}$) is equal to 1 at Ndesign of 125 gyrations, and decreases with the number of gyrations. Table 5.1 shows the calculated relative performance values with respect to the maximum performance for all mixtures used in this study.

Table 5.1 Relative performance of mixtures at different design gyrations

Mix Type	PG Grade	%AC	Ndesign	Relative Performance	
				Fatigue	Rutting
S9.5A	PG 64-22	6.0	50	100%	79%
	PG 64-22	5.77	75	93%	87%
	PG 64-22	5.56	100	87%	94%
	PG 64-22	5.7	125	83%	100%
S9.5B	PG 64-22	6.13	50	100%	74%
	PG 64-22	5.72	75	87%	86%
	PG 64-22	5.43	100	79%	95%
	PG 64-22	5.21	125	70%	100%
S9.5C	PG 70-22	5.95	50	100%	70%
	PG 70-22	5.61	75	92%	78%
	PG 70-22	5.37	100	88%	94%
	PG 70-22	5.18	125	84%	100%
S9.5D	PG 76-22	5.9	50	100%	78%
	PG 76-22	5.6	75	96%	96%
	PG 76-22	5.4	100	88%	97%
	PG 76-22	5.25	125	85%	100%
S12.5C	PG 70-22	5.71	50	100%	68%
	PG 70-22	5.41	75	96%	86%
	PG 70-22	5.2	100	92%	96%
	PG 76-22	5.03	125	85%	100%
S12.5D	PG 76-22	5.74	50	100%	84%
	PG 76-22	5.18	75	89%	95%
	PG 76-22	4.97	100	81%	96%
	PG 76-22	4.81	125	73%	100%

Once the relative performance values for each distress are calculated, these values are then plotted versus the asphalt content to determine the binder content that optimizes the pavement performance with respect to both distresses as shown in the illustrative example in Figure 5.2. The number of gyrations for the specific mixture is then determined from the plot of asphalt content vs. gyrations as shown in Figure 5.3.

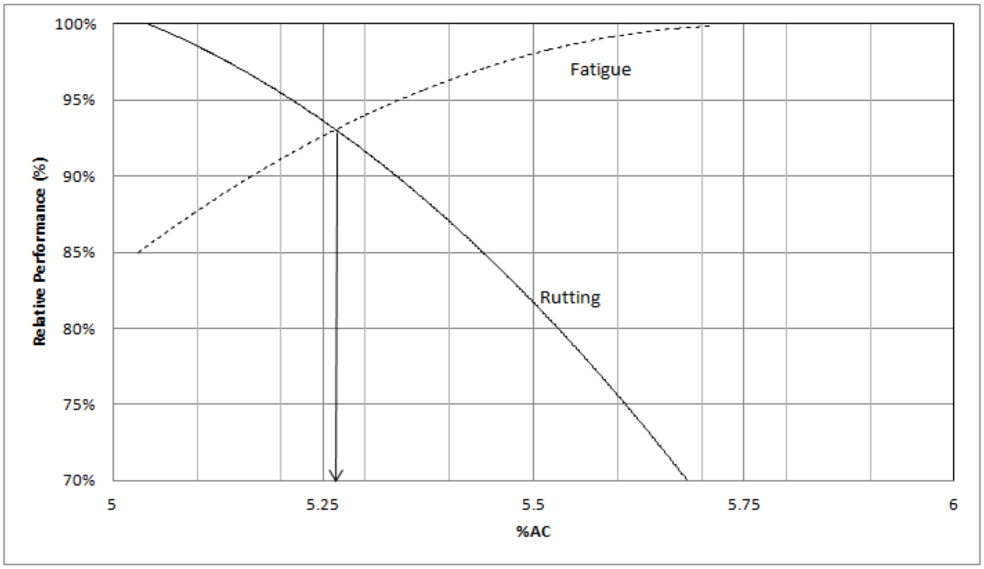

Figure 5.2 Relative Performance versus Asphalt Content - Illustration

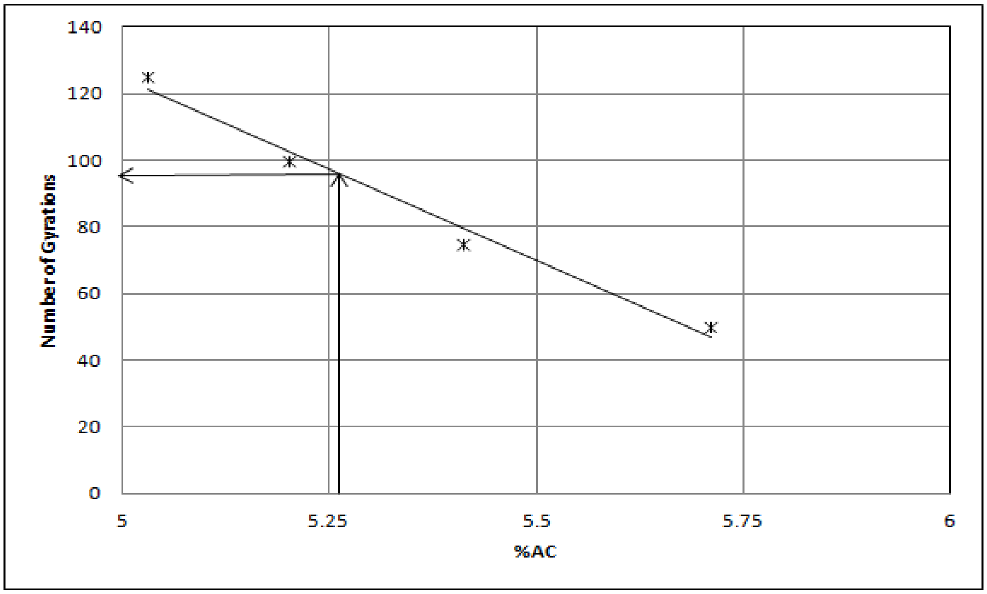

Figure 5.3 Number of Gyrations versus Asphalt Content - Illustration

The current version of the Mechanistic-Empirical design guide, DARWin-ME, was used to predict the number of load repetitions to failure (used as the measure of performance) in both rutting and fatigue. Model pavement sections were assumed for the analysis, which primarily consisted of an asphalt concrete layer on top of a granular base course, the third layer being the subgrade. The input parameters used for the pavement sections are given in **Appendix D**. The properties of the asphalt concrete layer were varied according to the measured volumetric properties for each surface mix type, and the base and subgrade modulus values were also selected accordingly. The failure criteria for analysis were selected as ¾" deformation in the surface layer for rutting, and greater than 10% surface cracking for fatigue.

After calculating the relative performance values, different reliability levels were assigned to the fatigue and rutting performances. By doing so, the reliability could be increased in terms of expected fatigue, rutting or both. The reliability of each distress can be selected independently; hence individual weightage can be assigned to one distress without compromising the overall pavement performance. For this study, two reliability levels, 70% and 90%, were chosen to demonstrate the effect of statistical reliability on the intersection point of the relative performance curves. However, due to the lack of variability in the predicted performance of the mixtures, the reliability curves are in general very similar to the average curves, thus the results presented within this report are based on the average curves.

5.1 Analysis of Relative Performance Data for S9.5A Mix

Using the test methods and analysis tools described earlier, the relative performance values for mixture S9.5A were calculated as shown below in Table 5.2. The relative performance for rutting and fatigue were also calculated at reliability levels of 70% and 90%, and plotted against the asphalt content in the mix as shown below in Figure 5.4.

Table 5.2 Relative Performance Data for S9.5A Mix

Mix Type	PG Grade	%AC	Ndesign	Relative Performance	
				Fatigue	Rutting
S9.5A	PG 64-22	6.0	50	100%	79%
	PG 64-22	5.77	75	93%	87%
	PG 64-22	5.56	100	87%	94%
	PG 64-22	5.7	125	83%	100%

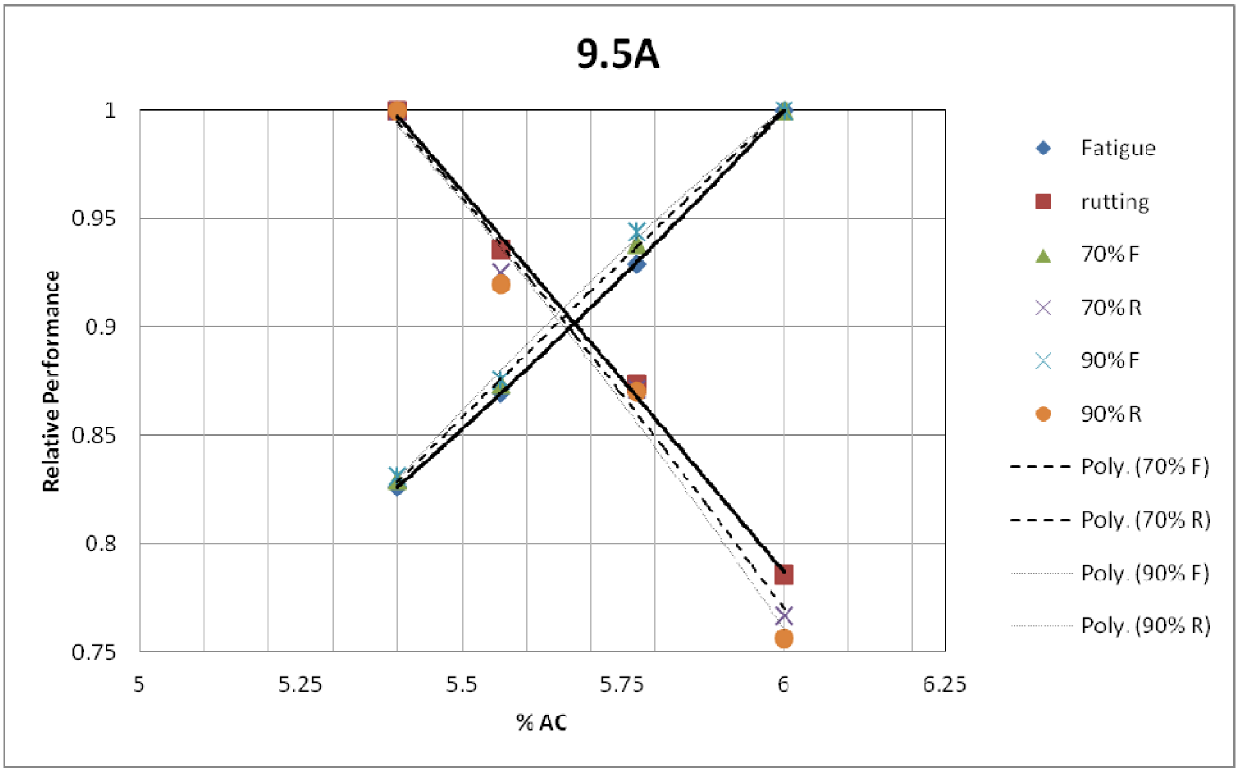

Figure 5.4 S9.5A Mixture Relative Performance versus Asphalt Content

Since the curves at different reliability levels do not show significant variability in the calculated relative performance, the curves representing the average values (50% reliability) were used for calculating the optimum asphalt content. The optimum number of gyrations was then determined from the plot of asphalt content versus gyrations. The percentage asphalt content that optimizes both rutting and fatigue for mixture S9.5A is determined to be 5.67% which corresponds to an Ndesign value of **85 gyrations** as shown in Figure 5.5 below.

The optimum number of gyrations obtained for the S9.5A mixture is significantly higher than the Ndesign value of gyrations currently in use by NCDOT. Compared to the original design gyrations for this mix, 85 gyrations improve rutting performance by roughly 15% while fatigue performance is reduced by 10%.

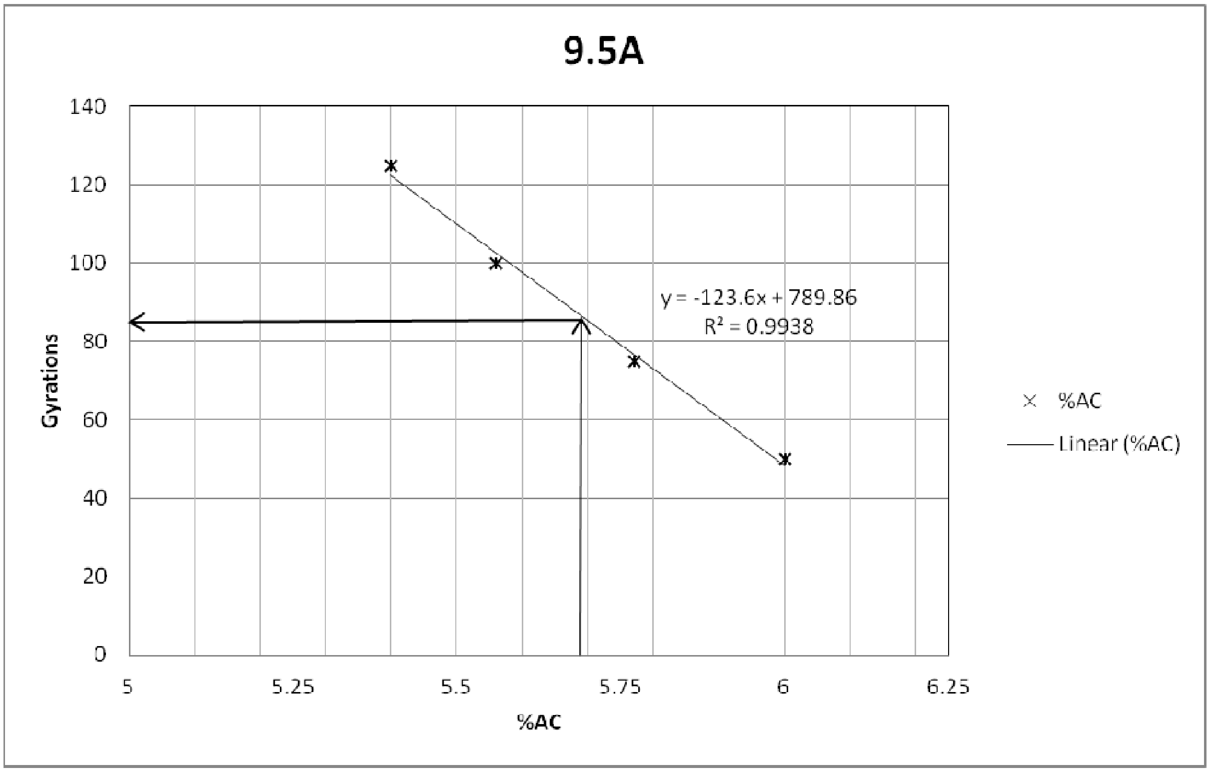

Figure 5.5 Number of Gyrations versus Asphalt Content for S9.5A Mix

Using the relative performance concept to determine the optimum number of gyrations means that the values of each distress are based on the highest observed performance. Therefore, if the difference in magnitude of relative performance values is high, the relative performance slopes will be different than those results with low variability. This dependence on the variability of the results severely impacts the intersection point of the best fit lines, which represents the optimum number of gyrations. The variability in relative performance is dependent on the methods and analysis procedures applied to obtain the results.

Figure 5.6 shows relative performance curves based on fatigue and rutting predicted using the E* results from dynamic modulus testing of mixtures. Figure 5.7 shows relative performance curves based on fatigue and rutting of mixtures tested using Beam Fatigue Test and Hamburg Wheel Test, respectively. In this study, using the dynamic modulus data and DARWin-ME to perform the analysis, the fatigue relative performance ranges between 100% and 83% and for rutting it is between 79% and 100%. In a similar study using beam fatigue test and Hamburg wheel tracking device for fatigue and rutting analysis respectively (*6*), fatigue relative performance varied from

100% to 21% with a difference in magnitude of roughly 80%, while rutting performance varied from 68% and 100%.

