STATE OF FLORIDA

Evaluation of Use of High Percentage of Reclaimed Asphalt Pavement (RAP) for Superpave Mixtures

Research Report
FL/DOT/SMO/07-507

Sungho Kim
Thomas Byron
Gregory A. Sholar
Jaeseung Kim

May 2007

STATE MATERIALS OFFICE

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The need to use more reclaimed asphalt pavement (RAP) material has been rising, since the quantity of the milled material has increased but the amount of RAP material included in HMA mixtures has declined after the adoption of the Superpave mix design in Florida in the late 1990's. To increase the use of RAP materials in terms of the environmental and cost saving issues, the performance of the RAP mixture should be guaranteed. According to many early studies, RAP materials have a positive effect for rutting resistance, but not for cracking, when the same binder was used. Recently, an NCHRP study has suggested that a PG grade binder with a reduced high temperature grade is recommended for a higher percentage RAP mixture in order to improve the cracking performance. Therefore, this research is focused on the laboratory performance with respect to rutting and cracking in terms of different levels of RAP materials included in the Superpave mixtures.

Four different percentages of RAP mixtures were designed: 0%, 25%, 35%, and 45%. The APA and the Servopac gyratory shear tests were used to evaluate the rutting performance. The Superpave indirect tension (IDT) test and energy ratio (ER) concept was used to assess the cracking performance.

Generally, the higher percentage of RAP mixture may have better rut-resistance due to an increased binder stiffness, as measured by binder viscosity. However, all RAP mixtures exhibited similar or a little more rut depth than the control mixture in the asphalt pavement analyzer (APA) test due to the stiffer virgin binder used in the control mixture and poor aggregate structures (gradation). For cracking resistance, although more RAP material may

reduce the creep compliance rate, the fracture energy (FE) and ER decreased as the percentage of RAP increased in mixtures. In addition, the ER was approximately half of the control mixture.

The gradation effect was investigated to improve the performance of the RAP mixture after the first stage. Since the gradation did not have good characteristics, especially for rutting performance based on the porosity of the dominant aggregate size range (DASR) and the percentage of the coarse aggregates analyses, the modified gradation was designed to have better interlocking in the aggregate structure of the mixture.

From the APA and Servopac gyratory shear tests, the modified gradation with 45% RAP showed distinctively better resistance to rutting. From the Superpave IDT tests, the modified 45% RAP mixture exhibited the lowest creep compliance rate and FE. The ER result indicated that it had slightly worse performance than the 0% RAP (control) mixture, but better than other RAP mixtures from the previous stage.

Therefore, the higher percentage RAP mixture seems to reduce the cracking performance. In addition, using the higher percentage of RAP materials with NCHRP recommendations may not guarantee the rutting performance based on the laboratory evaluation. However, the performance of a mixture even with a higher percentage of RAP materials and the lower high temperature PG grade binder can be improved by having good aggregate structures. The modified 45% RAP mixture showed better rutting performance, and a slightly lower ER than the control mixture but higher than other RAP mixtures in terms of the cracking performance. This result may also be affected by the amount of sand and AC content.

The recommendation of the NCHRP study to select the proper PG grade of virgin binder for RAP mixtures is needed to be carefully taken. In addition, since the viscosity of RAP materials is widely varied even for the same source, the determination of the viscosity of RAP should also be confirmed carefully.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In the United States, hot mix asphalt (HMA) paved in pavements is the material that is most often recycled (Davis 2000). According to the Federal Highway Administration (FHWA), there are 90 million tons of Recycled or Reclaimed Asphalt Pavement (RAP) milled annually and 33% of all RAP is re-used in HMA production (Cosentino and Kalajian 2001).

Florida once led the nation in the volume of recycled mix used in HMA production. From 1979 to 1994, 22 million tons of RAP were recycled into FDOT projects, saving $188 million in materials (Smith 1996). However, there has been a decline in the amount of RAP included in HMA mixes after the adoption of the Superpave mix design in Florida in the late 1990's.

1.2 OBJECTIVES

The purpose of this study is to explore the possibility of designing asphalt mixtures with higher percentages of RAP approaching 50% without sacrificing performance. The material properties should be measured according to Superpave specifications and the fracture resistance and rutting potential of HMA with high percentages of RAP will be tested in the laboratory.

1.3 SCOPE

The laboratory testing for this research was limited to a 12.5 mm nominal maximum aggregate size (NMAS) mixture. The Superpave mixture design procedure was used for the design of the mixtures. Mixtures with four different percentages of RAP materials were designed and tested.

To evaluate the mixture properties and performance, the asphalt pavement analyzer (APA), Servopac gyratory shear test, and Superpave indirect tensile (IDT) test were used.

The concept of the DASR porosity and coarse aggregate volume was used to evaluate the possibility to increase the performance of RAP mixture by modifying the gradation in the further study.

CHAPTER 2

LITERATURE REVIEWS

Decker (1997) lists the five recycling methods as defined by the Asphalt Recycling and Reclaiming Association: cold planning, hot recycling, hot in-place recycling, cold in-place recycling, and full depth reclamation. This literature search focuses on hot recycling combining RAP with virgin asphalt binder and aggregate to produce HMA. Either a batch or drum type hot mix plant may be used to produce the recycled mix, and the mix is placed and compacted in the same way as virgin HMA.

The original Superpave specification for HMA design was developed based on the use of virgin materials. The usage of RAP, especially large percentages of RAP, in HMA necessitates a modified methodology taking into account the difference between RAP and virgin materials. The National Cooperative Highway Research Program (NCHRP) Project 9-12 (McDaniel and Anderson 2001), titled as "*Incorporation of Reclaimed Asphalt Pavement in the Superpave System*", was funded to address this issue. The result from this research effort is reviewed in details.

2.1 PROPERTIES OF RAP

RAP is the old asphalt pavement that is milled up or ripped off at the end of the service life of materials. It consists of aggregates coated with asphalt binder. After years of service in the field, properties of the mixture have changed. When RAP is re-used to produce new mixtures, it is necessary to account for the difference of properties of RAP aggregate and binder from virgin ones.

2.1.1 Extraction of Binder

There are five methods to determine the binder content of an asphalt mixture: solvent extraction, nuclear asphalt content gauge (NAC), pycnometer method, automatic recordation, and the ignition method. Only the solvent extraction and the ignition method allow the determination of binder content and aggregate gradation (Zhang 1996).

2.1.1.1 Solvent Extraction

Two different methods have been used for the extraction of asphalt binder. ASTM D1856, *Recovery of Asphalt from Solution by Abson Method*, has been the major method to recover asphalt binder from RAP since it was introduced in 1933. Recently, ASTM D5404, *Recovery of Asphalt Using the Rotavapor Apparatus*, has become more widely used and is adopted by many laboratories to extract asphalt binders.

Typically, chemicals such as tricholoroethylene, methylene chloride, and 1,1,1-trichloroethane are used to dissolve asphalt binder. The extract passes through a filter system to remove the fine particles, and finally the extract is distilled to remove the solvent out of the asphalt binder.

During the Strategic Highway Research Program (SHRP), researchers raised concerns with respect to the above extraction procedure: (1) the reaction of asphalt binder and solvent; (2) the residual solvent remaining in the recovered binder; (3) the asphalt binder remaining in the aggregate. A modified extraction procedure was then developed to address these issues and became the AASHTO TP2, *Standard Test Method for the Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*. Later on, Peterson et al. (2000) modified the TP2 procedure to make it a more streamlined procedure.

2.1.1.2 Ignition Method

It is worth noting that the ignition method is a good alternative to determine the binder content of RAP and the gradation of aggregate. Different from the solvent extraction, however, no binder is left for the properties analysis in the ignition method.

As one of the first research efforts, Antrim and Busching (1969) placed asphalt mixture specimens in an oven at 843 ºC (1550 ºF) with an excess of oxygen. The binder and part of the aggregate were burned off. Depending on the type of aggregate, the loss of aggregate can be as much as 30% of its mass for limestone aggregate. Yu (1992) reduced the oven temperature to 538 ºC (1000 ºF) to minimize the mass loss of aggregate. To further address this issue, a correction factor was introduced. In a round-robin study of ignition method, Brown and Mager (1996) describe a procedure for determining the correction factor by placing an aggregate-only sample into the ignition oven and measuring the mass loss. They reported that the overall difference of the measured and actual asphalt binder content for 192 specimens was -0.02 percent, and the ignition method only resulted in a negligible change in the gradation of the specimen, although the mass loss occurred.

Noticing that the correction factor described above is only for asphalt mixtures with a single source of aggregate, Zhang (1996) developed a combined correction factor for multiple sources of aggregates. This study reported an accuracy of 0.11 percent at a 90 percent confidence level for the measurement of binder content and confirmed the previous observation that the ignition method does not significantly change the gradation of aggregate.

2.2 PROPERTIES OF BINDER

Asphalt binder is mixed and compacted at certain high temperature to achieve the suitable viscosity of asphalt binder and warrant the workability of the mix of binder and aggregate. At high temperature, the components of asphalt binder lose by volatility and react with atmospheric oxygen. This leads to short term aging of asphalt binder. Once paved in the road and opened to traffic, asphalt binder in HMA experiences the long term aging due to the exposition to the environment. Asphalt binder in RAP is subjected to both short term and long term aging. Peterson (1984) summarized three main factors for the aging of asphalt binder as:

1. Loss of oily components by volatility or absorption
2. Changes in composition by reaction with atmospheric oxygen
3. Molecular structuring that produces thixotropic effects (steric hardening)

The chemical components of asphalt binder change during aging as well. According to the simplest and most generally accepted concept of asphalt composition (Roberts et al., 1996), asphalt binder is considered to be composed of asphaltenes and maltenes, which consist of resins and oils. Asphaltenes are generally dark brown, friable solids. They are insoluble when the asphalt binder is dissolved in a nonpolar solvent such as pentane, hexane, or heptane. Asphaltenes are with the highest polarity among the components and have a very high tendency to interact and associate in conglomerates. They make significant contribution to the build-up of the viscosity of asphalt binder.

Maltenes are soluble components in asphalt binder. Resins are generally dark and semi-solid or solid in character. When heated they are fluid, and when cold they become brittle. Oils are usually colorless or white liquids. Resins work as agents that disperse the asphaltenes throughout the oils to provide a homogeneous liquid.

SIgnificant research have been performed to study how the contents of asphaltenes and maltenes change with respect to aging. Corbett (1975) found that as asphalt binder ages, some of the maltene phase is transformed into the asphaltene phase. For example, on oxidation resins yield asphaltene type molecules, and oils yield both asphaltene and resin molecules (Roberts et al. 1996). The result is that the asphaltene content increases and fewer maltenes are available to disperse the asphaltenes. The asphaltenes will associate without the presence of enough maltenes for dispersion, leading to increased viscosity and decreased ductility.

When recycling, RAP binder is typically mixed with a certain recycling agent or softer asphalt binders to lower its viscosity and attempt to restore its properties to those of a virgin asphalt binder. Most states use relatively low viscosity, soft asphalt cements as recycling agents, while some states, especially in the western U.S., permit the use of softening agents or rejuvenating agents as well as soft asphalts (Robert et al., 1996). Softening agents consist of flux oils and lube oils, which lower the viscosity of the aged asphalt cement. Terrel and Epps (1989) describe rejuvenating agents as a combination of lubricating oil extracts and extender oils, which contain a high proportion of the napthenic or polar aromatic fractions (maltene component). As explained previously, maltenes are necessary in order to keep the asphaltenes dispersed. Furthermore, the rejuvenating agents should also be compatible with asphalt binders. Bullin et al. (1997) point out that asphaltenes and saturates are highly incompatible, and as a result the recycling agent should have a low saturate content. Many researchers such as Davidson et al.

(1977), Dunning and Mendenhall (1978), Epps et al. (1978), and Peterson et al. (1994) have suggested that a recycling agent should have a control composition.

In the Superpave system, two types of laboratory-aging methods were developed to simulate two types of aging of asphalt binder. The Rolling Thin Film Oven test (RTFOT) (AASHTO T240, 2003) is developed to simulate short term aging, and the Pressure Aging Vessel (PAV) (AASHTO R28, 2002) to simulate long term aging. The properties of aged asphalt binder can be characterized by three tests: the dynamic shear rheometer (DSR) test (AASHTO T315, 2005), the bending beam rheometer (BBR) test (AASHTO T313, 2005), and the direct tension test (AASHTO T314, 2002). The complex shear modulus (G^*) and the phase angle (δ) are measured with the DSR test. The value of $G^*/sin\delta$ is used to evaluate the rutting resistance and determine the high temperature grade of asphalt binder in Superpave system, while the value of $G^*sin\delta$ is used to evaluate the fatigue resistance of asphalt binder. The BBR test and the DT test are used together to determine the low temperature performance of asphalt binder. In AASHTO MP1(AASHTO MP1, 1998), the creep stiffness (s_{60}) and the rate of relaxation (m-value) of asphalt binder at the 60th second obtained with the BBR test are used to define the low temperature grade of asphalt binder. Later, MP1 was modified and AASHTO MP1a, (2004) was proposed. In MP1a, the creep curve from the BBR test and the tensile strength from the DT test are used to determine the critical low cracking temperature (AASHTO PP42, 2003) and then the low temperature grade of asphalt binder.

Kandhal et al. (1995) evaluated the asphalt binders extracted from mixtures using virgin materials and RAP. The virgin mixtures used AC-30 asphalt and the RAP mixtures used AC-20, AC-20S (AC-20 with a penetration between 60 to 80), and AC-30 with RAP contents varying from 10 to 25 percent. The cores taken for the extraction of binder served in the field from 1.5 to

2.25 years. The penetration of the recovered binders in the recycled mixtures and virgin mixture were not statistically different. Neither were the mean viscosities at 60ºC. The DSR test was performed to evaluate the material's resistance to rutting and fatigue. The results showed no significant difference between the recycled and virgin mixtures. This study indicates that asphalt mixtures using RAP can perform as well as those using only virgin materials.

Solaimanian and Tahmoressi (1996) studied four RAP mixtures with high RAP contents from 35% to 50% and compared the variability of RAP mixtures to a control plant mixture with no RAP. They observed significant higher viscosities and lower penetrations from the binder extracted from high RAP content mixtures. The variability of RAP mixtures was also higher than the virgin mixture.

Kennedy et al. (1998) studied the effect of RAP on binder properties using the Superpave specification. Six unmodified asphalt binders were mixed with RAP binders with amounts of 0-100% by mass. They observed that as the percentage of RAP binder included increases, the stiffness of the blend increases and the rate of change of stiffness is either constant or increases at high temperatures.

Soupharath (1998) studied the rutting resistance of asphalt binder containing RAP. One base asphalt binder was blended with RAP at different percentage from 0 to 100% and evaluated with the DSR test. A good linear relationship between logarithm of rheological parameters and the percentage of RAP binders was obtained. This study also confirmed that the addition of RAP binder generally increases the resistance to rutting.

Lee et al. (1999) investigated the rheological and mechanical properties of blended asphalts containing RAP binders. Asphalt binders PG 58-28 and PG 64-22 were blended with RAP binders at contents of 0, 10, 20, 30, 40, 50, 75 and 100% by mass. DSR tests were performed at 52, 58, 64, 70 and 76°C for evaluating the rutting resistance, and at 19, 22, 25, 28 and 31°C for evaluating the fatigue resistance. A good linear relationship between rheological parameters and the percentage of RAP was observed at a double logarithm scale. The BBR tests were performed at –6, -12, -18 and –24 °C for measuring the low temperature performance. The creep stiffness increased and the m-value decreased as the percentage of RAP content increased, indicating that the addition of the RAP reduces the binder's resistance to low temperature cracking.

Li et al. (2005) studied the high temperature and low temperature properties of RAP binders. They tested recycled asphalt mixtures with two virgin asphalt binders: PG 58-28 and PG 58-34 and three different percentage of RAP: 0, 20%, and 40%. At high temperature, e.g. 6 ºC higher than the high PG grade temperature, the value of $G^*/\sin\delta$ increases as the content of RAP increases, which means the more RAP, the stiffer the material. At low temperature, e.g. -24 ºC, both the stiffness from the BBR test and the failure temperature increase and the m-value decreases as the content of RAP increases. They also pointed out that although the asphalt binder from RAP mixture is stiffer than the virgin one, only when the percentage of RAP larger than 20% by mass should significant differences be observed.

All the previous studies on mechanical properties of asphalt binder from RAP mixtures show that the use of RAP result in stiffer asphalt binders and consequently better rutting resistance and lower low temperature cracking resistance. Nevertheless, the significant change of properties of asphalt binder in RAP mixtures occurs only when the content of RAP in asphalt mixture is high enough (i.e., more than 20~30%).

2.3 RAP AGGREGATE

Depending on the hardness of RAP aggregate and the way RAPs are produced, the RAP aggregate may or may not change. Paul (1996) in Louisiana studied the gradations from the extracted cores of five recycled projects and decided there was little or no degradation of aggregate occurred after comparing with the original construction data.

However, different conclusions have been obtained when RAP materials are obtained by milling the pavement. Beam and Maurer (37) found that the gradation determined from core samples did not accurately represent the aggregate gradation after the milling process. Based on six projects observed, the milling process resulted in a finer aggregate gradation than the cores indicated. Brownie and Hironaka (1979) showed a similar reduction in aggregate gradation during a RAP crushing process and concluded that the reduction in size is dependent upon the hardness of the aggregate.

A large amount of fines is detrimental as it can result in a thin asphalt film thickness, which has been associated with poor mixture durability. It leads to the failure to meet the Superpave gradation requirements as well. Currently, this problem is addressed by restricting the maximum amount of RAP used in the mixture and blending in virgin aggregate. In order to allow a higher percentage of RAP, Stroup-Gardiner and Wagner (1999) suggested that RAP could be split into a coarse and fine fraction to keep the large amount of the dust fraction out of the mix.

2.4 DESIGN OF RAP MIXTURE

Different guides have been developed for different mix design methods. In this review, only the design guides based on Superpave system are included. Bukowski (1997) described guidelines to design HMA using RAP on Superpave Mixtures Expert Task Group (ETG) meeting at San

Antonio, Texas. He suggested the general principles in conventional mixtures be also applicable in RAP mixtures and proposed a three-tier system to select suitable asphalt binder and address the specialty of RAP in the design of mixtures. This guideline is summarized below. When the percentage of RAP is:

1. Less than 15%:

   Same asphalt binder should be used as with pure virgin materials.

2. 15% to 25%:

   An asphalt binder, which is one grade lower for both the high and low temperature required for virgin binder, should be used. It also suggests that the low temperature grade may not need to be adjusted for moderate climates. The binder grade can also be selected using a blending chart.

3. More than 25%:

   A blending chart for high and low temperatures should be used to select the grade for the asphalt binder to be used.

Later on, a study by Kandhal and Foo (1997) confirmed the use of the three-tier system in selecting asphalt binder in RAP mixture design. In the case that the three-tier system is not used, they recommend using a sweep blending chart at the high temperature and intermediate temperature. The sweep blending chart is in fact an iso-stiffness curve and constructed by determining the temperature at which a stiffness-related parameter reaches a certain criterion for different contents of virgin asphalt binder. At high temperature, this stiffness-related parameter is $G^*/\sin\delta$ and the corresponding criterion is 1.0 kPa for unaged binder and 2.2 kPa for RTFOT aged binder. At intermediate temperature, this stiffness-related parameter is $G^*\sin\delta$ and the corresponding criterion is 5000 kPa. An example is shown in Figure 1. In this example, a PG 64-22 binder is expected. The 64 °C line and 70°C line define the range of contents of virgin binder.

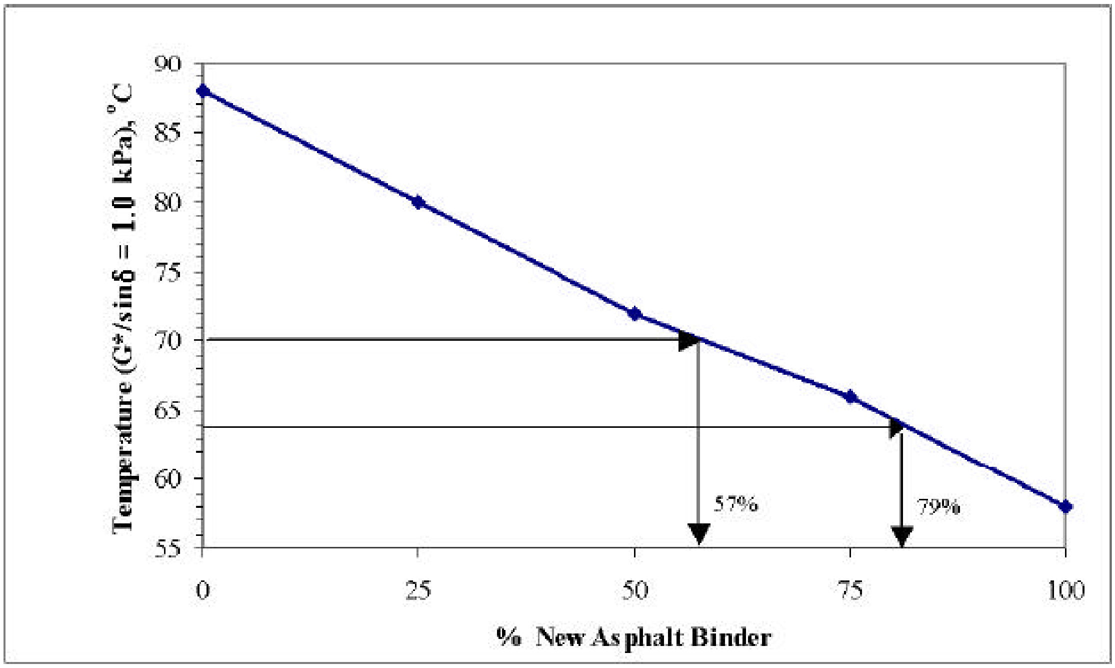


Figure 1. High Temperature Sweep Blending Chart [adapted from Kandhal and Foo (1997)]

To simplify the procedure and reduce the potential error in using sweep blending chart at the intermediate temperature, Kandhal and Foo (1997) suggested a specific grade blending chart as an alternative. As shown in Figure 2, at a specific temperature, e.g. the high temperature grade, G*/sinδ is measured as the content of virgin binder varies. A horizontal line, at which G*/sinδ equals to 1 kPa, is drawn to determine the maximum amount of virgin binder to be used, while the 2 kPa line is drawn to determine the minimum amount of virgin binder to be used.

