FINAL REPORT

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EVALUATION OF LABORATORY TESTING SYSTEMS FOR ASPHALT MIXTURE DESIGN AND EVALUATION

VOLUME II

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EXECUTIVE SUMMARY

Instability rutting is a major distress mode in hot mix asphalt (HMA) pavements that occurs when the structural properties of the compacted mix cannot resist near surface critical stress conditions caused by traffic loads. This mode of failure reduces serviceability and creates the hazard of hydroplaning because of accumulated water in the wheel-path ruts. Rehabilitation of this type of rutting usually involves asphalt concrete (AC) overlay or mill and replace. It was determined that there is no reliable existing approach for instability-rutting assessment of HMA. This study was undertaken to identify or develop laboratory test methods suitable for assessing instability rutting potential of asphalt mixture.

It was determined that critical stress states associated with instability rutting involve shear in the presence of minimal confinement or tension, which is a stress state that cannot be induced by existing laboratory tests in their present form. A modified version of the asphalt pavement analyzer (APA) was developed with a loading device that induces stress states similar to those found under radial truck tires. In addition, a modified measurement and interpretation method that is far more sensitive to the presence of instability rutting was developed for the APA. For purposes of quality control, a test method involving measurements obtained during instability induced using the gyratory compactor was developed.

The primary accomplishments of this work may be summarized as follows:

- Identified potential stress states that might be conducive to impending instability based on measured surface contact stresses under radial truck tires. Current mixture design and evaluation procedures do not properly account for these critical stress states – high near-surface shear stress with reduced confinement or tension.

- Determined that existing equipment, testing, and interpretation procedures may not capture these stress states and their effects.

- Identified test methods that would provide measurements of instability rutting resistance based on stress states identified above.

- Three approaches were identified to evaluate mixtures under conditions of impending instability:

  - Evaluation during the compaction process using the Servopac gyratory compactor, suitable for mix design and QC/QA
  - Mixture evaluation using a laboratory physical model with modified APA
  - Hollow Cylinder as a research tool for evaluation of the impending instability concept

- Specific procedures were developed and evaluated on a range of mixtures of known relative performance and verified the ability of the devices to distinguish between mixtures with varying performance. Specific parameters and criteria suitable for mixture design and specification purposes were determined.

The following conclusions were drawn from this study:

- Existing systems – even the dynamic modulus approach proposed as part of the new AASHTO pavement design guide – are unable to screen mixtures susceptible to instability rutting.

- Keys to developing a relevant test are a) to capture the critical stress states associated with instability (APA), and b) to measure the mixture's strength at impending instability (Servopac).

- Evaluation using the existing APA device could immediately improved by obtaining a detailed profile of the rutted surface, but greater 'reliability' can be achieved by introducing a modified loading system that more closely represents tire stresses.

The following recommendations are based on the findings and conclusions from this study:

- The implementation of the system on a large scale would require the capability to easily apply two angles of gyration and to measure the gyratory shear strength during the compaction process (Servopac or with modification to existing gyratory compactors widely available at this time)

- The new data-measurement method should be implemented immediately with the existing APA equipment.

- Whenever possible, specimens should be tested at both 7%AV and 4%AV when evaluating the mixture's ability to resist instability with the APA.

- At this point there is not enough evidence to support a move to higher temperature testing for single-condition test (specimen tested at one temperature).

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CHAPTER 1

SUPERPAVE™ GYRATORY COMPACTOR

1.1 BACKGROUND

One prevalent sign of pavement distress is rutting, which manifests itself as longitudinal depressions that form under traffic in the wheel path. Asphalt mixture rutting is generally a costly failure, which poses a considerable safety problem in terms of potential hydroplaning. Motorist comfort is also compromised. There are basically three different types of pavement ruts [Dawley, et al. 1990]. The first one is wear rutting, which is due to progressive loss of coated aggregate particles from the pavement surface. The second one is structural rutting, which is due to the permanent deformation of the pavement structure under repeated traffic loads, and may be a reflection of permanent deformation within the subgrade or inadequate compaction of the base layer. The third type of rutting is instability rutting within the wheel paths, which is due to lateral displacement of material within the asphalt concrete layer. Instability rutting occurs when the strength and/or stiffness properties of the compacted pavement are inadequate to resist the applied wheel loads. This project presents the development of a simple index test for instability rutting. The equipment used for obtaining the necessary parameters to evaluate the likelihood of rutting are obtained from Superpave™ gyratory compactor measurements with gyratory shear measurements.

Although the Superpave™ volumetric mixture design procedure has resulted in some significant improvements over the Marshall method of mixture design, it essentially remains a volumetric design procedure, except that a different compaction method is used to produce the laboratory specimens. Superpave™ Level I does not require any physical performance test on the asphaltic mixture to determine whether or not the volumetric design would actually result in a mixture with suitable resistance to rutting or cracking.

It is widely recognized among the pavement engineering community that a physical index test to evaluate rutting potential of asphalt mixtures is needed to verify results of volumetric designs. Furthermore, physical index tests that can be used to evaluate the rutting potential of mixtures may serve many other useful and necessary purposes (e.g., optimizing rutting resistance during mixture design). Therefore, the identification of an appropriate simple laboratory testing system that can be used to provide an index of the rutting potential of asphalt mixtures is crucial for successful design and production of rut-resistance asphalt mixtures. Ideally, the simple index test should allow testing during compaction/mix design to provide a history of responses under conditions representative of the field.

Current Superpave™ gyratory compactors operate on a "shear compaction" principle, meaning that compaction occurs under not only vertical pressure, but also shear displacement. These two elements allow for a closer simulation of mechanisms of field compaction. The Superpave™ gyratory compactor was developed only to densify mixtures. No attempts were made to measure resistance to compaction or gyratory shear strength during compaction, or to use the device to gauge mixture stability or sensitivity.

However, because of the implied relationship between compaction and mixture strength, numerous attempts have been made to develop compaction parameters that relate to the evolution of mixture strength. A number of gyratory compactors have now been developed that not only measure the change in height during compaction, but also the resistance to compaction through a parameter called the 'gyratory shear strength.' These include the Finnish Intensive Compaction Tester (ICT) gyratory compactor, the Superpave™ compatible Australian Servopac gyratory compactor, and the Gyratory Testing Machine (GTM). These compactors all were developed under the basic assumption that likely field performance of asphalt mixtures could be inferred by measuring the gyratory shear strength. These gyratory compactors have the advantages of simplicity of testing and the ability to obtain the gyratory shear for the range of void conditions experienced during compaction.

The gyratory compactor has been proved over the years to provide responses representative of the field during compaction. It provides densities in the laboratory specimen that closely approximate the ultimate densities of the asphalt concrete pavement when subjected to in-service traffic loads and climatic conditions and is likely to be a versatile tool when adapted with shear measurements for the evaluation of the shear resistance of paving mixtures which is indicative of their rutting resistance.

Various researchers have proposed methods of analysis of the compaction curve obtained from the Superpave gyratory compactor to evaluate the resistance to permanent deformation of asphalt mixtures [Anderson 1997, Langlois 1998, McGennis 1997, and Tarn et al. 1999] proposed the use of the compaction slope. Mallick (1999) suggested the use of parameters such as the Gyratory Ratio (N98 / N95), introduced the locking point concept, and Bahia (1998) proposed the use of the terminal densification energy (TDI92-98) which is the area bounded by the compaction curve from 8% air voids to 2% air voids.

Butcher (1998) and Guler (2000), presented procedures for measuring shear resistance of asphalt mixtures during compaction in the Servopac Superpave™ compatible gyratory compactor. Butcher (1998) discussed the use of the maximum shear stress with the Servopac compactor, and noted that mixtures using softer asphalt binders appear to have lower maximum shear stresses than mixtures with harder asphalt binders. Guler (2000) discussed the development of a shear measuring device to be used in conjunction with Superpave™ compatible compactors. Mixtures with higher asphalt binder contents experience drastic drops in shear resistance when compacted beyond the maximum shear. Anderson (2002), using the Superpave™ compactor with shear measurements proposed the parameter of cycles at maximum stress ratio (N-SRmax) as a measure of the permanent deformation resistance of mixtures.

The above developments are however not conclusive, with no single method capable of consistently identifying the true rutting potential of mixtures. Critical field conditions that may trigger rutting instability in the field are not captured in the present Superpave mode of compaction, which is used for mixture design purposes only. The Australian Servopac gyratory compactor allows for the change in gyratory angle during compaction. Thus, it is possible to compact at 1.25 degree gyratory angle up to a density level that corresponds to field compaction, and then increase the gyratory angle to 2.5 degrees to induce a shear failure in the mixture, which may be more consistent with observed rutting instability shear failures in the field.

1.2 RESEARCH HYPOTHESIS

Instability rutting occurs when the mixture fails under a state of high shear stresses at low confinement. Using the Superpave gyratory compactor (SGC), it is possible to compact hot mix asphalt mixtures to a density that is consistent with the density of field pavements immediately after construction. The subsequent application of high shear stresses by increasing the gyratory angle to 2.5 degrees will result in material states at which parameters can be measured that are relevant to instability rutting and rutting resistance.

1.3 OBJECTIVES

The primary objective of this research is to develop a new testing procedure for evaluating the rutting potential of mixtures using the Superpave gyratory compactor with shear measurements. A secondary objective is to quantify the various parts of the typical compaction curve obtained from the Superpave gyratory compactor with shear measurements. In particular, three main parts of compaction curves are of interest, namely the compaction part of the curve (air voids higher than 7 %), the densification part of the curve (air voids between 7 and 4 %), and the post peak part of the curve (air voids typically lower than 4 %).

Results from our study showed that the SGC using gyratory shear measurements and a modified compaction procedure can be used to evaluate the rutting potential of mixtures. A set of simple evaluation charts are developed and presented for evaluating the rutting resistance of mixtures. The results also show that the compaction curve can be broken down into three separate parts, which have distinct characteristics. Importantly, the post-peak part of the compaction curve is shown to be unsuitable for evaluating the stability of mixtures, due to the high degree of material degradation associated with a fixed gyration angle and low air voids.

1.4 SCOPE

Goals of our research were as follows:

- To conduct a thorough literature review of the state of practice of the use of the Superpave gyratory compactor with and without shear measurements for evaluating the rutting potential of asphalt mixtures and its comparison to other potentially suitable laboratory based testing systems.
- To obtain data on Florida mixtures of known relative rutting performance with emphasis on gradation effects, aggregate type, and fine aggregate type.
- To test mixtures using the Servopac gyratory compactor with gyratory shear measurements. Two replicates were tested per each mixture. The compaction curves from the Servopac are analyzed so as to delineate the compaction, densification, as well as instability zones of asphalt paving mixtures.

- To perform Asphalt Pavement Analyzer (APA) and Superpave Indirect Tension (IDT) tests to independently evaluate the rutting and creep behavior of these mixtures.

A total of 32 different mixtures, consisting of 10 mixes in which the aggregate type in the fine portion of the gradation (defined as material passing the No. 4 Sieve) is varied, eight limestone mixtures consisting of the same aggregate type, but different gradations, six granite mixtures consisting of the same aggregate type, but different gradations, six field mixtures of known field performance, and finally two mixtures from accelerated pavement testing using the Heavy Vehicle Simulator. One of the field mixtures, project number 8, was obtained from the plant; however, there was not enough for all the tests.

CHAPTER 2

PHASE I:

PRELIMINARY EVALUATION OF GYRATORY SHEAR STRENGTH

2.1 OVERVIEW

Current Superpave™ gyratory compactors operate on a "shear compaction" principle, meaning that compaction occurs under not only vertical pressure, but also shear displacement. These two elements allow for a closer simulation of the mechanisms of field compaction. However, the Superpave™ gyratory compactor was developed only to densify mixtures [Huber, 2000]. No attempts were made to measure resistance to compaction or gyratory shear strength during compaction, or to use the device to gauge mixture stability or sensitivity.

Because of the implied relationship between compaction and mixture strength, numerous attempts have been made to develop compaction parameters that relate to the evolution of mixture strength. A number of gyratory compactors have now been developed that not only measure the change in height during compaction, but also the resistance to compaction through a parameter called the 'gyratory shear strength.' These include the Finnish Intensive Compaction Tester (ICT) gyratory compactor, the Superpave™ compatible Australian Servopac gyratory compactor, and the previously developed Gyratory Testing Machine (GTM). These compactors all were developed under the basic assumption that likely field performance of asphalt mixtures could be inferred by measuring the gyratory shear strength. These gyratory compactors have the advantages of simplicity of testing and the ability to obtain the gyratory shear for the range of void conditions experienced during compaction. However, questions remain as to both the meaning of the gyratory shear strength and its relationship to mixture properties, such as stability and sensitivity.

The objectives of this study were to explore the use of the gyratory shear strength parameter as an index of mixture sensitivity and stability, while maintaining the Superpave™ framework for compaction, and to evaluate the effects of gyratory angle on compaction.

2.2 MATERIALS AND METHODS

2.2.1 Aggregate Selection

Four types of aggregates were used, including oolitic crushed limestone (L1, L6 from Florida, and L4 from Alabama), and one crushed granite (G1) from Georgia. All of these aggregates are used extensively in Florida and have been found to have varying performance in the field. The L4 aggregates have generally resulted in mixtures with good rutting performance in the field the rest – L6, L1, and G1 – following closely in order.

2.2.2 Mixture Design

The mixtures used as a basis for this study included a previously designed coarse-graded (L1C) and a fine-graded (L1F) Superpave™ mixture prepared by the Florida Department of Transportation (FDOT). The fine- and coarse-graded limestone L1F and L1C mixtures were both made up of crushed oolitic limestone from South Florida and Granite (G1) mineral filler blended together in different proportions, to meet current Superpave™ mixture design criteria. The effects of gradation and filler type on permanent deformation were minimized by volumetrically replacing the fine aggregate portion (minus the No. 4 Sieve size) of L1C and L1F with the three other fine aggregates. This procedure produced a total of four fine-graded and four coarse-graded mixtures (L1F, L1L4F, L1L6F, L1G1F, L1C, L1L4C, L1L6C, and L1G1C). Using the known weights of the aggregate that was retained on the No. 8 sieve through the No. 200 sieve for the L1C and L1F mixtures, the equivalent weights of the other aggregates were obtained by equal volumetric conversion using the specific gravity of the fine aggregate in question. For example, the L1L6F mix was obtained by replacing the fine portion of a L1F mixture by the L6 aggregate, etc.

Table 2-1 shows the gradation for the eight mixtures studied. Design asphalt contents for all the mixtures were determined such that each mixture had 4 percent air voids at N_{design} = 109 revolutions using a gyratory angle of 1.25 degrees. The asphalt used was AC-30 asphalt, commonly used in highway construction in Florida. Table 2-2 summarizes the volumetric properties of the mixtures studied.

Table 2-1. Gradations for limestone mixtures.

Sieve Size	Percent Passing							
	L1F	L1L6F	L1L4F	L1G1F	L1C	L1L6C	L1L4C	L1G1C
19 (3/4)	100	100	100	100	100	100	100	100
12.5 (1/2)	96	94.7	94.9	95.1	97.4	97.4	97.5	97.5
9.5 (3/8)	85	83.8	84.6	85.0	90	88.8	89.3	89.5
4.75 (#4)	69	66.0	67.6	68.5	60.2	54.8	56.5	57.6
2.36 (#8)	53	49.4	50.6	51.2	33.1	30.4	31.2	31.6
1.18 (#16)	34	33.3	33.9	34.3	20.3	20.5	20.9	21.1
600 (#30)	23	21.9	22.2	22.4	14.7	14.8	15.0	15.1
300 (#50)	15	13.9	14.0	14.0	10.8	11.0	11.0	11.0
150 (#100)	9.6	7.0	6.9	6.8	7.6	7.2	7.1	7.0
75 (#200)	4.8	4.5	4.3	4.2	4.8	5.5	5.3	5.2

2.3 Research Approach

This study uses mixtures consisting of aggregates with known rutting field performance to evaluate the use of the gyratory shear strength as an index for mixture stability and sensitivity. The research approach essentially involved evaluating changes in gyratory shear strength and mixture compactibility caused by changes in mixture gradations (coarse- versus fine-graded mixtures), aggregate type, and gyratory angle.

Table 2-2. Mixture properties.

Specimen		L1F	L1L6F	L1L4F	L1G1F	L1C	L1L6C	L1L4C	L1G1C
Maximum Specific Gravity	Gmm	2.338	2.381	2.480	2.410	2.328	2.386	2.454	2.393
Specific Gravity of Asphalt	Gb	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035
Bulk Specific Gravity of Compacted Mix	Gmb	2.247	2.293	2.378	2.311	2.249	2.297	2.337	2.308
Asphalt Content	Pb	6.5	6.7	5.3	5.9	6.3	6.5	5.8	6.25
Mixture Properties									
Bulk Specific Gravity of Aggregate	Gsb	2.448	2.403	2.524	2.488	2.469	2.418	2.535	2.578
Effective Specific Gravity of Aggregate	Gse	2.554	2.630	2.691	2.634	2.549	2.625	2.680	2.622
Asphalt Absorption	Pba	1.077	3.72	2.54	0.574	1.075	3.375	2.209	0.705
Effective Asphalt Content of Mixture	Pbe	5.29	3.23	3.41	5.7	5.27	3.34	3.72	5.6
Percent VMA in Compacted Mix	VMA	15.5	11.2	10.5	16.0	15.4	11.2	12.6	16.1
Percent Air Voids in Compacted Mix	Va	4.03	3.89	3.8	3.73	3.99	3.75	4.11	3.85
Percent VFA in Compacted Mix	VFA	74.0	65.2	63.8	76.8	74.0	66.5	67.4	77.3
Dust/Asphalt Ratio		0.74	0.83	1.18	0.761	1.16	1.04	0.614	0.816
Surface Area (m^2 /kg)	SA	4.19	4.4	4.3	4.3	5.3	4.8	4.7	4.7
Film Thickness (microns)	FT	8.9	6.3	5.2	10.2	8.4	7.0	9.3	7.8

The following tests and analyses were performed:

- Mixtures were designed according to the Superpave™ volumetric mix design method. The base mixtures were two existing FDOT limestone mixtures with 12.5 mm nominal maximum aggregate size. Other 12.5 mm mixtures were designed to have similar gradations by volumetrically replacing the fine aggregates in the two base mixtures with three other aggregate types. A total of eight different types of mixtures comprising four fine-graded and four coarse-graded mixes were obtained. Mixtures were then produced at their determined design asphalt content for testing.
- The designed mixtures were produced in the laboratory following the Superpave™ procedure. Once the mixing was completed, the loose mixture was short-term oven aged for two hours at 135C (275F) before compaction. The specimens were then compacted in the IPC Servopac Superpave™ gyratory compactor to N_{max} = 174 gyrations at a gyratory angle of 1.25 degrees. Two samples of each mix were prepared. This procedure was repeated with samples compacted at a gyratory angle of 2.5 degrees. The results were used to study the relationship between gyratory shear strength, mixture compactibility, and volumetrics during compaction.
- To evaluate the effects of mixture sensitivity to asphalt content, mixtures with asphalt contents 0.5 percent above and below the design asphalt content were prepared in the same way as described previously. Samples were compacted at gyratory angles of 1.25 and 2.5 degrees, and the relationship between gyratory shear strength, mixture compactibility, and volumetrics during compaction were studied. Finally, comparison between Gyratory Testing Machine (GTM) compacted mixtures and mixtures compacted at gyratory angles of 1.25 and 2.5 degrees was also performed.

