STATE OF FLORIDA

Evaluation of Segregation for Top-Down Cracking and Rutting Performance and Detecting Low-Performance Segregated Mixtures

Research Report
FL/DOT/SMO/06-500

Jaeseung Kim
Gregory A. Sholar
Howard L. Moseley

October 2006

STATE MATERIALS OFFICE

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Segregation in asphalt mixtures occurs as a result of the non-uniform distribution of coarse and fine aggregates and causes premature distresses, such as cracking, ravelling, and stripping. In Florida, top-down cracking and rutting are common and primary distress modes in flexible pavements. Experimental and analytical work performed in this study indicates that top-down cracking and rutting performance are affected by segregation of mixtures. However, the aggregate structure of mixtures appears to be a more critical factor that determines the cracking and rutting performance, rather than the level of segregation. Based on the mixtures evaluated, coarse aggregate volume in an asphalt mixture is an important factor that determines cracking and rutting performance. This effect holds true for mixtures with lower levels of air voids, but for mixtures with higher levels of air voids, the air voids effect becomes dominant, resulting in a reduction in both cracking and rutting performances. An air void content of 10% appears to be a threshold that determines the cracking and rutting performance of Superpave mixtures. Once the air void content exceeds 10%, cracking and rutting performance of Superpave mixtures decrease significantly, despite the coarse aggregate volume.

Meanwhile, at the lower level of air voids, an increase of coarse aggregate volume in an asphalt mixture is an important factor that results in good rutting performance, but for the cracking performance, a proper volume of coarse aggregate in asphalt mixtures is an important factor that results in good cracking performance. A coarse aggregate volume of 45% appears to be a threshold that determines the cracking performance of Superpave mixtures. Once the coarse aggregate volume exceeds 45%, the cracking performance of Superpave mixtures starts to decrease.

During this study, the Pavement Quality Indicator (PQI), a non-nuclear density gauge, was used to measure the in-place density of the pavements. This PQI appears to be effective in measuring the in-place density of the pavements and would be a useful tool in locating sections with 10% or higher in-place air voids. Prior to any remedial action for these sections, cores should be obtained and bulk density and maximum theoretical density should be determined to verify the PQI measurements.

CHAPTER 1

INTRODUCTION

BACKGROUND

Segregation in asphalt mixtures occurs as a result of the non-uniform distribution of coarse and fine aggregates. Segregation can typically be visually identified from the areas where coarse-aggregate-rich surface texture exists along the pavement surface. In general, coarse-aggregate-rich mixtures have high air voids and low asphalt contents. From the literature (Brown et al. 1989, and Cross and Brown 1993, Williams et al. 1996, and Stroup-Gardiner 2000), these mixtures lead to premature distresses, such as cracking, raveling, and stripping. Consequently, these distresses will reduce the performance and serviceability of the in-situ pavement.

Top-down cracking or surface-initiated longitudinal wheel path cracking, which initiates from the surface of an asphalt concrete layer and propagates downward, is now considered a common distress mode in flexible pavements. In Florida, approximately 85% of the deficient pavements are due to cracking with the majority of these experiencing top-down cracking. Several studies have shown logical explanations of the mechanics of this mode of failure (Myers et al. 1999, Myers et al. 2001, and Myers and Roque 2002, and Kim 2005). A recent forensic investigation conducted for evaluating top-down cracking in Colorado indicates that segregation has potential for the development of top-down cracking (Harmelink and Aschenbrener, 2003). Approximately 67% of the top-down cracking cores had visual signs of segregation. Nevertheless, a comprehensive top-down cracking laboratory evaluation related to segregation has not been performed yet. Although several researches successfully evaluated the effect of segregation related to fatigue, these laboratory evaluations appear to be limited to evaluating cracks occurring at the pavement surface. Therefore, it is important to identify the effect of segregation on top-down cracking associated with suitable approaches.

Instability rutting, which is shear related and occurs when the compacted mixture cannot resist critical stress conditions occurring at the pavement surface, is also a major distress mode in flexible pavements. Nevertheless, the effect of segregation on the performance of rutting has not been clearly identified. The pavement condition survey conducted on the pavements with various levels of segregation in six states reported that rutting performance was not strongly influenced by gradation segregation, except some areas with higher air voids (Stroup-Gardiner and Brown 2000). A similar conclusion was also reported by Cross (2000). In his study, laboratory tests performed using Asphalt Pavement Analyzer (APA) on two different mixtures with different levels of segregation did not show clear correlation between rut depths and the levels of segregation. This indicates that segregation may have positive and negative effects on the performance of rutting, but the field performance data or the laboratory testing alone appears to be limited in identifying these effects. Therefore, a suitable approach that can identify the positive and negative effects of segregation on the rutting performance needs to be developed.

The aggregate structure of asphalt mixtures has been well studied on the basis of experience and identified as an important factor that determines the performance of mixtures. For example, the cracking and rutting performance of mixtures appear to be significantly affected by aggregate gradation variation and air void content (Elliott et al. 1991). Also, Vavrik et al. (2001 and 2002) and Kim et al. (2005) indicate that the effect of coarse aggregate will provide great potential for evaluating the rutting performance of hot-mix asphalt. For the same reason, the performance of segregated mixtures may not be only a function of the level of segregation, but also related to the aggregate structure. Furthermore, considering that segregation changes the aggregate structure of a mixture, it is of particular interest to know what relationship can be made between segregation and its original gradation, and how the change can be related to the cracking and rutting performance of the mixture. An analytical approach based on the finite element method was considered and developed. To this purpose, a finite element program (ADINA) was used to evaluate these effects on the cracking and rutting potential of asphalt mixtures.

Recently, non-destructive techniques using either nuclear density gauges or non-nuclear density gauges have been widely studied in evaluating segregation because of their simplicity. Hence, this study investigated the effectiveness of a non-destructive density gauge by comparing in-place densities of asphalt mixtures with air void contents of the same mixtures measured in the laboratory. To this purpose, the research team evaluated a non-nuclear density gauge, the Pavement Quality Indicator (PQI) model 301.

OBJECTIVE

The primary objectives of this research study are listed below:

- Evaluate the effect of segregation on the cracking and rutting performance of dense-graded Superpave mixtures.
- Identify and evaluate the effect of aggregate structure on the cracking and rutting performance of asphalt mixtures with different gradations, asphalt contents, air void levels, and different levels of segregation.
- Develop and identify a criterion to effectively assess the cracking and rutting performance of segregated mixtures related to their gradation and volumetric properties.

- Evaluate the effectiveness of the Pavement Quality Indicator (PQI) density gauge to identify low-performance segregated mixtures.

SCOPE

This research focuses on identifying the effect of segregation on the cracking and rutting performance of asphalt mixtures. This study involves segregated and non-segregated mixtures obtained from three in-service pavements in Florida. The mixtures were composed of a variety of aggregates, including limestones and granites typically used in Florida.

The experimental portion of this study can be classified into two parts: 1) determining volumetric properties and 2) evaluating cracking and rutting performance. A complete set of laboratory tests that are commonly used to determine the volumetric properties of mixtures were performed on each cored sample, and a complete set of indirect tension tests, which are used to determine the top-down cracking performance of mixtures, and rutting tests using the Asphalt Pavement Analyzer (APA), which is widely used as a rutting performance test of asphalt mixtures, were performed on part of the cored samples.

The analytical work involved in this study is to predict cracking and rutting performance of the mixtures that have different gradations and different levels of segregation based on the aggregate structure. An analytical approach was developed using the finite element method (FEM). A finite element program (ADINA) was used to evaluate the effect of coarse aggregates and air voids on the cracking and rutting performance of asphalt mixtures.

CHAPTER 2

DESCRIPTION OF TEST SECTIONS

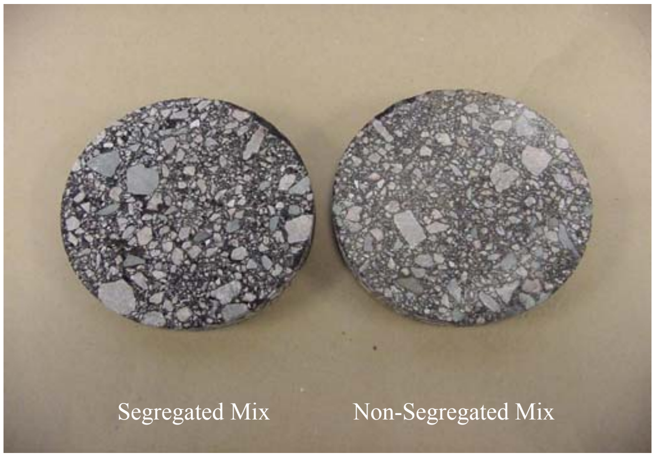
Three pavements having different degrees of visual segregation were selected for sampling and evaluation. The age of all pavements was less than one year when cores were obtained, and all mixtures used were designed by the Superpave mix design method. For each pavement, segregated and non-segregated areas were visually identified, and ten cores from each area were obtained. A brief description of each site follows:

SITE 1 - SR 222

Site 1 is located on SR 222 in Alachua County. The mixture was a fine graded, 12.5 mm nominal size aggregate mixture with an ARB-5 binder. From a picture taken of the core samples, Figure 1(a), segregation was apparent, but less significant than SR 16 or SR 21. Therefore, visual observations concluded that this site could be ranked as a low segregated site.

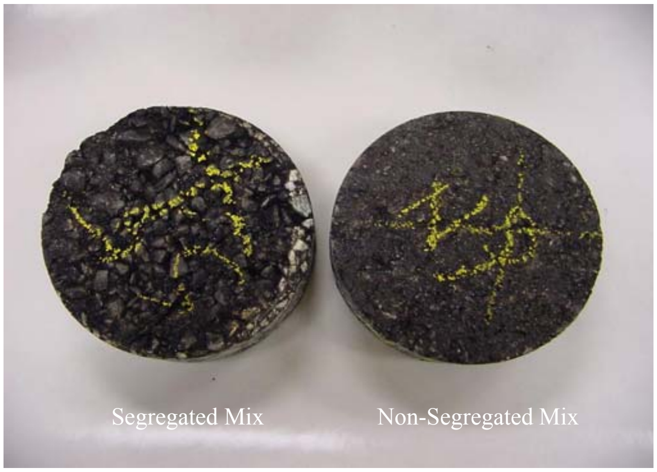
SITE 2 - SR 21

Site 2 is located on SR 21 in Clay County. The mixture was a fine graded, 12.5 mm nominal size aggregate mixture with PG 76-22 binder. From a picture taken of the core samples, Figure 1(b), segregation was less significant than SR 16, but more significant than SR 222. Thus, this site could be ranked as a medium segregated site.



(a) Site 1 (SR 222)

(b) Site 2 (SR 21)



(c) Site 3 (SR 16)

Figure 1. Cored Samples

SITE 3 - SR 16

Site 3 is located on SR 16 in Clay County. The mixture was a fine graded, 12.5 mm nominal size aggregate mixture with PG 76-22 binder. From a picture taken of the core samples, Figure 1(c), segregation was heavy. Thus, this site could be ranked as a heavily segregated site.

In summary, six sections from three pavements were evaluated to investigate the effect of segregation among mixtures having different gradations. Sites 1-N, 2-N, and 3-N represent non-segregated areas as well as mixtures with different gradations, while sites 1-S, 2-S, and 3-S represent areas segregated from the different gradations. A summary of the pavement conditions is shown in Table 1. In addition, it should be noted that the overwhelming mixture type used for FDOT work is a 12.5 mm nominal size aggregate mixture. Hence, the three mixtures chosen for this study are that type.

Table 1. Location and Condition of Sections

Site Number	Route	Country	Gradation	Code	Segregation Rating
Site 1	SR 222	Alachua	Fine	Site 1-N	No Segregation
				Site 1-S	Low Segregation
Site 2	SR 21	Clay	Fine	Site 2-N	No Segregation
				Site 2-S	Medium Segregation
Site 3	SR 16	Clay	Fine	Site 3-N	No Segregation
				Site 3-S	Heavy Segregation

SPECIMEN PREPARATION

This study intended to directly measure volumetric properties and laboratory rut depths from the segregated and non-segregated specimens. Thus, the commonly used laboratory segregation technique (Khedaywi and White 1995) was not considered.

A total of ten 150 mm diameter cores were obtained from the segregated and non-segregated areas of each pavement, respectively. The coring location was carefully selected through field inspection as being representative of segregated and non-segregated pavement conditions. All cores were carefully marked and delivered to the laboratory. Upon inspection in the laboratory, five, approximately 38 mm thick, specimens of the surface mixture were taken and prepared for the volumetric tests and indirect tension tests. Two 75 mm thick specimens, which were obtained by removing the bottom of cored mixtures, were taken and prepared for the rutting performance tests using Asphalt Pavement Analyzer (APA).

CHAPTER 3

EVALUATION OF VOLUMETRIC PROPERTIES

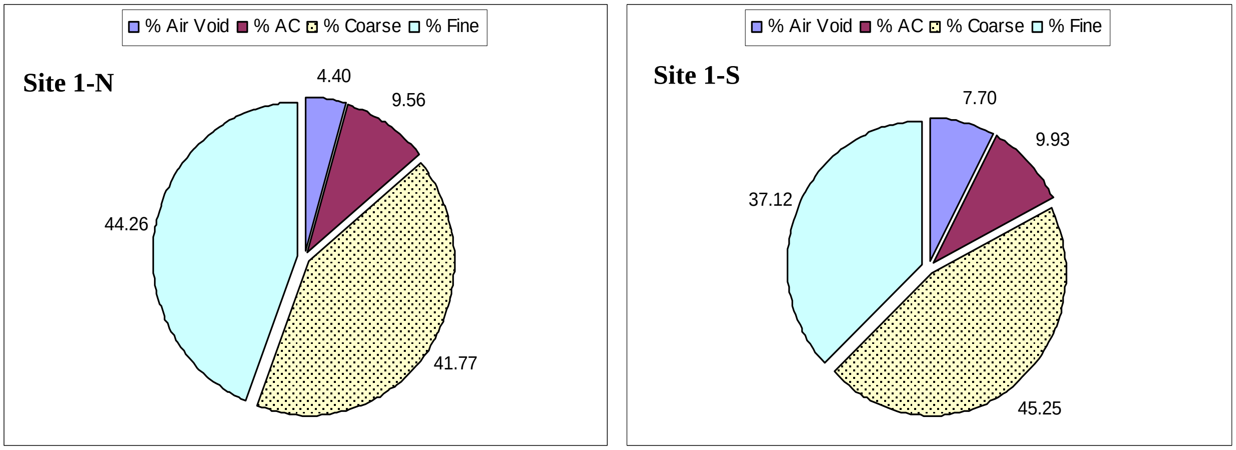
LABORATORY TESTING

The bulk specific gravity of five specimens was measured (FM 1-T 166) and then the specimens were dried. Two specimens, representing each mixture, were used for determination of maximum theoretical density (FM 1-T 209). The remaining cores were assigned for determination of asphalt contents using the ignition oven (FM 5-563) and sieve analyses (FM 1-T 30).

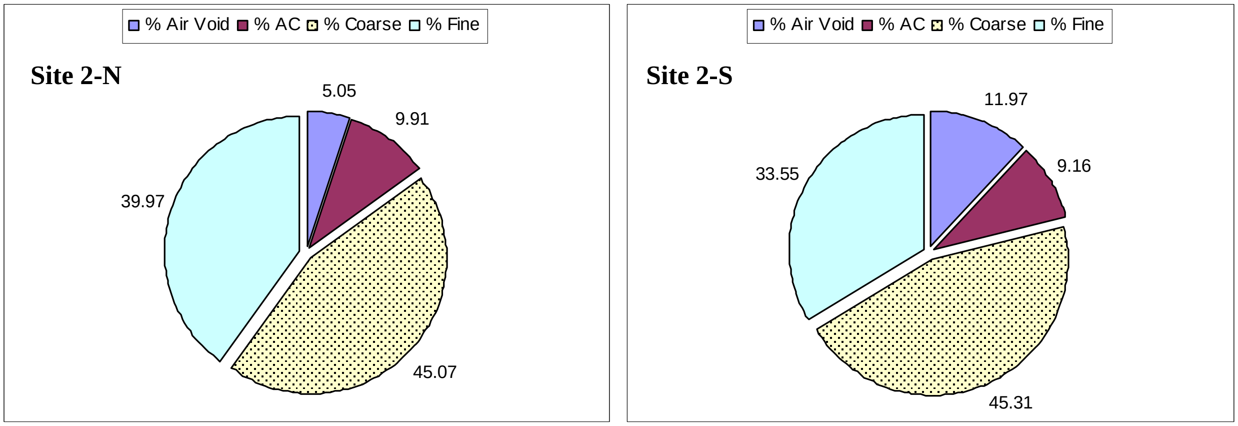
SUMMARY OF LABORATORY TEST RESULTS

Segregation in flexible pavements occurs as a result of the non-uniform distribution of coarse and fine aggregates. The areas where coarse-aggregate-rich surface texture exists can be visually identified as segregated areas. Since segregated mixtures have a higher amount of coarse aggregate than the non-segregated mixtures, these mixtures generally have lower asphalt contents and higher air voids.

