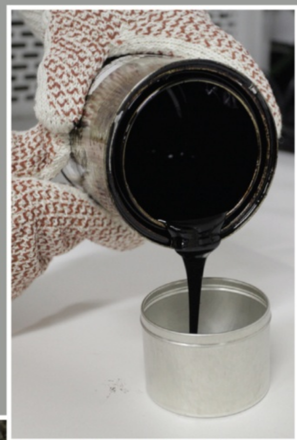
NCAT Report 13-08



ALTERNATIVE METHODS FOR INCREASING THE DURABILITY OF RAP MIXTURES

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J. Richard Willis, Ph.D.
Pamela Turner
Grant Julian
Nam Tran, Ph.D., P.E.
Flavio de Goes Padula, Ph.D.

April 2013

National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

277 Technology Parkway ■ Auburn, AL 36830

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CHAPTER 1 INTRODUCTION

1.1 Background

It is commonly accepted that using reclaimed asphalt pavement (RAP) in asphalt mixtures can provide economic savings to contractors and highway agencies by reducing the demand of both the virgin binder and aggregates in asphalt mixtures (*1*).

Recent increases in crude oil costs have caused escalations in both the cost of virgin asphalt binder and energy. This cost increase can be offset by using more RAP in asphalt mixtures. Recent reports have suggested that material costs can be decreased by 20 to 35 percent (*2*) by using 25 to 50 percent RAP in asphalt mixtures. Although RAP may be used for the construction of a granular base course 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 asphalt mixtures.

Recycled asphalt mixtures may use RAP from a range of sources, but three important concepts should be followed in their use (*3, 4*):

1. The aggregate in the RAP should meet the same requirements as required for virgin aggregates.
2. The moisture content in RAP stockpiles should be controlled at acceptable levels.
3. The recycled asphalt mixture should meet the same specification requirements as that required for virgin mixture.

Most highway agencies have decades of experience with asphalt mixtures containing low to moderate percentages of RAP (i.e., below 25 percent by weight of aggregate). One reason agencies 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 permitting high RAP percentages, agencies want assurance that high RAP mixes will provide satisfactory field performance. If high RAP mixtures cannot perform as well as virgin mixtures or even low content RAP mixtures, methods 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 M 323 are based on levels of RAP percentages (Table 1). Each level 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. Additionally, softer binder grades may prove to be scarce or more expensive when purchased (*5*).

Table 1 Binder Selection Guidelines for RAP Mixtures According to AASHTO M 323

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

Recent research has also suggested that the performance of RAP mixtures might also be related to the volume of the virgin binder in the mixture rather than the performance grade of the virgin binder (2). It has also been hypothesized that WMA might help improve high RAP mixture performance; however, little field data is available to strengthen this theory.

This study was completed as a companion to a previous research study (*2*) which studied the effects of changing the virgin binder grade and content for 25 and 50 percent RAP mixtures. The previous study showed that for 25 percent RAP mixtures, using additional virgin binder would give the greatest resistance to cracking without increasing rutting susceptibility. For the 50 percent RAP mixtures, using the softer grade of virgin binder gave the best mixture performance.

1.2 Objective

This research plan was developed to assess whether increasing the volume of effective virgin binder, using a softer binder, or using a WMA technology aided in improving the durability of mixtures containing high percentages of RAP. The objective of this research was to evaluate how increasing the volume of virgin binder, using a softer grade of virgin asphalt binders affects the durability of RAP mixtures. In addition to changing the grade of the virgin binder, a WMA chemical additive was added to the control RAP mixtures to assess how using this WMA technology affected the mixture's durability and rutting performance.

1.3 Scope of Work

To complete this objective, 10, 25 and 50 percent RAP mixtures were designed using a standard PG 67-22 virgin asphalt binder designed in accordance with AASHTO R35. The asphalt content required to achieve a design of 4 percent air voids will be referred to as the optimum asphalt content. The linear amplitude sweep (LAS) methodology was used to assess the fatigue properties of the blended RAP and virgin binders. 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 percent and 0.50 percent higher asphalt contents and at the optimum asphalt content using a softer PG 58-28 virgin binder rather than the PG 67-22 virgin binder. In addition to the previously described mixtures, samples using a PG 67-22 binder at the optimum asphalt content were made incorporating Evotherm 3G to assess how WMA affects mixture durability.

1.4 Organization of this Report

This report is divided into four chapters. Chapter 2 provides the laboratory testing plan and methodologies used to perform the research. Chapter 3 provides the results of the aforementioned tests. Chapter 4 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, using a WMA chemical additive, or reducing the asphalt binder performance grade will have on the cracking resistance and rutting of RAP mixtures.

2.1 Testing Plan

Multiple laboratory tests were conducted to quantify how increasing the volume of effective virgin binder, decreasing the performance grade of the virgin asphalt binder, or using a WMA chemical additive 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
- 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.
- 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 T 308-10 and the asphalt content was determined without the use of a correction factor. The gradation of the RAP aggregate was determined using AASHTO T 30-10. The bulk specific gravity of the RAP aggregate was quantified on the material recovered from the ignition test using AASHTO T 84 and T 85. In addition to the specific gravities, the consensus properties of the RAP stockpile aggregate were determined.

The RAP binder was extracted using ASTM D2171 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 10 percent, 25 percent and 50 percent RAP mixtures in accordance with AASHTO M 323-07, *Standard Specification for Superpave Volumetric Mix Design*, and AASHTO R 35-04, *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 by targeting four percent air voids. Each mix was designed using a 12.5 mm nominal maximum aggregate size (NMAS), and the gradations consisted of three aggregate stockpiles and a locally available RAP stockpile. Two different stockpiles of granite were used, #89's and #7's, obtained from Vulcan Materials' Barin Quarry in Columbus, Georgia. The natural sand was from Martin-Marietta Sand and Gravel in Shorter, Alabama. The RAP was sampled from East Alabama Paving in Opelika, Alabama. For the 10 and 25 percent RAP designs, the RAP stockpile was left unfractionated; however, to achieve acceptable volumetrics, the RAP stockpile was fractionated over the No. 4 sieve for the 50 percent RAP design.

A PG 67-22 virgin binder was the normal base binder used in the mixture design. The softer binder used in this study was a PG 58-28 binder which was a reduction in both the high and low temperature grades of the virgin binder. It should be noted that a reduction of the virgin binder grade is not standard practice for lower RAP mixtures; however, at the request of the research sponsor, NCAT assessed its effect on mixture properties for the 10 percent RAP mixture. When used, a chemical WMA additive was added to the asphalt binder during mixing at a prescribed rate of 0.53 percent by weight of the asphalt binder. These binders were mixed in the laboratory with the previously determined blend of aggregates and RAP. The mixtures without the WMA technology were all mixed between 297°F and 307°F when using a PG 67-22 binder and 287°F and 297°F when using the PG 58-28 binder. Both of these mixtures were compacted at 275°F. When using the WMA technology, the mixing temperature range was reduced to 280°F to 290°F and the compaction temperature was 250°F. All the samples were short-term aged in the oven at a temperature of 275°F for two hours before compaction as recommended by in NCHRP Report 714 (*15*). The design pills were compacted to an N_{des} level of 60 gyrations and a target height of 115 ±5 mm.

The bulk specific gravity of the compacted specimens was determined according to AASHTO T 166, and the maximum theoretical specific gravity of the loose mix was determined in accordance with AASHTO T 209. 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 (LAS) test 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, *Method A* with trichloroethylene (TCE) as the solvent. Once extracted, ASTM D5404 was used to remove the solvent from the asphalt binder. No additional aging of the RAP binder was completed for the LAS. 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. Complete documentation of the testing procedure used to conduct the LAS testing procedure has been documented elsewhere (*2*).

The binder fatigue performance parameter (N_f) is the end result of the LAS testing method. N_f can be changed during the testing procedure by adjusting the strain values to account for differences in pavement structure. Higher strain values correspond to thinner pavements or heavier traffic loading while lower strain magnitudes correspond to thicker pavements or lighter traffic loads. An example of the data is shown in Figures 1 and 2 (*7*). The damage intensity is then coupled with the continuum damage theory to predict N_f.

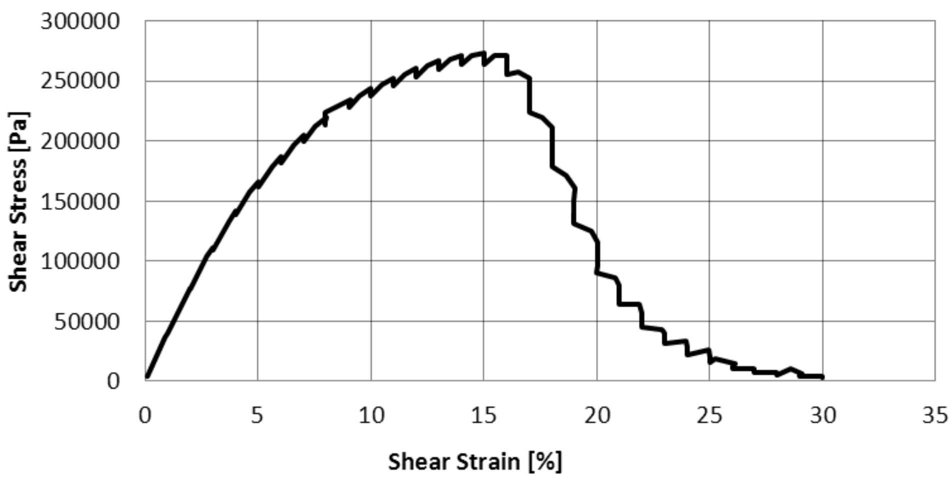

FIGURE 1 Plot of shear stress versus shear strain (*7*)

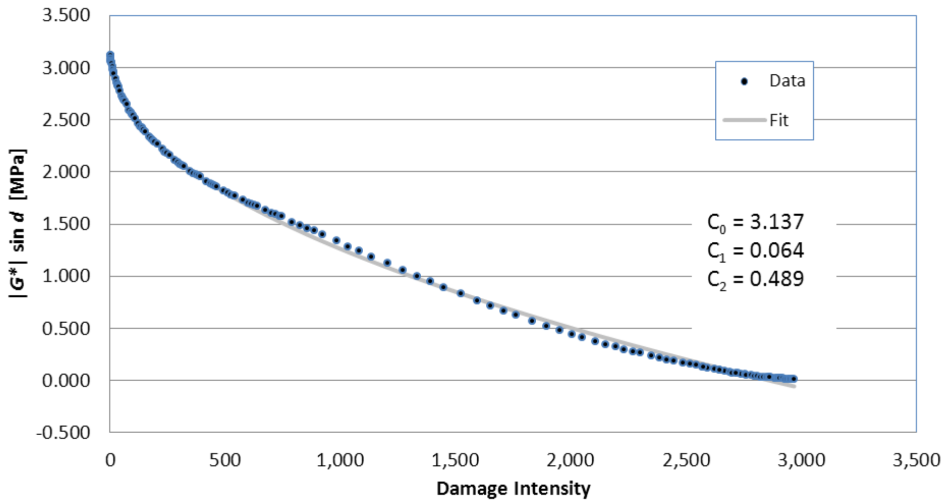

FIGURE 2 Damage intensity plot (*7*)

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 (*8*). This testing procedure has been used in past research cycles at the NCAT Pavement Test Track as a predictor of whether or not a mixture would be susceptible to top-down cracking (*9*). Florida has also used this methodology to predict and assess resistance to top-down cracking on its infrastructure (*8*). 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 in diameter by approximately 38 mm thick, cut from gyratory compacted samples (Figure 3). The target air voids for the cut specimens was 7 ± 0.5 percent. The hot mix asphalt (HMA) mixtures were aged for four hours at the compaction temperature while the WMA mixtures were aged for only two hours at the compaction temperature.