2.4 RESULTS

2.4.1 Servopac Gyratory Compactor versus Gyratory Testing Machine Results

Gyratory Testing Machine (GTM) compacted specimens have been shown to correlate well with field compaction [Ruth & Schaub, 1966; Sirgurjonsson & Ruth, 1990]. The angle of compaction in the GTM starts out at about 3 degrees, and ends up at around 1 degree or less. This variable angle is thought to be somewhat consistent with the process of field compaction, in which the compactor impacts the mat at higher angles at lower densities. In contrast to the

GTM, the Servopac gyratory compactor and other Superpave™ compactors use the same angle throughout the compaction process, so that the specimen continues to deform in shear throughout the compaction process. This means that the compaction process is somewhat analogous to a strain-controlled loading system. In contrast, the GTM angle of gyration changes in response to the resistance of the mixture during compaction, and hence is therefore somewhat analogous to a stress-controlled loading system. As such, since the Servopac at higher angles continues to shear the specimen ad infinitum, the aggregate and gradation characteristics should be brought out in a clear fashion throughout the compaction process.

Butcher [1998], comparing the Australian Servopac with the Superpave™ gyratory compactor, observed that the compaction process is highly sensitive to the gyratory angle below one degree and to a lesser extent between one and two degrees. This is explained by the observation that gyratory compactors with fixed angles of gyration less than two degrees are likely to have minor fluctuations in the angle during compaction. These fluctuations obviously affect the densification curves obtained. However, at angles of gyration between 2.0 to 3.0 degrees, the densification was found to be stable. Hence, in this study, the Servopac was kept at two angles, namely 1.25 degrees and 2.5 degrees for comparison purposes.

Figure 2-1 shows a typical comparison between air voids versus number of cycles for the GTM and the Servopac at 1.25 degrees and 2.5 degrees for the L1C mix. For a low number of cycles, the results show a close relationship between the densification obtained with the GTM and the Servopac at 2.5 degrees. As expected, with continued compaction, the GTM curve flattens and moves toward the densification curve obtained with the Servopac at 1.25 degrees.

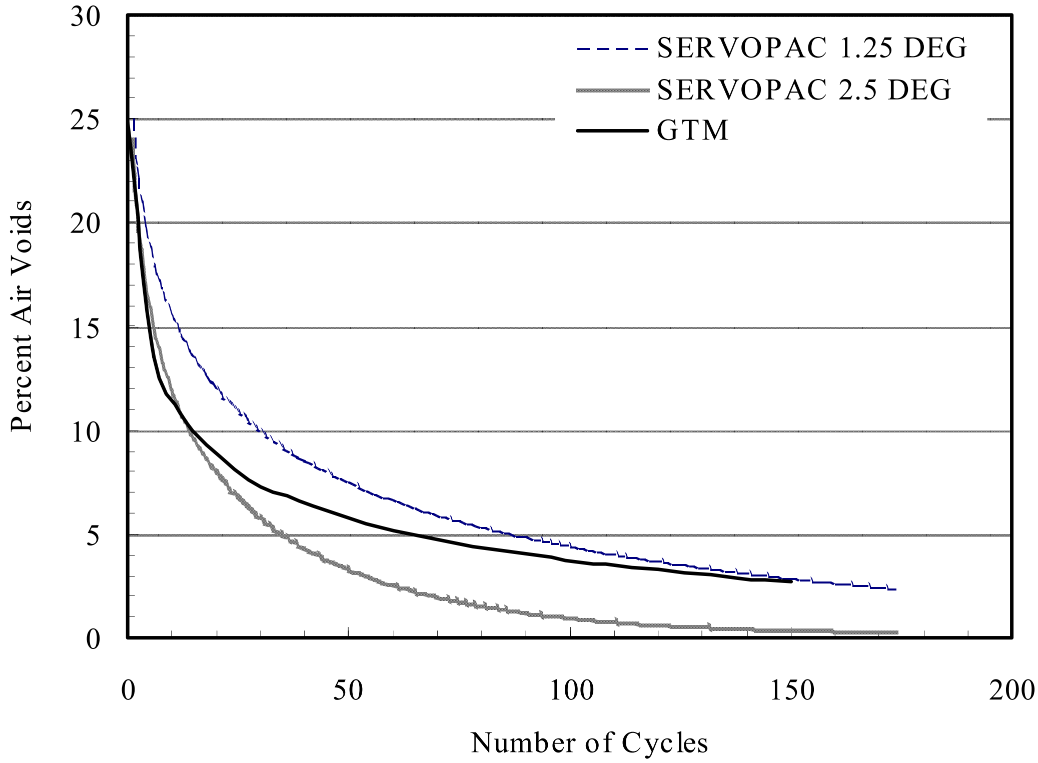


Figure 2-1. A typical comparison between air voids versus number of cycles for the L1C mix using GTM and Servopac at 1.25 and 2.5 degrees.

2.4.2 Gyratory Shear Strength and Stability

The gyratory shear strength can be thought of as the resistance of the mixture to compaction [Ruth & Schaub, 1966]. As a mix becomes denser, the gyratory shear will increase. Hence, the maximum gyratory shear strength achieved during compaction may not be a sufficient indicator of the rutting resistance of the mixture. For mixtures with stability problems, the resistance to compaction and hence the gyratory shear, will reach a peak and drop off at some point during compaction. Conversely, stable mixtures will not show this decrease in gyratory shear. Rather, the gyratory shear at low air void contents will tend to flatten out and become steady.

Table 2-3 shows the maximum gyratory shear strength reached during compaction with 1.25 and 2.5 degree gyratory angles, as well as the gyratory shear ratio defined as shear strength at N_{max} (174 cycles) over the maximum shear strength achieved during compaction. The only reason N_{max} was selected was to ensure that any post-peak drop would be taken into account, if present. The trends in the gyratory shear strength generally agree with historical experience. The coarse- and fine-graded L1L4 and L1L6 mixtures tended to show the highest gyratory shear strength, followed by the L1 and L1G1 mixtures. The gyratory shear ratio also shows the same trend at 2.5 degrees. However, the gyratory shear ratio obtained at a gyratory angle of 1.25 degrees does not clearly differentiate between the mixtures.

Figures 2-2 and 2-3 illustrate the difference between the compaction curves at 1.25 and 2.5 degrees, by comparing typical plots of the percent of maximum shear stress versus the volumetric strains at 1.25 and 2.5 degrees respectively. In this case, volumetric strain is defined as the decrease in volume from the start of compaction divided by the sample volume at the start of the gyratory compaction.

Table 2-3. Gyratory shear stress ratio and maximum shear stress.

AGGREGATE BLEND	1.25 Degrees		2.5 Degrees	
	$(Gs)@N_{max}/(Gs)_{max}$	Maximum Gs (kPa)	$(Gs)@N_{max}/(Gs)_{max}$	Maximum Gs (kPa)
COARSE AGGREGATE BLENDS				
L1L4C	0.99	525	0.86	541
L1L6C	0.985	498	0.90	557
L1C	1.00	476	0.75	515
L1G1C	0.99	459	0.69	485
FINE AGGREGATE BLENDS				
L1L4F	0.995	533	0.895	565
L1L6F	0.99	497	0.92	568
L1F	0.98	483	0.82	535
L1G1F	0.97	472	0.74	521

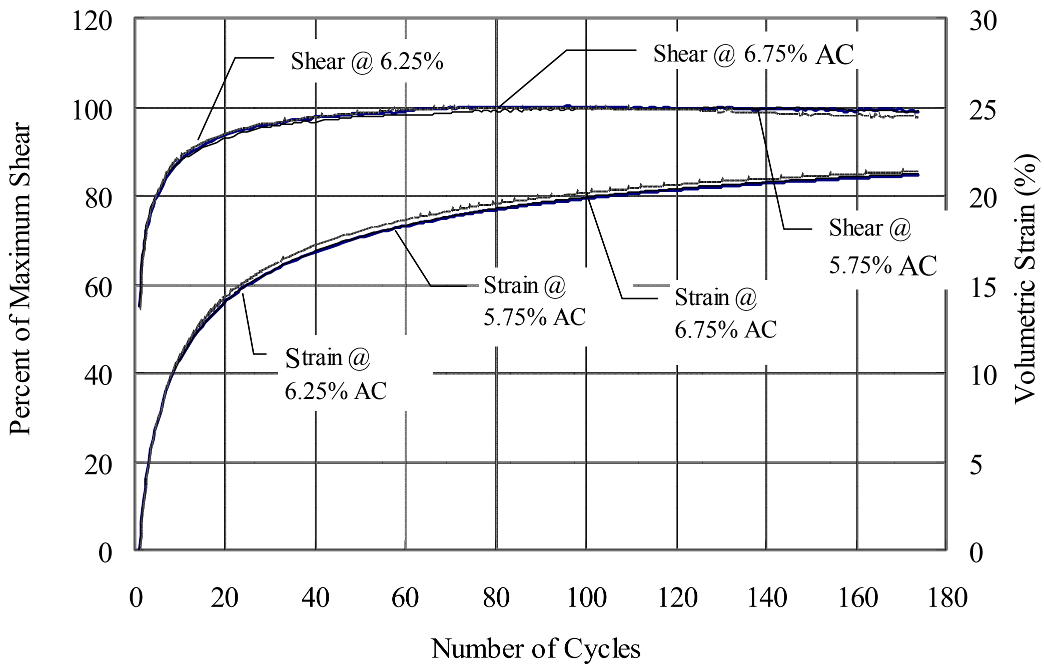


Figure 2-2. Servopac at 1.25 degrees: percent maximum shear and volumetric strain for L1G1C mix

The compaction curves for the two gyratory angles show a similar behavior up to the maximum shear stress. However, past the peak, the results differ drastically. The samples compacted at the 1.25 degree gyratory angle do not show a significant post-peak drop in the gyratory shear strength, whereas the samples compacted at 2.5 degrees show a drastic post-peak drop. Also, the volumetric strain curves at the different asphalt contents are virtually identical for the 1.25 degrees, whereas a clear distinction between curves with different asphalt contents can be seen at 2.5 degrees. This indicates that specimens compacted at 1.25 degrees may not have been sheared far enough to evaluate their stability using the gyratory shear strength.

2.4.3 Gyratory Shear Strength and Sensitivity

A proper understanding of mixture sensitivity with respect to asphalt content and gradation is important in all aspects of mix optimization, mix design, and mix production. Figures 2-4 and 2-5 show typical plots of air voids versus percent of maximum gyratory shear

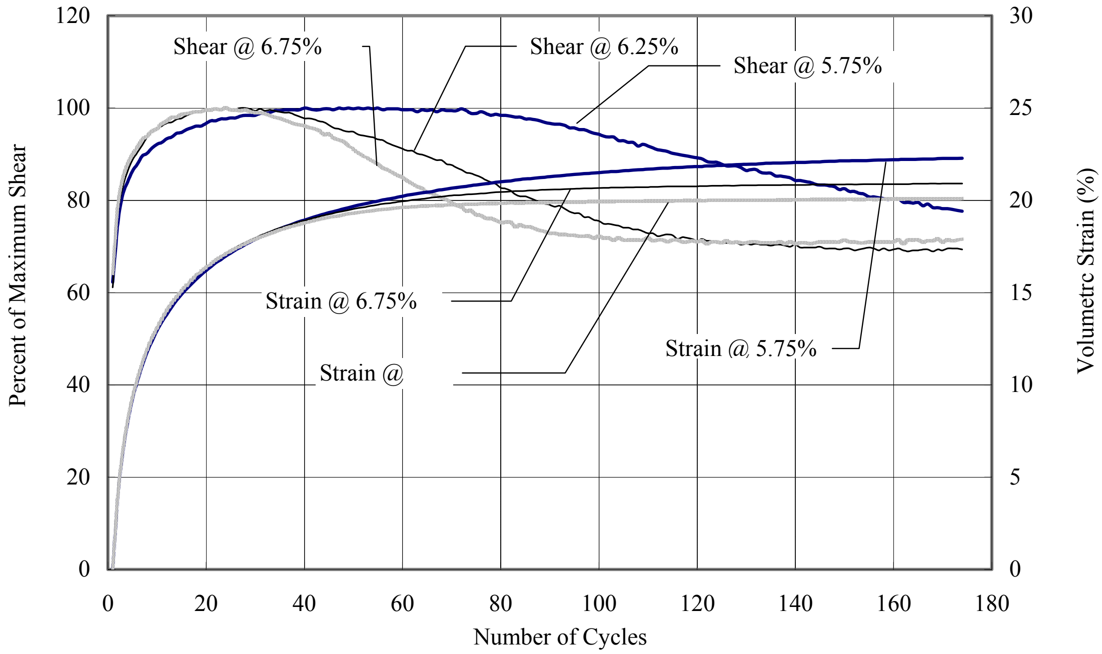


Figure 2-3. Servopac at 2.5 degrees: percent maximum shear and volumetric strain for L1G1C mix.

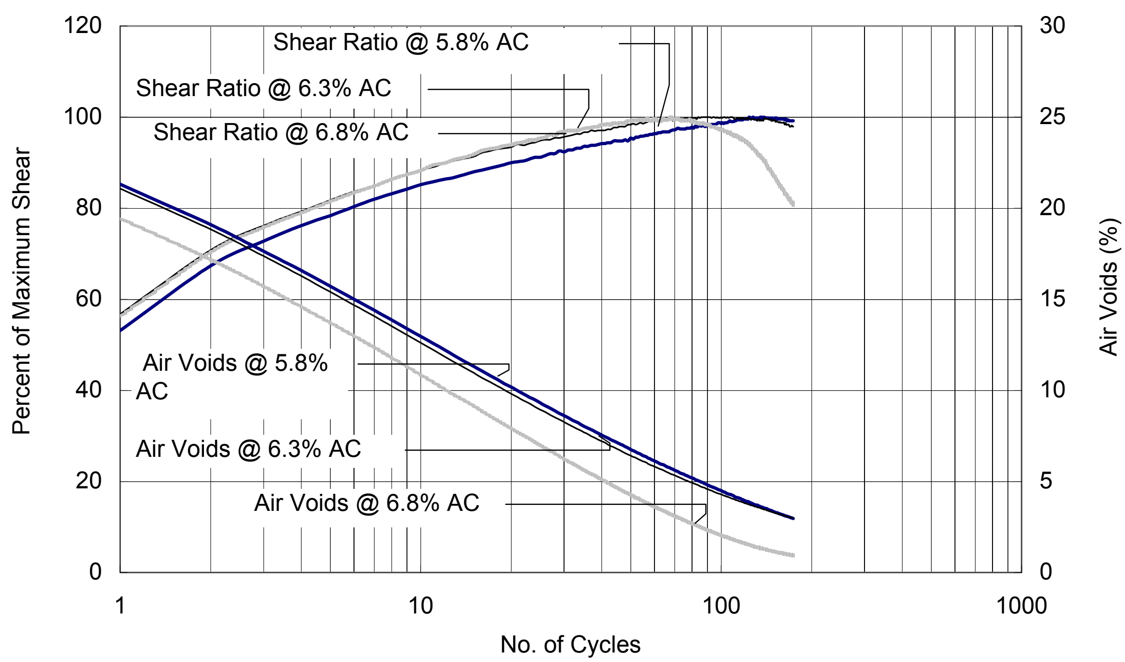


Figure 2-4. Effect of asphalt content on compaction curves for L1F mix, compacted at 1.25 degrees.

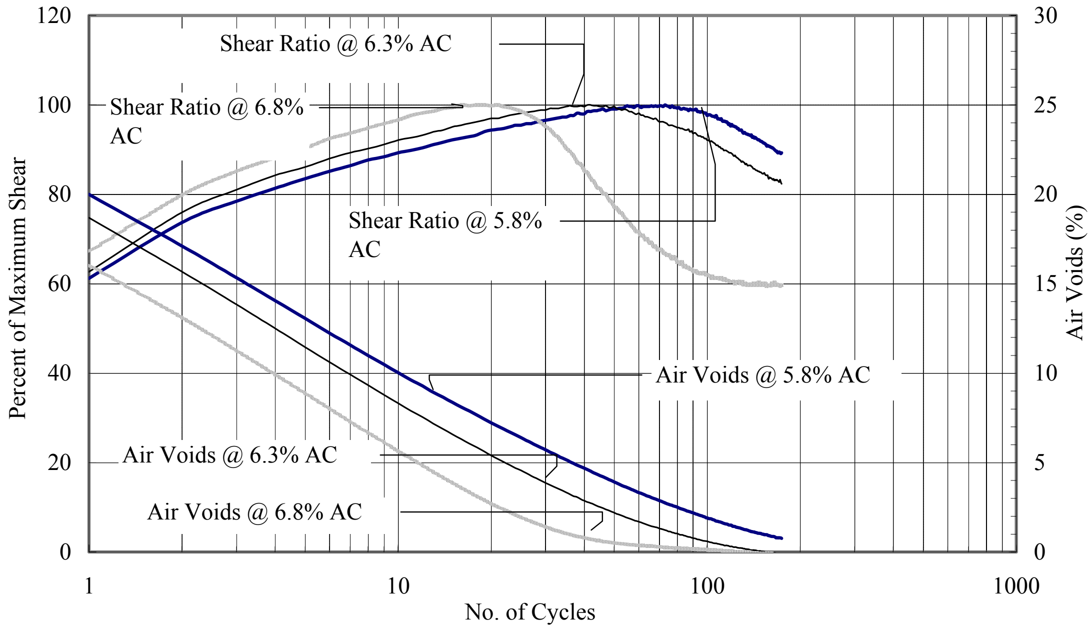


Figure 2-5. Effect of asphalt content on compaction curves for L1F mix compacted at 2.5 degrees.

strength for angles of 1.25 and 2.5 degrees, respectively. In both cases, the sensitivity of the mix to asphalt content can be observed by the spacing between the compaction curves for the three asphalt contents shown. The spacing between the compaction curves on the dry side and design asphalt content is fairly small, as compared to the spacing between the curves on the wet side and design asphalt content curves. The rather large shift in the curves on the wet side is an indicator of mixture sensitivity. The results indicate that the mixture sensitivity to asphalt content may be observed at both 1.25 and 2.5 degree angles during compaction, even though the changes are much more apparent for at 2.5 degrees.