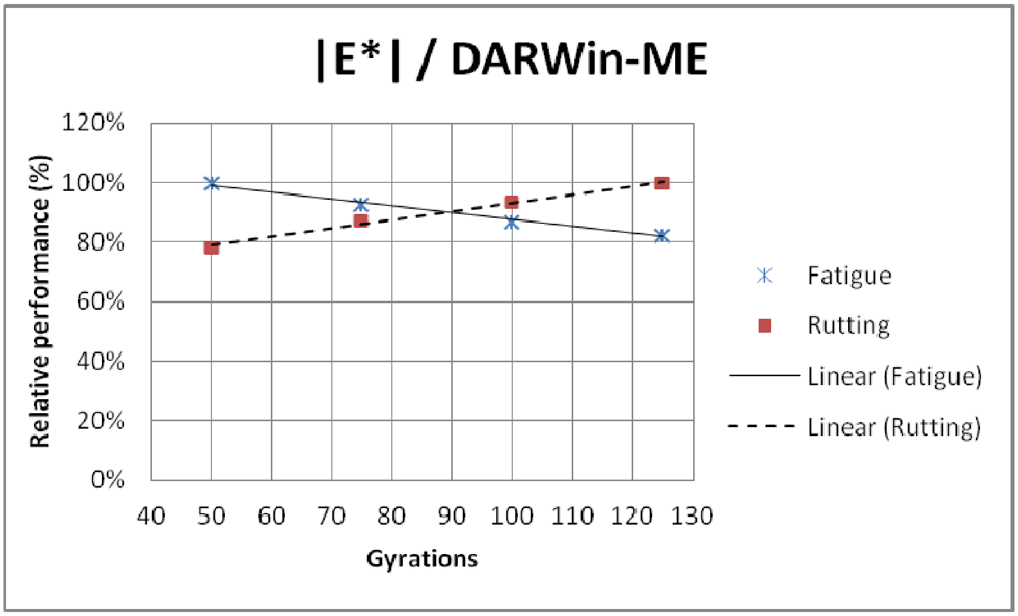

Figure 5.6 Relative Performance Variation using E* Test Results

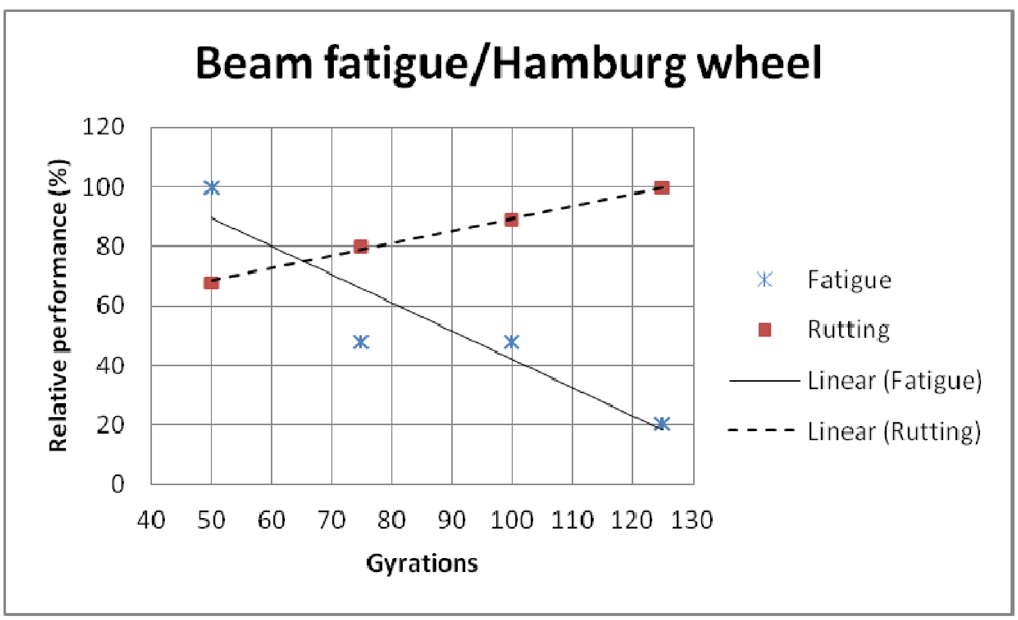

Figure 5.7 Relative Performance Variation Using Beam Fatigue/Hamburg Wheel Test Results

The calculated Ndesign is significantly higher than the current NCDOT value of 50 gyrations. Therefore, further analysis of the relative performance at Ndesign values other than the calculated optimum was conducted to identify a practically applicable Ndesign for S9.5A mix.

5.2 Analysis of Relative Performance Data for S9.5B Mix

The relative performance values for S9.5B mix were calculated from the predicted rutting and fatigue performance using the DARWin-ME. Table 5.3 shows the relative performance values for mixture S9.5B mix.

Table 5.3 Relative Performance Data for S9.5B Mix

Mix Type	PG Grade	%AC	Ndesign	Relative Performance	
				Fatigue	Rutting
S9.5B	PG 64-22	6.13	50	100%	74%
	PG 64-22	5.72	75	87%	86%
	PG 64-22	5.43	100	79%	95%
	PG 64-22	5.21	125	70%	100%

The results show that the variability in relative performance with the number of design gyrations is higher than S9.5A for both rutting and fatigue cracking. Figure 5.8 shows the relative performance curves plotted versus the asphalt content.

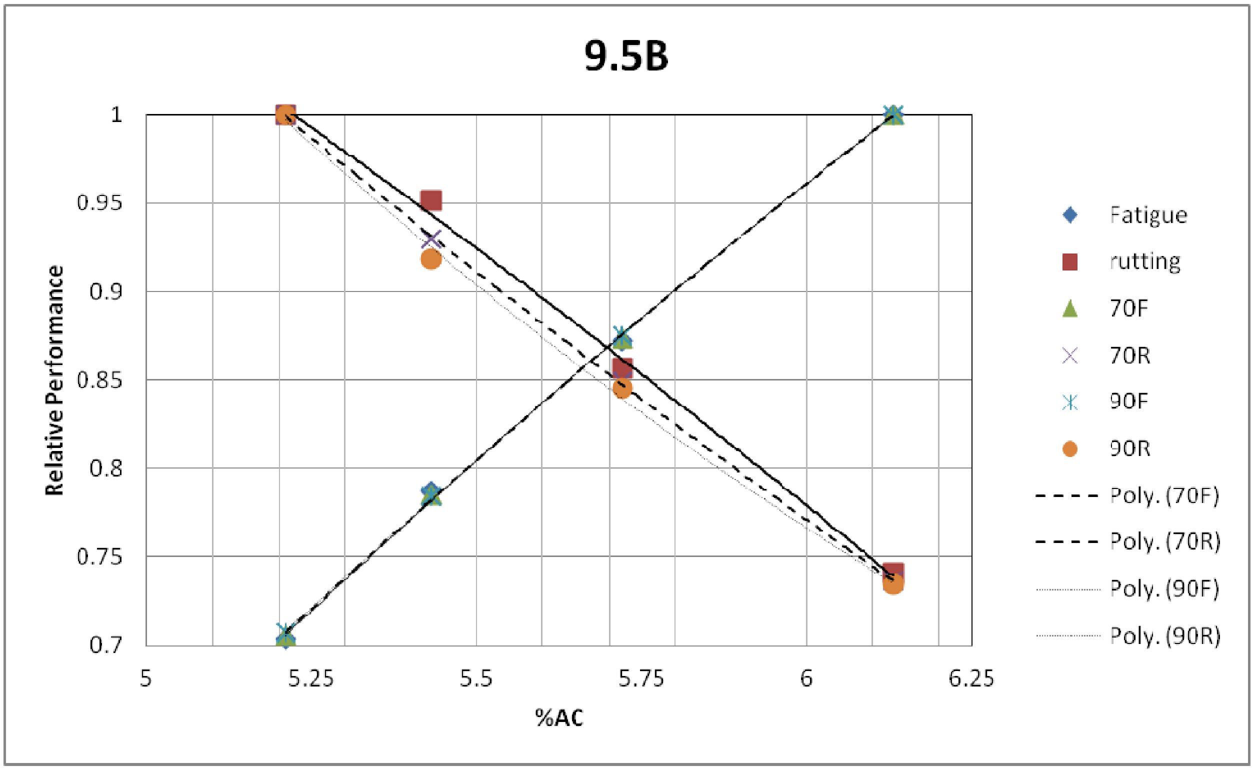

Figure 5.8 S9.5B Mixture Relative Performance versus Asphalt Content

From the above plot, the asphalt content that optimizes mixture performance is calculated to be 5.69%. This value is then substituted in the asphalt content and gyration plot as shown in Figure 5.9 to estimate the optimum Ndesign value, which was determined to be **82 gyrations**.

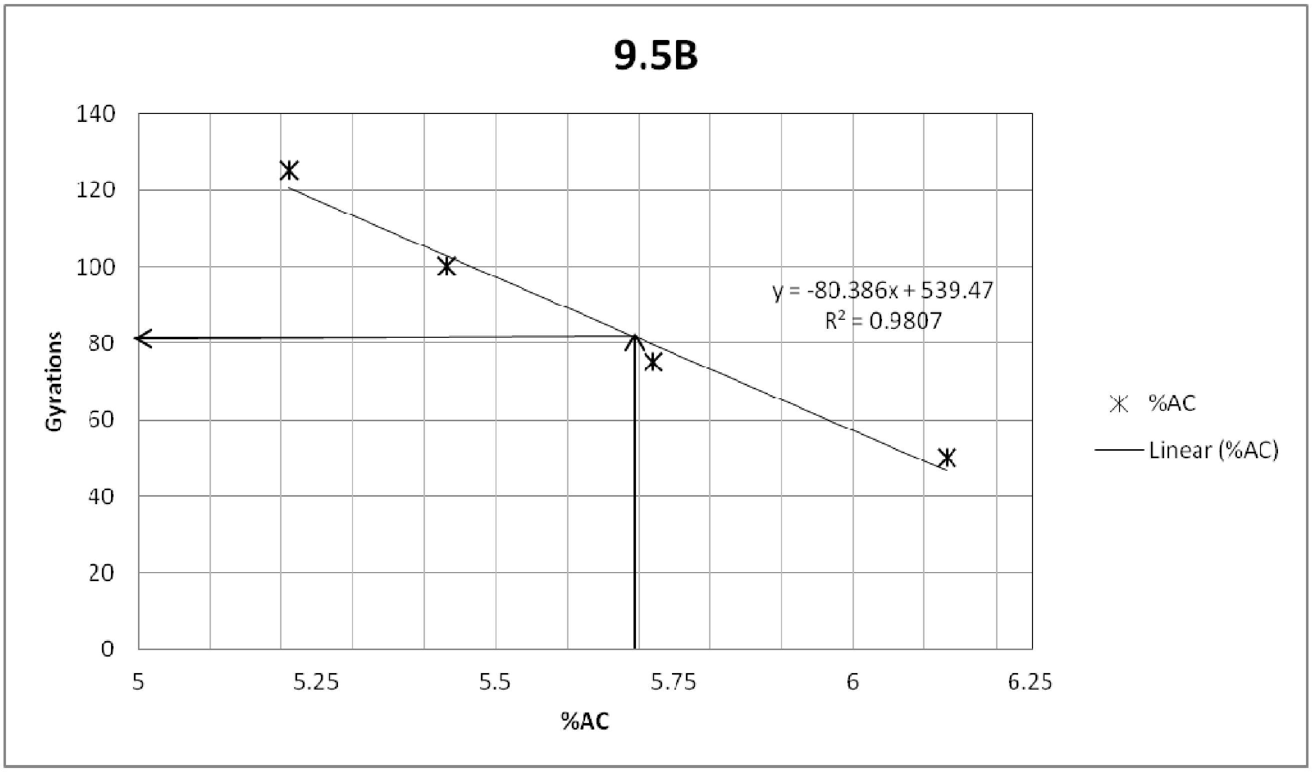

Figure 5.9 Number of Gyrations versus Asphalt Content for S9.5B Mix

The calculated optimum Ndesign for S9.5B mix is also higher than the current NCDOT specified level of 65 gyrations. This behavior can be attributed to the dependency on test procedure and approach used to measure relative performance, as explained in Section 5.1. Therefore, further analysis of the relative performance at Ndesign values other than the calculated optimum, including the current Ndesign specification was conducted to identify a practically applicable Ndesign for S9.5B mix.

5.3 Analysis of Relative Performance Data for S9.5C Mix

Based on the dynamic modulus and DARWin-ME analysis, the relative fatigue and rutting performance results for mixture S9.5C were calculated and tabulated as shown below in Table 5.4.

Table 5.4 Relative Performance Data for S9.5C Mix

Mix Type	PG Grade	%AC	Ndesign	Relative Performance	
				Fatigue	Rutting
S9.5C	PG 70-22	5.95	50	100%	70%
	PG 70-22	5.61	75	92%	78%
	PG 70-22	5.37	100	88%	94%
	PG 70-22	5.18	125	84%	100%

Figure 5.10 shows the relative performance curves for S9.5C mix. The variability in relative performance at different reliability levels was observed to be higher for the S9.5C mix as compared to S9.5A and B mixes. However, the optimum asphalt content for optimizing the mixture performance was calculated using the average curves as 5.43%.

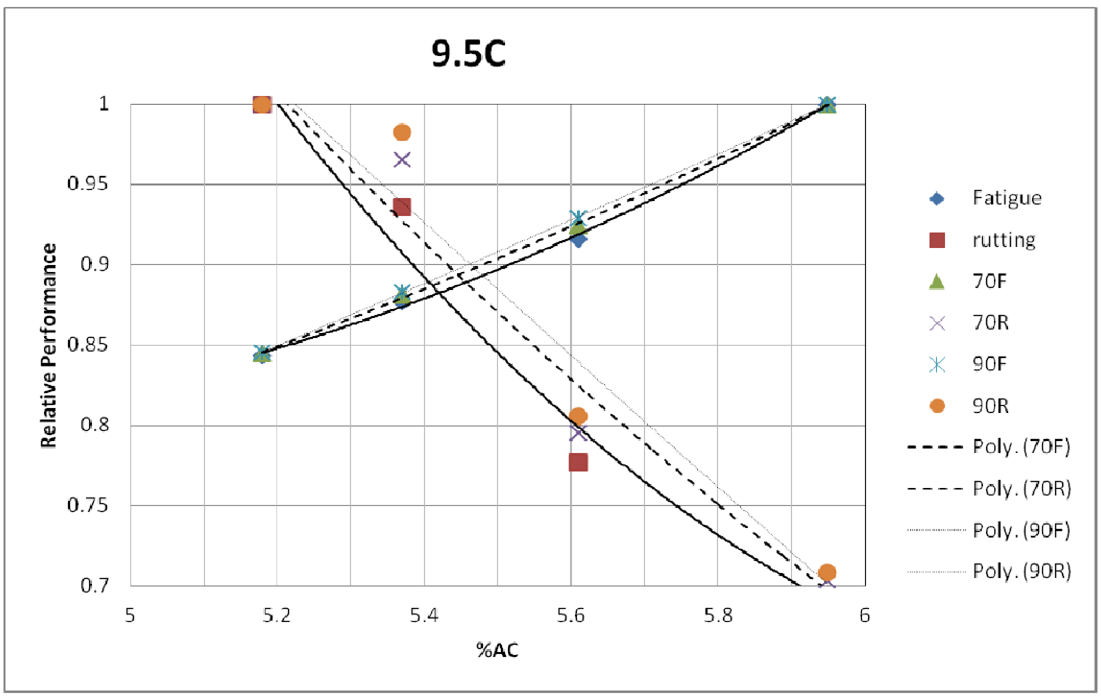

Figure 5.10 S9.5C Mixture Relative Performance versus Asphalt Content

To determine the optimum number of gyrations, the value corresponding to an asphalt content of 5.43% was calculated from the plot of gyrations versus asphalt content shown below in . The optimum Ndesign value calculated for S9.5C mix is **97 gyrations**.

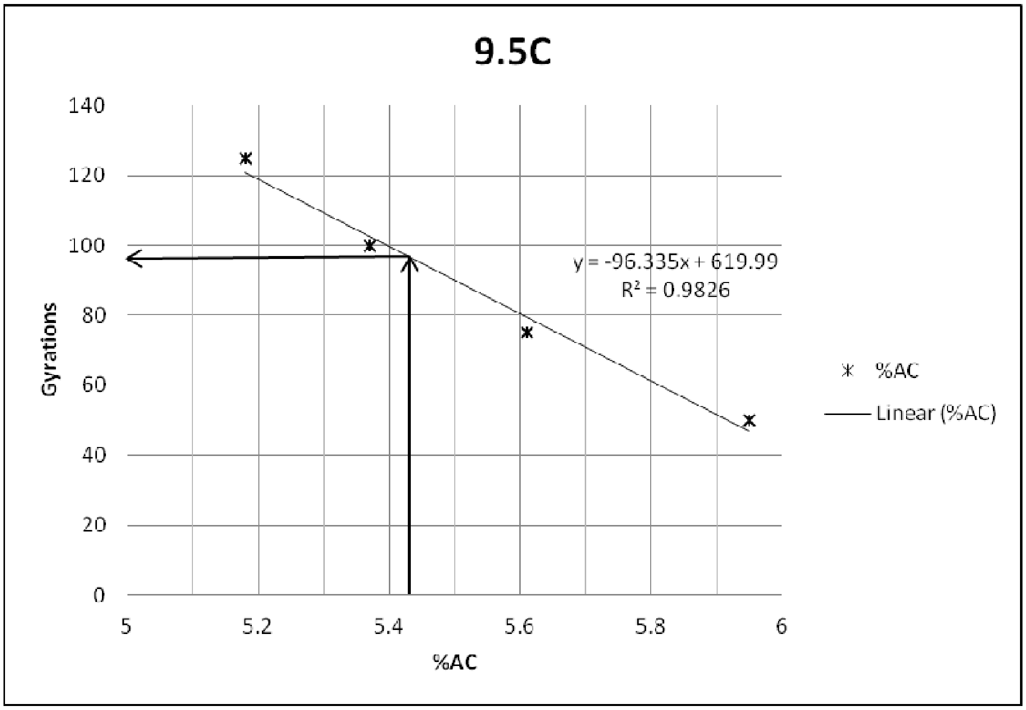

Figure 5.11 Number of Gyrations versus Asphalt Content for S9.5C Mix

The relative performance calculated for S9.5C mix show that the increases stiffness of the mix leads to lower variability in the observed fatigue cracking performance with variation in the design gyrations. This can be attributed to the use of a stiffer binder (PG 70-22) for the S9.5C mix as compared to the S9.5A and B mixes, which use PG 64-22. Therefore, the selection of the optimum Ndesign has a greater impact on the rutting life of the mix as compared to fatigue failure. This factor was considered in developing recommendations for the optimum Ndesign value to be used for S9.5C mixes, because a very low Ndesign can lead to a mix that is highly susceptible to rutting.

5.4 Analysis of Relative Performance Data for S9.5D Mix

The results for mixture S9.5D are presented below in Table 5.5. The relative performance results show that the fatigue performance decreases rapidly from 96% to 85% with increase in the number of gyrations from 75 to 125, whereas the rutting is not affected significantly. Therefore, a lower Ndesign value for S9.5D mix leads to better resistance of the mix to fatigue cracking without affecting its rutting susceptibility.

Table 5.5 Relative Performance Data for S9.5D Mix

Mix Type	PG Grade	%AC	Ndesign	Relative Performance	
				Fatigue	Rutting
S9.5C	PG 76-22	5.9	50	100%	78%
	PG 76-22	5.6	75	96%	96%
	PG 76-22	5.4	100	88%	97%
	PG 76-22	5.25	125	85%	100%

Figure 5.12 shows the relative performance curves for S9.5D mix. There was no observed deviation in the rutting performance, but the predicted fatigue cracking values showed a moderate level of deviation from the expected trend. This could be due to experimental error in measuring the dynamic modulus of the mix at an Ndesign level of 75 gyrations.