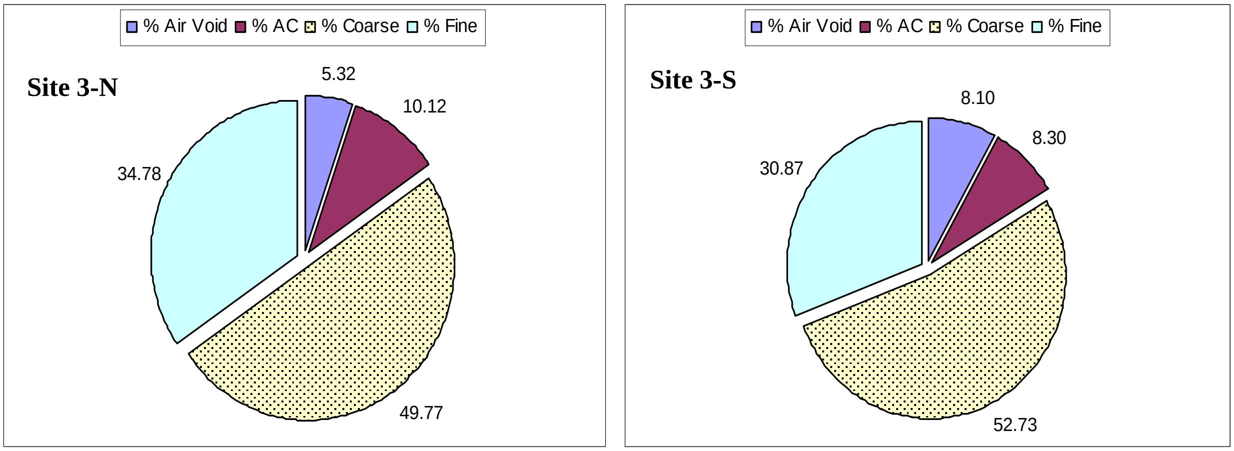
The laboratory tests performed on the segregated and non-segregated mixtures correlated with the fact illustrated above. Based on volume, results of each site are shown in a simple phase diagram (Figure 2) illustrating four phases: coarse aggregate and fine aggregate, where the 2.36 mm sieve was selected as the size separating coarse and fine aggregates, asphalt content, and air voids.



(a) Site 1 (SR 222)



(b) Site 2 (SR 21)



(c) Site 3 (SR 16)

Figure 2. Phase Diagram

DETERMINATION OF DEGREE OF SEGREGATION

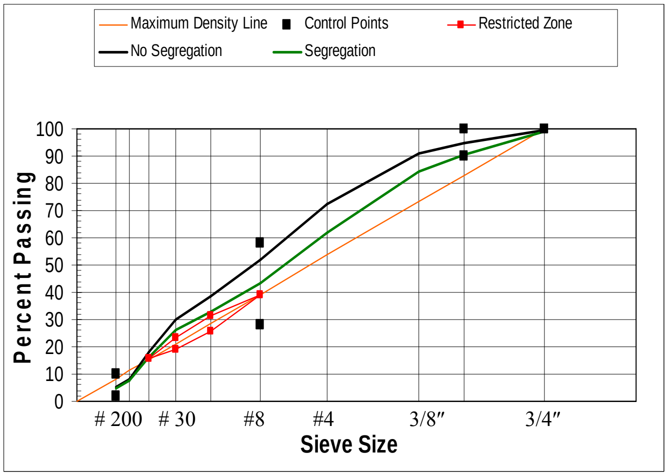
Although visual assessment is commonly used to detect potentially segregated mixtures, it appears subjective and may not be reliable. From literature review, it was found that the degree of segregation could not be accurately determined from field observations alone (Wu and Romero 2003). Likewise, a poor correlation was found from the comparison between the visual observations and the degree of segregation determined in this study.

A large segregation study performed on four pavements from Kansas (Cross et al. 1998) showed that a No. 4 sieve could be used for the determination of the level of segregation. Four severity levels of segregation, 0%, 5%, 10%, and 20%, were defined by the authors based on the gradations of field cores. The amount of segregation was quantified by subtracting the percent retained on the No. 4 sieve of each segregated core from the average percent retained on the No. 4 sieve of non-segregated cores. Another segregation study (Brown et al. 1989) performed on 19 sections suggested to use the No. 8 sieve for detecting segregation. The authors reported that segregated areas were generally 8 to 15 percent coarser than non-segregated areas based on the No. 8 sieve, and these mixtures also exhibited a significant loss of desirable mixture properties, such as tensile strength. National Cooperative Highway Research Program (NCHRP) project 9-11 on segregation examined 14 projects from across the nation and provided more detailed definitions of segregation. This research defined no, low, medium, and high levels of segregation based on statistical changes in key volumetric properties: gradation, asphalt content, and air voids (Stroup-Gardiner and Brown 2000).

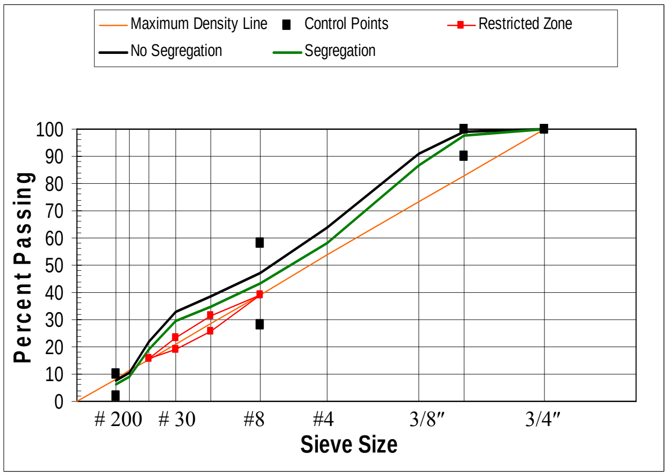
Although many researchers provided the various definitions that determine the level of segregation, gradation data from the segregated and non-segregated mixtures evaluated in this study agreed with the various definitions. Although some variations are present from sample to sample, the Site 1-S, which was obtained from SR 222 and ranked visually as a low segregated site, corresponded with criteria of the medium level of segregation, and Site 2-S and Site 3-S, which were obtained from SR 21 and SR 16 and ranked visually as medium and heavy segregated sites, respectively, corresponded with criteria of the low level of segregation. Consequently, Site 1-N, 2-N, and 3-N were ranked as non-segregated sites; Site 1-S, 2-S, and 3-S were ranked as medium, low, and low segregated sites, respectively. Gradations from the sites are shown in Table 2 and Figure 3.

Table 2. Gradation

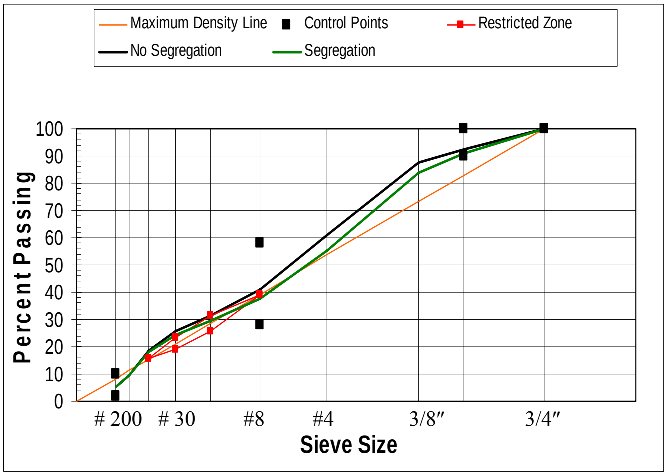
		Sections (Unit: Percent Passing)					
Size(mm)	Sieve	Site 1-N	Site 1-S	Site 2-N	Site 2-S	Site 3-N	Site 3-S
19	3/4"	100	100	100	100	100	100
12.5	1/2"	95	91	99	97	93	91
9.5	3/8"	91	84	91	87	87	84
4.75	# 4	72	62	64	58	61	55
2.36	# 8	52	43	47	43	41	38
1.18	# 16	38	33	38	35	32	30
0.6	# 30	30	26	33	29	26	25
0.3	# 50	18	16	22	19	19	18
0.15	# 100	8	7	10	9	9	9
0.075	# 200	5	5	8	6	5	5



(a) Gradation Curve from Site 1 (SR 222)



(b) Gradation Curve from Site 2 (SR 21)



(c) Gradation Curve from Site 3 (SR 16)

Figure 3. Gradation Curve

CHAPTER 4

EVALUATION OF TOP-DOWN CRACKING PERFORMANCE

EVALUATION OF TOP-DOWN CRACKING PERFORMANCE USING SUPERPAVE IDT

Overview

Zhang et al. (2001a and 2001b), Birgisson et al. (2002), and Roque et al. (2002) proposed a fundamental failure mechanism for evaluating the cracking performance of asphalt mixtures using the indirect tension test (Figure 4).

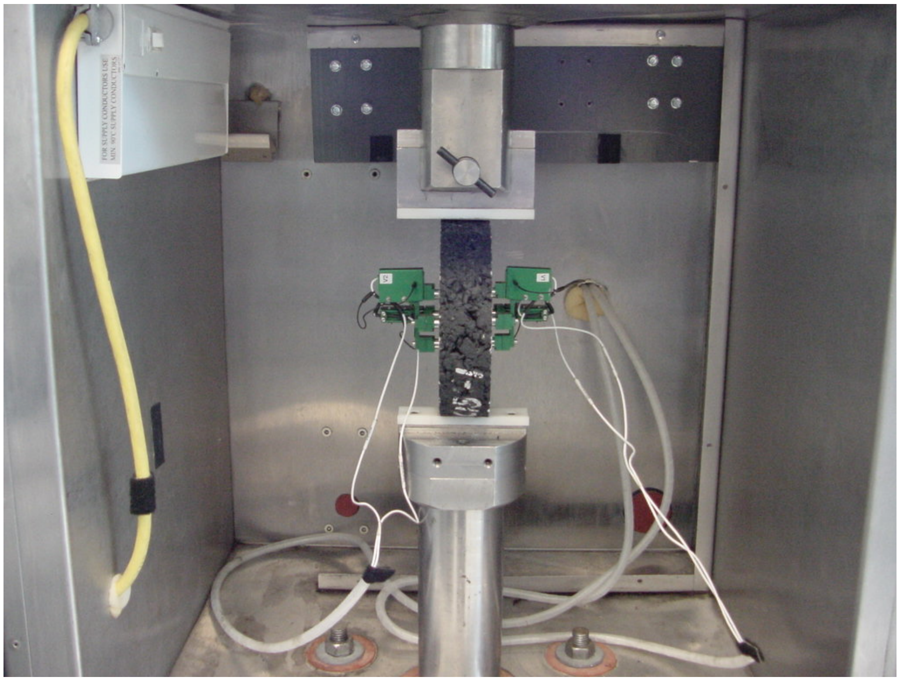


Figure 4. Superpave IDT

In their work, the failure of asphalt mixtures is governed by two main properties: energy dissipation and energy threshold. The concept is when accumulated energy dissipated from a mixture reaches its energy threshold, a crack initiates or propagates. An experimental study conducted using continuous cyclic loading with a 0.1-s loading duration and a 0.9-s unloading duration, applied to an asphalt mixture with a central crack had a good agreement with predicted crack propagation.

An extensive study (Roque et al. 2004) was performed on 14 field test sections, gathered from cracked and uncracked sections throughout the state of Florida, to evaluate top-down cracking performance. Through the prediction model developed, the number of cycles to propagate a crack to a length of 50 mm was evaluated. The resulting predictions clearly distinguished between cracked and uncracked pavements as shown in Figure 5. They identified a value of 6000 cycles as a threshold that separates the known cracking and non-cracking performance. However, the need to run the computer model required to predict cracking performance is somewhat sophisticated and cumbersome for use. Finally, the authors suggested the parameter Energy Ratio (ER), which is defined as the energy of a given mixture measured over the minimum energy required, representing top-down cracking performance of a given mixture (Equation 1). Consequently, a mixture with the higher value of ER provides better top-down cracking performance.

$$ER = \frac{DCSE_f \cdot \left[7.294 \cdot 10^{-5} \cdot \sigma^{-3.1}(6.36 - St) + 2.46 \cdot 10^{-8}\right]}{m^{2.98} \cdot D_1} \tag{1}$$

where,

$DCSE_f$ = Dissipated Creep Strain Energy at Failure (kJ/m^3)

σ = Applied Stress (kPa)

St = Tensile Strength (MPa)

m = Creep compliance power model parameter

D_1 = Creep compliance power model parameter (1/GPa)

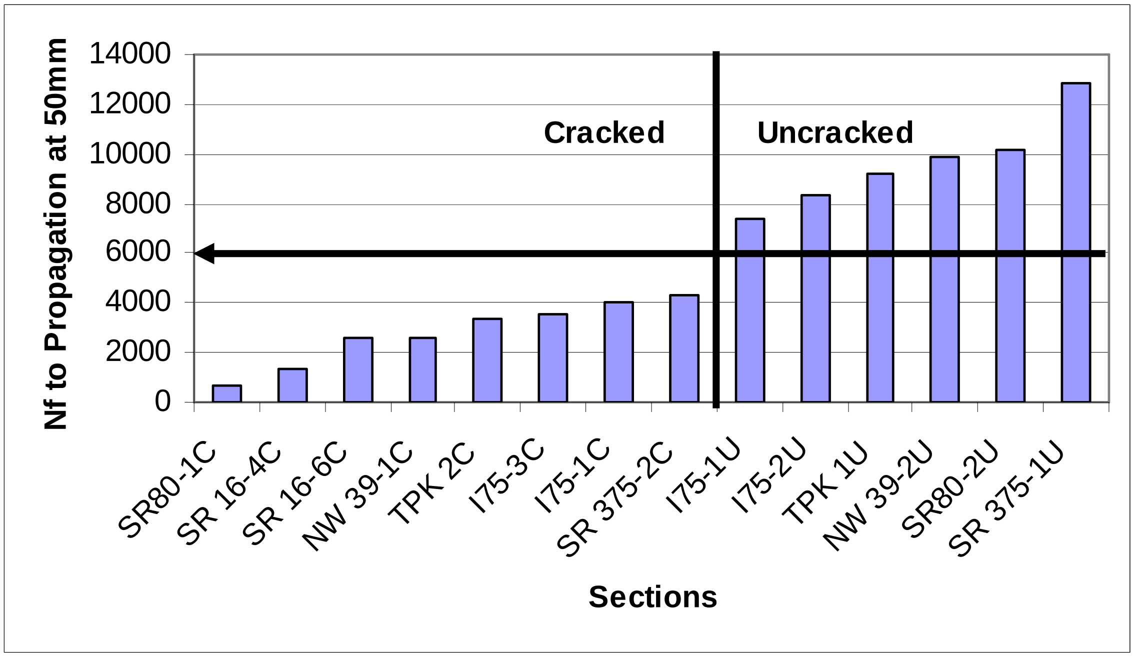


Figure 5. Predicted Number of Cycles to Crack Length of 50 mm (From Roque et al. 2004)

Laboratory Tests

Three mechanical mixture tests, using the indirect tension test, that are resilient modulus (Roque and Buttlar 1992), creep compliance (Buttlar and Roque 1994), and tensile strength (Roque et al. 1997) are required to evaluate mixture cracking performance. Figure 6(a) shows a schematic illustration of how the tensile strength and the dissipated creep strain energy threshold ($DCSE_f$) are obtained from the stress-strain response measured from the resilient modulus (Mr) and tensile strength tests. Figure 6(b) illustrates the physical meaning of the creep compliance power law parameters, and how to get the rate of creep compliance ($\dot{D}$(t)) that represents energy dissipation of asphalt mixtures.