Another way to illustrate how the larger compaction angle appears to magnify the effects of mixture sensitivity is shown in Figures 2-6 and 2-7, in which the gyratory shear strength ratio is plotted versus asphalt content for coarse-graded mixes compacted at 1.25 and 2.5 degrees, respectively. The curves for the coarse mixtures at 1.25 degrees (Figure 2-6) are all rather close together, whereas the curves in Figure 2-7 are spaced apart from each other, clearly showing the increase in definition by going to a higher gyratory angle.

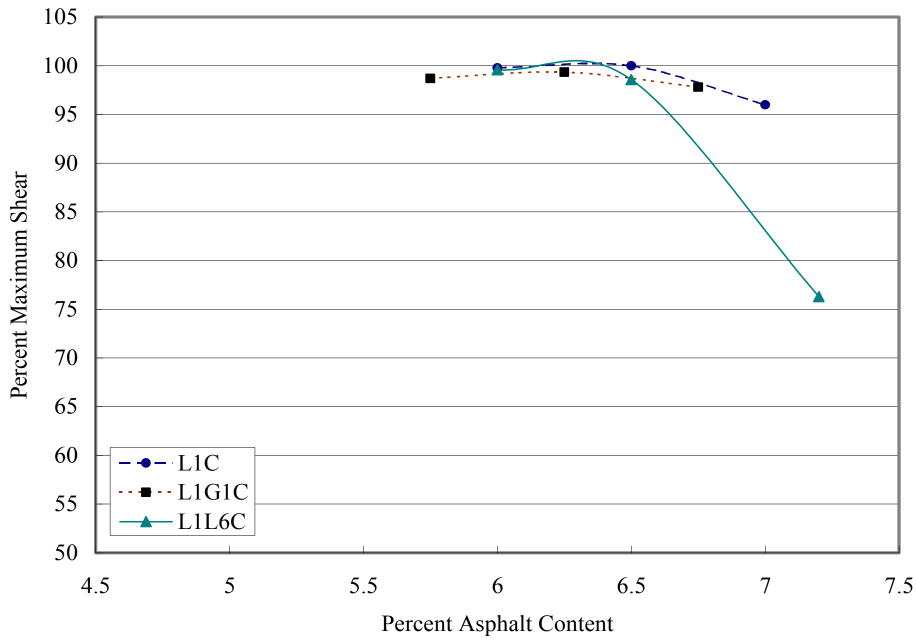


Figure 2-6. Shear stress ratio versus asphalt content for coarse aggregate blends compacted at 1.25 degrees.

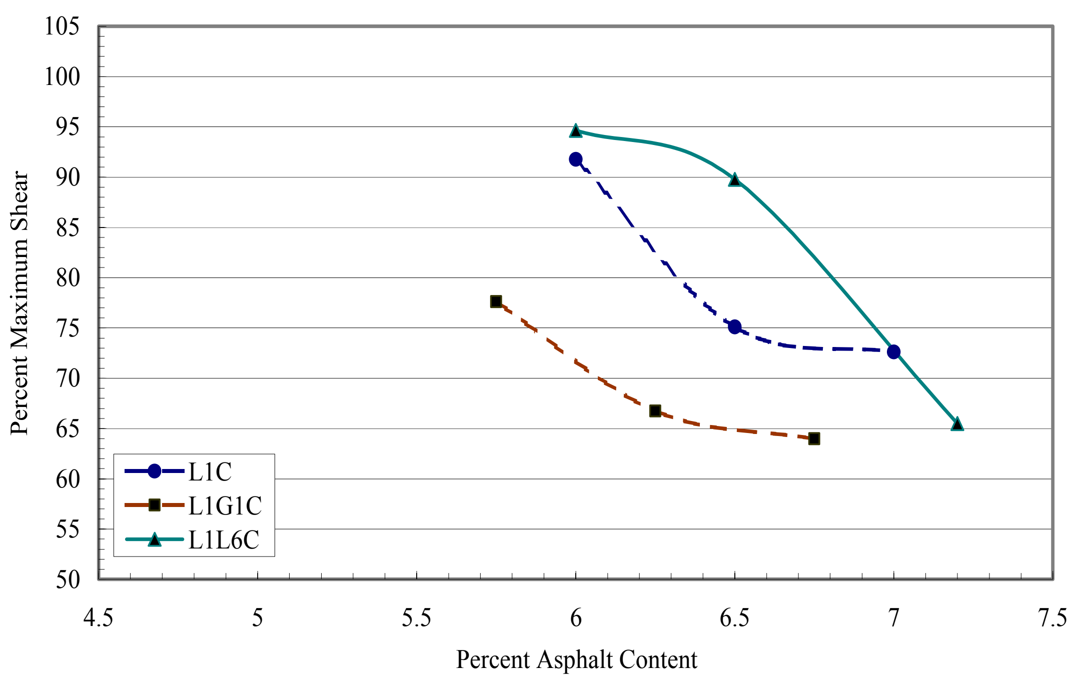


Figure 2-7. Shear stress ratio versus asphalt content for coarse mixtures compacted at 2.5 degrees.

A similar observation can be made for the fine mixtures, shown in Figures 2-8 and 2-9, although the Servopac at 1.25 degrees brings out the mixture sensitivity of the fine mixtures (Figure 2-8) better than for the coarse mixtures (Figure 2-6).

In summary, the results shown in Figures 2-6 through 2-9 clearly show that a higher angle of compaction, along with the incorporation of the post-peak behavior of the mixtures may be useful in highlighting the sensitivity of a given mix to asphalt content during compaction. Again, this result is not surprising, since the effect of the higher angle is to shear the mix to higher levels, and thus bring out the aggregate effect more clearly.

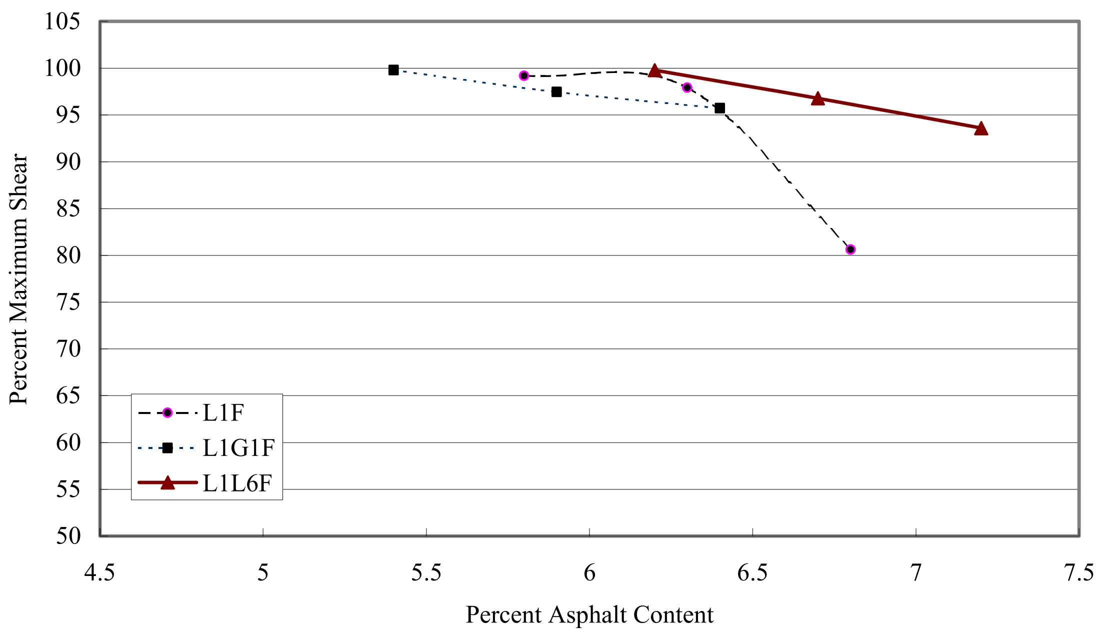


Figure 2-8. Shear stress ratio versus asphalt content for fine mixtures compacted at 1.25 degrees.

2.5 SUMMARY AND CONCLUSIONS

The following results and conclusions were obtained:

- At the early stages of compaction, a gyratory angle of 2.5 degrees was found to provide similar compaction results to the Gyratory Testing Machine. However, a gyratory angle of 1.25 degrees was found to provide similar results to the GTM at higher cycles of compaction.

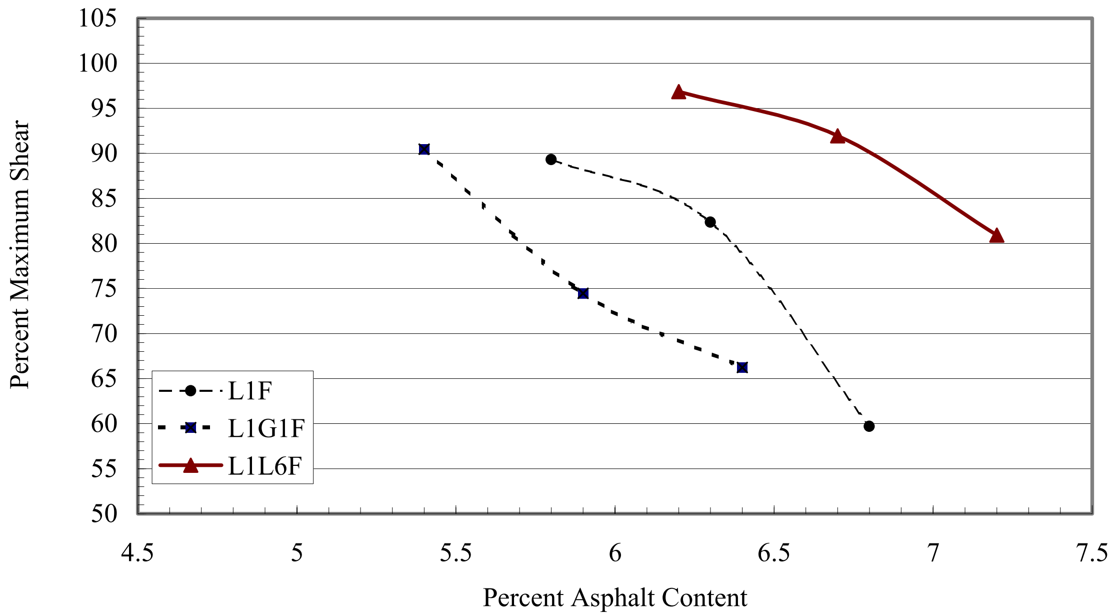


Figure 2-9. Shear stress ratio versus asphalt content for fine mixtures compacted at 2.5 degrees.

- Compaction at a gyratory angle of 2.5 degrees appears to provide insight into the stability of mixtures, which implies that the gyratory shear strength may potentially be used as an index to differentiate between mixtures of varying stability properties.
- Compaction at a gyratory angle of 1.25 degrees did not result in enough differences between mixtures to allow for a ranking of the stability behavior between the mixtures tested.
- Compaction at both 1.25 and 2.5 degree gyratory angles appears to provide insight into the sensitivity of mixtures with respect to asphalt content, which is recognized as important in mix design and optimization, but hard to quantify.

In conclusion, the results show that the gyratory shear strength may be used as an index to evaluate both the stability of hot-mix asphalt mixtures, as well as the sensitivity of mixtures to asphalt content. However, further studies are needed to explore the relationships presented in this paper further for mixtures with different source materials.

CHAPTER 3 PHASE II:
DETAILED EVALUATION AND IDENTIFICATION OF GYRATORY COMPACTION PARAMETERS

3.1 OVERVIEW

The main purpose of Superpave™ compaction is to simulate construction compaction and traffic densification in the field for the design of asphalt concrete mixtures [Huber 2000]. The Superpave gyratory compactor densifies HMA mixtures through the repeated application of shear forces. The rationale behind the shear compaction principle is that roller compaction in the field is also an induced shear process. This means that the measurement of the resistance to compaction in the laboratory may lead to a more detailed understanding of the compaction process. This part of the research (Phase II) describes a new approach for using the Superpave™ gyratory compactor with gyratory shear strength measurements as indicators of the potential rutting performance of HMA mixtures.

Numerous researchers have observed a relationship between resistance to compaction measured with the gyratory shear strength (Gs) parameter in the gyratory compactor and resistance to rutting, including Ruth and Schaub (1966), Bushing and Goetz (1964), Sigurjonsson and Ruth (1990), and Butcher (1998). Previous work by Butcher (1998) indicates that the gyratory shear measurement from the Servopac gyratory compactor shows promise as an index for relating the resistance to compaction to rutting resistance. In this study the compaction curves obtained with the Servopac Superpave gyratory compactor are analyzed for 31 mixtures, and simple gyratory compaction indices are developed which clearly differentiate between mixtures with respect to their rutting performance. The results are compared to Asphalt Pavement Analyzer (APA) testing results.

3.2 MATERIALS AND METHODS

The 31 mixtures used in this study are of varying gradations, aggregate structure, aggregate type, and can be divided into five distinct groups:

1. Ten mixtures, entitled "Fine Aggregate Angularity (FAA) Mixtures" with different fine aggregates, defined as material passing the No. 4 sieve, and the coarse portion of the aggregates consisting of oolitic limestone (Whiterock) from south Florida.
2. Eight mixtures of varying gradations with oolitic limestone (Whiterock) from south Florida, entitled "Limestone Gradation Study Mixtures."
3. Six mixtures of varying gradations with Georgia granite (GA185), entitled "Granite Gradation Study Mixtures."
4. Five field mixtures of varying gradations and aggregate types from Superpave™ monitoring test sites in Florida, entitled "Superpave Field Monitoring Mixtures."
5. Two mixtures with the same gradation, aggregate type, and aggregate structure but with and without a styrene-butadiene-styrene (SBS) modified binder, PG 76-22, used in an experiment at the Heavy Vehicle Simulator (HVS) test site in Florida and entitled "HVS Mixtures."

All mixtures were prepared using Superpave mixture design specifications. Details regarding aggregate gradations, aggregate sources, Job Mix Formulas (JMFs), compaction levels, and volumetric properties are provided by Darku (2003), Nukunya (2001), and Kestory (2000).

To isolate aggregate structure and aggregate type effects only one type of unmodified asphalt cement, AC 30 / PG67-22, which is commonly used in Florida, was used for all mixtures tested. The only exception was in one of the HVS mixtures, in which a SBS modified asphalt binder was used.

3.3 TESTING METHODOLOGY

Testing with the Superpave™ compatible Servopac gyratory compactor was performed on 150 mm diameter samples. The batch weights and the JMFs for all mixtures are given in Darku (2003). All mixtures were tested at gyratory angles of 1.25 degrees. For the AC-30 / PG 67-22 asphalt cement used the mixing temperature was 150°C for all the unmodified mixtures and 163°C for the SBS modified mixture. The mixes were subjected to short-term oven aging for approximately two hours at 135°C. They were then compacted in the Servopac gyratory compactor to a maximum number of gyrations of 174. Two replicates of all mixtures were compacted. The gyratory shear resistance and height during compaction were recorded. The vertical stress during compaction remained constant at 600 kPa, and the rate of rotation was 30 cycles per minute.

In order to provide references for the gyratory testing results, rut testing with the APA was performed at 60°C on cylindrical samples compacted with the Servopac gyratory compactor. All specimens were prepared as 150 mm diameter samples at air voids levels of 7.0 ± 1 percent. The specimens were trimmed to a height of 75 mm and allowed to air dry for about 48 hours. Two replicates of a sample were placed in the same APA mold and preheated in the APA test chamber to a temperature of 60°C for a minimum of six hours but not exceeding 24 hours before the test was performed. Details on the testing protocols used can be found in Darku (2003).

Finally, Superpave Indirect Tension (IDT) Creep Compliance tests were performed at 25°C for the FAA mixtures. The methodology for the IDT creep test is described in the Association of American State Highway and Transportation Officials AASHTO TP 9 and the overall IDT creep testing protocol can be found in the Long Term Pavement Performance LTPP testing protocol P07. Again, all mixtures tested were prepared to air void levels of 7±1.0 percent in the gyratory compactor. The IDT creep test was run for a total 1,000 seconds.

3.4 EXISTING ANALYSIS METHODS

Table 3-1 lists recently proposed methods for evaluating the rutting potential of mixtures using the Superpave gyratory compactor. These methods include the use of the compaction slope (k) proposed by Corté and Serfass (2000), the interaction of compaction slope and air

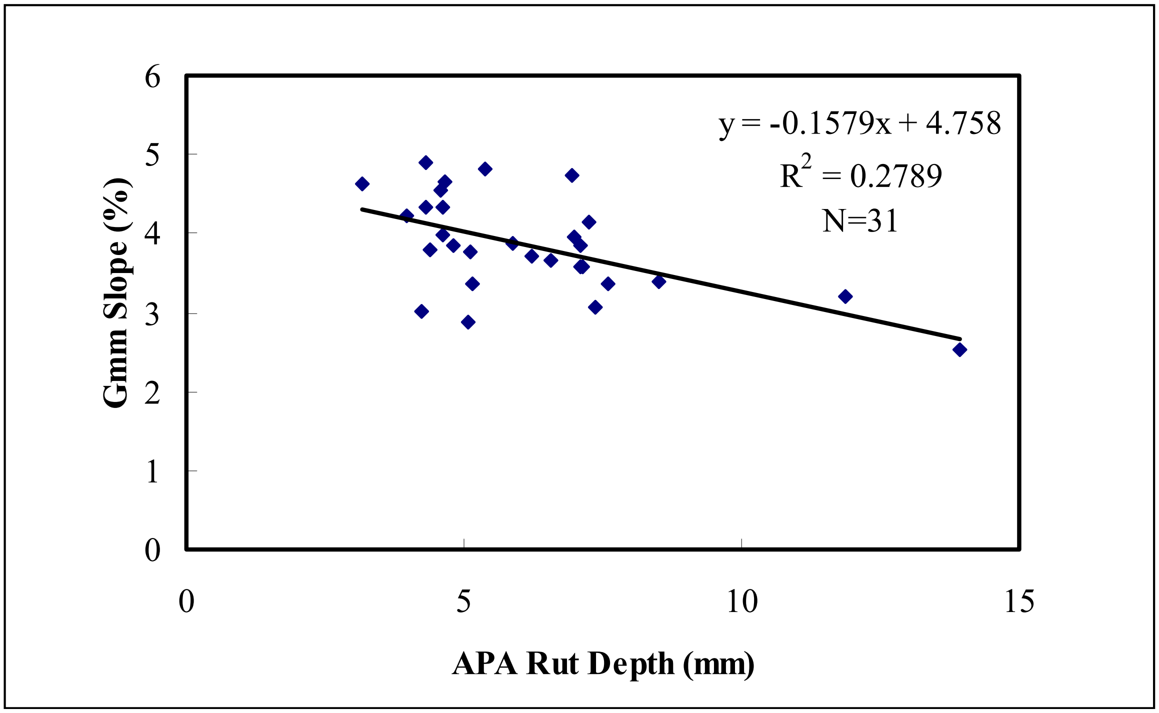
Table 3-1. Existing methods of analysis of Superpave™ gyratory compactor parameters.

