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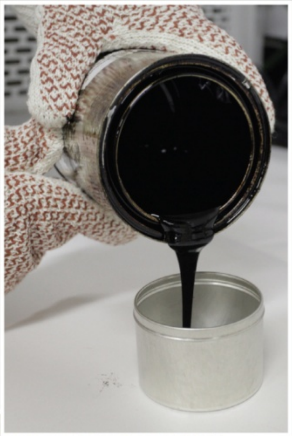

EFFECTS OF CHANGING VIRGIN BINDER GRADE AND CONTENT ON RAP MIXTURE PROPERTIES

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May 2012

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DISCLAIMER

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CHAPTER 1 INTRODUCTION

1.1 Background

Although asphalt pavement recycling started in the early 1900s, the modern practice of pavement recycling became a common practice after the oil embargo of the 1970s. Today, it is estimated that about 100 million tons of reclaimed asphalt pavement (RAP) material are recycled annually. Of this amount, 80 million tons (80%) are recycled into asphalt pavements (*1*). Most RAP is obtained as a result of milling to remove the top portions of existing asphalt pavements.

Recently, the asphalt paving industry found itself in a situation comparable to that of the 1970s during the oil embargo. There has been a rapid increase in asphalt binder and energy costs. This increase in additional cost can be partially offset by using more RAP in asphalt mixtures. In addition to price escalations, increased environmental awareness has resulted in greater restrictions on crude oil exploration and permits for new aggregate reserves. To reduce the demand on new virgin asphalt and aggregates, more attention has been devoted to increasing RAP contents in asphalt paving mixtures.

According to Page (*2*), most government agencies responsible for highways in the United States have reported a significant cost reduction in projects when RAP is used. The Florida Department of Transportation showed a reduction in cost of 15-30% compared to the cost of conventional pavement (using all virgin materials). Although RAP may be used for the construction of a granular base course (e.g., Full Depth Reclamation), or shoulder material, the greatest economic and environmental benefits can be realized when RAP is used to replace virgin binder and aggregates in the production of hot-mix asphalt (HMA) mixture.

Recycled asphalt mixture may use RAP from a range of sources. Three important concepts should be followed when using recycled asphalt mixture (*3, 4*):

a) The aggregate in the RAP should meet the same requirements as required for virgin aggregates.
b) Control the moisture content in RAP stockpiles at acceptable levels
c) The recycled asphalt mixture should meet the same specification requirements as that required for virgin mixture.

Most highway agencies have decades of experience with HMA containing low to moderate percentages of RAP (i.e., below 25% by weight of aggregate). One reason states are reluctant to increase RAP contents is the general perception that RAP mixtures may be more susceptible to various modes of cracking (i.e. fatigue, thermal, reflection). This is due to the fact that the RAP binder is aged, stiffer and less strain tolerant than a virgin binder. As the RAP proportion increases there is the potential for an increase in mixture stiffness and decrease in resistance to cracking resulting in earlier performance problems and increased rehabilitation costs. The goal of numerous research efforts is to increase the RAP percentage without sacrificing performance.

Before specifying high RAP percentages, agencies want assurance that high RAP mixes will provide satisfactory field performance. If RAP mixtures cannot perform as well as virgin mixtures, recommendations for improving the durability of these mixtures are necessary.

One suggested method of increasing the durability of high RAP mixtures is to adjust the grade of the virgin binder. Current recommendations provided by AASHTO M323 are based on tiers of RAP percentages (Table 1). Each tier represents a RAP percentage by weight of the aggregate. When between 15 and 25 percent RAP is used in an asphalt mixture, current guidance suggests that mix designers should reduce both the high and low critical temperatures by one performance grade. When more than 25 percent RAP is in the mixture, blending charts should be used to determine the appropriate virgin binder grade; however, many state agencies want to minimize the use of solvents required for extracting and recovering the RAP binder. Additionally, some state agencies do not want to change the grade of binder more than one or two grades since incomplete mixing may result in soft areas in the pavement instigating early distresses (5).

TABLE 1 Binder selection guidelines for RAP mixtures according to AASHTO M323

Recommended Virgin Asphalt Binder Grade	RAP Percent
No change in binder selection	< 15
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if PG 64-22 would normally be used)	15-25
Follow recommendations from blending charts	>25

Other research has suggested that the performance of RAP mixtures might be related to the volume of virgin binder in the mixture rather than the performance grade of the virgin binder (6).

1.2 Objective

This research plan was developed to assess whether increasing volume of effective virgin binder or using a softer binder aided in improving the durability of mixtures containing high percentages of RAP. The objective of this research was to quantify how increasing the volume of virgin binder or decreasing the performance grade of virgin asphalt binders affects the durability of RAP mixtures.

1.3 Scope of Work

To complete this objective, 0, 25 and 50 percent RAP mixtures at optimum asphalt content were designed using a standard PG 67-22 virgin asphalt binder. These mixtures were tested to evaluate the top-down (surface cracking) and reflection cracking susceptibility using the energy ratio (ER) and overlay tester (OT) methodologies. These tests were also conducted on the RAP mixtures with 0.25% and 0.50% higher asphalt contents and at the optimum asphalt content using a PG 58-28 virgin binder rather than the PG 67-22 virgin binder. Additionally, the linear amplitude sweep (LAS) methodology was used to assess the fatigue properties of the blended RAP and virgin binders.

1.4 Organization of this Report

This report is divided into five chapters. Chapter 2 provides the laboratory testing plan and methodologies used to perform the research while Chapter 3 provides the results of the aforementioned tests. An economic analysis was conducted in Chapter 4 to assess the potential materials savings associated with the different RAP mixtures evaluated in the study . Chapter 5 presents the final conclusions and recommendations based on the results of this study.

CHAPTER 2 LABORATORY TESTING PLAN AND METHODOLOGY

This chapter describes testing used to assess the impact increasing the asphalt content or reducing the asphalt binder performance grade has on the cracking resistance of RAP mixtures.

2.1 Testing Plan

Multiple laboratory tests were conducted to quantify how increasing the volume of effective virgin binder or decreasing the performance grade of the virgin asphalt binder affected the durability of RAP mixtures. The linear amplitude sweep (LAS) was utilized to characterize the fatigue properties of the blended RAP and virgin binder while the overlay tester (OT) was conducted to assess the resistance to reflection cracking of the RAP mixtures.
The energy ratio testing procedure was used to evaluate each mixture's resistance to surface cracking. Finally, the rutting resistance of the most durable mixtures was assessed using the asphalt pavement analyzer (APA) to ensure that increasing mixture durability did not cause the asphalt mixture to become susceptible to rutting.

2.2 RAP Characterization

When RAP is used in an asphalt mixture design, it must first be characterized. The RAP aggregate from each source was recovered using the ignition method following AASHTO T308-05. The asphalt content of the RAP was then determined using this test procedure. The gradation of the RAP aggregate was also determined using AASHTO T30-10. The bulk specific gravity of the RAP aggregate was also quantified on the material recovered from the ignition test using AASHTO T84 and T85. In addition to the specific gravities, the consensus aggregate properties the RAP stockpile were determined.

The RAP binder was extracted using ASTM D2171, *Test Methods for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures Method A* with trichloroethylene (TCE) as the solvent. Once extracted, ASTM D5404, *Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator* was used to remove the solvent from the asphalt binder. The recovered asphalt binder was then tested to determine its Performance Grade (PG) binder properties using AASHTO M320.

2.3 Mix Designs

Mix designs were conducted for the virgin, 25% and 50% RAP mixtures in accordance with AASHTO M323-07, *Standard Specification for Superpave Volumetric Mix Design*, and AASHTO R35-04, *Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt,* except the virgin asphalt binder grade was not changed for the mixes with RAP.The optimum binder contents were determined corresponding to 4 percent air voids. Each mix was designed using a 9.5 mm nominal maximum aggregate size (NMAS), and the gradations consisted of four aggregate stockpiles and a locally available unfractionated RAP stockpile. Two different stockpiles of granite were used, #89's and M10's. The granite was obtained from Vulcan Materials Barin Quarry in Columbus, Georgia. The Martin-Marietta quarry in Auburn, Alabama, was the source of the limestone #8910's. The natural sand was from Martin-Marietta Sand and

Gravel in Shorter, Alabama, while the RAP was sampled from East Alabama Paving in Opelika, Alabama.

A PG 67-22 virgin binder was the normal base binder used in the mixture design. When a softer binder was incorporated in the study, the binder was a PG 58-28. These binders were mixed in the laboratory with the previously determined blend of aggregates and RAP. All the samples were short-term aged in the oven at a temperature of 135°C for two hours before compaction. The design pills were compacted to an N_{des} level of 60 gyrations and a target height of 115 ±5 mm.

The loose mixes and compacted specimens were cooled down in the laboratory. Then, the bulk specific gravity of the compacted specimens was determined according to AASHTO T166, and the maximum theoretical specific gravity of the loose mix was determined in accordance with AASHTO T209. The specific gravity information was used to determine the volumetric properties of the mixes that are presented later in this report.

Moisture susceptibility testing was performed in accordance with AASHTO T 283.

2.4 Linear Amplitude Sweep

The Linear Amplitude Sweep Test (LAS) is an accelerated binder fatigue test that has been proposed to replace the current Dynamic Shear Rheometer (DSR) intermediate temperature G*sinδ parameter. The G*sinδ parameter is based on the assumption that asphalt binders in pavements function in the linear-viscoelastic range and are, therefore, insensitive to strain levels. These assumptions have long been challenged especially as modified asphalts have been shown to exhibit increased fatigue resistance and non-linear strain response. The LAS test was developed in response to the need for a fatigue test that could account for actual damage resistance as well as pavement structure and traffic loading. The LAS procedure uses cyclic loading with increasing load amplitude to accelerate damage. The end result is a prediction of binder fatigue life as a function of strain magnitude.

A blend of extracted RAP and virgin binders were tested using LAS methodology. The RAP binder was extracted using ASTM D2171, *Test Methods for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures Method A* with trichloroethylene (TCE) as the solvent. Once extracted, ASTM D5404, *Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator* was used to remove the solvent from the asphalt binder. The extracted RAP binder was then blended with the virgin binder source in proportion to the amount of reclaimed binder in each of the mixture designs.

This testing methodology was used to assess how the RAP binder affected the fatigue properties of the virgin binder. The nature of mixing the RAP and virgin binders assumes complete mixing of the virgin and RAP binders which may not actually occur during production.

The LAS test was run in the DSR and consisted of a frequency sweep from 0.1 to 30 Hz at a strain level of 0.1 percent followed by a strain sweep at a constant frequency of 10 Hz. During the strain sweep, the strain amplitude linearly increases from 0.1 to 30 percent. The test is performed on asphalt binder that has been aged in the rolling thin film oven (RTFO) and uses 8 mm plates. The testing temperature corresponds with either the intermediate temperature grade of the asphalt binder or the climatic intermediate temperature at the location where the asphalt will be used. In this study, the material was tested at 32.1°C which corresponds to the local climate intermediate temperature.

Analysis of the LAS was performed using viscoelastic continuum damage (VECD) theory which is based on Schapery's theory of work potential to model damage growth (Equation 1).

$$\frac{dD}{dt} = \left(\frac{\partial W}{\partial D}\right)^{\alpha} \qquad \text{(Equation 1)}$$

Where: D = damage intensity

W = work performed

α = material constant related to the rate at which damage progresses (*7*)

The LAS test is run in two parts on the same sample of material. First, a frequency sweep from 0.1 to 30 Hz is performed using a low strain level of 0.1% to prevent damaging the sample. During the frequency sweep, the complex shear modulus and phase angle of the binder are collected. These data are then used to calculate α, the slope of the log-log plot of relaxation modulus versus time.

Because not all DSRs are capable of performing a stress relaxation test to determine α, Johnson and Bahia (*8*) developed a methodology for converting frequency sweep data to relaxation modulus. Further work by Hintz, et al., (*7*) simplified this process by demonstrating the relationship could be estimated using the slope, m, of a log-log plot of storage modulus (G*cos(δ)) versus frequency (Equation 2). An example of the resultant plot is shown in Figure 1.

$$\alpha = 1 + \frac{1}{m} \qquad \text{(Equation 2)}$$

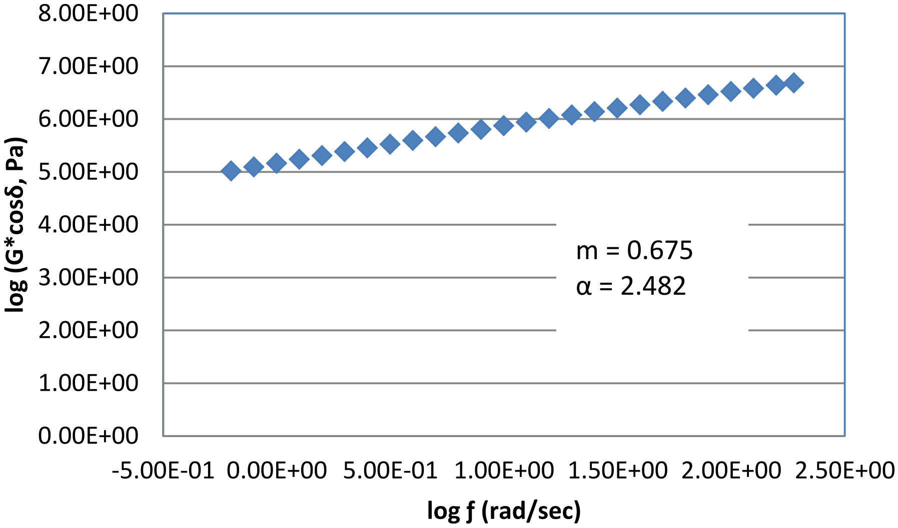

FIGURE 1 Calculation of α.