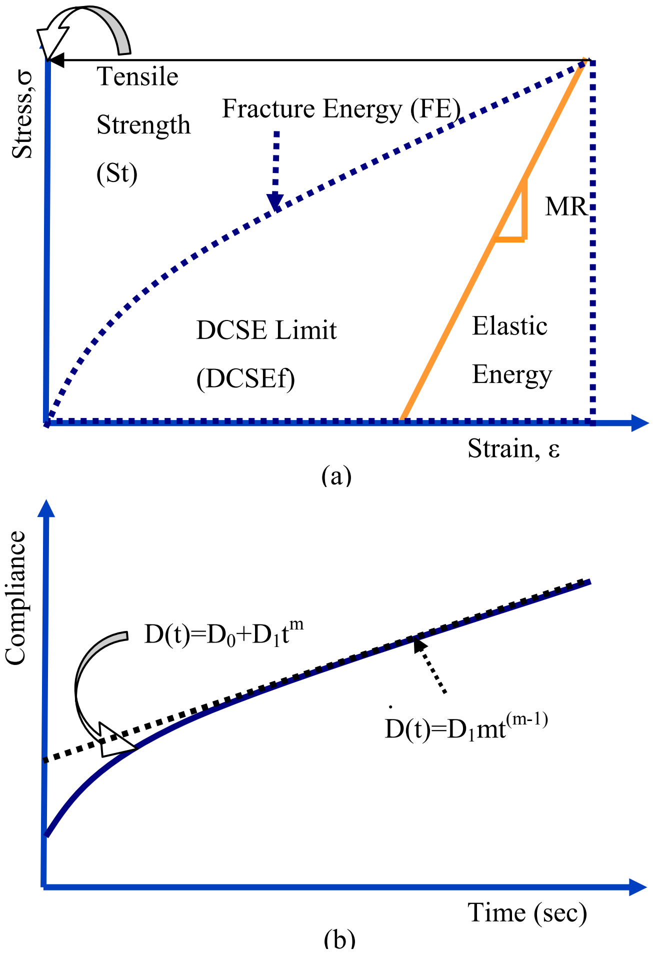


Figure 6. Schematic Illustration of Determination of Fracture Properties

Three specimens, 150 mm diameter by approximately 38 mm thick, cut from asphalt mixtures are required to perform one set of the indirect tension test. All tests are performed at 10°C. The detailed test procedures and data interpretation methods for determining mixture properties are described in Roque and Buttlar (1992), Buttlar and Roque (1994) and Roque et al. (1997).

Summary of Indirect Tension Test Results

For the six sections from three pavements, resilient modulus, creep compliance, and tensile strength tests were performed. Three key mixture properties; power law parameters from creep compliance, tensile strength, and $DCSE_f$, were obtained and used as input parameters of the ER (Equation 1). Figures 7 through 9 show the plots of these mixture properties. Here, the individual power model parameter, D_1 or m, was not plotted because they are not a single parameter that presents the performance of mixtures. Instead, the rate of creep compliance, $\dot{D}(t)$, determined at steady state was plotted in Figure 7.

As indicated above, the cracking performance of asphalt mixtures is mainly governed by two mixture properties: energy dissipation and energy threshold. The rate of creep compliance, representing energy dissipation, is a critical property to determine damage evolution of a given mixture, while the $DCSE_f$, representing energy threshold, is critical to determine its energy tolerance. Therefore, a mixture with a lower creep rate and higher $DCSE_f$ limit is desirable to ensure good cracking performance, and such a mixture provides a higher ER value as well.

Figure 10 shows the ER values of six sections. Site 1-S, which was determined as the medium level of segregation, shows better cracking performance than that of the non-segregated section, Site 1-N, whereas Site 2-S and 3-S, which were determined as the low level of segregation, show worse cracking performance than the Site 2-N and 3-N. Such a trend is completely opposite to the premise that a less segregated mixture may show better top-down cracking performance. On the other hand, for all sections, it is commonly observed that segregated sections have lower $DCSE_f$s and tensile strengths than those of non-segregated sections (Figures 8 and 9). However, no consistent trend was observed from the creep rates (Figure 7).

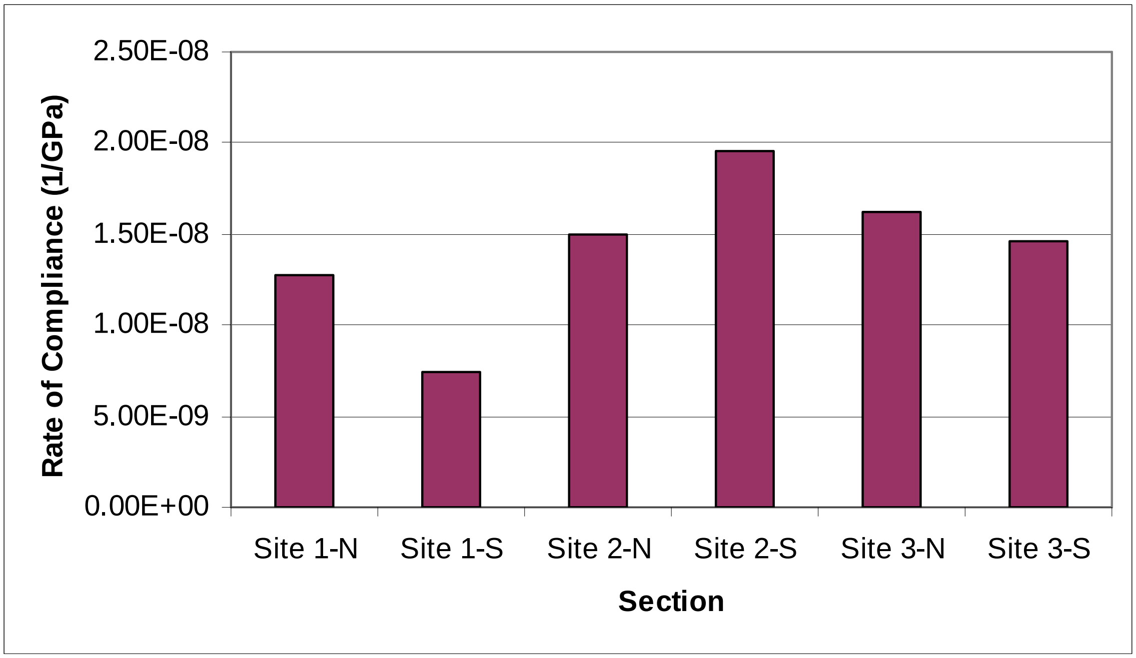


Figure 7. Rate of Creep Compliance

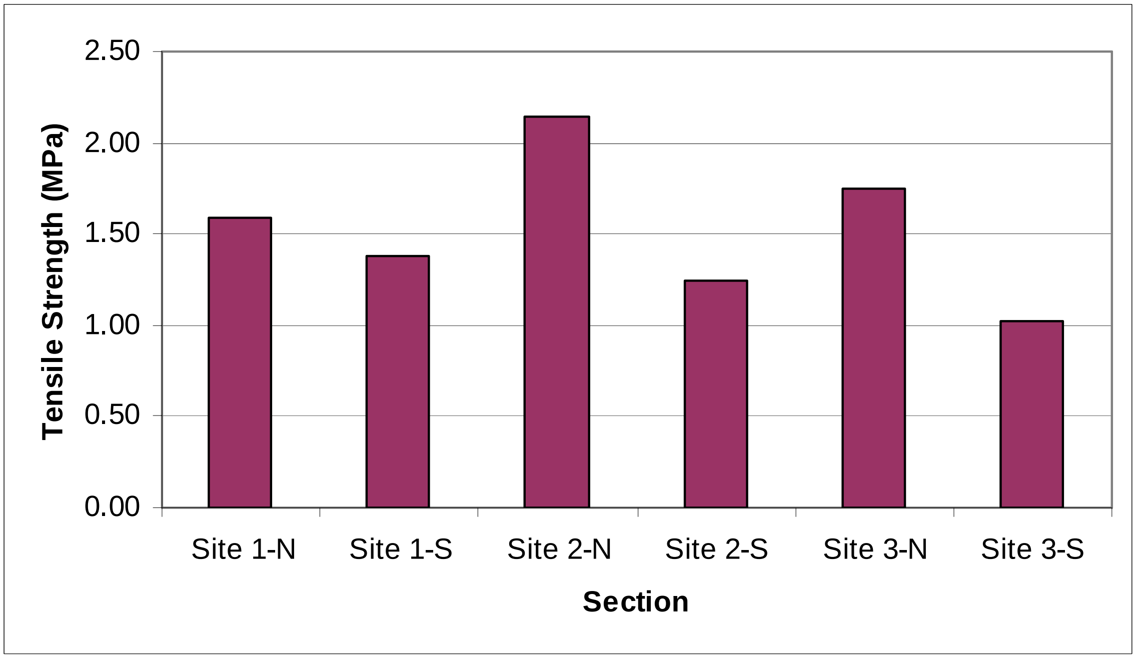


Figure 8. Tensile Strength

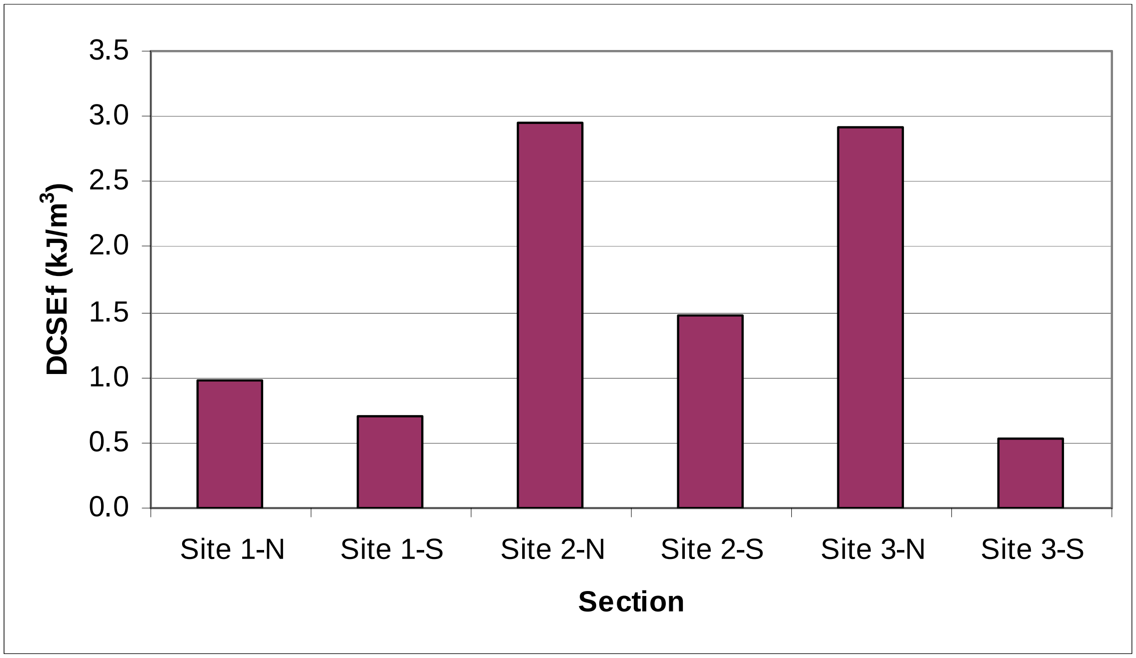


Figure 9. Dissipated Creep Strain Energy ($DCSE_f$)

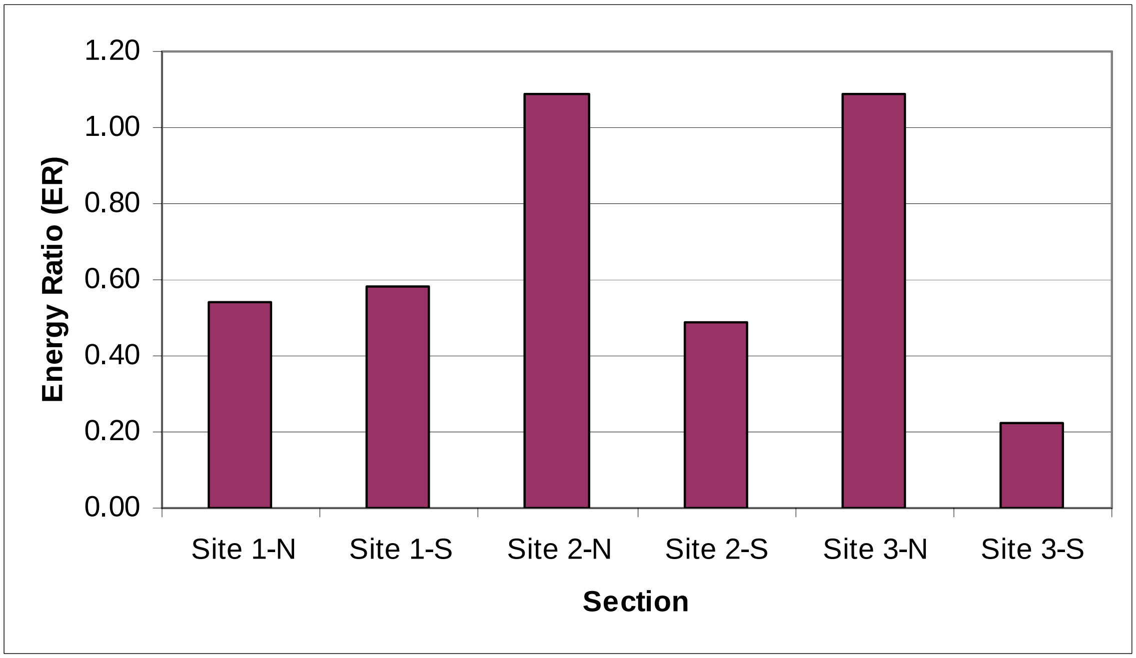


Figure 10. Energy Ratio (ER)

From these observations, it indicates that the cracking performance of segregated mixtures is not a primary function of its degree of segregation. Other factors may play a more critical role. An analytical approach using a finite element method (FEM) will help explain this phenomenon.

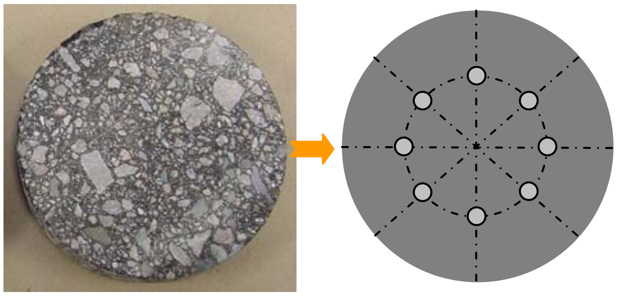
FURTHER MODELING USING A FINITE ELEMENT METHOD

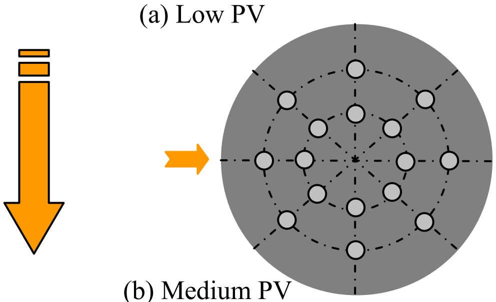
Overview

Aggregate structure of asphalt mixtures plays an important role in determining the performance of flexible pavements. From the literature, the effect of coarse aggregate appears important for resistance to rutting (Vavrik et al. 2001 and 2002, and Kim et al. 2005). Likewise, the effect of coarse aggregate may also be critical to determine the cracking performance of asphalt mixtures. Also, Elliott et al. (1991) emphasized that the importance of air void content for the performance of cracking and rutting in hot-mix asphalt. In this study, development of a conceptual and theoretical approach to evaluate the effect of coarse aggregate and air voids on cracking performance was a primary focus. Considering that segregation increases the amount of coarse aggregate and air void content, this approach may be also applicable to identifying the effect of segregation on cracking performance.

Development of Conceptual Approach

A primary concept employed in the conceptual development is to simulate the interaction between coarse aggregates and air voids. First, to simulate the effect of coarse aggregate, it was hypothesized that the total volume of an asphalt mixture can be divided into two volumes: primary and circumferential volumes. The primary volume (PV) represents the volume of coarse aggregate, while the circumferential volume (CV) refers to the total volume (TV) excluding the primary volume. Thus, the CV includes fine aggregates, asphalt, and air voids. A second assumption is the PV can be divided into several circles in two-dimensional space where each circle represents the dominant effect of coarse aggregate. Therefore, to simulate the volume increase of coarse aggregates, more circles can be added into the CV. Second, to simulate the effect of air voids, the same hypothesis was used, but for this case, the PV represents the volume of air voids, while the CV includes coarse and fine aggregates and asphalt.


(a) Low PV


(b) Medium PV

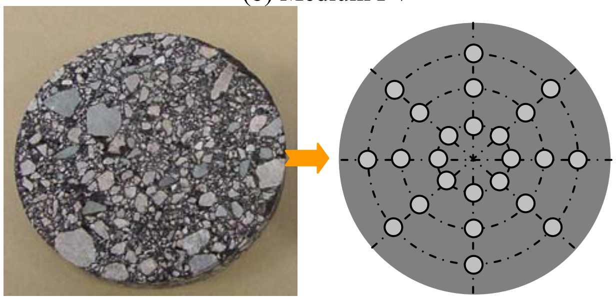

(c) High PV

Figure 11. Schematic Illustration of Conceptual Approach

Figure 11 shows a schematic illustration of the concept described above. To simplify the modeling effort and reduce computation time, the condition of an asphalt mixture was limited to the testing condition used in the indirect tension test and two-dimensional plane stress. First, eight circles, representing the PV, were assigned to the dashed circle passing equal distance from both the center and edge of the specimen. Then, the circles were equally distributed over the dashed circle. In this way, three cases, 8, 16, and 24 circles, representing the volume increase of coarse aggregate, were considered in further finite element modeling.