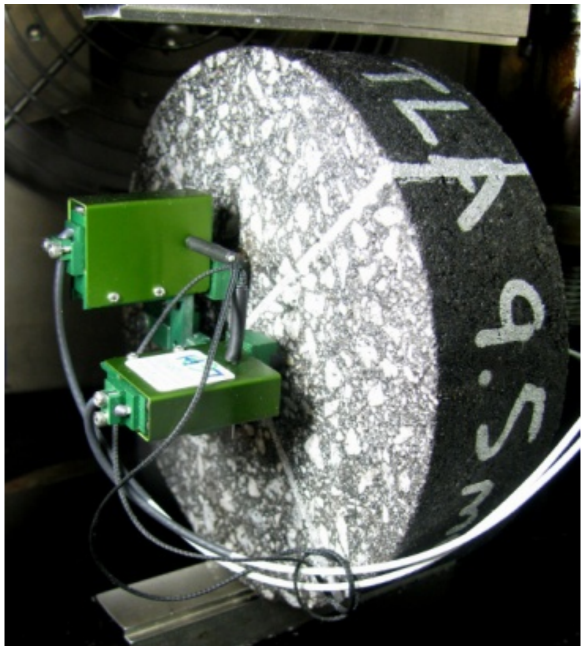

FIGURE 3 Energy ratio test specimen setup

Detailed testing procedures and data interpretation methods for the three testing protocols are described elsewhere (*8, 9, 10*). The results from these tests were then used to evaluate each mixture's surface cracking resistance using Equation 1. Data analysis was performed using a software package developed at the University of Florida. The details of the software operation are documented elsewhere (*10*). 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.

$$ER = \frac{DCSE_f\left[7.294\times10^{-5}\times\sigma^{-3.1}(6.36-S_t)+2.46\times10^{-8}\right]}{m^{2.98}D_1} \quad (1)$$

where:

ER = energy ratio
$DCSE_f$ = dissipated creep strain energy at failure
σ = tensile stress at the bottom of the asphalt layer, 150 psi
S_t = tensile strength
D_1, m = power function parameters

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 4). 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 5). Three replicates with air voids 7 +/- 1 percent after trimming were tested. Each sample was short-term oven aged as previously described in Section 2.5.

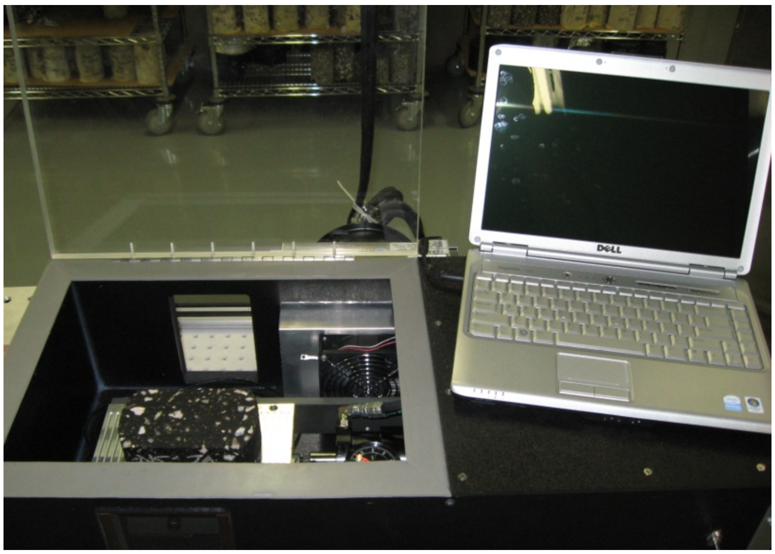

FIGURE 4 Overlay tester

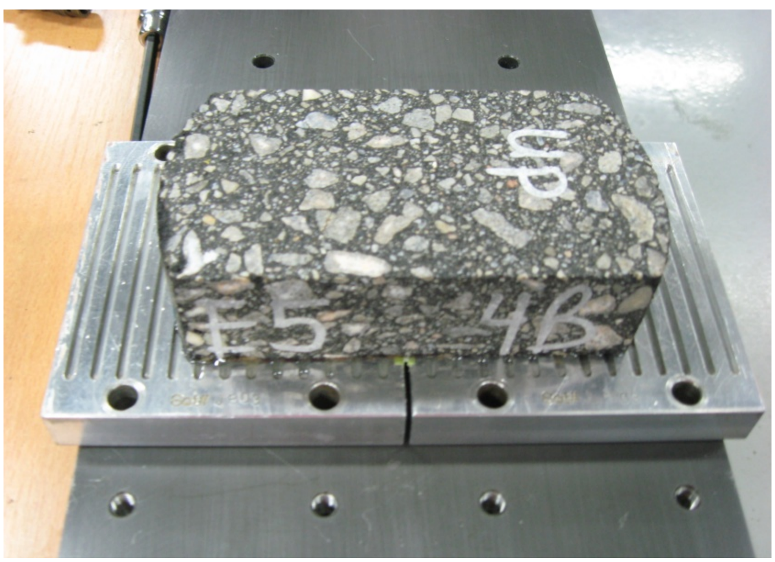

FIGURE 5 Overlay tester specimen

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 6). Loading occurs at a rate of one cycle every ten seconds with a sawtooth waveform (Figure

7). 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 percent reduction in load magnitude from the first cycle (*11*).

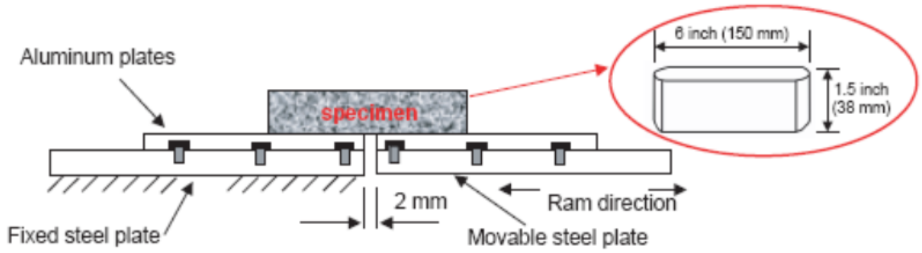

FIGURE 6 Overlay tester specimen (*11*)

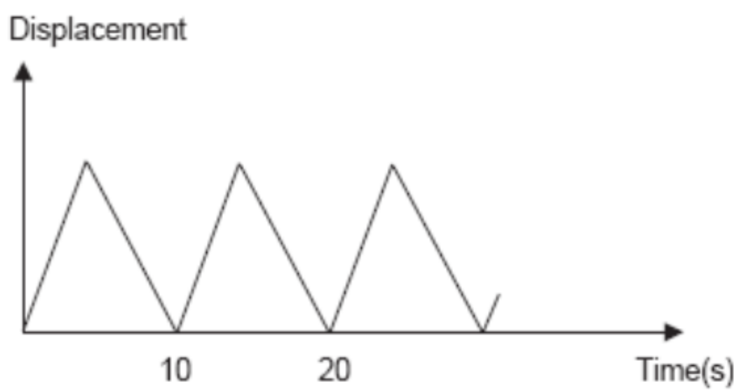

FIGURE 7 Loading form of the overlay tester (*11*)

TxDOT 248-F specifies a maximum opening displacement of 0.025 inches, which is equal to about 32 percent strain on the specimen. However, past research has shown that using this crack opening displacement can instantaneously fail RAP mixtures (*12*). Therefore, to get reliable and usable data, it was determined that the crack opening displacement needed to be reduced. Previous research had shown that an opening displacement of 0.017 inches was still a harsh condition for testing high RAP mixtures (*12*); however, if the crack opening was too small, a low RAP mixture might not fail.

Two previous studies at NCAT have used 0.013 inches as displacements for high RAP mixtures. While this displacement is not based on scientific theory, it provides a more appropriate displacement which could provide a range of material responses while still being able to achieve failure within the confines of the software (*2*).

2.7 Asphalt Pavement Analyzer

The rutting susceptibility of asphalt mixtures is commonly assessed using the Asphalt Pavement Analyzer (APA) (Figure 8). 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. The samples were short-term oven aged as described in Section 2.5.

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 (*13*).

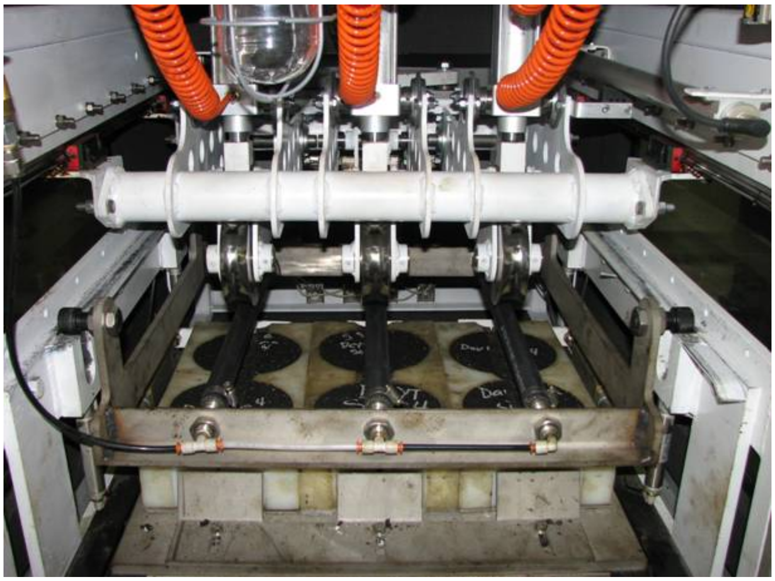

FIGURE 8 Asphalt Pavement Analyzer.

CHAPTER 3 LABORATORY TEST RESULTS

This 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. It should be noted that statistical analyses between the RAP contents were not conducted. The research was designed to assess how to improve mix designs at specific RAP contents and not compare and contrast their behavior.

3.1 RAP Characterization

After extracting and recovering the RAP binder for characterization, it was then tested to determine its Performance Grade (PG) binder properties using AASHTO M 320. 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. Table 4 shows the asphalt content and specific gravities of the RAP material.