Once α and *m* were determined, a strain sweep was performed on the aged asphalt binder. During the strain sweep, the load amplitude increased to inflict damage on the sample. The strain sweep began at 0.1 percent strain and increased linearly to 30 percent strain. At each strain level, multiple readings of G*, δ, and oscillatory stress were recorded. Accumulated damage levels in the specimen were calculated for each data point using Equation 3 (*9*).

$$D(t) \cong \sum_{i=1}^{N}[\pi I_D \gamma_0^2(|G^*|sin\delta_{i-1} - |G^*|sin\delta_i)]^{\frac{\alpha}{1+\alpha}}(t_i - t_{i-1})^{\frac{1}{1+\alpha}} \qquad \text{(Equation 3)}$$

Where: I_d = average value of │G*│ from the initial interval of 0.1 percent applied strain, MPA
γ_0 = applied strain for a given data point
│G*│= dynamic shear modulus, MPa
t = testing time, seconds

Only damage levels above 100 were considered in the analysis as damage levels below 100 exhibit non-linear behavior. The datapoints calculated in Equation 3 were then used to determine the constants needed to form the relationship shown in Equation 4 (*9*).

$$|G^*|sin\delta = C_0 - C_1(D)^{C_2} \qquad \text{(Equation 4)}$$

Where: C_0 = the average value of │G*│sinδ from the initial interval of 0.1 percent applied strain
$\log(C_1)$ = intercept of a line formed as $\log(C_0 - |G^*|\sin\delta)$ versus $\log(D(t))$
C_2 = slope of a line formed as $\log(C_0 - |G^*|\sin\delta)$ versus $\log(D(t))$

After determining the three constants, the damage corresponding to 35 percent reduction in the undamaged │G*│sinδ (represented by C_0) was calculated using Equation 5.

$D_f = (0.35\frac{C_0}{C_1})^{\frac{1}{C_2}}$ (Equation 5)

The binder fatigue performance parameter (N_f) was then calculated using Equation 6. N_f can be adjusted to account for difference in pavement structure by changing γ_{max}. Higher strain values correspond to thinner pavements or heavier traffic loading while lower strain magnitudes correspond to thicker pavements or lighter traffic loads (LAS standard). An example of the data is shown in Figures 2 and 3 (*9*).

$N_f = A(\gamma_{max})^B$ (Equation 6)

Where: γ_{max}= applied binder strain for given pavement structure

B = -2

$A = \frac{f(D_f)^k}{k(\pi\frac{I_D}{|G^*|}C_1C_2)^\alpha}|G^*|^{-\alpha}$

Where: f = loading frequency (10 Hz)

k = 1+(1-C_2)α

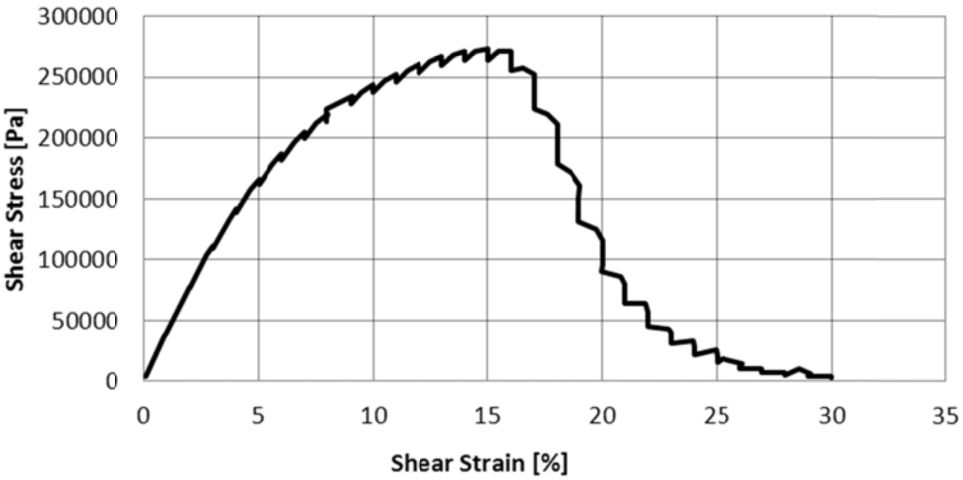

FIGURE 2 Plot of shear stress versus shear strain.

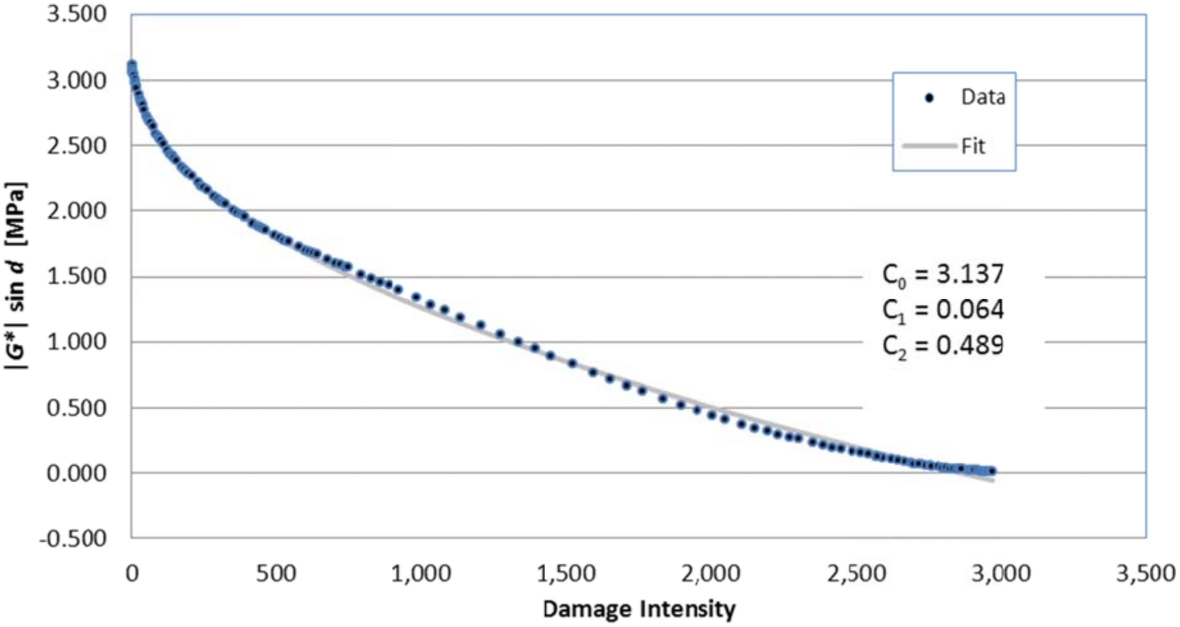

FIGURE 3 Damage intensity plot.

2.5 Energy Ratio Testing

The energy ratio test procedure was developed to assess an asphalt mixture's resistance to top-down or surface cracking (*10*). This testing procedure has been used in past research cycles at the NCAT Test Track as a predictor of whether or not a mixture would be susceptible to top-down cracking (*11*). The energy ratio is determined using a combination of three tests: resilient modulus, creep compliance, and indirect tensile strength. These tests are described in greater detail below. These tests were performed at 10°C using an MTS® testing device. The tests were conducted on three specimens 150 mm diameter by approximately 38 mm thick, cut from gyratory compacted samples (Figure 4). The target air voids for the specimens was 7 ± 0.5 percent.

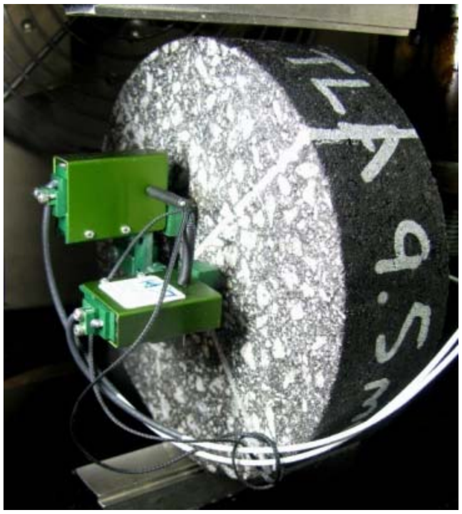

FIGURE 4 Energy ratio test specimen setup.

The resilient modulus was obtained by applying a repeated haversine waveform load in load control mode. The load was applied for 0.1 second and then followed by a 0.9 second rest. The resilient modulus was calculated using the stress-strain curve as shown in Figure 5.

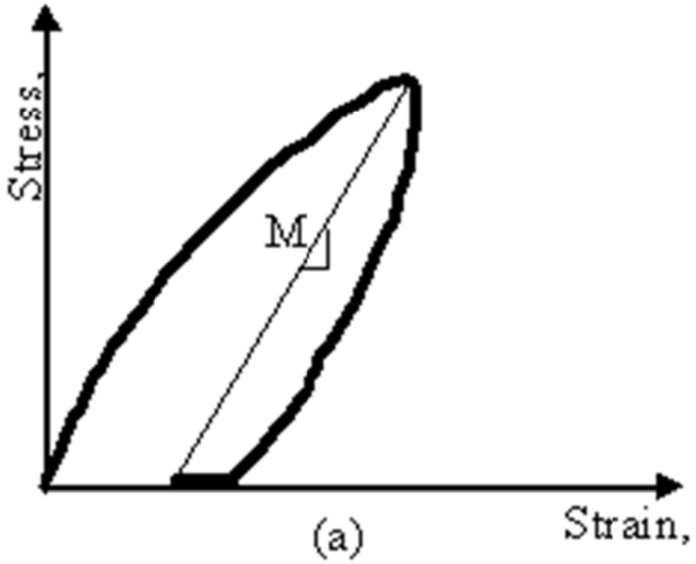

FIGURE 5 Resilient modulus results.

The creep compliance test was performed as described in AASHTO T322-07; however, the temperature of the test was 10°C with test duration of 1000 seconds. The power function properties of the creep compliance test were determined by curve-fitting the results obtained during constant load control mode (Figure 6).

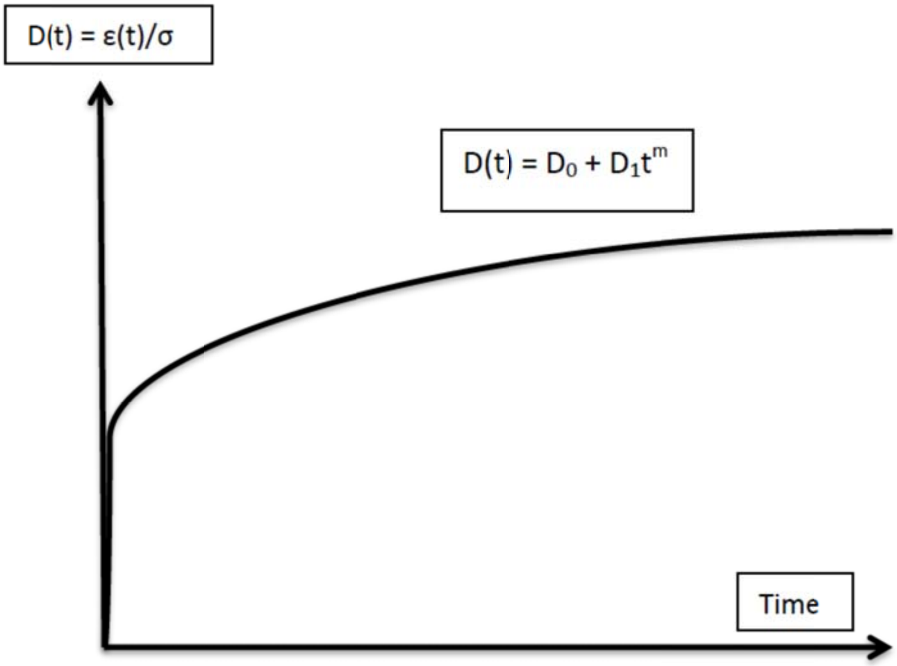

FIGURE 6 Creep compliance results.