The latest guideline was developed in NCHRP Project 9-12 (McDaniel and Anderson 2001) and is reviewed in detail in this review. Three studies were performed in this research: black rock study, binder effects study, and mixture effects study. In the black rock study, the RAP in actual practices was compared with two extreme cases: the “black rock” case, at which the RAP binder was completely removed from RAP mixture and the RAP aggregate was blended with virgin binder and aggregate; the "total blending" case, at which RAP binder was recovered and physically blended with virginal binder before they were mixed with both RAP and virgin aggregate. The black rock case was to simulate the case that RAP binder does not interact with virgin binder at all, while the total blending case was to simulate the case that RAP binder is as active as virgin binder although with different grade. Three different RAPs, two different virgin binders, and two RAP contents (10% and 40%) were tested. It was found that at the low RAP content (10%) there was no significant difference among the three different blending cases. At the high RAP content (40%) the actual practice and the total blending case were not statistically different, although both of them were different from the black rock case. This confirmed that the RAP binder should be considered when large content of RAP is used in producing asphalt mixture, which is the assumption behind the three-tier system proposed by Bukowski (1997).

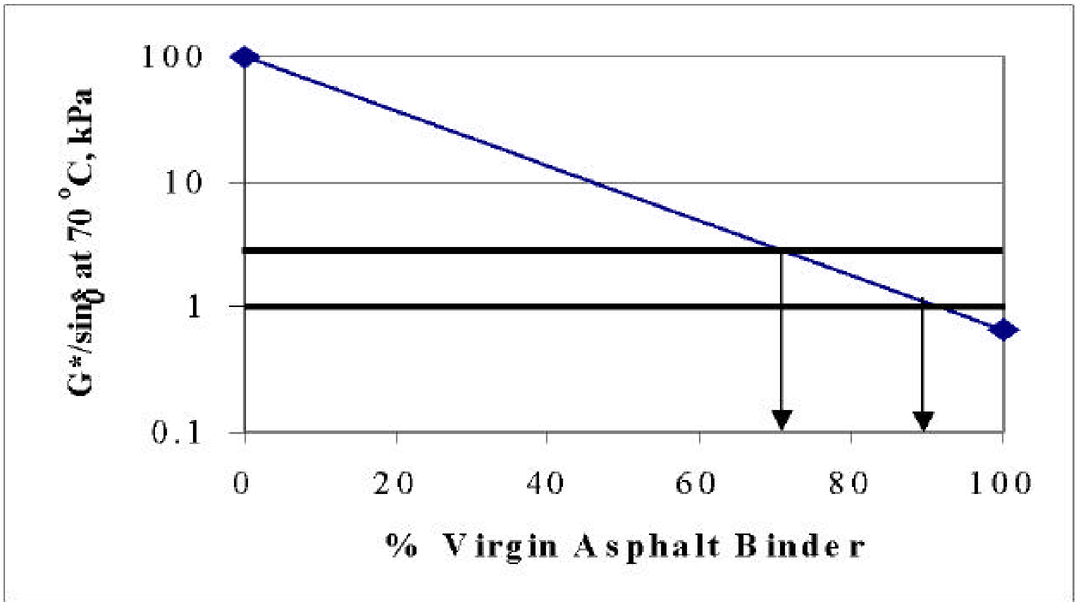


Figure 2. Specific Grade Blending Chart [adapted from Kandhal and Foo (1997)]

To understand the effect of RAP binder and select the right virgin binder, the binder effect study was performed on the same RAPs and virgin binders at five RAP binder contents of 0, 10, 20, 40, and 100 percent. This study concluded that linear blending equations are appropriate to develop a blending chart to determine the RAP content and the grade of virgin binder, and when RAP content is less than a certain amount, the effect of RAP binder can be ignored.

The mixture effects study was then used to investigate the RAP effect on mixture properties. Mixture properties with RAP contents of 0, 10, 20, and 40 percent were measured and results showed that at high RAP contents, a stiffer mixture is expected. This again supported the RAP binder effect observed in previous studies and suggested a softer virgin binder should be used with high RAP contents.

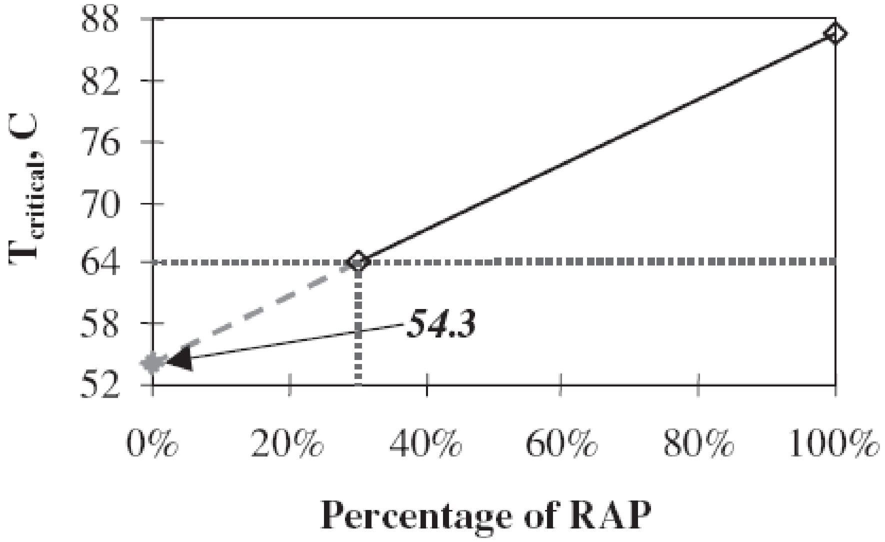
Considering the above findings, a new three-tier system was proposed, as shown in Table 1. Different from the previous version, the RAP percentage, at which no blending chart is needed for selecting the grade of virgin binder, depends on the low grade of RAP binder. The lower the low grade of RAP binder, the larger the RAP percentage is allowed to use without applying a blending chart.

Table 1. Binder Selection Guidelines for RAP Mixtures [McDaniel and Anderson (2001)]

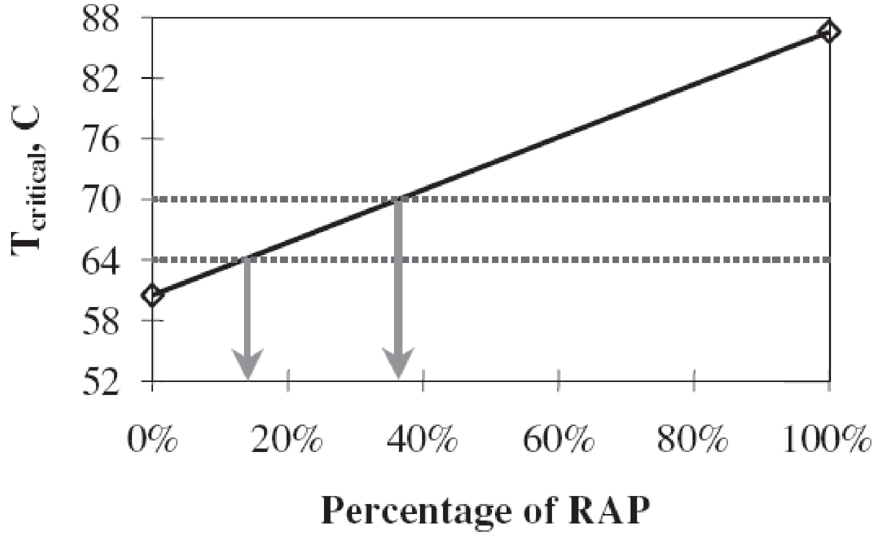
	RAP Percentage		
	Recovered RAP Grade		
Recommended Virgin Asphalt Binder Grade	**PG xx-22 or lower**	**PG xx-16**	**PG xx-10 or higher**
No change in binder selection	<20%	<15%	<10%
Select virgin binder one grade softer than normal (e.g. select a PG 58-28 if a PG 64-22 would normally be used)	20-30%	15-25%	10-15%
Follow recommendations from blending charts	>30%	25%	15%

A blending chart was designed to select the binder in RAP mixtures. The performance of asphalt binder in RAP mixture results from the interaction between the virgin binder and RAP binder and the binder grade of RAP mixture, consequently, depends on both the grade of virgin binder and the percentage of RAP binder. Two scenarios were considered: (1) given the RAP percentage, estimate the grade of virgin binder to use; (2) given the grade of virgin binder, estimate the RAP percentage. Based on a linear assumption, the blending chart is established by drawing a line from the grade temperature of 100% RAP to the grade temperature of 0% RAP in a grade temperature-RAP percentage plot, as shown in Figure 3. This blending chart can be used to decide both the high and low grade of binder. The critical temperature ($T_{critical}$) could be the temperature at which $G^*/\sin\delta$, $G^*\sin\delta$, or the s_{60} and m-value reach the critical values prescribed in Superpave specifications.

For two scenarios described above, different ways are used to determine the grade temperature at 0% RAP. For scenario 1, one point corresponding to 100% RAP is known and the other point can be determined with the designed $T_{critical}$ and the RAP percentage. The blending line is then built by connecting these two points. The $T_{critical}$, with which the grade of binder can be decided, can be estimated by extrapolating the blending line to 0% RAP and calculating the intercept on the axis of the $T_{critical}$. For scenario 2, one point corresponding to 100% RAP and one point to 0% RAP can be easily determined to build the blending line. The RAP percentage is then estimated by starting from the critical temperature axis and checking the corresponding percentage through the blending line. Note that since the asphalt binder is graded at 6 ºC interval, a range for the grade temperature is associated with a PG grade and, consequently, a range for RAP percentage is obtained. This range is typically different for the high temperature grade and low temperature grade and only overlapped range should be used to decide the RAP percentage.



(a) High-Temperature Blending Chart (RAP percentage known)



(b) High-Temperature Blending Chart (RAP percentage known)

Figure 3. Blending Chart McDaniel and Anderson (2001)]

Once the RAP percentage and the virgin binder grade are decided, the rest of the mix design process is very much the same as the conventional mix. Nevertheless, it should always be kept in mind that RAP aggregates contain RAP binders and they should be always treated in such a way to minimize the change of RAP binders. McDaniel and Anderson (2001) detailed this point as follows:

1. The RAP aggregate must be heated gently to avoid changing the RAP binder properties.
2. The RAP aggregate specific gravity must be estimated.
3. The weight of the binder in the RAP must be accounted for when batching aggregate.
4. The total asphalt content is reduced to compensate for the binder provided by the RAP
5. A change in virgin binder grade may be needed depending on the amount of RAP, desired final binder grade, and RAP binder grade.

2.5 PROPERTIES OF RAP MIXTURES

Many research efforts have been performed to characterize RAP mixtures designed according to the above mix design procedure, estimate the field performance of RAP mixtures, and compare with virgin mixtures. Since the modulus is one of the most important parameters in pavement design, studies on different types of moduli are of great interest in this review.

2.5.1 Resilient Modulus (E_R)

Sondag et al. (2002) tested three types of asphalt mixtures with RAP contents of 0%, 15%, 30%, and 40%. The resilient modulus testing was performed at -18, 0, 25, and 32 °C and at frequencies of 0.33, 0.5, and 1 Hz. During mix design, they reported that the average voids in the mineral aggregate (VMA) from their mixtures was 12.9% and less than the minimum value of 14% required by Superpave design system. They argued that since the mixtures in their study were paved in low volume roads, the reduction of durability due to less VMA could be compensated by using a higher asphalt content yielding a low air content.

Their results showed that a stiffer asphalt binder results in a higher resilient modulus. This was observed at 25 and 32 °C, but not clearly showed at 1 and -18°C. They explained this by the larger variability at low temperatures resulting from small deformation and relatively large electronic noise. They also showed that the addition of RAP results in a stiffer mixture and the larger percentage of RAP, the stiffer the mixture. This effect is significant especially at high temperatures. Furthermore, as mentioned by many previous studies, they reported large variability of RAP mixtures, especially at higher RAP contents.

2.5.2 Complex Modulus (E^* and G^*)

As a complex variable, complex modulus of asphalt mixtures can be presented in two forms: (1) the norm of complex modulus, also called the dynamic modulus in asphalt literature, and the phase angle (δ); (2) two components: the storage modulus corresponding to $\cos\delta$ and the loss modulus corresponding to $\sin\delta$. Complex modulus can be measured with different types of load. Under the tensile and compressive load, the complex compressive modulus E^* is measured, while under the shear load, the complex shear modulus G^* is obtained.

2.5.2.1 Complex compressive modulus (E*)

The compressive modulus can be measured with different geometries. Sondag et al. (2002) followed the procedure developed by Zhang et al. (1997) and determined the E^* using the IDT test. Similar to their resilient modulus test, E^* were measured at four temperatures of -18, 0, 25, and 32 °C. The dynamic modulus, $|E^*|$, increases and the phase angle decreases as temperature decreases and/or the frequency increases. The more RAP is added, the larger the dynamic modulus of mixture. With specimens with different RAP contents tested for each type of three mixtures, $|E^*|$-based blending curves were built to estimate the percentage of RAP necessary for reaching the same $|E^*|$ of a virgin mixture with a stiffer binder. These curves showed that as the temperature changes, the modulus of both the RAP mixture and virgin mixture change but at a different rate. The RAP percentage needed to reach the same modulus as virgin mixture changes as well. They also noted that a stiffer binder seems to be more sensitive to the addition of RAP than a softer binder.

A uniaxial compression test is proposed in AASHTO TP62 (2003) to determine the dynamic modulus $|E^*|$, the norm of complex compressive modulus, of asphalt mixtures. The recently developed AASHTO Design Guide heavily relies on this parameter. Many research efforts were performed to relate the $|E^*|$ with the volumetric properties of asphalt mixtures. However, few projects focusing on the relation between RAP content and the $|E^*|$ of RAP mixtures are in progress and not available for review at this time.

2.5.2.2 Complex shear modulus (G*)

Superpave Simple Shear Tester (SST) (AASHTO TP 7) is used to measure the shear modulus of asphalt mixtures at high and intermediate temperatures. The SST has two hydraulic actuators which are set perpendicular to one another and can be operated independently. This feature allows applying direct shear load to the specimen and vertical load at the same time to simulate the stress state in a pavement layer. A so-called frequency sweep test at constant height (FSTCH) is used to measure the G^*. A constant cyclic shear strain is applied to the specimen and a vertical load is applied to restrict the specimen from the vertical dilation. The resulting load and measured strain are used to compute the G^* at each frequency. Note that in FSTCH, only small shear strain is applied and the specimen is not damaged at the end of test.

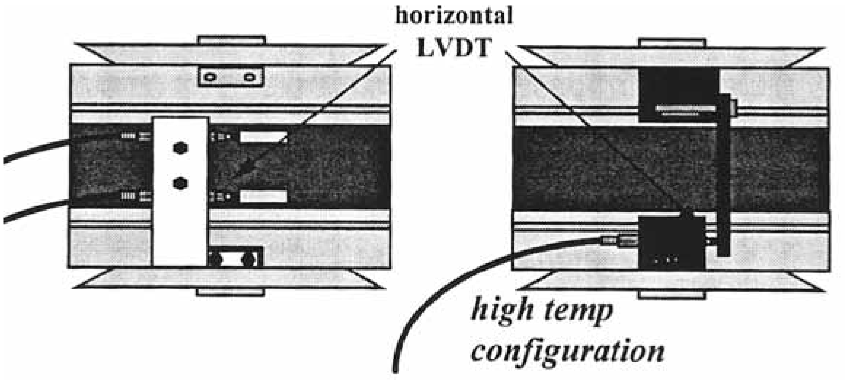


Figure 4. Schematic Plot of Simple Shear Tester (SST) [Asphalt Institute (1996)]

McDaniel and Shah (2002) applied FSTCH to asphalt mixtures using RAP materials from Indiana, Michigan, and Missouri. In this study, they tried to use the RAP content up to 50% on RAPs from all three locations. However, with the 50% RAP from Michigan no mix design had been found to successfully meet all Superpave volumetric requirements and only 40% RAP were used for Michigan RAP. The FSTCH results showed that mixtures with 0 and 15% RAP show similar $|G^*|$ and the mixture with 50% RAP showed a significant increase in $|G^*|$, which was explained due to the stiffening effect of RAP binder.

2.5.3 Permanent Deformation

The permanent deformation of asphalt mixture is measured with repeated shear test at constant height (RSTCH) using SST and used to predict the rutting resistance. Different from the FSTCH, a repeated haversine shear stress is applied to the specimen while a vertical load is applied to keep the height constant at the same time. By the end of the RSTCH, the permanent deformation is recorded and thus the damage is introduced. Recall that during FSTCH only small shear strain is applied and the test is non-destructive.

McDaniel and Shah (2002) also measured the permanent deformation of asphalt mixtures with RAPs from Indiana, Michigan, and Missouri with RSTCH at 58 °C. None of the mixtures tested showed tertiary flow. The plastic shear strain at 5,000 cycles is used to rate the rutting potential of asphalt mixtures based on a general guideline by Asphalt Institute. Most mixtures tested indicate good rutting resistance except Michigan mix with 40% RAP. However, mixed results were reported on the measurement of permanent strain. With Indiana and Michigan mixes, the 0% RAP shows the smallest permanent strain, while with Missouri mixes the 0% RAP shows the largest strain. With Indiana and Missouri mixes, the larger the RAP content the smaller the permanent strain, which indicates a stiffening effect of RAP. The opposite, however, was observed on Michigan mix. They claimed adding RAP stiffens the mix due to stiffer RAP binder and decreases the mixture performance due to the change of aggregate structure. No further tests were performed to study the balance of the two effects from the addition of RAP.

2.5.4 Low Temperature Cracking

In the Superpave system, the low temperature properties of asphalt mixtures are characterized by the IDT creep test and strength test (AASHTO T322). A constant load is applied diametrically on a disc-shaped specimen. The horizontal and vertical deformation are collected with LVDTs mounted on the surface of the specimen. The creep compliance is computed using the recorded load and deformation and converted to the relaxation modulus. The strength test is performed using the same configuration. The specimen is still loaded diametrically but at a constant rate of loading until the specimen breaks. The ultimate load is recorded to estimate the tensile strength of the asphalt mixture.

Few literatures have been found on the low temperature properties of RAP mixtures. McDaniel and Shah (2002) mentioned that with the IDT tests conducted under NCHRP 9-12 the addition of RAP does not significantly affect the tensile strength of RAP mixture, but does increase the stiffness of RAP mixture. This means the thermal stress due to the restraint from the free shrinkage of asphalt layer can build up faster and results in less resistance to low temperature cracking. They suggested that the grade of virgin binder should be adjusted to properly account for the stiffening effect from adding RAP, especially at large contents.

2.6 SUMMARY

Since the 1970's, RAP materials have been used in large volume and studied systematically. As the Superpave system was proposed and implemented in the 1990's, many research efforts have been performed to adjust the design of RAP mixtures to meet Superpave standards. Of great interest is how to account for RAP binder as RAP is mixed with virgin binder and aggregates. With NCHRP project 9-12 a three-tier system was proposed to address this issue. The principle behind this tiered system is that the contribution of RAP binder depends on its percentage in mixture. When small percentage of RAP is used, the contribution of RAP binder can be ignored. When the percentage of RAP becomes large enough, the influence of RAP binder should be handled using a blending chart. The addition of RAP binder results in a stiffer asphalt binder, which indicates better rutting resistance and lower low temperature cracking resistance.

The gradation of RAP is also studied. For RAP ripped off pavements, the gradation shows little or no degradation, while for RAP from milling, the gradation becomes finer than the original aggregate. When too many fines are brought into asphalt mixture along with RAP, the asphalt mixture will fail to meet Superpave volumetric requirements. In fact a couple of studies referred in this literature review mention that at large percentages of RAP certain Superpave criteria cannot be met.

Different types of moduli of RAP mixtures have been measured and used to estimate the performance of mixtures. The resilient modulus increases as the RAP percentage increases. The complex compressive modulus is measured with the indirect tensile test and the complex shear modulus is measured with the Superpave simple shear tester. The norm of complex modulus, called dynamic modulus, is used to study the stiffening effect of RAP. Results show that a large percentage of RAP results in both higher dynamic shear modulus and dynamic compressive modulus. However, the permanent strain measured with the Superpave simple shear tester implies the stiffening effect of RAP is counteracted by its potential weakening effect from the change of RAP aggregate resulting in an inferior gradation compared to the original gradation.

CHAPTER 3

MATERIALS AND TEST METHODS

3.1 INTRODUCTION

To investigate the mixture properties and performance using higher percentages of RAP, 45% RAP was selected for the highest % RAP mixture. However, a 0% RAP (control) mixture containing only virgin materials was also tested along with mixtures containing 25% and 35% RAP to determine changes in terms of the mixture properties and performance by the addition of RAP materials.

3.2 MATERIALS

3.2.1 RAP Materials

Traditionally, the majority of RAP aggregate used in Florida consisted of Florida limestone. However, with the proliferation of granite aggregate used in the production of asphalt, many projects are increasingly yielding more and more granite source RAP. Therefore, RAP materials used in this research also include both limestone and granite. Two types of RAP were used in terms of fraction: coarse RAP and fine RAP.

3.2.2 Virgin Aggregate Materials

The virgin aggregates used in the mix designs, were Florida limestone. Local sand and dust were used to match gradations among different % RAP mixtures. The detailed information of aggregate sources is presented in Table 2.

Table 2. Aggregate Sources

Type	FDOT code	Pit No.	Producer
Coarse RAP		A0721	P&S Paving
Fine RAP		A0721	P&S Paving
S-1-A	42	87-090	Rinker Materials Corp.
S-1-B	52	87-090	Rinker Materials Corp.
Screenings	21	87-090	Rinker Materials Corp.
Crushed Screen		87-090	Rinker Materials Corp.
Local Sand			P&S Paving

3.2.3 Virgin Asphalt Binder

For the control mixture, an unmodified PG 67-22 used commonly in Florida was selected. The binder grade was selected based on the viscosity of the virgin binder and RAP binder, and the percentage of RAP by FDOT specification. Since RA 2000 was not available, the same binder was used for 35% and 45% RAP. According to the NCHRP report by McDaniel and Anderson (2001), the types of binder for each mixture with varied percentage of RAP were shown in Table 3. The binder selection by FDOT specification is also allowable by the NCHRP recommendation. However, the 35% RAP mixture should be blended with RA-2000 based on FDOT specification, but RA-1000 is also appropriate by the NCHRP recommendation, which has a decision procedure based on the critical temperature of the PG grade system.