TABLE 4 RAP Properties

Aggregate	Asphalt Content, %	G_{sb}	G_{sa}
RAP	5.33	2.708	2.744
Fine RAP (-#4)	5.91	2.674	2.704
Coarse RAP (+#4)	3.24	2.636	2.711

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 Appendix A. The first binder was a PG 67-22 (AASHTO Designation PG 64-22). 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 M 320. The test results are given in Table 5.

TABLE 5 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 for the 10, 25, and 50 percent RAP designs is given in Tables 6-8. According to AASHTO M 323, the minimum voids in mineral aggregate (VMA) requirement for a 12.5 mm mixture is 14.0 percent. The voids filled with asphalt (VFA) requirement is 65-75 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. When the asphalt contents increased by 0.25 and 0.5 percent, it was noted that the VMA of the asphalt mixtures decreased below 14 percent for the 10 and 50 percent RAP mixtures designs. Additional dust could not be removed from these mixtures to increase the VMA; therefore, the mix designs, while not ideal, were used for the research.

TABLE 6 10% RAP Mix Design Properties

Property	**10% RAP**		
Mix Version	Opt.	Opt. +0.25%	Opt. + 0.5%
AC, %	5.10	5.35	5.60
AC_{RAP}, %	0.53	0.53	0.53
AC_{Virgin}, %	4.57	4.82	5.07
RAP Binder/Total Binder, %	10.39	9.91	9.46
Air Voids, %	4.0	3.4	2.4
VMA, %	14.0	13.60	13.50
VFA, %	69.8	76.1	82.3
Effective AC, %	4.22	4.47	4.72
Dust/Asphalt Ratio	0.98	0.93	0.87

TABLE 7 25% RAP Mix Design Properties

Property	**25% RAP**		
Mix Version	Opt.	Opt. + 0.25%	Opt. + 0.5%
AC, %	5.05	5.30	5.55
AC_{RAP}, %	1.33	1.33	1.33
AC_{Virgin}, %	3.72	3.97	4.22
RAP Binder/Total Binder, %	26.34	25.09	23.96
Air Voids, %	4.0	3.4	2.5
VMA, %	14.1	14.05	14.1
VFA, %	70.7	76.1	81.6
Effective AC, %	4.33	4.57	4.83
Dust/Asphalt Ratio	0.97	0.91	0.85

TABLE 8 50% RAP Mix Design Properties

Property	**50% RAP**		
Mix Version	Opt.	Opt. + 0.25%	Opt. + 0.5%
AC, %	5.25	5.50	5.75
AC_{RAP}, %	2.02	2.02	2.02
AC_{Virgin}, %	3.23	3.48	3.73
RAP Binder/Total Binder, %	38.48	36.73	35.13
Air Voids, %	4.0	3.5	2.7
VMA, %	14.1	13.75	13.85
VFA, %	71.0	75.5	80.7
Effective AC, %	4.30	4.56	4.82
Dust/Asphalt Ratio	0.86	0.82	0.77

Moisture susceptibility testing was performed on the three completed mix designs in accordance with AASHTO T 283. Table 9 gives a summary of the TSR results for the three mixtures. AASHTO M 323 requires mixtures to have a tensile-strength ratio of at least 0.80. All three mixtures met this requirement using 0.5 percent ArrMAZ ad-here LOF 6500 anti-strip by weight of the virgin binder.

TABLE 9 Moisture Susceptibility Results

Mixture	**Average Conditioned Strength, psi**	**Average Unconditioned Strength, psi**	**TSR**
10% RAP	109.2	121.2	0.90
25% RAP	125.8	131.6	0.96
50% RAP	120.0	129.6	0.93

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 10, 25 and 50 percent 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 percent. The increase in virgin binder should theoretically increase the fatigue life of the binder, as asphalt pavements with higher asphalt contents tend to have better fatigue life. This is due to the increased asphalt binder film thickness surrounding the aggregate particles. The reduction in overall binder stiffness due to the increased virgin binder and filling in the voids between the coated particles should also improve the binder fatigue life.

Table 10 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 9-11 compare the results graphically by RAP content.

TABLE 10 LAS Test Results

Binder	% RAP	Binder Content	N_f @ 2.5% Strain	N_f @ 5.0% Strain
			Average	*Average*
PG 67-22	0	Opt.	346,216	14,127
PG 67-22	10	Opt.	68,981	2,682
PG 67-22	10	Opt. + 0.25%	75,562	3,047
PG 67-22	10	Opt. + 0.50%	68,816	2,735
PG 67-22	10	Opt. + WMA	69,402	2,794
PG 58-28	10	Opt.	972,326	33,984
PG 67-22	25	Opt.	73,532	2,026
PG 67-22	25	Opt. + 0.25%	75,238	2,196
PG 67-22	25	Opt. + 0.50%	80,422	2,300
PG 67-22	25	Opt. + WMA	84,683	2,429
PG 58-28	25	Opt.	506,143	14,669
PG 67-22	50	Opt.	84,356	1,882
PG 67-22	50	Opt. + 0.25%	103,643	2,330
PG 67-22	50	Opt. + 0.50%	79,140	1,867
PG 67-22	50	Opt. + WMA	112,190	2,481
PG 58-28	50	Opt.	327,497	8,182

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 to show 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 10 percent RAP mixture, these reductions were approximately 80 percent at both strain levels. The 25 percent RAP mixture at optimum asphalt saw a 78 percent reduction in fatigue life at 2.5 percent strain and an 86 percent reduction at 5.0 percent strain. For the 50 percent RAP mixture, the reductions were 75 and 87 percent for the 2.5 and 5.0 percent strain loadings respectively.

While the 25 percent RAP binder test results follow the expected trends, deviations from expectations occurred in the 10 and 50 percent binder blends. For example, the 10 percent RAP mix design increased its binder fatigue life by adding an additional 0.25 percent virgin asphalt to the binder blend; however, using an additional 0.5 percent virgin asphalt added no additional fatigue life to the optimum blend. This same trend was noticed with the 50 percent RAP binder blends; however, it should be noted that the 50 percent RAP binder blends had longer fatigue lives than the 10 percent RAP binder blends.

Overall, 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 was 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 was most likely due to the increased intermediate temperature stiffness. The PG 58-28 binder was still fairly soft at intermediate temperatures as evidenced by its true grade intermediate temperature, 15.5°C. The PG 67-22 binder was stiffer with an intermediate true grade temperature of 23.9°C. The addition of the RAP binder did not have as great an effect on the intermediate temperature properties of the PG 67-22 binder as it did on the PG 58-28 binder.

Using a WMA additive to increase the fatigue life of the binder blends had more of an effect at higher RAP contents. At 10 percent RAP, the WMA additive had little to no effect on the predicted fatigue life. When 25 percent RAP was used, a 15 percent increase in fatigue life was seen at low strains and a 20 percent increase was seen at the higher strain level. This increase in fatigue life was even more pronounced for the 50 percent RAP mixtures, as the WMA increased fatigue lives by approximately 32 percent at both strain levels.