Development of Theoretical Approach

Fracture mechanics was used to develop the model (Zhang et al. 2001a and 2001b, Birgisson et al. 2002, and Roque et al. 2002), which is called a HMA fracture mechanics model. According to general fracture mechanics theory, the fracture of materials that shows the linear elastic fracture behavior is governed by stress intensity factor (K) or energy release rate (J) and fracture toughness (Kc or Jc). The basic concept is when the development of the stress intensity factor or energy release rate of a cracked body reaches its fracture toughness, cracks proceed from the existent crack tip. Similar to the HMA fracture mechanics model, the stress intensity factor or the energy release rate is a critical property to determine the damage evolution of a given specimen, while the fracture toughness is critical to determine its fracture tolerance. Therefore, materials with a lower K or J and higher Kc or Jc provide better fracture resistance.

Since elastic and viscoelastic fracture behaviors are analogous as indicated above, the HMA fracture mechanics model may correspond with the linear elastic fracture behavior. For example, if the rate of creep compliance represents the damage evolution of viscoelastic materials, it corresponds to the J integral (J) of elastic materials, and also if the $DCSE_f$ represents the fracture tolerance of visocelastic materials, it corresponds to the fracture toughness of elastic materials. Based on this assumption, each of three cases, representing the different effect of coarse aggregate structure and the different effect of air voids, was analyzed. More detailed explanation will continue.

Modeling Using a Finite Element Method

Based on the conceptual and theoretical approach illustrated above, three models (Figure 11) with three levels of PV, corresponding to three levels of CV, were generated using a commercial finite element program ADINA.

It is well known that finite element analysis does not allow for the direct evaluation of fracture toughness. It should be evaluated from a proper fracture test. However, this modeling did not intend to obtain an exact value of the fracture properties, but intended to investigate a general fracture behavior. Based on the knowledge that tensile strength of materials has a strong correlation with their fracture toughness or fracture energy, it appears convenient to estimate the failure strength, instead of the fracture toughness. For example, an asphalt mixture having higher $DCSE_f$ generally accompanies higher tensile strength. This observation agrees with the fact that many researchers use tensile strength as an indicator that determines the cracking performance of asphalt mixtures. Therefore, J integral and tensile strength were evaluated from the finite element (FEM) models. Again, it is noted that this does not mean tensile strength can replace fracture toughness or fracture energy of materials, but intends to identify the general fracture behavior.

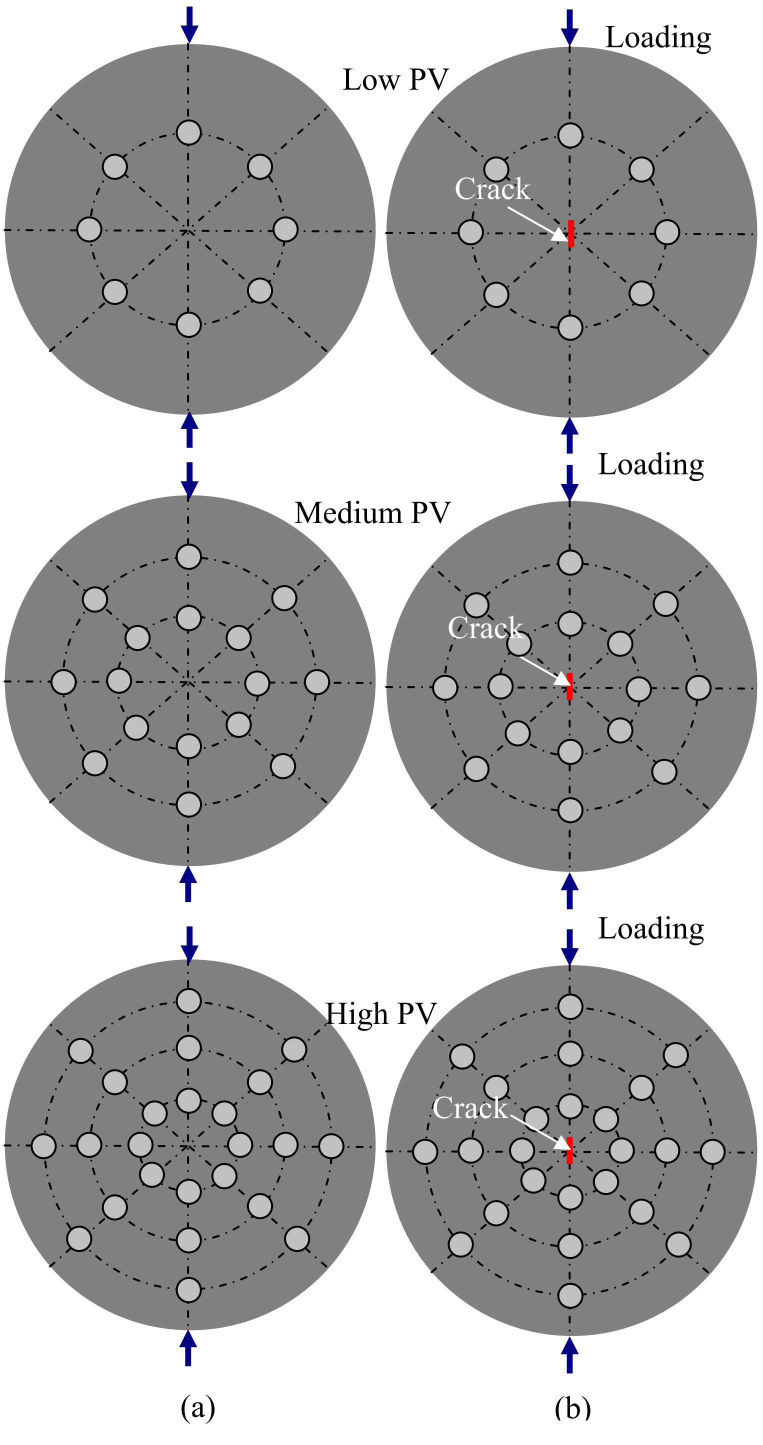


Figure 12. Finite Element Model of Primary Volume

The system modeled in the FEM analysis is represented in Figure 12. The FEM analysis was conducted to investigate potential effects of coarse aggregate volume and air void content increases on stress concentrations within the asphalt aggregate structure. The concept was higher internal stresses involved in a mixture imply that the mixture will fail at lower load levels and also induce lower tensile strength. An identical load, loaded from the top and bottom of the circular disk, was applied to the three cases, and then the maximum internal tensile stress was checked for each case (Figure 12(a)). Since the internal stress of a mixture is inversely proportional to its tensile strength, the inverse values of the maximum internal stresses measured from the three cases were plotted in Figure 13. Meanwhile, to evaluate the J integral, a virtual crack positioned at the center of the circular disk was identically generated in the three models, and the same level of the dead load was applied on the top of the circular disk (Figure 12(b)). Then, the J integral was obtained at the crack tip present in each model. The J integral versus the percent PV for each case was also plotted in Figure 13, as a different scale to the comparative purpose.

From the FEM analysis, it was found that the effect of coarse aggregate played an important role in determining cracking performance. However, an increase or decrease of the PV does not appear to be a unique solution to increase cracking performance. From Figure 13, the increase of PV decreased J values, representing damage development, but also decreased tensile strengths, representing fracture tolerance. In detail, the J values decrease rapidly at the lower PV level, but decrease moderately at the higher PV level, whereas tensile strengths decrease moderately at the lower PV level, but decrease rapidly at the higher PV level. Consequently, it can be imagined that overall cracking performance in terms of Energy Ratio will increase up to a certain point, and then start to decrease rapidly. A schematic illustration of the prediction of the ER is shown in Figure 14.

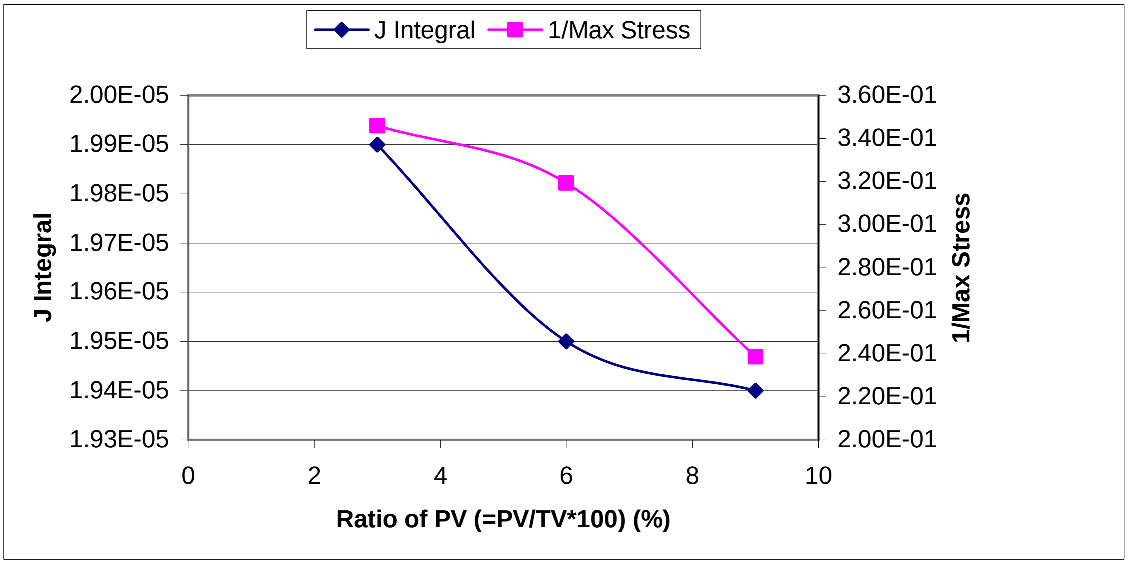


Figure 13. Effect of PV (Coarse Aggregate Volume) from FEM Analysis

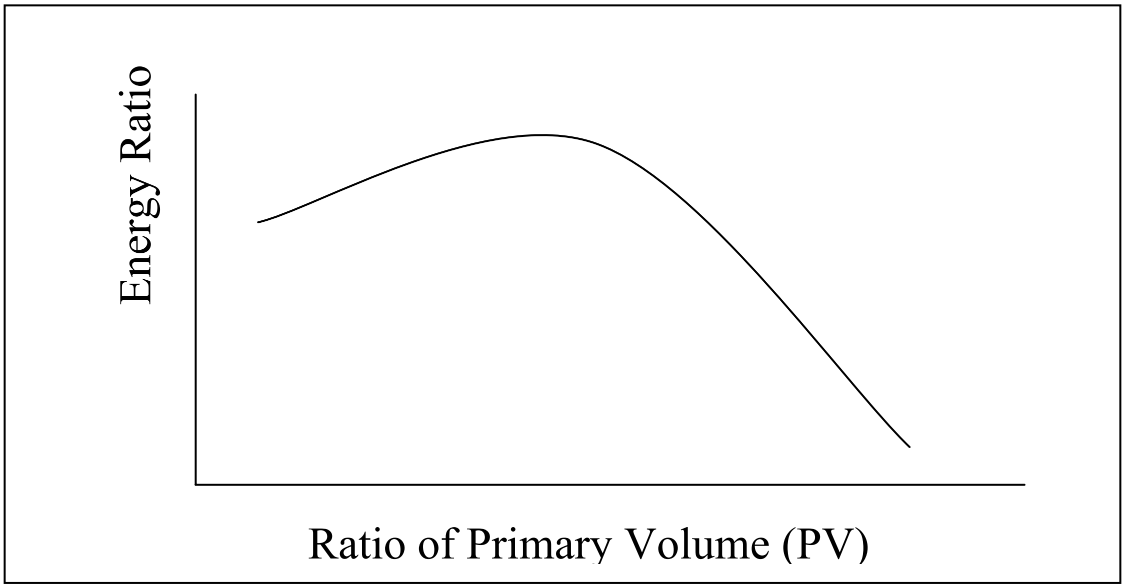


Figure 14. Prediction of Cracking Performance versus PV (Coarse Aggregate Volume)

Meanwhile, as shown in Figure 15, increase of the PV, which now represents air void content, increases J values and decreases tensile strengths. This indicates that the increase of air void content appears to decrease cracking performance. In detail, the J values increase somewhat at the lower PV level, but increase rapidly at the higher PV level, whereas tensile strengths decrease almost linearly, regardless of the PV levels. This observation indicates that overall cracking performance in terms of Energy Ratio will moderately decrease up to a certain point, and start to decrease rapidly. A schematic illustration of the prediction of ER is shown in Figure 16.

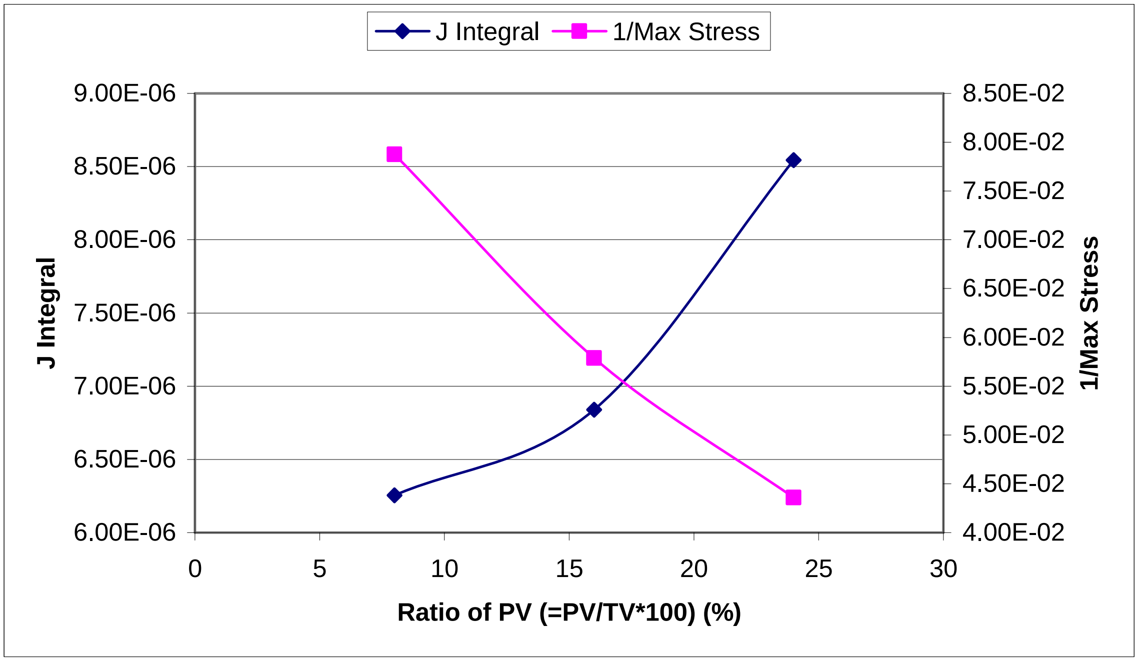


Figure 15. Effect of PV (Air Void Content) from FEM Analysis

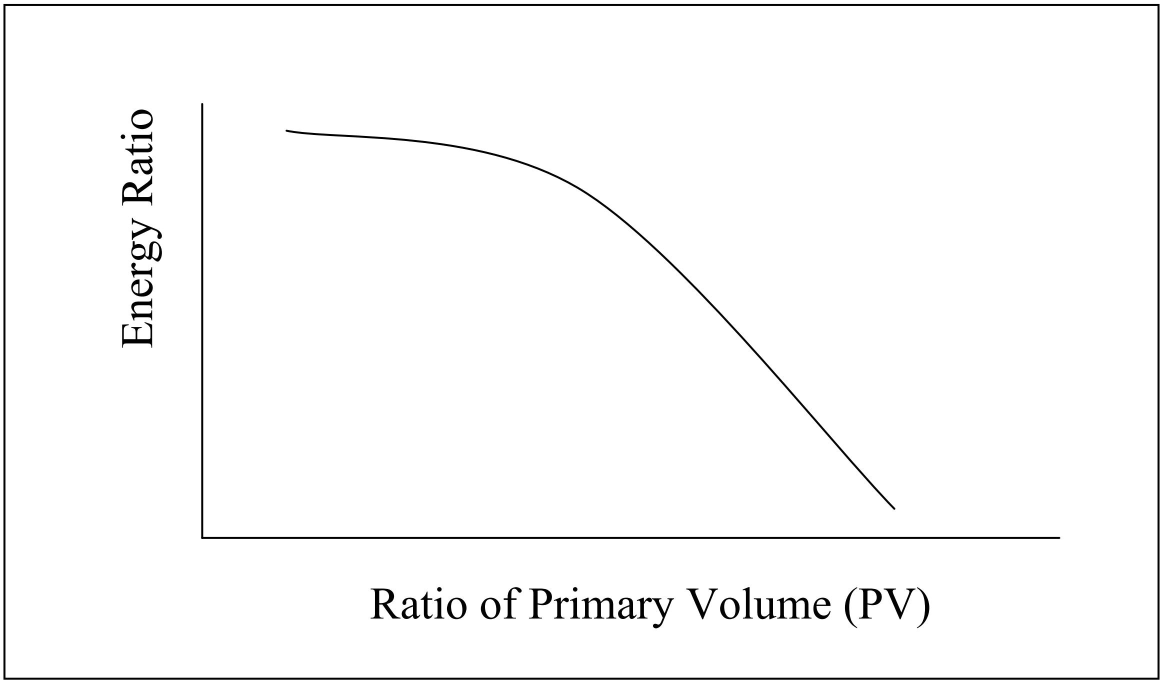


Figure 16. Prediction of Cracking Performance versus PV (Air Void Content)

VERIFICATION USING EXPERIMENTAL RESULTS

According to the FEM analysis, for the increase of coarse aggregate volume, it was found that damage development decreased rapidly at the lower PV level, but decreased moderately at the higher PV level, whereas tensile strength decreased moderately at the lower level, but rapidly decreased at the higher level. On the other hand, for the increase of air void content, it was found that damage development increased somewhat at the lower PV level, but increased rapidly at the higher PV level, whereas tensile strength decreased linearly.