Finally, the tensile strength and dissipated creep strain energy (DCSE) at failure are determined from the stress-strain curve of the given mixture during the indirect tensile strength test (Figure 7).

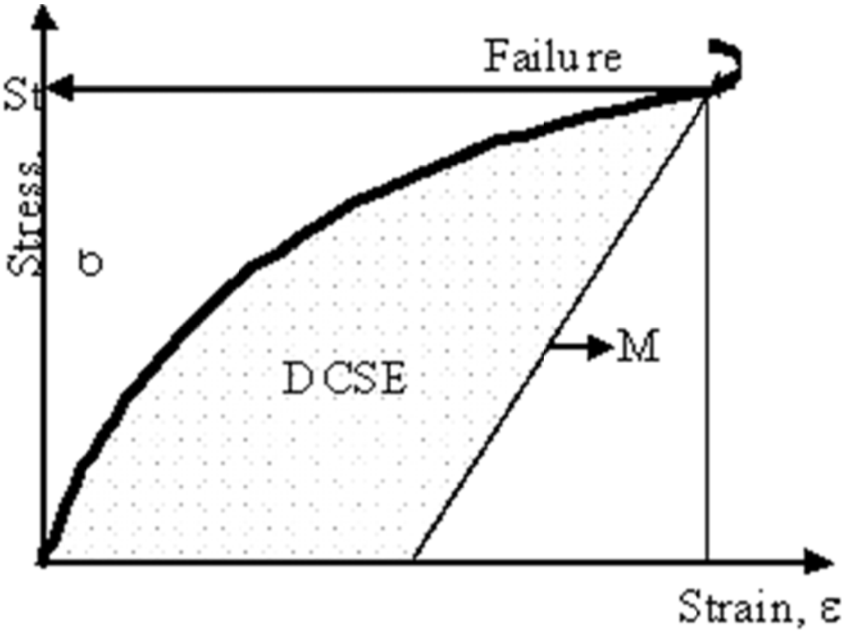

FIGURE 7 Strength test results.

Detailed testing procedures and data interpretation methods for the three testing protocols are described elsewhere (*10, 11, 12*). The results from these tests are then used to evaluate each mixture's surface cracking resistance using Equation 7. Data analysis was performed using a software package developed at the University of Florida. The details of the software operation are documented elsewhere (*12*). A higher energy ratio provides more resistance to surface cracking. Table 2 lists the recommended thresholds for the energy ratio as a function of rate of traffic.

$$ER = \frac{DSCE_f\left[7.294\times10^{-5}\times\sigma^{-3.1}(6.36-S_t)+2.46\times10^{-8}\right]}{m^{2.98}D_1} \qquad \text{(Equation 7)}$$

Where: σ = tensile stress at the bottom of the asphalt layer, 150 psi
M_r = resilient modulus
D_1, m = power function parameters
S_t = tensile strength
$DSCE_f$ = dissipated stress creep energy at failure
ER = energy ratio

TABLE 2 Recommended Energy Ratio Criteria (*10*)

Traffic: (ESALs/yr)	Minimum Energy Ratio
< 250,000	1
< 500,000	1.3
< 1,000,000	1.95

2.6 Overlay Tester

The overlay tests were performed in accordance with TxDOT 248-F (Figure 8). The procedure states that a 150 mm diameter Superpave gyratory sample should be compacted to a height of 115 ± 5 mm. Upon achieving the desired height, the specimens were trimmed to the following dimensions: 150 mm long by 75 mm wide by 38 mm tall (Figure 9). Three replicates with air voids between 6 and 8 percent after trimming were tested.

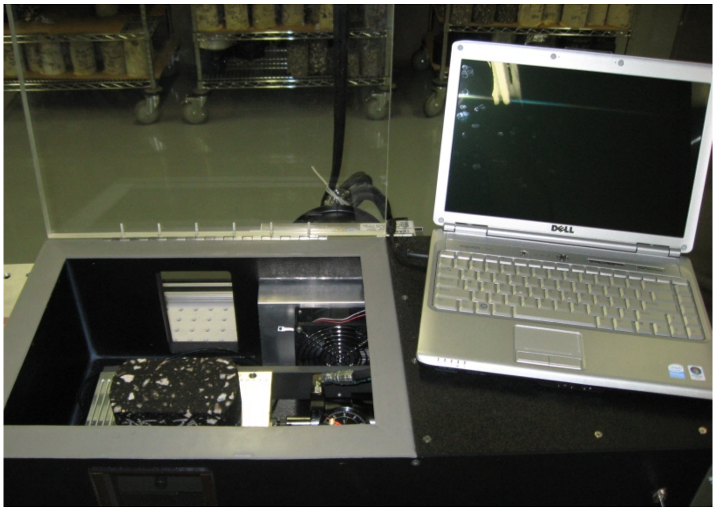

FIGURE 8 Overlay tester.

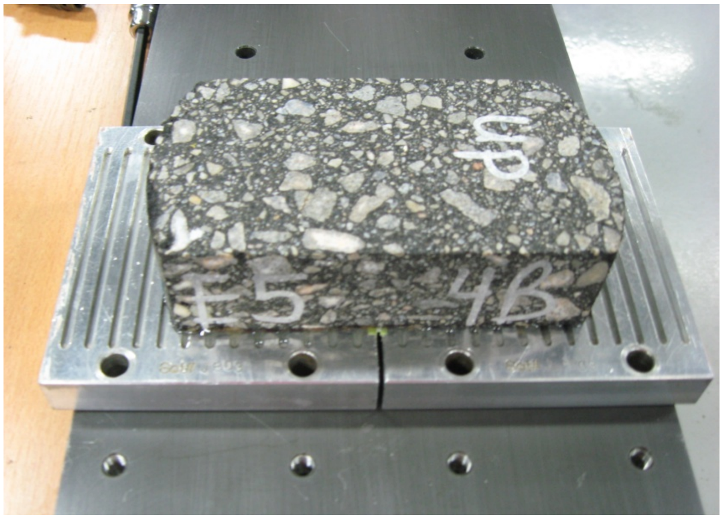

FIGURE 9 Overlay tester specimen.

The samples were tested at 25°C in controlled displacement mode. Loading occurs when a movable steel plate attached to the asphalt specimen slides away from the other plate (Figure 10). Loading occurs at a rate of one cycle every 10 seconds with a sawtooth waveform (Figure 11). The maximum load the specimen resists in controlled displacement mode is recorded for each cycle. The test continues until the sample fails. Failure is defined as 93% reduction in load magnitude from the first cycle (*13*).

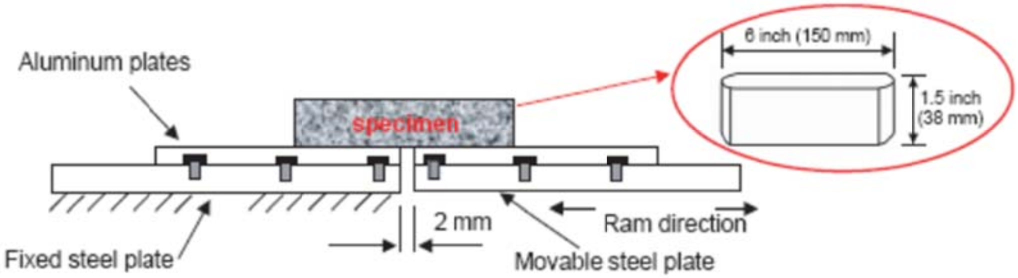

FIGURE 10 Overlay tester specimen (*13*).

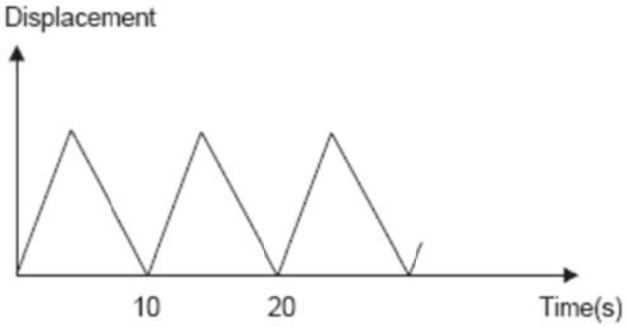

FIGURE 11 Loading form of the overlay tester (*13*).

TxDOT 248-F specifies a maximum opening displacement of 0.025 inches, which is equal to about 32% strain on the specimen. However, past research has shown that using this crack opening displacement can instantaneously fail RAP mixtures (*14*). Therefore, to get reliable and usable data, it was determined that the crack opening displacement needed to be reduced.

To determine an appropriate crack opening displacement, three replicate samples of the 25 percent RAP mixture at the optimum asphalt content were tested at three maximum opening displacements. Previous research had shown that an opening displacement of 0.017 inches is still a harsh condition for testing high RAP mixtures (*14*); however, if the crack opening were too small, the virgin mixture might not fail. Therefore, maximum opening displacements of 0.01, 0.013, and 0.015 inches were chosen for this pilot study.

The results of this experiment are shown in Figure 12. As shown, the results at the larger crack opening were more variable than the two smaller crack openings. Additionally, the average number of cycles to failure for the largest crack opening was still less than 100 cycles. It was desired to have the number of cycles until failure greater than 100 for most of the mixtures (*15*).

While the 25 percent RAP mixture using the largest crack opening did not achieve a high enough fatigue life, the average cycles to failure at the 0.01 inch opening was over 2000. If this crack opening were used, the research team believed that the virgin mixtures and/or the mixtures using a softer grade of asphalt binder might not achieve failure. Therefore, the crack opening of 0.013 inches was chosen for the experimental plan of this study.

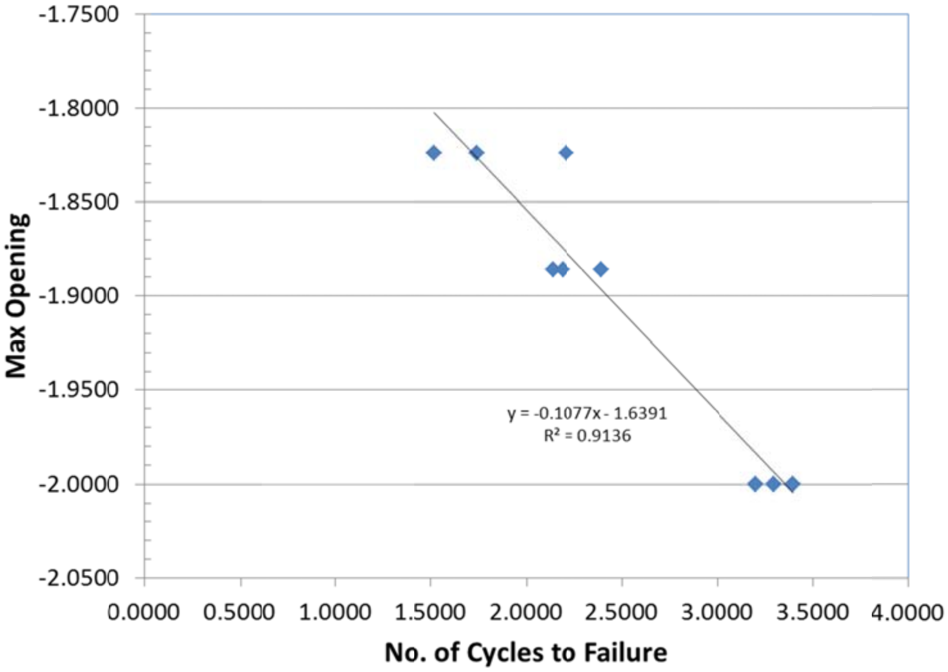

FIGURE 12 OT Pilot Study Results.

2.7 Asphalt Pavement Analyzer

The rutting susceptibility of asphalt mixtures is commonly assessed using the Asphalt Pavement Analyzer (APA) (Figure 13). While the objective of this research was to determine how increasing the volume of effective binder or reducing the asphalt binder performance grade affected the mixture durability, one does not want to sacrifice rutting resistance for mixture durability. Therefore, the mixtures were also assessed for rutting susceptibility using AASHTO TP 63-09.

Tests were conducted at 64°C Manual depth readings were taken at two locations on each sample after 25 loading cycles and at the conclusion of testing to determine the sample rut depth.

Past research at NCAT suggests that mixtures with less than 5.5 mm of rutting in the APA should be able to withstand 5 million equivalent single axle loads (ESALs) without rutting more than 9.5 mm (*16*).