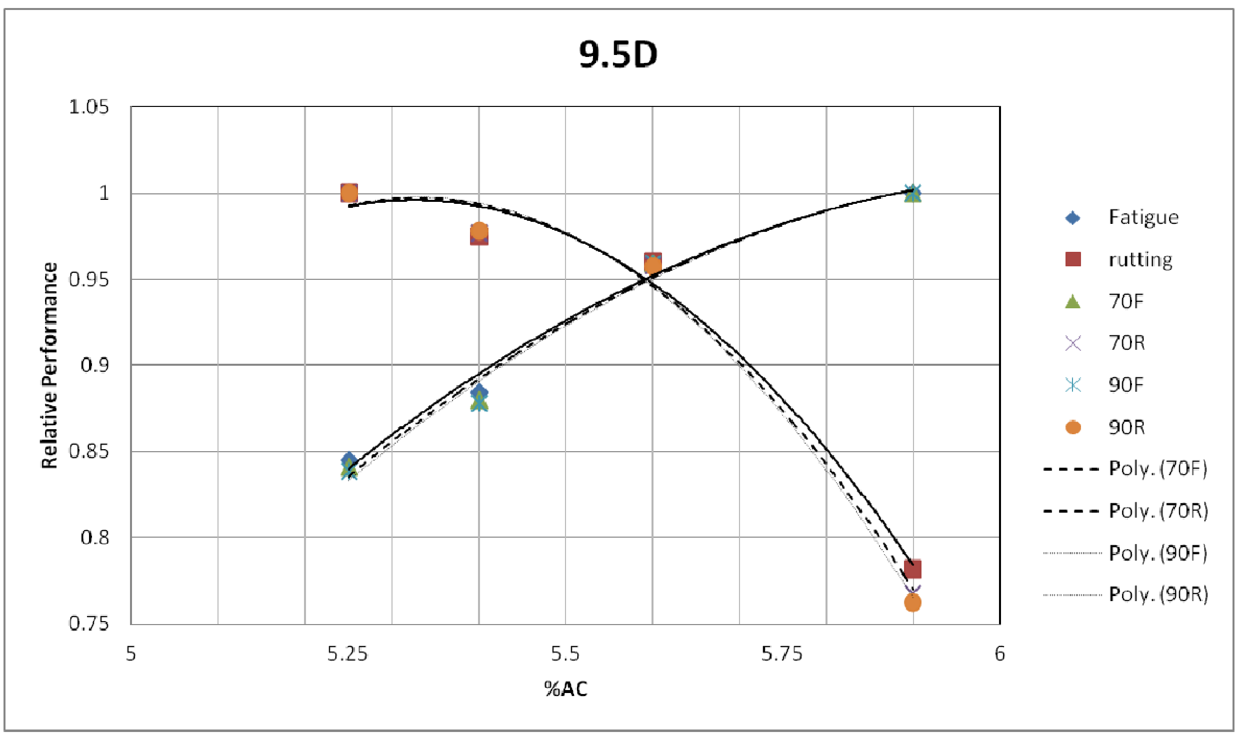

Figure 5.12 S9.5D Mixture Relative Performance versus Asphalt Content

The optimum number of design gyrations for S9.5D mix was determined from Figure 5.13 to be 5.6% which corresponds to 79 gyrations. The calculated Ndesign value is lower than the current NCDOT specification of 100 gyrations, but is consistent with the observed trend in relative performance curves for fatigue cracking as explained above.

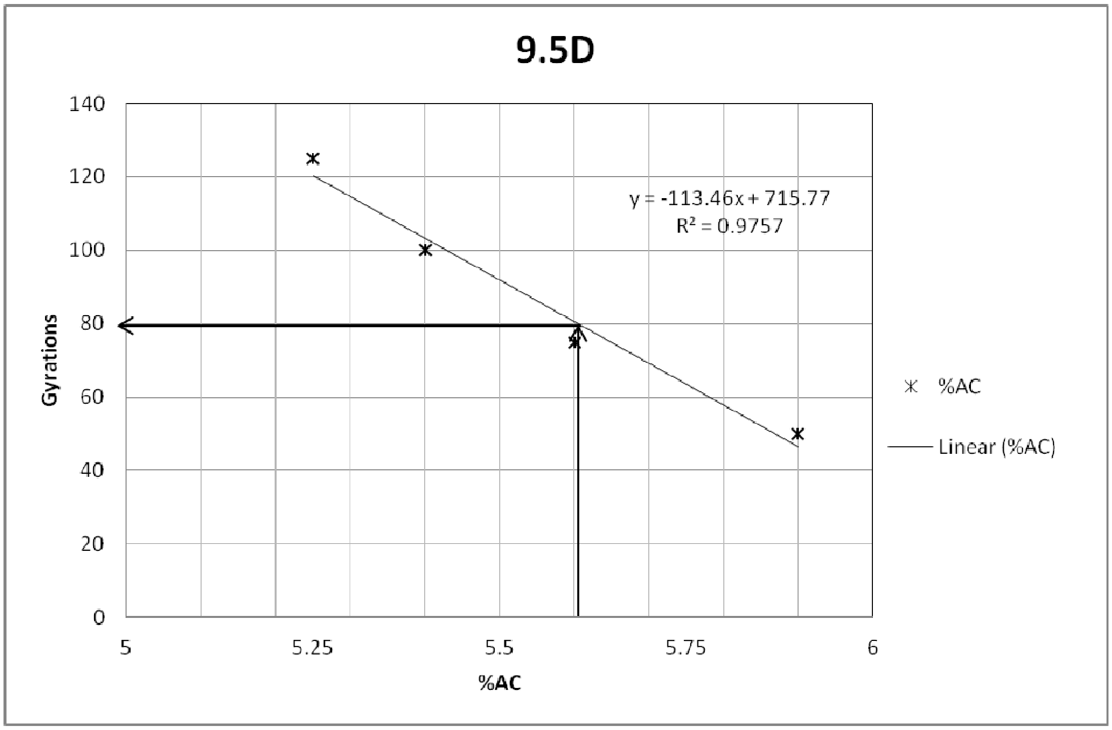

Figure 5.13 Number of Gyrations versus Asphalt Content for S9.5D Mix

5.5 Analysis of Relative Performance Data for S12.5C Mix

Table 5.6 below shows the relative performance values for S12.5C mixes. It can be observed from the relative performance values that the fatigue performance decreases at a relatively constant rate with an increase in the number of design gyrations. However, the rutting performance is very low at lower Ndesign values and increases rapidly with the number of gyrations.

Table 5.6 Relative Performance Data for S12.5C Mix

Mix Type	PG Grade	%AC	Ndesign	Relative Performance	
				Fatigue	Rutting
S9.5C	PG 70-22	5.71	50	100%	68%
	PG 70-22	5.41	75	96%	86%
	PG 70-22	5.2	100	92%	96%
	PG 70-22	5.03	125	85%	100%

The plot of relative performance versus asphalt content for this mix are shown below in Figure 5.14. It can be observed from the figure that rutting curves have a much steeper slope as compared to the fatigue curves.

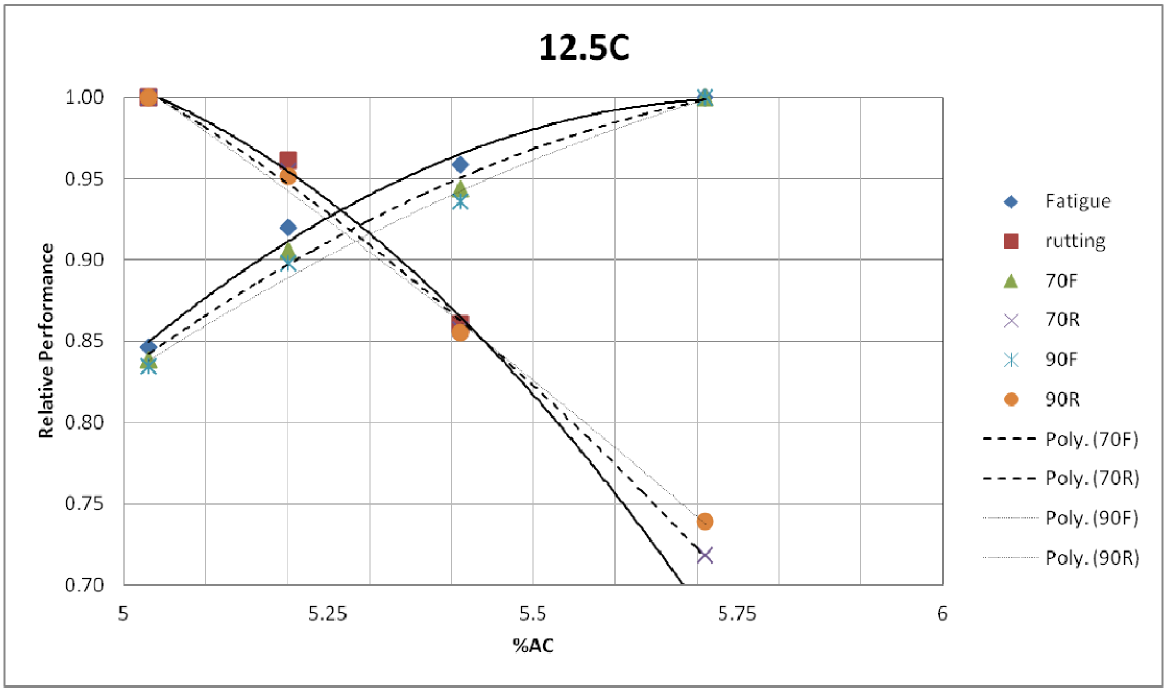

Figure 5.14 S12.5C Mixture Relative Performance versus Asphalt Content

The optimum asphalt content that optimizes mixture performance is calculated as 5.27%. The corresponding number of gyrations were calculated from Figure 5.15 as **95 gyrations**. The calculated Ndesign is higher than the current NCDOT specification of 75 gyrations for S12.5C mix because the optimization approach requires better improvement in rutting performance as compared to the fatigue performance.

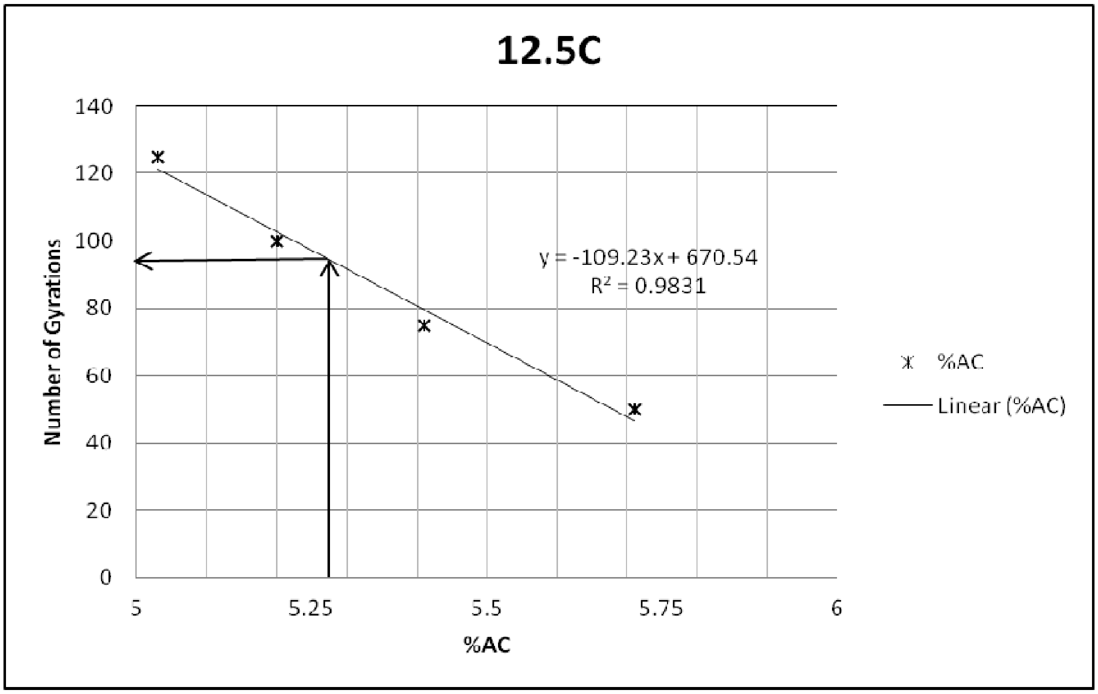

Figure 5.15 Number of Gyrations versus Asphalt Content for S12.5C Mix

5.6 Analysis of Relative Performance Data for S12.5D Mix

The relative performance values calculated for S12.5D mix are shown below in Table 5.7. The trends in relative performance values for both fatigue and rutting are similar to those observed for S9.5D mix. This similarity in mixture performance in both D level mixes could be due to the fact that both mixes use a virgin binder grade of PG 76-22.

Table 5.7 Relative Performance Data for S12.5D Mix

Mix Type	PG Grade	%AC	Ndesign	Relative Performance	
				Fatigue	Rutting
S9.5C	PG 70-22	5.71	50	100%	84%
	PG 70-22	5.41	75	89%	95%
	PG 70-22	5.2	100	81%	96%
	PG 70-22	5.03	125	73%	100%

The plot relative performance versus asphalt content for S12.5D mix is shown below in Figure 5.16.

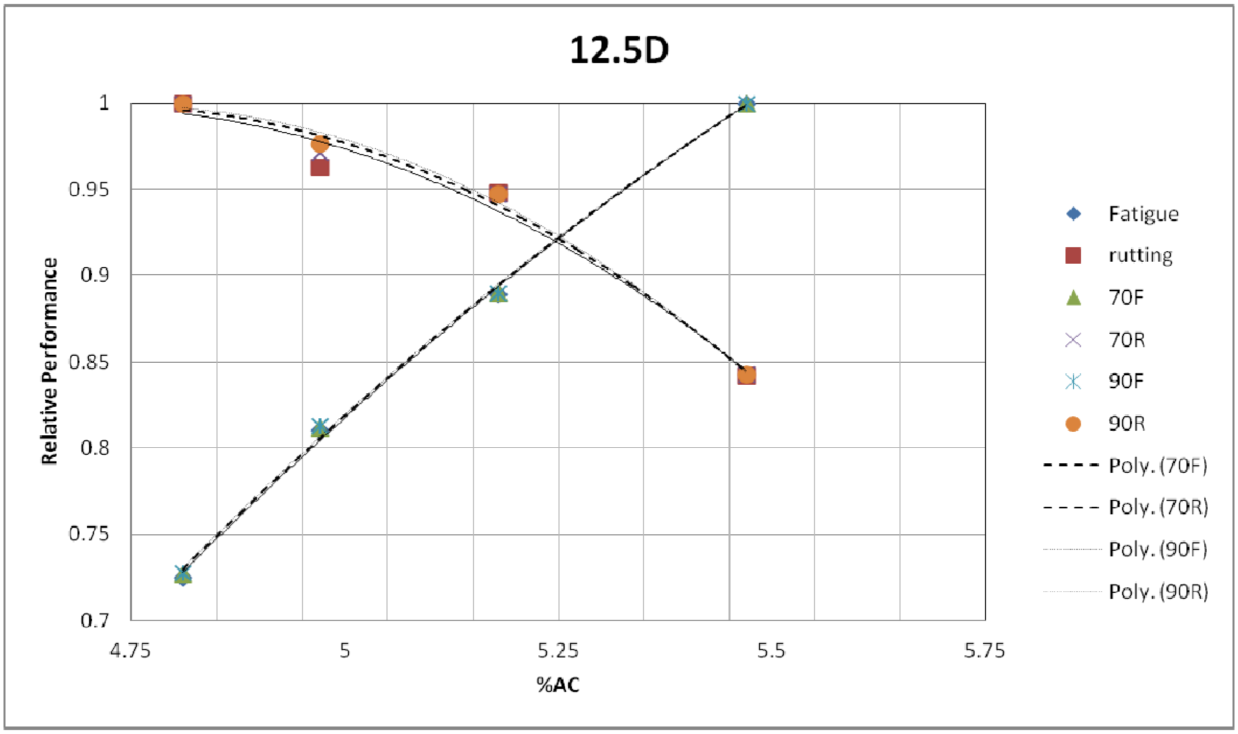

Figure 5.16 S12.5D Mixture Relative Performance versus Asphalt Content

The relative performance curves for both rutting and fatigue show a very good fit and no deviation is observed at any gyration level. This behavior supports the explained deviation in the relative fatigue performance curves for S9.5D at the 75 gyrations level.

The asphalt content corresponding to optimum mixture performance is equal to 5.25%. From Figure 5.17, the optimum number of gyrations is calculated as 72 gyrations. The calculated optimum is lower than the current NCDOT specification of 100 gyrations for S12.5D mix, which is primarily due to optimizing the mix performance to improve its fatigue resistance.