3.3 GRADATIONS

To reduce the gradation effect, all mixtures with varied percentage of RAP materials were designed for the same Job Mix Fomulas (JMF). Figure 5 shows the selected JMF.

Table 3. Virgin Binder Used in Study and NCHRP Recommendation

	NCHRP	Used in Research
	PG 64-22 or lower	
No change in binder selection	<20%	PG 67-22
Select virgin binder one grade softer than normal (select a PG 58-28, if a 64-22 would be used.)	20-30%	PG 64-22
Follow recommendations from blending charts	>30%	RA 1000 (PG 58-28)

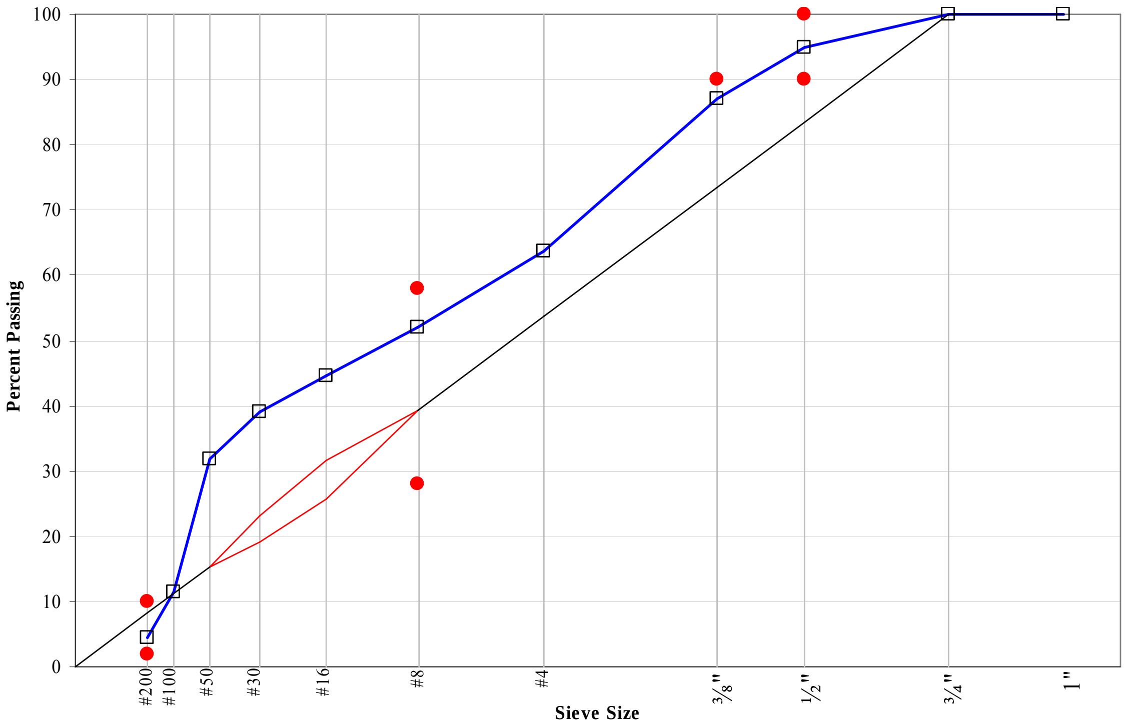


Figure 5. Target Gradation for all mixtures

3.4 MIX DESIGN

All mixtures were designed for traffic level C, which is greater than or equal to 3 million ESALs and less than 10 million ESALs. Compaction levels corresponding to traffic level C are 7 gyrations for $N_{initial}$, 115 gyrations for N_{max} and 75 gyrations for N_{design}.

Table 4 presents the design information for mixtures with varied percentages of RAP materials. All Mixtures except for the 45% RAP mixture meet the Superpave criteria such as voids in mineral aggregate (VMA) and voids filled with asphalt binder (VFA). However, VMA of the 45% RAP mixture (13.8%) is slightly less than the specified minimum value (14.0%).

Table 4. Designed volumetric information

Mixture	AC (%)	G_{mm}	G_{sb}	AV (%)	VMA (%)	VFA (%)
Control	6.5	2.337	2.465	4.0	14.9	73.3
25% RAP	6.5	2.329	2.454	3.8	14.7	73.9
35% RAP	6.0	2.342	2.457	4.1	14.0	71.1
45% RAP	5.9	2.347	2.460	4.0	13.8	71.0

3.5 COMPACTION

The samples were compacted in the Servopac Gyratory Compactor (SGC). The three main parameters that control the compaction effort of this equipment for the Superpave design procedure are the vertical pressure, which is set at 600 kPa (87 psi), the angle of gyration, which is set at 1.25 degree, and the number of gyrations to get the desired air void content. In the process of compaction, the height of the specimen and the gyratory shear are measured for each gyration. After cooling the specimen at room temperature, it was cut to the required thickness for testing. The bulk specific gravity was determined to check if the air voids of the specimen are within the required range.

3.6 ASPHALT BINDER TESTS

The virgin binders were tested with the basic binder tests to determine the binder grade. The RAP binder and aged binder from the mixtures for different percentages of RAP were also extracted and recovered for binder testing to have information such as penetration, viscosity, and G* values.

3.7 MIXTURE PERFORMANCE TESTS

3.7.1 APA for Rutting Performance

The Asphalt Pavement Analyzer (APA), shown in Figure 6, is equipment designed to test the rutting susceptibility or rutting resistance of hot mix asphalt (HMA). Rut performance tests are performed by means of a constant load applied repeatedly through a pressurized hose to a compacted test specimen. The cylindrical test specimens are 150 mm diameter by 115 mm tall. The target air void range is 4 ± 0.5%.

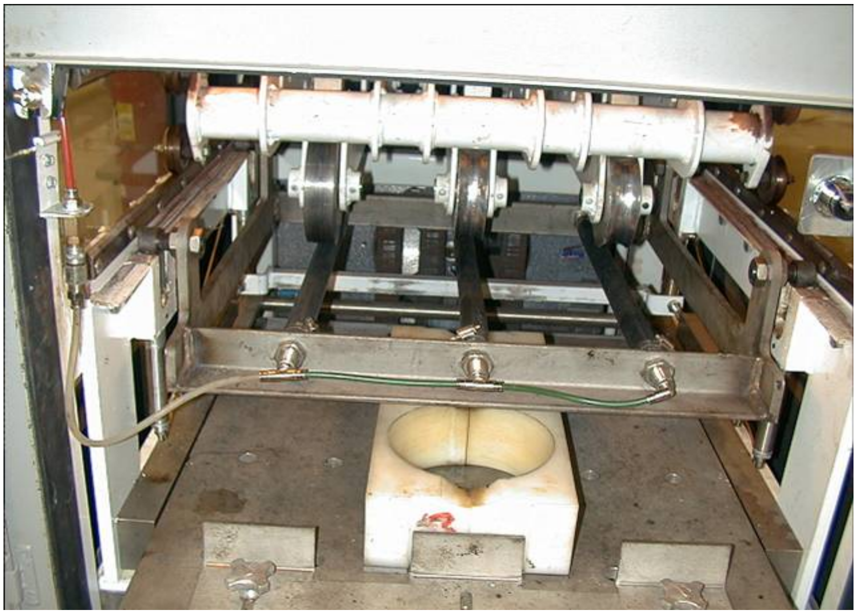


Figure 6. Asphalt Pavement Analyzer

The steps for the APA testing procedure using the pressurized hose are outlined below:

- Preheat the specimen in the APA chamber to 64°C (147°F) for a minimum of 6 hours but not more than 24 hours before the test.
- Set the hose pressure gauge reading to 100±5 psi.
- Calibrate each wheel with the load cell to read a load of 100±5 lbs.
- Secure the preheated, molded specimen in the APA, close the chamber doors and allow about 10 minutes for the temperature to stabilize.
- Apply 25 load cycles and take initial measurements.
- Place the specimen back in the APA, close the chamber doors and allow about 10 minutes for the temperature to stabilize.
- Restart the APA and continue rut testing for 8,000 cycles.
- The difference between the initial and final rut depth are calculated and averaged.

3.7.2 Servopac for Rutting Susceptibility

Servopac rutting analysis procedures developed by Birgisson et al. (2004) were designed to evaluate the mixture's shear resistance with a Superpave Gyratory compactor. Two parameters obtained from the procedure, which is based on shear stress measurements obtained during compaction, are determined from measurements made at compaction angles of 1.25 and 2.50 degrees:

- Gyratory shear slope, which is the rate of change in shear resistance during the densification portion of compaction at 1.25 degrees; and
- Vertical failure strain, which is the amount of vertical strain developed in the mixture between the time instability is induced by increasing the compaction angle to 2.50 degrees and the time the mixture begins to regain strength after instability.

Gyratory shear slope is obtained using regression analyses on the gyratory shear resistance versus the number of cycles in the densification zone. The best-fit regression curve was found using a relationship in the form:

$$G_S = k_1 \log(N) + k_2$$

where,

G_S= gyratory shear resistance
N= number of gyrations
k_1= slope of regression line
k_2= intercept of regression line

The data used to obtain the regression parameters was obtained from one of the following two ranges: a) 7 percent to 4 percent, if the maximum gyratory shear strength was not reached until less than 4 percent air voids, or b) from 7 percent to the air voids at maximum gyratory shear strength if the maximum gyratory shear strength was reached at air voids greater than 4 percent (Figure 7).

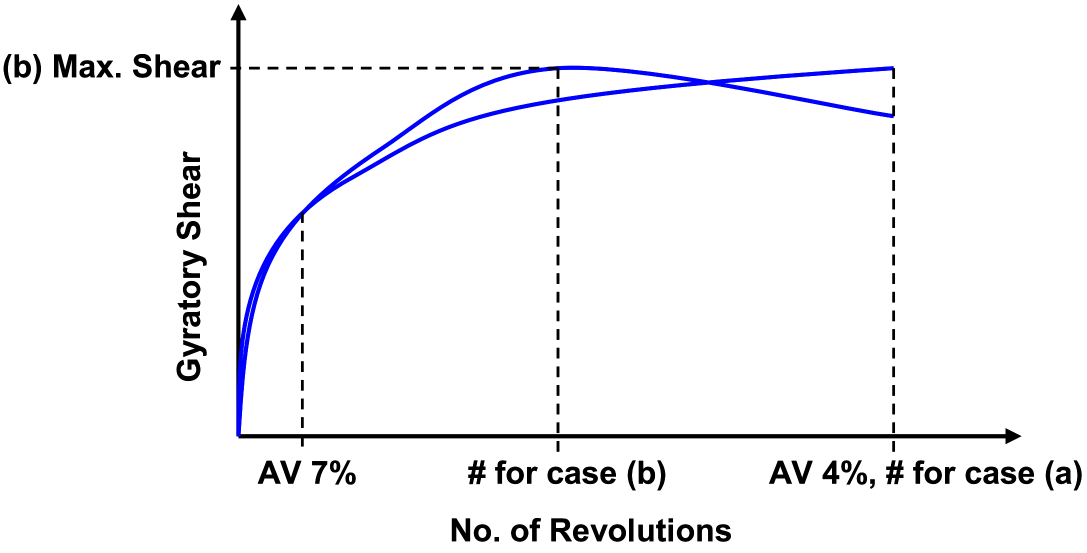


Figure 7. Determination of the Number of Revolution for Different Types of Shear Development

The vertical "failure" strain, measured from the onset of the compaction with the 2.50 degree gyratory angle, to the local minimum on the gyratory shear curve (Figure 8) was found to be 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. 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 at an angle of 1.25 degrees. Once the target air voids level was reached, the mixture was compacted for another 100 gyrations at an angle of 2.50 degrees, and the failure strain was calculated.

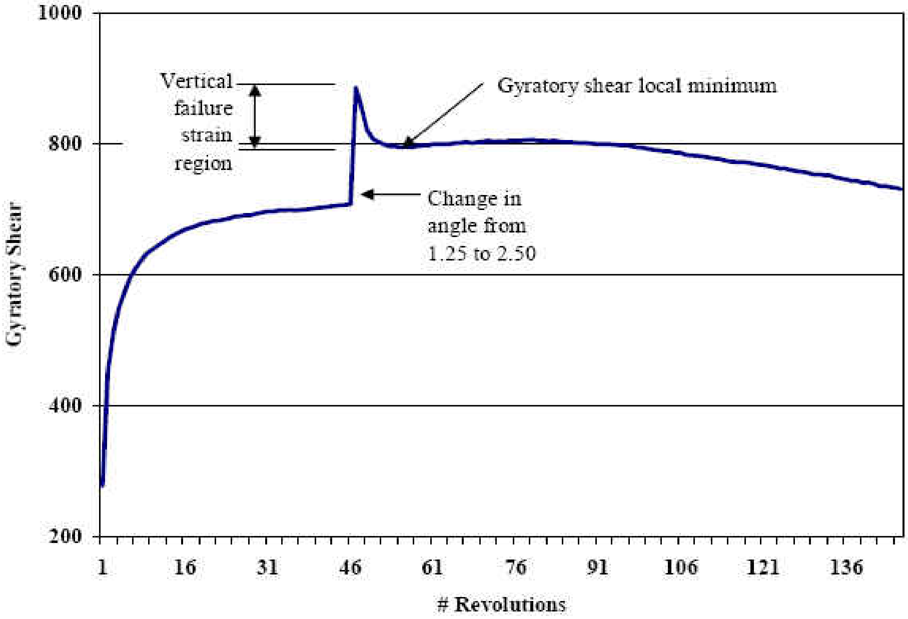


Figure 8. Gyratory Shear Strength versus Number of Gyrations for the Modified Compaction Procedure

Based on the criteria developed by Birgisson et al. (2004), mixtures are considered to exhibit optimal behavior when the percent vertical failure strain is between 1.4 and 2.0, and the gyratory shear slope is greater than 15 kPa (Figure 9).

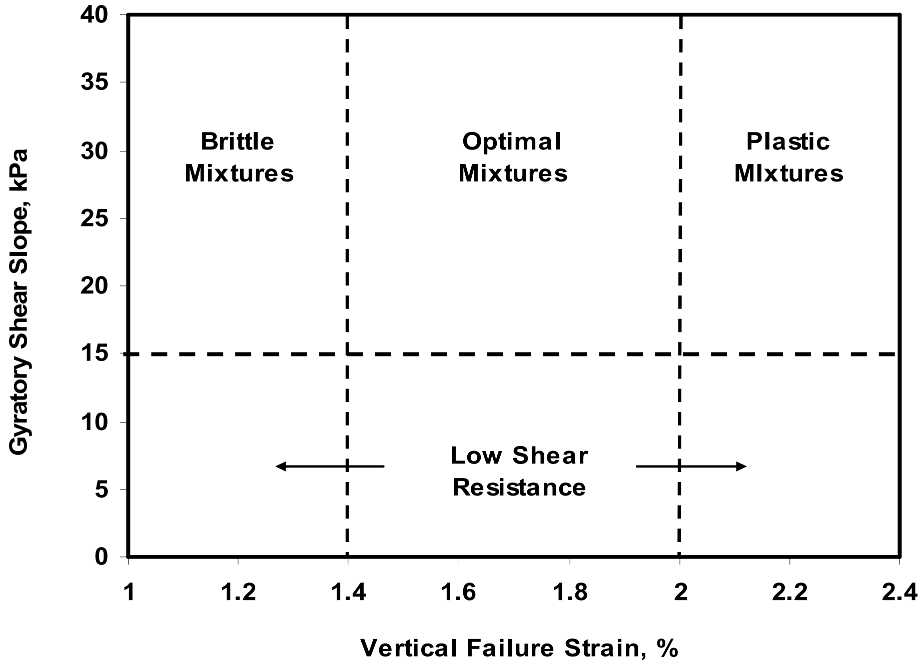


Figure 9. An Illustration of the Evaluation of Mixture Rutting Potential

3.7.3 Superpave IDT for Crack Performance

The Superpave indirect tension test (IDT) shown in Figure 10 was used to evaluate the mixtures' resistance to cracking. This test was performed to obtain the mixture properties: resilient modulus (MR), creep compliance [D(t)], m-value, D1, tensile strength, fracture energy (FE), and dissipated creep strain energy (DCSE) to failure (Roque et al. 1997, Zhang et al. 2001a and 2001b). Figure 11 presents the schematic of Superpave IDT and determination of DCSE to failure based on indirect tensile strength test results. The testing procedure is described below:

- The top and bottom of the 150 mm diameter gyratory compacted specimens are trimmed using a wet saw, and then the remainder of the specimen is cut in half to produce two test specimens with a thickness of about 1.5 inches. The air voids is targeted at 7 ± 0.5%.

- The specimens are dried and gage points are applied to both faces, which should be smooth and parallel. The specimens are then further dried in a dehumidifying chamber and brought to the appropriate testing temperature (10°C).

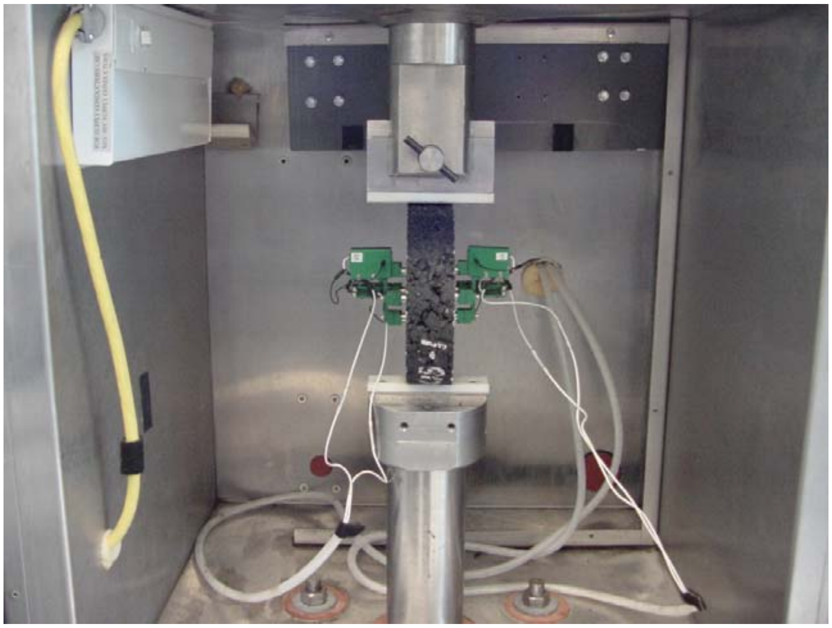


Figure 10. Superpave IDT

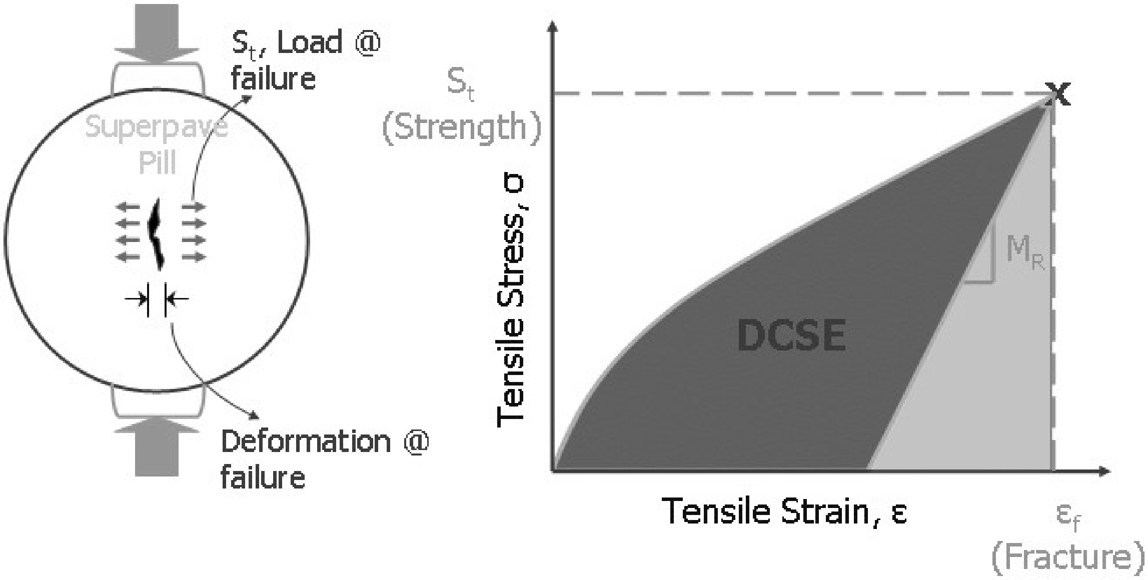


Figure 11. Schematic of Superpave IDT and Determination of DCSE to Failure

- Three different tests were performed on each of three specimens in sequential order. The final results are therefore based on the average of three specimens.
- The resilient modulus and Poisson's ratio are determined by applying a haversine wave load for 0.1 seconds followed by a rest period of 0.9 seconds.
- A creep test is performed by applying a constant load for 1,000 seconds. Several parameters are determined from this test including the creep compliance as a function of time, m-value and D_1, which are used to determine the mixture's resistance to creep and damage.
- An indirect tensile strength test is performed at a rate of 50 mm/min until the specimen has failed to obtain tensile strength.
- Finally, fracture energy and dissipated creep strain energy to failure are calculated.

The energy ratio (ER), which is defined as the DCSE threshold of a material ($DCSE_f$) divided by the minimum DCSE ($DCSE_{min}$) needed, is calculated from IDT results as follows (Roque et al. 2004).

$$ER = \frac{DCSE_f}{DCSE_{\min}}$$

The $DCSE_{min}$ is a function of material properties and the pavement structure.

$$DCSE_{\min} = \frac{m^{2.98} D_1}{A}$$

where, m and D1 are the creep compliance power law parameter.

Parameter "A" accounts for the tensile stresses in the pavement structure at the bottom of the asphalt layer and the tensile strength of the material. Unless the tensile stresses in the pavement structure are given, 150 psi is used for the default value.

$$A = 0.0299 \times \sigma^{-3.10}(6.36 - S_t) + 2.46 \times 10^8$$

where, σ is the applied tensile stress, S_t is the tensile strength.