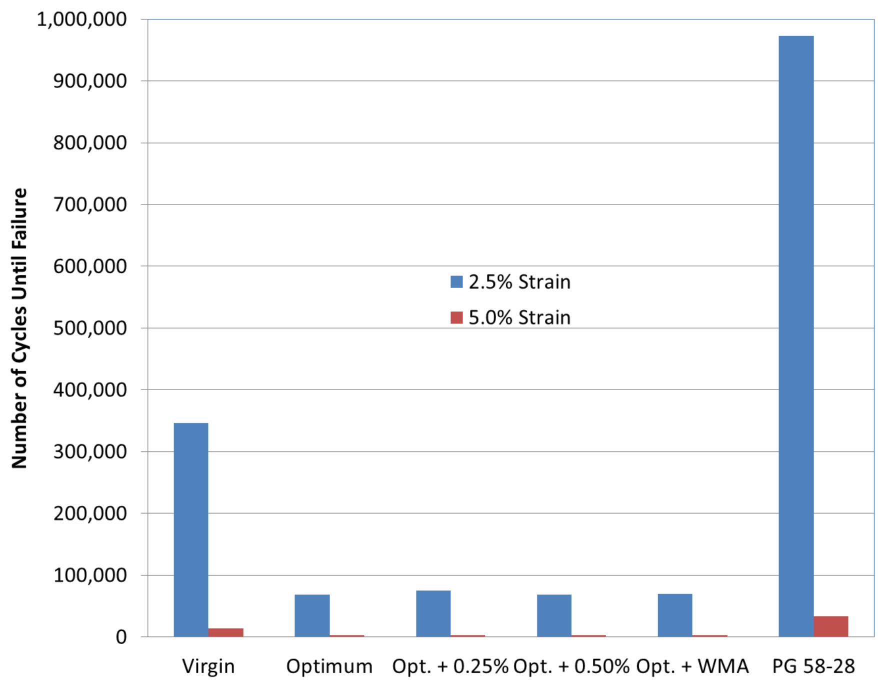

FIGURE 9 LAS Results for 10 percent RAP mixtures

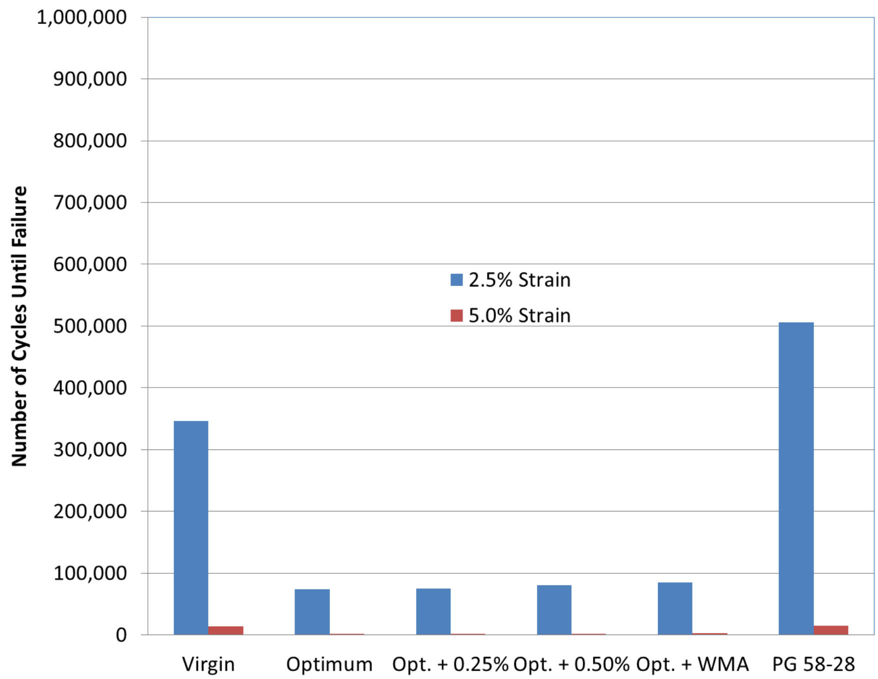

FIGURE 10 LAS results for 25 percent RAP mixtures

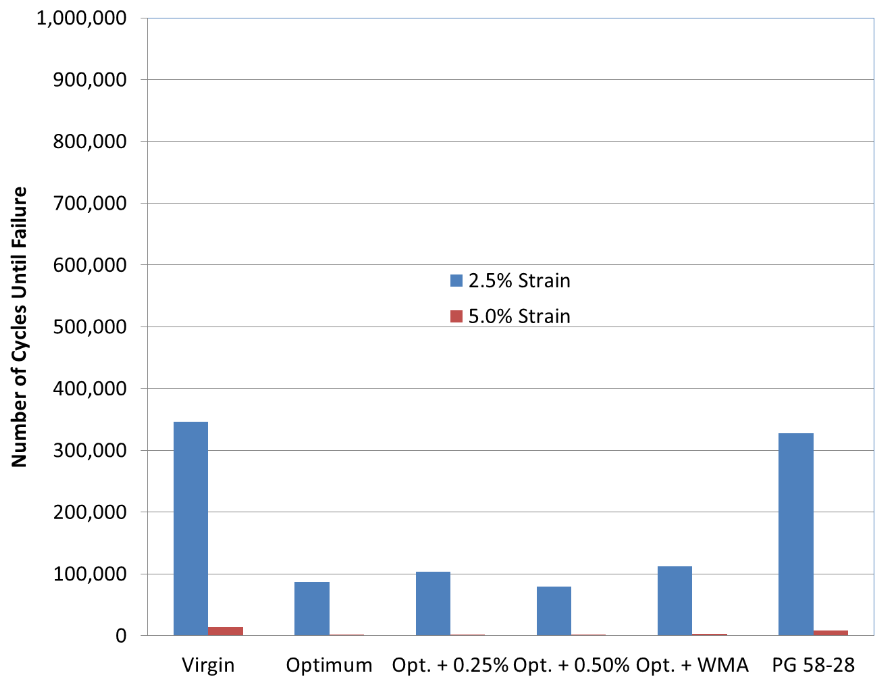

FIGURE 11 LAS results for 50 percent RAP mixtures

Overall, using the softer binder had the greatest impact on blended binder fatigue life. The use of WMA additives shows the greatest affect when used in conjunction with high 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 FEs for the RAP mixtures are shown in Figures 12-14. The FE of mixtures has been linked to fatigue performance at WesTrack (*14*); however, there are no generally accepted criteria for minimum FE requirements.

The numerical results show that using the PG 58-28 improves the FE for both the 10 and 50 percent RAP mixtures when compared to the 10 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 10 percent RAP mixture by approximately 300 percent while using a softer binder for the 50 percent RAP mixture increased the fracture energy of the mixture by 100 percent. There was a slight reduction in the FE of the 25 percent RAP mixture when using the softer binder, possibly due to more creep in the specimen.

Increasing the effective volume of the virgin binder increased the FE of the 10 percent RAP mixtures as did using WMA additives. While using an additional quarter percent virgin binder increased the FE of the 10 percent RAP mixture by only 30 percent, using an additional half percent virgin binder increased the FE by 160 percent. A 140 percent increase was seen with the WMA additive.

For the 25 percent RAP mixtures, using WMA, increased virgin binder content, or a softer binder did not positively affect the mixture's FE.

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 71 percent. Further increasing the amount of virgin asphalt in the mixture by 0.5 percent only improved the FE by another 40 percent. A 100 percent increase in FE was measured when using the WMA additive.

The General Linear Model (GLM) was used to assess statistical differences between the different durability options for each of the three RAP contents at a five percent level of significance. Statistical differences were found between the durability options for both the 10 (p = 0.000) and 50 percent (p = 0.010) RAP mixtures while no statistical differences were found between the options for the 25 percent RAP mixtures (p = 0.709).

Tukey-Kramer groupings at a five percent significance level were used to statistically determine which mix iterations of the 10 and 50 percent RAP mixtures had the highest FE. Table 11 shows the statistical groupings for the 10 and 50 percent RAP mixtures. For the 10 percent RAP mixtures despite not being common practice, using the softer binder produced the mix with the highest FE. WMA technologies and using 0.5 percent additional asphalt increased the FE statistically; however, despite a numerical increase in the FE, using 0.25 percent additional binder did not statistically increase the FE of the mixture compared to its optimum asphalt content.

For the 50 percent RAP mixtures, the WMA additive and using 0.5 percent additional asphalt were the only two options that produced FE results statistically different than the 50 percent RAP mixture at the optimum asphalt content.

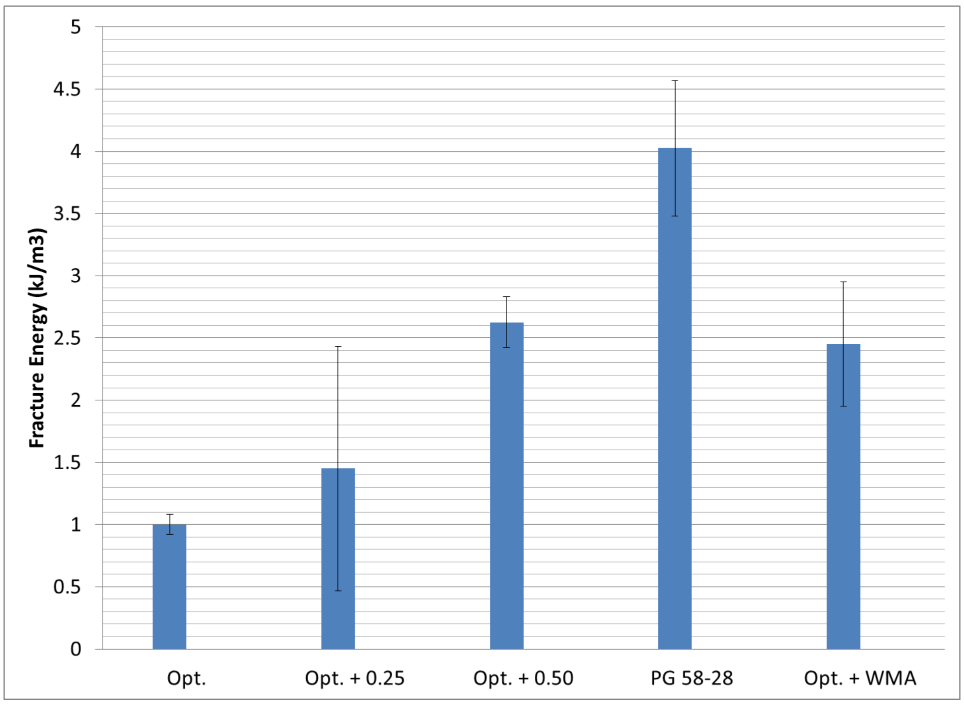

FIGURE 12 Fracture energy results for 10 percent RAP mixtures

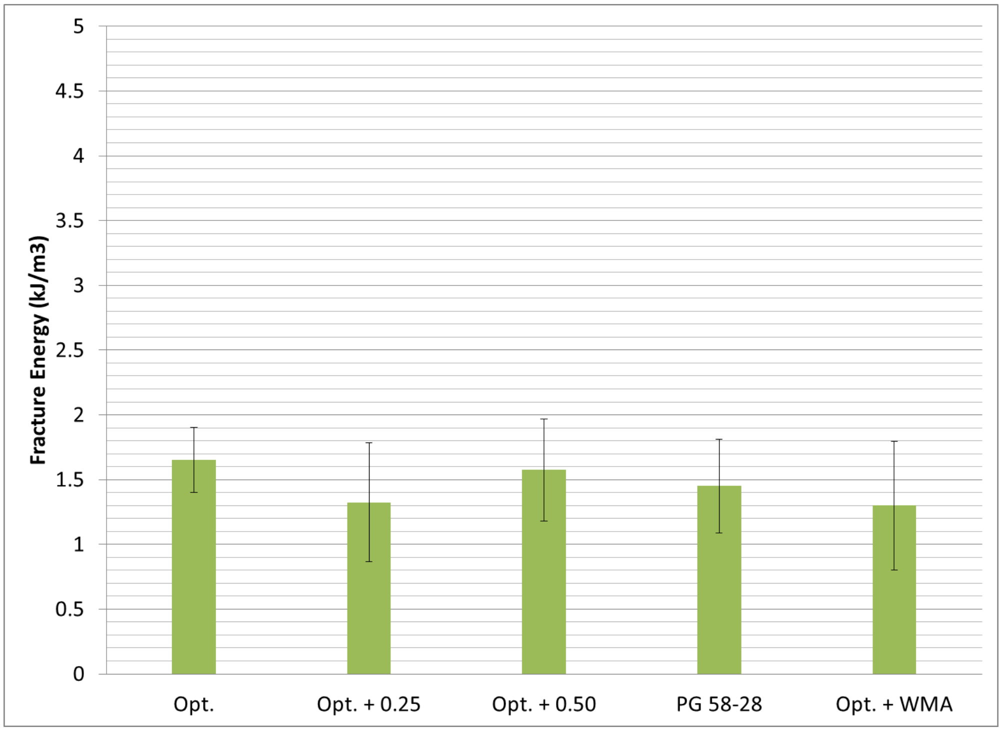

FIGURE 13 Fracture energy results for 25 percent RAP mixtures

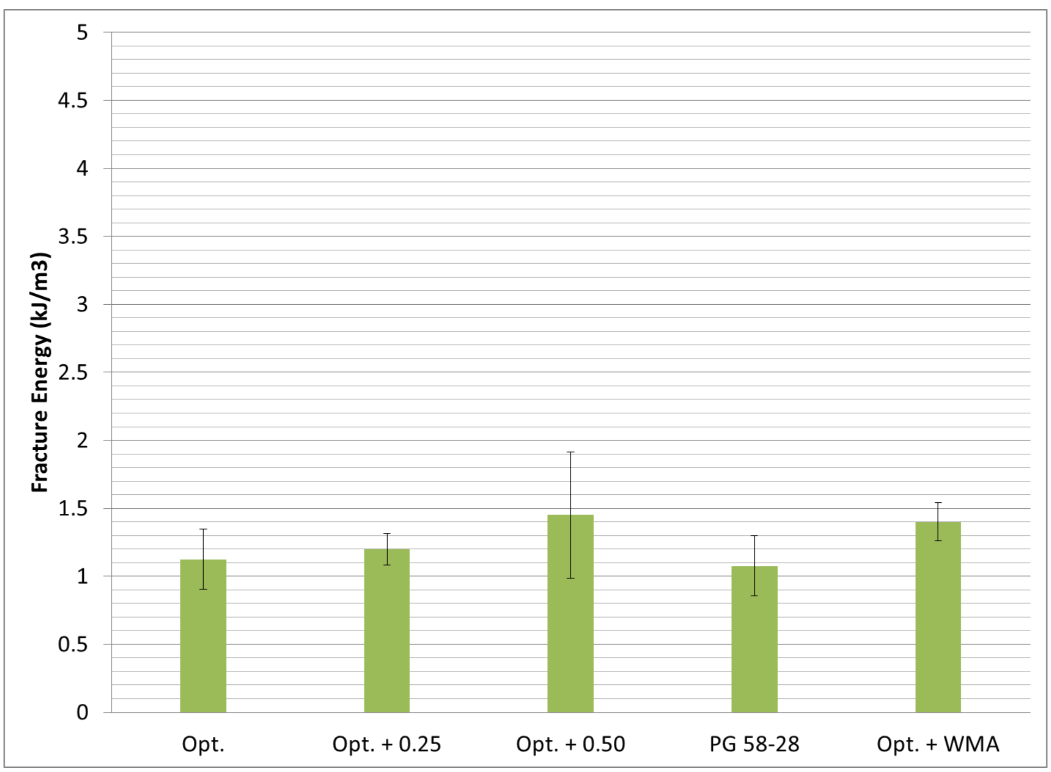

FIGURE 14 Fracture energy results for 50 percent RAP mixtures

TABLE 11 FE Tukey-Kramer Groupings

Mix Option	10% RAP	50% RAP
Opt.	C	B
Opt. + 0.25% AC	B C	A
Opt. + 0.50% AC	B	A
PG 58-28	A	A B
Opt. + WMA	B	A