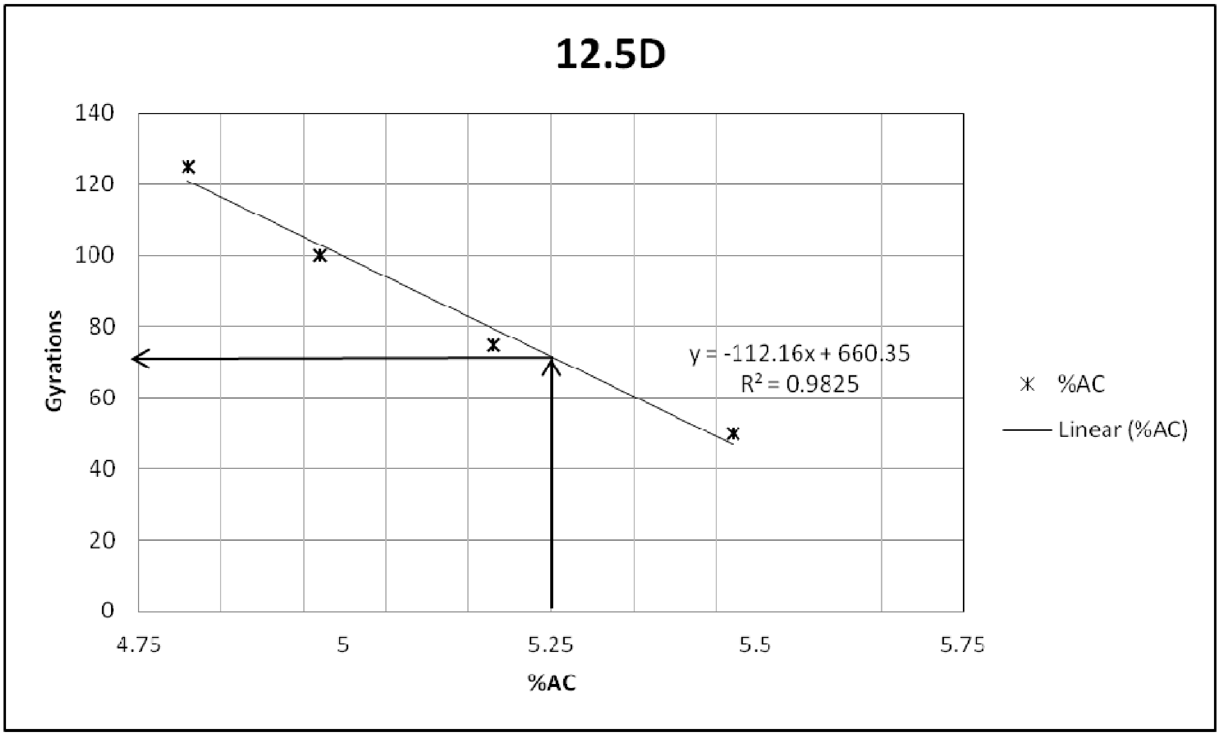

Figure 5.17 Number of Gyrations versus Asphalt Content for S12.5D Mix

5.7 Recommendations

The optimum number of gyrations calculated for different mixtures is observed to be a direct function of the binder grade used, i.e., surface mixtures with the same binder grade (PG 64-22, PG70-22, and PG76-22) have very similar optimum Ndesign values. Mixtures S9.5A and S9.5B with PG64-22 resulted in optimum number of gyration of 85 and 82, respectively. The optimum Ndesign value for mixtures S9.5C and S12.5C, both of which use a virgin binder grade of PG 70-22 was 97 and 95, respectively. For mixtures S9.5D and S12.5D which use a virgin binder grade of PG76-22, the optimum number of gyrations were 79 and 72, respectively. From these findings, it can be concluded that the performance of asphalt concrete mixtures is dependent to a large extent on the binder grade used in the mixing process. Therefore, the calculated values of optimum design gyrations for the surface mixes presented in the previous sections were modified to reflect the effect of the binder grade. The recommended design gyration level for surface mixes using PG 64-22 is 65, mixes using PG 70-22 and PG 76-22 is 85 gyrations. The recommendations for optimum design gyrations for different surfaces mixes are explained in detail in the subsequent sections.

5.7.1 ***Surface Mixes Containing Virgin Binder PG64-22*** In this section, recommendations for surface mixtures S9.5A and S9.5B, which use a virgin binder grade of PG 64-22 are explained.

5.7.1.1 Recommendations for S9.5A Mix

The optimum number of gyrations as determined by the intersection point of fatigue and rutting relative performance curves for this mix was 85 gyrations. Comparing the observed optimum gyrations with current NCDOT specification of 50 gyrations for this mix, the rutting is improved and the fatigue performance is decreased. However, rutting is not a major concern for pavements containing this mixture type due to the low design traffic volume for such pavements. In addition, it is generally accepted that Superpave mixes are relatively dry mixes that perform well with respect to rutting with the current compaction levels. To satisfy the objective of modifying the compaction levels to improve the performance and durability of the pavements, it is recommended to set the Ndesign level for this mix at 65 gyrations.

Figure 5.18 and Figure 5.19 show the relative performances of the original Ndesign value for this mix in the Superpave tables, the current NCDOT Ndesign, the calculated optimum value, and the recommended compaction level of both fatigue and rutting, respectively. The reduction in compaction effort from the calculated value of 85 gyrations to the recommended value of 65 gyrations improves the fatigue performance by 5% and reduces the rutting performance by 6%. However, when compared to the current Ndesign value in the NCDOT specification of 50 gyrations, fatigue resistance is decreased by 4% and rutting resistance is enhanced by 5%. Additionally, the reduction in the asphalt content from 6% by weight of mix at 50 gyrations to 5.86% by weight of mix at 65 gyrations is equivalent to cost savings due to a reduction of 2% by weight of total asphalt binder used in the mix. For a low traffic mix, a reduction of 4% in the fatigue performance is acceptable considering the improvement in the rutting resistance and the savings associated with the reduction in the amount of binder, which can be in the millions of dollars given the amount of paving NCDOT approves on a yearly basis and the ever increasing cost of asphalt.

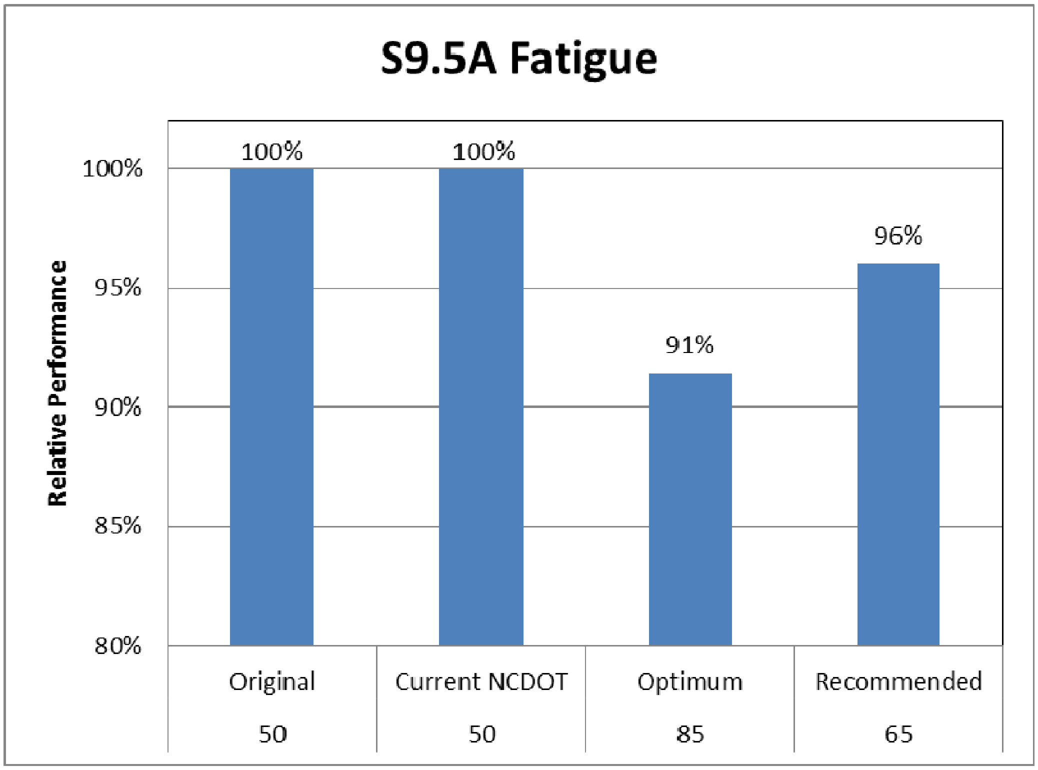

Figure 5.18 Relative Fatigue Performance at Different Gyration Levels for S9.5A Mix

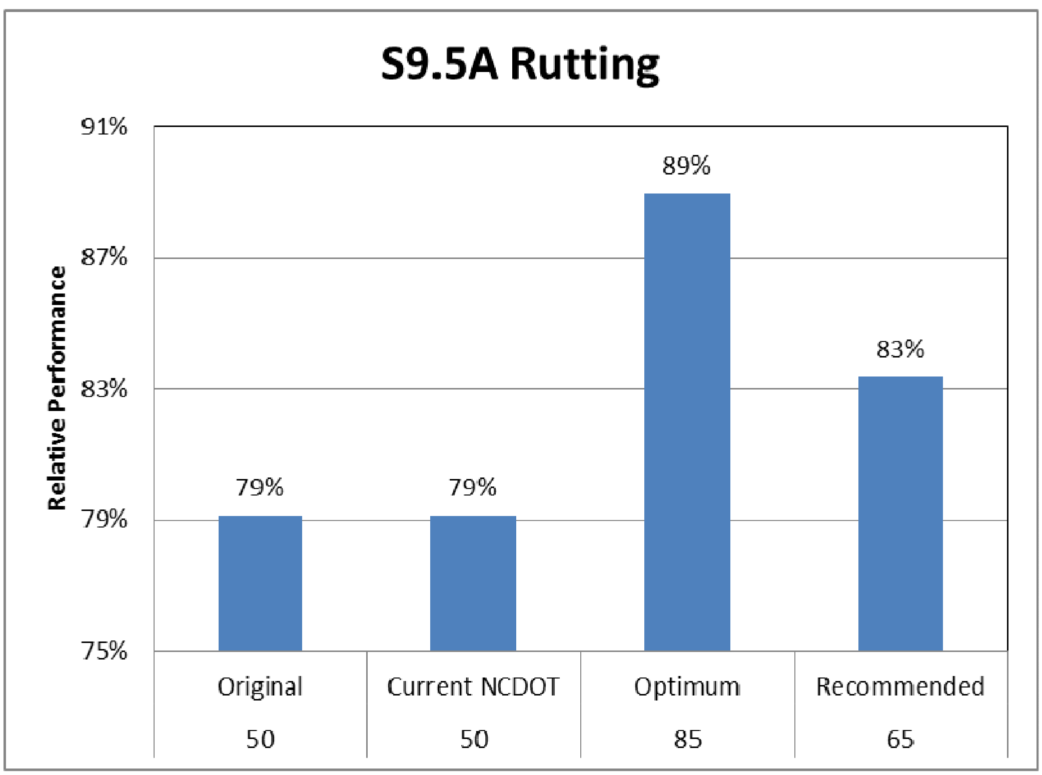

Figure 5.19 Relative Rutting Performance at Different Gyration Levels for S9.5A Mix

5.7.1.2 Recommendations for S9.5B Mix

The calculated optimum Ndesign value for S9.5B mixture is 82 gyrations. Compared to the current Ndesign value of 65 used by NCDOT, the rutting is slightly improved and the fatigue performance is reduced by the same amount. Fatigue cracking is a more severe distress mechanism observed in the state of North Carolina, as compared to rutting. Due to the emphasis on fatigue resistance, it is recommended to use the current NCDOT specified Ndesign value of 65 gyrations for this mix. Fatigue and rutting relative performance values are shown in Figure 5.20 and Figure 5.21, respectively at the original, current NCDOT, calculated optimum, and recommended gyrations for this mixture. The use of 65 gyrations as Ndesign results in an 8% improvement in fatigue resistance and a 7% reduction in rutting performance as compared to the calculated optimum of 82 gyrations.

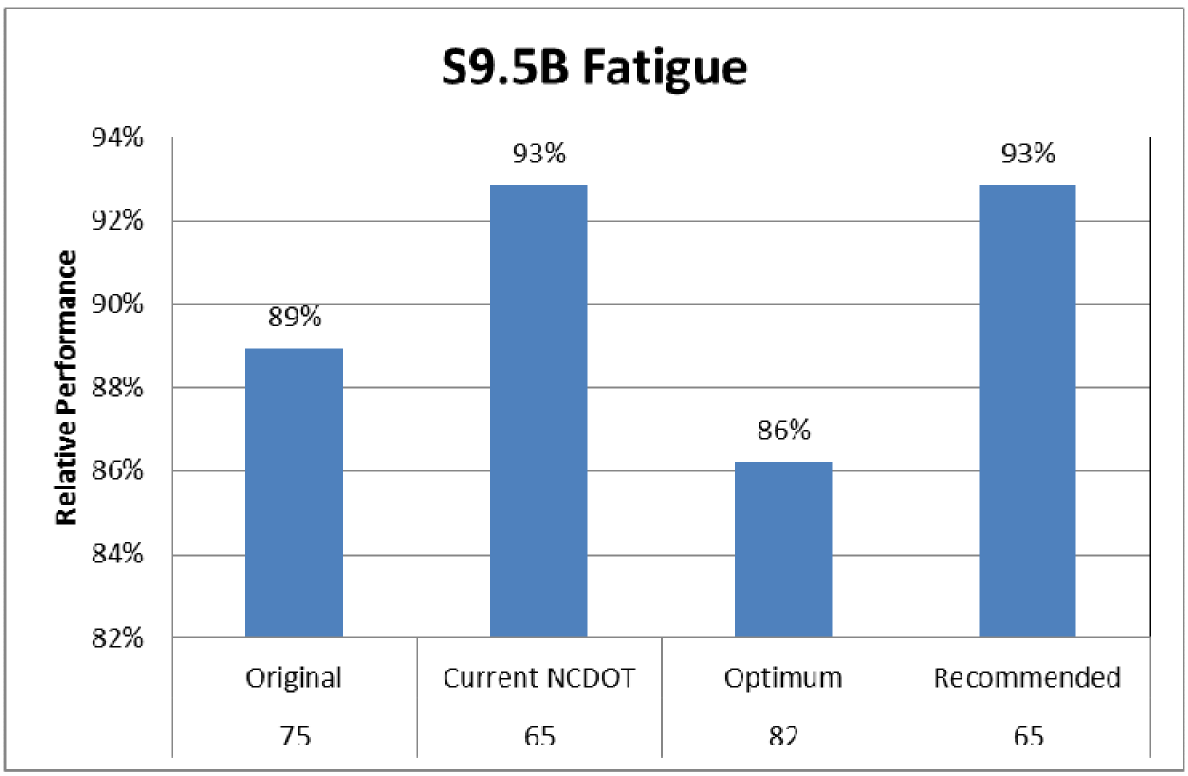

Figure 5.20 Relative Fatigue Performance at Different Gyration Levels for S9.5B Mix

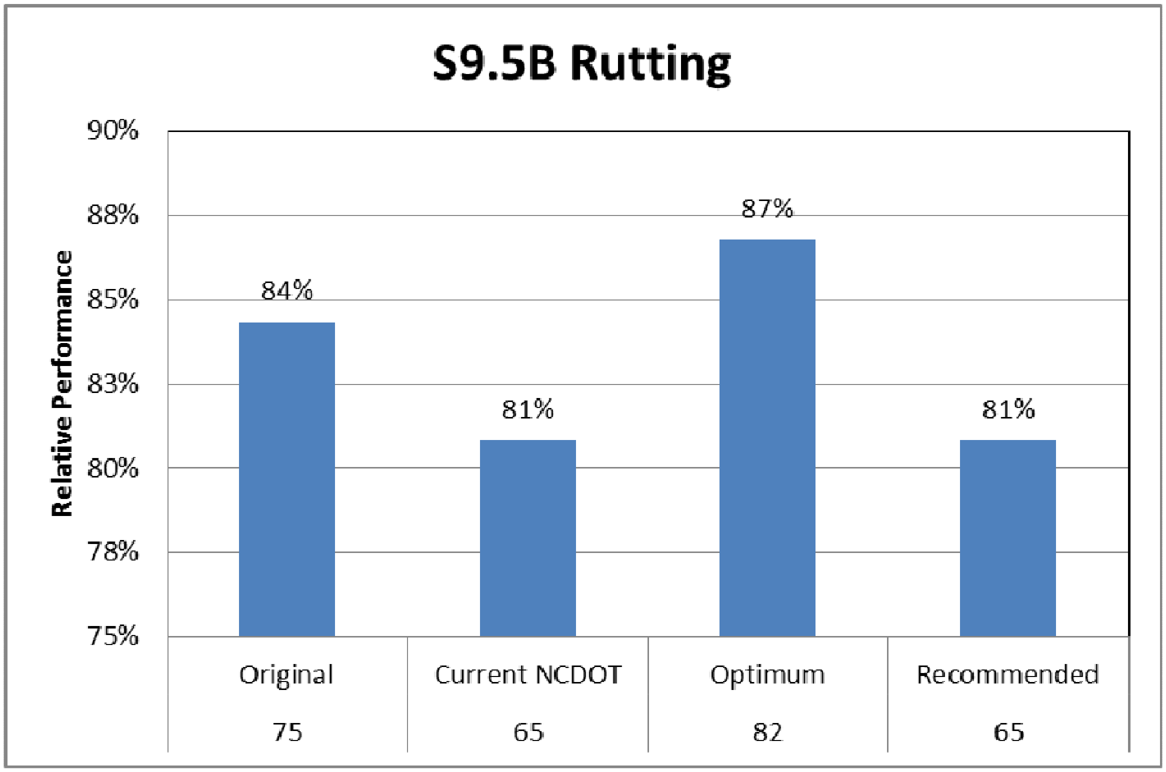

Figure 5.21 Relative Rutting Performance at Different Gyration Levels for S9.5B Mix

5.7.2 ***Binder Type: PG70-22*** In this section, recommendations for surface mixtures S9.5C and S12.5C, which use a virgin binder grade of PG 70-22 are explained.

5.7.2.1 Recommendations for S9.5C Mix

Based on the relative performance curves, the optimum number of gyrations for this mix is 97, which is similar to the original Ndesign value recommended for mixes designed for similar traffic loads by NCHRP (*2*). The calculated value is higher than the current NCDOT specification of 75 gyrations, which results in increased rutting resistance while fatigue is decreased. However, it is important to note that the selection of the current value was not a result of any detailed study but rather it was based on an arbitrary reduction in the original Superpave Ndesign table in an effort to improve the durability of mixtures.