Therefore, ER can be calculated directly once the mixture creep compliance parameters (m-value and D_1), the tensile stress, and the tensile strength are known. In Florida, ER values less than 1.0 have been associated with pavements that have exhibited poor cracking performance. Therefore, ER should be greater than 1.0 for the mixture to be acceptable.

CHAPTER 4

TEST RESULTS

4.1 INTRODUCTION

To compare mixture properties, virgin binders and recovered binders from each of the mixture types were recovered and tested. APA tests and Servopac tests were performed in terms of the rutting resistance. Superpave IDT tests were also performed in order to evaluate cracking performance.

4.2 BINDER TEST RESULTS

The virgin binders (i.e., PG 67-22, PG 64-22, and RA-1000) and recovered binders were tested to determine their PG grade. Table 5 shows the final PG grade for aged binders. For PG grades of the recovered binder from two 45% RAP mixtures shows PG70-22 and PG76-22. However, one of them passed barely. The 45% RAP mixture was mixed with RA-1000 based on the FDOT specification, but it exhibited stiffer behavior than the other recovered binders. However, the recovered binder for the 35% RAP mixture, which should had been blended with an RA-2000, showed the same PG grade as the others, even though it was mixed with RA-1000 due to no availability of RA-2000.

Penetration tests were performed at 25°C and absolute viscosity tests were performed at 60°C for virgin asphalt binders and recovered samples from mixtures. As shown in Figure 12, the penetration values decreased as RAP content increased. As expected, the results appeared to show an increase in the viscosity of the binder after adding more RAP content in spite of using softer virgin binders for RAP mixtures. The 25% RAP mixture had slightly higher viscosity than the 35% RAP mixture. G*/sinδ at 70 °C and 76°C exhibited similar trends with the viscosity results as shown in Figure 13. However, the 35% RAP mixture had lower values than the others.

Table 5. Virgin and Recovered Binder PG Grade

RAP Content,%		**0 (Control)**	**25**	**35**	**45**
PG grade	**Virgin Binder**	67-22	64-22	58-28	58-28
	Recovered Binder	70-22	70-22	70-22	70/76-22

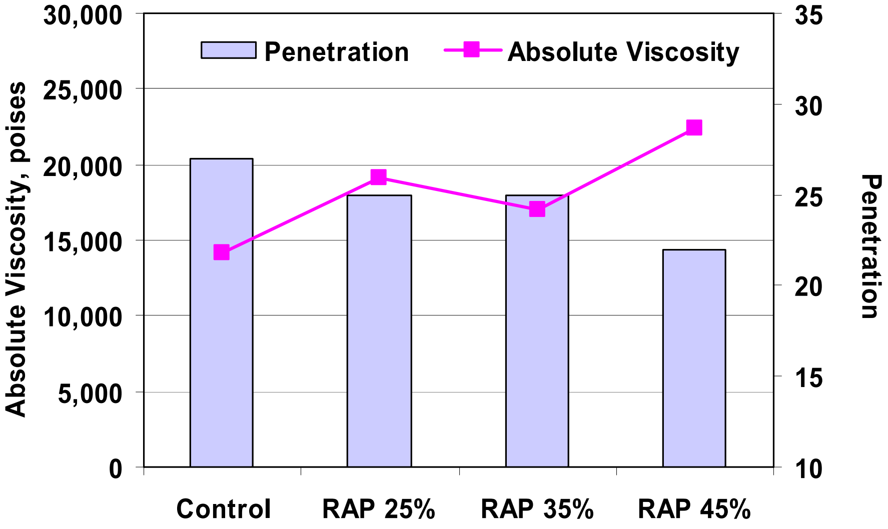


Figure 12. Viscosity and Penetration Results from Recovered Binders

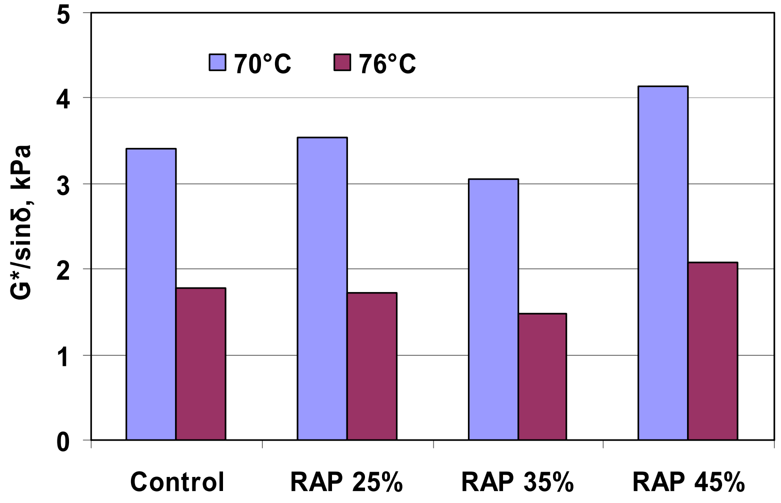


Figure 13. DSR Result from Recovery Binders

4.3 MIXTURE TEST RESULTS

4.3.1 Evaluation of Rutting Performance

4.3.1.1 APA test results

Figure 14 presents rut depth results from the APA test. The control mixture showed better performance than the 25% RAP mixture, but there is no significant difference among the control, 35% RAP, and 45% RAP mixtures when analyzed using the Student t-test. Although the 25% RAP mixture showed more rutting than the control mixture, rut depth decreases as the percentage of RAP materials increases, except for the control mixture. This trend is generally reasonable based on other studies, which evaluated mixture with different contents of RAP utilizing the same binder type.

However, rut depths for RAP mixtures have been observed to have extra rutting due to the use of softer binders. Chehab and Daniel (2006) have evaluated RAP mixtures and predicted performance using the Mechanistic Empirical pavement design guide level 3 analysis. They reported that there was a slight increase in rutting with an increase in RAP content from 15% to

25%. Although using more RAP in mixture could reduce rutting slightly with RAP percentage greater than 25%, the effect of the high temperature PG grade for the virgin binder was more dominant than RAP content. Therefore, even though a decrease in rutting with an increase in RAP content was expected by using the same binder, when the rejuvenator binder was varied more or similar rutting was exhibited overall due to the effect of the softer virgin binder used in the mix design.

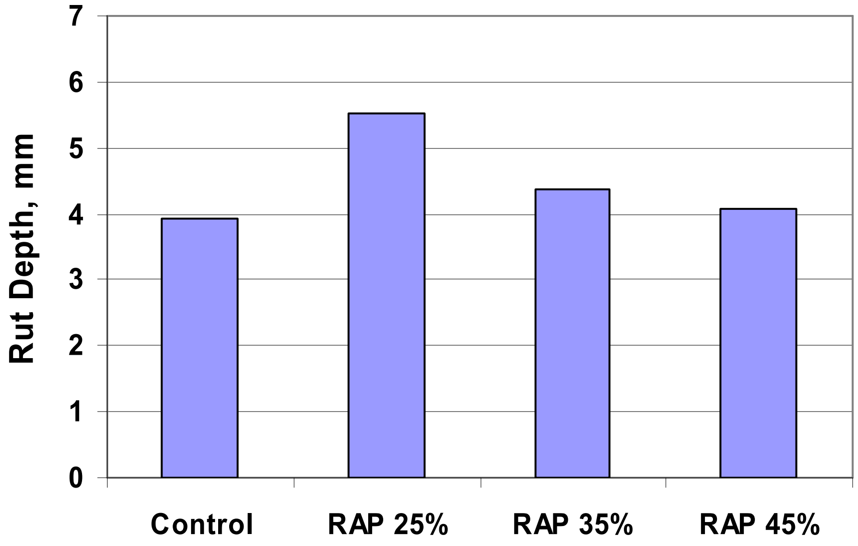


Figure 14. APA Result

4.3.1.2 Servopac gyratory shear test results

Results of the analysis using a Servopac gyratory compactor with gyratory shear measurements, which were developed by Birgisson et al. (2004), are presented for each of the mixtures in Figure 15. Although all the mixtures are located within the brittle mixture area, there is a reasonable trend in order to rank their rutting performance in terms of the vertical failure strain.

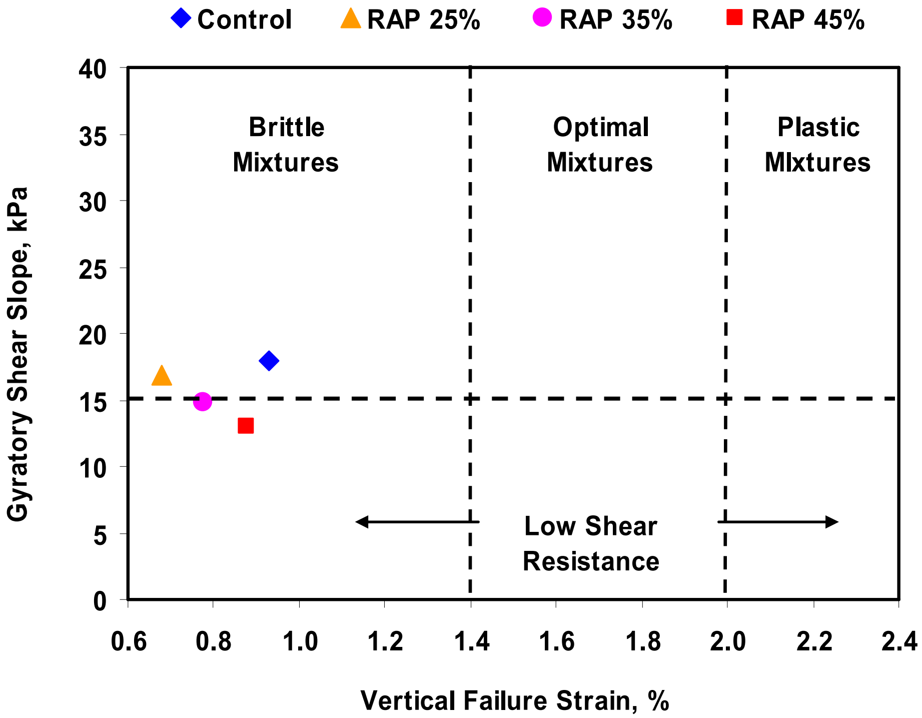


Figure 15. Servopac Gyratory Shear Test Results

4.3.2 Evaluation of Cracking Performance Using Superpave IDT

The Superpave IDT was used to perform resilient modulus, creep, and tensile strength tests to define the mixture characteristics and energy ratio (ER).

Figure 16 shows that the tensile strength decreased as RAP content of a mixture increased. This will be discussed more in section 5.3.4.

As shown in Figure 17, the fracture energy (FE) decreases as RAP content of a mixture increased. The FE for the mixture with the 45% RAP mixed with the same binder (RA-1000) for 35% RAP mixture was less than the 35% RAP mixture. This may result from the use of more RAP with the same binder. However, comparing 35% with 25% RAP mixtures, FE for the 35% RAP mixture was only slightly lower. Since the 35% RAP mixture used a softer binder than the 25% RAP mixture, it seems to compensate for the use of more RAP.

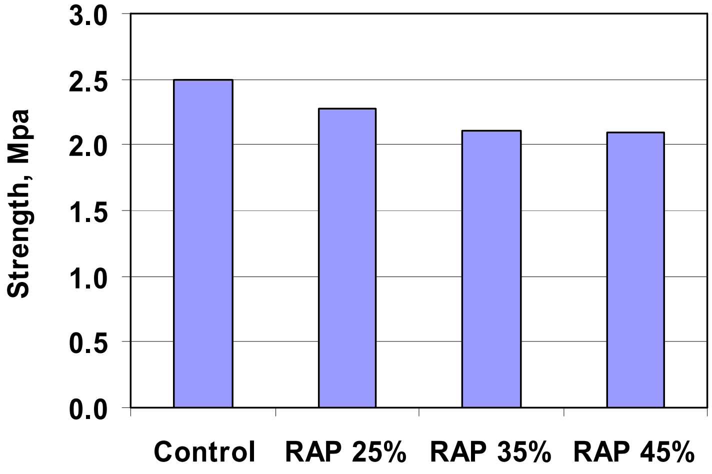


Figure 16. Tensile Strength from Superpave IDT Test

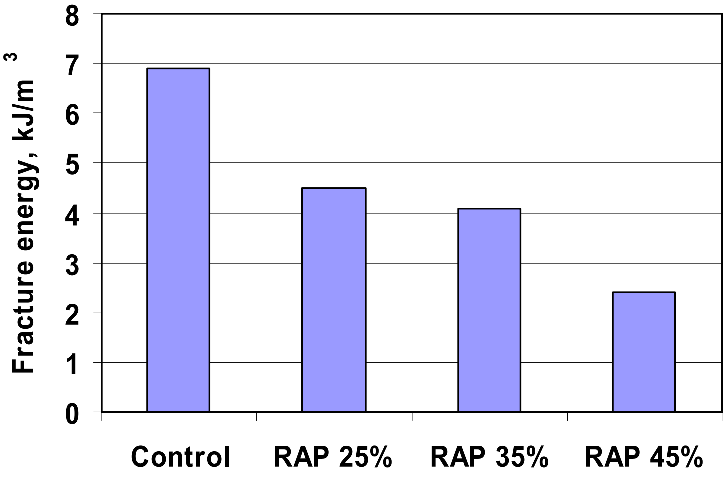


Figure 17. Fracture Energy from Superpave IDT Test

The results for the creep compliance rate are more complicated and are shown in Figure 18. The control mixture shows a higher creep compliance rate than the 25% RAP mixture. Although the 25% RAP mixture was blended with a softer binder (PG 64-22), the RAP materials might have overcome the effect of the softer binder, resulting in a lower creep compliance rate than the control mixture. However, the 35% RAP mixture blended with RA-1000 showed a higher rate of the creep compliance than the other mixtures due to the softer asphalt binder. The 45% RAP mixture with RA-1000 binder had a reduced rate of creep compliance compared to the 35% RAP mixture since it contained more RAP materials but the same virgin binder as the 35% RAP mixture. This result correlates with G*/sinδ. A mixture with a higher G*/sinδ shows lower creep compliance rate. Except for comparing the control mixture to the 35% RAP mixture, the result also correlates with viscosity in general. The complete creep compliance results shown in Figure 19 show the same trend.

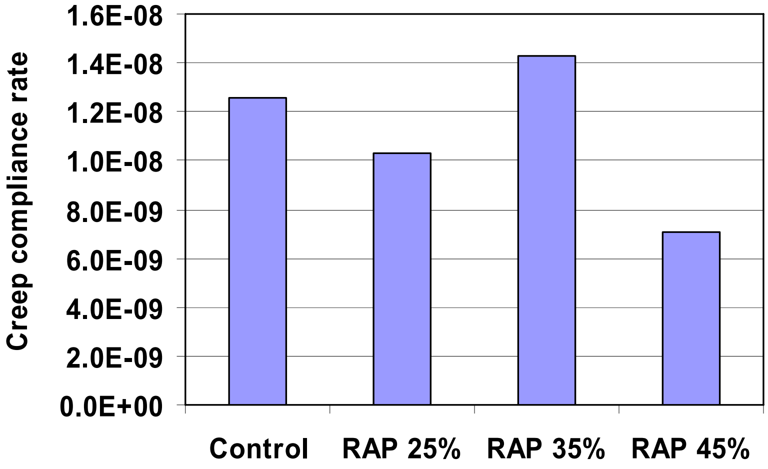


Figure 18. Creep Compliance Rate from Superpave IDT Test

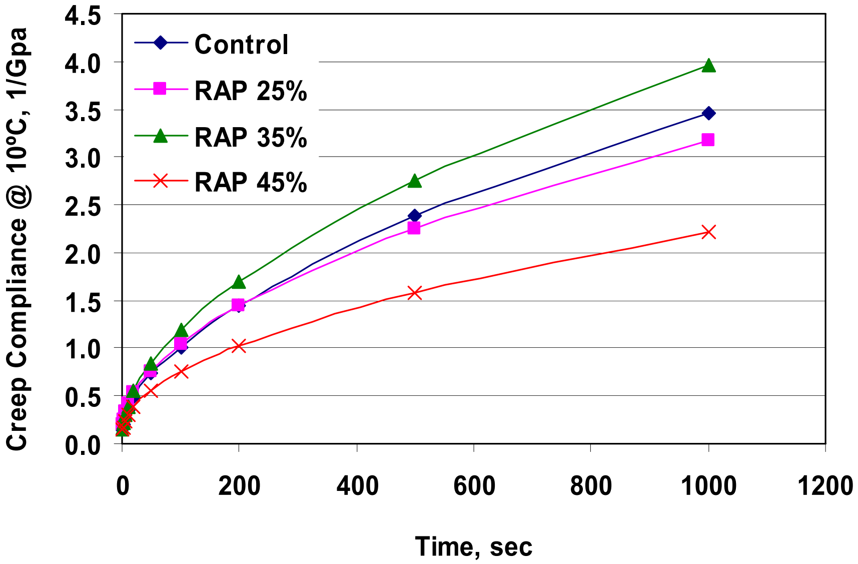


Figure 19. Creep Compliance from Superpave IDT Test

Considering the energy dissipation and energy threshold, the ER results are presented in Figure 20. The control mixture showed the highest ER. The ER decreases as RAP content of a mixture increased overall. Even though the 35% RAP mixture had higher FE than the 45% RAP mixture, its ER was similar with the ER for the 45% RAP mixture due to higher creep compliance rate. Therefore, based on these results, RAP mixtures did not perform as well as the control mixture, in terms of the resistance to the load associated cracking.

4.4 SUMMARY

Mixtures with various contents of RAP materials were tested using the APA, the Servopac gyratory compactor, and the Superpave IDT test. The control mixture with 0% RAP material was blended with PG 67-22 for the virgin asphalt binder. Mixtures with vary percentages of RAP (25%, 35%, and 45%) were designed. The 25% RAP mixture was blended with PG 64-22, and the 35% and 45% RAP mixtures were blended with RA-1000 (PG 58-28).

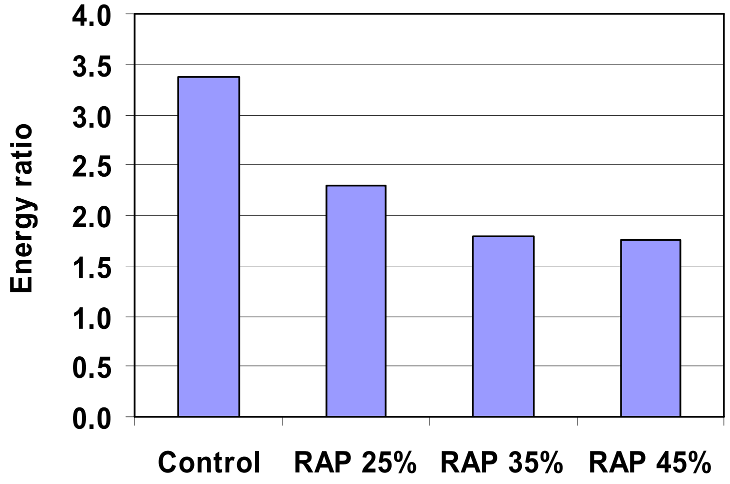


Figure 20. Energy Ratio from Superpave IDT Test

APA tests showed that for mixtures containing RAP, more RAP resulted in less rutting. All RAP mixtures exhibited a little more rutting than the control mixture due to the effect of the stiffer virgin binder used in the control mixture. These results agreed well with the percentage of the vertical failure strain from the Servopac gyratory shear test.

From the Superpave IDT tests, a mixture with more RAP materials showed lower FE. The ER results showed that using higher percentages of RAP materials may reduce cracking performance.

In summary, a mixture using a higher percentage of RAP materials (45%) may perform as well as the control mixture with respect to rutting performance. However, mixtures containing 25 ~ 35% RAP and using a binder with a lower high temperature PG grade may reduce the rutting performance. In terms of the cracking performance, using a higher percentage of RAP material may not be good, even with the binder of the lower high temperature PG grade. Since using different binders, percentage of RAP materials, and AC content, it is difficult to clearly define the solution for a RAP mixture to have good cracking performance. Chehab and Daniel (2006) also reported that a universal statement on how increasing RAP affects the performance could not be made because the influence of the amount of RAP on predicted performance depended on the differences between the mixtures.

CHAPTER 5

FURTHER EVALUATION

5.1 OVERVIEW

Generally, VMA may be reduced as the gradation is modified to be closer to the maximum density line (MDL). The 45% RAP gradation used for this study is an actual mix utilized by a contractor for FDOT projects. As shown in Figure 5, the JMF for the previous experimental stage is a fine-graded gradation which is quite far from the MDL. Even though many studies about gradation have found that there is no significant difference between coarse and fine-graded mixtures (Kandhal and Rajib 2001, Hand et al. 2001, Hand and Epps 2001, Kandhal and Cooley 2002, Gokhale et al. 2006), the gradation effect on performance cannot be disregarded. Most of experimental studies have mentioned the effect and importance of the gradation. Recently, the Bailey method (Vavrik et al. 2001, 2002) has been used to evaluate the characteristics of gradation based on packing theory.

Kim et al. (2006-b) have developed a procedure to evaluate the gradation of a Superpave mixture in terms of performance. In addition, Kim et al. (2006-a) analyzed field mixtures that were segregated and non-segregated and developed a criteria for gradation to optimize performance for an asphalt mixture. Therefore, additional work was conducted in this study that focused on the improvement of performance for the high percentage RAP mixture by modifying the gradation.

5.2 MODIFIED GRADATION

To modify the gradation to optimize performance, it was moved closer to the MDL, while still staying above the MDL. The porosity of the dominant aggregate size range (DASR) was used as one of the mixture characteristics to optimize the gradation of the 45% RAP mixture (Kim et al. 2006-b). In addition, the gradation was also evaluated by the percentage of coarse aggregate (Kim et al. 2006-a). Figure 21 presents the modified gradation.