SGC Parameter	Description	Symbol	Reference
Compaction Slope	Slope of regression line of semi-logarithmic plot of percent Gmm versus number of cycles (From 10 gyrations to 96% Gmm).	k	Anderson et al. [12]; Corté and Serfass [9]
Interaction of slope and air voids	The product of the compaction slope and the air voids (%) at the design number of gyrations.	kxAV	Anderson [10]
Densification Energy Index	The area under the compaction curve (Gmm vs. cycles) from 92% Gmm to 96% Gmm.	DEI_{92-96}	Bahia [11]
Number of Gyrations to maximum stress ration	Number of gyrations to maximum stress ratio obtained by fitting a quadratic equation tot he compaction curve (stress ratio vs. cycles) and solving for the number of gyrations N.	N-SRmax	Anderson [10]

voids proposed by Anderson (2002), the Densification Energy Index (DEI) proposed by Bahia (1998), and the number of gyrations to the maximum stress ratio (N-SRmax), proposed by Anderson (2002). In the following, the test results from the Servopac gyratory compactor, are analyzed using these proposed analysis methods.

3.4.1 Analysis of Compaction Slope (k)

The Compaction Slope is the slope of the compaction curve, in percent of maximum theoretical density Gmm versus the log of gyratory cycles, as discussed by Corté and Serfass (2000) and Anderson (1997). Figure 3-1 shows the Compaction Slope (k) plotted against APA rut measurements, in mm, for the 31 mixtures studied. Generally, the plot shows a weak relationship as defined by e.g., Draper and Smith (1981) and indicated by an R^2 value of 0.279, between the Compaction Slope and the APA rut depth measurements, similar to observations by Corté et al. (2000) and Anderson (2002). Mixtures with high slope values tend to have good APA rutting performance while a low slope value is likely to be associated with mixtures with poor APA rutting performance.



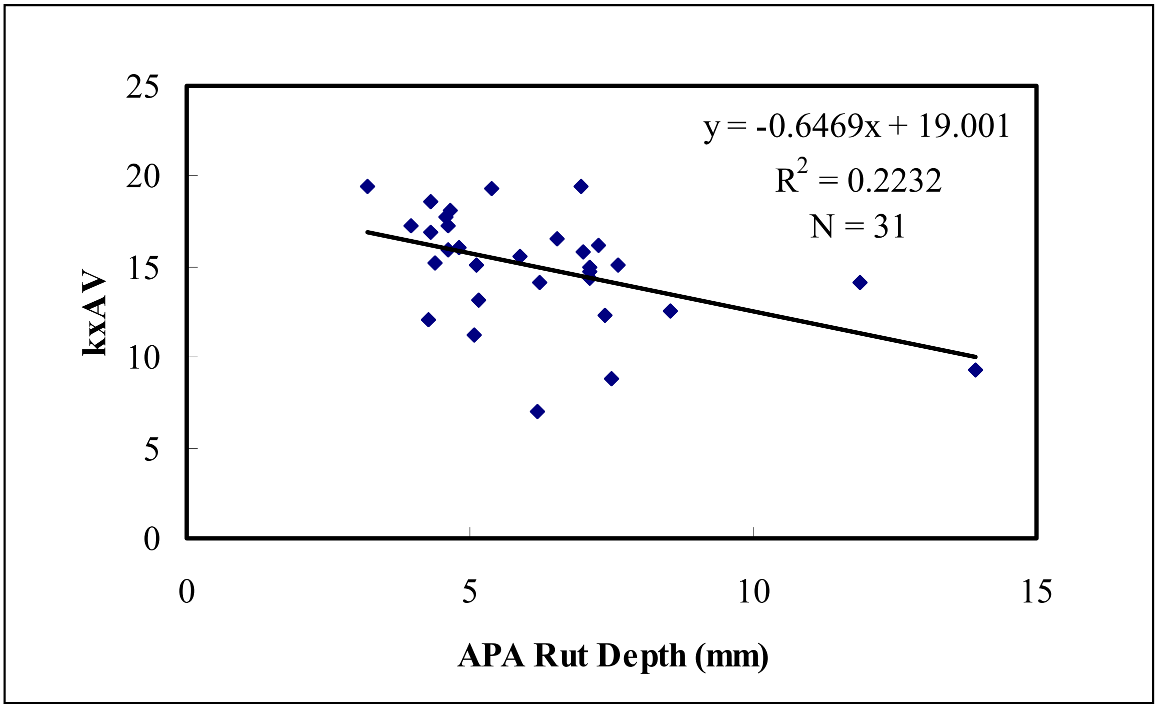
Note: R^2 is the coefficient of determination and n denotes the number of mixtures.

Figure 3-1. Plot of the compaction slope for all the mixtures tested.

3.4.2 Interaction of Slope and Air Voids (kxAV)

Anderson (2002) evaluated a modified version of the compaction slope concept in which the product of the Compaction Slope and air voids, percent at N_{design} is used as an indicator of rutting potential. Figure 3-2 shows a plot of the interaction of Compaction Slope and air voids versus APA rut depths.

A comparison of Figures 3-1 and 3-2 shows little difference in correlation for the two analysis methods. There was a slight reduction of the R^2 when the interaction of the Compaction Slope with air voids was used in comparing the mixtures. These results indicate that there is no advantage in using the interaction of Compaction Slope and air voids in analyzing the potential rutting potential of mixtures.



Note: R^2 is the coefficient of determination and n denotes the number of mixtures.

Figure 3-2. Interaction of compaction slope and air voids (kxAV) for all mixtures.

3.4.3 Analysis of Densification Energy Index (DEI)

Bahia et al. (1998) proposed the use of the DEI for evaluating the rutting performance of mixtures. The method relies on the compaction of mixtures down to 2 percent air voids. Unfortunately, all mixtures in this paper were compacted to the Superpave™ N_{max}, which is the number of gyrations required to produce a density in the laboratory that should absolutely never be exceeded in the field. The air voids at this point are required to be at least 2 percent, according to Superpave™ mixture design specifications. Therefore, all the mixtures tested in this work never reached an air void level of 2 percent. The use of the Terminal Densification Energy ($TDI_{92\text{-}98}$) parameter for the evaluation of these mixtures therefore was not possible. The Densification Energy Index ($DEI_{92\text{-}96}$) was however calculated for all the mixtures and used to evaluate these mixtures. Figure 3-3 shows the plot of the $DEI_{92\text{-}96}$ for all the mixtures evaluated.

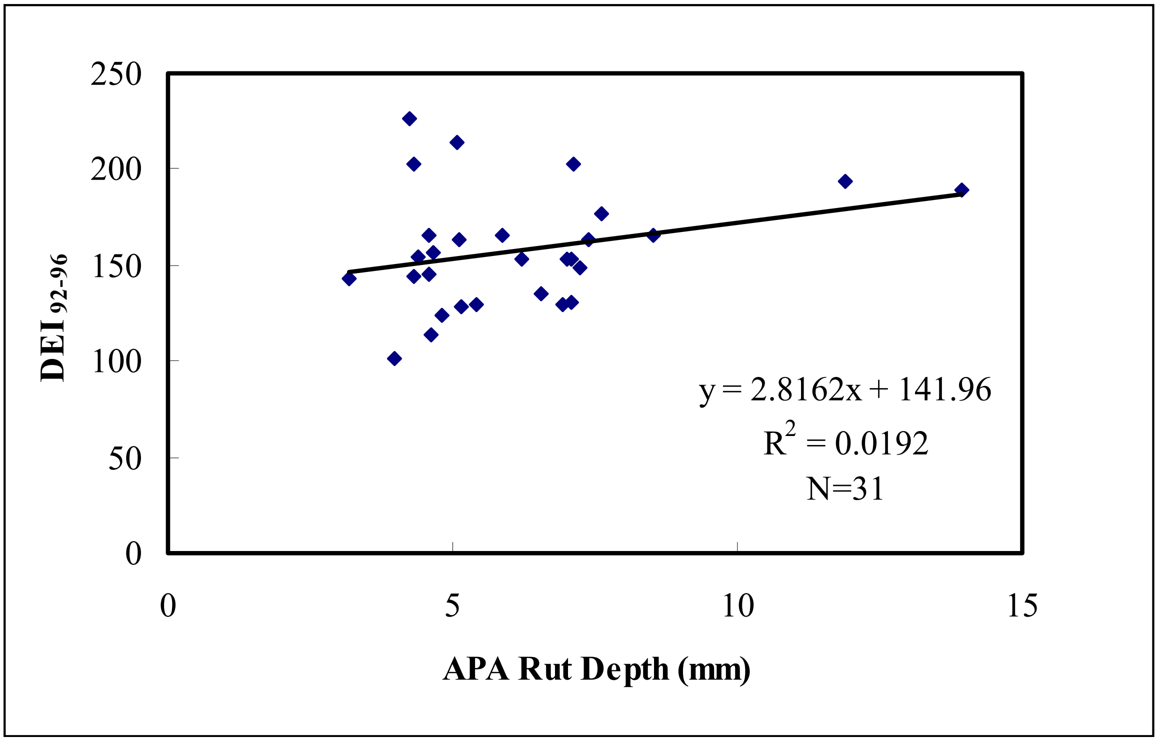


Figure 3-3. Densification energy index (DEI_{92-96}) versus APA rut depth for all mixtures.

3.4.4 Evaluation of Number of Gyrations to Maximum Stress Ratio (N-SRmax)

Anderson (2002) proposed the use of the number of gyrations to maximum stress ratio (N-SRmax) as an index for mixture rutting performance. Figure 3-4 shows a plot of the number of gyrations to the maximum stress ratio versus the APA rut depth for all 31 mixtures evaluated.

Again, due to scatter in the data, the results show little correlation with APA rutting performance. However, a discernable trend between N-SRmax and APA rut depth measurements is visible. Mixtures with high N-SRmax values are likely to have good rutting performance while mixtures with low N-SRmax values tend to have relatively poorer performance.

Based on the analysis of existing methods, the slope of the compaction curve appears to be most related to the APA rutting performance of mixtures. Unfortunately, the slope has however been observed to be insensitive to asphalt content, as discussed by Anderson (2002). In

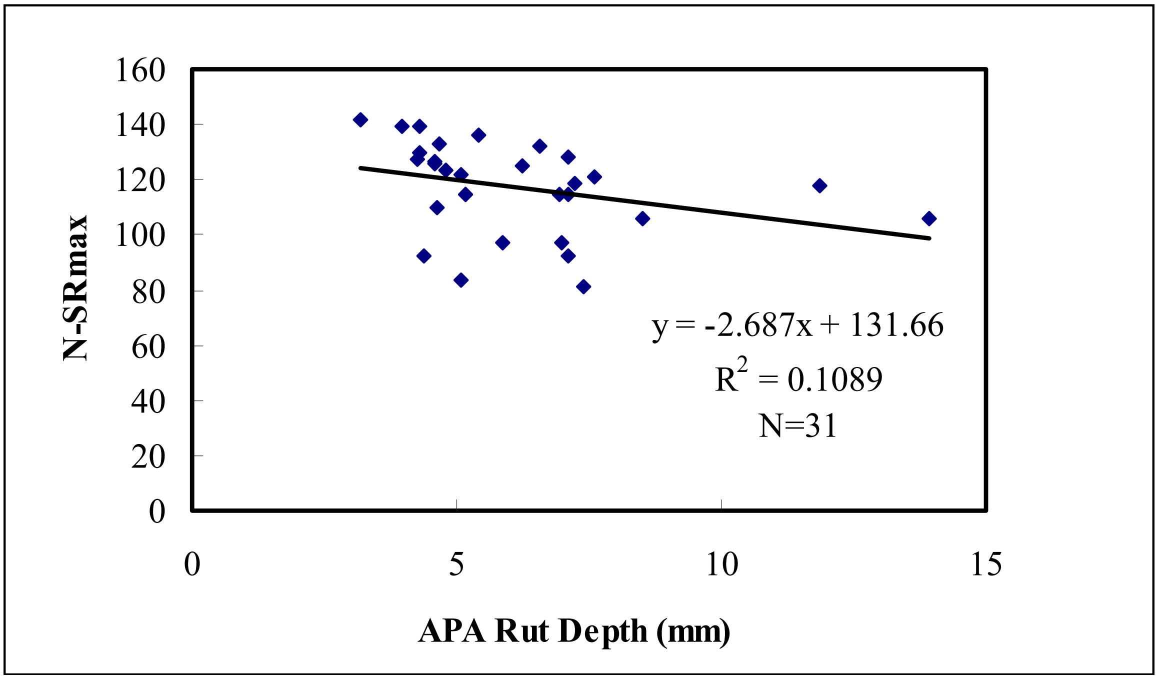


Figure 3-4. Number of gyrations to maximum stress ratio (N-SRmax) for all mixtures.

view of the results from this review, there is clearly a need for the development of improved analysis methods for rutting performance using the Superpave gyratory compactor.

3.5 EVALUATION OF GYRATORY SHEAR STRENGTH CURVES

A close look at a typical compaction plot depicted in Figure 3-5 shows that the curve can be divided into three distinctive regions or segments, namely:

1. The compaction region, in which air voids range from initial air void levels to about 7 percent.
2. The densification region, in which air voids typically range between 7 and 4 percent.
3. The post-peak part of the curve, in which air void levels are typically below 4 percent.

In the following, the properties of the mixture in the densification zone will be evaluated with respect to determining possible relationships between mixture rutting performance and engineering parameters obtained from these different regions.

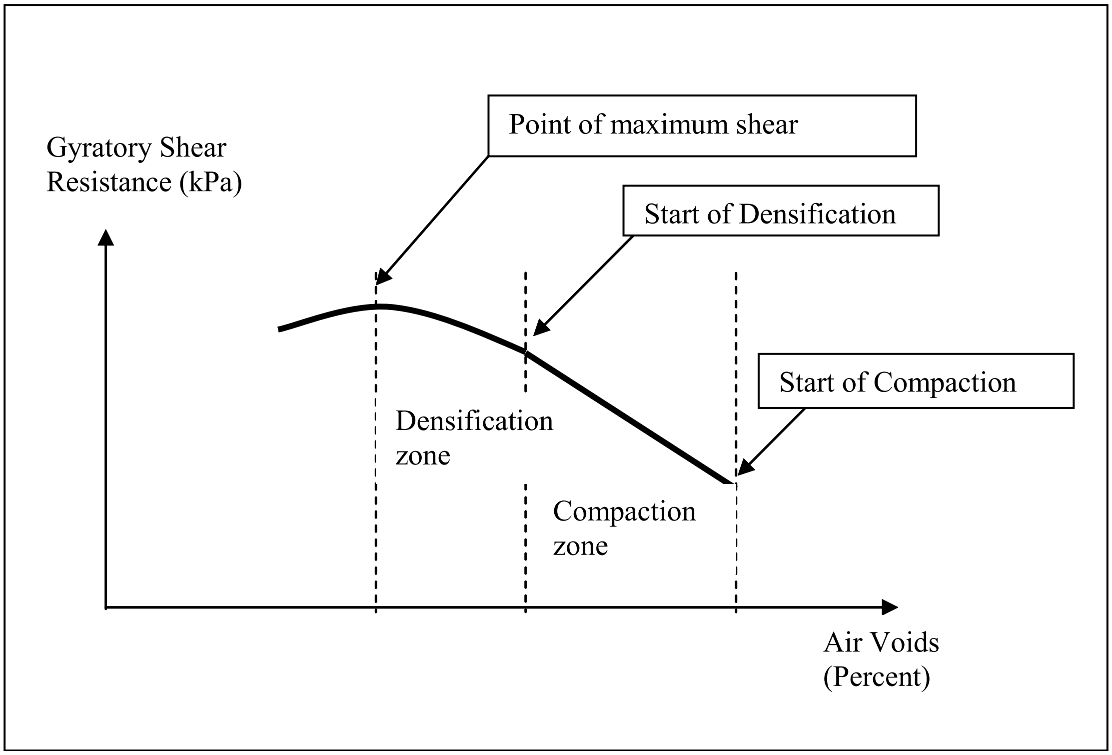


Figure 3-5. Gyratory shear strength versus air voids.

In the shear driven densification part of the compaction curve the primary mode of compaction is controlled shearing of the mix, causing aggregate particles to roll and slide over each other, gradually squeezing the mastic outward and the aggregates into a tighter structure, resulting in lower air voids. As the mastic is squeezed outward, the compaction curve starts to become increasingly nonlinear due to the decrease in mastic lubrication effect between aggregates. Therefore, a shear strength measurement, such as the gyratory shear strength, should be a measure of the resistance to compaction.

The use of the gyratory shear strength also minimizes potential problems identified by Anderson (2002) associated with using the slope of the density curve in mixtures that contain too much asphalt cement. In these mixtures, the mix will continue to increase in density with compaction, whereas the gyratory shear strength will drop off once the mixture has been compacted past an optimum air void level. Figure 3-6 shows a comparison between the percent of maximum gyratory shear strength and the density for a typical mixture at an asphalt content that is 0.5 percent higher than the optimum asphalt content. The results illustrate how the gyratory shear strength peaks and then drops off, whereas the density continues to increase, implying that the density curve is insensitive to changes in the mixture during compaction.