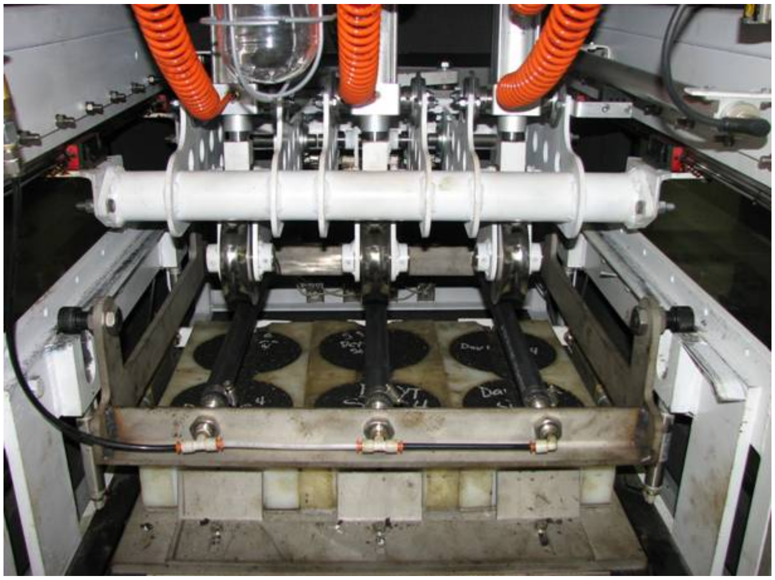

FIGURE 13 Asphalt Pavement Analyzer.

CHAPTER 3 LABORATORY TEST RESULTS

The chapter describes the RAP characterization process and mix design iterations used in the laboratory testing described in Chapter 2. The objective of this work was to quantify the effect of either using a softer asphalt binder or increasing the amount of effective virgin asphalt in RAP mixtures.

3.1 RAP Characterization

The RAP binder was extracted using ASTM D2171, *Test Methods for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures Method A* with trichloroethylene (TCE) as the solvent. Once extracted, ASTM D5404, *Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator* was used to remove the solvent from the asphalt binder. The recovered asphalt binder was then tested to determine its Performance Grade (PG) binder properties using AASHTO M320. The recovered RAP binder properties are shown in Table 3.

TABLE 3 RAP Binder Performance Grades

Binder	$T_{crit, high}$	$T_{crit, int}$	$T_{crit, low}$	PG Grade
RAP	99.1	33.1	-9.2	94-4

The asphalt content, gradation and bulk specific gravity of the RAP aggregate were also determined. Tables 4 and 5 show the asphalt content, gradation, and specific gravities of the RAP material.

TABLE 4 RAP Properties

Aggregate	Asphalt Content, %	G_{sb}	G_{sa}	Water Absorption, %
RAP	5.33	2.708	2.744	0.5

TABLE 5 RAP Gradation

Sieve Size (mm)	Sieve Size (Inches)	Percent Passing
12.5	1/2"	100
9.5	3/8"	99.2
4.75	# 4	83.1
2.36	# 8	64.3
1.18	# 16	49.5
0.600	# 30	34.9
0.300	# 50	22.4
0.150	#100	14.9
0.075	#200	9.5

3.2 Mixture Designs

The gradations of the individual stockpiles, the gradation of the total blend, and the percentages of each stockpile used in the final blends are shown in Appendix A with the aggregate specific gravities, absorptions, and consensus properties (crushed face count, uncompacted voids in fine aggregate, sand equivalency, and flat and elongated particle percentages) for each of the four stockpiles. The weighted average of each of the four consensus properties fell within the specification for an acceptable mix design set forth in AASHTO M 323-07.

Two virgin binders were used in this study with the aggregate gradations described in Section 3.2. The first binder was a PG 64-22 (or PG 67-22). The second binder was chosen to be one grade softer for both the high and low critical temperature (i.e. PG 58-28). Both of these binders were tested and graded according to AASHTO M320. The test results are given in Table 6.

TABLE 6 Virgin Binder Performance Grades

Binder	$T_{crit, high}$	$T_{crit, int}$	$T_{crit, low}$	PG Grade
67-22	67.0	23.9	-23.2	67-22
58-28	60.3	15.5	-31.7	58-28

A summary of the volumetric properties of the three mixtures is given in Table 7. According to AASHTO M323, the minimum voids in mineral aggregate (VMA) requirement for a 9.5 mm mixture is 15.0 percent. The voids filled with asphalt (VFA) requirement is 73-76 for high traffic mixtures, and the dust to asphalt ratio should be between 0.6 and 1.2. All three mixtures meet these standards at the optimum asphalt contents.

TABLE 7 Mix Design Properties

Property	Virgin	25% RAP			50% RAP		
Mix Version	Opt.	Opt.	+0.25%	+0.5%	Opt.	+0.25%	+0.5%
AC, %	6.1	5.9	6.15	6.4	6.15	6.40	6.65
AC_{RAP}, %	0	1.33	1.33	1.33	2.67	2.67	2.67
AC_{Virgin}, %	6.1	4.57	4.82	5.07	3.49	3.73	3.98
RAP Binder/Total Binder, %	--	22.5	21.6	20.8	43.4	41.7	40.2
Air Voids, %	4.0	4.0	3.0	2.4	4.0	3.4	2.9
VMA, %	16.5	15.9	15.7	15.6	16.9	16.9	17.1
VFA, %	75.4	75.6	79.5	83.3	75.7	79.2	82.7
Effective AC, %	5.4	5.16	5.41	5.67	5.63	5.88	6.13
Dust/Asphalt	1.08	1.02	0.98	0.84	0.9	0.88	0.84

Moisture susceptibility testing was performed on the three completed mix designs in accordance with AASHTO T 283. Table 8 gives a summary of the TSR results for the three mixtures. AASHTO M323 requires mixtures to have a tensile-strength ratio of at least 0.80. All three mixtures met this requirement using 0.5% LOF anti-strip by weight of the virgin binder.

TABLE 8 Moisture Susceptibility Results

Mixture	Average Conditioned Strength, psi	Average Unconditioned Strength, psi	TSR
Virgin	120.6	130.5	0.92
25% RAP	163.0	171.9	0.95
50% RAP	167.8	210.6	0.80

3.3 Linear Amplitude Sweep Test Results

Blends of the virgin and extracted RAP binders were created corresponding to the amounts of each binder in the 25 and 50% RAP mixture designs. The blends with the PG 67-22 virgin binder were then adjusted to correspond to an increase in the effective virgin binder content by 0.25 and 0.5%. The increase in virgin binder should theoretically increase the fatigue life of the binder. Asphalt pavements with higher asphalt contents tend to have better fatigue life due to the increased asphalt binder film thickness surrounding the aggregate particles. The reduction in overall binder stiffness due to the increased virgin binder should also improve the binder fatigue life.

Table 9 shows the N_f values for each design iterative at strain levels of 2.5 and 5.0 percent. The results shown are the average of two test results. Test results for replicate samples did not vary by more than 15 percent. Figures 14 and 15 compare the results graphically by RAP content.

TABLE 9 LAS Test Results

Binder	**% RAP**	**Binder Content**	**% RAP Binder**	**N_f @ 2.5% Strain**		**N_f @ 5.0% Strain**	
				Sample 1	*Sample 2*	*Sample 1*	*Sample 2*
PG 67-22	0	Optimum	0	341,465	350,787	13,915	14,338
PG 67-22	25	Optimum	22.5	250,704	247,907	8,036	7,809
PG 67-22	25	Opt. + 0.25%	21.6	273,886	290,126	9,105	9,587
PG 67-22	25	Opt. + 0.50%	20.8	338,059	285,957	11,337	9,793
PG 58-28	25	Optimum	22.5	1,039,946	1,038,887	38,051	37,379
PG 67-22	50	Optimum	43.5	224,850	237,793	5,294	5,564
PG 67-22	50	Opt. + 0.25%	41.7	267,219	230,865	6,328	5,528
PG 67-22	50	Opt. + 0.50%	40.2	250,531	215,068	6,298	5,390
PG 58-28	50	Optimum	43.5	497,464	472,253	14,919	13,909

It can be seen that the LAS testing protocol is capable of capturing the expected trend in binder fatigue life relative to strain magnitude. As the strain on the asphalt binder decreases, the number of cycles required to fail the binder increases showing better fatigue performance.

The test results also show that blending RAP binder with the PG 67-22 virgin asphalt binder reduces expected fatigue performance of the blends. For the 25% RAP mixture, these reductions were 27 and 43 percent for the 2.5 and 5.0 percent strain loadings, respectively. For the 50 percent RAP mixture, the reductions were 33 and 62 percent for the 2.5 and 5.0 percent strain loadings respectively.

Overall, the results shown in Figures 14 and 15 match the expected trends for binder fatigue life. The PG 58-28 virgin-RAP binder blends had longer fatigue lives than the PG 67-22 virgin-RAP binder blends. The reduction of fatigue life caused by increasing the RAP content from 25 to 50 percent is more noticeable for the PG 58-28 binder blends. The reduced sensitivity of the PG 67-22 binder to the addition of RAP when compared to the PG 58-28 binder is most likely due to the increased intermediate temperature stiffness. The PG 58-28 binder is still fairly soft at intermediate temperatures as evidenced by its true grade intermediate temperature, 15.5°C. The PG 67-22 binder is stiffer with an intermediate true grade temperature of 23.9°C. The addition of the RAP binder would not have as great an effect on the intermediate temperature properties of the PG 67-22 binder as it would on the PG 58-28 binder.

Table 9 and Figures 14 and 15 also show the effect of increasing the amount of virgin binder in the PG 67-22 blends on the predicted fatigue life. For the 25% RAP mix designs, these data show that increasing the virgin binder content of the virgin-RAP binder blend increased the predicted binder fatigue life. For the 50% RAP mix designs, increasing the virgin binder content does not increase the fatigue performance of the binder. At this higher RAP content, the increased binder stiffness due to the addition of the RAP binder most likely overshadowed the effect of the increased virgin binder content.

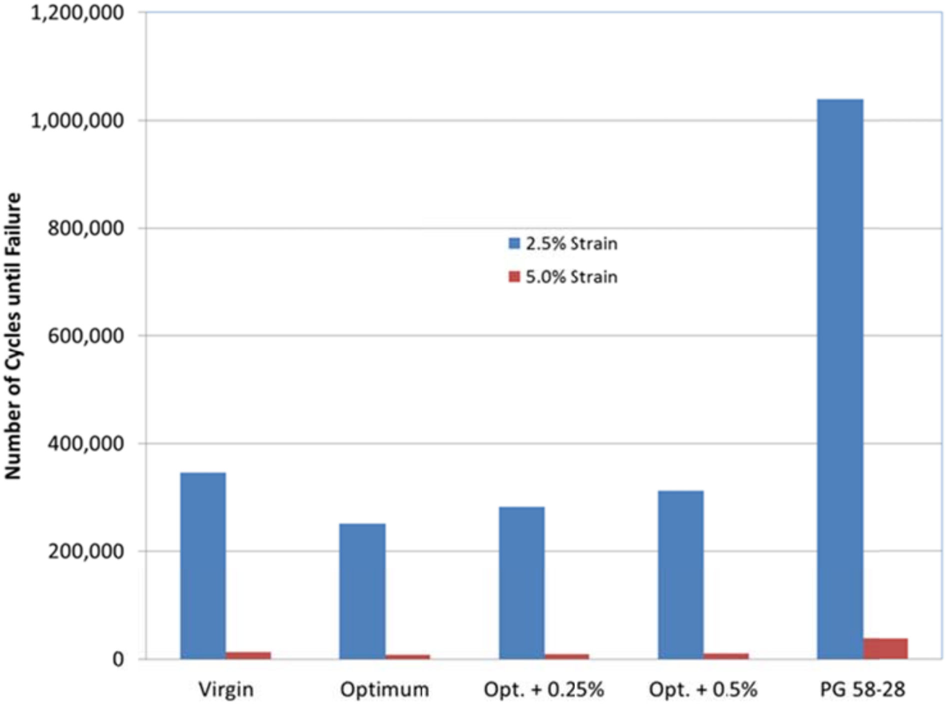

FIGURE 14 LAS Results for 25 Percent RAP Mixtures.

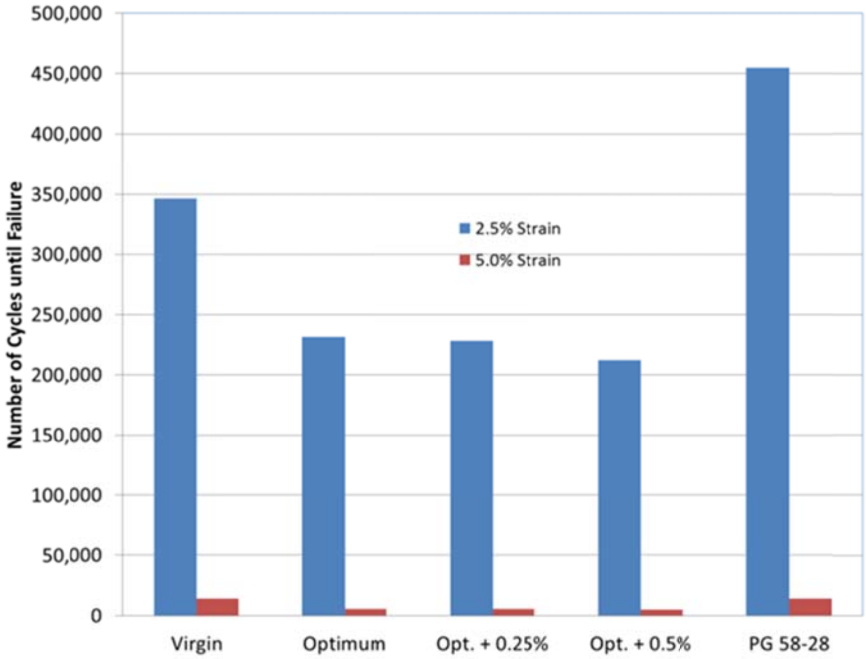

FIGURE 15 LAS Results for 50 Percent RAP Mixtures.