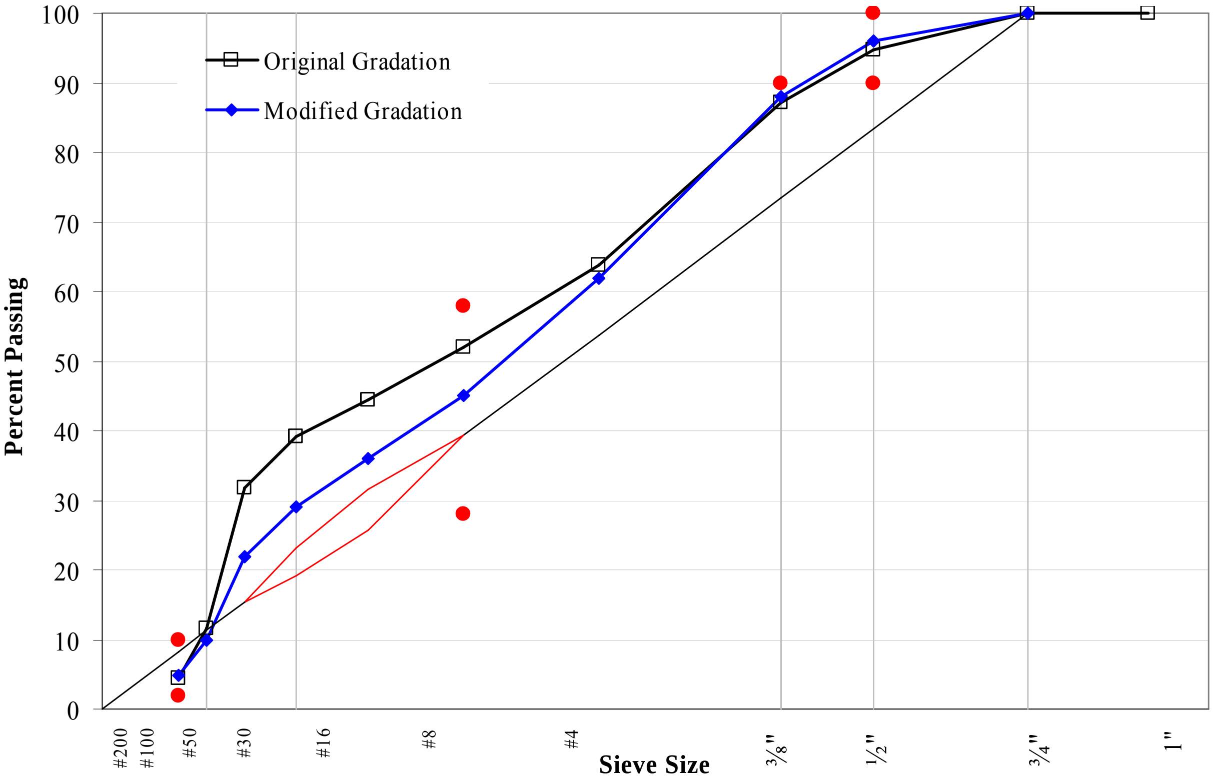


Figure 21. Modified Gradation

There are interesting things about the volumetric properties of the mixture using the modified gradation. Due to denser gradation than the original gradation, the optimum asphalt content was lower (i.e., 4.9% versus 5.9%). In addition, it did not meet the VMA and VFA criteria for the Superpave specification (i.e., VMA = 10.8%: minimum 14.0% , VFA = 62.9%:

65.0 ~ 75.0%). However, the research done by the University of Florida (Roque et al. 2006) found that mixtures with lower VMA can also have good performance depending upon their gradation characteristics. In addition, Kandhal and Cooley (2002) found that mixtures, which failed Superpave VMA criteria, showed better rutting performance in APA tests. Sholar et al. (2004) also recommended that the potential for a lower than specified VMA should be considered for situations where rutting performance is a high priority.

5.3 LABORATORY TESTING RESULTS

The modified 45% RAP mixture with the modified gradation was evaluated by the same tests; the APA test, the Servopac shear resistance test, and the Superpave IDT.

5.3.1 Recovered Binder Tests

As shown in Figures 22 and 23, the addition of RAP materials resulted in higher viscosity and G*/sinδ, which is a rutting factor in the Superpave binder specification, in general. This trend becomes clearer for the 35% and 45% RAP mixtures which were blended with the same virgin binder. The modified 45% RAP mixture, which has a different gradation, exhibited higher viscosity and G*/sinδ values because of the lower content of virgin binder and the effect of aggregate structure on binder aging (Roque et al. 2002, Villers 2004).

From Figure 24, G*sinδ, which represents asphalt binder's resistance to fatigue cracking in the Superpave binder specification, for the control, 25% RAP, and modified 45% RAP mixtures showed similar values. However, the 35% RAP mixtures had lower G*sinδ, since the lower PG grade (PG 58-28) was used for mixtures containing more than 30% RAP. Based on the binder recovery tests, the selection of PG grade for the virgin binder by NCHRP recommendation seems to be appropriate in terms of the binder properties in general.

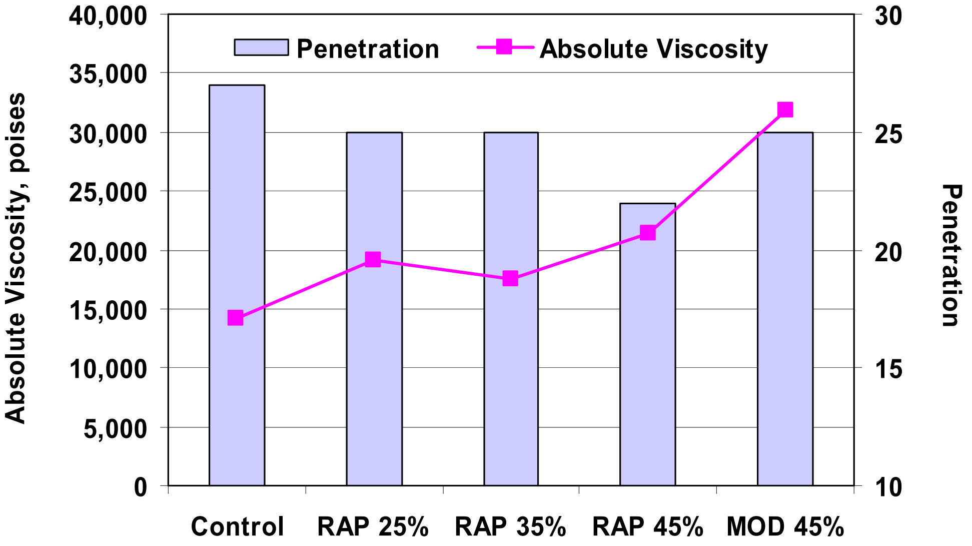


Figure 22. Results for Penetration and Viscosity

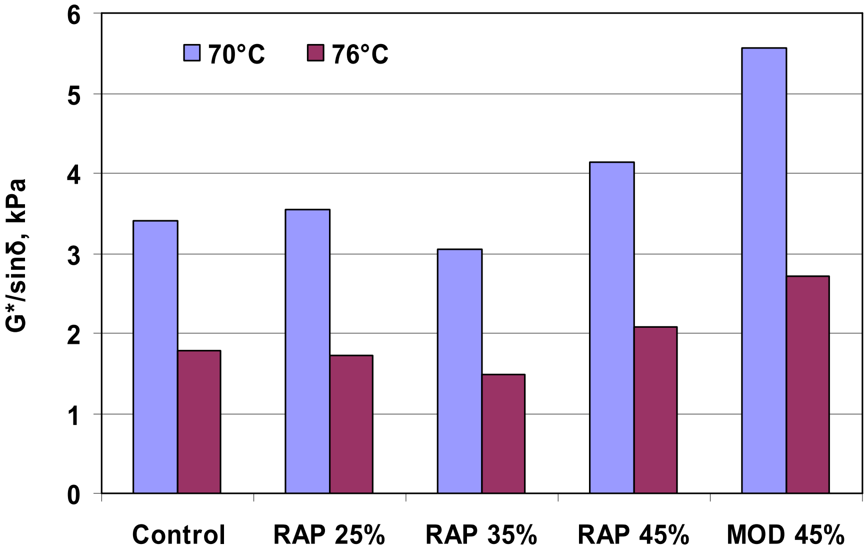


Figure 23. G*/sinδ from DSR

However, the virgin binder selected for the 35% RAP mixture seems to have lower value than expected. As mentioned before, although the 35% RAP mixture was blended with RA-1000 due

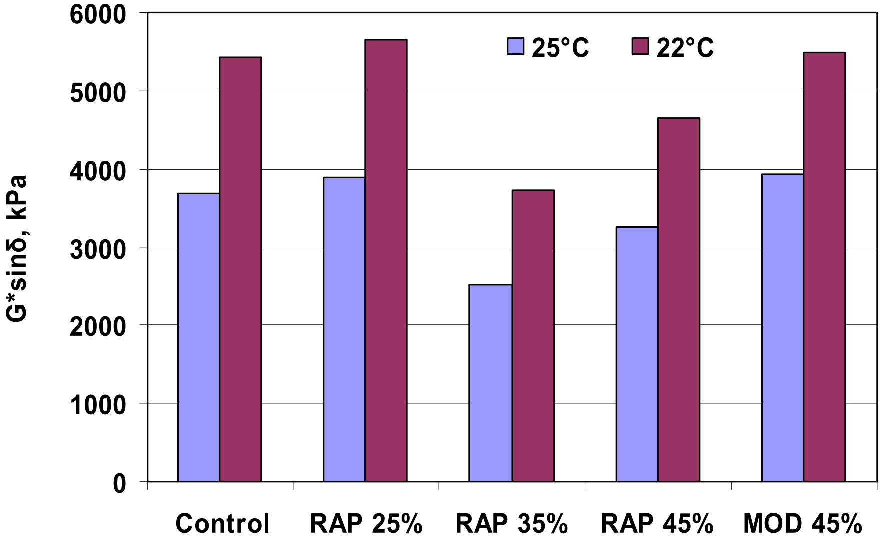


Figure 24. G*sinδ from DSR

to no availability of RA-2000 selected by FDOT specification, RA-1000 is also appropriate for the 35% RAP mixture in terms of the NCHRP recommendation. Therefore, the basic idea of the FDOT specification, which recommends using the viscosity to design, may be more appropriate than the NCHRP recommendation with respect to binder properties. However, since there are large variations in the viscosity of RAP materials, the determination of the viscosity of RAP should also be confirmed carefully.

5.3.2 APA Test

Figure 25 shows the results from the APA test with samples from the previous experimental stage. The rut depth of the modified 45% RAP mixture is distinctly lower than the others. The gradation seems to be the main contributor. However, to modify the gradation, there are other changes in materials:

- The percentage of local sand used was reduced from around 15% to 0%.
- The optimum asphalt content was reduced from 5.9% to 4.9%.

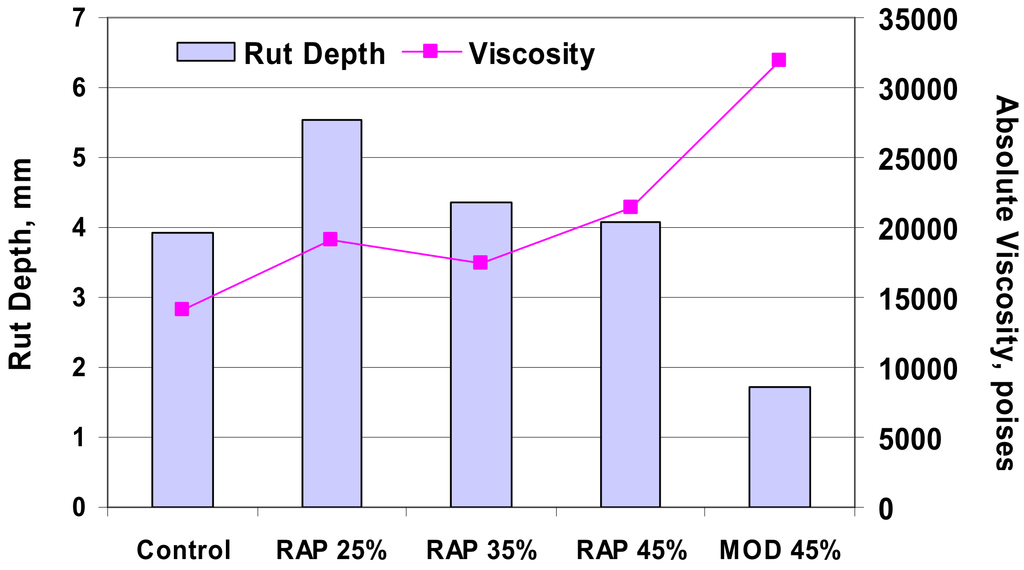


Figure 25. Rut Depth Result from APA Test

Gokhale and Sholar (2007) have shown the effect of sand content in the mixture on the APA rut depth. Note that their analysis was performed only on the mixtures containing 15% RAP. They suggested that the sand content in the mixture has a significant effect on the measured APA rut depth, with a higher percentage of sand resulting in a higher rut depth. An evaluation of the data showed that the average rut depth of mixtures with 10% sand is more than the average rut depth of mixtures with 0% sand, and this effect seemed to be more pronounced in the mixtures with unmodified binder. Therefore, the two changes mentioned above for the modified gradation may be helpful for better rutting performance.

In terms of the binder characteristics, the modified 45% RAP mixture appeared to have the highest viscosity. Although the 35%, 45%, and modified 45% RAP mixtures were mixed with the same virgin binder, they showed different viscosity results especially for the 45% versus the modified 45% RAP mixtures. Roque et al. (2002) investigated that binder aging was primarily related to the gradation regardless of other volumetric properties. However, using the same gradation, volumetric properties might have some effects on binder aging. Consequently, to increase the rut resistance, gradation may be the most important factor even with the high percentage of RAP mixtures which contain the lower grade of asphalt binder according to NCHRP study (McDaniel and Anderson 2001). In addition, as shown in Figure 26, the modified 45% RAP mixture showed the lowest coefficient of variance (COV) although addition of RAP materials exhibited higher COV in general. Nassar and Nassar (2006) also reported that the variability of RAP materials and mix properties was a major problem.

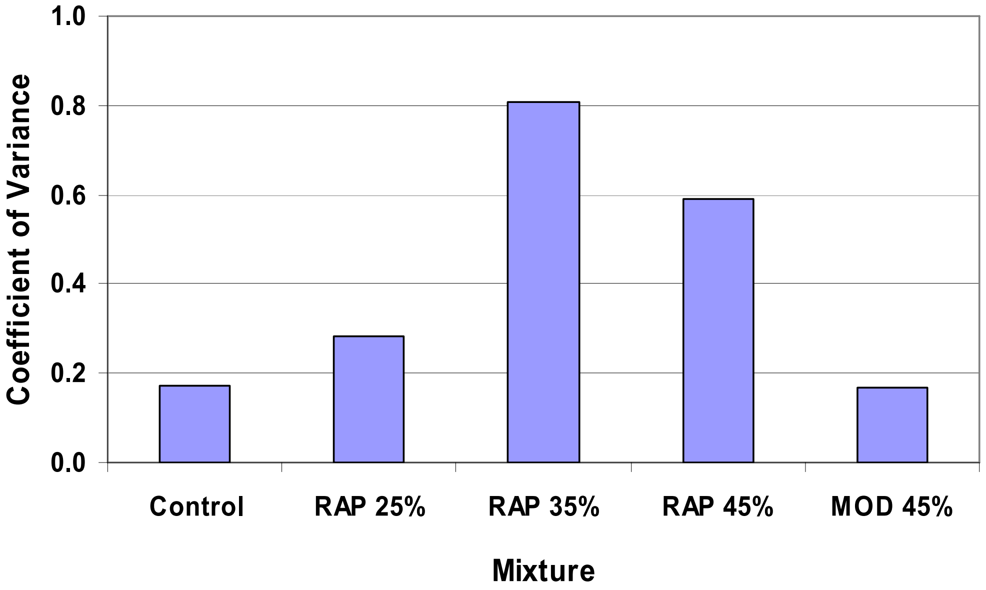


Figure 26. Coefficient of Variance for Rut Depth Results from APA Test

5.3.3 Servopac Gyratory Shear Test

Servopac gyratory shear test results are shown in Figure 27 including data from the previous experimental stage. Although the modified 45% RAP mixture did not perform well enough to be within the optimal range, it showed better shear resistance than the other mixtures.

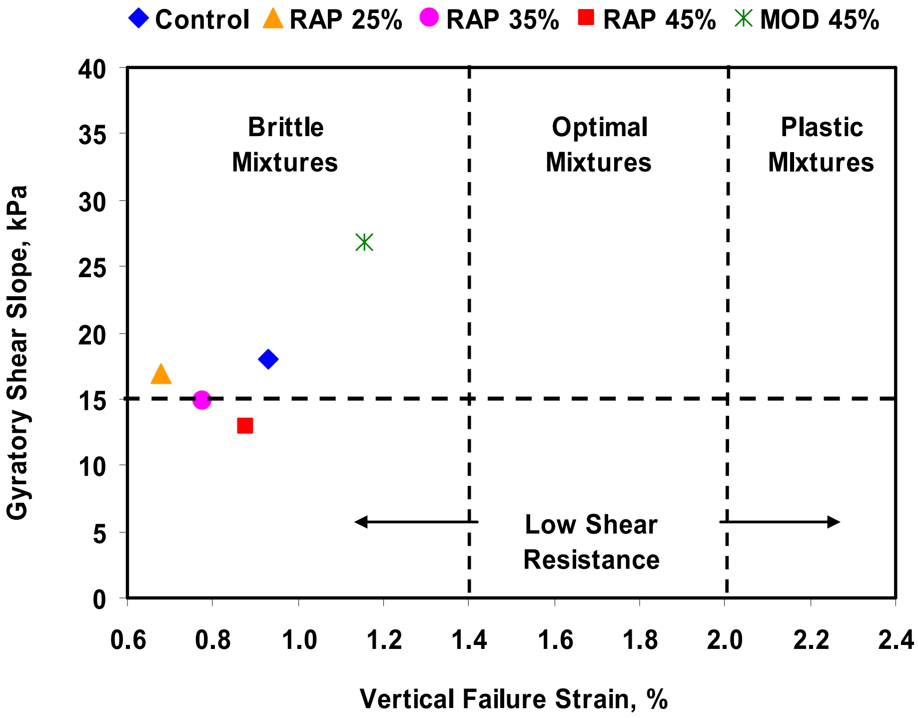


Figure 27. Servopac Test Results

Figure 28 presents the relationship between the vertical failure strain from the Servopac gyratory shear test and the rut depth from the APA test. Therefore, the vertical failure strain confirmed the rutting performance from APA test (Roque et al. 2006).

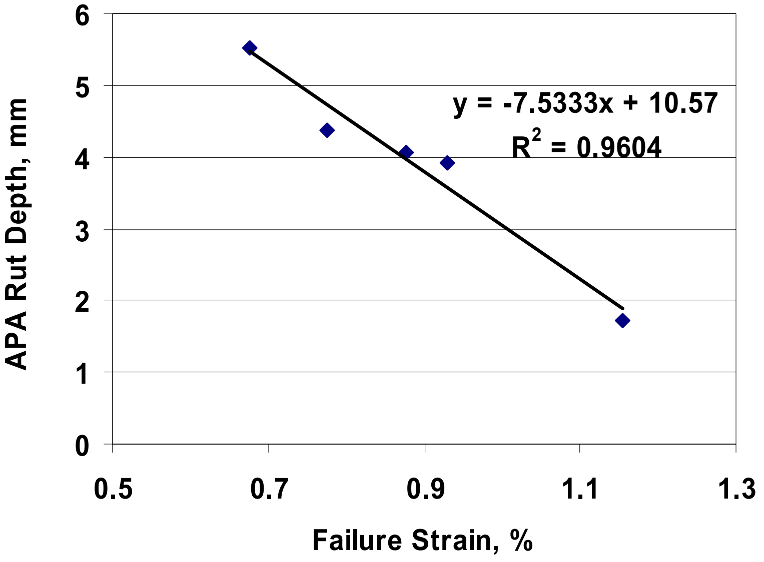


Figure 28. Relationship Between Vertical Failure Strain and APA Rut Depth

5.3.4 Superpave IDT Test

Although it cannot be explained by a single factor, in general, the tensile strength increased as the dust content increased and/or AC decreased (Villiers 2004). In contrast, Figure 29 shows that the tensile strengths for the control and 25% RAP mixtures were slightly more than the ones for 35% and 45% RAP mixtures. The 35% and 45% RAP mixtures (with AC contents in the range of 5.9 ~ 6.0%) have around 0.5% less asphalt content than the control and 25% RAP mixtures (6.5% AC). However, the modified 45% RAP mixture with 4.9% AC had a tensile strength closer to the control mixture than the 35% and 45% RAP mixtures. It appeared that the tensile strength was affected by the aggregate interlocking of the mixtures.

From Figure 30, addition of RAP materials to a mixture increased the resilient modulus. Sondag et al. (2002) also found the same result especially at high temperatures. Interestingly, the modified 45% RAP mixture showed the highest resilient modulus.

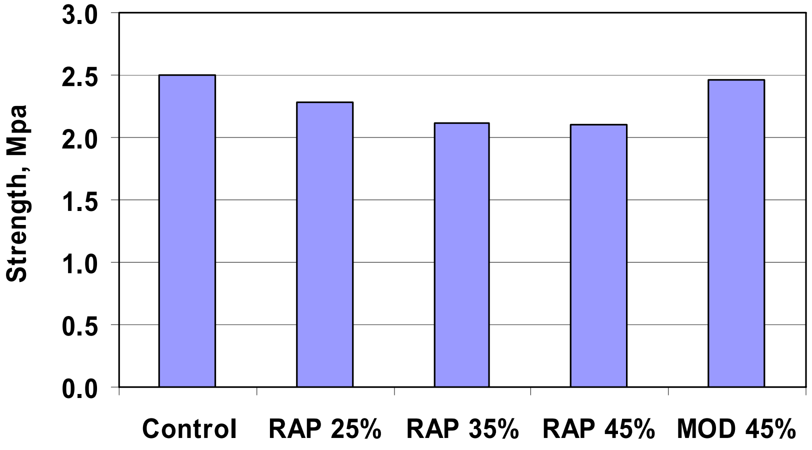


Figure 29. Tensile Strength from Superpave IDT Test

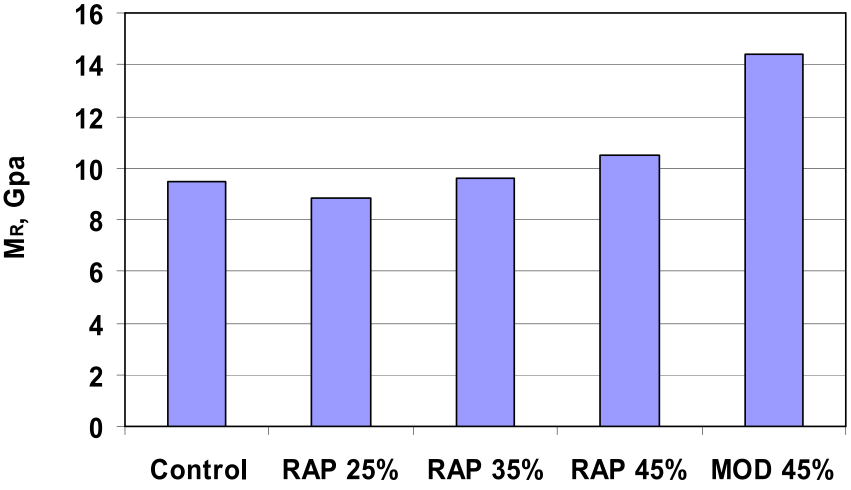


Figure 30. Resilient Modulus from Superpave IDT Test

From Figure 31, the FE of the modified 45% RAP mixture was the lowest. This might be the problem for this mixture, because the higher strength and lower FE result in a brittle mixture. From the original 45% RAP mixture and the modified 45% RAP mixture, more RAP induced the lower FE than the others. In addition, lower AC content in the modified 45% RAP mixture resulted in lower FE than the original 45% RAP mixture. The original 45% RAP mixture contained 0.6% less AC and the modified 45% RAP mixture contained 1.6% less AC than the control mixture. If a mixture with a good gradation uses a similar amount of AC to a mixture with a bad gradation, it would be expected to have a better FE (Roque et al. 2006).