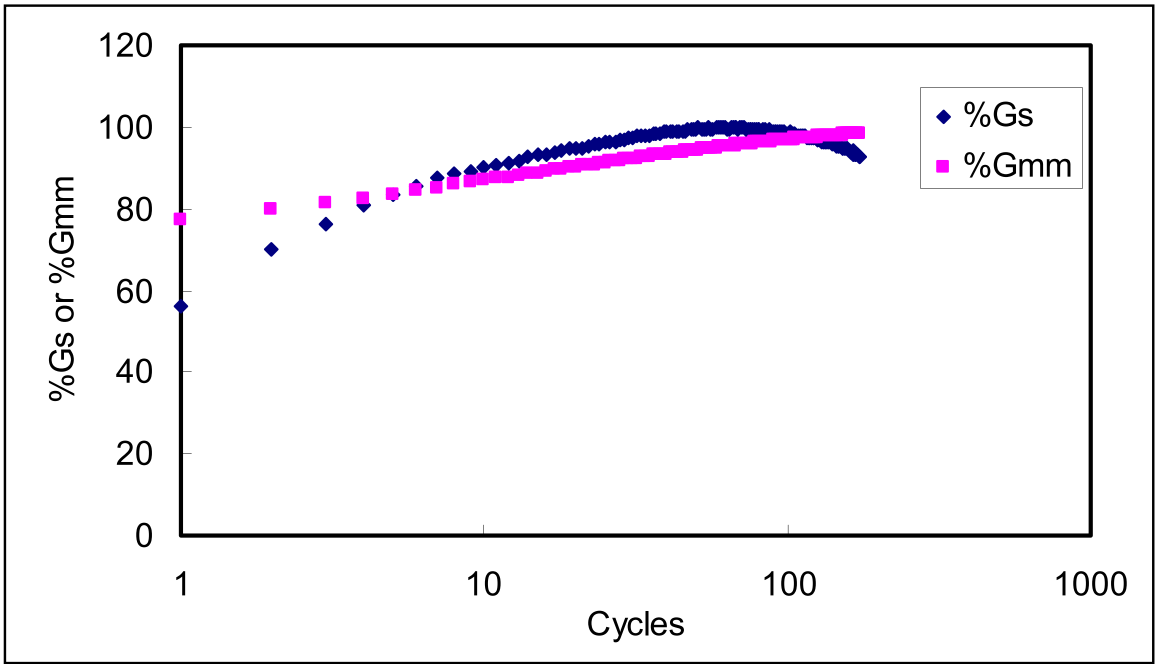


Figure 3-6. Variation of density (% Gmm) and percent of maximum gyratory shear strength (% Gs) with gyratory revolutions.

The gyratory shear strength versus the log of the number of gyratory revolutions was studied for all 31 mixtures at air void levels ranging from: a) 7 percent to 4 percent if the maximum gyratory shear strength was not reached at 4 percent air voids, or b) from 7 percent air voids to the air voids at maximum gyratory shear strength. Figure 3-7 shows a series of typical regression results in this air void range. The results from the regression analyses on the semi-log plots of the gyratory shear resistance versus the number of cycles in the densification zone of the compaction plots provided a best-fit relationship in the form:

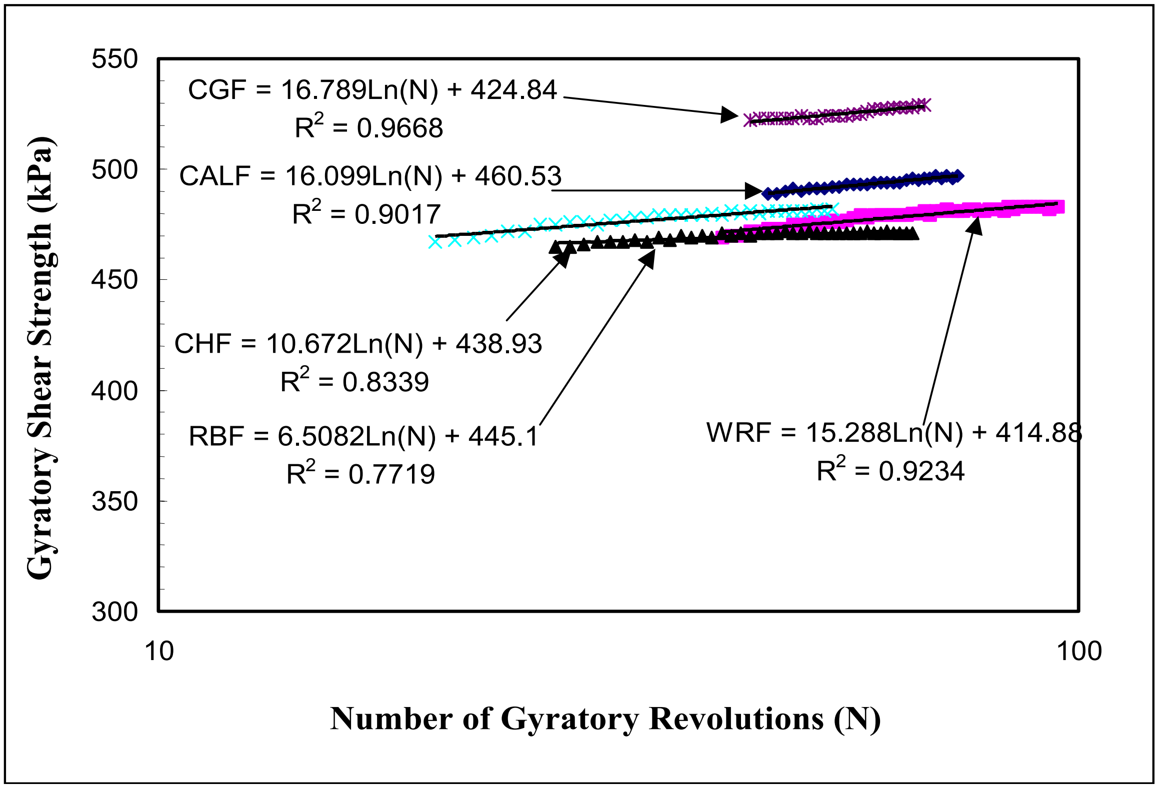


Figure 3-7. Typical regression relationships between gyratory shear strength versus natural log of gyratory revolutions.

$$Gs = k_1 \ln (N) + k_2 \qquad (1)$$

Where Gs = Gyratory Shear Strength, N = Number of gyratory revolutions, and k_1 and k_2 are the slope and intercept of the regression lines respectively. In the following, the Gyratory Shear Slope (k_1) will be evaluated as an index for rutting.

3.6 EVALUATION OF THE GYRATORY SHEAR SLOPE AS AN INDEX OF MIXTURE RUTTING POTENTIAL

APA rut depth measurements and Superpave IDT creep compliance tests were obtained for the ten FAA mixtures for the purpose of evaluating the gyratory shear slope as an index for mixture rutting potential. Table 3-2 shows the APA rut depths and creep compliances for the mixtures studied, in addition to the gyratory shear slopes.

Table 3-2. Comparison of measurements of shear slope to creep compliance and APA rut depth measurements.

Aggregate Blend	APA Rut Depth (mm)	Slope of Shear Resistance (kPa)	Creep Compliance (1/Gpa) @ 25°C
Coarse Graded Mixtures			
CGC	4.30	26.18	10.01
CALC	6.95	21.23	51.43
WRC	5.40	20.84	62.63
CHC	11.88	6.26	94.66
RBC	7.25	14.61	86.40
Fine Graded Mixtures			
CGF	4.65	17.76	17.59
CALF	6.22	16.05	19.27
WRF	5.10	16.30	22.90
CHF	13.92	11.90	35.38
RBF	8.52	7.12	82.86

Generally, mixtures with high APA rut depths had high IDT creep compliance and low shear slope and vice versa. The CHF mixture showed excessive breakdown of fines during compaction, which may explain the very high APA rut measurements.

The correlation between the gyratory shear slopes and the APA rut depths was fair, R^2=0.5163, for the ten mixtures, as shown in Figure 3-8. The correlation between the gyratory shear slopes and the IDT creep compliances was also fair, R^2=0.4014 for the mixtures as shown in Figure 3-9.

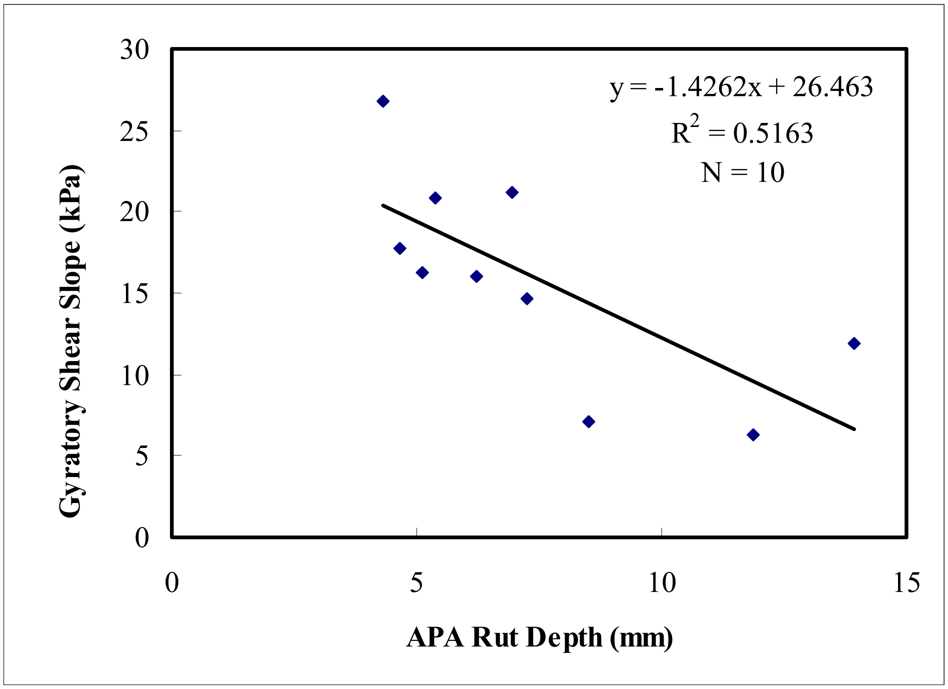


Figure 3-8. Comparison of gyratory shear slope with APA test results for the FAA mixtures.

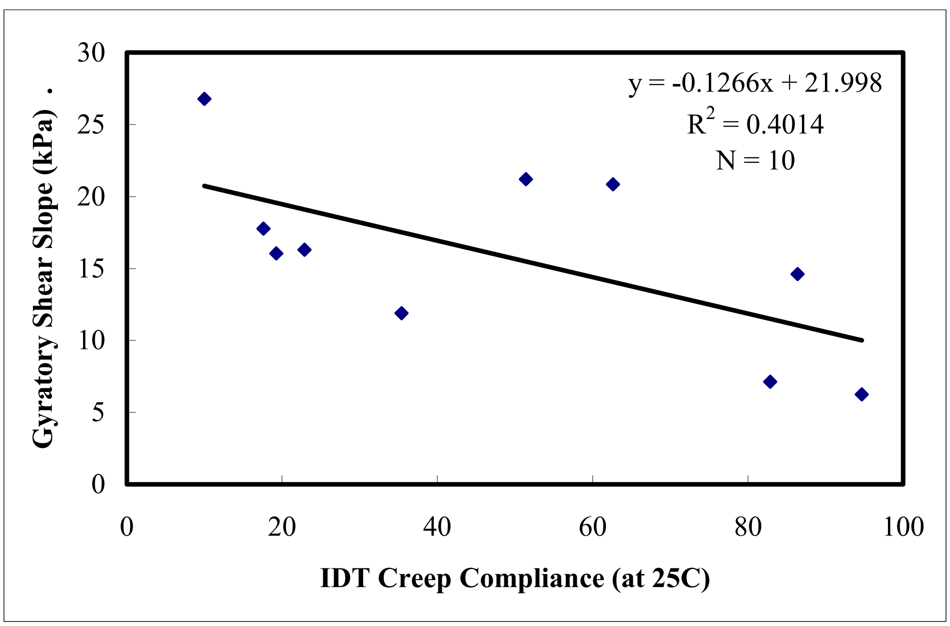


Figure 3-9. Comparison of gyratory shear slopes with indirect tension (IDT) creep compliance at 25°C for the FAA mixtures.

3.7 EVALUATION OF GYRATORY SHEAR SLOPE FOR OTHER MIXTURES

To further study the relationship proposed in equation 1, all 31 mixtures were used and the resulting relationship between gyratory shear slope and APA rut depths were observed. Figure 3-10 shows the plot of the gyratory shear slope with the APA rut depth. The results show that generally, the slope of the gyratory shear strength versus log of cycles has a fair correlation, $R^2 = 0.5379$, to the APA rut depth measurements. Given the wide range of mixtures studied, this level of correlation is promising.

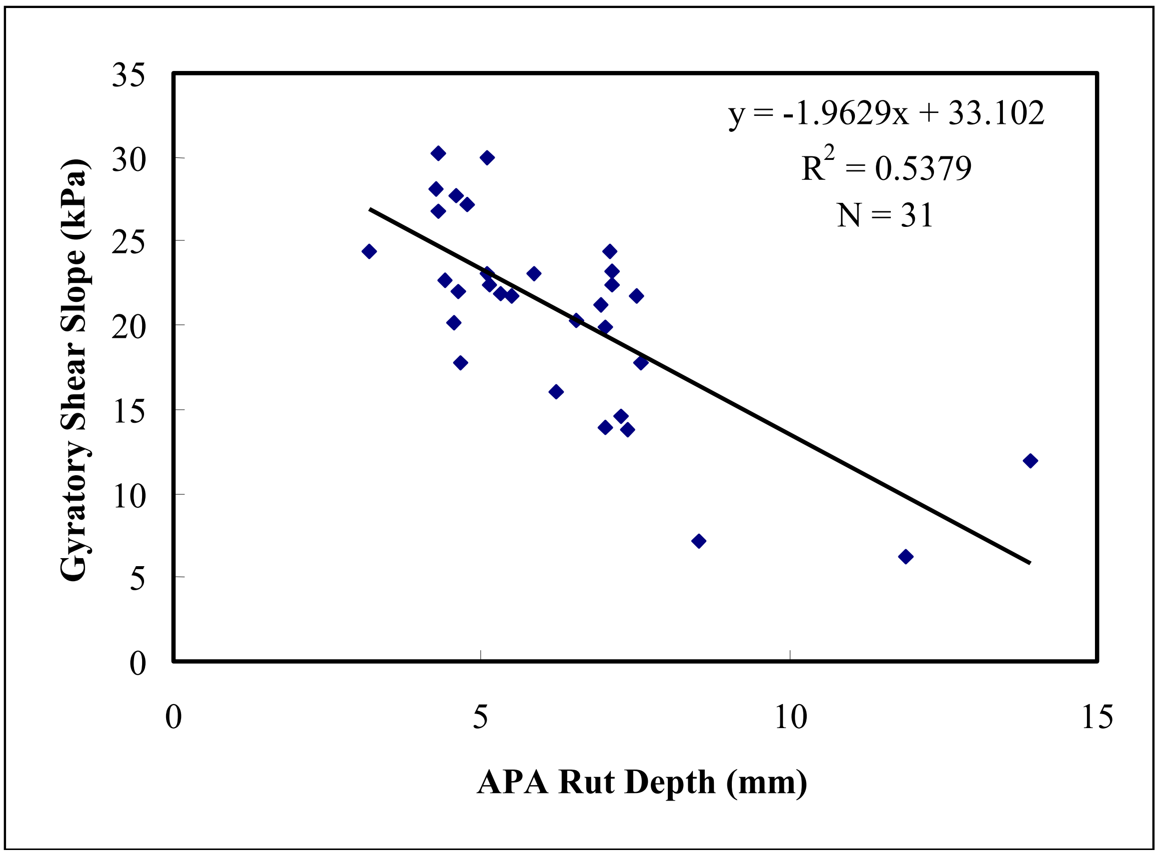


Figure 3-10. Gyratory shear slope versus APA rut depth for all mixtures.

A further evaluation of the 31 mixtures, by gradation type, namely coarse-graded versus fine-graded is shown in Figures 3-11 and 3-12. In this case, mixtures are classified as coarse-graded if their gradation passes below the Superpave restricted zone and fine-graded if their

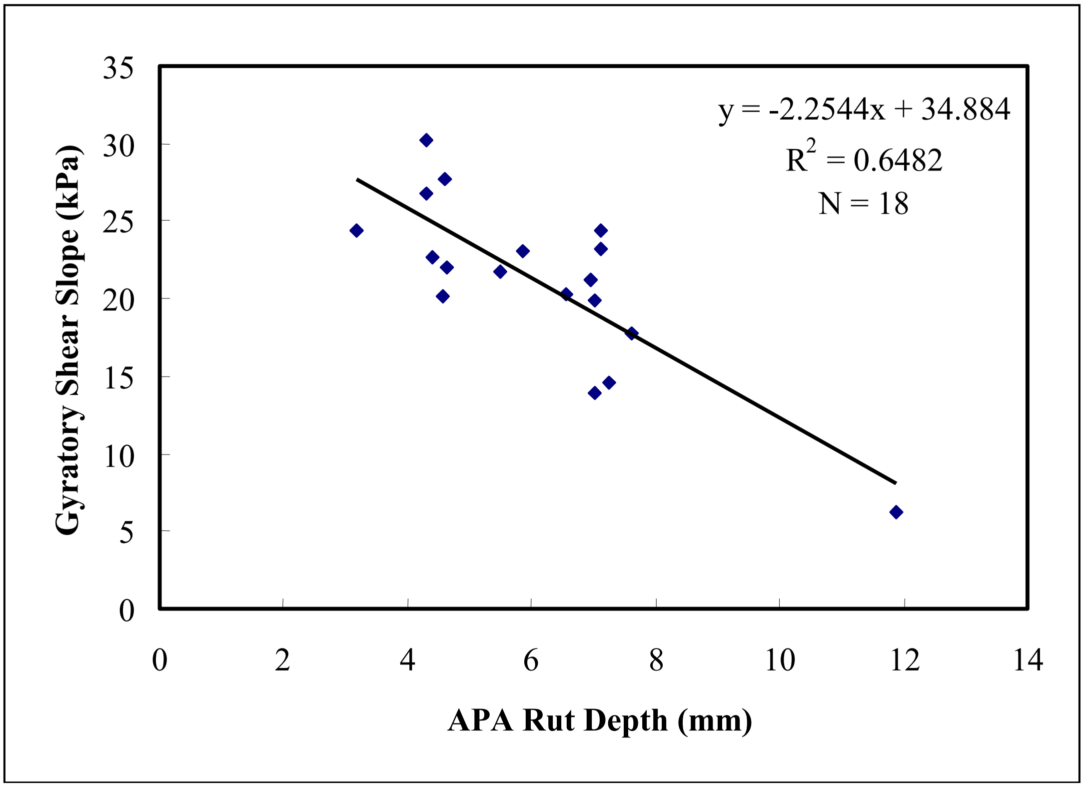


Figure 3-11. Gyratory shear slope versus APA rut depth for course-graded mixtures.