Figure 5.22 and Figure 5.23 display the relative performances at the original Ndesign value for the S9.5C mix in the Superpave tables, the current NCDOT Ndesign, the calculated optimum value, and the recommended compaction level with respect to fatigue and rutting, respectively. Based on the relative performance analysis, an Ndesign level of 85 is recommended for this mix.

This value reduces the fatigue performance by 2% compared to the current NCDOT specification of 75 gyrations and the rutting is improved by a factor of 5%. Also, the asphalt content decreases from 5.66% to 5.55% which represents a 2% reduction in the quantity of asphalt binder used in the mix. <u>The reduction in the fatigue resistance associated with recommended value is insignificant compared to the savings in the asphalt costs and the improvement in the rutting resistance.</u>

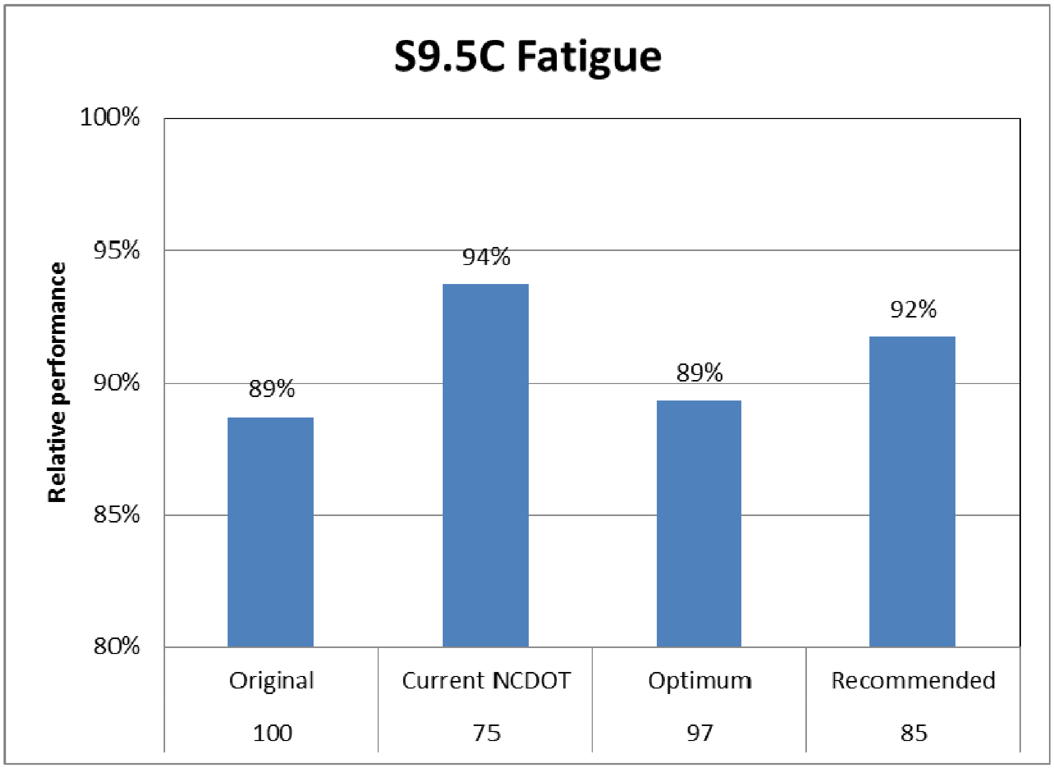

Figure 5.22 Relative Fatigue Performance at Different Gyration Levels for S9.5B Mix

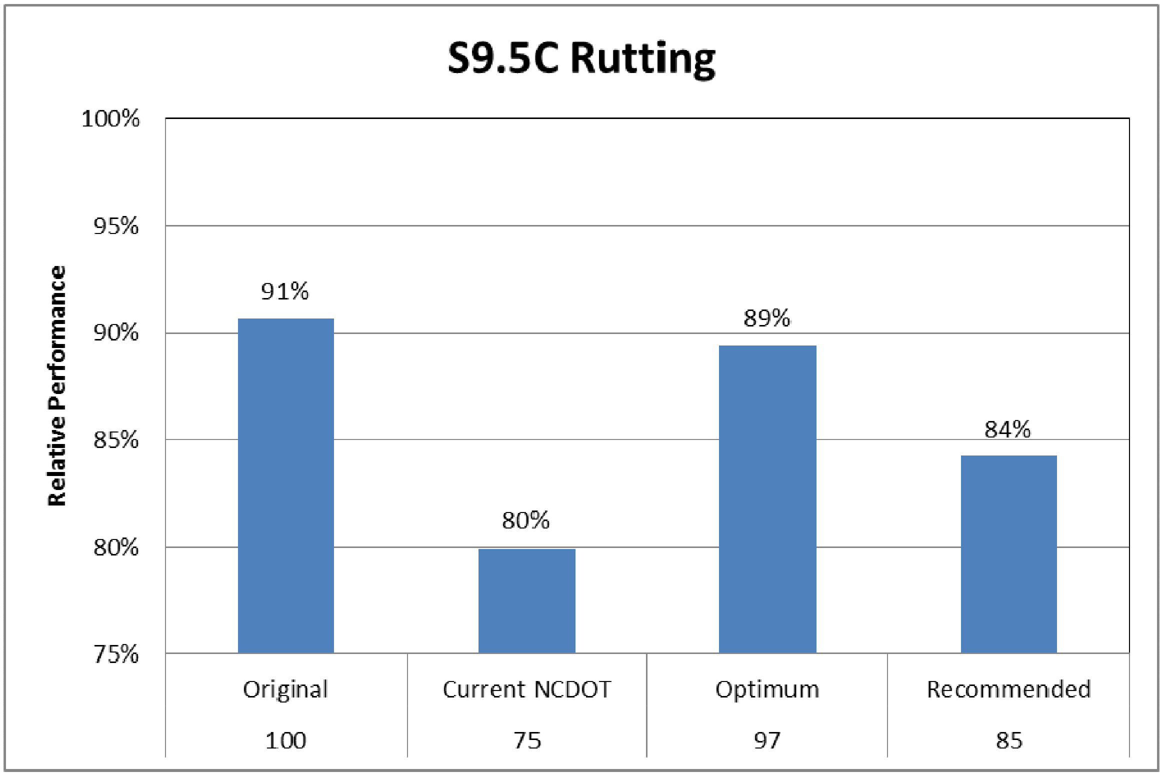

Figure 5.23 Relative Rutting Performance at Different Gyration Levels for S9.5C Mix

5.7.2.2 Recommendations for S12.5C Mix

The number of gyrations that optimizes the performance of S12.5C mix was calculated to be 95 gyrations. The fatigue performance is decreased and the rutting resistance is increased compared to the current compaction level of 75 gyrations being used by NCDOT. It was inferred from the relative performance curves for S12.5C mix that variation in rutting performance with the number of gyrations is greater than the variation in fatigue cracking performance. Therefore, the effect of increasing the Ndesign value is more pronounced on the improvement in rutting than on the reduction in fatigue resistance. Hence, the Ndesign value for the 12.5C mix is recommended as 85 gyrations.

Replacing the current Ndesign with 85 gyrations results in a reduction in asphalt content from 5.45% to 5.36% which represents a 2% decrease accompanied by a 2% decrease in fatigue performance as a result of the reduced flexibility of the pavement, on the other hand, the rutting is improved by 5% due to the increased compaction effort. A comparison of relative performance of original Ndesign, current NCDOT Ndesign, optimum Ndesign, and the recommended Ndesign for both fatigue and rutting is displayed in Figure 5.24 and Figure 5.25 , respectively. The practical implications of the recommended value of 85 gyrations are improvement in rutting resistance and potential savings from reduction in the amount of asphalt binder used in the mix.

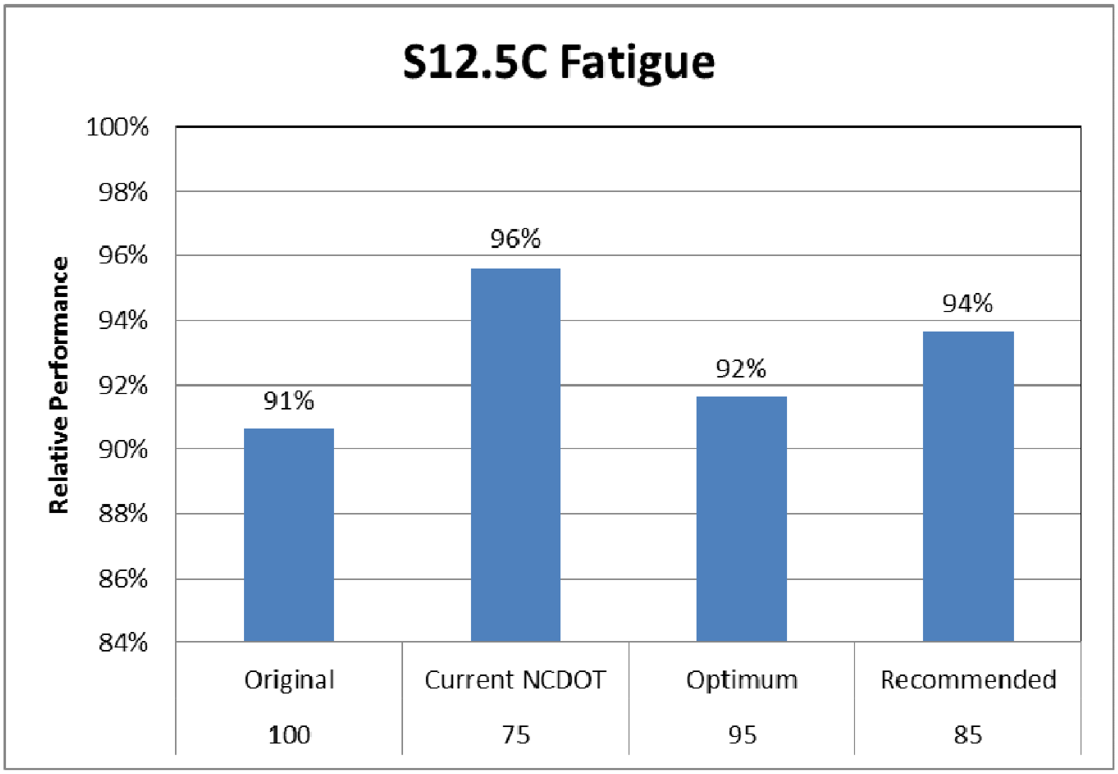

Figure 5.24 Relative Fatigue Performance at Different Gyration Levels for S12.5C Mix

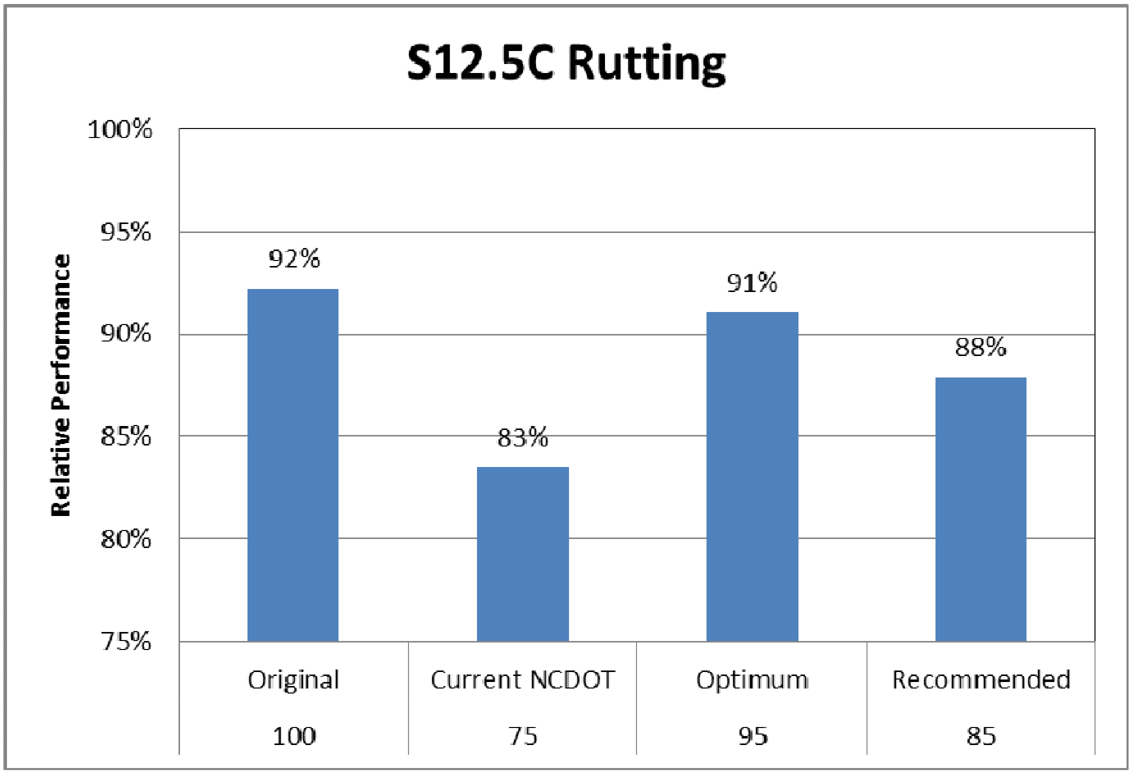

Figure 5.25 Relative Rutting Performance at Different Gyration Levels for S12.5C Mix

5.7.3 ***Binder Type: PG76-22*** In this section, recommendations for surface mixtures S9.5D and S12.5D, which use a virgin binder grade of PG 76-22 are explained.

5.7.3.1 Recommendations for S9.5D Mix

The optimum number of gyrations for this mix, as determined from the relative performance analysis, is 79 gyrations. The flexibility and durability of the pavement are expected to be significantly improved compared to the current Ndesign value due to the increase in binder content in the mix. The relative performance curves for D-level mixes show that the number of gyrations have a greater effect on fatigue performance as compared to rutting. Based on this analysis, it is recommended to reduce the Ndesign level for this mix to 85 gyrations. The recommendation also allows the Ndesign table to only two values - one for low traffic mixes and the other for intermediate to high traffic mixes.

Graphical representations of the fatigue and rutting relative performance values for the original, current NCDOT, calculated optimum, and recommended gyrations for this mixture are shown in

Figure 5.26 and Figure 5.27, respectively. An alternate Ndesign value of 75 gyrations was also considered to evaluate the improvement in fatigue performance based on the calculated value of 72 gyrations. Compared to the current compaction level of 100 gyrations, an Ndesign of 85 gyrations improves the fatigue performance by 4% and decreases the rutting resistance by the same amount. Since rutting failure is not a major concern for Superpave mixtures, the observed reduction of in rutting performance is not significant compared to the improvement in the flexibility and fatigue performance of the pavement. Therefore, the selection of the appropriate Ndesign value is based on the improved fatigue performance of the mix as opposed to the increase in amount of asphalt binder used in the mix.

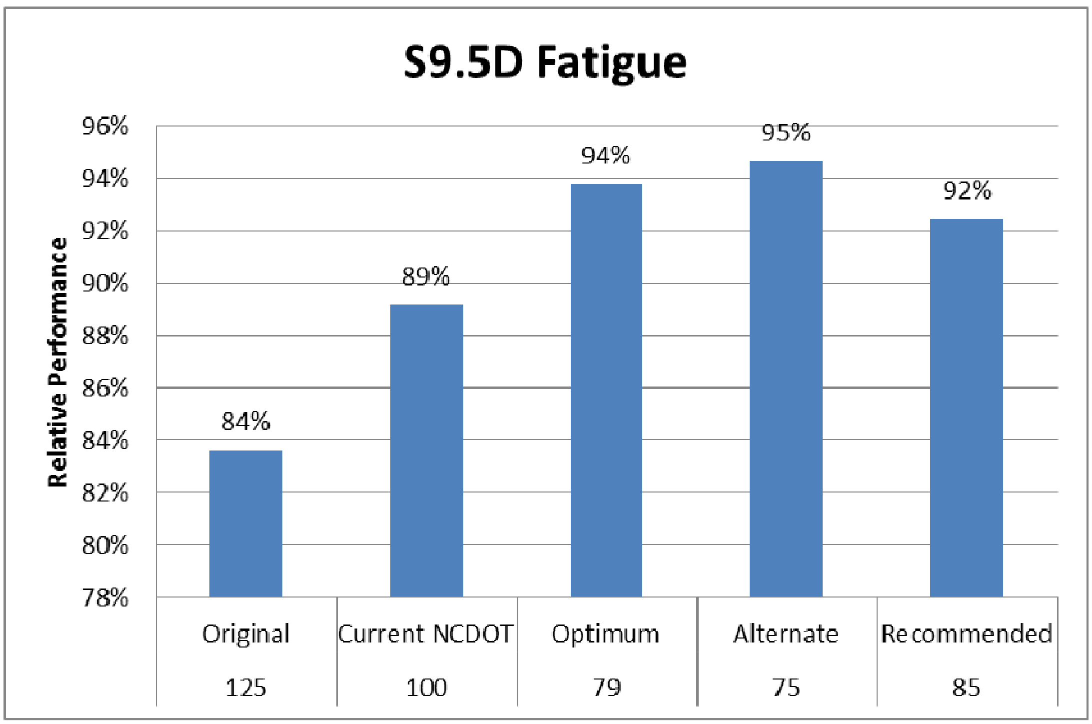

Figure 5.26 Relative Fatigue Performance at Different Gyration Levels for S9.5D Mix

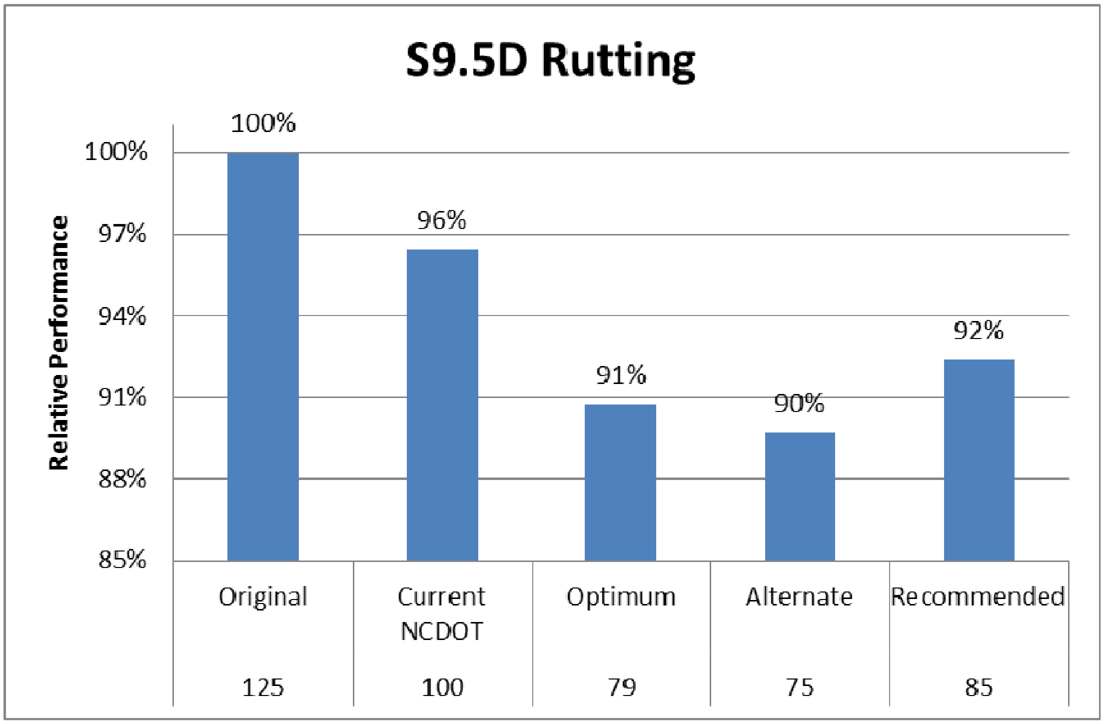

Figure 5.27 Relative Rutting Performance at Different Gyration Levels for S9.5D Mix

5.7.3.2 Recommendations for S12.5D Mix

From the relative performance analysis, the fatigue and rutting performances are optimized at an Ndesign level of 72gyrations. Compared to the current NCDOT Ndesign for this mix, the flexibility of the pavement is improved due to the increase in the design asphalt content in the mix. Similar to the S9.5D mixture, it is recommended to reduce the Ndesign level for this mix to either 85 gyrations.