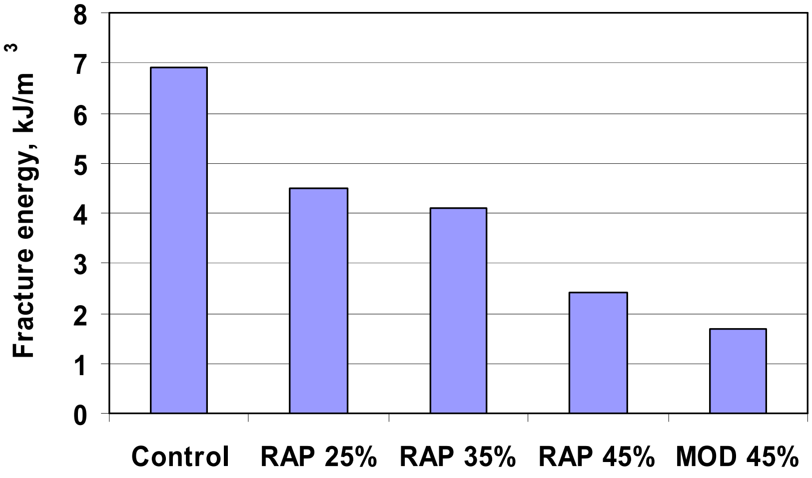


Figure 31. Fracture Energy from Superpave IDT Test

Figure 32 shows the creep compliance rate for all the mixtures tested. As expected by the APA results and the failure strain results from the Superpave IDT test in general, the modified 45% RAP mixture exhibited the lowest creep compliance rate. Compared even with the original 45% RAP mixture, the modified 45% RAP mixture showed much lower rate. Therefore, higher viscosity and lower AC content, combined with better gradation characteristics resulted in a lower creep compliance rate. The lower creep compliance rate results in the better ER in terms of the cracking resistance, if the same DCSE is applied.

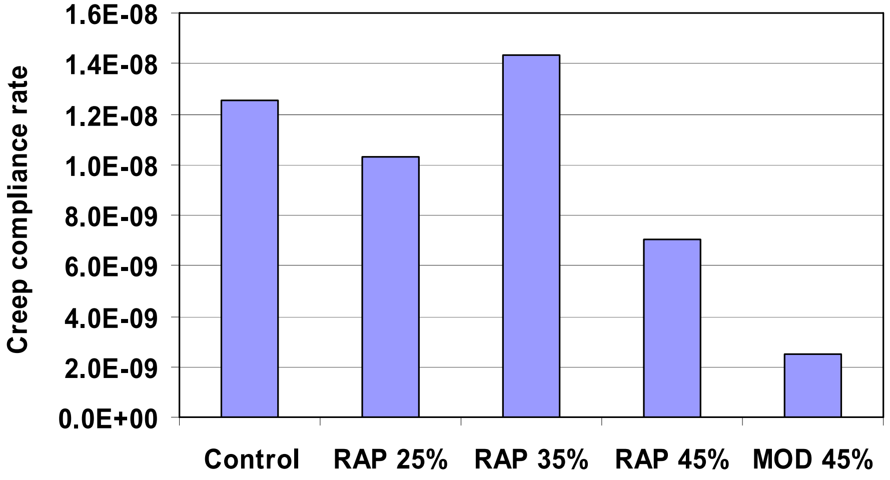


Figure 32. Creep Compliance Rate from Superpave IDT Test

The creep compliance also showed similar result as shown in Figure 33. Daniel and Lachance (2005) also reported that the 25% and 40% RAP mixtures did not follow the expected trend such that addition of RAP materials decrease in compliance is evident for the mixture containing 15% RAP. Their result indicated that the difference in gradation and volumetric properties between the mixtures was significantly affecting the materials properties.

From Figure 34, the ER for the modified 45% RAP mixture was higher than other mixtures with RAP materials, and slightly lower than the control mixture. These results indicate that a mixture with good gradation characteristics can perform better in terms of both cracking and rutting. However, reducing the FE and DCSE limits, even with better ER, may induce problems in terms of the critical loading, which exceeds the FE limit, and/or thermal-induced cracking. Tam et al. (1992) and Daniel and Lachance (2005) reported that mixtures with RAP are less resistance to thermal cracking.

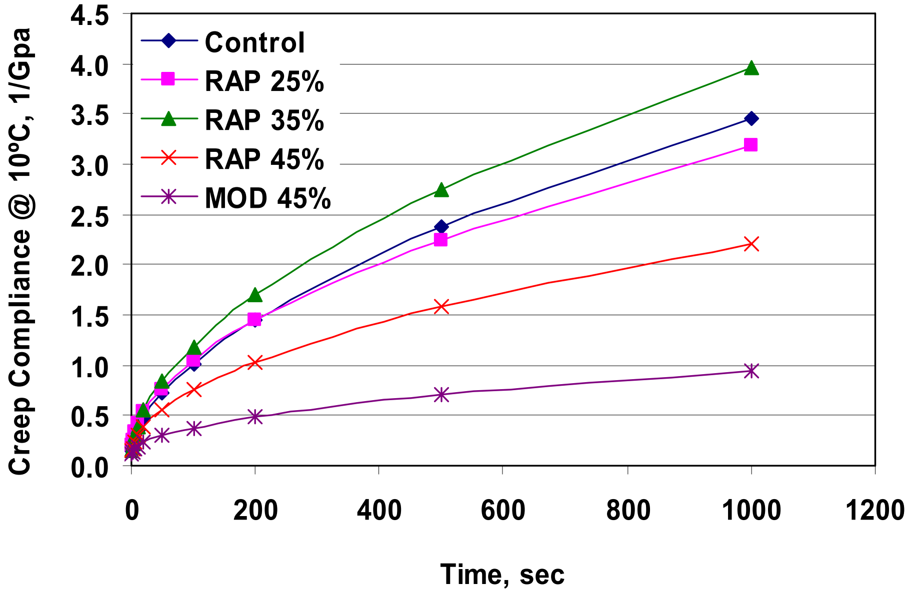


Figure 33. Creep Compliance from Superpave IDT Test

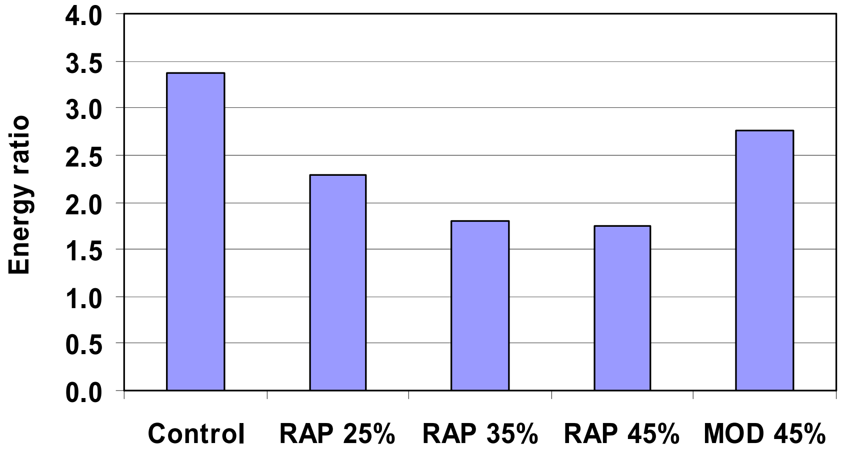


Figure 34. Energy Ratio from Superpave IDT Test

5.4 EFFECT OF FILM THICKNESS

Recently, Heitzman (2006) recommended using two procedures to calculate film thickness; the index model and the virtual model. The former was based on the mixture volumetric properties on a 2-D surface to calculate the surface area. In addition, it also included the surface area and volume factors to consider different particle shapes. The latter was adopted as the virtual model by Heitzman (2006) because it counts for 3-D model. To cover 3-D aggregates having the same surface area, asphalt content should be more than for 2-D aggregates. However, the virtual model doesn't count for particle shape. The virtual model was applied for mixtures already tested in this study.

Figure 35 shows the trends between Superpave IDT results and film thickness. Most of results from the Superpave IDT test, except for the resilient modulus, deceased as film thickness decreased overall. Since they have same gradation except for the modified 45% RAP, film thickness directly related to AC content. Therefore, in general, film thickness decreased as AC content decreased. However, strength and ER for the modified 45% RAP didn't decrease and showed higher values than expected by the trend because of a better aggregate structure.

Figure 36 presents that the relationships between Superpave IDT results and film thickness. In general, the relationships are good. As mentioned above, however, the relationship between film thickness, and strength and ER was better when excluding the modified 45% RAP mixture due to the gradation effect.

5.5 SUMMARY

From the first stage of this research study, the higher percentage of RAP mixture with the lower high PG grade binder showed a similar rut-depth with the control mixture, although it had a higher viscosity for the aged binder. In addition, the ER for the RAP mixture was half of that of the control mixture.

Based on the DASR porosity and the percentage of the coarse aggregates analyses, the

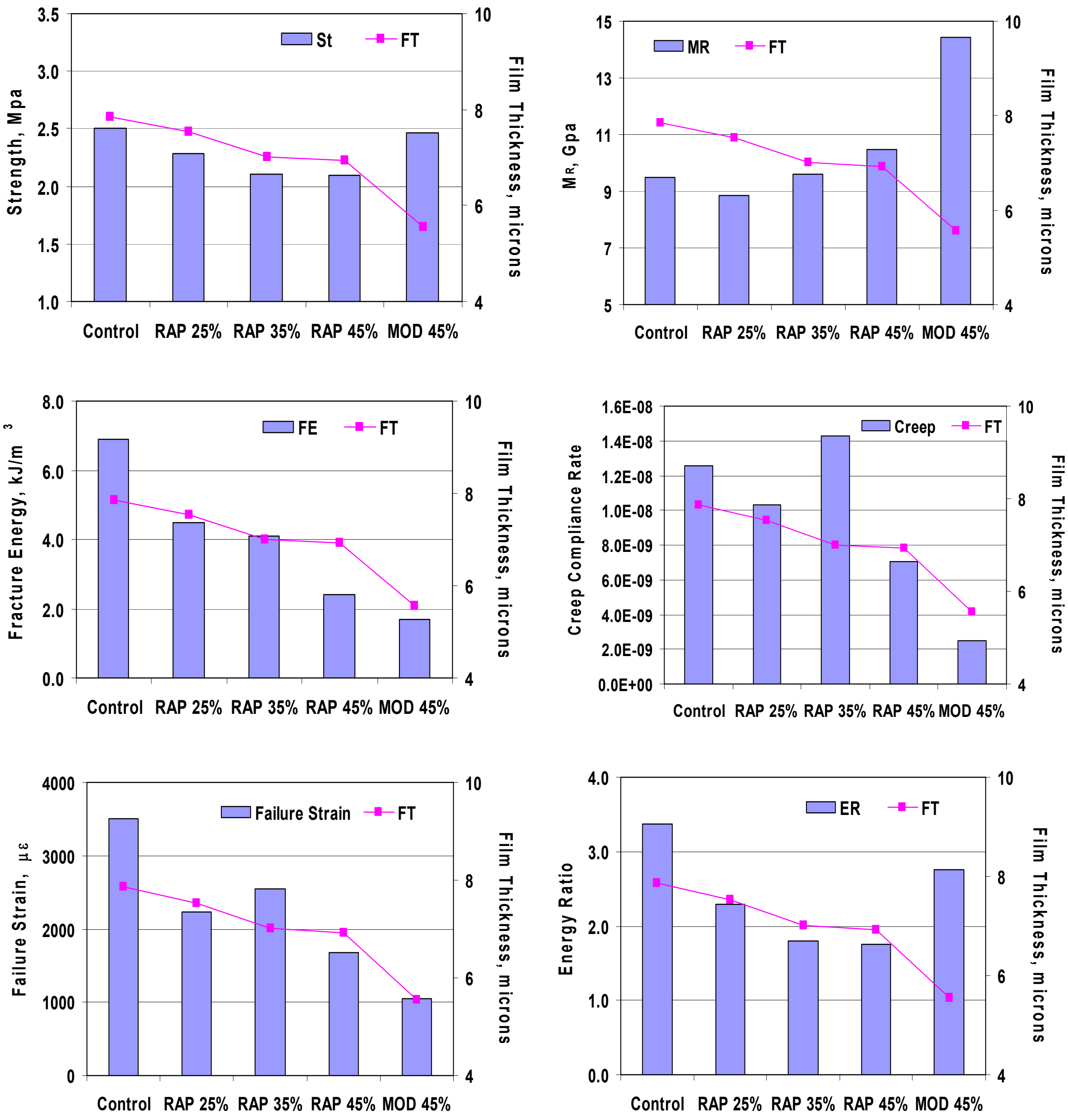


Figure 35. Comparison between Superpave IDT Results and Film Thickness

gradation had poor characteristics, especially for rutting performance. Therefore, the modified gradation was designed to provide better aggregate interlock. Note that the modified gradation mixture had less local sand and a reduced binder content than the unmodified gradation mixture.

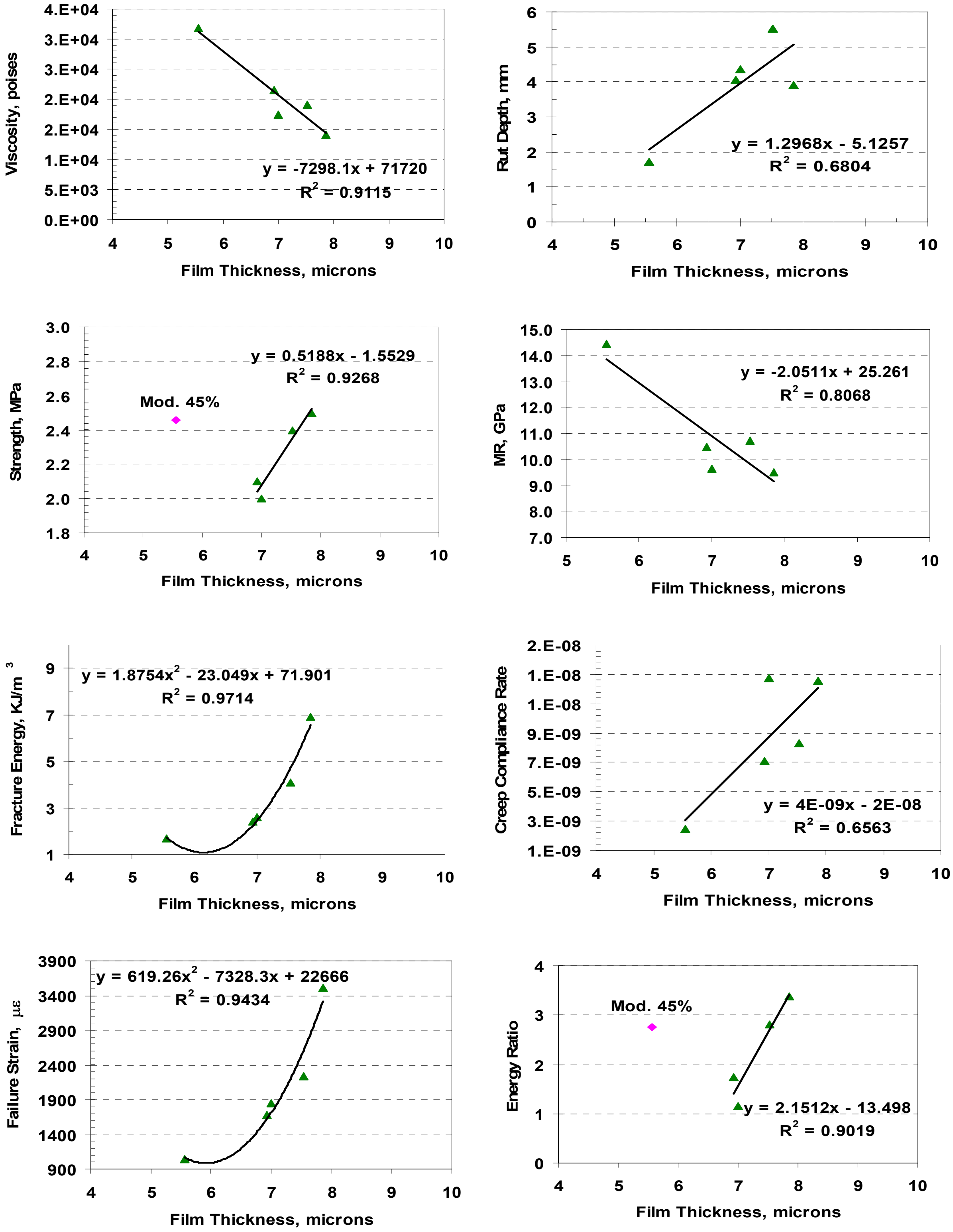


Figure 36. Relationship between Superpave IDT Results and Film Thickness

From the APA and Servopac gyratory shear tests, the modified gradation with 45% RAP showed distinctively better resistance to rutting with consistency. From the Superpave IDT tests, the modified 45% RAP mixture exhibited the lowest creep compliance rate and FE. The ER results indicated that the modified gradation mixture had slightly worse performance than the control mixture, but better than the other mixtures containing RAP materials. However, reduced FE and DCSE limits, even with better ER, may result in problems in terms of the higher impact loading and/or temperature-induced cracking. There are also relationship between test results and the film thickness.

Finally, even if the higher percentage of RAP materials is used, the mixture can perform as well as the control mixture by having a good aggregate structure with a lower high temperature PG grade binder resulting in a reduced binder effect based on this laboratory evaluation.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 SUMMARY

Mixtures with various contents of RAP materials were tested using the APA, Servopac gyratory shear compactor, and Superpave IDT test. The control mixture, with 0% RAP material, was blended with PG 67-22 virgin asphalt binder. RAP mixtures were fabricated containing different amounts of RAP materials in the following percentages: 25%, 35%, and 45% by the weight of aggregates. According to a recent NCHRP recommendation and current FDOT specification requirements, the 25% RAP mixture was blended with a PG 64-22 binder, whereas, the 35% and 45% RAP mixtures, and the modified 45% RAP mixture were blended with RA-1000.

For the first stage of this research study, four different mixtures with varying percentages of RAP were designed: 0%, 25%, 35%, and 45%. The APA rutting test and the Servopac gyratory shear test were used to evaluate the rutting performance, and the Superpave IDT test was used to assess the cracking performance.

Generally, the higher percentage RAP mixture showed better rut-resistance with higher binder viscosity. However, all RAP mixtures exhibited similar or a little more rut depth than the control mixture in the asphalt pavement analyzer (APA) test due to the stiffer virgin binder used in the control mixture. For the cracking resistance, although the more RAP materials may reduce the creep compliance rate, the FE and ER decreased as the percentage of RAP increased in mixtures. In addition, the ER of the 45% RAP mixture was about half of the value for the control mixture.

The gradation effect was investigated to improve the performance of the RAP mixture after the first stage. Since the gradation appeared to have poor characteristics, especially for rutting performance, the DASR porosity and the percentage of the coarse aggregates analyses were conducted to modify the gradation to have better interlock within the aggregate structure.

From the APA and Servopac gyratory shear tests, the modified gradation with 45% RAP showed distinctively better resistance to rutting with consistency. From the Superpave IDT tests, the modified 45% RAP mixture exhibited the lowest creep compliance rate and FE. The ER was slightly less than the control mixture, but better than other RAP mixtures from the previous stage.

Therefore, the higher percentage of RAP mixture seems to reduce the cracking performance. In addition, using the higher percentage of RAP materials with NCHRP recommendations may not guarantee the rutting performance based on the laboratory evaluation. However, the performance of a mixture even with higher percentage of RAP materials and the lower high temperature PG grade binder can be improved by having good aggregate structures. The modified 45% RAP mixture showed better rutting performance, and slightly lower ER than the control mixture but higher than other RAP mixtures in terms of the cracking performance. This result may also be affected by the amount of sand and AC content.

6.2 CONCLUSIONS

From this comparative study for various amount of RAP materials included in Superpave mixtures, the following conclusions were derived from the findings of the first stage experiment:

- The viscosity of the aged binder increases as the amount of RAP materials increases in a mixture.

- The recommendation of the NCHRP study to select the proper PG grade of virgin binder for RAP mixtures is needed to be carefully taken. In addition, since the viscosity of RAP materials is widely varied even for the same source, the determination of the viscosity of RAP should also be confirmed carefully.

- Generally, the rut depth decreases as the amount of RAP materials increases in a mixture. However, comparing with the control mixture, RAP mixtures showed more and/or similar rut depth due to using the lower high temperature PG grade virgin binder.

- The vertical failure strain from the Servopac gyratory shear test correlated well with the rut depth from the APA test.

- The ER decreases as the amount of RAP materials increase in a mixture by reducing the FE. Therefore, the cracking performance of the RAP mixture even with the softer binder decreases as the amount of RAP materials increase in a mixture.