Considering that the coarse aggregate volumes of the Site 1-N, 1-S, 2-N, 2-S, 3-N, and 3-S were 41.77, 45.25, 45.07, 45.31, 49.77, and 52.73%, respectively (Figure 2), the former observation corresponds well with the rate change of creep compliance or tensile strength of the individual site (Figures 7 and 8), except those of Site 2-S. For Site 1, which had a lower level of coarse aggregate volume, the creep rate reduced significantly, but the tensile strength decreased moderately, as its coarse volume increased, while for Site 3, which had a higher level of coarse aggregate volume, the creep rate moderately reduced, but the tensile strength decreased significantly. Consequently, the Energy Ratio of Site 1-S increased, while that of Site 3-S decreased (Figure 10). Meanwhile, considering that the air void content of Site 2-S was relatively higher than the others (Figure 2), the later observation corresponds with the plot shown in Figures 7 and 8. For Site 2, which had a higher level of air void content, the creep rate increased, but the tensile strength decreased significantly. Consequently, the Energy Ratio of Site 2-S decreased (Figure 10).

From this observation, it is interesting to note that at the lower levels of air voids, the cracking performance was dominated by the effect of coarse aggregates, but once the air void content reached a certain critical point, the effect of coarse aggregates became less and were overwhelmed by the air void effect. This implies that not all the segregated mixtures reduce the cracking performance, but instead, their gradations and air void contents appear more critical. Although some variations exist in this analysis, it appears that the gradation and air void content of mixtures are key factors that determine cracking performance. From the mixtures evaluated, the creep rate increased, and DCSE (or tensile strength) decreased clearly as the air void content increased to more than 10%. Therefore, 10% air voids appears to be an important threshold that determines the cracking performance of asphalt mixtures.

INTEGRATION OF ANALYTICAL AND EXPERIMENTAL RESULTS

Since each site has different characteristics, such as aggregate, binder, aging, etc., it may not allow for a direct comparison between the sites. For the same reason, overall cracking performance represented as Energy Ratio was identified only in a relative manner. Although this approach gives an idea that quantifies the effect of coarse aggregate or air void content related to segregation, it may not provide a single criterion that defines the limitation for either the amount of coarse aggregate used, or segregation occurred from its use. Therefore, the effect that hides the pure effect of coarse aggregate has to be separated.

From the developed performance prediction using FEM analysis, for mixtures with the same characteristics, such as aggregate type, binder type, aging, etc., with only difference being the level of PV (coarse aggregate volume), the critical fracture properties, the creep rate and tensile strength, at the lower air void level should follow the same trend as shown in Figure 13. Likewise, if only the volumetric effect of coarse aggregate remained in the fracture properties of the sites, then a trend of those properties should match with the trend obtained from the FEM analysis. This indicates that by visually adjusting the fracture properties of two sites and fixing those of the other site, the other characteristic effects can be removed. Then, the remaining fracture properties may represent the volumetric effect of coarse aggregate. This concept was achieved by shifting both the creep rate and tensile strength of Site 2 and Site 3 as shown in Figure 17. Finally, by reducing the Energy Ratios of Site 2 and Site 3 with the same reduction rate, respectively, overall cracking performance represented as Energy Ratio was obtained and is shown in Figure 18. It is important to note that the plot follows the same trend of the predicted ER from the FEM analysis shown in Figure 14, except that of Site 2-S. Also, these results appear to correlate well with fatigue test results performed on mixtures with different gradations and air void content (Elliott et al. 1991) or with different levels of segregation (Khedaywi and White 1996).

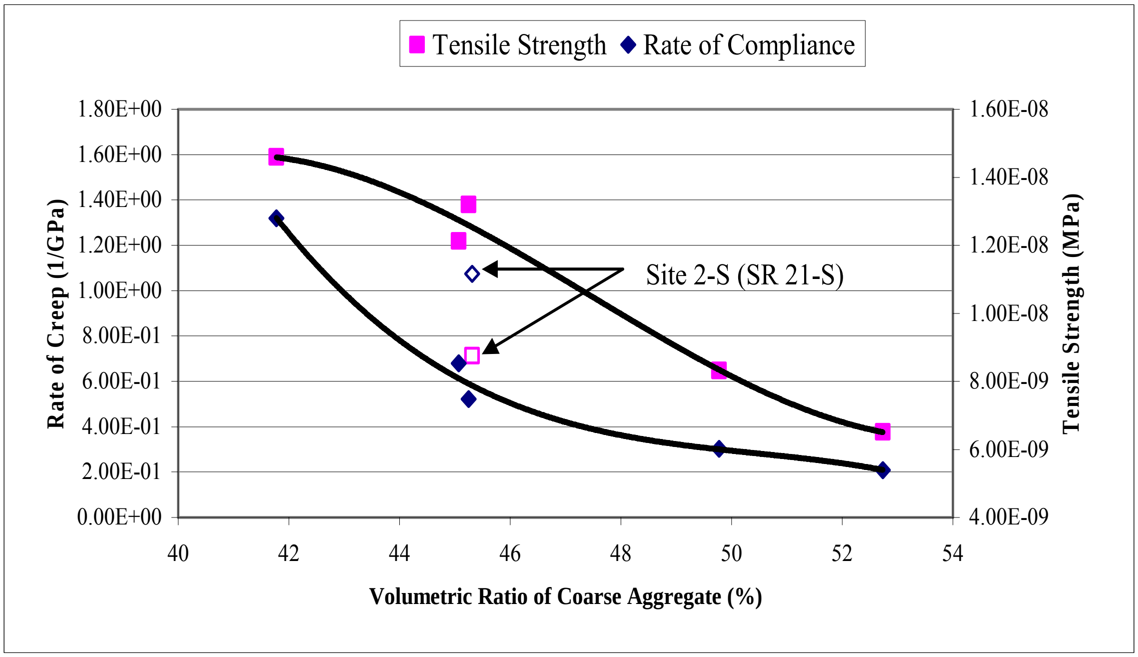


Figure 17. Adjusted Fracture Properties

Figure 18 indicates that a gradation of mixtures is a key factor that determines cracking performance at the lower air void level. It also indicates that there exists a range that maximizes cracking performance. From the mixtures evaluated, coarse aggregate volume from 42% up to 48% appears to be a range that promises good cracking performance. However, Energy Ratios decreased significantly as the coarse aggregate volume increased to more than 45%. Therefore, 45% appears to be an important threshold that determines a poor or good cracking performance of mixtures. Again, as shown in Figure 18, it is important to note that Energy Ratio of the Site 2-S, which had a higher air void content, was significantly lower than the others, despite the coarse aggregate volume.

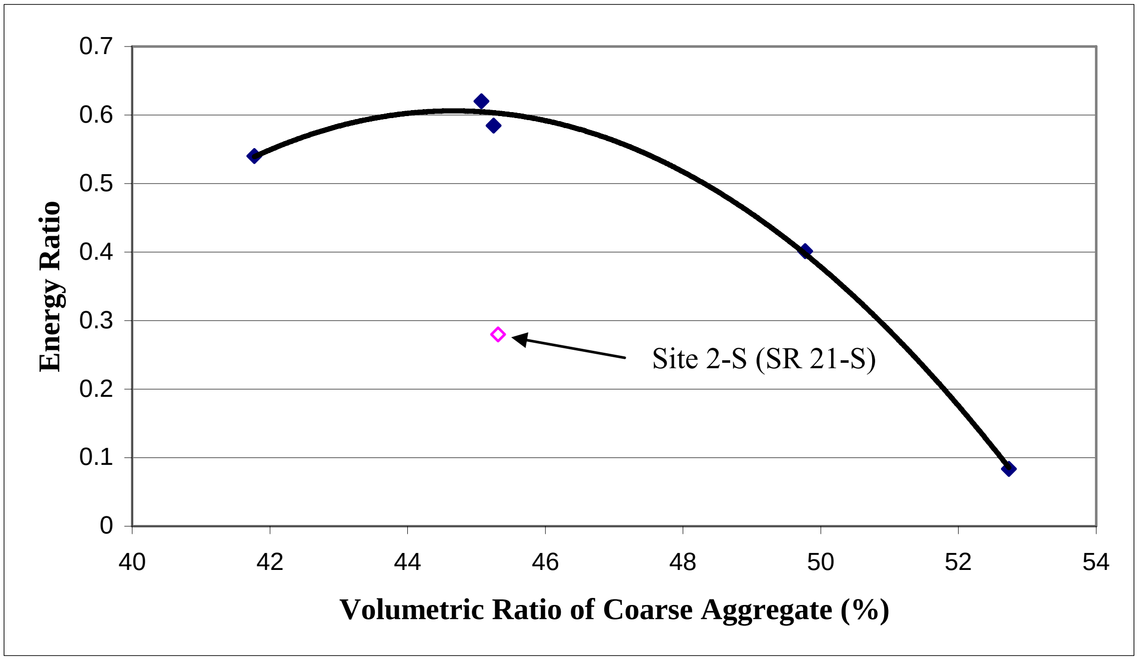


Figure 18. Corrected Energy Ratio

CHAPTER 5

EVALUATION OF RUTTING PERFORMANCE

EVALUATION OF RUTTING PERFORMANCE USING ASPHALT PAVEMENT ANALYZER (APA)

Overview

More mechanistic-based rutting prediction tests, such as triaxial or simple shear tests, may provide more meaningful results for the prediction of rutting performance. However, they are relatively more complicated and costly than commonly used torture tests, such as the Hamburg Wheel-Track Test, French Pavement Rutting Tester, Asphalt Pavement Analyzer, etc. Also, the cored specimens obtained from the field sections may not meet the size requirements required by the mechanistic tests.

The Georgia Loaded Wheel Tester (GLWT) developed by the Georgia Institute of Technology has been subsequently modified and improved since 1985 to evaluate the rutting susceptibility of asphalt mixtures (Lai 1986b, Collins et al. 1995, and Collins et al. 1996). The Asphalt Pavement Analyzer (APA), which is the second generation of the GLWT, was first manufactured in 1996 by Pavement Technology, Inc. (Figure 19). The APA has been widely used in an attempt to evaluate the rutting, fatigue, and moisture resistance of asphalt mixtures. Although the APA is not a mechanistic test, it does tend to simulate the realistic situation in the field. A load is applied through an aluminum wheel onto a linear hose with internal pressure that simulates the effect of a pneumatic tire. The wheel tracks back and force to simulate traffic loads in the field. Lai (1986a) reported that results of the GLWT were more compatible with the rutting characteristics normally experienced in flexible pavements under vehicular loading than those achieved by the triaxial and creep tests. Also, Williams and Prowell (1999) reported that rut depths obtained from the APA tests correlated well with the permanent deformation of the WesTrack sections with 89.9% accuracy. Therefore, the APA was favorably selected as a tool for the prediction of rutting performance.

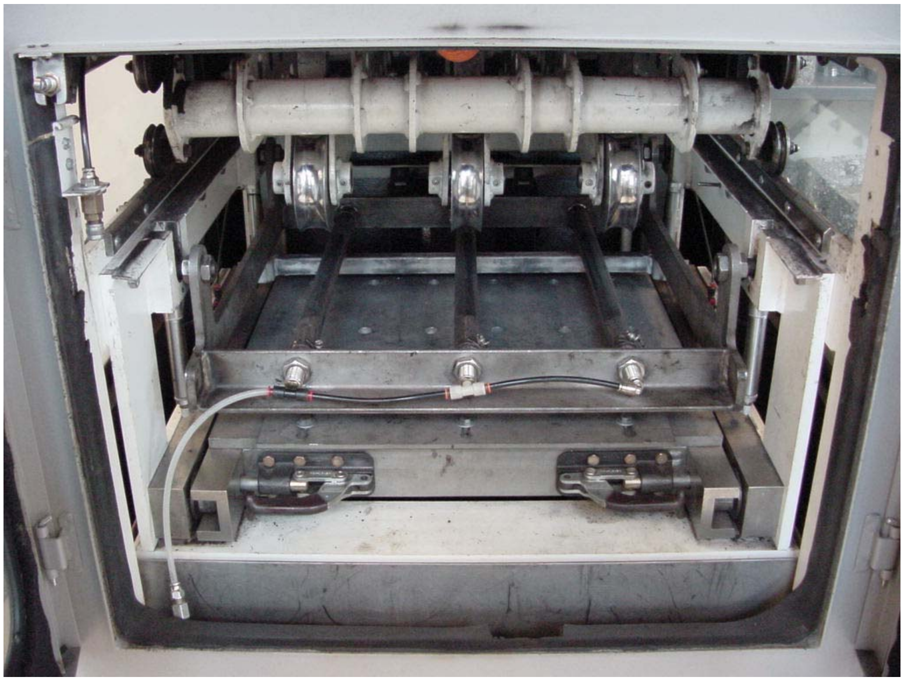


Figure 19. Asphalt Pavement Analyzer (APA)

Laboratory Tests

The twelve specimens obtained from the segregated and non-segregated areas in the three pavements were tested at 64 °C. The internal horse pressure was set to 700 kPa and the vertical load was set for 445 N. Specimens were heated for 14 hours to reach test temperature prior to testing. A 25 cycle seating load was applied and initial rut depths were manually recorded.

Final rut depths were also manually recorded after an additional 8000 loading cycles. All procedures for determining the rutting performance using the APA followed the standard method as described in AASHTO TP 63-03.

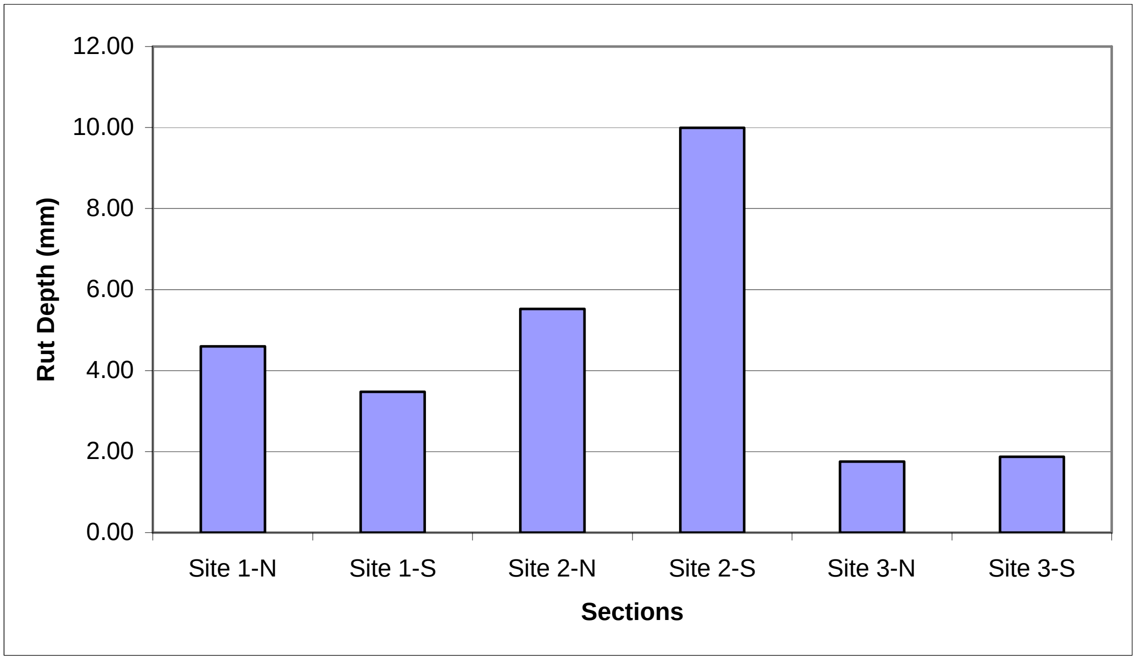


Figure 20. APA Results

Summary of APA Test Results

The APA tests were performed for the six sections from three pavements. Figure 20 shows the rut depths of six sections, Site 1-N, Site 1-S, Site 2-N, Site 2-S, Site 3-N, and Site 3-S. Site 1-S, which was determined as the medium level of segregation, shows better rutting performance than that of the non-segregated section, Site 1-N. However, Site 2-S, which was determined as the low level of segregation, shows worse rutting performance than Site 2-N, as well as the worst rutting performance among the segregated sections. Meanwhile, Site 3-S, which was determined as the low level of segregation, shows about the same rutting performance as Site 3-N. No consistent trend from the results of test data related to the level of segregation was identified in this analysis. It may indicate that the rutting performance of segregated mixtures is not a primary function of their levels of segregation. It appears to be affected by something else. A more analytical approach will be examined.