While increasing the virgin binder content of the 25 percent RAP mixtures did improve the expected binder fatigue performance, using a softer virgin binder had the greatest impact on improving fatigue life for both the 25 and 50 percent RAP mixtures.

3.4 Energy Ratio Test Results

3.4.1 Fracture Energy

As part of the energy ratio test procedure, the fracture energy (FE) of each mixture was determined. The FE for the 25 and 50 percent RAP mixtures are shown in Figures 16 and 17, respectively. The FE of mixtures has been linked to fatigue performance at WesTrack (*19*); however, there are no generally accepted criteria for minimum FE requirements.

The results show that using the PG 58-28 improves the FE for both the 25 and 50 percent RAP mixtures when compared to the 25 and 50 percent RAP mix designs with PG 67-22 binder at the optimum asphalt content. Using a softer binder increased the FE of the 25 percent RAP mixture by approximately 34 percent while using a softer binder for the 50 percent RAP mixture increased the fracture energy of the mixture by 229 percent.

Increasing the effective volume of the virgin binder did not affect the FE of the 25 percent RAP mix. A maximum difference of 3.4 percent was seen between the three 25 percent RAP mixtures using PG 67-22 binder. Therefore, using a softer binder was the most efficient way to improve the FE of the 25 percent RAP mixtures.

The FE of the 50 percent RAP mixture at the optimum asphalt content with the PG 67-22 binder had the lowest FE of all the mixtures tested. While increasing the effective virgin binder content did not improve the FE of the 25 percent RAP mixtures, increasing the virgin binder content by 0.25 percent improved the FE by 214 percent. Further increasing the amount of virgin asphalt in the mixture by 0.5 percent only improved the FE by another 14 percent. Therefore, there was no practical benefit to increasing the volume of virgin asphalt in the 50 percent RAP mixture beyond 0.25 percent.

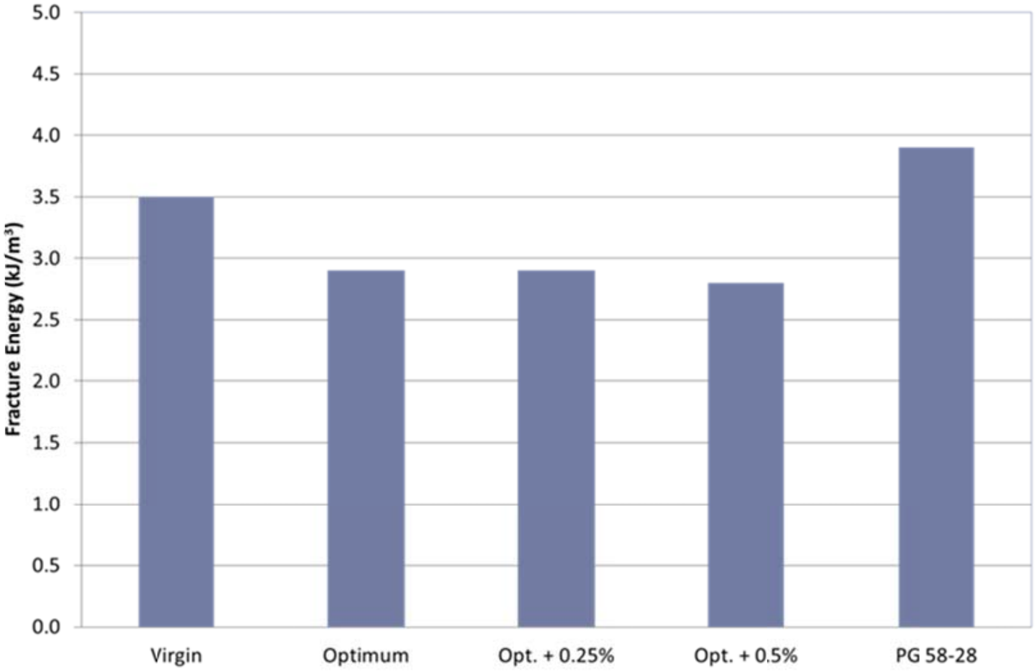

FIGURE 16 Fracture Energy Results for 25 Percent RAP Mixtures.

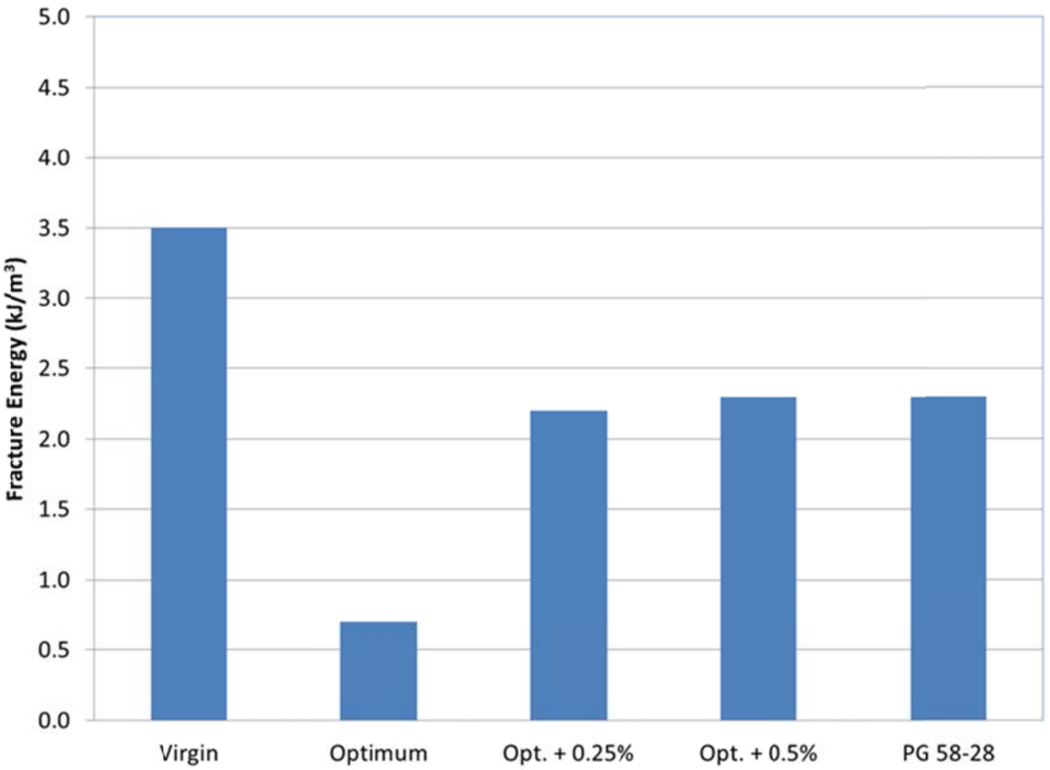

FIGURE 17 Fracture Energy Results for 50 Percent RAP Mixtures.

3.4.2 Energy Ratio

The energy ratio was developed to assess an asphalt mixture's susceptibility to surface cracking using a combination of indirect tension tests described in Section 2.5. Each mixture described in Section 3.2 was evaluated using the energy ratio methodology. The individual components used to calculate the energy ratio is provided in Tables 10 and 11 while Figures 18 and 19 graphically compare the energy ratios of the 25 and 50 percent RAP mixtures.

All four of the 25 percent RAP mixtures and the virgin mixture passed the energy ratio criterion of 1.95 to withstand surface cracking for trafficking up to 1,000,000 equivalent single axle loads per year. However, the results for the 25 percent RAP mixtures did not follow the expected trends. One would expect the stiffer mixtures to be more susceptible to surface cracking. Thus, the mixtures with a higher percentage of RAP binder would be expected to have a lower energy ratio. Examination of Equation 7 shows that the energy ratio is inversely related to creep compliance. In the context of the energy ratio, this means that mixtures with higher susceptibility to creep are more susceptible to damage.

As seen in Figure 18, the 25% RAP mixture with the largest energy ratio is the 25 percent RAP mixture using the PG 67-22 binder at the optimum asphalt content. As more virgin binder is added to the mixture, the energy ratio continues to decrease. These results indicate that the mixture most susceptible to surface cracking is the mix using the softest grade of asphalt binder.

TABLE 10 Energy Ratio Test Results for 25 Percent RAP Mixtures

	Virgin	*PG 67-22 @ Opt.*	*PG 67-22 @ Opt. + 0.25%*	*PG 67-22 @ Opt. + 0.5%*	*PG 58-28 @ Opt.*
m-value	0.38	0.29	0.35	0.34	0.39
FE (kJ/m^3)	3.5	2.9	2.9	2.8	3.9
DSCE$_{HMA}$ (kJ/m^3)	3.32	2.59	2.59	2.50	3.61
DSCE$_{MIN}$ (kJ/m^3)	0.59	0.26	0.36	0.48	0.87
ER	5.61	9.91	7.16	5.19	4.17
Rate of Creep Compliance (s/GPa x 10^{-9})	2.73	1.00	1.46	1.94	3.80

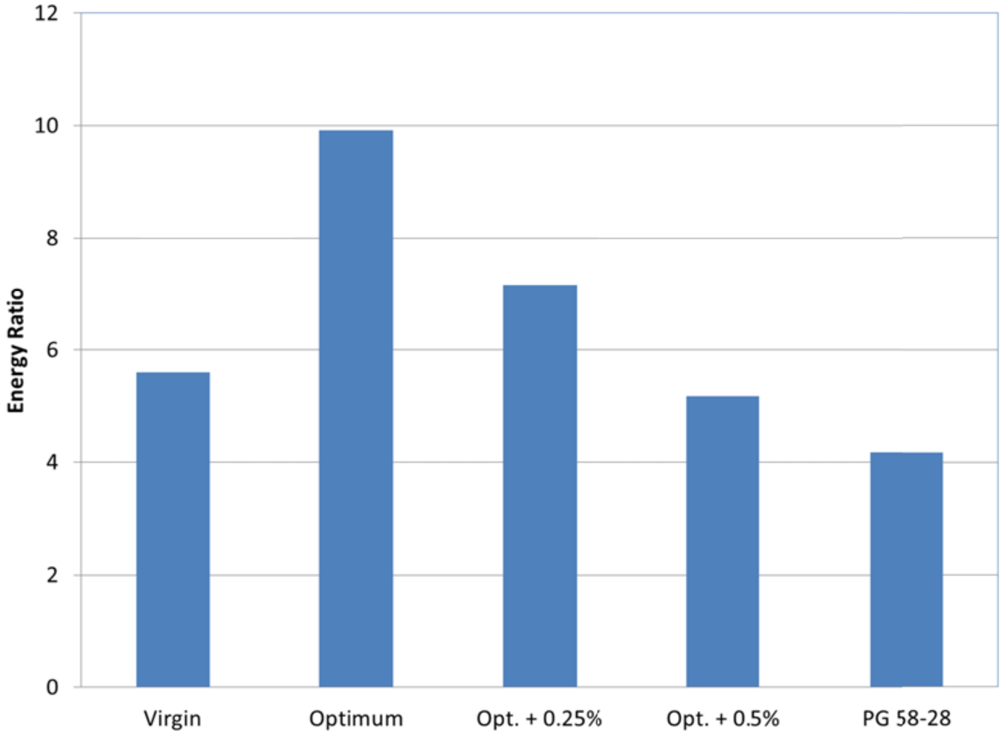

FIGURE 18 Energy ratio results for 25 percent RAP mixtures.

While the results are less extreme, a similar trend is evident with the 50 percent RAP mixtures. When 0.25% additional virgin binder is added to the 50 percent RAP mixture, the energy ratio increases. However, when the volume of virgin binder is increased by another quarter percent or a softer grade of virgin asphalt is used at the optimum asphalt content, the energy ratio decreases.