- It is difficult to make a statement on how increasing RAP affects the performance because the influence of the amount of RAP on performance depended on the differences between the mixtures (i.e., binder grade, AC content, and aggregate structure)

From the further evaluation for the 45% RAP mixture with the modified gradation, the following conclusions were drawn:

- The modified 45% RAP mixture performed better than the other RAP mixtures in terms of the rutting and cracking performance.

- Although the amount of sand and AC may affect the rutting performance, the aggregate structure in a mixture seems to be dominant. The aggregate structure may also affect the mixture aging.

6.3 RECOMMENDATIONS

To have more definitive answers, the following can be issues for the further research:

- The relative performance for different amount of RAP mixtures with a better gradation (i.e., the modified gradation in this study).

- The improvement of the crack resistance (e.g., thermal induced) for higher percentage of RAP contained in a mixture with higher AC content (i.e., +0.5%) than the Superpave design.

- The test for the water damage and/or temperature effect due to lower FE, DCSE, and failure strain.
- The effect of different sources of RAP materials.

ACKNOWLEDGEMENT

The work reported herein was the result of a team effort. The authors would like to thank Shanna Johnson, Kenneth Green, and Chase Cochran for their assistance in the laboratory, and also David Webb Jr., Gale Page, Richard (Glenn) Roberts, and technicians in the asphalt bituminous lab for the valuable information and asphalt binder tests.

REFERENCES

AASHTO MP1-98, *Standard Specification for Performance Graded Asphalt Binder*, American Association of State Highway and Transportation Officials.

AASHTO MP1a-04, *Standard Specification for Performance Graded Asphalt Binder*, American Association of State Highway and Transportation Officials.

AASHTO PP42-03, *Standard Practice for Determination of Low Temperature Performance Grade (PG) of Asphalt Binders*, American Association of State Highway and Transportation Officials.

AASHTO T240-03, *Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)*, American Association of State Highway and Transportation Officials.

AASHTO T313-05, *Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)*, American Association of State Highway and Transportation Officials.

AASHTO T314-02, *Standard Method of Test for Determining the Fracture Properties of Asphalt Binder in Direct Tension (DT)*, American Association of State Highway and Transportation Officials.

AASHTO T315-05, *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*, American Association of State Highway and Transportation Officials.

AASHTO T322-03, *Standard Method of Test for Determining the Creep Compliance and Strength of Hot=Mix Asphalt (HMA) Using the Indirect Tensile Test Device*, American Association of State Highway and Transportation Officials.

AASHTO TP2-01, *Standard Test Method for the Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*, American Association of State Highway and Transportation Officials.

AASHTO TP62-03, *Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures*, American Association of State Highway and Transportation Officials.

ASTM D1856-95a (Reapproved 2003), *Standard Test Method for Recovery of Asphalt from Solution by Abson Method*, American Society for Testing and Materials, Philadelphia, PA.

ASTM D5404-03, *Standard Practice for Recovery of Asphalt Using the Rotavapor Apparatu*, American Society for Testing and Materials, Philadelphia, PA.

Antrim, J. D. and Busching, H. W. (1969) "Asphalt content determination by the ignition method." *Bituminous Materials and Mixes, Highway Research Record, No. 273*.

Asphalt Institute - National Asphalt Training Center II (1996), *Superpave Asphalt Mixture Analysis: Course Notebook*, Washington DC: Federal Highway Administration, Office of Technology Applications, May 1996.

Beam, J. L. and Maurer, D. (1991) "*Evaluation of Recycled Hot Mix Asphaltic Concrete in Pennsylvania.*" Pennsylvania Department of Transportation Research Project 82-05, February, 1991.

Birgisson, B., D. Darku, R. Roque, and G. Page. (2004) "The Need for Inducing Shear Instability to Obtain Relevant Parameters for HMA Rut-Resistance." *Journal of Association of Asphalt Paving Technologists*, Vol. 73, pp. 23-52.

Brown, E. R. and Mager, S. (1996) "Round-Robin Study of Asphalt-Concrete Content by Ignition." *Transportation Research Record 1543*, pp. 132-138.

Brownie, R. B. and Hironaka, M. C. (1979) *Recycling of Asphalt Concrete Airfield Pavement – A Laboratory Study*. Federal Aviation Administration Report FAA-RD-78-58, May, 1979.

Bukowski, J. R. (1997) "Guidelines for the Design of Superpave Mixtures Containing Reclaimed Asphalt Pavement (RAP)." Memorandum, ETG Meeting, FHWA Superpave Mixtures Expert Task Group, San Antonio, Texas, March, 1997.

Bullin, J. A., Davison, R. R., Glover, C. J., Chaffin, J., Liu, M., Madrid, R. (1997) *Development of Superior Asphalt Recycling Agents. Phase 1: Technical Feasibility.* Final Technical Progress Report, Department of Energy Report DE97006951, July, 1997.

Corbett, L. W. (1975) Industrial Engineering Chemistry Process Design and Development, Volume 13, pp. 181.

Cosentino, P.J. and Kalajian, E.H. (2001) *Developing Specifications for Using Recycled Asphalt Pavement as Base, Subbase or General Fill Materials.* Final report submitted Florida Department of Transportation.

Daniel, J. S. and Lachance A. (2005) “Mechanistic and Volumetric Properties of Asphalt Mixtures with RAP.” *Transportation Research Record,* Transportation Research Board, Washington D.C.

Davidson, D. D., Canessa, W., and Escobar, S. J. (1977) “Recycling of Substandard or Deteriorated Asphalt Pavements – A guideline for Procedures,” *Journal of the Association of Asphalt Paving Technologists*, Vol. 46.

Davis, B. (2000) “Asphalt Pavement Recycling Leader,” California Asphalt Magazine, May/June.

Decker, D. S. (1997) “State of the Practice for use of RAP in Hot Mix Asphalt,” *Journal of the Association of Asphalt Paving Technologists*, Vol. 66, pp. 704.

Dunning, R. L. and Mendenhall, R. L. (1978) “Design of Recycled Asphalt Pavements and Selection of Modifiers.” *Recycling of Bituminous Pavements, ASTM STP 662*, Ed. L.E. Wood, American Society for Testing and Materials, Philadelphia, PA, pp. 35.

Epps, J. A., Little, D. N., O’Neal, R. J., and Gallaway, B. M. (1978) “Mixture Properties of Recycled Central Plant Materials.” *Recycling of Bituminous Pavements, ASTM STP 662,* L. E. Wood, Ed., American Society for Testing and Materials, Philadelphia, PA, pp. 68-103.

Gokhale, S., Choubane, B., Sholar, G., and Moseley, H. (2006) “Evaluation of Coarse and Fine Graded Superpave Mixtures Under Accelerated Pavement Testing.” FDOT/SMO/06-494, Florida DOT.

Gokhale, S. and Sholar, G. (2007) “Analysis of APA Rut Data for Production Laboratory Mix Design Pills With and Without Polymer Modified Binder.” FDOT/SMO/07-501, Florida DOT.

Sholar, G., Page, G., Musselman, J., and Moseley, H. (2004) “Evaluating the Use of Lower VMA Requirements for Superpave Mixtures.” FDOT/SMO/04-479, Florida DOT.

Hand A. J. and Epps, A. L. (2001) “Impact of Gradation Relative to Superpave Restricted Zone on Hot-Mix Asphalt Performance.” *Transportation Research Record No. 1767,* Transportation Research Board, Washington D.C., pp. 158-165.

Hand, A., Stiady, J., White, T., Noureldin, A. and Khaled, G. (2001) “Gradation Effects on Hot-mix Asphalt Performance.” *Transportation Research Record No. 1767,* Transportation Research Board, Washington D.C., pp. 152-157.

Heitzman, M. (2006) “New Approaches for Computing Film Thickness.” *Journal of Association of Asphalt Paving Technologists*, Vol. 75.

Kandhal P. S. and Cooley, L. A. (2002) “Coarse Versus Fine-Graded Superpave Mixtures: Comparative Evaluation of Resistance to Rutting.” NCAT Report 02-02, National Center for Asphalt Technology, Auburn University.

Kandhal, P. S. and Foo, K. Y. (1997) “Designing Recycled Hot Mix Asphalt Mixtures Using Superpave Technology.” *Progress of Superpave (Superior Performing Asphalt Pavements): Evaluation and Implementation, ASTM STP 1322*, R. N. Jester, Ed., American Society for Testing and Materials.

Kandhal, P. S. and Rajib, M. (2001) Effect of Mix Gradation on Rutting Potential of Dense-Graded Asphalt Mixtures. *Transportation Research Record No. 1767,* Transportation Research Board, Washington D.C., pp. 146-151.

Kandhal, P. S., Rao, S. S., Watson, D. E., and Young, B. (1995) “Performance of Recycled Hot-Mix Asphalt in Georgia.” *Transportation Research Record 1507*, Transportation Research Board, Washington D.C., pp. 67-77.

Kennedy, T. W., Tam, W. O. and Solaimanian, M. (1998) *Effect of Reclaimed Asphalt Pavement on Binder Properties Using the Superpave System*. Research Report 1205-1, Center for Transportation Research, Bureau of Engineering Research, The University of Texas at Austin.

Kim, J., Sholar, G., and Moseley, H. (2006-a) “Evaluation of Segregateion for Top-Down Cracking and Rutting Performance and Detecting Low-Performance Segregated Mixtures.” FDOT/SMO/06-500, Florida DOT.

Kim, S., Roque, R., Birgisson, B. and Guarin, A. (2006-b) “Identification and Assessment of The Dominant Aggregate Size Range (DASR) of Asphalt Mixture.” *Journal of the Association of Asphalt Paving Technologists*, In press.

Lee, K. W., Soupharath, N., Shukla, N., Franco, C.A. and Manning, F.J. (1999) “Rheological and Mechanical Properties of Blended Asphalt Containing Recycled Asphalt Pavement Binders.” *Journal of the Association of Asphalt Paving Technologists*, Volume 68, pp. 89-125.

Li, X., Clyne, T. R. And Marasteanu, M. O. (2003) “Recycled Asphalt Pavement (RAP) Effects on Binder and Mixture Quality.” Final Report MN/RC-2005-02, University of Minnesota.

McDaniel, R. and Anderson, R. M. (2001) *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician’s Manual.* National Cooperative Highway Research Program (NCHRP) Report 452.

McDaniel, R., S. Soleymani, H. and Shah, A. (2002) "Use of Reclaimed Asphalt Pavement (RAP) Under Superpave Specifications." *A Regional Pooled Fund Project SPR-2143*, FHWA/IN/JTRP-2002/6, Purdue University.

Nassar, K. and Nassar, W. (2006) "Reclaimed Asphalt Pavement Detection and Quantity Determination." *Practice Periodical on Structural Design and Construction*, ASCE, pp. 171-176.

Paul, H. R. (1996) "Evaluation of Recycled Projects for Performance." *Journal of the Association of Asphalt Paving Technologists*, Volume 65, pp. 231.

Peterson, G. D., Davison, R. R., Glover, C. J. and Bullin, J. A. (1994) "The Effects of Composition on Asphalt Recycling Agent Performance." *Transportation Research Record 1436*, pp. 38-46.

Petersen, J. C. (1984) "Chemical Composition of Asphalt as Related to Asphalt Durability: State of the Art." *Transportation Research Record 999*, pp. 13-30.

Peterson, R.L., Soleymani, H.R., Anderson, R.M., and McDaniel, R.S. (2000) "Recovery and Testing of RAP Binders from Recycled Asphalt Pavements." *Journal of the Association of Asphalt Paving Technologists*, Vol. 69, pp.72-91.

Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D-Y. and Kennedy, T. W. (1996) *Hot Mix Asphalt Materials, Mixture Design, and Construction*. NAPA Research and Education Foundation, Second Edition.

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. 229-255.

Roque, R., Birgisson, B., Tia, M. and Nukunya, B. (2002) "Evaluation of Superpave Criteria for VMA and Fine Aggregate Angularity: Volume 1 VMA." Final Report, FDOT BB-498, University of Florida.

Roque, R., Buttlar, W., Ruth, B. E., Tia, M., and Dickison, S. W. (1997) "*Evaluation of SHRP Indirect Tension Tester to Mitigate Cracking in Asphalt Concrete Pavements and Overlays.*" Final Report, FDOT B-9885, University of Florida.

Roque, R., Kim, S., and Guarin, A. (2006) "Mixture to Evaluate Gradations for Investigations in the Accelerated Pavement Testing Facility." Final Report, Proj. No. 00056261, University of Florida.

Smith, L. L. (1996) “Wasting No Time – Florida’s History of Successfully Recycling for Transportation.” *TR News* No. 184: 4-7.

Solaimanian, M. and Tahmoressi, M. (1996) “Variability Analysis of Hot-Mix Asphalt Concrete Containing High Percentages of Reclaimed Asphalt Pavement.” *Transportation Research Record 1543*, pp. 88-96.

Sondag, M., Chadbourn, B. A., and Drescher, A. (2002) I*nvestigation of Recycled Asphalt Pavement (RAP).* Mixtures. Minnesota Department of Transportation Research Report MN/RC – 2002-15.

Soupharath, N. (1998) *Evaluation of Rutting Resistance Characteristics of Asphalt Binder Containing Recycled Asphalt Pavement.* Department of Civil & Environmental Engineering, University of Rhode Island.

Stroup-Gardiner, M. and Wagner, C. (1999) “Use of RAP in Superpave HMA Applications.” *Transportation Research Record 1681*, pp. 1-9.

Tam, K. K., Joseph, P. and Lynch, D. F. (1992) “Five-Year Experience of Low-Temperature Performance of Recycled Hot Mix.” *Transportation Research Record 1362*, pp. 56-65.

Terrel, R. L. and Epps, J. A. (1989) “Using Additives and Modifiers in Hot Mix Asphalt,” *National Asphalt Pavement Association, Quality Improvement Series* QIP 114 A.

Vavrik, W. R., Pine, W. J., Huber, G. and Carpenter, S. H. (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*, 70, 132-175.

Vavrik, W. R., Huber, G., Pine, W. J., Carpenter, S. H., and Bailey, R. (2002). “Bailey Method for Gradation Selection in HMA Mixture Design.” *Transportation Research Circular*, E-C044, Washington, D.C.

Villiers, C. (2004) “Evaluation of Sensitivity of Superpave Mixtures for Development of Performance Related Specifications.” Ph.D. Dissertation, University of Florida.

Yu, L. (1992) *Determination of Asphalt Content and Aggregate Gradation of HMA by Ignition Heating.* Master Thesis, Auburn University, AL.

Zhang, W. (1996) *Determination of Asphalt Concrete by Ignition Method.* Minnesota Department of Transportation Research Report 96-30.

Zhang, W., Drescher, A., and newcomb, D.E. (1997) “Viscoelastic Behavior of Asphalt Concrete in Diametric Compression.” *ASCE, Journal of Transportation Engineering*, Vol. 123, No. 6, November/December, pp. 495-502.

Zhang, Z., Roque, R., and Birgisson, B. (2001a) “Evaluation of Laboratory-Measured Crack Growth Rate for Asphalt Mixtures.” *Transportation Research Record 1767*, pp. 67-75.

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

.

APPENDIX A

JMF AND BATCH SHEET

A.1 Control Mixture (0% RAP)

	Type of Material	FDOT Code	Producer	Pit
1.	S-1-A	42	Rinker	87-090
2.	S-1-B	52	Rinker	87-090
3.	Screenings	21	Rinker	87-090
4.	Local Sand		P & S Paving	
5.	Crushed Screens		Rinker	87-090

		Percent Passing						
Blend		11%	36%	31%	15%	7%		100%
Number		1	2	3	4	5	6	JMF
Sieve Size	3/4"	100	100	100	100	100		100
	1/2"	51	100	100	100	100		95
	3/8"	23	88	100	100	100		87
	# 4	4	29	100	100	100		64
	# 8	3	5	92	100	100		53
	# 16	2	2	69	100	100		44
	# 30	2	2	49	99	100		38
	# 50	2	1	31	91	99		31
	# 100	2	1	9	23	70		12
	# 200	1.5	1.0	2.2	1.7	38.0		4.1

Batch Sheet for 0% RAP Mix

Stone	S-1-A	S-1-B	Screenings	Local Sand	Crushed Screens
Pit	87-090	87-090	87-090		
Code	42	52	21		
Percentage	11%	36%	31%	15%	7%
3/4"					
1/2"	232				
3/8"	364	550			
# 4	640	1554			
# 8	1559	1930	2037		
-8	2051	2129	3356	4001	4302

Aggregate Batch Weight	4302.0
% AC	AC Wt. (g)
6.5	299.1

RAP Study (0% RAP)

SGC Pills, Ndes = 75

6.5 % AC

299.1 g of AC

A.2 25% RAP Mixture

	Type of Material	FDOT Code	Producer	Pit	Terminal
1.	Coarse RAP		P & S Paving	A0721	
2.	Fine RAP		P & S Paving	A0721	
3.	S-1-A	42	Rinker	87-090	
4.	S-1-B	52	Rinker	87-090	
5.	Screenings	21	Rinker	87-090	
6.	Local Sand		P & S Paving		
7	Crushed Screen		Rinker	87-090	

		Percent Passing							
Blend		9.9%	15.1%	9.5%	27.9%	18.3%	17.9%	1.4%	100.0%
Number		1	2	3	4	5	6	7	JMF
Sieve Size	3/4"	100	100	100	100	100	100	100	100.0
	1/2"	94	100	51	100	100	100	100	94.8
	3/8"	78	100	23	88	100	100	100	87.2
	# 4	37	93	4	29	100	100	100	63.8
	# 8	31	74	3	5	92	100	100	52.1
	# 16	27	61	2	2	69	100	100	44.6
	# 30	24	52	2	2	49	99	100	39.1
	# 50	19	41	2	1	31	91	99	31.9
	# 100	10	19	2	1	9	23	70	11.1
	# 200	5.6	9.6	1.5	1.0	2.2	1.7	38.0	3.7

Batch Sheet for 25% RAP Mix

Stone	Coarse RAP	Fine RAP	S-1-A	S-1-B	Screenings	Local Sand	Crushed Screen
Pit	A0721	A0721	87-090	87-090	87-090		
Code			42	52	21		0
Percentage	9.9%	15.1%	9.5%	27.9%	18.3%	17.9%	1.4%
3/4"							
1/2"	53		250				
3/8"	393		506	648			
# 4	860	952	1028	1728			
# 8	1740	1924	1928	2213	2275		
-8	2291	2690	2702	2761	3476	4236	4296

Aggregate Batch Weight	4248.0	
Total Weight (agg.+ RAP AC)	4296	RAP Study (25% RAP)
% AC	AC Wt. (g)	SGC Pills, Ndes = 75
PG 64-22		
6.5	247.4	6.5 % AC

A.3 35% RAP Mixture

	Type of Material	FDOT Code	Producer	Pit	Terminal
1.	Coarse RAP		P & S Paving	A0721	
2.	Fine RAP		P & S Paving	A0721	
3.	S-1-A	42	Rinker	87-090	
4.	S-1-B	52	Rinker	87-090	
5.	Screenings	21	Rinker	87-090	
6.	Local Sand		P & S Paving		
7	Crushed Screen		Rinker	87-090	

		Percent Passing							
Blend		15.0%	20.0%	8.7%	24.0%	15.1%	16.5%	0.7%	100.0%
Number		1	2	3	4	5	6	3	JMF
Sieve Size	3/4"	100	100	100	100	100	100	100	100.0
	1/2"	94	100	51	100	100	100	100	94.8
	3/8"	78	100	23	88	100	100	100	87.1
	# 4	37	93	4	29	100	100	100	63.8
	# 8	31	74	3	5	92	100	100	52.0
	# 16	27	61	2	2	69	100	100	44.5
	# 30	24	52	2	2	49	99	100	39.1
	# 50	19	41	2	1	31	91	99	31.9
	# 100	10	19	2	1	9	23	70	11.4
	# 200	5.6	9.6	1.5	1.0	2.2	1.7	38.0	4.0

Batch Sheet for 35% RAP Mix

Stone	Coarse RAP	Fine RAP	S-1-A	S-1-B	Screenings	Local Sand	Crushed Screen
Pit	A0721	A0721	87-090	87-090	87-090		
Code			42	52	21		
Percentage	15%	20%	9%	24%	15%	17%	0.7%
3/4"							
1/2"	79		260				
3/8"	475		578	700			
# 4	1019	1140	1210	1808			
# 8	1826	2070	2073	2317	2368		
-8	2392	2918	2929	2979	3567	4264	4294

Aggregate Batch Weight	4228.0	
Total Weight (agg.+ RAP AC)	4294	RAP Study (35% RAP)
% AC	AC Wt. (g)	SGC Pills, Ndes = 75
RA-1000		
6.0	204.0	6.0 % AC
		204.0 g of AC

A.4 45% RAP Mixture

	Type of Material	FDOT Code	Producer	Pit
1.	Coarse RAP		P & S Paving	A0721
2.	Fine RAP		P & S Paving	A0721
3.	S-1-A	42	Rinker	87-090
4.	S-1-B	52	Rinker	87-090
5.	Screenings	21	Rinker	87-090
6.	Local Sand		P & S Paving	

Percent Passing								
Blend		20%	25%	8%	20%	12%	15%	100%
Number		1	2	3	4	5	6	JMF
Sieve Size	3/4"	100	100	100	100	100	100	100
	1/2"	94	100	51	100	100	100	95
	3/8"	78	100	23	88	100	100	87
	# 4	37	93	4	29	100	100	64
	# 8	31	74	3	5	92	100	52
	# 16	27	61	2	2	69	100	44
	# 30	24	52	2	2	49	99	39
	# 50	19	41	2	1	31	91	32
	# 100	10	19	2	1	9	23	12
	# 200	5.6	9.6	1.5	1.0	2.2	1.7	4.4

Batch Sheet for 45% RAP Mix

Stone	Coarse RAP	Fine RAP	S-1-A	S-1-B	Screenings	Local Sand
Pit	A0721	A0721	87-090	87-090	87-090	
Code			42	52	21	
Percentage	20%	25%	8%	20%	12%	15%
3/4"						
1/2"	106		272			
3/8"	558		653	754		
# 4	1180	1331	1395	1893		
# 8	1917	2221	2225	2428	2468	
-8	2500	3157	3167	3209	3675	4309

Aggregate Batch Weight	4225.0
Total Weight (agg.+ RAP AC)	4309
% AC	AC Wt. (g)
5.9	180.8

RAP Study (45% RAP)

SGC Pills, Ndes = 75

5.9 % AC

180.8 g of AC

A.5 Modified 45% RAP Mixture

	Type of Material	FDOT Code	Producer	Pit
1.	Coarse RAP		P & S Paving	A0721
2.	Fine RAP		P & S Paving	A0721
3.	S-1-A	42	Rinker	87-090
4.	S-1-B	52	Rinker	87-090
5.	Screenings	21	Rinker	87-090

Percent Passing								
Blend		5.6%	39.4%	8.1%	33.6%	13.3%		100.0%
Number		1	2	3	4	5	6	JMF
Sieve Size	3/4"	100	100	100	100	100		100
	1/2"	94	100	51	100	100		96
	3/8"	78	100	23	88	100		88
	# 4	37	93	4	29	100		62
	# 8	31	74	3	5	92		45
	# 16	27	61	2	2	69		36
	# 30	24	52	2	2	49		29
	# 50	19	41	2	1	31		22
	# 100	10	19	2	1	9		10
	# 200	5.6	9.6	1.5	1.0	2.2		4.8

Batch Sheet for MOD 45% RAP Mix

Stone	Coarse RAP	Fine RAP	S-1-A	S-1-B	Screenings	0
Pit	A0721	A0721	87-090	87-090	87-090	
Code			42	52	21	
Percentage	6%	39%	8%	34%	13%	0%

3/4"						
1/2"	31		205			
3/8"	289		389	566		
# 4	690	937	1005	1877		
# 8	1884	2383	2386	2741	2788	
-8	2797	3874	3885	3959	4497	

Aggregate Batch Weight	4398.0
Total Weight (agg.+ RAP AC)	4497
% AC	AC Wt. (g)
4.9	127.4

RAP Study (MOD 45% RAP)

SGC Pills, Ndes = 75

4.9 % AC

127.4 g of AC

APPENDIX B

BINDER TEST RESULTS

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

Performance Grade Binder Grading Report

(0107-AC139)

Project	RAP Study; recovered (**Coarse RAP**)			Date Received	2-7-07
Submitted By	Bit Research – SJ			Date Tests Completed	2-9-07
Lab Number	11055LB	Tested By:	Filer	Date Reported	2-26-07

Requested tests are: complete Reflux, Penetration, and Absolute Viscosity.