Fatigue and rutting relative performance values are shown in Figure 5.28 and Figure 5.29 at the original, current NCDOT, calculated optimum, and recommended gyrations for this mixture. Compared to the current compaction level of 100 gyrations, an Ndesign of 75 gyration results in an increase in fatigue performance of 11% and a 4% reduction in the rutting performance, whereas 85 gyrations improves the fatigue performance by 7% and decreases the rutting resistance by 2%. In terms of asphalt content, a level of 75 gyrations means an increase of 7% from 4.87% to 5.22% in the amount of asphalt, and 5% for 85 gyrations increasing from 4.87% to 5.13%. Superpave mixtures are known to perform well in terms of rutting; therefore, a reduction of 2% or 4% in rutting performance is insignificant considering the improvement in fatigue performance of the pavement. The selection of the appropriate Ndesign value depends on the specific requirements of the projects, the cost/benefit analysis of the amount of asphalt versus the achieved improvement in fatigue performance, and finally the designer's judgment.

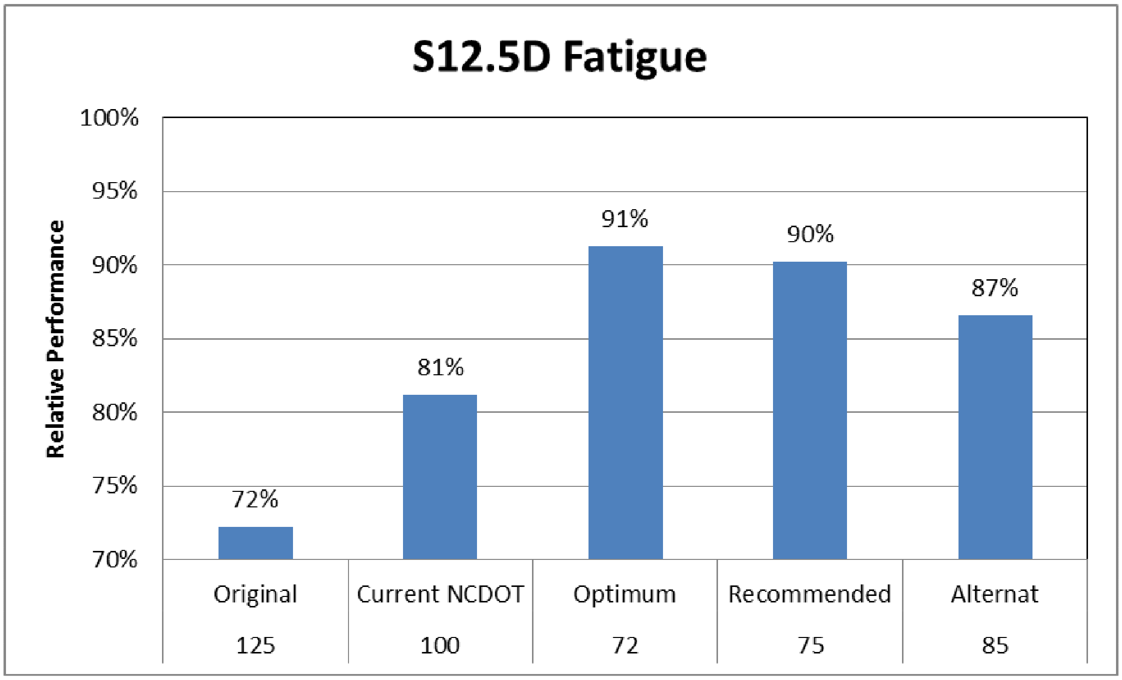

Figure 5.28 Relative Fatigue Performance at Different Gyration Levels for S12.5D Mix

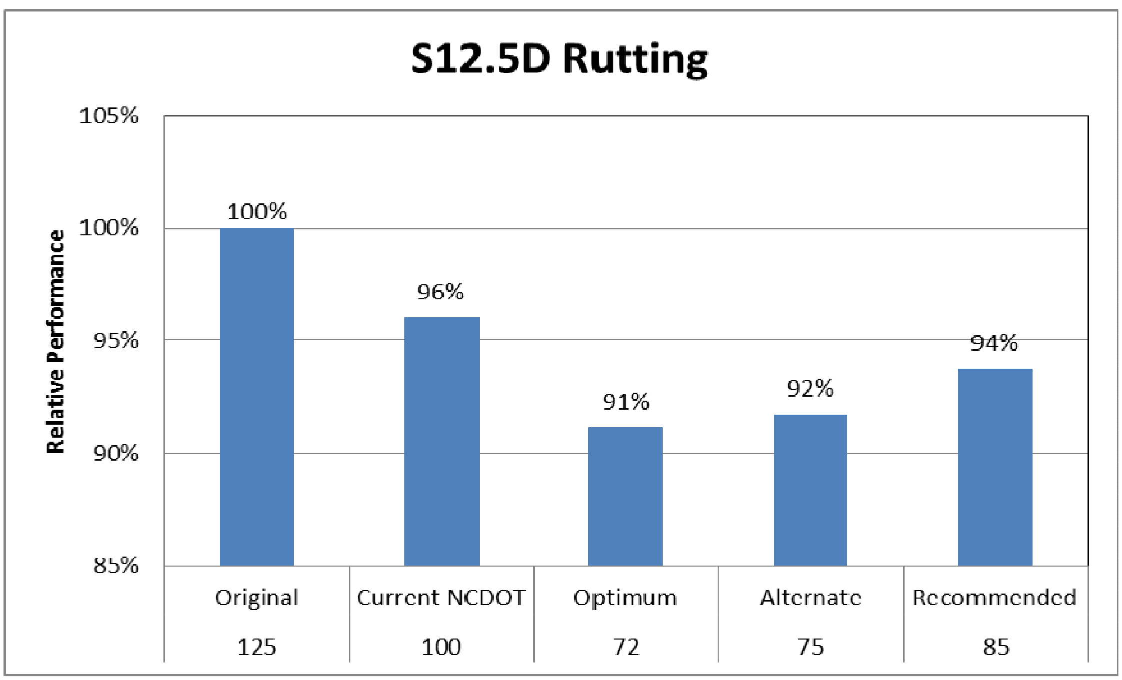

Figure 5.29 Relative Rutting Performance at Different Gyration Levels for S12.5D Mix

6. SUMMARY AND CONCLUSIONS

6.1 Summary

In this study, the number of design gyrations for Superpave design of asphalt concrete mixes (Ndesign) that optimizes mixture performance with respect to fatigue cracking and rutting was evaluated for North Carolina surface mixes. The Ndesign values in the current NCDOT specification for design of Superpave mixes are based on traffic level expressed in terms of ESALs. For different traffic levels, NCDOT also specifies the use of virgin binder grades of PG 64-22 for A and B mixes, PG 70-22 for C mixes and PG 76-22 for D mixes. As Ndesign increases, the resistance of a mix to rutting increases whereas fatigue resistance decreases due to lower asphalt content required to achieve the target air void content of 4%. In order to study the effect of Ndesign on performance, asphalt concrete specimens were prepared at different gyration levels and the rutting and fatigue performance was analyzed for each type of surface mix.

Dynamic modulus and flow number of six types of surface mixes, S9.5A, S9.5B, S9.5C, S9.5D, S12.5C and S12.5D were measured for specimens compacted to four different Ndesign levels - 50, 75, 100 and 125 gyrations. The dynamic modulus values were used as an input parameter in the mechanistic-empirical software analysis tool to predict the fatigue and rutting performances of the mixtures. DARWin-ME software was used to accomplish this task due to its widespread use by many highway agencies and organizations. Motivation for this research was based on the fact that Superpave mixes are relatively drier mixes that perform well with respect to rutting but exhibit poor fatigue resistance due to insufficient asphalt binder in the mix.

Superpave mix design of all surface mixes was performed to determine the optimum asphalt content corresponding to the four Ndesign levels. Test specimens for the dynamic modulus test were prepared at the optimum asphalt contents for all mixes in accordance with AASHTO TP79-09 procedure for testing in the Asphalt Mixture Performance Tester (AMPT). The dynamic modulus data from AMPT testing was used to generate E* master curves to obtain the necessary inputs for analysis using the DARWin-ME software.

Fatigue and rutting performance predicted using the DARWin-ME software was compared to the analysis limits of 10 percent or more cracking in the pavement, and 0.75 inches deformation in the AC layer, respectively to identify the failure traffic loads. In order to compare the performance of the mix in rutting and fatigue, the relative performance concept was defined as ratio of the number of trucks to failure at a specific level of compactive effort to the number of trucks to failure at a fixed level of compaction or control limit performance. The relative performance values for both fatigue and rutting were plotted versus the number of gyrations and the optimum number of design gyrations was determined from the point of intersection of the two curves. The Ndesign values thus determined for different surface mixes were then compared to the current NCDOT Superpave mix design specification as well as NCHRP recommended values to study the effect of varying Ndesign on pavement performance.

6.2 Conclusions and Recommendations

The results of mix design for all the surface mixes show that the optimum asphalt content decreased with an increase in Ndesign level to which specimens were compacted. Results from AMPT testing also show that the modulus of the mix at different temperatures and frequencies increases with an increase in Ndesign as observed from the trend in E* master curves for each mix at different Ndesign levels. These findings reinforce the theoretical basis for this study that using a higher Ndesign for mix design requires a lower binder content and results in a stiffer mix.

The optimum Ndesign for each type of surface mix was determined from the relative performance plots of rutting and fatigue versus asphalt content, and the plot of asphalt content versus Ndesign values. The calculated Ndesign values are 85 gyrations for S9.5A mix, 82 gyrations for S9.5B mix, 97 gyrations for S9.5C mix, 79 gyrations for S9.5D mix, 95 gyrations for S12.5C mix and 72 gyrations for S12.5D mix. It can be observed that mixtures containing the same binder grade had very similar optimum Ndesign values. From the rutting and fatigue performance data, relative performance values were calculated for the obtained Ndesign values as well as NCHRP recommended values.

The final recommendations for optimum Ndesign were developed based on two primary considerations:

- Effect of using a lower Ndesign on rutting and fatigue - improvement in pavement life with respect to fatigue life and corresponding increase in rutting
- Effect of using a higher Ndesign - Economic benefits from reduced use of asphalt binder in the mix weighed against the reduction in fatigue life. The reduction in the required asphalt content is calculated as a percentage of the asphalt binder required for mix design using the current NCDOT specifications.

Since surface mixes containing same asphalt binder grade had similar optimum Ndesign values, the binder PG grade was also considered as a factor in the recommendations. Based on the analysis of relative performance values, the following optimum Ndesign values are recommended for the surface mixes evaluated in this study.

6.2.1 Surface Mixes S9.5A and S9.5B

The recommended Ndesign value for S9.5A and S9.5B mixes is **65 gyrations**. The current NCDOT specification for S9.5A mix is 50 gyrations and the calculated optimum from relative performance analysis is 89 gyrations. Since the A level surface mix uses the same binder grade as B mix (PG 64-22), it is recommended to use the same number of design gyrations for both mixes. The increase in Ndesign for A mixes leads to a reduction in fatigue life by 4% and increase in rutting life by 4%. However, this leads to a 2% reduction in asphalt binder requirement which results in significant cost savings. As the recommended value for S9.5B mix is the same as current NCDOT specification, there is no impact on variation in performance of the mix.

6.2.2 Surface Mixes S9.5C and S12.5C

The recommended number of design gyrations for C-level surface mixes, S9.5C and S12.5C is **85 gyrations**. The current NCDOT specification for these surface mixes is 75 gyrations, both of which use a PG 70-22 binder grade. The calculated optimum Ndesign values for the two mixes are 97 and 95, respectively. The current specification results in better fatigue resistance, whereas the calculated Ndesign leads to improved rutting resistance. Therefore, the recommended Ndesign value of 85 gyrations leads to optimum pavement performance with respect to both distresses. In terms of relative performance, the recommended Ndesign of 85 gyrations leads to a reduction in fatigue life of 2% and increases rutting life by 4% as compared to the current NCDOT specification of 75 gyrations. The recommended increase in Ndesign leads to a 2% reduction in the quantity of asphalt binder required, which is similar to that observed for a S9.5A mix.

6.2.3 Surface Mixes S9.5D and S12.5D

The recommended number of design gyrations for D-level surface mixes, S9.5D and S12.5D is **85 gyrations**. The current NCDOT specification for these surface mixes is 100 gyrations, both of which use a PG 76-22 binder grade. The calculated optimum Ndesign values for the two mixes are 79 and 72, respectively, which are lower than those obtained for the C-level mixes. This indicates that the mix stiffness and subsequently its performance in rutting and fatigue varies more rapidly with a change in the Ndesign value. Hence, the recommended value of 85 gyrations leads to a 3% increase in fatigue life for S9.5D mix and 6% increase in fatigue life for S12.5D mix as compared to the current NCDOT specified value of 100 gyrations. The reduction in rutting for the two mixes is 4% and 2%, respectively.

6.3 Recommendations for Future Work

The optimum number of design gyrations, Ndesign for surface mixes used in North Carolina was evaluated using performance testing of mixtures compacted to different gyration levels. For S9.5A, S9.5C and S12.5C mixes, the recommendations were developed by comparing the improvement in pavement performance with the potential reduction in asphalt binder requirement. Laboratory preparation of specimens at the recommended design gyrations was not performed as part of this research. Therefore, Superpave design of mixtures compacted to the recommended Ndesign levels should be performed to validate the effect of binder content reduction on volumetric properties of the mix such as Voids in Mineral Aggregate (VMA) and Voids Filled with Asphalt (VFA). It is also recommended that dynamic modulus tests on specimens at the new Ndesign values should be conducted to analyze the performance of the mixtures and compare the results with those obtained from this study.