The results of these tests were mixed in that the FE of both the 10 and 50 percent RAP mixtures was increased statistically by using WMA additives or an additional 0.5 percent virgin asphalt. However, the 25 percent RAP mixture with the optimum asphalt content using the standard binder had the greatest fracture energy of the 25 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 are provided in Tables 12-14 while Figures 15-17 graphically compare the energy ratios of the 25 and 50 percent RAP mixtures.

Of the five 10 percent RAP mixtures, the mixture with the lowest ER was the mixture using the PG 67-22 binder at the optimum asphalt content. Increasing the virgin binder content by 0.25 percent only slightly improved (11 percent) the mixture performance; however, using 0.5 percent additional binder almost doubled the ER of the control mixture. The mix with the best performance was the 10 percent RAP mixture using the WMA additive; however, using 0.5 percent additional binder, WMA, or a softer binder all increased the allowable traffic the mixture could withstand without surface cracking.

TABLE 12 Energy Ratio Test Results for 10 Percent RAP Mixtures

	PG 67-22 @ Opt.	PG 67-22 @ Opt. + 0.25%	PG 67-22 @ Opt. + 0.5%	PG 58-28 @ Opt.	PG 67-22w/ WMA
m-value	0.4162	0.4537	0.4447	0.4695	0.3904
FE (kJ/m^3)	1.0	1.3	2.6	4.0	2.4
$DSCE_{HMA}$ (kJ/m^3)	0.821	1.123	2.366	3.747	2.192
$DSCE_{MIN}$ (kJ/m^3)	0.5962	0.7463	0.9324	1.6910	0.6901
ER	1.38	1.50	2.53	2.21	3.17
Rate of Creep Compliance (s/GPa x 10^{-9})	2.888	3.958	4.712	9.261	3.134
Allowable Traffic (ESALs/year)	<500,000	<500,000	<1,000,000	<1,000,000	<1,000,000

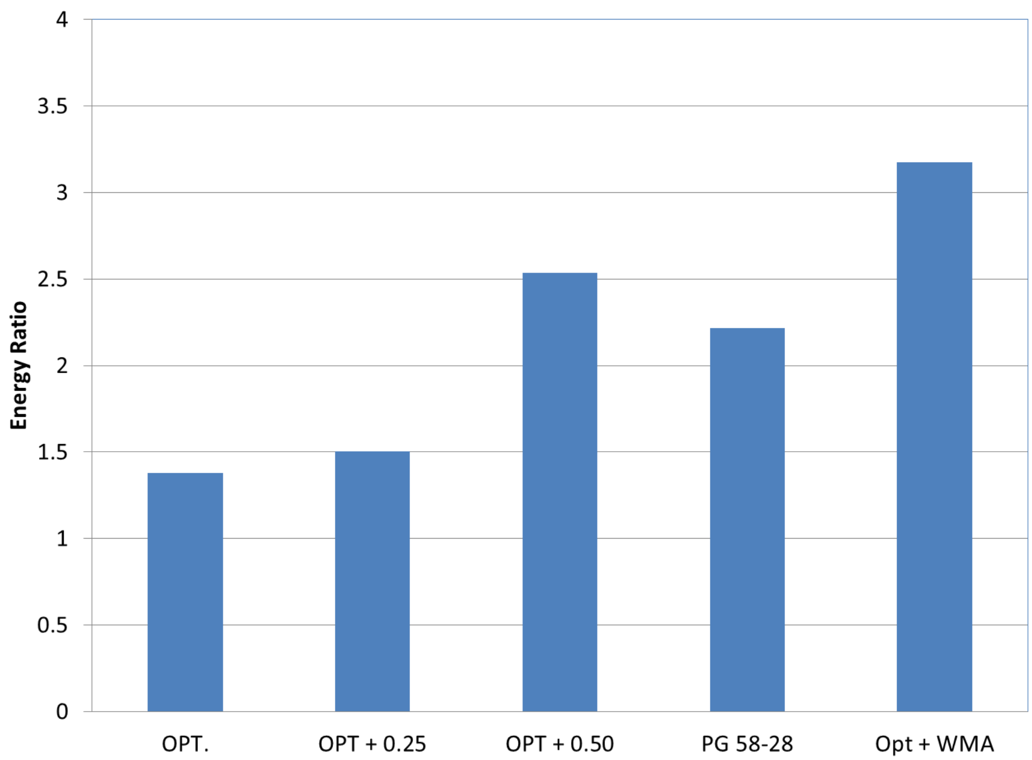

FIGURE 15 Energy ratio results for 10 percent RAP mixtures

All five 25 percent RAP mixtures had ER values great enough to withstand less than 1,000,000 ESALs of traffic per year. However, the mixture which had the greatest numerical ER was the PG 67-22 mixture at the optimum asphalt content. Past research has shown two of the biggest contributors to determining the ER are FE and rate of creep compliance. If the FE is small, then the ER will be small. Conversely, if the rate of creep compliance is small, then then ER will be large. The 25 percent RAP mixture that had the highest ER also had the highest FE and a smaller rate of creep compliance. Thus, this accounted for the higher ER when compared to some of the other mixtures.

TABLE 13 Energy Ratio Test Results for 25 Percent RAP Mixtures

	PG 67-22 @ Opt.	**PG 67-22 @ Opt. + 0.25%**	**PG 67-22 @ Opt. + 0.5%**	**PG 58-28 @ Opt.**	**PG 67-22w/ WMA**
m-value	0.381	0.368	0.372	0.383	0.343
FE (kJ/m^3)	1.6	1.3	1.6	1.4	1.3
$DSCE_{HMA}$ (kJ/m^3)	1.368	1.073	1.381	1.188	1.103
$DSCE_{MIN}$ (kJ/m^3)	0.3861	0.3864	0.4806	0.5489	0.4198
ER	3.54	2.78	2.87	2.16	2.62
Rate of Creep Compliance (s/GPa x 10^{-9})	1.645	1.679	2.092	2.456	1.381
Allowable Traffic (ESALs/year)	<1,000,000	<1,000,000	<1,000,000	<1,000,000	<1,000,000

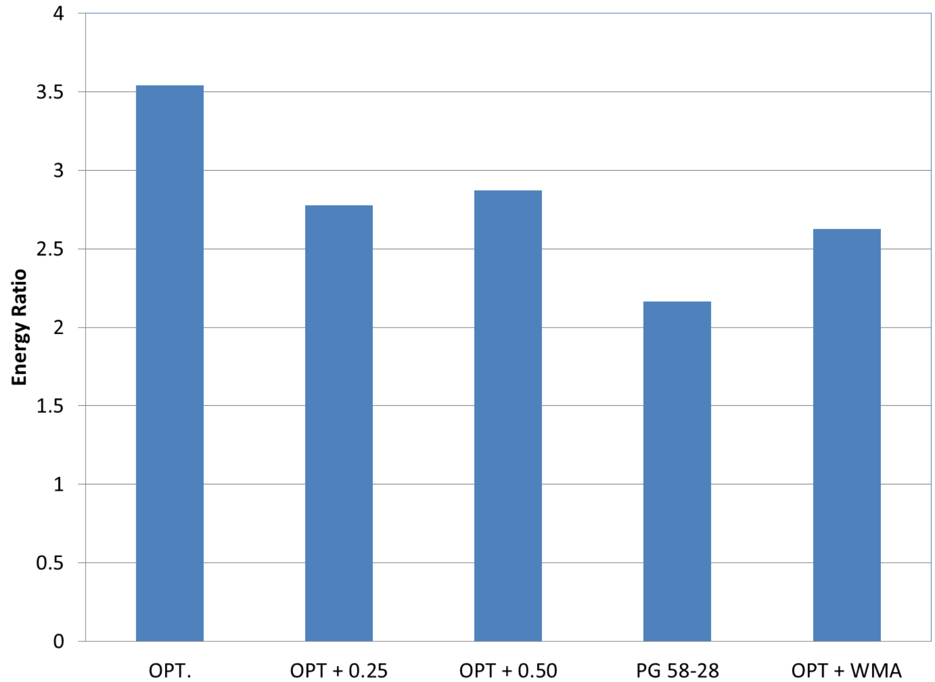

FIGURE 16 Energy ratio results for 25 percent RAP mixtures

The 50 percent RAP mixtures somewhat followed the expected trend. Adding virgin binder increased the ER of the mixtures at both the quarter and half percent level by one traffic level for the quarter percent and two traffic levels for the half percent virgin binder increase. Using the softer grade of asphalt only increased the mixture's resistance to surface cracking by one traffic level. The method of increasing mixture durability that had the greatest influence on the ER results was using 50 percent RAP at the standard binder grade with the WMA additive. In this case, the mixture was able to resist less than 1,000,000 ESALs of traffic per year and showed a 100 percent increase in the ER compared to the 50 percent RAP control mixture.