TABLE 11 Energy Ratio Test Results for 50 Percent RAP Mixtures

	Virgin	*PG 67-22 @ Opt.*	*PG 67-22 @ Opt. + 0.25%*	*PG 67-22 @ Opt. + 0.5%*	*PG 58-28 @ Opt.*
m-value	0.38	0.33	0.28	0.31	0.37
FE (kJ/m^3)	3.5	0.7	2.2	2.3	2.3
DSCE$_{HMA}$ (kJ/m^3)	3.32	0.52	1.97	2.00	2.09
DSCE$_{MIN}$ (kJ/m^3)	0.59	0.30	0.23	0.32	0.43
ER	5.61	1.75	8.53	6.33	4.92
Rate of Creep Compliance (s/GPa x 10^{-9})	2.73	1.26	9.42	1.23	1.86

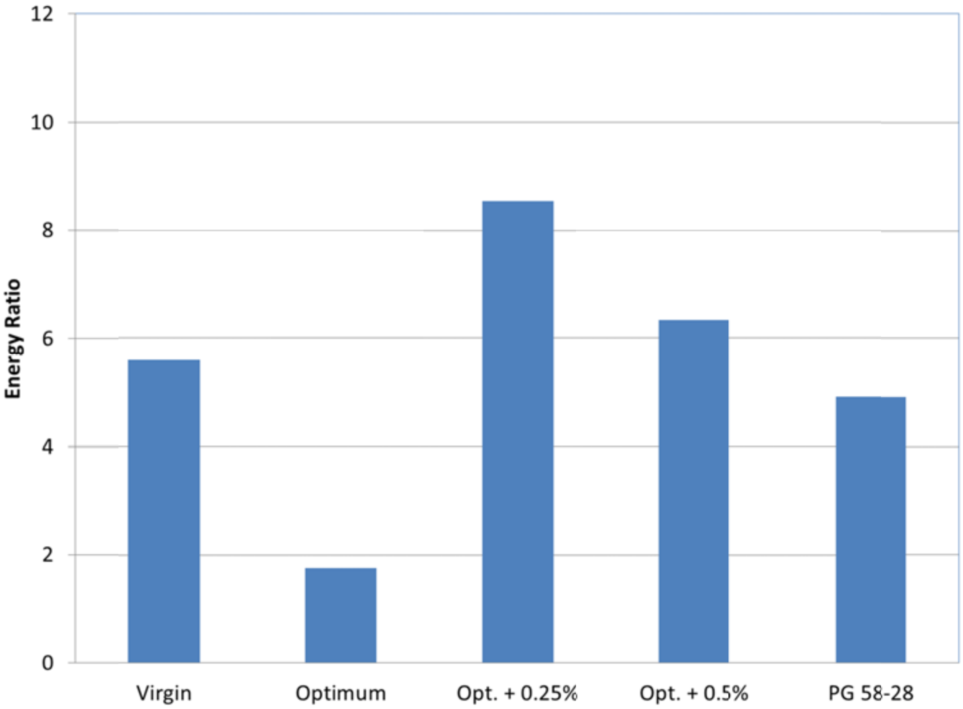

FIGURE 19 Energy ratio results for 50 percent RAP mixtures.

The reason for this unexpected trend is the results from the creep compliance tests. Tables 10 and 11 show that when the mixtures contained additional virgin binder or a softer binder, the rate of creep compliance increased. This fits the given understanding that softer mixtures will creep more than stiffer mixtures under a static loading.

When the rate of creep compliance and energy ratio are graphically compared (Figure 20), it can be seen that a strong relationship exists between the two mixture parameters. The exception to this relationship is the 50 percent RAP mixture using a PG 67-22 binder at the optimal asphalt content. While this mixture has a low rate of creep compliance, it also has the lowest energy ratio. This, however, is explained when one examines the fracture energies of the mixtures. While the majority of the mixtures tested had fracture energies between 2.2 and 3.5, the energy ratio of the 50 percent RAP mixture with a PG 67-22 binder at optimum was controlled by a fracture energy of 0.7 instead of the creep compliance term. When this mixture was removed from the dataset, the relationship between rate of creep compliance and energy ratio could be defined by a power function with little scatter ($R^2 = 0.85$) (Figure 21).

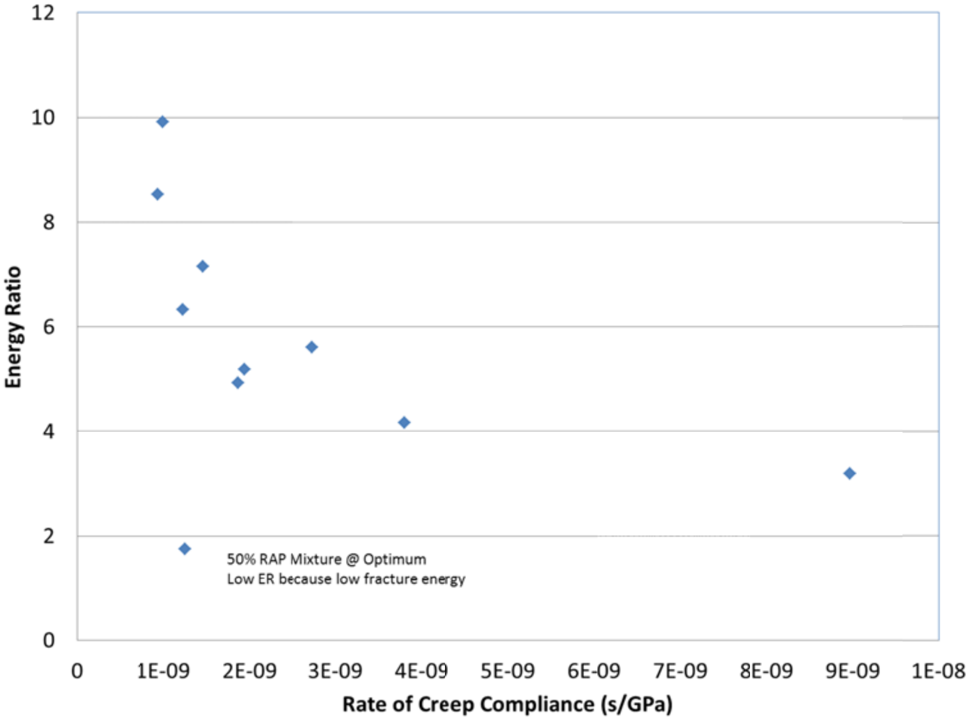

FIGURE 20 Rate of creep compliance versus energy ratio.

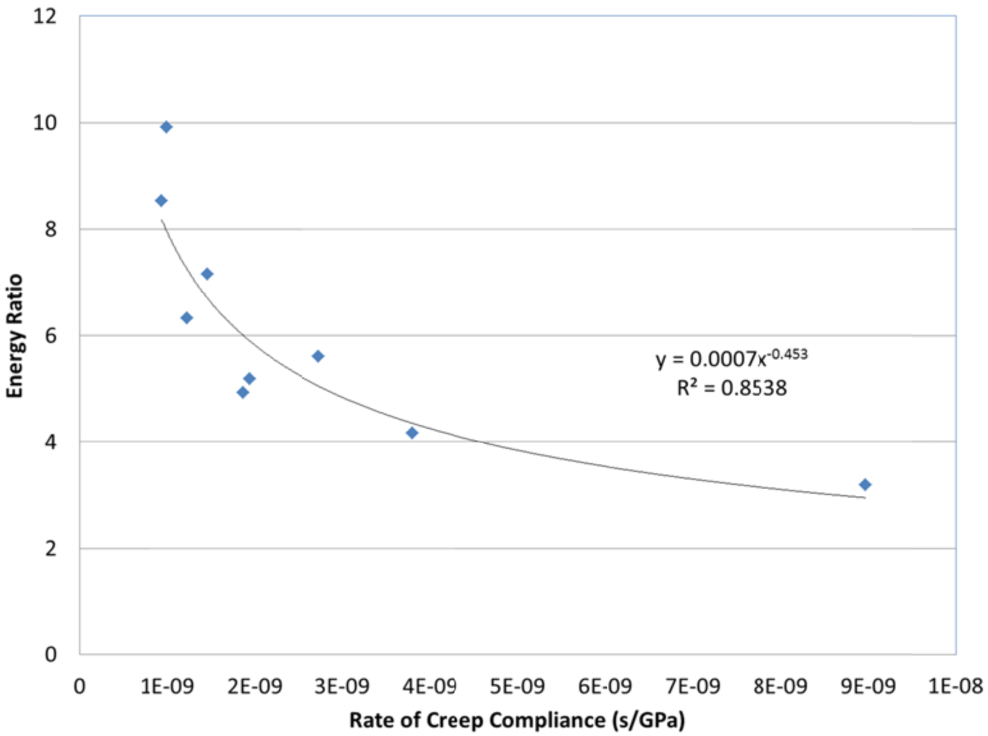

FIGURE 21 Rate of creep compliance versus energy ratio with outlier removal.

In order for a mixture to have a high energy ratio, it must perform well in both fracture and creep. If the mix was too stiff, the fracture energy was low resulting in a small energy ratio. However, if the mix was too soft, the high rate of creep compliance also reduced the energy ratio. The two best performing mixtures in terms of the energy ratio were the 25 percent RAP mixture at the optimum asphalt content with a PG 67-22 binder and the 50 percent RAP mixture with the optimum binder content plus an additional quarter percent asphalt binder.

3.5 Overlay Tester Results

The Overlay Tester (OT) was used to assess the resistance to reflection cracking for all nine mixtures in this study. Each mixture was tested in the Overlay Tester at 25°C using a maximum opening displacement of 0.013 inches as previously reported. The OT results are shown in Figure 22.

While the purpose of this study was to determine the optimal way to improve the durability of RAP mixtures, the test results reiterate the harsh conditions of the OT as indicated in section 2.6. The virgin mixture lasted 4368 cycles before the stiffness dropped by 93 percent ; however, the 25 percent RAP mixture only lasted 179 cycles. The 50 percent RAP mixture at the optimum asphalt content had an average life of 133 cycles before it achieved failure. Thus, increasing the RAP content drastically decreased the cycles to failure in this extremely high strain test. These results are consistent with other research using the overlay tester to evaluate mixes containing recycled binders (*14, 17, 18*).

The General Linear Model (α = 0.05) was used to assess differences in OT results for the virgin mixture and the four 25 percent RAP mixtures. According to this statistical analysis (Table 12), the 25 percent RAP mixture using the PG 58-28 binder was statistically equivalent to the virgin mixture. Using additional asphalt did not statistically increase the number of cycles to failure compared to the 25 percent mixture at the optimum asphalt content.

While there was no statistical difference between the 25 percent RAP mixture at optimum asphalt and the mixtures containing additional asphalt, the additional 0.25 percent asphalt increased the number of cycles to failure by more than five times. However, increasing the virgin binder by 0.5 percent above optimum did not provide any additional durability compared to the mixture containing 0.25 percent asphalt above optimum.

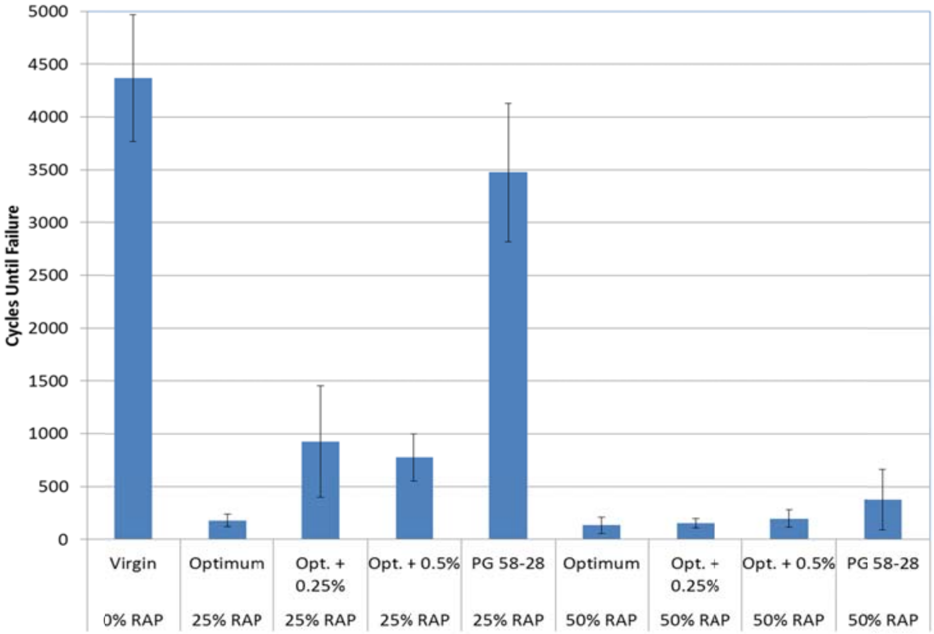

FIGURE 22 Overlay tester results.