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APPENDIX A: Dynamic Modulus Results

S9.5A		50			75			100			125		
4 C	10 Hz	18856	17451	17721	20737	18398	17531	19337	19856	18979	19723	19068	20264
	1 Hz	14642	13571	13727	16197	14576	13686	15174	15405	14759	15329	14739	15805
	0.1 Hz	10578	9804	9935	11972	10778	9913	11188	11090	10683	11118	10602	10358
20 C	10 Hz	9028	8061	8111	10110	8713	8340	9238	9223	8742	9339	8988	9538
	1 Hz	5601	4840	4817	6325	5380	5070	5620	5585	5249	5666	5387	5780
	0.1 Hz	3131	2604	2601	3641	2994	2781	3077	2952	2863	3105	2903	3186
40 C	10 Hz	2506	2118	2104	3110	2551	2322	2685	2458	2660	2665	2460	3890
	1 Hz	1187	929	923	1524	1151	1023	1220	1061	1273	1158	1079	1767
	0.1 Hz	600	433	433	809	548	474	562	478	564	565	510	842

S9.5B		50			75			100			125		
4 C	10 Hz	18404	18493	18449	19100	18753	18927	19402	19402	19402	19739	20011	19875
	1 Hz	13855	14132	13994	14585	14226	14406	14996	14996	14996	15289	15459	15374
	0.1 Hz	9375	9991	9683	10218	9906	10062	10723	10723	10723	11004	11081	11042.5
20 C	10 Hz	7694	8210	7952	9096	8504	8800	9590	9590	9590	9422	9815	9618.5
	1 Hz	4321	4806	4564	5368	4999	5184	5810	5810	5810	5690	6439	6064.5
	0.1 Hz	2136	2295	2216	2821	2625	2723	3148	3148	3148	3049	3727	3388
40 C	10 Hz	1878	2104	1991	2430	2209	2320	2699	2699	2699	2474	3055	2764.5
	1 Hz	755	924	840	1091	968.1	1030	1182	1182	1182	1093	1541	1317
	0.1 Hz	335	438	387	543.3	474.1	509	547.8	547.8	548	493.1	827.5	660.3

S9.5C		50			75			100			125		
4 C	10 Hz	19483	18768	19126	20579	20101	20340	20694	20831	25657	23817	24883	24350
	1 Hz	15555	15086	15321	16083	16002	16043	17117	17163	20750	19362	20317	19839.5
	0.1 Hz	11679	11378	11529	13075	12031	12553	13411	13403	15549	14872	15479	15175.5
20 C	10 Hz	9943	9559	9751	11006	10027	10517	11583	11597	13073	12897	13303	13100
	1 Hz	6362	6034	6198	7298	6397	6848	7824	7955	8772	8710	8965	8837.5
	0.1 Hz	3663	3426	3545	4448	3666	4057	4720	4949	5448	5413	5507	5460
40 C	10 Hz	2924	2650	2787	3594	2864	3229	3933	3786	4603	4267	4544	4405.5
	1 Hz	1356	1197	1277	1787	1357	1572	1890	1865	2386	2211	2393	2302
	0.1 Hz	627	552	590	874	659.6	767	894	922	1318	1205	1349	1277

S9.5D		50			75			100			125		
4 C	10 Hz	17280	17282	17281	19469	19269	19369	20021	20016	20019	20762	20830	20796
	1 Hz	13582	13604	13593	15739	15280	15510	15976	16050	16013	16643	16552	16597.5
	0.1 Hz	10059	10193	10126	12052	11617	11835	12160	12157	12159	12569	12408	12488.5
20 C	10 Hz	8311	8547	8429	9519	9592	9556	9512	9753	9633	9987	10058	10022.5
	1 Hz	5164	5429	5297	6120	6109	6115	6080	6230	6155	6353	6362	6357.5
	0.1 Hz	2918	3213	3066	3607	3577	3592	3558	3588	3573	3712	3688	3700
40 C	10 Hz	2244	2367	2306	2817	2649	2733	2639	2645	2642	2686	2770	2728
	1 Hz	1016	1131	1074	1291	1246	1269	1222	1226	1224	1208	1290	1249
	0.1 Hz	514	601	558	636	630	633	613	627	620	589	636	612.5

S12.5C		50			75			100			125		
4 C	10 Hz	18449	17889	18169	19772	19523	19648	20639	20514	20577	22608	21065	21837
	1 Hz	13994	14209	14101	16340	15954	16147	17119	16918	17019	18405	17225	17815
	0.1 Hz	9683	10577	10130	12512	12252	12382	13379	13176	13278	14101	13286	13694
20 C	10 Hz	7952	8977	8465	9933	10168	10051	11150	11054	11102	11799	11439	11619
	1 Hz	4564	5633	5098	6445	6559	6502	7390	7390	7390	7567	7524	7546
	0.1 Hz	2216	3149	2682	3783	3759	3771	4407	4495	4451	4390	4457	4424
40 C	10 Hz	1991	2530	2261	2943	3047	2995	3418	3510	3464	3418	3614	3516
	1 Hz	840	1135	987	1388	1392	1390	1577	1657	1617	1577	1733	1655
	0.1 Hz	387	563	475	685	650	668	735	798	767	735	879	807

S12.5D		50			75			100			125		
4 C	10 Hz	18361	18407	18384	18742	19287	19015	19362	19883	19623	20111	20901	20506
	1 Hz	14517	14623	14570	15137	15555	15346	15698	15768	15733	15985	16778	16382
	0.1 Hz	10675	10861	10768	11565	11804	11685	11894	11771	11833	11972	12761	12367
20 C	10 Hz	8599	8942	8771	9502	9732	9617	9304	9989	9647	9989	10138	10064
	1 Hz	5261	5551	5406	6151	6226	6189	5940	6496	6218	6496	6458	6477
	0.1 Hz	2964	3137	3051	3642	3468	3555	3481	3901	3691	3901	3771	3836
40 C	10 Hz	2346	2312	2329	2806	2800	2803	2889	2995	2942	3224	2800	3012
	1 Hz	1107	1013	1060	1326	1278	1302	1373	1399	1386	1680	1278	1479
	0.1 Hz	600	507	554	672	720	696	701	639	670	992	638.6	815

APPENDIX B: E* Master Curve Calculations (PSI)

Column 2 under mixture type indicates the temperature in ^{0}F.

S9.5A		0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
50 Gyrations	14	2391051	2639191	2725407	2884169	2937230	2995705
	40	1299620	1710208	1879244	2232618	2364201	2517789
	70	332024.4	562722.8	691666.4	1050283	1222677	1457323
	100	74994.49	126041.5	160122.6	282157.9	358455.2	485514.2
	130	29712.62	40671.82	47864.37	74467.33	92362.15	125041.4
75 Gyrations	14	2440791	2684491	2769495	2926773	2979638	3038137
	40	1367938	1773532	1939478	2285593	2414476	2565123
	70	375931.3	620578.2	754284.4	1118818	1291349	1524266
	100	88605.23	147729.5	186469	321790.6	404412	539594.6
	130	34663.1	47877.67	56491.05	87986.4	108891.4	146584.8
100 Gyrations	14	2524509	2760956	2842316	2991005	3040350	3094506
	40	1442938	1858331	2026200	2371797	2498724	2645692
	70	403786.2	662314.2	803126.2	1184649	1363765	1603845
	100	99088.94	161944.7	203049.1	346461.4	433928.7	576845.2
	130	41288.78	55538.72	64784.47	98429.55	120682.1	160729.4
125 Gyrations	14	2540896	2773425	2853380	2999436	3047893	3101067
	40	1472360	1883948	2049797	2390562	2515522	2660105
	70	428562.6	691397.2	833357.6	1215325	1393678	1632021
	100	111165.7	177948.6	221100.4	369729.2	459400	604871.8
	130	48234.41	63967.27	74082.42	110458.2	134243.8	176667.5

S9.5B		0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
50 Gyrations	14	2434993	2689318	2776168	2933306	2984815	3040835
	40	1283231	1718516	1897789	2270070	2407160	2565601
	70	299261.6	523010.8	652163.6	1021255	1202082	1450130
	100	67418.57	111425.4	141447	252523.2	324304	446938.2
	130	29302.89	38470.46	44501.33	66970.31	82257.45	110551.9
75 Gyrations	14	2511303	2758290	2842698	2995715	3046014	3100841
	40	1380405	1811958	1987873	2351014	2484266	2638139
	70	356026.5	599304.4	735878.5	1116387	1299041	1546753
	100	86979.51	140456.7	176054.5	303699.6	383803.5	517698.1
	130	38738.12	50575.89	58269.1	86424.71	105218.2	139411.6
100 Gyrations	14	2564373	2794692	2873527	3017030	3064482	3116454
	40	1487823	1905889	2073172	2414680	2539149	2682638
	70	414230.1	685028.8	831563.1	1224761	1407448	1650479
	100	95254.14	160365.5	203327.4	353967.8	445897.6	595733.1
	130	36981.12	51076.46	60343.4	94577.34	117505.2	159098.5
125 Gyrations	14	2613247	2840098	2916856	3055010	3100138	3149160
	40	1525925	1951357	2120790	2464191	2588209	2730163
	70	435138.3	708700	857338.2	1257647	1443964	1691682
	100	112469.1	179105.1	222619.7	374438.2	467055.2	618327.3
	130	50710.15	66034.06	75931.28	111768.6	135386.2	177818.3

S9.5C		0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
50 Gyrations	14	2578120	2788677	2859894	2988267	3030316	3076106
	40	1549926	1957649	2117781	2439411	2554847	2686686
	70	447691.5	734146.2	886595.8	1287631	1470271	1709856
	100	102305.7	173340.3	220128.8	383066.4	481521.1	640385.3
	130	39054.43	54259.71	64304.04	101567.6	126581.8	171959
75 Gyrations	14	2683534	2878455	2943195	3058040	3095043	3134918
	40	1676570	2085367	2242704	2552646	2661701	2784649
	70	516435.6	825872.5	988137	1407732	1595401	1838275
	100	131362.8	212481.8	265124.3	445675.2	553321.6	725276.3
	130	56599.71	74970.11	86929.37	130509	159298	210920
100 Gyrations	14	2865302	3021507	3071174	3156027	3182331	3209992
	40	1934898	2335172	2481314	2755448	2847240	2947510
	70	647235.1	1011642	1196866	1656059	1851993	2096707
	100	176973.3	277067	341832.3	561996.7	691403.3	894741.8
	130	84708.56	107331.8	122091.7	175918.7	211469.9	275142.6
125 Gyrations	14	2994860	3124148	3163104	3226545	3245228	3264236
	40	2095609	2503284	2645295	2898901	2979341	3064069
	70	697528.8	1094547	1298296	1799270	2008377	2263327
	100	211711.6	310998.2	376638.7	606427.3	745087.1	966293.4
	130	122929.6	144361.6	158496.7	210680.4	245617.5	309063.9

S9.5D		0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
50 Gyrations	14	2409934	2653717	2738838	2896402	2949369	3007974
	40	1344350	1745431	1910201	2254942	2383638	2534254
	70	374410.1	612255.2	742547.5	1099275	1268896	1498648
	100	93673.44	152056.8	189999.2	321799.1	402080.7	533462.7
	130	39145.42	52720.52	61470.33	93057.43	113798.2	150932.8
75 Gyrations	14	2617709	2832278	2904256	3032899	3074635	3119785
	40	1556410	1977817	2143474	2475339	2593867	2728626
	70	441524.4	725340	878533.5	1286678	1474331	1721522
	100	107559.9	175708.4	220637.7	378356.6	474727	631810.7
	130	46028.32	61034.31	70840.98	106850.1	130871.3	174383.5
100 Gyrations	14	2673336	2881020	2949276	3068973	3107029	3147658
	40	1591693	2028739	2198354	2532719	2649929	2781408
	70	432331.8	723121.7	882318.9	1309449	1505929	1763697
	100	104740.8	169491	212908	368759.8	465953.1	626557.6
	130	47662.05	61443.15	70501.45	104074.3	126724.6	168218.8
125 Gyrations	14	2732653	2934836	3000771	3115654	3151946	3190539
	40	1650574	2093074	2262956	2594587	2709732	2838138
	70	447179.8	752406.9	918733.9	1361329	1562965	1825524
	100	104355.9	171456.1	216779.2	380336.6	482529.4	651213.9
	130	46275.85	60136.26	69317.21	103670	127045.8	170131.1

S12.5C		0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
50 Gyrations	14	2458628	2704501	2789195	2943924	2995213	3051434
	40	1351568	1771964	1943808	2300250	2431857	2584570
	70	349350.6	589219.9	723132.4	1094544	1272378	1513497
	100	81641.73	134946.8	170458.4	297472.9	376844.2	508973.4
	130	33977.76	45584.18	53168.91	81089.9	99802.57	133904.1
75 Gyrations	14	2668423	2873980	2942621	3064917	3104488	3147240
	40	1628323	2046401	2208815	2531234	2645495	2774858
	70	477492.5	778185.6	937974.8	1356559	1545996	1793019
	100	114680	189454.9	238594.7	409639.4	513014.1	679803.1
	130	47361.53	63693.97	74412.02	113900.6	140276.1	188003.4
100 Gyrations	14	2772614	2959524	3021243	3130287	3165301	3202965
	40	1778525	2188253	2343613	2646169	2751575	2869779
	70	557566.8	892913.6	1065747	1503854	1696055	1941689
	100	132055.2	221612.1	280025.7	479820.2	597943	784735.4
	130	51663.74	71000.21	83781.58	131119.6	162773.6	219880.4
125 Gyrations	14	2860005	3036284	3092866	3190256	3220668	3252788
	40	1850200	2276894	2435522	2737362	2839769	2952481
	70	561510.8	911282.3	1094114	1559699	1763242	2021327
	100	137920.1	224250.6	281485.9	481936.2	603112.8	797544.4
	130	61617.89	79935.27	92040.01	137027.2	167336.6	222564.8

S12.5D		0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
50 Gyrations	14	2536013	2776908	2858936	3007219	3055834	3108743
	40	1416862	1847160	2021383	2379008	2509567	2659879
	70	374500.6	625473.8	765260.1	1151385	1335241	1583235
	100	92816.59	149284.8	186716.8	320121.6	403303.5	541591.6
	130	41578.9	54181.75	62361.5	92229.07	112110.4	148184.2
75 Gyrations	14	2630301	2854636	2930348	3066321	3110638	3158712
	40	1545885	1971795	2140863	2482486	2605493	2746022
	70	444830.4	722263.2	872616.5	1276308	1463608	1712060
	100	116081.5	184159.8	228550.8	383132.3	477250.4	630718.3
	130	52821.43	68538.64	78681.6	115365	139510.6	182846.3
100 Gyrations	14	2629629	2852316	2928230	3065996	3111425	3161104
	40	1569724	1985366	2150158	2484178	2605160	2744142
	70	465730.9	751324	903324.7	1304970	1489122	1732125
	100	115258.7	188992.2	236798.4	401073	499518.9	657909.1
	130	47039.49	63845.37	74766.2	114481.5	140669.4	187573.7
125 Gyrations	14	2737650	2950777	3021017	3144434	3183741	3225744
	40	1640727	2081465	2253383	2593835	2713683	2848445
	70	478059.8	770963.6	930312.6	1357574	1554581	1813821
	100	135296.6	205886.5	251973.3	413305.6	512156.2	674081.4
	130	69319.83	85804.56	96401.37	134553.1	159594.6	204524.1

APPENDIX C: Reliability Levels and Relative Performance Calculations

						S9.5A Mixture						
	%AC	6	5.77	5.56	5.4			%AC	6	5.77	5.56	5.4
	Gyrations	50	75	100	125			Gyrations	50	75	100	125
	1	1660000	1580000	1460000	1370000			1	1.54E+06	1.79E+06	1.88E+06	1.91E+06
	2	1670000	1520000	1430000	1390000			2	1.55E+06	1.65E+06	1.79E+06	2.07E+06
Fatigue	3	1662830	1539390	1451160	1363790		Rutting	3	1550610	1720060	1858550	1928600
	Mean	1664277	1546463	1447053	1374597			Mean	1546870	1720020	1842850	1969533
	St. Dev	5154.57	30619	15415.9	13696.3			St. Dev	5957.41	70000	47009.2	87502.3
						Reliability Levels						
	70%	1667372	1564848	1456310	1382821			70%	1550447	1762051	1871076	2022074
	80%	1668086	1569091	1458446	1384718			80%	1551273	1771751	1877590	2034198
	90%	1669172	1575543	1461694	1387605			90%	1552528	1786502	1887497	2052638
	95%	1670110	1581112	1464498	1390095			95%	1553611	1799232	1896046	2068552
	99%	1671940	1591984	1469972	1394959			99%	1555727	1824087	1912738	2099621
						Relative performance						
			Fatigue								Rutting	
	50%	1	0.92921	0.86948	0.82594			50%	0.7854	0.87331	0.93568	1
	70%	1	0.93851	0.87342	0.82934			70%	0.76676	0.87141	0.92533	1
	80%	1	0.94065	0.87432	0.83012			80%	0.7626	0.87098	0.92301	1
	90%	1	0.94391	0.8757	0.83131			90%	0.75636	0.87034	0.91955	1
	95%	1	0.94671	0.87689	0.83234			95%	0.75106	0.8698	0.91661	1
	99%	1	0.95218	0.8792	0.83434			99%	0.74096	0.86877	0.91099	1

S9.5B Mixture

Fatigue					Rutting				
%AC	6.13	5.72	5.43	5.21	%AC	6.13	5.72	5.43	5.21
Gyrations	50	75	100	125	Gyrations	50	75	100	125
1	2.86E+06	2.55E+06	2.26E+06	2.00E+06	1	2.43E+06	3.07E+06	3.18E+06	3.22E+06
2	2.91E+06	2.49E+06	2.28E+06	2.06E+06	2	2.67E+06	2.82E+06	3.29E+06	3.62E+06
3	2892910	2511410	2275750	2029510	3	2494240	2892910	3288750	3417750
Mean	2887637	2517137	2271917	2029837	Mean	2531413	2927637	3252917	3419250
St. Dev	25413.7	30407.17	10536.64	30001.33	St. Dev	124243.3	128566.9	63150.78	200004.2
Reliability Levels									
70%	2902896	2535394	2278243	2047851	70%	2606014	3004834	3290835	3539341
80%	2906418	2539608	2279703	2052008	80%	2623230	3022649	3299586	3567055
90%	2911773	2546016	2281924	2058330	90%	2649412	3049742	3312894	3609202
95%	2916395	2551546	2283840	2063786	95%	2672008	3073124	3324378	3645576
99%	2925419	2562342	2287581	2074439	99%	2716123	3118774	3346801	3716592
Relative performance									
	Fatigue					Rutting			
50%	1	0.871694	0.786774	0.70294	50%	0.740342	0.856222	0.951354	1
70%	1	0.873402	0.784817	0.705451	70%	0.736299	0.848981	0.929787	1
80%	1	0.873793	0.784369	0.706027	80%	0.735405	0.847379	0.925017	1
90%	1	0.874387	0.783689	0.706899	90%	0.734071	0.844991	0.917902	1
95%	1	0.874897	0.783104	0.70765	95%	0.732945	0.842973	0.911894	1
99%	1	0.875889	0.781967	0.709108	99%	0.73081	0.839149	0.900503	1