PREDICTION OF RUTTING PERFORMANCE USING A FINITE ELEMENT METHOD (FEM)

Overview

Instability rutting in an asphalt layer usually occurs in the top 100 mm of the pavement surface and develops gradually with increasing numbers of load applications, typically appearing as a longitudinal depression channel with a small upheaval to each side of the wheel path. In many cases, instability rutting may be caused by a combination of extra compaction due to air voids and dislocation of the aggregate or asphalt binder in an asphalt mixture.

The aggregate structure of asphalt mixtures plays an important role in determining the performance of flexible pavements. From the literature, the effect of coarse aggregate appears important for resistance to rutting (Vavrik et al. 2001 and 2002, and Kim et al. 2005). Also, Elliott et al. (1991) emphasized the importance of air void content for the performance of cracking and rutting in hot-mix asphalts. In this study, the development of a theoretical and conceptual approach to evaluate the effect of coarse aggregates and air voids on rutting performance was a primary focus. Considering that segregation increases the amount of coarse aggregate and air void content in an asphalt mixture, this approach may be also applicable to identifying the effect of segregation on rutting performance.

Development of Theoretical Approach

Several studies have shown that the shear properties of asphalt mixtures are fundamental in resisting instability rutting. Harvey et al. (2001) indicated that rutting was mainly caused by shear distortion. Shear moduli measured from simple shear tests in the laboratory correlated best with rutting performance in the field. Bekheet (2004) also reported that shear stiffness directly measured from in-situ shear testing had a good agreement with the rutting of the test sections. Therefore, it appears that shear is a key factor that determines the amount of permanent deformation in asphalt mixtures.

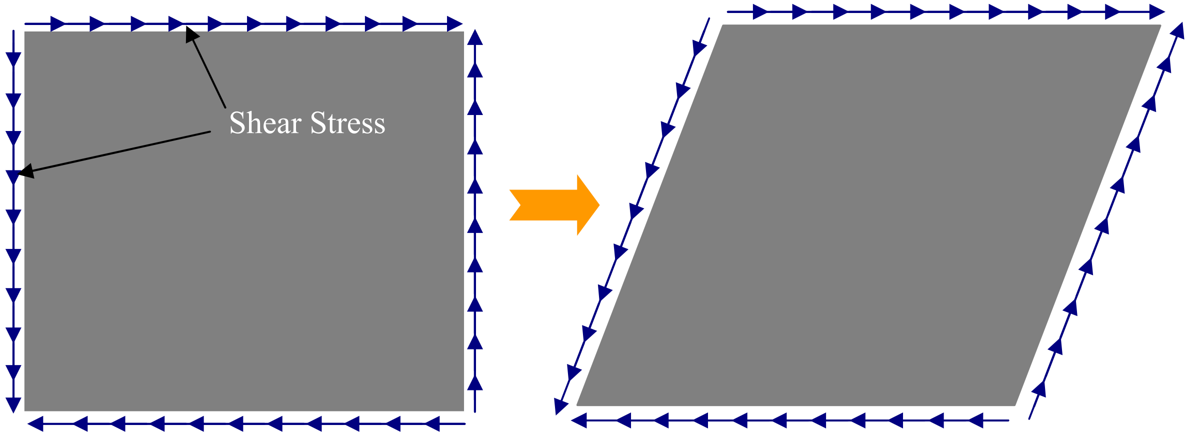


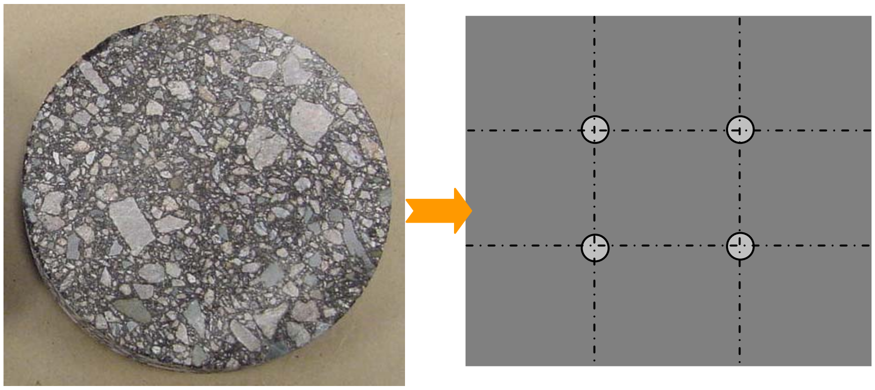
Figure 21. Pure Shear Stress Condition

To evaluate rutting performance using a finite element method, a proper model that can represent the effect of different aggregate structures as well as the effect of shear response needs to be identified. To this purpose, the pure shear stress condition (Figure 21) was favorably selected due to its simplicity and capability to examine pure shear response. The concept used in this approach was if the square element with a particular aggregate structure, used in the stress condition, yields higher shear deformation under a given stress level, then the effect of the aggregate structure becomes dominant, while if the element yields lower shear deformation under the same stress level, then the effect of the aggregate structure becomes less. By generating several elements with different aggregate characteristics, the effect of a target component can be identified in terms of the shear deformation. Finally, by comparing these results to the equivalent rut depths measured from the APA tests, the effect of the target component can be identified.

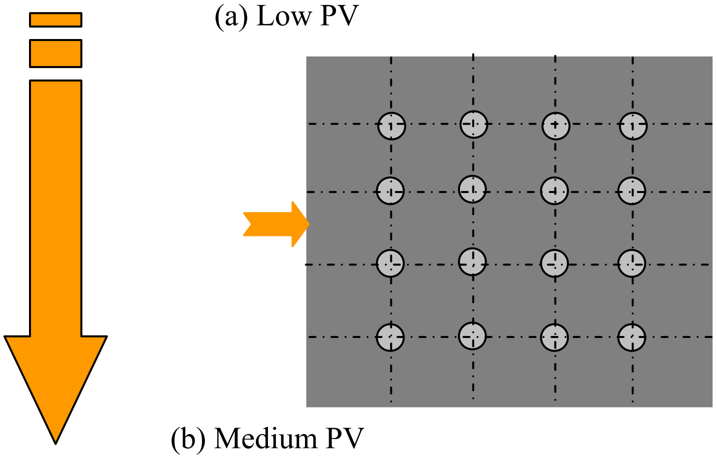
Development of Conceptual Approach

A primary concept employed in this conceptual development is to simulate the interaction between coarse aggregates and air voids. First, to simulate the effect of coarse aggregate, it was hypothesized that the total volume of an asphalt mixture can be divided into two volumes: primary and circumferential volumes. The primary volume (PV) represents the volume of coarse aggregate, while the circumferential volume (CV) refers to the total volume (TV) excluding the primary volume. Thus, the CV includes fine aggregates, asphalt, and air voids. A second assumption is the PV can be divided into several circles in two-dimensional space where each circle represents the dominant effect of coarse aggregates. Therefore, to simulate the volume increase of coarse aggregates, more circles (PV) can be added into the CV. Second, to simulate the effect of air voids, the same hypothesis was used above, but for this case, the PV represents the volume of air voids, while the CV includes coarse aggregates, fine aggregates, and asphalt.

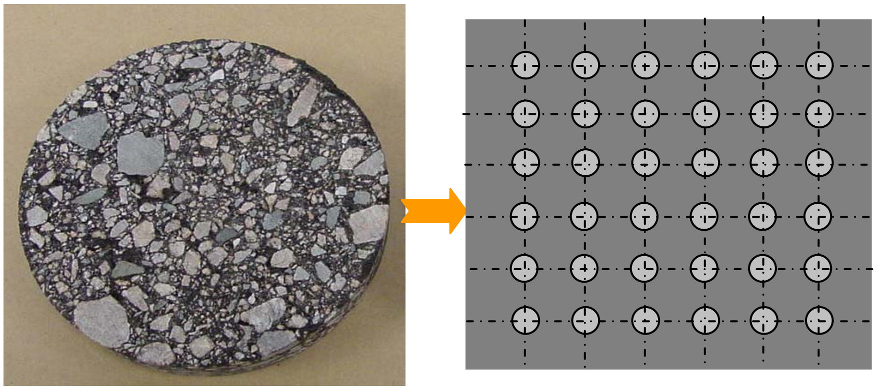
Figure 22 shows a schematic illustration of the concept described above. The condition of an asphalt mixture was limited to the two-dimensional plane stress state. First, for the predetermined two-dimensional plate, four dashed lines passing equal distance from both the horizontal and vertical edges of the plate were assigned. Then, four circles, representing the PV, were assigned to the nodal points of the regular net with equal mesh sides. In this way, three cases, 4, 16, and 36 circles, representing the volume increase of coarse aggregates and air voids, were considered in further finite element modeling.



(a) Low PV

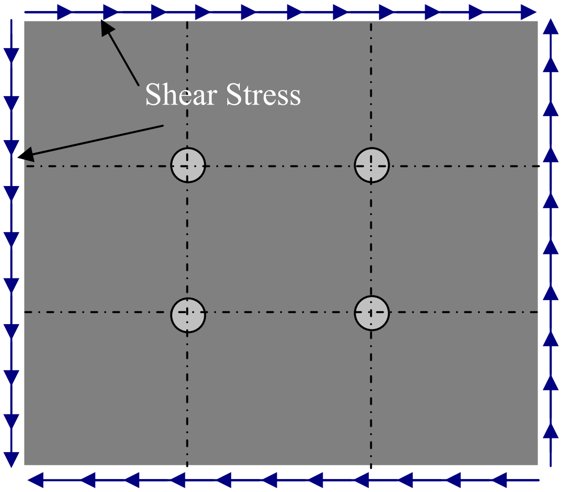


(b) Medium PV

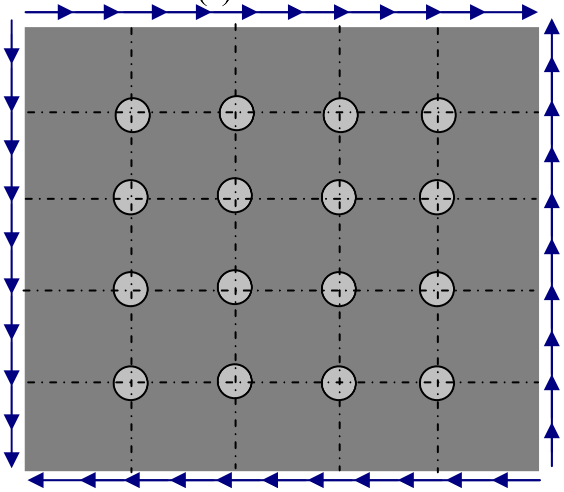


(c) High PV

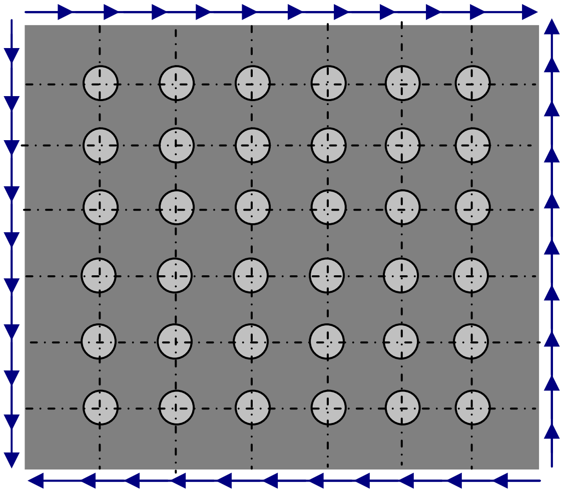
Figure 22. Schematic Illustration of Conceptual Approach



(a) Low PV



(b) Medium PV



(c) High PV

Figure 23. Finite Element Model of Primary Volume

Modeling Using a Finite Element Method

Based on the theoretical and conceptual approach illustrated above, three models (Figure 23) with three levels of PV, corresponding to three levels of CV, were generated using the commercial finite element program ADINA. Since this modeling did not intend to obtain exact material responses from this modeling, but instead, intended to investigate a general rutting behavior of asphalt mixtures, the linear elastic analysis was used to reduce modeling time and computational effort. From this modeling, maximum shear deformation occurred at the corner of each model was recorded and plotted in Figures 24 and 25.

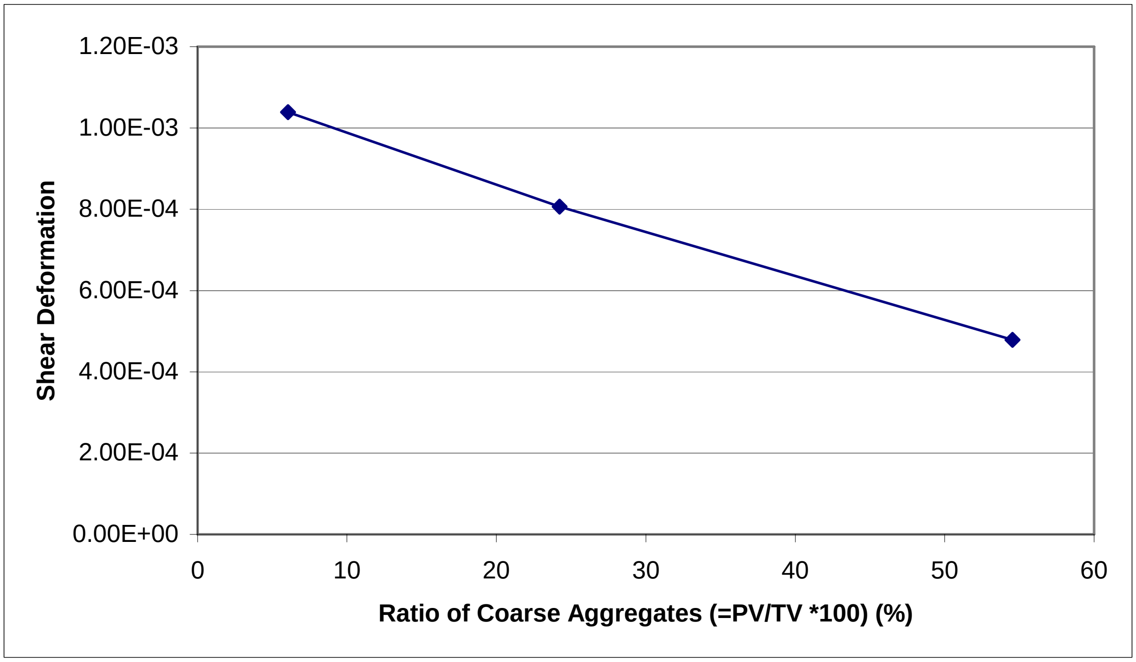


Figure 24. Effect of Coarse Aggregate Volume from FEM Analysis

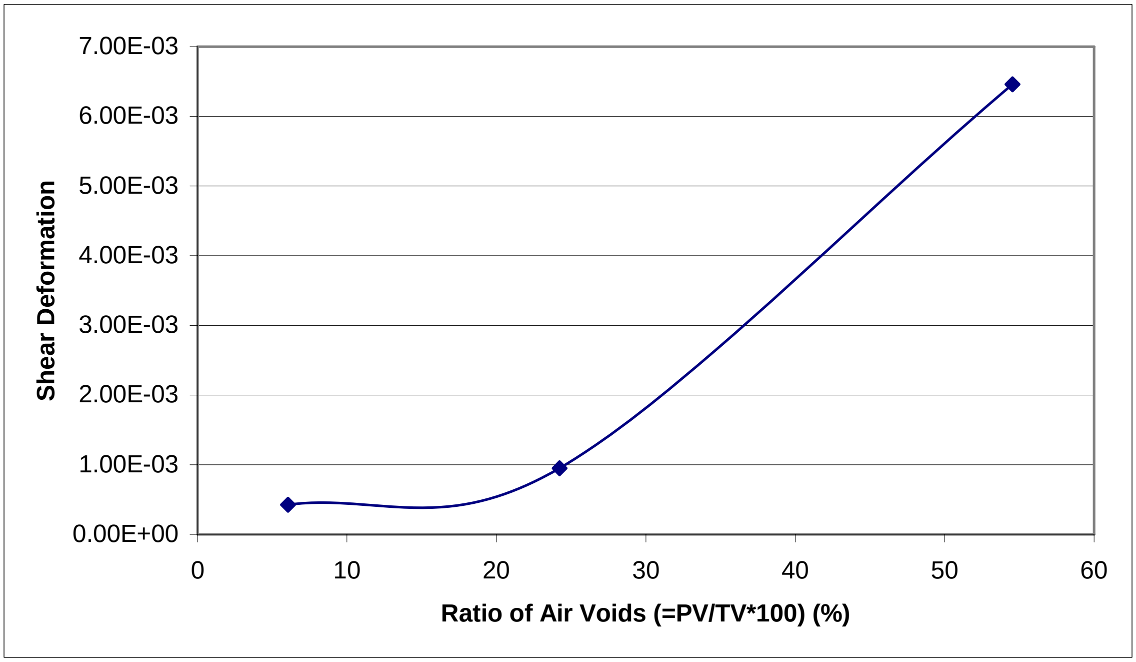


Figure 25. Effect of Air Void Content from FEM Analysis

Figure 24 represents the effect of coarse aggregates. Increase of the PV, which represented the volume of coarse aggregates, decreased shear deformations continuously. It is believed that the increase of coarse aggregate volume enhances the interlocking between coarse aggregates and results in reduction of the shear deformations. Such a result indicates that the effect of coarse aggregates plays an important role in determining rutting performance. It is also interesting to note that the relation between coarse aggregate volume and shear deformation shows a complete linear trend. Meanwhile, as shown in Figure 25, increase of the PV, which now represented air void content, increased shear deformations somewhat at the lower level of PV, but increased shear deformations rapidly at the higher level of PV. This indicates that the effect of air voids is dominant when the air void content is higher, but its effect is less or negligible when it is lower. Therefore, the effect of air voids on rutting appears to have a threshold, since the relation between air void content and shear deformation was exponential.