TABLE 14 Energy Ratio Test Results for 50 Percent RAP Mixtures

	PG 67-22 @ Opt.	**PG 67-22 @ Opt. + 0.25%**	**PG 67-22 @ Opt. + 0.5%**	**PG 58-28 @ Opt.**	**PG 67-22w/ WMA**
m-value	0.3866	0.3876	0.3925	0.4123	0.3598
FE (kJ/m^3)	0.7	1.2	1.5	1.1	1.4
$DSCE_{HMA}$ (kJ/m^3)	0.567	0.977	1.321	0.937	1.193
$DSCE_{MIN}$ (kJ/m^3)	0.411	0.527	0.584	0.542	0.442
ER	1.38	1.85	2.26	1.73	2.70
Rate of Creep Compliance (s/GPa x 10^{-9})	1.91	2.38	2.72	2.62	1.91
Allowable Traffic (ESALs/year)	<250,000	<500,000	<1,000,000	<500,000	<1,000,000

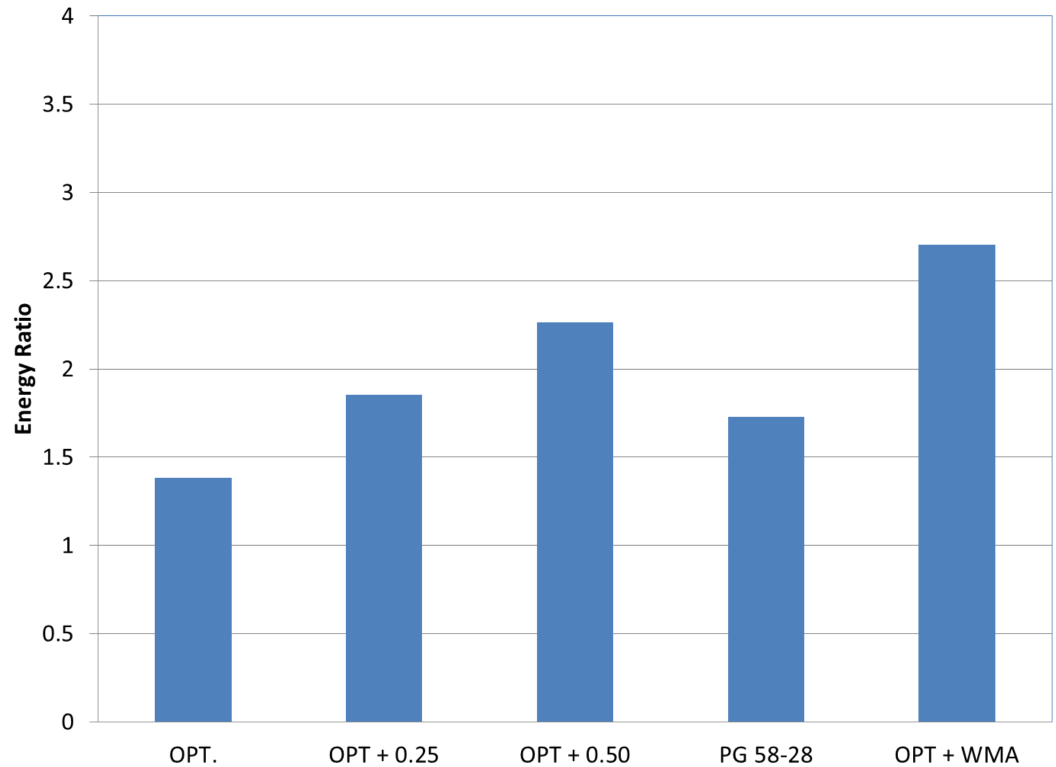

FIGURE 17 Energy ratio results for 50 percent RAP mixtures

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 Figures 18-20. The tails on the test represent one standard deviation from the average based on three tests.

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 10 percent RAP mixture lasted 813 cycles before the stiffness dropped by 93 percent; however, the 25 percent RAP mixture only lasted 108 cycles. The 50 percent RAP mixture at the optimum asphalt content had an average life of 183 cycles before it achieved failure. Thus, increasing the RAP content beyond 10 percent 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 (*2, 11, 12*).

The General Linear Model ($\alpha = 0.05$) was used to assess differences in OT results for the five 10 percent RAP mixtures. According to this statistical analysis (Table 15), there are no statistical differences between any of the variables. This statistical finding is most likely due to the high variability of the data. While there were no statistical differences, changing the binder grade, volume or using a softer binder increased the cycles until failure by at least 65 percent. The two mixtures which performed the best were the PG 58-28 mixture at optimum content and the PG 67-22 mixture using an additional quarter percent binder.

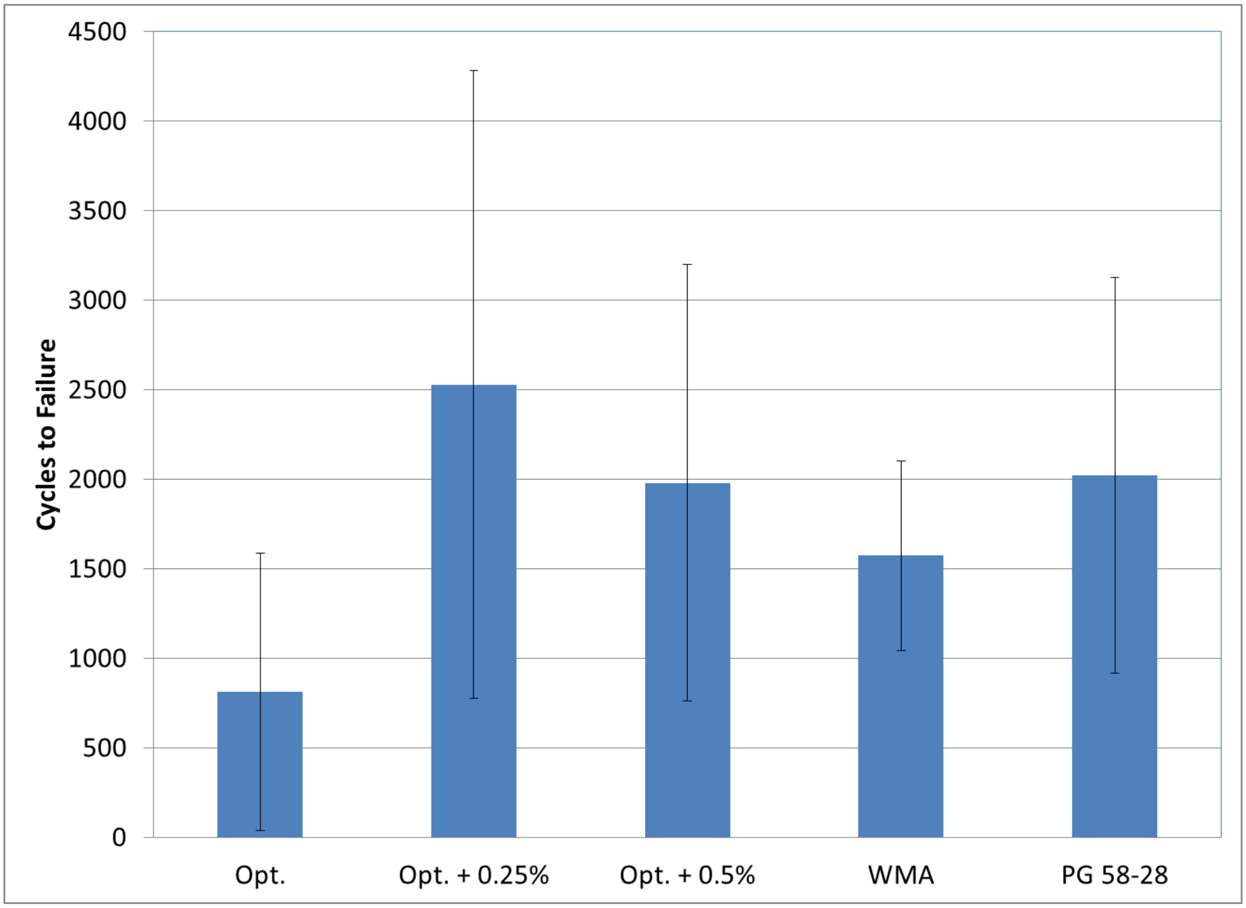

FIGURE 18 10 percent RAP overlay tester results

TABLE 15 10 Percent RAP OT Statistical Groupings

Mixture	Mean Cycles to Failure	Grouping
PG 67-22 @ Opt.	813	A
PG 67-22 @ Opt. + 0.25%	2529	A
PG 67-22 @ Opt. + 0.50%	1468	A
PG 67-22 + WMA	1574	A
PG 58-28 @ Opt.	2023	A

The General Linear Model (α = 0.05) was also used to assess differences in OT results for the five 25 percent RAP mixtures. According to this statistical analysis (Table 16), there are no statistical differences between any of the variables. This statistical finding is again probably due to the high variability of the data. While there were no statistical differences, changing the binder grade, volume or using WMA increased the cycles until failure by at least 78 percent.

The mixture which incorporated WMA with the RAP and the mixture which used a softer binder had the highest numerical cycles until failure.

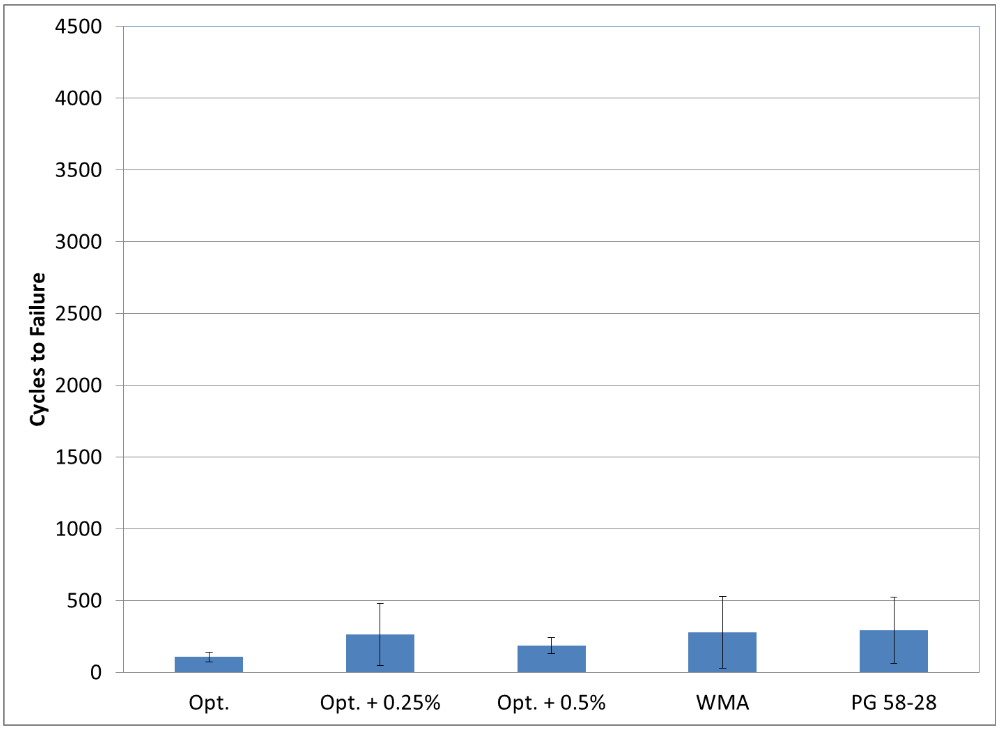

FIGURE 19 25 percent RAP overlay tester results

TABLE 16 25 Percent RAP OT Statistical Groupings

Mixture	Mean, Cycles to Failure	Grouping
PG 67-22 @ Opt.	108	A
PG 67-22 @ Opt. + 0.25%	264	A
PG 67-22 @ Opt. + 0.50%	189	A
PG 67-22 + WMA	294	A
PG 58-28 @ Opt.	278	A

The General Linear Model (α = 0.05) was also used to assess differences in OT results for the five 50 percent RAP mixtures. According to this statistical analysis and due to high testing variability (Table 17), there are no statistical differences between any of the variables. Using a softer binder with 50 percent RAP increased the mixture performance by 326 percent. Incorporating WMA in the mixture had minimal effect on the mixture performance.