Test	**Test Temp.**	**Test Result**	**P / F**	**Florida Specification**
Penetration	77°F	11	n/a	n/a
Absolute Viscosity, poises	140°F	149,577	n/a	n/a

Note:

Project	RAP Study; recovered (**Fine RAP**)			Date Received	2-7-07
Submitted By	Bit Research – SJ			Date Tests Completed	2-9-07
Lab Number	11055LB	Tested By:	Filer	Date Reported	2-26-07

Requested tests are: complete Reflux, Penetration, and Absolute Viscosity.

Test	**Test Temp.**	**Test Result**	**P / F**	**Florida Specification**
Penetration	77°F	15	n/a	n/a
Absolute Viscosity, poises	140°F	98,739	n/a	n/a

Note:

Project	RAP Study; recovered asphalt from RAP			Date Received	03-26-07
Submitted By	Bit Research – SJ			Date Tests Completed	04-02-07
Lab Number	11086LB	Tested By:	Filer, Hill, Stickles	Date Reported	04-04-07

Test	Test Temp.	Test Result	P / F	Florida Specification
Penetration	77°F	12	n/a	n/a
Absolute Viscosity, poises	140°F	205,280	n/a	n/a
RTF Dynamic Shear, G*/sinδ, kPa	76°C	8.42 kPa	P	Minimum 2.20 kPa
		G* = 8.1240E3		
	82°C	4.11 kPa	P	
		G* = 4.0318E3		
	°C	2.00 kPa	F	
		G* = 1.9777E3		
The High Temperature Grade is **82-xx**				
PAV Dynamic Shear, G*sinδ, kPa	28°C	3788 kPa	P	Maximum 5000 kPa
		G* = 5.7345E6		
	25°C	5228 kPa	F	
		G* = 8.3195E6		
The initial Low Temperature Grade is **82-34**				
Creep Stiffness S, MPa	-12°C	179	P	S Maximum 300 MPa M-value
Creep Stiffness, M-value		0.296	F	
Creep Stiffness S, MPa	-6°C	92	P	
Creep Stiffness, M-value		0.339	P	
This sample graded out to a final grade of: PG 82-16				

Note: All of the tests results above were obtained on the asphalt as it was rendered from the recovery process. As RAP material, it has already been aged naturally and aging it further in the PAV test would serve no purpose.

Project	RAP Study; sample of PG 67-22			Date Received	10/03/06
Submitted By	Bit Research – SJ			Date Tested	10/25/06
Lab Number	10888LB	Tested By:	Hill & Stickles	Date Reported	10/25/06

Test	**Test Temp.**	**Test Result**	**P / F**	**Florida Specification**
Spot Test	n/a	Negative	P	Negative
Solubility,%	n/a	100%	P	Minimum 99.0%
Smoke Point, COC	n/a	330°F	P	Minimum 260°F
Flash Point, COC	n/a	625°F	P	Minimum 450°F
Penetration	77°F	53	P	Minimum 50 Units
Absolute Viscosity, poises	140°F	2992	P	2400 – 3600 poises
Rotational Viscosity, Pa•s	135°C	0.48	P	Maximum 3.0 Pa•s
Original Dynamic Shear, G*/sinδ, kPa	67°C	1.30	P	Minimum 1.0 kPa
	70°C	0.88	F	
The initial High Temperature Grade is **67-xx**				
RTF Mass Loss,%	163°C	0.117	P	Maximum 0.500%
RTF Dynamic Shear, G*/sinδ, kPa	67°C	2.73	P	Minimum 2.20 kPa
	70°C	1.95	F	
The final High Temperature Grade is **67-xx**				
PAV Dynamic Shear, G*sinδ, kPa	25°C	3628	P	Maximum 5000 kPa
	22°C	5327	F	
The initial Low Temperature Grade is **-22**				
Creep Stiffness S, MPa	-12°C	183	P	S Maximum 300 MPa M-value Minimum 0.300
Creep Stiffness, M-value	-12°C	0.324	P	
Creep Stiffness S, MPa	-18°C	379	F	
Creep Stiffness, M-value	-18°C	0.274	F	
This sample graded out to a final grade of: PG 67-22				

Project	RAP Study; sample of PG 64-22			Date Received	12/18/06
Submitted By	Bit Research – SJ			Date Tests Completed	01/04/07
Lab Number	10988LB	Tested By:	Stickles & Hill	Date Reported	01/08/07

Test	**Test Temp.**	**Test Result**	**P / F**	**Florida Specification**
Spot Test	n/a	Negative	P	Negative
Solubility,%	n/a	99.99%	P	Minimum 99.0%
Smoke Point, COC	n/a	355°F	P	Minimum 260°F
Flash Point, COC	n/a	500+°F	P	Minimum 450°F
Penetration	77°F	70	P	Minimum 60 Units
Absolute Viscosity, poises	140°F	2194	P	1600 – 2400 poises
Rotational Viscosity, Pa•s	135°C	0.46	P	Maximum 3.0 Pa•s
Original Dynamic Shear, G*/sinδ, kPa	64°C	1.45	P	Minimum 1.0 kPa
	67°C	1.08	P	
	70°C	0.69	F	
The initial High Temperature Grade is **<u>67-xx</u>**				
RTF Mass Loss,%	163°C	0.060	P	Maximum 0.500%
RTF Dynamic Shear, G*/sinδ, kPa	64°C	3.18	P	Minimum 2.20 kPa
	67°C	2.11	F	
The final High Temperature Grade is **<u>64-xx</u>**				
PAV Dynamic Shear, G*sinδ, kPa	25°C	3073	P	Maximum 5000 kPa
	22°C	4614	P	
	19°C	5579	F	
The initial Low Temperature Grade is **<u>64-28</u>**				
Creep Stiffness S, MPa	-12°C	138	P	S Maximum 300 MPa
Creep Stiffness, M-value	-12°C	0.349	P	
Creep Stiffness S, MPa	-18°C	346	F	M-value Minimum 0.300
Creep Stiffness, M-value	-18°C	0.270	F	
This sample graded out to a final grade of: <u>PG 64-22</u>				

Note: This sample passed the Absolute Viscosity specification for RA-2000.

Project	RAP Study; sample of RA-1000			Date Received	9/22/06
Submitted By	Bit Research – SJ			Date Tested	10/25/06
Lab Number	10886LB	Tested By:	Hill & Stickles	Date Reported	10/25/06

Test	Test Temp.	Test Result	P / F	Florida Specification
Spot Test	n/a	Negative	P	Negative
Solubility,%	n/a	99.98	P	Minimum 99.0%
Smoke Point, COC	n/a	310°F	P	Minimum 260°F
Flash Point, COC	n/a	615°F	P	Minimum 450°F
Penetration	77°F	97		
Absolute Viscosity, poises	140°F	1158	P	800 – 1200 poises
Rotational Viscosity, Pa•s	135°C	0.30	P	Maximum 3.0 Pa•s
Original Dynamic Shear, G*/sinδ, kPa	58°C	1.60	P	Minimum 1.0 kPa
	64°C	0.75	F	
The initial High Temperature Grade is **58-xx**				
RTF Mass Loss,%	163°C	0.155	P	Maximum 0.500%
RTF Dynamic Shear, G*/sinδ, kPa	58°C	3.72	P	Minimum 2.20 kPa
	64°C	1.61	F	
The final High Temperature Grade is **58-xx**				
PAV Dynamic Shear, G*sinδ, kPa	25°C	1811	P	Maximum 5000 kPa
	22°C	2786	P	
	19°C	4162	P	
	16°C	6241	F	
The initial Low Temperature Grade is **-28**				
Creep Stiffness S, MPa	-12°C	109	P	S Maximum 300 MPa
Creep Stiffness, M-value	-12°C	0.389	P	
Creep Stiffness S, MPa	-18°C	252	P	M-value Minimum 0.300
Creep Stiffness, M-value	-18°C	0.322	P	
This sample graded out to a final grade of: PG 58-28				

Note: The failing DSR result at 16°C disqualifies the sample for the low temperature grade -34, so the Bending Beam was not performed at -24 (the temperature that corresponds to 16°C and grade -34).

Project	RAP Study; recovered (0% RAP; 6.5%AC)			Date Received	12/21/06
Submitted By	Bit Research – SJ			Date Tests Completed	01/04/07
Lab Number	10990LB	Tested By:	Filer, Stickles & Hill	Date Reported	01/08/07

Test	Test Temp.	Test Result	P / F	Florida Specification
Penetration	77°F	27	n/a	n/a
Absolute Viscosity, poises	140°F	14,118	n/a	n/a
RTF Dynamic Shear, G*/sinδ, kPa	64°C	7.85 kPa	P	Minimum 2.20 kPa
		G* = 7.7178E3 Pascal		
	67°C	5.52 kPa	P	
		G* = 5.4448E3 Pascal		
	70°C	3.41 kPa	P	
		G* = 3.3730E3 Pascal		
	76°C	1.78 kPa	F	
		G* = 1.7733E3 Pascal		
The High Temperature Grade is **70-xx**				
PAV Dynamic Shear, G*sinδ, kPa	25°C	3683 kPa	P	Maximum 5000 kPa
		G* = 4.9794E6 Pascal		
	22°C	5419 kPa	F	
		G* = 7.7733E6 Pascal		
	n/a			
The initial Low Temperature Grade is **70-28**				
Creep Stiffness S, MPa	-12°C	143	P	S Maximum 300 MPa
Creep Stiffness, M-value		0.324	P	
Creep Stiffness S, MPa	-18°C	340	F	M-value Minimum 0.300
Creep Stiffness, M-value		0.258	F	
This sample graded out to a final grade of: PG 70-22				

Project	RAP Study; recovered (25%RAP; 6.5% AC)			Date Received	02/26/07
Submitted By	Bit Research – SJ			Date Tests Completed	03/09/07
Lab Number	11062LB	Tested By:	Filer, Hill, & Stickles	Date Reported	03/09/07

Test	**Test Temp.**	**Test Result**	**P / F**	**Florida Specification**
Penetration	77°F	25	n/a	n/a
Absolute Viscosity, poises	140°F	19,123	n/a	n/a
RTF Dynamic Shear, G*/sinδ, kPa	67°C	5.78 kPa	P	Minimum 2.20 kPa
		G* = 5.6874E3 Pascal		
	70°C	3.54 kPa	P	
		G* = 3.5011E3 Pascal		
	76°C	1.72 kPa	**F**	
		G* = 1.7150E3 Pascal		
The High Temperature Grade is **70-xx**				
PAV Dynamic Shear, G*sinδ, kPa	25°C	3891 kPa	P	Maximum 5000 kPa
		G* = 5.3922E6 Pascal		
	22°C	5642 kPa	**F**	
		G* = 8.2514E6 Pascal		
The initial Low Temperature Grade is **70-28**				
Creep Stiffness S, MPa	-12°C	162	P	S Maximum 300 MPa M-value Minimum 0.300
Creep Stiffness, M-value		0.326	P	
Creep Stiffness S, MPa	-18°C	332	**F**	
Creep Stiffness, M-value		0.281	**F**	
This sample graded out to a final grade of: PG 70-22				

Project	RAP Study; recovered (35% RAP; 6.0%AC)			Date Received	12/21/06
Submitted By	Bit Research – SJ			Date Tests Completed	01/04/07
Lab Number	10991LB	Tested By:	Filer, Stickles, & Hill	Date Reported	01/08/07

Test	**Test Temp.**	**Test Result**	**P / F**	**Florida Specification**
Penetration	77°F	25	n/a	n/a
Absolute Viscosity, poises	140°F	16,992	n/a	n/a
RTF Dynamic Shear, G*/sinδ, kPa	64°C	5.56 kPa	P	Minimum 2.20 kPa
		G* = 5.4709E3 Pascal		
	67°C	3.97 kPa	P	
		G* = 3.9175E3 Pascal		
	70°C	2.55 kPa	P	
		G* = 2.5323E3 Pascal		
	76°C	1.27 kPa	F	
		G* = 1.2592E3 Pascal		
The High Temperature Grade is **70-xx**				
PAV Dynamic Shear, G*sinδ, kPa	25°C	2655 kPa	P	Maximum 5000 kPa
		G* = 3.6122E6 Pascal		
	22°C	3937 kPa	P	
		G* = 5.6415E6 Pascal		
	19°C	5623 kPa	F	
		G* = 8.4663E6 Pascal		
The initial Low Temperature Grade is **70-34**				
Creep Stiffness S, MPa	-12°C	117	P	S Maximum 300 MPa M-value
Creep Stiffness, M-value		0.338	P	
Creep Stiffness S, MPa	-18°C	263	P	
Creep Stiffness, M-value		0.263	F	
This sample graded out to a final grade of: PG70-22				

Project	RAP Study; recovered (35% RAP; 6.0%AC)			Date Received	04/03/07
Submitted By	Bit Research – SJ			Date Tests Completed	04/19/07
Lab Number	11115LB	Tested By:	Filer, Hill, Stickles	Date Reported	04/20/07

Test	**Test Temp.**	**Test Result**	**P / F**	**Florida Specification**
Penetration	77°F	25	n/a	n/a
Absolute Viscosity, poises	140°F	17,962	n/a	n/a
RTF Dynamic Shear, G*/sinδ, kPa	67°C	5.47 kPa	P	Minimum 2.20 kPa
		G* = 5.3864E3 Pascal		
	70°C	3.54 kPa	P	
		G* = 3.5009E3 Pascal		
	76°C	1.70 kPa	F	
		G* = 1.6854E3 Pascal		
The High Temperature Grade is **70-xx**				
PAV Dynamic Shear, G*sinδ, kPa	25°C	2387 kPa	P	Maximum 5000 kPa
		G* = 3.2657E6 Pascal		
	22°C	3502 kPa	P	
		G* = 5.0325E6 Pascal		
	19°C	4907 kPa	P	
		G* = 7.4647E6 Pascal		
The initial Low Temperature Grade is **70-40**				
Creep Stiffness S, MPa	-12°C	139	P	S
Creep Stiffness, M-value		0.343	P	Maximum 300 MPa
Creep Stiffness S, MPa	-18°C	285	P	
Creep Stiffness, M-value		0.286	F	M-value
This sample graded out to a final grade of: PG 70-22				

Note: There was no need to take the PAV DSR to failure as 19°C is the lowest temperature grade for PAV material when the high temperature grade is 70.

Project	RAP Study; recovered (45% RAP; 5.9%AC)			Date Received	12/21/06
Submitted By	Bit Research – SJ			Date Tests Completed	01/04/07
Lab Number	10989LB	Tested By:	Filer, Stickles, & Hill	Date Reported	01/08/07

Test	Test Temp.	Test Result	P / F	Florida Specification
Penetration	77°F	22	n/a	n/a
Absolute Viscosity, poises	140°F	22,344	n/a	n/a
RTF Dynamic Shear, G*/sinδ, kPa	64°C	10.50 kPa	P	Minimum 2.20 kPa
		G* = 1.0195E4 Pascal		
	67°C	7.50 kPa	P	
		G* = 7.3176E3 Pascal		
	70°C	4.66 kPa	P	
		G* = 4.5753E3 Pascal		
	76°C	2.32 kPa	P	
		G* = 2.2928E3 Pascal		
	82°C	1.07 kPa	F	
		G* = 1.0631E3 Pascal		
The High Temperature Grade is **76-xx**				
PAV Dynamic Shear, G*sinδ, kPa	25°C	3387 kPa	P	Maximum 5000 kPa
		G* = 4.7741E6 Pascal		
	22°C	4765 kPa	P	
		G* = 7.0555E6 Pascal		
	19°C	6364 kPa	F	
		G* = 9.7460E6 Pascal		
The initial Low Temperature Grade is **76-34**				
Creep Stiffness S, MPa	-12°C	122	P	S Maximum 300 MPa M-value Minimum 0.300
Creep Stiffness, M-value		0.323	P	
Creep Stiffness S, MPa	-18°C	279	P	
Creep Stiffness, M-value		0.261	F	
This sample graded out to a final grade of: PG 76-22				

Project	RAP Study; recovered (45% RAP; 5.9%AC)			Date Received	04/03/07
Submitted By	Bit Research – SJ			Date Tests Completed	04/19/07
Lab Number	11116LB	Tested By:	Filer, Stickles, & Hill	Date Reported	04/20/07

Test	**Test Temp.**	**Test Result**	**P / F**	**Florida Specification**
Penetration	77°F	21	n/a	n/a
Absolute Viscosity, poises	140°F	20,592	n/a	n/a
RTF Dynamic Shear, G*/sinδ, kPa	67°C	5.36 kPa	P	Minimum 2.2 kPa
		G* = 5.2690E3 Pascal		
	70°C	3.62 kPa	P	
		G* = 3.5784E3 Pascal		
	76°C	1.83 kPa	F	
		G* = 1.8201E3 Pascal		
The High Temperature Grade is **70-xx**				
PAV Dynamic Shear, G*sinδ, kPa	25°C	3121 kPa	P	Maximum 5000 kPa
		G* = 4.3470E6 Pascal		
	22°C	4527 kPa	P	
		G* = 6.5849E6 Pascal		
	19°C	6290 kPa	F	
		G* = 9.7423E6 Pascal		
The initial Low Temperature Grade is **70-34**				
Creep Stiffness S, MPa	-12°C	145	P	S Maximum 300 MPa M-value
Creep Stiffness, M-value		0.331	P	
Creep Stiffness S, MPa	-18°C	283	P	
Creep Stiffness, M-value		0.279	F	
This sample graded out to a final grade of: PG 70-22				

Project	RAP Study; recovered (45% Mod RAP)			Date Received	2-12-07
Submitted By	Bit Research – SJ			Date Tests Completed	2-23-07
Lab Number	11055LB	Tested By:	Filer & Stickles	Date Reported	2-26-07

Requested tests are: complete Reflux, Penetration, Absolute Viscosity, and PG Grading (report G* also).

Test	**Test Temp.**	**Test Result**	**P / F**	**Florida Specification**
Penetration	77°F	25	n/a	n/a
Absolute Viscosity, poises	140°F	31,872	n/a	n/a
RTF Dynamic Shear, G*/sinδ, kPa	70°C	5.57 kPa	P	Minimum 2.20 kPa
		G* = 5.4660E3 Pascal		
	76°C	2.72 kPa	P	
		G* = 2.6864E3 Pascal		
	82°C	1.30 kPa	F	
		G* = 1.2976E3 Pascal		
The High Temperature Grade is **76-xx**				
PAV Dynamic Shear, G*sinδ, kPa	25°C	3934 kPa	P	Maximum 5000 kPa
		G* = 5.6506E6 Pascal		
	22°C	5478 kPa	F	
		8.2780E6 Pascal		
The initial Low Temperature Grade is **76-34**				
Creep Stiffness S, MPa	-12°C	146	P	S Maximum 300 MPa
Creep Stiffness, M-value		0.322	P	
Creep Stiffness S, MPa	-18°C	298	P	M-value Minimum 0.300
Creep Stiffness, M-value		0.280	F	
This sample graded out to a final grade of: PG 76-22				

APPENDIX C

SUPERPAVE IDT TEST RESULTS

Project Name	m-value	D_1 (1/psi)	S_t (Mpa)	M_R (Gpa)	FE (kJ/m^3)	$DCSE_{HMA}$ (kJ/m^3)	Stress (psi)	a	$DCSE_{MIN}$ (kJ/m^3)	ER	Creep Rate	Failure Strain
RAP 0%	0.536	5.77E-07	2.50	9.50	6.9	6.6	150	4.61E-08	1.950	3.37	1.25E-08	3512.51
RAP 25%	0.482	7.66E-07	2.28	8.83	4.5	4.2	150	4.73E-08	1.837	2.29	1.03E-08	2237.07
RAP 35%	0.531	6.87E-07	2.11	9.62	4.1	3.9	150	4.83E-08	2.158	1.79	1.43E-08	2551.99
RAP 45%	0.477	5.49E-07	2.1	10.49	2.4	2.2	150	4.84E-08	1.252	1.75	7.06E-09	1674.51
MOD 45%	0.410	3.58E-07	2.46	14.43	1.7	1.5	150	4.63E-08	0.542	2.75	2.49E-09	1046.35