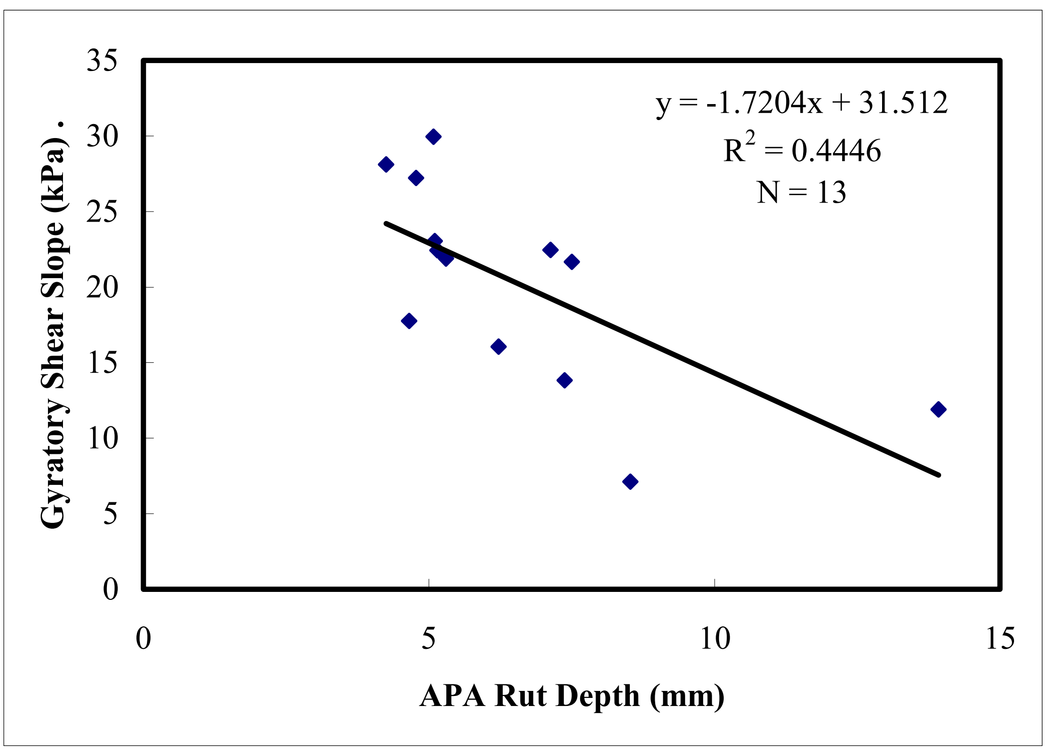


Figure 3-12. Gyratory shear slope versus APA rut depth for fine-graded mixtures.

gradation passes above the restricted zone. Figure 3-11 shows that the coarse-graded mixtures have a coefficient of determination of $R^2 = 0.65$, whereas Figure 3-12 shows that the coefficient of determination for the fine-graded mixtures is $R^2 = 0.44$. In summary, the gyratory shear slope shows a significantly stronger correlation with APA rutting performance than the other methods reviewed.

3.8 SUMMARY AND CONCLUSIONS

The following results were obtained:

- Existing proposed relationships between Superpave gyratory compaction parameters and the rutting potential of mixes were evaluated for 31 mixtures of varying gradation and aggregate type. It was concluded that none of the relationships showed significant promise for mixture work and a new relationship was needed.
- A relationship between the slope of the gyratory shear strength and the number of revolutions in the Superpave gyratory compaction was identified for air void levels between 7 and 4 percent.
- The slope of the relationship between gyratory shear strength and the number of revolutions was shown to be inversely related to rut depths in the APA. This means that as the gyratory shear slope increased, the rut resistance increased, implying that mixtures with high rut resistance show a greater increase in gyratory shear strength per revolution than mixtures with low rut resistance.
- The gyratory shear slope may provide the framework for a simple and economical index for separating bad rutting performers from good performers.

In conclusion, the results show that the use of the gyratory shear resistance with the Superpave gyratory compactor may provide a viable parameter for mixture optimization and design. However, further work is needed on the framework for using the proposed gyratory shear slope in mixture optimization and design.

CHAPTER 4

PHASE III:

DEVELOPMENT OF APPROPRIATE TESTING AND INTERPRETATION PROCEDURES

4.1 OVERVIEW

This study illustrates that it may be necessary to induce instability in mixtures to determine parameters that are relevant to mixture rut resistance. The Superpave™ gyratory compactor with shear measurement and the option of changing the gyratory angle during compaction is used. Mixtures are compacted to a density that is consistent with the air voids of field pavements immediately after construction, namely 7 (± 0.5) percent air voids. The subsequent application of high shear stresses by increasing the gyratory angle from 1.25 degrees to 2.5 degrees results in material states at which parameters can be measured that define clear differences in mixtures. Three basic responses are observed during the resulting rearrangement of the aggregate structure. Mixtures that don't require much aggregate rearrangement to loose their strength almost immediately are "brittle" mixtures. Mixtures that continue to loose strength upon rearrangement and never regain another stable configuration are referred to as "plastic" mixtures. Once plastic mixtures are subjected to any condition that promotes the rearrangement of the aggregate structure, the resulting deformation is continuous. Consequently, the third type of response is that of "optimal" mixtures, which are mixtures that lie in between these extremes – i.e. mixtures that lock up again in a stable arrangement when forced to rearrange their aggregate structure.

The results presented in this study identify key mixture parameters relevant for HMA rut-resistance. A framework for the evaluation of mixture rut-resistance is proposed that uses gyratory compaction with induced shear instability. The rutting potential of 31 mixtures is evaluated, and the results are compared to APA rut depth measurements. The results show that a laboratory test that induces instability in the aggregate structure may be essential for the evaluation of mixture rutting potential.

4.2 MATERIALS AND TESTING METHODOLOGY

4.2.1 Mixtures Used

The 31 mixtures used in this study can be divided into a number of distinct groups of which the first three groups are laboratory-based mixtures:

- Eight oolitic limestone mixtures of varying gradations, referred to as “Limestone Gradation Study Mixtures”
- Six granite mixtures of varying gradations, referred to as “Granite Gradation Study Mixtures”
- Ten mixtures with different fine aggregate types referred to as FAA mixtures (fine aggregate defined as material passing the No. 4 Sieve)

Mixtures with proven field performance that were included in the study consist of the following two groups of mixtures:

- Six field mixtures of varying gradations and aggregate types from existing Superpave™ monitoring test sites in Florida, referred to as “Superpave™ Field Monitoring Project” mixtures
- Two mixtures with the same aggregate type and gradation, but with and without a SBS modified binder (PG 76-22) used in a recent Heavy Vehicle Simulator (HVS) test program in Florida, referred to as “HVS mixtures”

With the exception of the one HVS mixture that used an SBS modified binder, only one type of binder was used for remaining 30 of the mixtures studied, namely PG 67-22 (AC-30), which is commonly used in Florida. The mixtures gradations are listed in Tables 4-1a and 4-1b whereas Tables 4-2a and 4-2b provide the volumetric properties and design number of gyrations, N_{design}, for all mixtures used.

Table 4-1a. Gradations for FAA and Superpave™ field monitoring project mixtures.

Sieve Size (mm)	MIXTURES														
	Coarse FAA					Fine FAA					Superpave Field Monitoring				
	WR/ C1	CG	RB	CH	CAL	WR/ F1	CG	RB	CAL	CH	P1	P2	P3	P7	P8
25 (1”)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
19 (3/4”)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
12.5 (1/2”)	97.4	97.4	97.5	97.5	97.5	95.5	97.4	95.1	94.9	95.0	100	98	94	95	94
9.5 (3/8”)	90.0	88.8	89.5	89.4	89.3	85.1	83.8	85.0	84.6	84.7	99	89	90	88	90
4.75 (#4)	60.2	54.8	57.6	56.9	56.5	69.3	66.0	68.5	67.6	67.9	64	45	67	70	59
2.36 (#8)	33.1	30.4	31.6	31.3	31.2	52.7	49.4	51.2	50.6	50.8	40	28	34	57	32
1.18 (#16)	20.3	20.5	21.1	20.9	20.9	34.0	33.3	34.2	33.9	34.0	29	22	25	41	25
0.6 (#30)	14.7	14.8	15.1	15.0	15.0	22.9	21.9	22.4	22.2	22.2	21	17	18	30	18
0.3 (#50)	10.8	11.0	11.0	11.0	11.0	15.3	13.9	14.0	14.0	14.0	14	12	13	19	12
0.15 (#100)	7.6	7.2	7.0	7.1	7.1	9.6	7.0	6.9	6.9	6.9	8	7	7	9	7
0.075 (#200)	4.8	5.5	5.2	5.2	5.3	4.8	4.5	4.3	4.3	4.3	5.1	4.9	4.4	4.2	4.5

Table 4-1b. Gradations for HVS, limestone, and granite gradation study mixtures.

Sieve Size (mm)	MIXTURES															
	Limestone Gradation Study								Granite Gradation Study						HVS	
	C2	C3	C4/ F3	C5	F2	F4	F5	F6	C1	C2	C3	F1	F2	C4	67-22	76-22
25 (1”)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
19 (3/4”)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
12.5 (1/2”)	91.1	97.6	94.5	97.4	90.8	95.5	95.5	95.5	97.4	90.9	97.3	94.7	90.5	94.6	97.4	97.1
9.5 (3/8”)	73.5	89.3	84.9	89.9	78.0	85.1	85.1	85.1	89.0	72.9	89.5	84.0	77.4	85.1	95.7	94.6
4.75 (#4)	47.1	57.4	66.5	47.1	61.3	69.3	61.3	69.3	55.4	45.9	55.4	66.4	60.3	65.1	76.3	76.5
2.36 (#8)	29.6	36.4	36.6	33.1	44.1	52.7	52.7	44.4	29.6	28.1	33.9	49.2	43.2	34.8	54.2	55.2
1.18 (#16)	20.2	24.0	26.1	20.3	34.7	40.0	34.0	34.7	19.2	18.9	23.0	32.7	34.0	26.0	44.1	45.3
0.6 (#30)	14.4	17.7	20.5	14.7	23.6	29.0	22.9	23.6	13.2	13.2	16.0	21.0	23.0	18.1	37.8	39.2
0.3 (#50)	10.4	12.9	13.6	10.8	15.7	20.0	15.3	15.7	9.2	9.2	11.2	12.9	15.3	12.5	23.7	24.0
0.15 (#100)	6.7	9.0	8.3	7.6	8.9	12.0	9.6	9.1	5.3	5.6	6.8	5.9	8.7	7.7	8.9	8.8
0.075 (#200)	4.8	6.3	5.8	4.8	6.3	6.3	4.8	6.3	3.4	3.9	4.7	3.3	5.4	5.8	4.2	3.9

Table 4-2a. Volumetrics for FAA and Superpave™ field monitoring project mixtures.

Volumetric Property	MIXTURES														
	Coarse FAA					Fine FAA					Superpave Field Monitoring				
	WR-C1	CG	RB	CH	CAL	WR-F1	CG	RB	CAL	CH	P1	P2	P3	P7	P8
G_{mm}	2.328	2.386	2.393	2.394	2.454	2.338	2.381	2.416	2.480	2.407	2.509	2.523	2.216	2.334	2.382
G_b	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035
G_{mb}	2.235	2.295	2.300	2.289	2.353	2.244	2.288	2.327	2.386	2.315	2.407	2.445	2.122	2.229	2.284
P_b	6.5	6.5	6.25	5.7	5.8	6.3	6.7	5.9	5.3	5.5	5.5	5.0	8.3	6.1	6.0
G_{sb}	2.469	2.418	2.576	2.535	2.540	2.488	2.403	2.599	2.524	2.549	2.691	2.694	2.325	2.47	2.503
G_{se}	2.549	2.625	2.622	2.601	2.680	2.554	2.630	2.637	2.691	2.608	2.736	2.725	2.475	2.573	2.598
P_{ba}	1.1	1.2	1.2	1.0	1.2	1.1	1.2	1.2	1.2	1.0	0.6	0.4	2.7	1.7	1.4
P_{be}	5.3	3.3	5.6	4.7	3.7	5.3	3.2	5.7	3.4	4.8	4.9	4.5	5.7	5.2	4.5
VMA (%)	15.4	11.2	16.1	14.8	12.6	15.6	11.2	16.0	10.5	14.1	15.5	14.8	16.4	16.0	14.0
Va (%)	4.0	3.8	3.9	4.4	4.1	4.0	3.9	3.7	3.8	3.7	4.1	4.4	4.2	4.5	3.9
VFA (%)	74.0	66.5	77.3	70.6	67.4	74.2	65.2	76.8	63.8	73.7	73.7	70.6	74.1	71.9	72.4
D/A	1.0	1.7	0.9	1.1	1.4	0.8	1.4	0.7	1.3	0.9	1.2	0.6	0.6	0.6	1.0
	Design Number of Gyrations (N_{design})														
	109	109	109	109	109	109	109	109	109	109	96	96	96	84	96
	Measured APA Rut Depths After 8000 Cycles (mm)														
	5.4	4.4	7.2	11.9	6.9	5.1	4.9	8.5	6.2	13.9	7.1	6.6	3.2	4.3	5.5

Table 4-2b. Volumetrics for HVS, limestone, and granite gradation study mixtures.

Volumetric Property	MIXTURES															
	Limestone Gradation Study								Granite Gradation Study						HVS	
	WR-C2	WR-C3	WR-C4/ F3	WR-C5	WR-F2	WR-F4	WR-F5	WR-F6	GA-C1	GA-C2	GA-C3	GA-F1	GA-F2	GA-C4/F3	PG 67-22	Pg 76-22
G_{mm}	2.347	2.349	2.347	2.388	2.375	2.368	2.326	2.341	2.442	2.500	2.492	2.473	2.532	2.505	2.267	2.272
G_b	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035
G_{mb}	2.255	2.254	2.254	2.244	2.281	2.272	2.233	2.244	2.442	2.399	2.391	2.473	2.433	2.404	2.202	2.202
P_b	5.8	5.3	5.6	6.3	5.4	5.7	6.7	6.1	6.63	5.26	5.25	5.68	4.56	5.14	7.90	7.90
G_{sb}	2.465	2.474	2.468	2.469	2.489	2.491	2.485	2.489	2.687	2.687	2.686	2.686	2.687	2.687	2.346	2.346
G_{se}	2.545	2.528	2.537	2.554	2.565	2.568	2.555	2.550	2.710	2.719	2.709	2.706	2.725	2.720	2.525	2.532
P_{ba}	1.3	0.9	1.1	1.07	1.2	1.2	1.2	1.0	0.37	0.43	0.31	0.28	0.53	0.46	3.10	3.20
P_{be}	4.6	4.5	4.5	5.3	4.2	4.5	5.6	5.2	6.32	4.85	4.96	5.42	4.06	4.70	5.04	4.95
VMA (%)	13.8	13.6	14.0	15.5	13.2	14.0	16.2	15.4	18.5	15.4	15.7	16.6	13.6	15.1	13.6	13.6
Va (%)	3.9	4.0	3.9	4.0	3.9	4.0	4.0	4.2	4.0	4.0	4.1	4.0	3.9	4.0	3.1	3.2
VFA (%)	71.6	70.2	71.8	74.0	70.1	71.2	75.0	72.8	78.5	73.8	74.2	75.9	71.2	73.3	78.9	77.3
D/A	0.8	1.2	1.0	0.9	1.4	1.3	0.8	1.1	0.6	0.8	0.9	0.6	1.2	1.2	0.8	0.8
	Design Number of Gyrations (Ndesign)															
	109	109	109	109	109	109	109	109	109	109	109	109	109	109	100	100
	Measured APA Rut Depths After 8000 Cycles (mm)															
	4.6	4.6	4.3	4.6	5.2	4.2	7.1	4.8	7.1	7.1	5.9	5.1	5.1	4.4	7.5	5.3

4.2.2 Specimen Preparation and Testing

The following tests were performed:

- All mixtures were designed according to the Superpave™ volumetric mix design method.
- Once the mix design was established, mixtures were produced in the laboratory, and short term oven aged (STOA) for two hours and compacted to N_{max} in a Servopac Superpave™ gyratory compactor with shear measurements.
- Another set of mixtures was aged at STOA for two hours and compacted to 7 (±0.5) percent air voids using a gyratory angle of 1.25 degrees. Then, the compaction angle was changed to 2.5 degrees and compaction was continued for another 100 revolutions.
- APA Testing: A set of mixtures was prepared in the same manner as the two previous sets (STOA and compacted to 7 (±0.5) percent air voids). The specimens were trimmed to 75-mm height and left to air dry for about 48 hours. Then the specimens were tested in the APA at 64°C for 8000 cycles. The hose and wheel load were 690 kPa and 445 N (100 psi and 100 lb), respectively.

The compaction temperatures for the PG 67-22 mixtures were at 135°C (275°F) and temperature of 150°C (300°F) for the PG 76-22 mixture that produced equal viscosity to the PG 67-22 mixtures.

4.3 THE USE OF INDUCED SHEAR INSTABILITY FOR THE EVALUATION OF MIXTURE RUT-RESISTANCE

The Superpave™ gyratory compactor shears and compacts mixtures continuously under the same angle and vertical stress throughout the compaction process. If compaction is continued until maximum shear strength is reached, the gyratory shear strength tends to drop off slightly [Birgisson et al 2002]. Research by Darku (2003) has shown that the post-peak part of the compaction curve is not suitable for analysis of mixture stability, due to excessive breakdown of aggregate.

In the pre-peak region of the compaction curve, the mixture may not be changing enough to allow for an evaluation of mixture stability. The slope of the density line and the gyratory shear slope both measure the overall resistance to further deformation, which may not be enough to determine the rutting potential for mixtures. Instability rutting is manifested by the rearrangement of the aggregate structure. Therefore, it is important to measure a mixture's shear resistance during aggregate rearrangement. The characteristics of the gyratory shear curve during rearrangement should be uniquely related to rutting characteristics.

One way to induce instability in mixtures during the compaction process is to first compact the mixture to an air void level that is consistent with field compaction, say 7 (± 0.5) percent air voids. Second, increase the gyratory angle from 1.25 degrees to 2.5 degrees and continue the compaction. The change to a higher angle forces the rearrangement of aggregates. Figure 4-1 shows the resulting gyratory compaction curve. Immediately after increasing the gyratory angle, the gyratory shear strength spikes, followed by a rapid drop as the aggregate structure is being rearranged.