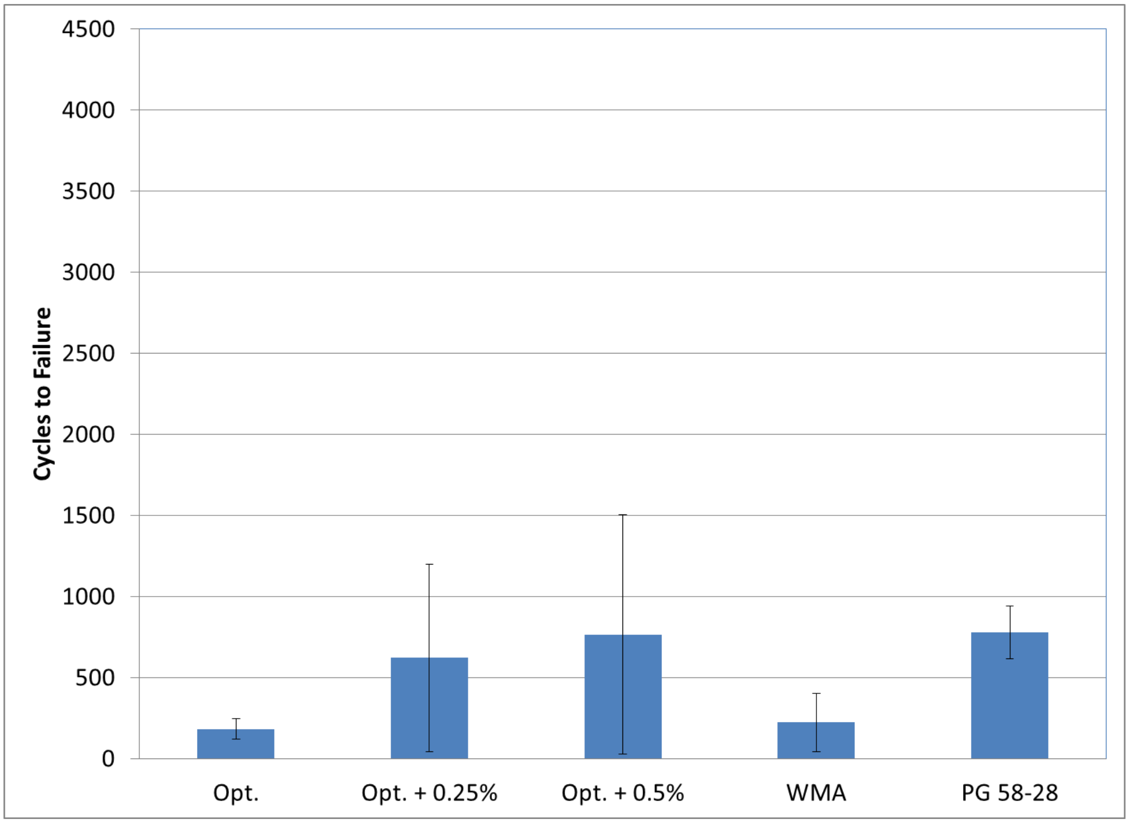

FIGURE 20 50 percent RAP overlay tester results

TABLE 17 50 Percent RAP OT Statistical Groupings

Mixture	Mean, Cycles to Failure	Grouping
PG 67-22 @ Opt.	183	A
PG 67-22 @ Opt. + 0.25%	622	A
PG 67-22 @ Opt. + 0.50%	766	A
PG 67-22 + WMA	223	A
PG 58-28 @ Opt.	780	A

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 RAP mixtures are shown in Figures 21-23.

The GLM ($\alpha = 0.05$) was used to statistically compare the rutting of the of the five 10 percent RAP mixtures (Table 18). Statistically speaking, the mixture with the most rutting was the 10 percent RAP mixture with the PG 58-28 binder at the optimum asphalt content. All of the mixtures which used additional asphalt content or WMA were statistically equivalent to the 10 percent RAP mixture at the optimum asphalt content; therefore, they did not negatively influence the rutting performance of the mixtures.

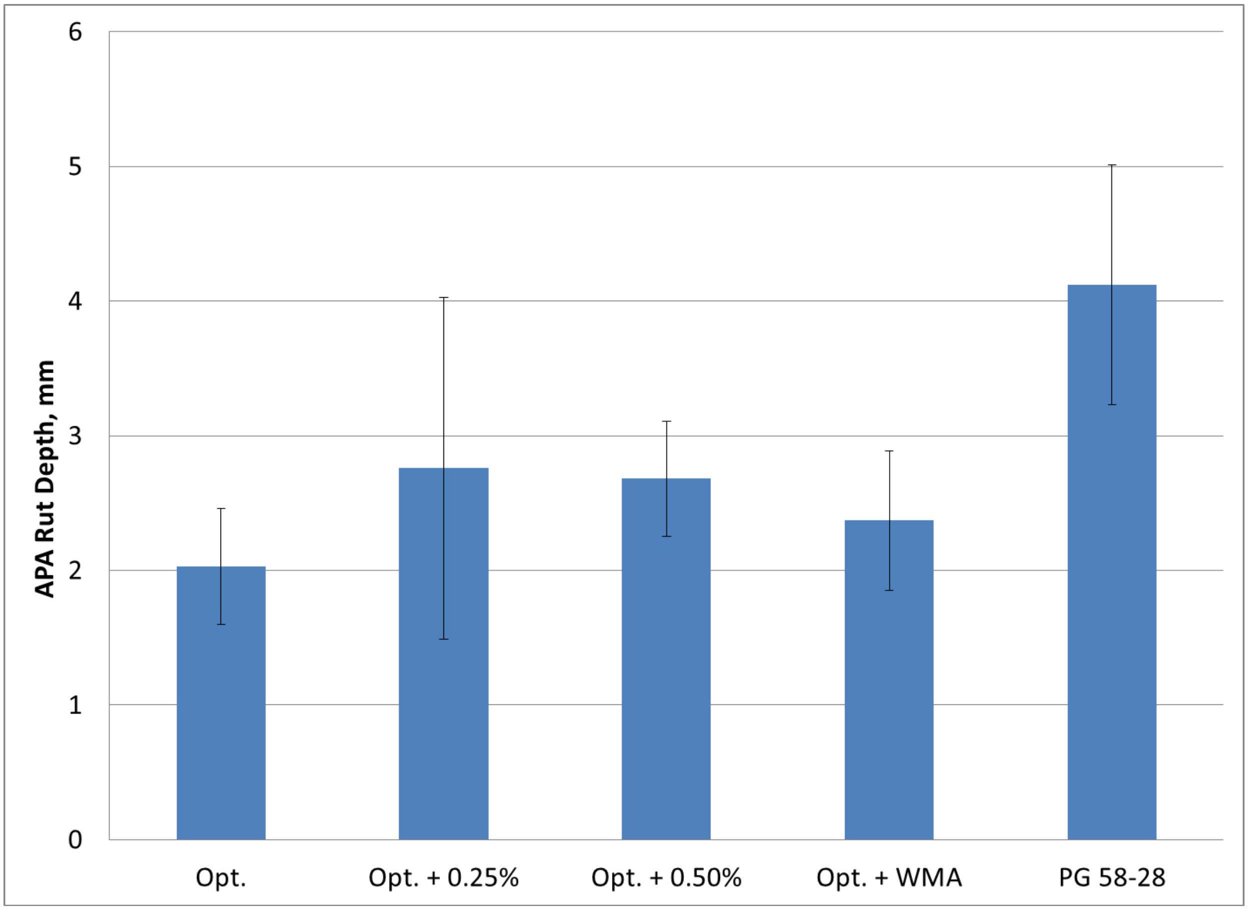

FIGURE 21 10 percent RAP APA test results

TABLE 18 10% RAP Mixture APA GLM Groupings

Mixture	Mean Rut Depth, mm	Group
PG 67-22 @ Opt.	2.03	B
PG 67-22 @ Opt. + 0.25%	2.76	B
PG 67-22 @ Opt. + 0.5%	2.68	B
PG 67-22 + WMA	2.37	B
PG 58-28 @ Opt.	4.12	A

The GLM (α = 0.05) was also used to statistically compare the rutting of the 25 percent RAP mixtures (Table 19). Three mixtures were grouped into one classification with the greatest rutting susceptibility. These three mixtures were the 25 percent RAP mixture with the softer binder, the mixture at the optimum asphalt content, and a mixture using an additional quarter percent binder. While the mixture with the PG 67-22 binder at optimum asphalt content was statistically equivalent to the worst performing rutting mixtures, it was also statistically equivalent to the best performing mixtures in terms of rutting (PG 67-22 at optimum + 0.5 percent and the mixture using WMA additives). It should be noted that based on these test results and a maximum allowable rut depth of 5.5 mm, none of these mixtures are considered susceptible to rutting.