TABLE 12 25 Percent RAP OT Statistical Groupings

Mixture	**Mean, Cycles to Failure**	**Grouping**
Virgin	4368	A
PG 67-22 @ Opt.	179	B
PG 67-22 @ Opt. + 0.25%	930	B
PG 67-22 @ Opt. + 0.50%	777	B
PG 58-28 @ Opt.	3475	A

The General Linear Model (α = 0.05) was also used to compare OT results among the virgin mixture and the four 50 percent RAP mixtures (Table 13). In this analysis, the cycles to failure for the virgin mixture were statistically higher than the other four mixtures. Additionally, neither using a softer binder grade nor adding additional virgin asphalt to the mixture had a statistical effect on the cycles to failure for the 50 percent RAP mixtures.

Again, while there was not a statistical difference in the OT results among the 50 percent RAP mixtures, the number of cycles until failure for the 50 percent RAP mixture did increase by more than two times when using a PG 58-28 binder instead of the standard PG 67-22.

TABLE 13 50 Percent RAP OT Statistical Groupings

Mixture	Mean, Cycles to Failure	Grouping
Virgin	4368	A
PG 67-22 @ Opt.	133	B
PG 67-22 @ Opt. + 0.25%	152	B
PG 67-22 @ Opt. + 0.50%	198	B
PG 58-28 @ Opt.	378	B

3.6 Asphalt Pavement Analyzer Results

The APA was used to assess the rutting potential of all nine mixtures in this study. Each mixture was tested in the APA at 64°C using a maximum load and pressure of 100 lbs and 100 psi, respectively. The results for the 25 and 50 percent RAP mixtures are shown in Figure 23 and individually given in Appendix C.

The GLM ($\alpha = 0.05$) was used to statistically compare the rutting of the virgin mixture to the four 25 percent RAP mixtures (Table 14). Statistically speaking, the two mixtures with the most rutting were the 25 percent RAP mixtures with the PG 58-28 binder at the optimum asphalt content and the PG 67-22 binder with an additional 0.5% virgin asphalt. The virgin mixture, the 25 percent RAP mixture at the optimum asphalt content, and the 25 percent RAP mixture using 0.25 percent additional asphalt all had statistically equivalent APA results.

When these five results were compared to the rutting threshold of 5.5 mm, only the 25 percent RAP mixture using the softer binder exceeded that criteria. The 25 percent RAP mixture using an additional 0.5 percent asphalt had an average rut depth of 5.37 mm. Therefore, using a softer binder may make an asphalt mixture susceptible to rutting under heavy traffic in a warmer climate.

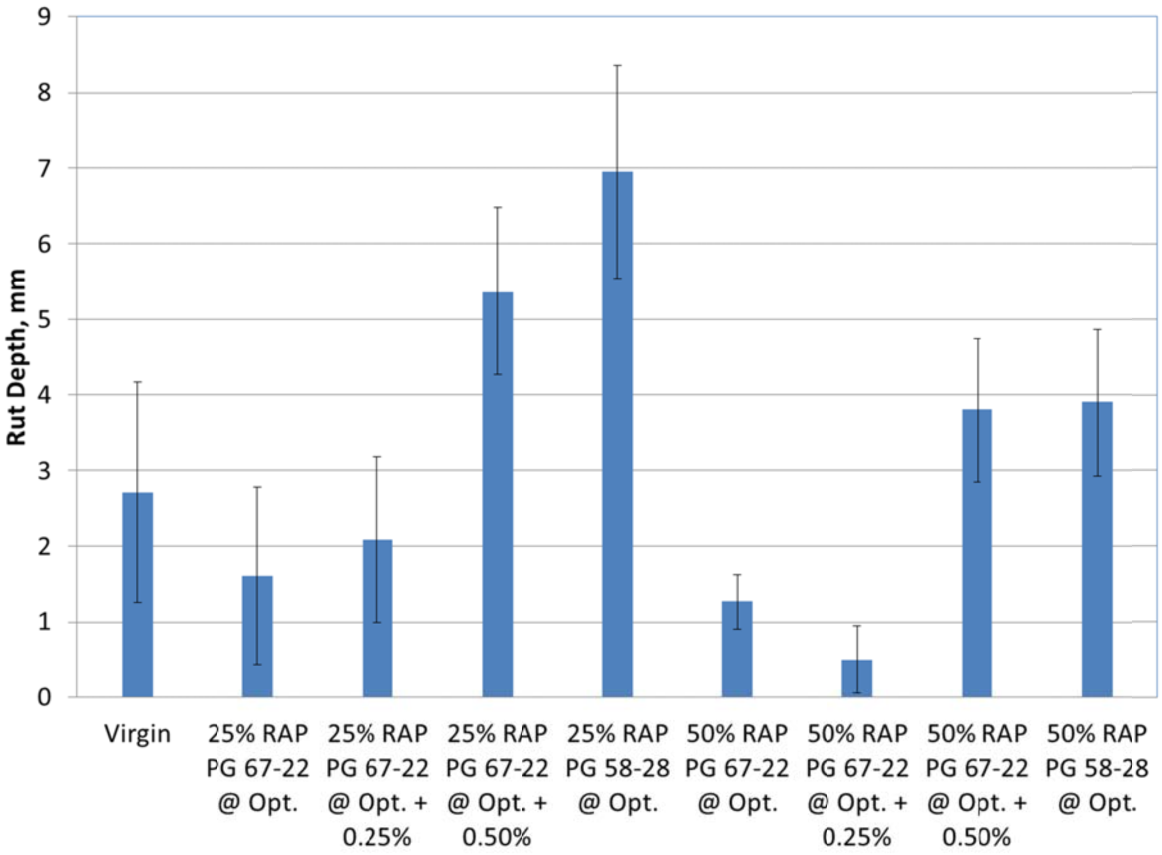

FIGURE 23 APA test results.

The GLM (α = 0.05) was used to statistically compare the APA results of the virgin mixture to the four 50 percent RAP mixtures. The groupings for these five mixtures are shown in Table 15. Mixtures with similar grouping letters are considered statistically equivalent in terms of APA rut depths. The two mixtures with the lowest APA rut depthswere the 50 percent RAP mixture using the PG 67-22 at optimum and with an additional 0.25 percent asphalt. The two mixtures with the highest APA results were the 50 percent RAP mixtures using the PG 58-28 binder and an additional 0.5 percent virgin asphalt. However, while the rutting susceptibility of the mixtures did increase with the softer binder and additional 0.5 percent asphalt, none of the mixtures exceeded the 5.5 mm APA threshold.

TABLE 14 25% RAP Mixture APA GLM Groupings

Mixture	**Mean Rut Depth, mm**	**Group**
Virgin	2.71	B
PG 67-22 @ Opt.	1.61	B
PG 67-22 @ Opt. + 0.25%	2.09	B
PG 67-22 @ Opt. + 0.5%	5.37	A
PG 58-28 @ Opt.	6.95	A

TABLE 15 50% RAP Mixture APA GLM Groupings

Mixture	Mean Rut Depth, mm	Group
Virgin	2.71	A B
PG 67-22 @ Opt.	1.27	B C
PG 67-22 @ Opt. + 0.25%	0.50	C
PG 67-22 @ Opt. + 0.5%	3.80	A
PG 58-28 @ Opt.	3.90	A

3.7 Summary

The following sections present a summary of the test results for both the 25 and 50 percent RAP mixtures.

3.7.1 25 Percent RAP Mixtures

Linear amplitude sweep test results on the blend of RAP and virgin binders suggest that the most effective way of increasing the fatigue resistance was to use a softer asphalt binder. Increasing the effective virgin asphalt content only slightly increased the fatigue life of the blended binders. This trend was also noticed for the fracture energy comparisons of the 25 percent RAP mixtures. Using the softer grade of asphalt increased the fracture energy of the mixture while additional virgin asphalt did not affect the overall fracture energy of the mixture.

Energy ratio test results indicate that additional virgin binder and using a softer grade of virgin asphalt will increase the mixture's susceptibility for surface cracking; however, these results were indicative of the mixture's rate of creep compliance. The softer the mixture was, the more it would creep. Thus, the energy ratio of the mixture was reduced. All of the 25 percent RAP mixtures had energy ratio's high enough to be used for projects with up to 1 million ESALs per year in climates similar to Florida

Although increasing the amount of virgin binder in the mixture did not statistically improve the performance of the 25 percent RAP mixtures in the Overlay Tester, the results of this test did show a substantial improvement in cracking resistance. The most effective way of increasing the OT cycles to failure was to use a softer grade of virgin binder.

APA test results indicate that a softer binder grade might make the mixture susceptible to rutting in the field. Each of the other three 25 percent RAP mixtures met the criterion for rutting in the field.

Thus, the 25 percent RAP mixture which is expected to have the best performance in terms of both cracking and rutting is the 25 percent RAP mixture with an additional 0.25 percent virgin asphalt. While this mixture statistically had similar OT test results to the 25 percent RAP mixture compacted designed at the optimum asphalt content, the average cycles to failure for the mix with an additional 0.25 percent virgin asphalt was more than 5 times that of the 25 percent RAP mixture at the optimum asphalt content.

3.7.2 50 Percent RAP Mixtures

Using a softer grade of asphalt increased the fatigue life of the virgin-RAP binder blend on the LAS test. Increasing the effective virgin asphalt content did not increase the binder fatigue life. In contrast, the fracture energy of the mixture increased when using either a softer grade of asphalt or an increased effective virgin asphalt content. However, using 0.5 percent additional asphalt in the mixture provided no additional benefit in terms of fracture energy compared to the mixture using 0.25 percent additional asphalt.

Analysis of the energy ratio results shows that the rate of creep compliance dominated the ability to withstand surface cracking. Therefore, the mixtures that contained additional virgin binder or a softer virgin binder that were more compliant had low Energy Ratio results. However, the 50 percent RAP mixture at optimum had the lowest ER due to its low fracture energy. This was the only mixture which did not meet Florida's recommended minimum criterion of 1.95 for trafficking of 1 million ESALs per year. However, it did meet the criterion for trafficking of 500,000 ESALs per year.

The OT cycles to failure were not statistically improved for the 50 percent RAP mixtures by either using a softer grade of asphalt or increasing the amount of virgin asphalt in the mixture. Numerically, the mixture using a PG 58-28 binder at optimum had a fatigue life approximately three times that of the PG 67-22 mixture at optimum asphalt content.

While increasing the effective virgin asphalt content by 0.5 percent or using a softer binder made the mixture more susceptible to rutting in the APA, both mixtures still passed the APA field criterion of 5.5 mm.

The best performing mixture using 50 percent RAP was the mix which used the PG 58-28 binder at the optimum asphalt content. This mixture had an increased fracture energy compared to the 50 percent RAP mixture at the optimum asphalt content. Additionally, while there was not a statistical difference in the OT results, the mixture using the softer binder had a fatigue life more than three times that of the mix at the optimum asphalt content using the standard binder.

CHAPTER 4 ECONOMIC ANALYSIS

While laboratory tests can potentially quantify the effects of either using a softer virgin binder or increasing the volume of virgin binder in asphalt mixtures containing RAP, economic analyses are also needed to determine the financial implications of altering the standard RAP mixtures. Though using RAP will save the contractor monies previously devoted to virgin aggregate and virgin asphalt binder, the savings need to be quantified in terms of the costs required to increase the durability of the mixtures.

4.1 Assumptions

Numerous assumptions were required to conduct the cost analysis of the nine mixtures analyzed in this study. These assumptions are given Table 16. The assumptions include the costs of asphalt binder, aggregate, and RAP. The costs of the aggregate and asphalt binder include the material cost, tax, and freight. The cost of the RAP includes the expense of milling and processing the materials.

The assumptions were coupled with the actual mixtures' asphalt contents, RAP asphalt contents, RAP percentages and virgin aggregate percentages from the designs to determine the total costs of the mixtures in the study. These assumptions are conservative estimates of current costs. The actual values may vary depending on the location of the contractor.

TABLE 16 Assumptions for Economic Analysis

Material	Type	Cost ($/ton)
Asphalt Binder	PG 67-22	$500.00
	PG 58-28	$550.00
Aggregate	Virgin	$15.00
	RAP	$9.00

This cost analysis only includes materials costs. It does not include the cost of adding an additional tank for the softer grade of asphalt or any other additional production costs.