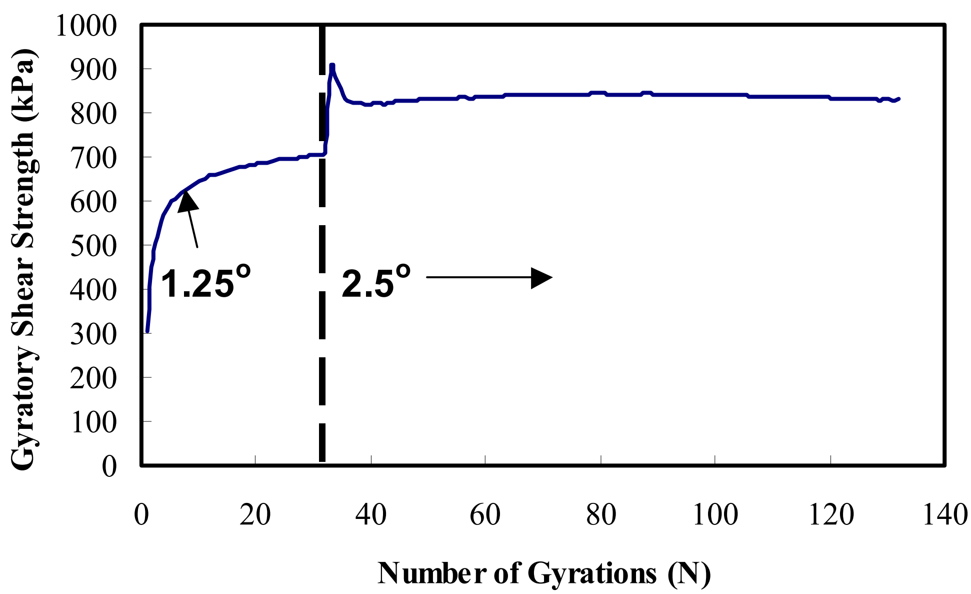


Figure 4-1. Gyratory shear strength versus number of gyrations for the modified compaction procedure.

Figure 4-2 shows the three basic responses observed during aggregate rearrangement. Results define clear differences in mixes. Mixtures that loose their strength almost immediately and don't require much rearrangement are "brittle" mixtures. Mixtures that continue to loose strength upon rearrangement and never regain another stable arrangement are referred to as "plastic" mixtures. Once plastic mixtures are subjected to any condition that promotes the rearrangement of the aggregate structure, the resulting deformation is continuous. Consequently, the third type of response is that of "optimal" mixtures, which are mixtures that lie in between these extremes – i.e., mixtures that when forced to rearrange their aggregate structure can lock up again in a stable arrangement.

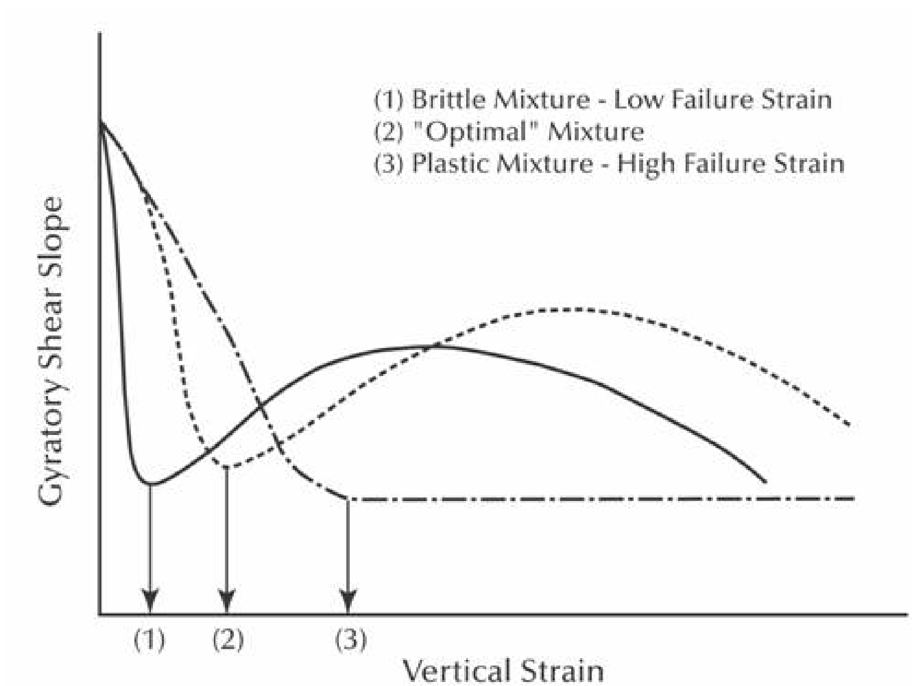


Figure 4-2. Three basic characteristics of gyratory shear curves observed immediately after change of gyratory angle from 1.25° to 2.5° degrees.

In lieu of the gyratory shear strength, the vertical "failure" strain, measured from the onset of the compaction with the 2.5 degree gyratory angle, to the local minimum on the gyratory shear curve (Figure 4-3) is an indicator of how "brittle" or how "plastic" a mixture will respond during the rearrangement of the aggregate structure. A "low" failure strain indicates a brittle mixture and a "high" value indicates a plastic mixture.

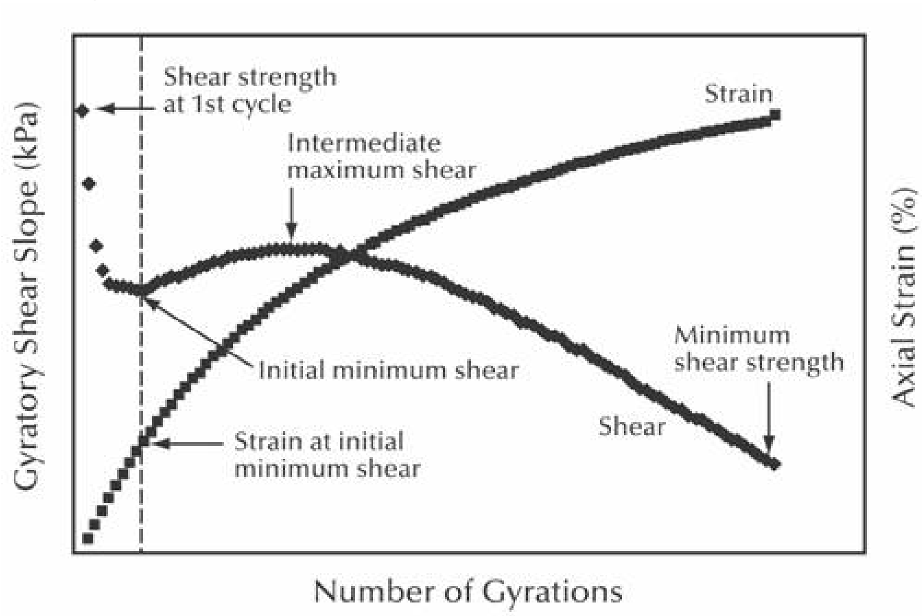


Figure 4-3. Definition of the failure strain (strain at the initial minimum shear strength) following the change of gyratory angle from 1.25° to 2.5° degrees.

Based on the previous discussion, the following observations may be stated:

- The gyratory shear slope calculated between air void levels of 4 and 7 percent, is an indicator of the resistance to further deformation. The higher the gyratory shear slope, the greater the resistance to deformation.
- The vertical "failure" strain measured during aggregate rearrangement at a gyration angle of 2.5 degrees is an indicator of the stability characteristics of mixtures.

Based on these observations, Figure 4-4 presents a framework for the evaluation of mixture rutting behavior. Mixtures with "low" gyratory shear slope will not "lock in" the strength necessary for sufficient rut-resistance. Mixtures with low "failure strain" are "brittle." Mixtures with high "failure strain" are "plastic." Mixtures that are neither brittle nor plastic are optimal. In the following, the framework proposed in Figure 4-4 will be evaluated using the 31 mixtures described previously.

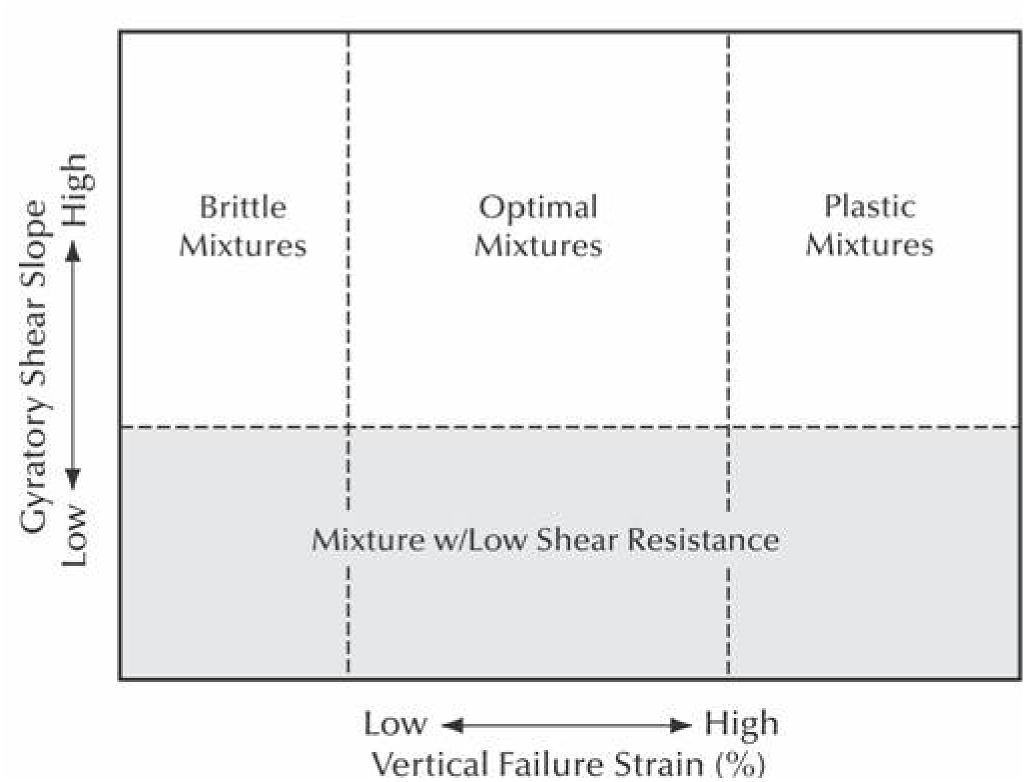


Figure 4-4. Proposed framework for the evaluation of mixture rutting potential.

4.4 EVALUATION OF PROPOSED FRAMEWORK

For the 31 mixtures available, gyratory shear slopes were calculated following the procedure provided by Birgisson, Roque, and Ruth (2003), discussed previously. Since the mixture design pills for each of these mixtures were compacted using a Superpave™ gyratory compactor with shear measurements, there was no need for additional material preparation to obtain gyratory shear slopes. To obtain failure strains, a set of replicate samples for each mixture were compacted to a target air void level of 7 (± 0.5) percent. Once the target air voids level was reached, the compaction angle was increased from 1.25 degrees to 2.5 degrees and the mixtures were compacted for another 100 gyrations, and the failure strain was calculated.

Table 4-3 shows the predicted categories and Figure 4-5 shows a plot of the gyratory shear slope versus failure strain for the mixtures tested. APA rut depth measurements were used to identify divisions between mixtures based on their rutting performance. The criterion between

Table 4-3. Classification of mixtures using proposed framework for the evaluation of mixture rut-resistance.

Mixtures	Classification Category	Gyratory Shear Slope (kPa)	Failure Strain (%)	APA Rut Depth (mm)
WR-C1	Optimal	23.2	1.88	5.4
CG_{Course}	Brittle	26.8	1.38	4.4
RB_{Course}	Low Shear Resistance/ Plastic	14.6	2.14	7.2
CH_{Course}	Low Shear Resistance	6.26	1.62	11.9
CAL_{Course}	Optimal	21.2	1.50	6.9
WR-F1	Optimal	23.0	1.76	5.1
CG_{Fine}	Brittle	17.8	1.32	4.9
RB_{Fine}	Low Shear Resistance/Plastic	7.1	2.02	8.5
CAL_{Fine}	Brittle	16.0	1.3	6.2
CH_{Fine}	Low Shear Resistance	11.9	1.56	13.9
P1	Plastic	20.0	2.11	7.1
P2	Optimal	20.2	1.58	6.6
P3	Optimal	24.4	1.48	3.2
P7	Optimal	17.8	1.46	4.2
P8	Optimal	21.7	1.53	5.5
WR-C2	Optimal	20.2	1.72	4.6
WR-C3	Optimal	27.7	1.66	4.6
WR-C4/F3	Optimal	30.2	1.63	4.3
WR-C5	Optimal	22.0	1.57	4.6
WR-F2	Brittle	32.4	1.26	5.2
WR-F4	Brittle	28.1	1.38	4.2
WR-F5	Brittle	22.5	1.33	7.1
WR-F6	Optimal	27.2	1.69	4.8
GA-C1	Low Shear Resistance/Plastic	13.9	2.13	7.1
GA-C2	Optimal	23.0	1.7	7.1
GA-C3	Optimal	24.5	1.61	5.9
GA-F1	Low Shear Resistance	13.8	1.66	5.1
GA-F2	Optimal	29.9	1.45	5.1
GA-C4/F3	Optimal	22.7	1.60	4.4
HVS PG 67-22	Plastic	21.7	2.06	7.5
HVS PG 76-22	Optimal	21.9	1.6	5.3

mixtures of adequate and poor rutting performance was set at 7-mm APA rut depth. The higher 8 mm APA rut depth limit recommended by Kandhal and Cooley (2002) did not identify mixtures that were known to be plastic. Based on visual divisions between the data points shown in Figure 4-5, a set of categories was determined. A gyratory shear slope of 15-kPa separates mixtures with APA rut depths greater than 7-mm from mixtures with rut depths less than 7-mm. A failure strain greater than 2.0 percent separates plastic mixtures from optimal mixtures. Finally, failure strains less than 1.4 percent identify brittle mixtures. Interestingly, most of the brittle mixtures shown in Figure 4-5 also showed cracking during APA testing.

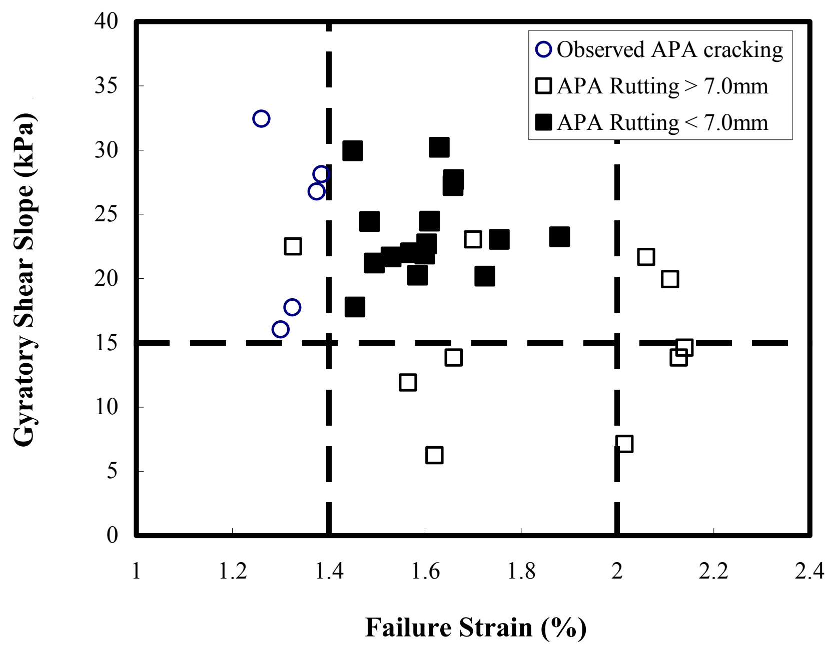


Figure 4-5. Framework for the evaluation of mixture rut-resistance.

In the following, a stepwise discriminant function category statistical analysis is presented that further validates the categories identified in Figure 4-5.

4.4.1 Statistical Evaluation of Results

A stepwise discriminant function analysis was performed to test the validity of the categories proposed. The statistical analysis can be broken down into three basic steps. First, the validity of the proposed categories was evaluated. Second, underlying predictive functions were identified. Third, the underlying predictive equations were used to reclassify each mixture into predicted categories and the results were compared to the original classification.

The hypothesized categories to be tested are as follows:

1. Category 1 – Optimal mixtures (shear slope > 15-kPa and failure strain between 1.4 percent and 2.0 percent).
2. Category 2 – Brittle mixtures (with failure strain < 1.4 percent)
3. Category 3 – Mixtures with low shear slope (with shear slope < 15-kPa).
4. Category 4 – Plastic mixtures (with failure strain > 2.0 percent).

Categories 3 and 4 initially had three joint mixtures, as shown in Figure 4-5. Table 4-4 summarizes the basic statistics for each category. Initially, the two predictor variables studied were the shear slope and the failure strain, with category status as the criterion variable, with an alpha level of 0.05 for statistical significance.

Table 4-5 presents a summary of the stepwise discriminant analysis. Since the criterion variable, category status, has more than three groups, the number of discriminant functions computed is two. The eigenvalues in Table 4-5 show how much of the variance in the criterion variable is accounted for by each of the functions (i.e., function 1 accounting for 92%, function 2 accounting for 8%). Wilks's lambda in Table 4-6 shows that each function is statistically significant (i.e., $p < .05$). The smaller the Wilks's lambda, the more important the predictor variable to the discriminant function. Therefore, the result shows the discriminant function 1 is a more important than function 2.

Table 4-4. Descriptive statistics for predictor variables for by the four categories.

Category	Statistic	Strain (percent)	Slope (kPa/ln(N))	APA Rut Depth (mm)
Category 1	N	17	17	17
	Mean	1.61	23.59	5.29
	Std. Deviation	0.11	3.43	1.05
	Minimum	1.45	17.79	3.18
	Maximum	1.88	30.22	7.10
	Range	0.43	12.43	3.92
	Median	1.60	23.04	5.10
Category 2	N	6	6	6
	Mean	1.33	23.94	5.28
	Std. Deviation	0.05	6.33	1.16
	Minimum	1.26	16.05	4.25
	Maximum	1.39	32.43	7.13
	Range	0.13	16.38	2.88
	Median	1.33	24.64	4.90
Category 3	N	6	6	6
	Mean	1.85	11.27	9.33
	Std. Deviation	0.27	3.67	2.89
	Minimum	1.57	6.26	7.00
	Maximum	2.14	14.61	13.93
	Range	0.58	8.35	6.93
	Median	1.84	12.87	7.95
Category 4	N	5	5	5
	Mean	2.09	15.44	7.48
	Std. Deviation	0.05	5.74	0.62
	Minimum	2.02	7.12	7.00
	Maximum	2.14	21.68	8.53
	Range	0.13	14.56	1.53
	Median	2.11	14.61	7.25

Table 4-5. Eigenvalue and canonical correlation for calculated discriminant functions.

Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1*	4.69	92.00	92.00	0.91
2*	0.41	8.00	100.00	0.54
* First 2 canonical discriminant functions were used in the analysis				

Table 4-6. Wilks' Lamda and Chi-square for calculated discriminant functions.