VERIFICATION USING EXPERIMENTAL RESULTS

According to the FEM analysis, it was found that shear deformations decreased linearly as the coarse aggregate volumes increased, and as air void contents increased, shear deformations increased somewhat at the lower level, but increased rapidly at the higher level. Considering that coarse aggregate volumes of the Site 1-N, 1-S, 2-N, 2-S, 3-N, and 3-S were 41.77, 45.25, 45.07, 45.31%, 49.77, and 52.73%, respectively (Figure 2), the former observation corresponds with the plot shown in Figure 26. As the coarse aggregate volumes increased, the rut depths measured from all sites proportionally decreased, except that of Site 2-S. Meanwhile, considering the air void content of Site 2-S was relatively higher than the others (Figure 2), the later observation corresponds with the plot shown in Figure 27. In this plot, the rut depths measured from all sites did not show an apparent trend regarding the air void contents, except that of Site 2-S. From this observation, it is interesting to note that at the lower levels of air voids, the rutting performance was dominated by the effect of coarse aggregates, but once the air void content reached a certain critical point, the effect of coarse aggregates became less and were overwhelmed by the air void effect.

This implies that not all the segregated mixtures reduce rutting performance, but instead, their gradations and air void contents appear more critical. Although some variations exist in this analysis due to different material characteristics, such as aggregate, binder, aging, or testing variability, it appears that the gradation and air void content of mixtures is a key factor that determines rutting performance. From the mixtures evaluated, the increase of coarse aggregate volume appears to show good rutting performance at the lower level of air voids. However, rutting performance decreased significantly as the air void content increased to more than 10%. Therefore, 10% air voids appears to be an important threshold that is related to the rutting performance of asphalt mixtures.

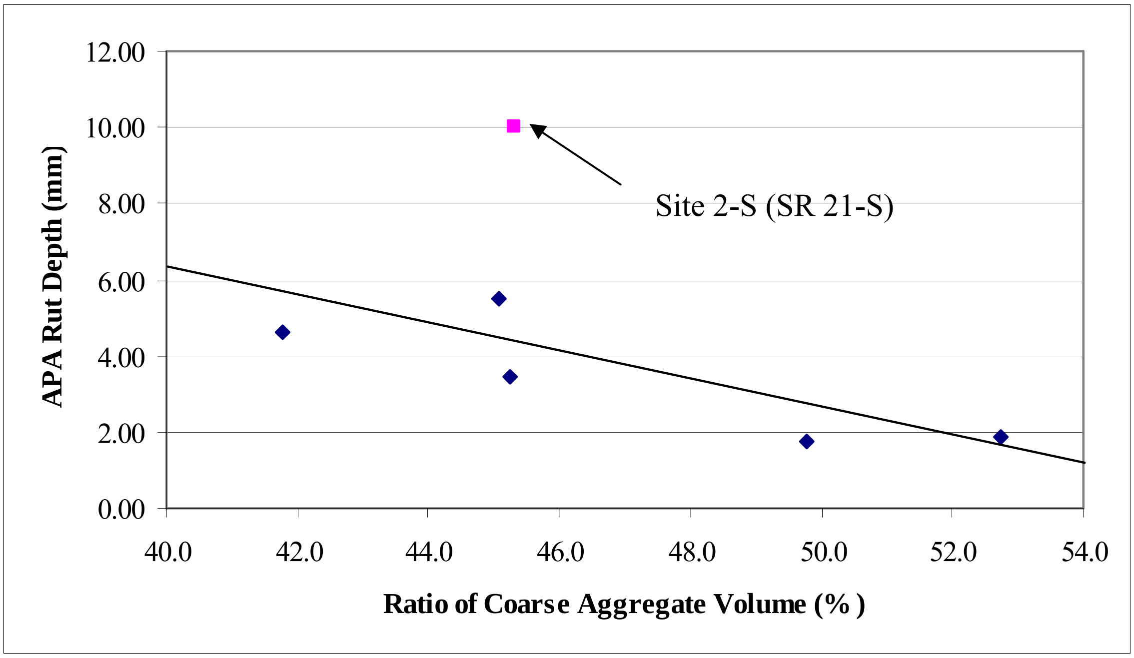


Figure 26. Coarse Aggregate Volume versus APA Rut Depth

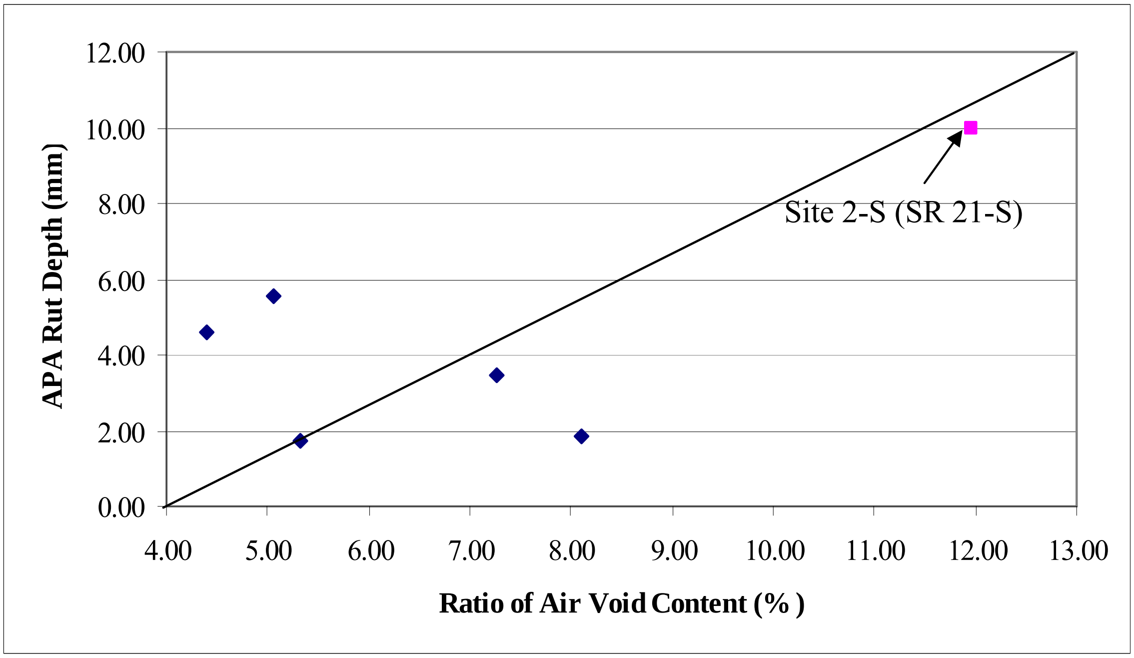


Figure 27. Air Void Content versus APA Rut Depth

CHAPTER 6

DETECTING SEGREGATED MIXTURES WITH HIGH AIR VOID CONTENT

DETECTING SEGREGATED MIXTURES USING PAVEMENT QUALITY INDICATOR (PQI)

Overview

In the previous chapters 4 and 5, it was found that at the lower level of air voids, cracking and rutting performance were dominated by gradation of mixtures. The amount of coarse aggregate was an important factor that determines cracking and rutting performance. Considering that segregation generally increases the coarse aggregate volume of mixtures, it may have positive or negative effects on the cracking performance, depending on the original gradation used and segregation occurred from its use. Thus, segregation caused by an only gradation change may or may not be detrimental to performance. On the other hand, at the higher level of air voids, the amount of air void content was an important factor that determines cracking and rutting performance. As the air void content of mixtures increases, both cracking and rutting performances decrease significantly. Segregated mixtures with such a high air void content should be replaced. Therefore, it would be advantageous to find a means to quickly measure the in-place density of the pavement.

In determining air void content, the commonly used laboratory tests, bulk specific gravity and maximum specific gravity tests, are desirable and will preclude any controversy. However, the time delay involved in the laboratory tests may not allow one to widely check air void contents for all potentially segregated mixtures. Hence, it is important to identify a preliminary test that can quickly screen segregated mixtures with higher air void content from the potentially segregated mixtures.

Recently, non-destructive techniques using either nuclear density gauges or non-nuclear density gauges have been widely studied in evaluating segregation because of their simplicity (Stroup-Gardiner and Brown 2000, Chang et al. 2002, and Wu and Romero 2003). Hence, this study investigated the effectiveness of a non-destructive density gauge by comparing in-place densities of asphalt mixtures with air void contents of the same mixtures measured in the laboratory. To this purpose, the research team evaluated a non-nuclear density gauge, Pavement Quality Indicator (PQI) model 301 (Figure 28).

Figure 28. Pavement Quality Indicator (PQI) Model 301

Description of PQI Tests

The following steps were used in the reading of PQI density:

- Before starting density measurement, one extra core, which is closely located to both the segregated and non-segregated areas, was cored. The thickness of the surface mixture was measured and used as an input of the LIFT THICKNESS displayed in the PQI screen.
- For the predetermined segregated and non-segregated areas, each location was divided into ten locations where cores would be taken (Figure 29). Placing the PQI in each location on the asphalt mat, a circle was drawn around the PQI. The round sensor plate was used as a guide.
- At each location, five readings were made and recorded. The pattern used in this reading (i.e., this pattern is recommended in the PQI manual) is shown in Figure 30.
- After completing the reading process, coring was performed at the center of each circle.

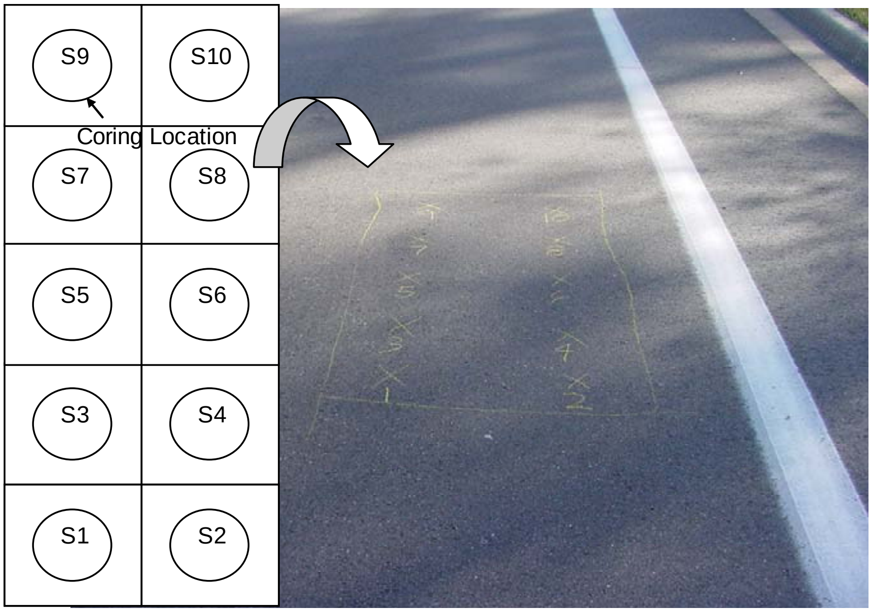


Figure 29. Division of Segregated Area

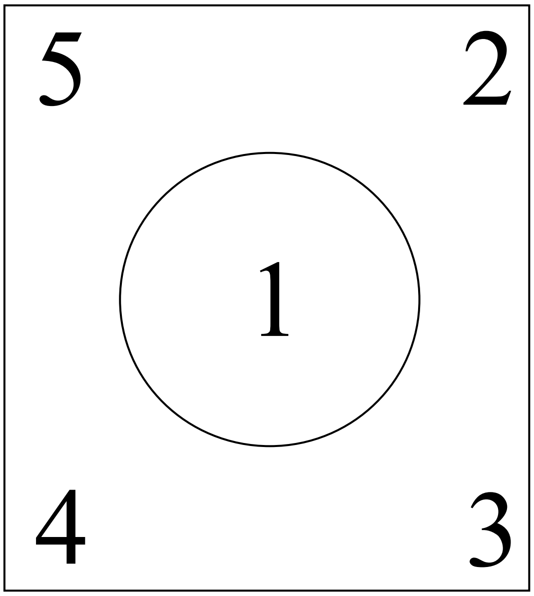


Figure 30. PQI Reading Pattern

Laboratory Tests

For five cores, the bulk specific gravity was measured. Two cores, being representative of each segregated and non-segregated area, were used to determine the maximum specific gravity.

STATISTICAL ANALYSIS FOR PQI DENSITY MEASUREMENTS

As indicated above, the objective of this study is to evaluate the effectiveness of the PQI non-nuclear density gauge in identifying segregated mixtures with high air void content. Therefore, it is the most critical whether the PQI can discriminate mixtures with higher air void contents from the mixtures with lower air void contents. In this study, it was hypothesized that segregated mixtures with high air void content may lead to significantly lower PQI density values than those of non-segregated mixtures. Statistical comparisons were performed for the PQI density values measured from segregated and non-segregated areas. To determine a significance level from the

PQI density values, the student's t-test was used to compare the means of the two populations. The null hypothesis (H_0) was the two means are equal (H_0: $\mu 1 = \mu 2$), and the alternative hypothesis (H_1) was the two means are not equal (H_0: $\mu 1 \neq \mu 2$). The results of each t-test were characterized using the p-value.

Table 3 shows five PQI values measured from the segregated and non-segregated areas of each test site. Each value was an average of five PQI readings measured, as shown in Figure 30. Since volumetric properties, gradations, asphalt contents, and air voids, were determined from the cores obtained at the five locations, the five PQI values were considered to evaluate the effectiveness of the PQI density gauge. This analysis was performed using built-in statistical functions in Excel. The key statistical parameters, mean, standard deviation, and p-value determined from the two-tailed test, are shown in Table 4.

As shown in Table 4, it was found that the p-values from this statistical analysis effectively identified segregated mixtures with high air void content. The p-value of Site 2 was extremely lower than that of Site 1 and Site 3. This indicates that the PQI has an ability that can identify the segregated mixtures with high air void content. However, the p-values from comparison of PQI values between segregated and non-segregated areas were exceptionally small and beyond those usually encountered in statistical tests. For the same reason, the confidence level of the p-value couldn't be appropriately determined from a statistical α level. Therefore, it was determined from the known performance results. A similar approach was used by Chang et al. (2002).

Table 3. PQI Measurements

PQI Measurements					
Site 1-N	Site 1-S	Site 2-N	Site 2-S	Site 3-N	Site 3-S
130.3	129.9	125.0	121.7	130.4	126.1
133.3	131.3	124.6	121.3	130.4	130.7
129.7	131.2	124.4	118.9	134.4	126.5
132.5	129.4	124.6	118.7	132.7	124.9
131.3	130.5	124.7	119.9	132.6	127.3

Table 4. Statistical Analysis Results

	Site 1		Site 2		Site 3	
Parameters	Site 1-N	Site 1-S	Site 2-N	Site 2-S	Site 3-N	Site 3-S
Mean	131.4	130.4	124.7	120.1	132.1	127.1
Standard Deviation	1.488	0.814	0.197	1.377	1.699	2.185
P-Value	2.32E-01		8.13E-05		3.58E-03	

DETERMINATION OF A STATISTICAL THRESHOLD

A suitable threshold p-value is not able to be determined from a typical plot using a normal scale because the relationship appears non-linear. After several trials, it was found that p-values plotted in a log scale resulted in an almost linear trend. Knowing that the Site 3 showed a large difference in air void content, a critical threshold perhaps exits above the p-value of the Site 3. Based on the plot as shown in Figure 31, a p-value from the student's t-test of approximately 10^{-3} appears to be a suitable threshold value that separates the Site 3 from the other sites. Therefore, it is recommended to use a p-value of 10^{-3} as a threshold value. If a p-value determined in this way is less than 10^{-3}, this indicates the area may be potentially segregated and have high air void content, exceeding 10%.