4.2 Material Cost Analysis

In completing the economic analysis, the percent of virgin aggregate, virgin asphalt, RAP aggregate, and RAP binder needed to be assessed for each of the nine mixture types. To determine the total material cost of the mixture (Equation 9), the individual costs of the RAP, aggregate, and virgin binder were individually determined using Equations 10-12.

$$Cost_{Mix} = Cost_{Virgin,Asphalt} + Cost_{Virgin,Aggregate} + Cost_{Rap} \qquad \text{(Equation 9)}$$

$$Cost_{Virgin,Asphalt} = Price_{Virgin,Asphalt} * (AC_{Mix} - AC_{RAP} * \%_{RAP}) \qquad \text{(Equation 10)}$$

$$Cost_{Virgin,Aggregate} = Price_{Virgin,Aggregate} * (\%_{Agg} - \%_{RAP} * (1 - AC_{RAP})) \qquad \text{(Equation 11)}$$

$$Cost_{RAP} = Price_{RAP} * \%_{RAP} \qquad \text{(Equation 12)}$$

Where: Cost_{mix} = material cost for total mixture ($/ton of mix)
$\text{Cost v}_{\text{irgin,Asphalt}}$ = cost of virgin asphalt in mixture ($/ton of mix)
$\text{Cost}_{\text{Virgin,Aggregate}}$ = cost of virgin aggregate in mixture ($/ton of mix)
Cost_{RAP} = cost of RAP in mixture ($/ton of mix)
$\text{Price}_{\text{Virgin,Asphalt}}$ = price of virgin asphalt ($/ton of asphalt)
AC_{mix} = asphalt content of mixture, %
AC_{RAP} = asphalt content of RAP, %
$\%_{\text{RAP}}$ = percent RAP used in mixture by weight of aggregate, %
$\text{Price}_{\text{Virgin, Aggregate}}$ = price of virgin aggregate ($/ton of aggregate)
$\%_{\text{Agg}}$ = percent aggregate in mixture, %
$\text{Price}_{\text{RAP}}$ = price of RAP ($/ton of RAP)

Table 17 summarizes the cost of each material used for the virgin and 25 percent RAP mixtures. The virgin mixture was the most expensive mixture using the previously mentioned assumptions. As seen, using 25 percent RAP at the optimum asphalt content can reduce the cost of an asphalt mixture by approximately 20 percent. Increasing the volume of virgin binder by 0.25 percent increased the cost of the mix by approximately $1.25 per ton of mix. Additionally, while using a softer binder was cheaper than the original virgin mixture, it cost approximately $1.74 per ton more to produce than the 25 percent RAP mixture at optimum using a PG 67-22 binder.

TABLE 17 Material Cost for 25 Percent RAP Mixtures

RAP Content	Binder Grade	AC	Aggregate Cost ($/ton of Mix)	Virgin Binder Cost ($/ton of mix)	RAP Cost ($/ton of mix)	Total Cost ($/ton of mix)	% Savings versus Virgin Mixture
0	67-22	Opt.	$14.10	$30.00	$0.00	$44.59	0.00
25	67-22	Opt.	$10.35	$23.75	$2.25	$35.69	19.96
25	67-22	Opt. + 0.25%	$10.35	$25.00	$2.25	$36.94	17.16
25	67-22	Opt. + 0.5%	$10.35	$26.25	$2.25	$38.19	14.35
25	58-28	Opt.	$10.35	$26.13	$2.25	$37.97	14.85

Table 18 quantifies the cost of each material used for the virgin and 50 percent RAP mixtures. The virgin mixture was the most expensive mixture using the previously mentioned assumptions. As seen, using 50 percent RAP at the optimum asphalt content can reduce the cost of an asphalt mixture by approximately 35 percent. Increasing the virgin binder by 0.25 percent, increased the cost of the mix by approximately $1.25 per ton of mix. Additionally, while using a softer binder was cheaper than the original virgin mixture, it would cost $2.28 per ton more than the 50 percent RAP mixture at optimum using a PG 67-22 binder.

TABLE 18 Cost of 50 Percent RAP Mixtures

RAP Content	Binder Grade	AC	Aggregate Cost ($/ton of Mix)	Virgin Binder Cost ($/ton of mix)	RAP Cost ($/ton of mix)	Total Cost ($/ton of mix)	% Savings versus Virgin Mixture
0	67-22	Opt.	$14.09	$30.50	$0.00	$44.59	0.00
50	67-22	Opt.	$7.04	$17.45	$4.50	$28.99	34.99
50	67-22	Opt. + 0.25%	$7.04	$18.70	$4.50	$30.24	32.18
50	67-22	Opt. + 0.5%	$7.04	$19.95	$4.50	$31.49	29.38
50	58-28	Opt.	$7.04	$19.20	$4.50	$30.73	31.08

It should be noted that all of the binders used in this analysis were not modified by polymers. The results of this analysis would not be valid for contractors who would need to grade bump to a polymer modified binder.

4.3 Summary

Using 25 and 50 percent RAP mixtures at the optimum asphalt content reduced the materials costs by approximately 20 and 35 percent, respectively. An additional $1.25 per ton of mix was added to the cost for each additional 0.25 percent virgin asphalt added to the mixture. Using the softer binder grade (PG 58-28 compared to the PG 67-22) increased the cost of the 25 and 50 percent RAP mixtures at the optimum asphalt contents by $2.28 and $1.74 per ton of mix, respectively.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

This chapter describes the conclusions and recommendations based on the previously detailed research methodology and results.

5.1 Conclusions

The following conclusions can be drawn based on the experimental plan and results. These conclusions are based on laboratory data using some tests DOTs do not commonly use and have not been thoroughly validated in the field.

- Using a softer binder had the greatest impact on improving the fatigue life of both the 25 and 50 percent RAP binder blends based on the LAS binder fatigue test.
- Increasing the effective virgin binder content increased the number of cycles to failure for 25 percent RAP binder blends in the LAS binder fatigue test; however, this trend was not seen for the 50 percent RAP binder blends.
- Using a softer virgin binder grade was the only method which increased the fracture energy of the 25 percent RAP mixtures.
- Using a softer virgin asphalt and increasing the effective virgin binder content increased the fracture energy of 50 percent RAP mixtures. There was no additional benefit of increasing the effective virgin asphalt 0.5 percent beyond optimum binder content.
- The ER decreased when using the softer virgin asphalt or increasing the effective virgin asphalt content of a mixture for both 25 and 50 percent RAP mixtures. The 25 percent RAP mixture using a softer grade of virgin binder had the best OT results. Increasing the effective virgin binder content numerically increased the OT results; however, there was not a statistical difference in the mixtures.
- Neither using a softer virgin binder grade nor increasing the effective virgin asphalt content statistically increased the OT results for the 50 percent RAP mixtures. Using a softer virgin binder grade did numerically increase the cycles until failure by more than three times that of the mixture using the standard binder at the optimum asphalt content.
- The 25 percent RAP mixture with the softer virgin binder grade was the only mixture that failed to meet the NCAT APA test criteria for heavy traffic pavements.
- While using a softer grade of virgin binder or increasing the effective virgin binder content of a mixture can increase binder costs, the net effect of using these techniques in conjunction with 25 or 50 percent RAP can *decrease* the materials costs by 20 to 35 percent.

5.2 Recommendations

Based on this limited study, technical and cost effective options for enhancing the durability of high RAP mixtures appear viable. Further work is needed to validate these solutions in the field. To improve cracking resistance, increase the amount of virgin asphalt by 0.1 percent for every 10 percent of RAP binder in the mixture for up to 30 percent RAP binder. When the RAP binder exceeds 30 percent, a softer grade of asphalt should be used to increase the mixture's resistance to cracking. All mixtures with increased virgin binder content or a softer grade of asphalt should be evaluated with a laboratory rutting test to ensure the mixture will be resistant to permanent deformation in the field.

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APPENDIX A AGGREGATE PROPERTIES

TABLE A.1 Aggregate Gradations for Control Mixture

Sieve Size (mm)	Sieve Size (Inches)	Percent Passing				
		Columbus Granite 89's	**MM Auburn Limestone 8910's**	**Columbus Granite M10's**	**Shorter Natural Sand**	**Total Blend**
12.5	1/2"	100	100	100	100	100.0
9.5	3/8"	99.5	100	100	100	99.8
4.75	# 4	35	99.5	99	99.2	75.1
2.36	# 8	3.3	97.1	86	91.6	58.9
1.18	# 16	1.6	67.1	65	75.2	45.2
0.600	# 30	1.6	51.9	47	46.1	29.5
0.300	# 50	1.6	37.9	31	11.6	17.0
0.150	#100	1.6	25.7	19.7	3.6	10.1
0.075	#200	1.6	16.8	10.6	0.7	5.9
Cold Feed (%)		**36**	**15**	**18**	**31**	**--**

TABLE A.2 Aggregate Gradations for 25 Percent RAP Mixture

Sieve Size (mm)	Sieve Size (Inches)	Percent Passing					
		Columbus Granite 89's	**EAP Limestone 8910's**	**Columbus Granite M10's**	**Shorter Natural Sand**	**RAP**	**Total Blend**
12.5	1/2"	100	100	100	100	100	100
9.5	3/8"	99.5	99.5	100	100	99.2	99.6
4.75	# 4	31.9	99.4	99.3	99.5	83.1	71.7
2.36	# 8	4.9	90.0	88.6	89.3	64.3	53.6
1.18	# 16	2.6	65.4	70.5	70.0	49.5	40.8
0.600	# 30	2.0	47.8	53.5	38.7	34.9	26.0
0.300	# 50	1.6	36.1	36.8	14.0	22.4	14.4
0.150	#100	1.2	27.5	23.0	4.4	14.9	8.7
0.075	#200	0.8	20.2	13.2	0.8	9.5	5.3
Cold Feed (%)		**35**	**12**	**0**	**28**	**25**	**--**

TABLE A.3 Aggregate Gradations for 50 Percent RAP Mixture

Sieve Size (mm)	Sieve Size (Inches)	Percent Passing					
		Columbus Granite 89's	EAP Limestone 8910's	Columbus Granite M10's	Shorter Natural Sand	RAP	Total Blend
12.5	1/2"	100	100	100	100	100	100
9.5	3/8"	99.5	99.5	100	100	99.2	99.5
4.75	# 4	31.9	99.4	99.3	99.5	83.1	74.4
2.36	# 8	4.9	90.0	88.6	89.3	64.3	55.7
1.18	# 16	2.6	65.4	70.5	70.0	49.5	42.9
0.600	# 30	2.0	47.8	53.5	38.7	34.9	27.6
0.300	# 50	1.6	36.1	36.8	14.0	22.4	15.1
0.150	#100	1.2	27.5	23.0	4.4	14.9	8.8
0.075	#200	0.8	20.2	13.2	0.8	9.5	5.1
Cold Feed (%)		**25**	**0**	**0**	**25**	**50**	**--**

TABLE A.4 Consensus Aggregate Properties

Consensus Property	Columbus Granite 89's	EAP Limestone 8910's	Columbus Granite M10's	Shorter Natural Sand	RAP
Bulk Specific Gravity (Gsb)	2.610	2.819	2.707	2.614	2.708
Absorption (%)	1.5	0.5	0.3	0.2	0.5
Crushed Faces (%)	100	N/A	N/A	N/A	NA
(Uncompacted Void Content)	N/A	48.4	50.2	45.8	46.6
Sand Equivalence	N/A	78	72	81	89
Flat and Elongated Particles (%) **	0	N/A	N/A	N/A	NA

** - Weighted Average Based on Gradation (5:1)

APPENDIX B OVERLAY TESTER RESULTS

TABLE B.1 Overlay Tester Results

RAP Content	Binder Content	Binder Grade	Cycles Until Failure				
			1	2	3	Average	COV, %
Virgin	Optimum	67-22	4,873	4,524	3,708	4,368	13.7
25% RAP	Opt.	67-22	137	154	247	179	33.0
25% RAP	Opt. + 0.25%	67-22	434	869	1,486	930	56.9
25% RAP	Opt. + 0.50%	67-22	784	998	548	777	29.0
25% RAP	Opt.	58-28	3,881	2,718	3,826	3,475	18.9
50% RAP	Opt.	67-22	114	220	66	133	59.1
50% RAP	Opt. + 0.25%	67-22	203	122	132	152	29.0
50% RAP	Opt. + 0.50%	67-22	274	108	211	198	42.4
50% RAP	Opt.	58-28	708	205	221	378	75.6

APPENDIX C APA RESULTS

TABLE C.1 APA Results

%RAP	**Binder Content**	**Binder Grade**	**Rut Depth, mm**							
			1	2	3	4	5	6	Average	COV, %
Virgin	Optimum	67-22	0.61	NA	4.39	2.87	3.60	2.08	2.71	53.8
25	Opt.	67-22	3.53	0.57	2.36	1.64	0.51	1.05	1.61	72.9
25	Opt. + 0.25%	67-22	3.30	0.33	2.56	2.08	2.91	1.36	2.09	52.4
25	Opt. + 0.50%	67-22	4.40	4.19	6.79	6.21	6.04	4.59	5.37	20.6
25	Opt.	58-28	5.98	5.52	6.89	6.87	9.58	6.85	6.95	20.3
50	Opt.	67-22	1.82	0.92	1.58	1.04	1.03	1.22	1.27	28.1
50	Opt. + 0.25%	67-22	1.27	0.21	0.26	NA	0.50	0.27	0.50	88.7
50	Opt. + 0.50%	67-22	3.13	2.38	4.80	4.72	4.18	3.60	3.80	25.0
50	Opt.	58-28	2.68	3.02	3.83	4.62	5.27	3.98	3.90	24.8