Test of Function(s)	Wilks' Lambda	Significance
1 through 2	0.125	0.00
2	0.711	0.01

Next, a predictive discriminant function analysis was performed using the model yielded by the stepwise analysis. The standardized canonical discriminant function coefficients in Table 4-7 serve the same purpose as beta weights in multiple regression - they indicate the relative importance of the predictor variables in predicting the criterion variable. For function 1, the strain is most related to the discriminant factor (r = .872), followed by the gyratory shear slope (r = -.605). On the other hand, for function 2, the gyratory shear slope is most related to the discriminant factor (r = .805), followed by the strain (r = .505). The standardized discriminant function coefficients should be used to assess each independent variable's unique contribution to the discriminant function. In summary, even though the failure strain was shown to be a more important predictor variable, since it dominates function 1, both variables were shown to be statistically significant, since the gyratory shear slope dominates function 2.

Table 4-7. Standardized canonical discriminant function coefficients for calculated.

	Function	
	1	**2**
Strain	0.872	0.505
Slope	-0.605	0.805

Table 4-8 presents the classification results based on the hypothesized categorization. About 88.2% of the cases are correctly classified, which is a satisfactory discriminant analysis in terms of statistical significance. Only a few data points got misclassified, mostly due to the common data points in Categories 3 and 4. Subsequently, the divisions between Categories 3 and 4 were adjusted, assigning all mixtures with strains greater than 2.0 percent to Category 4, and a new stepwise discriminant analysis were performed. As shown in Table 4-9, the discriminant analysis now correctly classifies 96.8% of the cases.

Table 4-8. Initial classification results based on two predictor variables (strain and slope).

			Predicted Group Membership (%)				Total
		Category	category 1	category 2	category 3	category 4	
Original	Count	category 1	16	1	0	0	17
		category 2	0	6	0	0	6
		category 3	0	0	4	2	6
		category 4	0	0	1	4	5
	%	category 1	94	6	0	0	100
		category 2	0	100	0	0	100
		category 3	0	0	67	33	100
		category 4	0	0	20	80	100

* 88.2% of original grouped cases correctly classified.

Table 4-9. Reclassification results based on two predictor variables (strain and slope).

		Predicted Group Membership (%)					Total
		Category	category 1	category 2	category 3	category 4	
Original	Count	category 1	15	1	0	0	16
		category 2	0	7	0	0	7
		category 3	0	0	3	0	3
		category 4	0	0	0	5	5
	%	category 1	94	6	0	0	100
		category 2	0	100	0	0	100
		category 3	0	0	100	0	100
		category 4	0	0	0	100	100

* 96.8% of original grouped cases correctly classified.

Finally, a stepwise discriminant analysis was performed using three predictor variables: strain, slope and APA rut depth. Table 4-10 shows the results. The analysis yielded two dominant variables, namely strain and APA rut depth, which maximize separation between the categories. As shown in Table 4-10, the stepwise discriminant analysis correctly classified 93.75 % of the cases, which is satisfactory discriminant analysis in terms of statistical significance. In summary, the results of the statistical analysis presented verify the significance of the parameters used and the hypothesized categories.

4.4.2 Evaluation of Mixtures with Known Field Rutting Performance

Mixtures listed in Tables 1 and 2 with known field performance include the following mixtures: P1, P2, P3, P7, and P8. In addition, the HVS unmodified (PG 67-22) and SBS modified (PG 76-22) mixtures were also included. Field instability rutting was observed for mixtures P1 and HVS PG 67-22. Figure 4-6 shows the resulting classification. The proposed framework correctly classified all seven mixtures. Also, interestingly, the failure strain appears to be sensitive to the effects of SBS modification. The SBS modified HVS PG 76-22 mixture had a failure strain that was significantly smaller that the unmodified HVS PG 67-22 mixture.

Table 4-10. Reclassification results based on three predictor variables (strain, slope, and APA rut depth).

		Predicted Group Membership (%)					Total
		Category	category 1	category 2	category 3	category 4	
Original	Count	category 1	15	1	0	0	16
		category 2	0	8	0	0	8
		category 3	1	0	2	0	3
		category 4	0	0	0	5	5
	%	category 1	93.75	6.25	0	0	100
		category 2	0	100	0	0	100
		category 3	33.3	0	66.7	0	100
		category 4	0	0	0	100	100

* 93.75% of original grouped cases correctly classified.

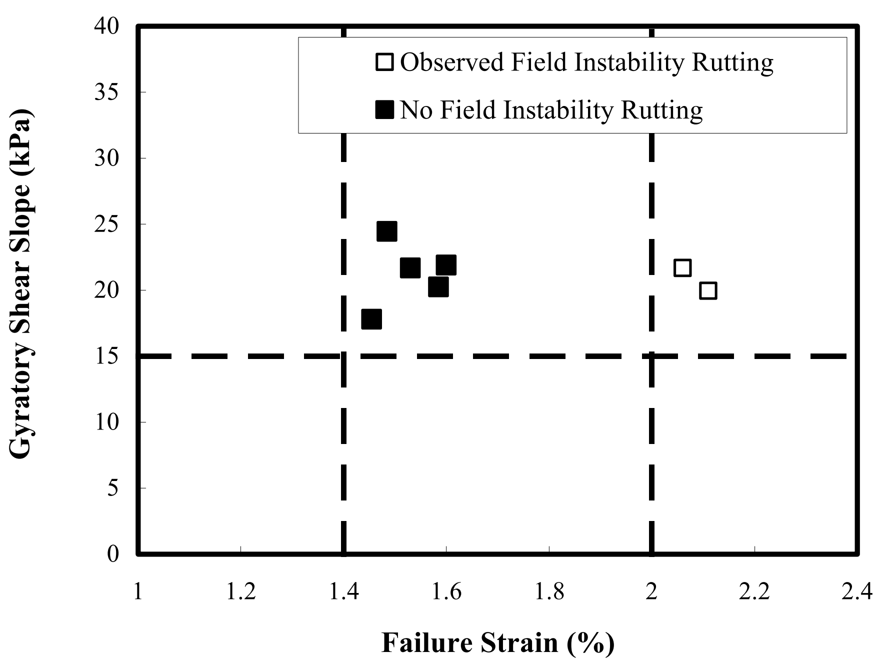


Figure 4-6. Illustration of categorization of mixtures with known field rutting performance.

4.4.3 Comparison to N-SRmax Criterion

Anderson (2002) proposed the use of the N-SRmax parameter for screening mixtures with potential rutting problems. The N-SRmax parameter is the number of gyrations at which the ratio of the shear stress divided by the vertical stress reaches a maximum value. This parameter was able to differentiate the rut-resistance between the mixtures evaluated by Anderson (2002), which consisted of eight limestone mixtures and eight gravel mixtures. Following the method for determining N-SRmax and the proposed rut-performance criteria for mixtures outlined by Anderson (2002), all the mixtures tested in this work were evaluated and classified in accordance with the proposed range of performance.

Figure 4-7 shows the plot of all mixtures based on the N-SRmax parameter. The use of the N-SRmax parameter resulted in most of the granite mixtures being classified as "poor" mixtures, while most of the limestone mixtures were classified as "fair." Also, mixtures with

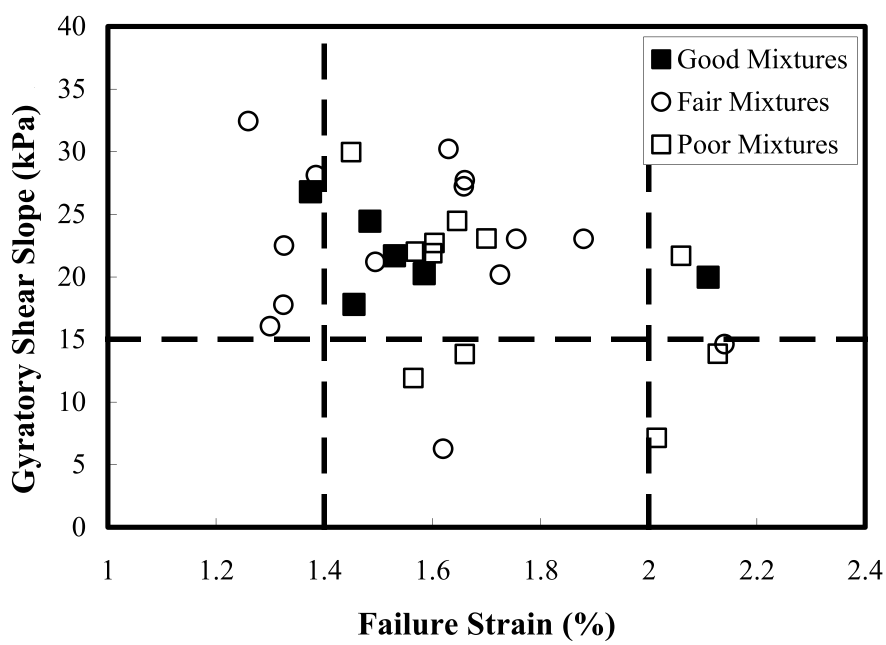


Figure 4-7. Illustration of N-SRmax categorization for the 31 mixtures evaluated.

other volumetric problems did not always get identified. For example, the only "good" mixture that is shown in the "brittle" region (failure strain lower than 1.4 percent) is the CGC mixture, which is an extremely dry mix, with high dust to asphalt ratio. Similarly, the only mix in the "plastic" category identified as a "good" mixture is the Superpave™ Field Monitoring Project No. 1 mixture, which is the only field project mixture that is known to be showing signs of instability rutting. In summary, the N-SRmax parameter failed to consistently identify mixtures with known good and bad rutting performance.

4.4.4 Comparison to Superpave Volumetric Criteria

Figure 4-8 is based on whether or not a mixture passed or failed the Superpave™ volumetric screening criteria (primarily, air voids, voids in the mineral aggregate, voids filled with asphalt, and the dust to asphalt ratio). Thus, "failed" mixtures in Figure 4-8 consist of those that did not satisfy one or more of the volumetric acceptance criteria, based on the traffic levels in Tables 4-2a and 4-2b.

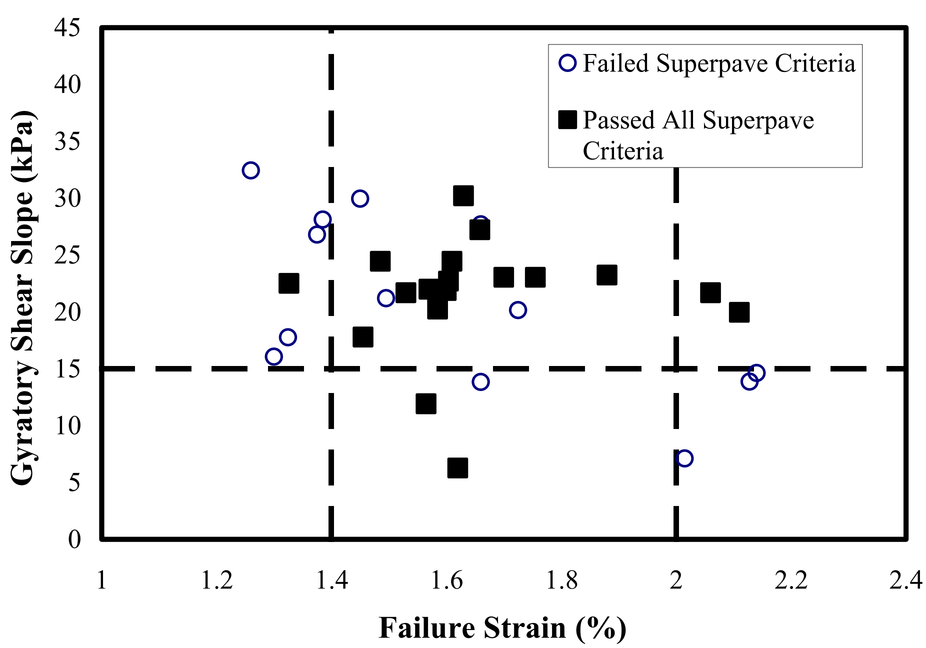


Figure 4-8. Illustration of mixtures that passed/failed Superpave™ volumetric design criteria (based on traffic levels provided in Tables 4-2a and 4-2b).

Interestingly, out of the six mixtures with gyratory shear slope of 15-kPa or below, the Superpave™ volumetric criteria identified four. Similarly, the Superpave™ volumetric criteria identified five out of the six mixtures that had strains below 1.4 percent (i.e. mixtures in the "brittle" category), due to these mixtures having high dust to asphalt contents. The only mixture in the brittle category that satisfied all Superpave™ volumetric design criteria was the WR-F5 mixture (Table 4-2b), which is a gap-graded limestone mixture. Importantly, a number of mixtures that satisfied all Superpave™ volumetric design criteria had either a low shear slope, or high failure strain. The results in Figure 4-8 show the need for additional performance-based criteria or screening tools for identifying mixtures that meet all Superpave™ volumetric design criteria, but may be rut-susceptible.

4.5 SUMMARY AND CONCLUSIONS

Instability rutting in hot mix asphalt pavements occurs when the structural properties of the compacted mix cannot adequately resist critical near surface stress states consisting of high shear stresses and low confinement. On the mixture level, instability rutting is manifested in a rearrangement of the aggregate structure. This study illustrated that it may be necessary to induce instability in mixtures to determine parameters that are relevant to mixture rut resistance. The Superpave™ gyratory compactor with shear measurements and the option of changing the compaction angle during compaction was used in this study. Mixtures were compacted to a density that is consistent with the air voids of field pavements immediately after construction, namely 6 to 8 percent air voids. The subsequent application of high shear stresses by increasing the gyratory angle from 1.25 degrees to 2.5 degrees results in material states at which parameters can be measured that define clear differences in mixtures. Based on the testing of 31 mixtures with different void structure and aggregate characteristics, the results of this paper can be summarized as follows:

- During the mixture aggregate structural rearrangement phase, three distinctive responses were observed: a) brittle response, where mixtures loose their strength almost immediately, b) plastic response, where once the mixtures loose strength due to rearrangement they never regain another stable rearrangement, and c) optimal response, which is bracketed by the plastic and brittle types of responses. Optimal mixture will eventually lock up again in a stable arrangement.
- Key parameters were identified that are relevant to the rut-resistance of mixtures, namely gyratory shear slope and failure strain.
- Using gyratory shear slope and failure strain, a framework for the evaluation of mixture rutting potential is developed.
- The rutting potential of 31 mixtures is evaluated with the framework. Based on a comparison to APA rut depth measurements and a statistical analysis of results, the validity of the proposed framework is established.
- The proposed framework was also evaluated for seven field mixtures with known rutting performance. All seven mixtures were classified correctly, including a mixture with a SBS modified binder.
- The results show that the proposed framework has the potential for being developed into an index test for evaluating the rutting potential of mixtures.

Based on the findings in this paper, the proposed approach for evaluating mixture rut-potential should be studied further and validated for a larger variety of asphalt mixtures. The proposed framework provides an index of the rut-resistance of mixtures, and could potentially be used to rapidly identify mixtures that may need further mechanical performance testing and evaluation.

CHAPTER 5

PROPOSED GYRATORY COMPACTOR ANALYSIS FRAMEWORK

5.1 SUMMARY AND CONCLUSIONS

The use of the Superpave™ gyratory compactor with shear strength measurements was examined for its potential as an index test for evaluating the rutting potential of mixtures. A comprehensive review of methods in the existing literature for relating gyratory compaction parameters to rutting potential concluded that no existing interpretation method could reliably differentiate between mixtures of poor and adequate rutting potential. The research subsequently focused on carefully studying the gyratory compaction curve with shear measurements. It was determined that there were three distinct regions present: 1) the compaction region, which is defined from the onset of compaction to about 7-8 percent air voids; 2) the densification region, defined from about 7-8 percent air voids to about 4 percent air voids or the air voids at the peak stress, whichever comes first; and 3) the post-peak part of the curve. Based on these findings, it was further determined that neither the compaction region nor the post-peak region could be used reliably to evaluate the rutting potential of mixtures. A careful focus on the densification region revealed that the slope of the gyratory shear strength curve versus log of gyratory revolutions provided an indicator of the rutting potential of mixtures. Unfortunately, the scatter around the observed trends precluded the use of the gyratory shear slope as a single predictive parameter of rutting instability. In view of these findings, the research refocused on identifying and incorporating fundamental stress states associated with the onset of rutting instability. Based on careful finite element modeling of measured tire contact stresses under radial truck tires, a condition of impending instability was identified. The presence of near surface shear stresses along with reduced confinement at the edge of modeled truck tires implies that these critical stress states, combined with critical temperature and air voids, may define a condition of impending rutting instability. Based on a review of possible stress states in the Superpave gyratory compactor, it was also determined that it was not possible to induce low confinement during compaction. However, high shear stresses and strains, which are representative of response at impending instability, can be induced by increasing the compaction angle from 1.25 to 2.5 degrees. Subsequently, a condition of impending instability was induced by compacting mixtures to about 7 percent air voids at a gyratory compaction angle of 1.25 degrees, followed by an increase in the gyratory compaction angle to 2.5 degrees and further compaction. At the condition of impending instability, the mixture will rearrange its aggregate structure to distribute the increased shear stresses associated with the higher compaction angle. Mixtures that are rut susceptible were found to never regain gyratory shear strength. Mixtures that had adequate rutting resistance, were found to rearrange the aggregate structure into a stable aggregate structure, eventually leading to an increase in the gyratory shear strength. Mixtures that were over asphalted or contained a large amount of fines were found to show a sharp decrease in gyratory shear strength during the condition of impending instability. Based on the measurement of the vertical strain during the condition of impending instability, it was possible to determine whether a mixture was likely to show rutting instability, or was on the dry and brittle side. Subsequently, a new framework for the evaluation of the rutting potential of mixtures was proposed. The framework consists of the vertical strain measurement during condition of impending instability and the gyratory shear slope measured between 7 and 4 percent air voids at a compaction angle of 1.25 degrees. The proposed framework was evaluated for a total of 31 mixtures, comprising of 10 mixes for fine aggregate angularity effects, eight mixtures of limestone-based mixtures used to study gradation effects, seven field mixtures and six granite based mixtures for aggregate type effects. The evaluation of mixture rut potential for these mixtures included the use of the new framework, a comparison to known field performance and APA rut depth measurements, as well as a statistical analysis of results. The results showed that the proposed framework has the potential for being developed into an index test for evaluating the rutting potential of mixtures.

Based on these findings, the proposed approach for evaluating mixture rut-potential should be studied further and validated for a larger variety of asphalt mixtures. The proposed framework provides an index of the rut-resistance of mixtures, and could potentially be used to rapidly identify mixtures that may need further mechanical performance testing and evaluation.

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