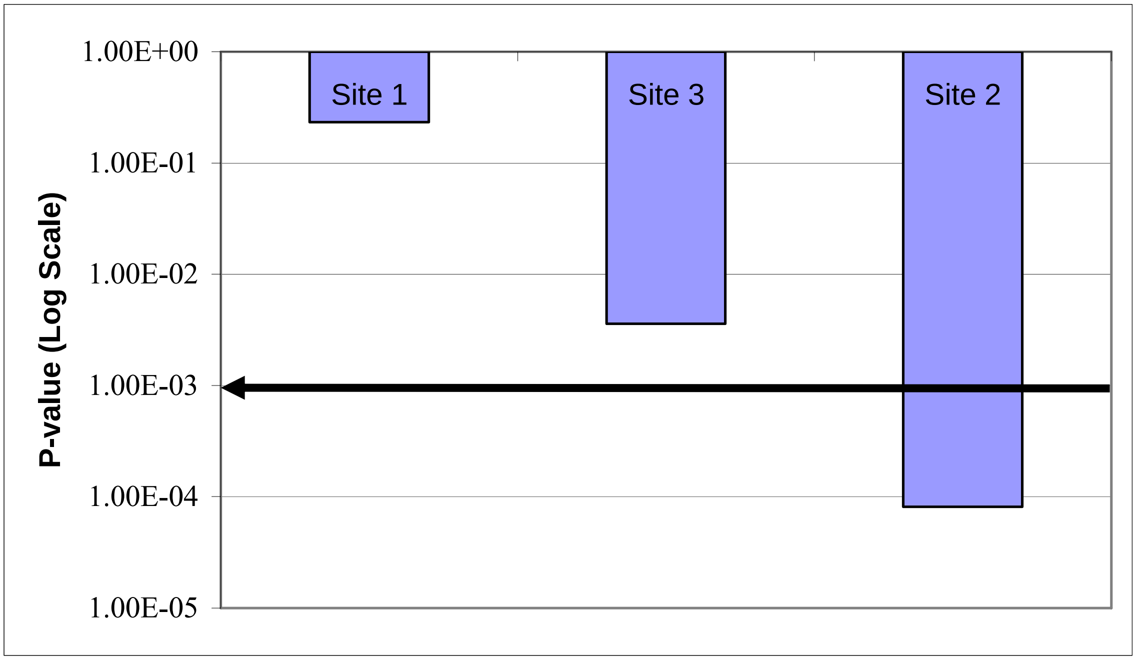


Figure 31. Critical P-value

However, one should not automatically conclude that an area that shows less than the p-value of 10^{-3} is a segregated area with high air void content. There are two critical deficiencies of PQI density measurements: 1) PQI readings at a location often show high variability. 2) PQI values sometimes show large differences with the air voids measured in laboratory (Figure 32). Therefore, this study strongly recommends using the PQI as a screening tool. If the p-value from the PQI measurements indicates unacceptable density difference, then cores should be taken to measure the exact density and air voids should be determined.

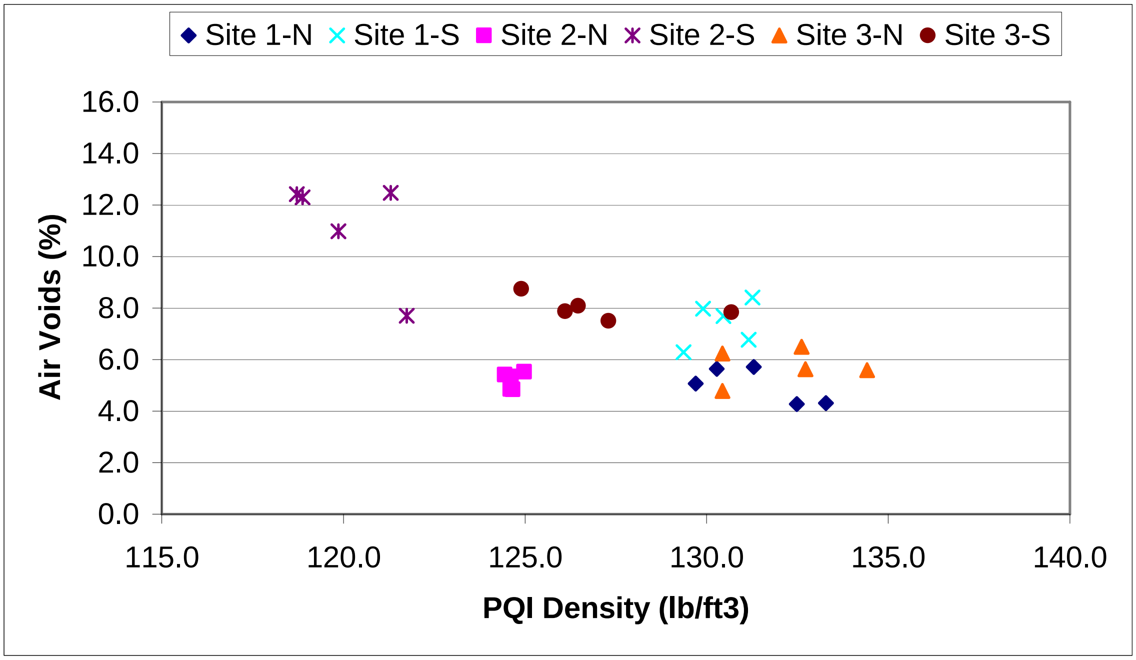


Figure 32. PQI Density versus Air Voids

CHAPTER 7

SUMMARY AND CONCLUSIONS

A primary focus of this research was to identify the effect of segregation on cracking and rutting performance. Three fine graded Superpave mixtures, representative of mixtures commonly used for the construction of state roads in Florida, and two levels of segregation, occurring from construction variability in the state, were cored and evaluated.

To evaluate the cracking and rutting performance of mixtures, a total of 48 specimens were prepared. A portion of the specimens were tested using the indirect tension testing system and analyzed with the HMA fracture mechanics model, and a portion of the specimens were tested using the APA. From the experimental results combined with the analytical study performed using FEM analysis, it was found that the gradation and air void content of mixtures appear to be critical factors that determine the cracking and rutting performance, rather than the degree of segregation.

Based on the findings of this investigation, the following conclusions can be made:

For top-down cracking performance,

- Top-down cracking performance is affected by segregation of mixtures. However, the gradation and air void content of mixtures appear to be more critical factors that determine the cracking performance, rather than the level of segregation.
- From the FEM analysis performed, the effect of coarse aggregate plays an important role in determining the cracking performance of mixtures at the lower level of air voids.

Based on the mixtures evaluated, the coarse aggregate volume from 42% up to 48% appears to be a range that promises good cracking performance. A coarse aggregate volume of 45% appears to be a threshold for the cracking performance of these Superpave mixtures. Once the coarse aggregate volume exceeds 45%, the cracking performance of these Superpave mixtures starts to decrease.

- From the FEM analysis performed, as air void content increases, the effect of air voids becomes dominant so that the cracking performance of mixtures decreases. However, it appears that a threshold that determines the dominant effect of air voids clearly exists in the experimental results. An air void content of 10% appears to be the threshold. Once the air void content exceeds 10%, the cracking performance decreases significantly, despite the coarse aggregate volume.

For rutting performance,

- Rutting performance is affected by segregation of mixtures. However, the percentage of coarse aggregate and air void content of mixtures appear to be more critical factors that determine the rutting performance, rather than the level of segregation.
- From the FEM analysis performed, the effect of coarse aggregate plays an important role in determining the rutting performance of mixtures at the lower level of air voids. Based on the mixtures evaluated, the increase of coarse aggregate volume appears to promise good rutting performance at the lower level of air voids.
- An air void content of 10% appears to be a threshold that determines the rutting performance of Superpave mixtures. Once the air void content exceeds 10%, the rutting performance of Superpave mixtures decreases significantly.

For use of PQI,

- The PQI appears to be effective to discriminate the segregated mixtures with high air void content. The density difference with p-value 10^{-3} appears to be a threshold value that separates those mixtures form the segregated mixtures with lower air voids.
- However, due to variability, this study recommends using the PQI as a screening tool. If the p-value from the PQI measurements indicates unacceptable density difference, then cores should be taken to measure the exact density and air voids should be determined.

ACKNOWLEDGEMENT

The work reported herein was the result of a team effort. The authors would like to thank Shanna Johnson and Stephen Ross for their assistance in coring and testing mixtures.

REFERENCES

Bekheet, W., Abd El Halim, A.O., Easa, S. M., and Ponniah, J. (2004). “Investigation of Shear Stiffness and Rutting in Asphalt Concrete Mixes,” *Canadian Journal of Civil Engineering*, Vol. 31, pp 253–262.

Birgisson, B., Roque, R., Sangpetngam, B., and Zhang, Z. (2002), “Hot Mix Asphalt Fracture Mechanics: A Fundamental Crack Growth Law for Asphalt Mixtures,” *Journal of the Association of Asphalt Paving Technologists*, Vol. 71, pp 816-827.

Brown, E. R., Collins, R., and Brownfield, J. R. (1989). “Investigation of Segregation of Asphalt Mixtures in the State Of Georgia,” *Transportation Research Record*, No. 1217, pp 1-8.

Buttlar, W. G., and Roque, R. (1994). “Development and Evaluation of the Strategic Highway Research Program Measurement and Analysis System for Indirect Tensile Testing at Low Temperatures,” *Transportation Research Record*, No. 1454, pp. 163-171.

Chang, C-M, Baladi, G. Y., and Wolff, T. F. (2002) “Detecting Segregation in Bituminous Pavements,” *Transportation Research Record*, No. 1813, pp 77-86.

Collins, R., Shami, H., and Lai, J. S. (1996). “Use of Georgia Loaded Wheel Tester to Evaluate Rutting of Asphalt Samples Prepared by Superpave Gyratory Compactor,” *Transportation Research Record*, No. 1492, pp 202-207.

Collins, R., Watson, D., and Campbell, B. (1995). “Development And Use Of Georgia Loaded Wheel Tester,” *Transportation Research Record*, No. 1545, pp 161-168.

Cross, S. A. (2000). *Effect of Segregation on Hot Mix Asphalt Using the Asphalt Pavement Analyzer*, Final Report for K-TRAN KU-98-2 Contract, University of Kansas, Lawrence, Kansas.

Cross, S. A., and Brown, E. R. (1993). “Effect of Segregation on Performance of Hot-Mix Asphalt,” *Transportation Research Record*, No. 1417, pp 117-126.

Cross, S. A., Hainin, M. R., and Ado-Osei, A. (1998). *Effects of Segregation on Mix Properties of Hot Mix*, Final Report for K-TRAN KU-96-6 Contract, University of Kansas, Lawrence, Kansas.

Elliott, R. P., Ford, M. C., Ghanim, M., and Tu, Y. F. (1991). “Effect of Aggregate Gradation Variation on Asphalt Concrete Mix Properties,” *Transportation Research Record*, No. 1317, pp 52-60.

Harvey, J., Weissman, S., Long, F., and Monismith, C. (2001). “Tests to Evaluate the Stiffness and Permanent Deformation Characteristics of Asphalt/Binder-Aggregate Mixes, and Their Use in Mix Design and Analysis,” *Journal of the Association of Asphalt Paving Technologists*, Vol. 70, pp 572-604.

Harmelink, D., and Aschenbrener, T. (2003). *Extent of Top-Down Cracking in Colorado*, Final Report for CDOT-DTD-R-2003-7, Colorado Department of Transportation, Denver, Colorado.

Khedaywi, T. S. and White, T. D. (1995). “Development and Analysis of Laboratory Techniques for Simulating Segregation,” *Transportation Research Record*, No. 1492, pp 36-45.

Khedaywi, T. S., and White, T. D. (1996). “Effect of Segregation on Fatigue Performance of Asphalt Paving Mixtures,” *Transportation Research Record*, No. 1543, pp 63-70.

Kim, J. (2005). *Accurate Determination of Dissipated Creep Strain Energy and Its Effect on Load- and Temperature-Induced Cracking of Asphalt Pavement*, Ph.D. Dissertation, University of Florida, Gainesville, Florida..

Kim, S., Roque, R., and Birgisson, B. (2005). “Identification and Assessment of the Dominant Aggregate Size Range (DASR) of Asphalt Mixture,” *Journal of the Association of Asphalt Paving Technologists*, in press.

Lai, J. S. (1986a). *Development of a Simplified Test Method to Predict Rutting Characteristics of Asphalt Mixes*, Final Report for GDOT Research Project 8502, Georgia Institute of Technology, Atlanta, Georgia.

Lai, J. S. (1986b). *Evaluation of Rutting Characteristics of Asphalt Mixes Using Loaded-Wheel Tester*, Final Report for GDOT Research Project 8609, Georgia Institute of Technology, Atlanta, Georgia.

Myers, L. A., and Roque R. (2002). “Top-Down Crack Propagation in Bituminous Pavements and Implications for Pavement Management,” *Journal of the Association of Asphalt Paving Technologists*, Vol. 71, pp. 651-670.

Myers, L. A., Roque, R., and Birgisson, B. (2001). “Propagation Mechanisms for Surface-Initiated Longitudinal Wheel Path Cracks,” *Transportation Research Record*, No. 1778, pp. 113-122.

Myers, L. A., Roque, R., Ruth, B. E., and Drakos, C. (1999). “Measurement of Contact Stresses for Different Truck Tire Types to Evaluate Their Influence on Near-Surface Cracking And Rutting,” *Transportation Research Record*, No. 1655, pp. 175-184.

Roque, R., Birgisson, B., Drakos, C., and Dietrich, B. (2004). “Development and Field Evaluation of Energy-Based Criteria for Top-down Cracking Performance of Hot Mix Asphalt,” *Journal of the Association of Asphalt Paving Technologists*, Vol. 73, pp. 229-260.

Roque, R., Birgisson, B., Zhang, Z., Sangpetngam, B., and Grant, T. (2002). *Implementation of SHRP Indirect Tension Tester to Mitigate Cracking in Asphalt Pavements and Overlays*, Final Report for FDOT BA-546 Contract, University of Florida, Gainesville, Florida.

Roque, R., and Buttlar, W. G. (1992). "The Development of a Measurement and Analysis System to Accurately Determine Asphalt Concrete Properties Using the Indirect Tensile Mode," *Journal of the Association of Asphalt Paving Technologists*, Vol. 61, pp. 304-332.

Roque, R., Buttlar, W. G., Ruth, B. E., Tia, M., Dickison, S. W., and Reid, B. (1997). *Evaluation of SHRP indirect tension tester to mitigate cracking in asphalt concrete pavements and overlays*, Final Report for FDOT B-9885 Contract, University of Florida, Gainesville, Florida.

Stroup-Gardiner, M. (2000). "Influence of Segregation on Pavement Performance," *Journal of the Association of Asphalt Paving Technologists*, Vol. 69, pp 424-454.

Stroup-Gardiner, M. and Brown, E. R. (2000). *Segregation in Hot-Mix Asphalt Pavements*, Report No. 441, Transportation Research Board, National Research Council, Washington, DC.

Vavrik, W. R., Pine, W. J., and Carpenter, S. H. (2002). "Aggregate Blending for Asphalt Mix Design: Bailey Method," *Transportation Research Record*, No. 1789, pp 146-153.

Vavrik, W. R., Pine, W. J., Huber, G., Carpenter, S. H., and Bailey, R. (2001). "The Bailey Method of Gradation Evaluation: The Influence of Aggregate Gradation and Packing Characteristics on Voids in the Mineral Aggregate," *Journal of the Association of Asphalt Paving Technologists*, Vol. 70, pp 132-175.

Williams, R. C., Duncan, G., and White, T. D. (1996). "Hot-Mix Asphalt Segregation: Measurement and Effects," *Transportation Research Record*, No. 1543, pp 97-105.

Williams, R. C., and Prowell, B. D. (1999). "Comparison of Laboratory Wheel-Tracking Test Results with WesTrack Performance," *Transportation Research Record*, No. 1681, pp 121-128.

Wu, J-X, and Romero, P. (2003). “Analysis of Multivariate Models to Evaluating Segregation in Hot-Mix Asphalt Pavements,” *Transportation Research Record*, No. 1900, pp 33-40.

Zhang, Z., Roque, R., and Birgisson, B. (2001a). “Evaluation of Laboratory-Measured Crack Growth Rate for Asphalt Mixtures,” *Transportation Research Record*, No. 1767, pp 67-75.

Zhang, Z., Roque, R., Birgisson, B., and Sangpetngam, B. (2001b). “Identification and Verification of a Suitable Crack Growth Law,” *Journal of the Association of Asphalt Paving Technologists*, Vol. 70, pp 206-241.