S9.5C Mixture

Fatigue					Rutting				
%AC	5.95	5.61	5.37	5.18	%AC	5.95	5.61	5.37	5.18
Gyrations	50	75	100	125	Gyrations	50	75	100	125
1	2770000	2510000	2360000	2280000	1	2220000	2530000	2710000	3030000
2	2710000	2580000	2410000	2340000	2	2050000	2240000	3120000	3150000
3	2749150	2448840	2448840	2321950	3	2155250	2406540	2814300	3056330
Mean	2743050	2512947	2406280	2313983	Mean	2141750	2392180	2881433	3078777
St. Dev	30461.6	65629.6	44536.7	30783.1	St. Dev	85800.3	145532	213085	63070.5
Reliability Levels									
70%	2761340	2552354	2433022	2332467	70%	2193268	2479564	3009379	3116647
80%	2765561	2561448	2439193	2336732	80%	2205157	2499730	3038905	3125386
90%	2771981	2575278	2448578	2343219	90%	2223238	2530398	3083809	3138677
95%	2777521	2587214	2456678	2348818	95%	2238842	2556865	3122562	3150148
99%	2788337	2610517	2472492	2359748	99%	2269307	2608540	3198222	3172542
Relative performance									
	Fatigue					Rutting			
50%	1	0.91611	0.87723	0.84358	50%	0.69565	0.77699	0.9359	1
70%	1	0.92432	0.8811	0.84469	70%	0.70373	0.79559	0.96558	1
80%	1	0.92619	0.88199	0.84494	80%	0.70556	0.79981	0.97233	1
90%	1	0.92904	0.88333	0.84532	90%	0.70834	0.8062	0.98252	1
95%	1	0.93148	0.88449	0.84565	95%	0.71071	0.81167	0.99124	1
99%	1	0.93623	0.88673	0.84629	99%	0.7153	0.82222	1.00809	1

S9.5D Mixture

	%AC	5.9	5.6	5.4	5.25		%AC	5.9	5.6	5.4	5.25
	Gyrations	50	75	100	125		Gyrations	50	75	100	125
Fatigue	1	4830000	4700000	4310000	4120000	Rutting	1	3550000	4310000	4310000	4440000
	2	4900000	4640000	4310000	4120000		2	3610000	4250000	4310000	4440000
	3	4898700	4703320	4313830	4122280		3	7739820	9747720	9967750	10187800
	Mean	4876233	4681107	4311277	4120760		Mean	4966607	6102573	6195917	6355933
	St. Dev	40044.5	35638.1	2211.25	1316.36		St. Dev	2401861	3156932	3266503	3318494
	Reliability Levels										
	70%	4900278	4702505	4312604	4121550		70%	6408790	7998135	8157270	8348504
	80%	4905827	4707444	4312911	4121733		80%	6741602	8435573	8609890	8808328
	90%	4914265	4714954	4313377	4122010		90%	7247753	9100842	9298250	9507644
	95%	4921548	4721435	4313779	4122250		95%	7684568	9674978	9892313	10111163
	99%	4935767	4734089	4314564	4122717		99%	8537397	10795912	11052152	11289462
	Relative performance										
		Fatigue						Rutting			
	50%	1	0.95998	0.88414	0.84507		50%	0.78141	0.960138	0.974824	1
	70%	1	0.95964	0.88007	0.84109		70%	0.76766	0.958032	0.977094	1
	80%	1	0.95956	0.87914	0.84017		80%	0.76537	0.957681	0.977472	1
	90%	1	0.95944	0.87773	0.83878		90%	0.76231	0.957213	0.977976	1
	95%	1	0.95934	0.87651	0.83759		95%	0.76001	0.956861	0.978356	1
	99%	1	0.95914	0.87414	0.83527		99%	0.75623	0.956282	0.97898	1

S12.5C Mixture

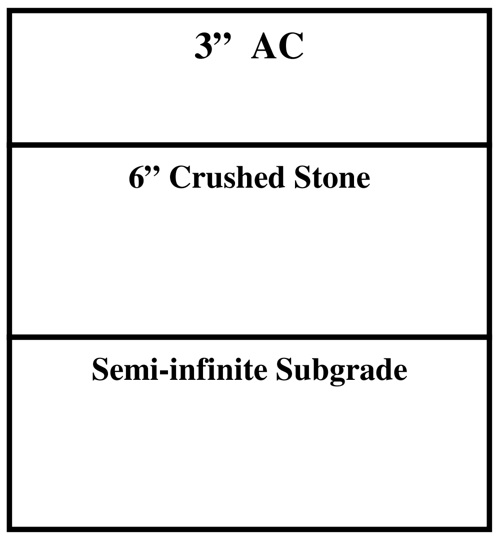
	%AC	5.71	5.41	5.2	5.03		%AC	5.71	5.41	5.2	5.03
	Gyrations	50	75	100	125		Gyrations	50	75	100	125
Fatigue	1	2.22E+06	2.18E+06	2.09E+06	1.91E+06	Rutting	1	1.63E+06	2.26E+06	2.53E+06	2.66E+06
	2	2.34E+06	2.18E+06	2.09E+06	1.91E+06		2	1.99E+06	2.28E+06	2.53E+06	2.60E+06
	3	2.26E+06	2.18E+06	2.09E+06	1.95E+06		3	1766980	2258920	2533440	2641290
	Mean	2272973	2178660	2091013	1923177		Mean	1795660	2266307	2531147	2633763
	St. Dev	61221.9	2320.95	1755.14	22822.7		St. Dev	181706	11871.1	1986.08	30700
	Reliability Levels										
	70%	2309734	2180054	2092067	1936880		70%	1904764	2273435	2532339	2652197
	80%	2318217	2180375	2092310	1940043		80%	1929942	2275079	2532614	2656451
	90%	2331118	2180864	2092680	1944852		90%	1968233	2277581	2533033	2662920
	95%	2342252	2181286	2092999	1949003		95%	2001279	2279740	2533394	2668504
	99%	2363991	2182111	2093623	1957107		99%	2065797	2283955	2534099	2679404
	Relative performance										
		Fatigue						Rutting			
	50%	1.00	0.96	0.92	0.85		50%	0.68178	0.86048	0.96104	1
	70%	1.00	0.94	0.91	0.84		70%	0.71818	0.85719	0.95481	1
	80%	1.00	0.94	0.90	0.84		80%	0.72651	0.85644	0.95338	1
	90%	1.00	0.94	0.90	0.83		90%	0.73913	0.85529	0.95122	1
	95%	1.00	0.93	0.89	0.83		95%	0.74996	0.85431	0.94937	1
	99%	1.00	0.92	0.89	0.83		99%	0.77099	0.85241	0.94577	1

						S12.5D Mixtures						
	%AC	5.47	5.18	4.97	4.81			%AC	5.47	5.18	4.97	4.81
	Gyrations	50	75	100	125			Gyrations	50	75	100	125
	1	3930000	3490000	3170000	2860000			1	3490000	3930000	3930000	4120000
	2	3990000	3550000	3240000	2920000			2	3550000	3990000	4120000	4190000
Fatigue	3	3990000	3550000	3240000	2860000		Rutting	3	3490000	3930000	3990000	4190000
	Mean	3970000	3530000	3216667	2880000			Mean	3510000	3950000	4013333	4166667
	St. Dev	34641	34641	40414.5	34641			St. Dev	34641	34641	97125.3	40414.5
						Reliability Levels						
	70%	3990800	3550800	3240933	2900800			70%	3530800	3970800	4071652	4190933
	80%	3995600	3555600	3246533	2905600			80%	3535600	3975600	4085110	4196533
	90%	4002900	3562900	3255050	2912900			90%	3542900	3982900	4105577	4205050
	95%	4009200	3569200	3262400	2919200			95%	3549200	3989200	4123241	4212400
	99%	4021500	3581500	3276750	2931500			99%	3561500	4001500	4157727	4226750
						Relative performance						
			Fatigue							Rutting		
	50%	1	0.88917	0.81024	0.72544			50%	0.8424	0.948	0.9632	1
	70%	1	0.88975	0.8121	0.72687			70%	0.84249	0.94747	0.97154	1
	80%	1	0.88988	0.81253	0.7272			80%	0.8425	0.94735	0.97345	1
	90%	1	0.89008	0.81317	0.7277			90%	0.84253	0.94717	0.97634	1
	95%	1	0.89025	0.81373	0.72813			95%	0.84256	0.94701	0.97883	1
	99%	1	0.89059	0.81481	0.72896			99%	0.84261	0.94671	0.98367	1

APPENDIX D: Input Parameter Values for DARWin-ME Analysis

Appendix D1 S9.5A Darwin-ME inputs

Traffic Info		Climatic Info	
Initial Two-way AADTT	600	Latitude	35.871
No. of Lanes in Design Direction	2	Longitude	-78.786
Growth Rate (%)	2	Elevation	397
Other Traffic Inputs	Default	Depth to Water Table (ft)	20
Operational Speed	35		



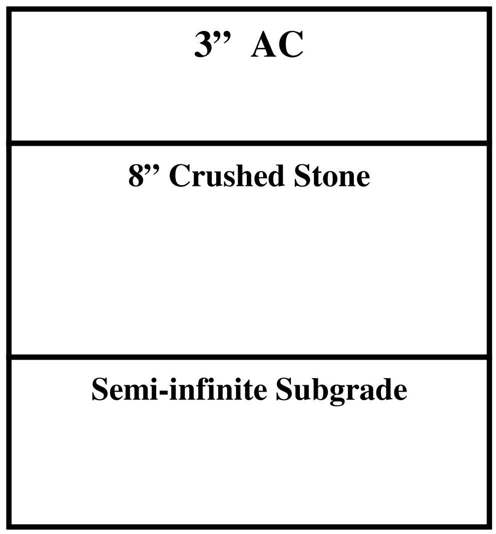
HMA Properties		
Binder Type	PG 64-22	
Air Voids (%)	8	
Unit Weight (Pcf)	142.6	
Effective Binder Content (%)	50 Gyrations	12
	75 Gyrations	11.5
	100 Gyrations	11.1
	125 Gyrations	10.8

Other Layer Properties			
Subgrade		Aggregate Base	
Type	A-7-5	Type	Crushed Stone
Resilient Modulus (Psi)	6700	Resilient Modulus (Psi)	23628

Appendix D2

S9.5B Darwin-ME inputs

Traffic Info		Climatic Info	
Initial Two-way AADTT	900	Latitude	35.871
No. of Lanes in Design Direction	2	Longitude	-78.786
Growth Rate (%)	2	Elevation	397
Other Traffic Inputs	Default	Depth to Water Table (ft)	20
Operational Speed	45		



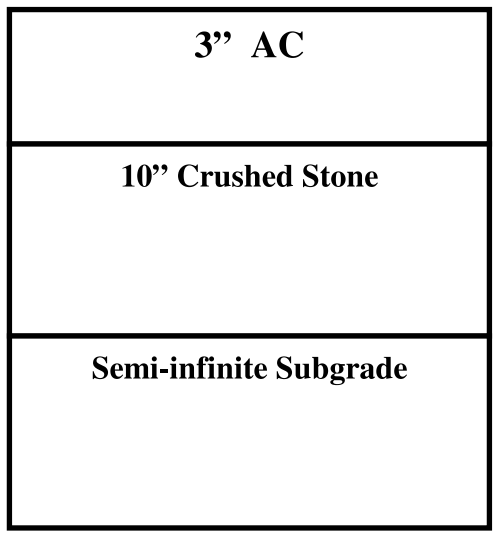
HMA Properties		
Binder Type	PG 64-22	
Air Voids (%)	8	
Unit Weight (Pcf)	142.6	
Effective Binder Content (%)	50 Gyrations	12.3
	75 Gyrations	11.5
	100 Gyrations	10.9
	125 Gyrations	10.4

Other Layer Properties			
Subgrade		Aggregate Base	
Type	A-7-5	Type	Crushed Stone
Resilient Modulus (Psi)	6700	Resilient Modulus (Psi)	23628

Appendix D3

S9.5C Darwin-ME inputs

Traffic Info		Climatic Info	
Initial Two-way AADTT	1200	Latitude	35.871
No. of Lanes in Design Direction	2	Longitude	-78.786
Growth Rate (%)	2	Elevation	397
Other Traffic Inputs	Default	Depth to Water Table (ft)	20
Operational Speed	55		



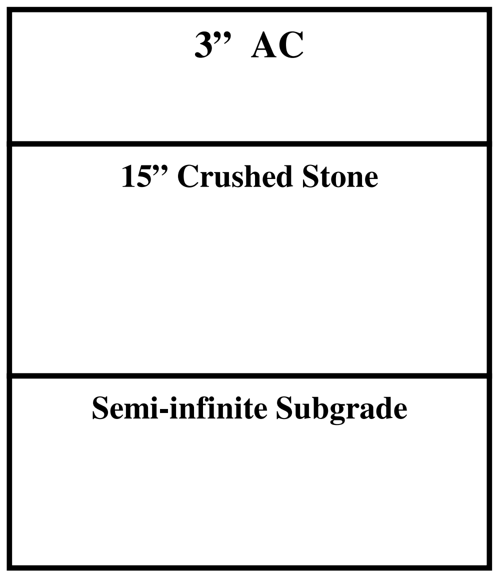
HMA Properties		
Binder Type	PG 70-22	
Air Voids (%)	8	
Unit Weight (Pcf)	142.6	
Effective Binder Content (%)	50 Gyrations	11.9
	75 Gyrations	11.2
	100 Gyrations	10.8
	125 Gyrations	10.4

Other Layer Properties			
Subgrade		Aggregate Base	
Type	A-7-5	Type	Crushed Stone
Resilient Modulus (Psi)	6700	Resilient Modulus (Psi)	23628

Appendix D4

S9.5D Darwin-ME inputs

Traffic Info		Climatic Info	
Initial Two-way AADTT	4000	Latitude	35.871
No. of Lanes in Design Direction	2	Longitude	-78.786
Growth Rate (%)	2	Elevation	397
Other Traffic Inputs	Default	Depth to Water Table (ft)	20
Operational Speed	65		



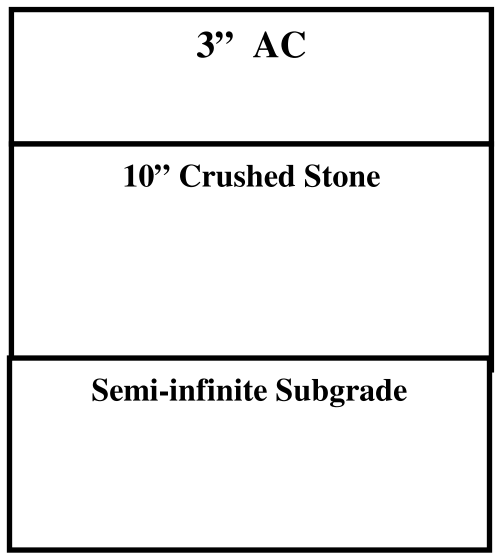
HMA Properties		
Binder Type	PG 76-22	
Air Voids (%)	8	
Unit Weight (Pcf)	142.6	
Effective Binder Content (%)	50 Gyrations	11.8
	75 Gyrations	11.2
	100 Gyrations	10.8
	125 Gyrations	10.5

Other Layer Properties			
Subgrade		Aggregate Base	
Type	A-7-5	Type	Crushed Stone
Resilient Modulus (Psi)	6700	Resilient Modulus (Psi)	23628

Appendix D5

S12.5C Darwin-ME inputs

Traffic Info		Climatic Info	
Initial Two-way AADTT	1200	Latitude	35.871
No. of Lanes in Design Direction	2	Longitude	-78.786
Growth Rate (%)	2	Elevation	397
Other Traffic Inputs	Default	Depth to Water Table (ft)	20
Operational Speed	55		



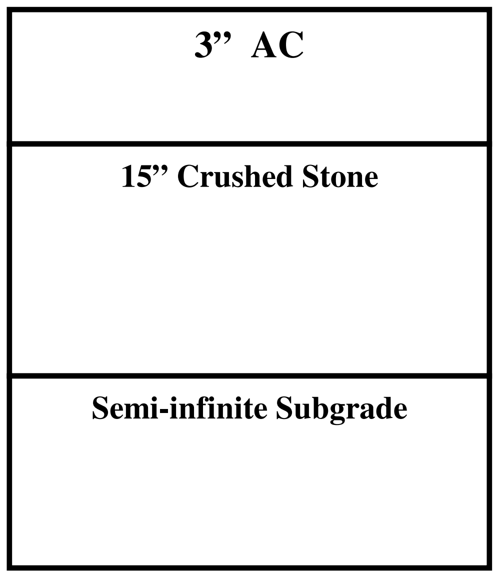
HMA Properties		
Binder Type	PG 70-22	
Air Voids (%)	8	
Unit Weight (Pcf)	142.6	
Effective Binder Content (%)	50 Gyrations	11.4
	75 Gyrations	10.8
	100 Gyrations	10.4
	125 Gyrations	10

Other Layer Properties			
Subgrade		Aggregate Base	
Type	A-7-5	Type	Crushed Stone
Resilient Modulus (Psi)	6700	Resilient Modulus (Psi)	23628

Appendix D6

S12.5D Darwin-ME inputs

Traffic Info		Climatic Info	
Initial Two-way AADTT	4000	Latitude	35.871
No. of Lanes in Design Direction	2	Longitude	-78.786
Growth Rate (%)	2	Elevation	397
Other Traffic Inputs	Default	Depth to Water Table (ft)	20
Operational Speed	65		



HMA Properties		
Binder Type	PG 76-22	
Air Voids (%)	8	
Unit Weight (Pcf)	142.6	
Effective Binder Content (%)	50 Gyrations	11
	75 Gyrations	10.4
	100 Gyrations	10
	125 Gyrations	9.6

Other Layer Properties			
Subgrade		Aggregate Base	
Type	A-7-5	Type	Crushed Stone
Resilient Modulus (Psi)	6700	Resilient Modulus (Psi)	23628