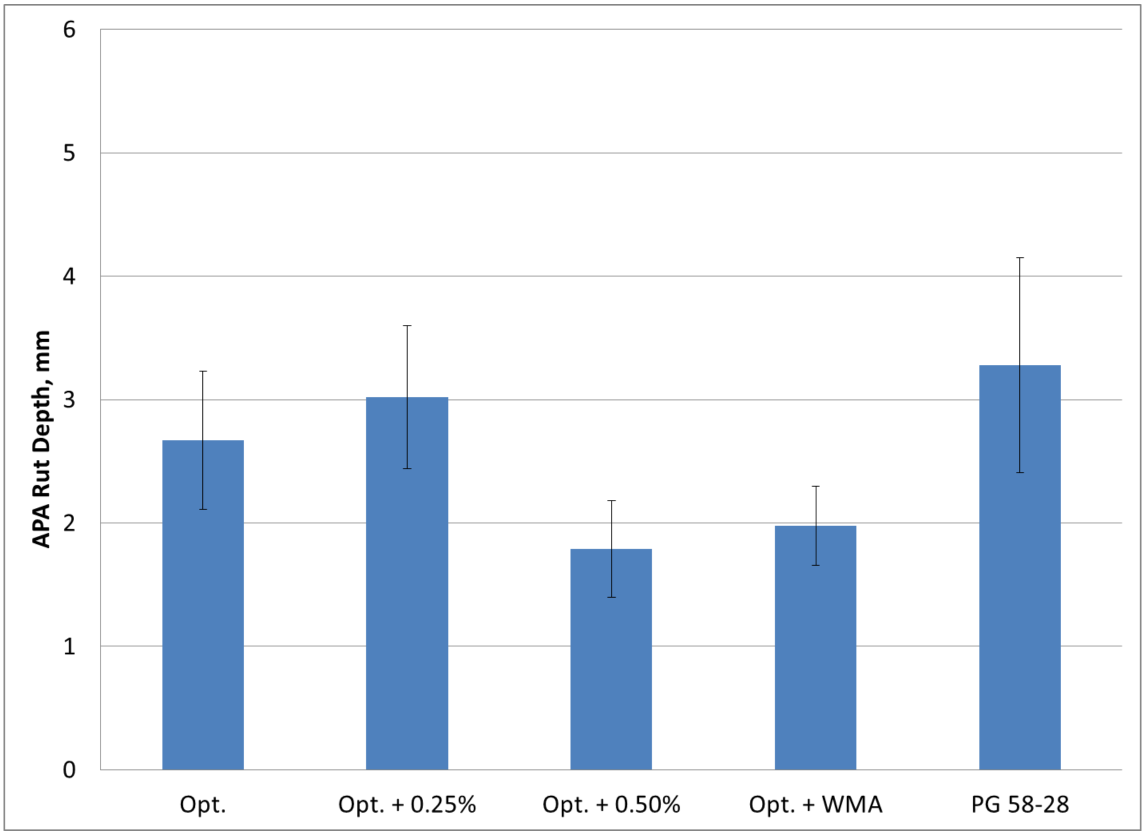

FIGURE 22 25 percent RAP APA test results

TABLE 19 25% RAP Mixture APA GLM Groupings

Mixture	Mean Rut Depth, mm	Group
PG 67-22 @ Opt.	2.67	A B
PG 67-22 @ Opt. + 0.25%	3.02	A
PG 67-22 @ Opt. + 0.5%	1.79	B
PG 67-22 + WMA	1.98	B
PG 58-28 @ Opt.	3.28	A

The GLM (α = 0.05) was also used to statistically compare the rutting of the of the five 50 percent RAP mixtures (Table 20). Two sets of test results were statistically grouped together. Statistically speaking, the mixture which had the least amount of rutting was the 50 percent RAP mixture at optimum + 0.25 percent asphalt. All of the other four mixtures were statistically equivalent. Again, these results indicate that none of the mixtures would be considered susceptible to rutting.

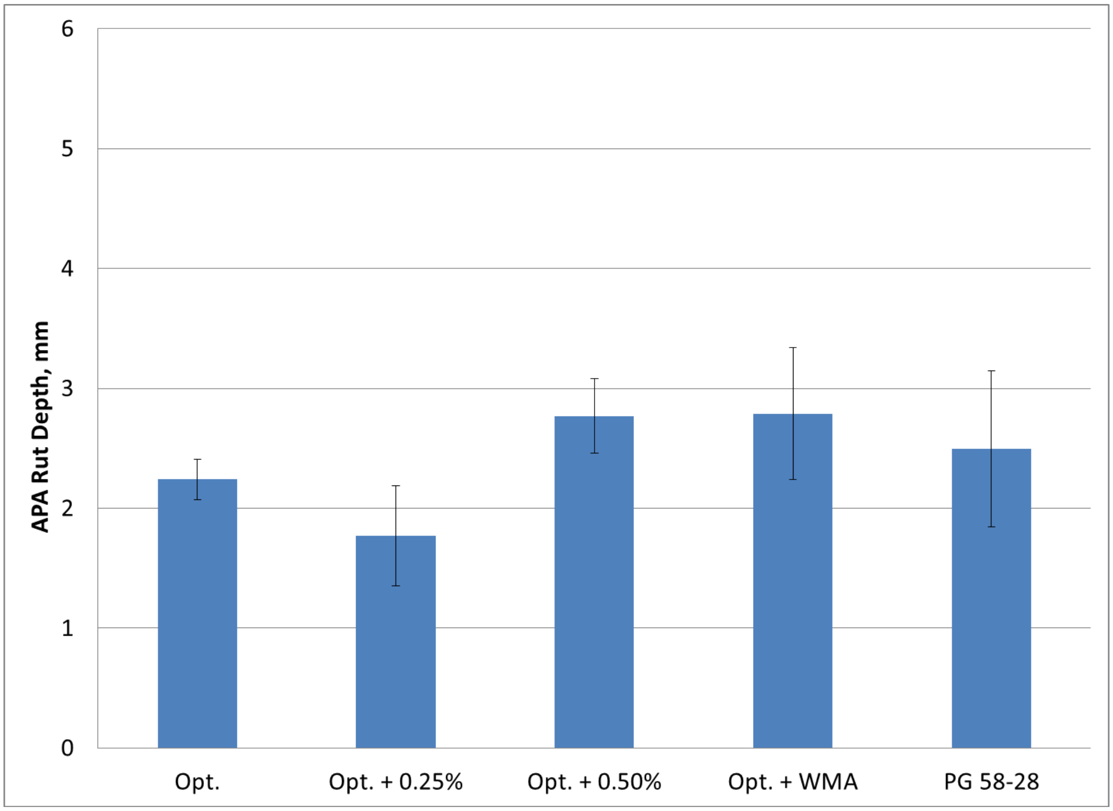

FIGURE 26 50 percent RAP APA test results

TABLE 20 50% RAP Mixture APA GLM Groupings

Mixture	Mean Rut Depth, mm	Group
PG 67-22 @ Opt.	2.24	A B
PG 67-22 @ Opt. + 0.25%	1.77	B
PG 67-22 @ Opt. + 0.5%	2.77	A
PG 67-22 + WMA	2.79	A
PG 58-28 @ Opt.	2.50	A B

3.7 Summary

The following sections present a summary of the test results for three different RAP content mixtures.

3.7.1 10 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 and using WMA only slightly changed the fatigue life of the blended binders.

The FE of the mixtures was positively affected by using a softer binder. Both using an additional half percent asphalt and WMA additives had the second greatest effect on improving the FE test results. Energy ratio test results indicate that the three mixtures with the highest FE also had the highest ER ratio. All three of these mixtures would be considered resistant to top-down cracking in Southeastern states for traffic levels less than 1,000,000 ESALs.

Although increasing the amount of virgin binder in the mixture did not statistically improve the performance of the 10 percent RAP mixtures in the Overlay Tester, the results of this test did show a substantial numerical improvement in cracking resistance. The most effective way of increasing the OT cycles to failure was to use an additional quarter percent of asphalt.

APA test results indicate that a softer binder grade might increase the rutting susceptibility of the RAP mixtures. Therefore, one should ensure that the mixture is resistant to rutting before placing the mixture on a roadway.

The 10 percent RAP mixtures which are expected to have the best performance in terms of both cracking and rutting are the RAP mixture with an additional 0.5 percent asphalt or WMA additives. These mixtures improved both the FE and ER of the mixtures without increasing the rutting susceptibility of the RAP mixture at the optimum asphalt content.

3.7.2 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 and using WMA only slightly changed the fatigue life of the blended binders.

The FE of the mixtures was not affected by changing the binder content, grade, or using a WMA; however, the ER of the mixture was reduced by changing the binder content, grade, or using a WMA. While this reduction was evident, all of the mixtures were still able to withstand the most stringent loading case based on current recommendations.

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 numerical improvement in cracking resistance. The most effective way of increasing the OT cycles to failure was to use an additional quarter percent of asphalt, use WMA, or soften the binder grade.

APA test results show that using softer binders, WMA additives and increased binder volume did not negatively affect the rutting susceptibility of the mixtures.

The 25 percent RAP mixtures expected to have the best performance in terms of both cracking and rutting are the RAP mixture with the WMA and the softer binder grade. This is based on increasing the reflective cracking resistance of the mixture in the OT. The mixtures increased OT performance without decreasing the rutting or cracking resistance below commonly assumed thresholds. However, it should be noted that the test results for the 25 percent RAP mixture were inconsistent and highly variable. Additional testing should be conducted to further validate or substantiate any conclusions.

3.7.3 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 WMA additive or increased 0.5 percent effective virgin asphalt content. Using 0.5 percent additional asphalt in the mixture provided the greatest benefit to FE. While the additional virgin binder content showed the greatest improvement to FE, using the WMA had the greatest impact on ER. The mixtures using a half percent additional virgin binder or WMA were the only two to meet the criterion for the most rigorous trafficking. The other mixtures would be appropriate for lower volume roads.

The OT cycles to failure were not statistically improved for the 50 percent RAP mixtures by using any of the theorized methods. 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. The additional half percent virgin asphalt also showed increased performance; however, these test results were highly variable.

All five mixtures should be resistant to rutting in the APA.

The best performing mixtures using 50 percent RAP were the mix which used the 0.5 percent virgin asphalt above optimum and the mix with a softer binder. These mixtures had increased fracture energy and ER 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 CONCLUSIONS AND RECOMMENDATIONS

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

4.1 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. Field verification is critical of any laboratory finding before implementation becomes widespread.

- Using a softer binder had the greatest impact on improving the fatigue life of all the RAP binder blends based on the LAS binder fatigue test.
- Increasing the effective virgin binder content had little effect on the LAS test results.
- Using a 0.5 percent additional virgin asphalt, and the WMA technology improved the FE of both 10 and 50 percent RAP mixtures; however, no increase in FE was noticed for the 25 percent RAP mixtures. Using a softer asphalt only statistically increased the FE for the 10 percent RAP mixture.
- The Energy Ratio decreased for the 25 percent RAP mixtures that used the softer virgin asphalt or had an increased asphalt content.. Using a half percent additional asphalt or WMA showed the greatest Energy Ratio increase for the 10 and 50 percent RAP mixtures.
- Overlay test results were not statistically affected by added asphalt, softer virgin binder, or WMA at any RAP content.
- For the 10 percent RAP mixture, using a softer binder increased the APA rutting results, but the results were less than 5 mm and would be acceptable for moderately trafficked roadways. APA results for the higher RAP content mixtures were not detrimentally affected by using a softer virgin asphalt, a higher asphalt content, or WMA.

4.2 Recommendations

Although the data is somewhat inconsistent, there appears to be some general trends. 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. When using less than 25 percent RAP, using an additional 0.5 percent virgin asphalt or incorporating a WMA technology in the RAP mixture should provide additional durability. At 25 percent RAP, a softer binder or WMA technologies should be used to increase the mixture durability. Finally, at 50 percent RAP, an additional 0.5 percent most consistently had the greatest impact on mixture durability. It should be noted that these results do not correlate with results of the previous RAP durability study (*2*). In the previous study, using additional asphalt provided the best benefits at 25 percent and using a softer binder was the most effective way of increasing mixture durability at 50 percent RAP. This shows that there is not a one-size-fits-all method for ensuring mixture durability. Choosing between additional asphalt and softer binders may require highway agencies and contractors to assess which method is best on a case-by-case basis using local materials incorporated in the mix designs.

When using alternative technologies to increase mixture durability, one must ensure the mixture will not become susceptible to rutting. These options should be validated in the field and further analyzed on a regional basis. The authors also understand that using a different WMA additive or foaming technology may change the performance of the mixtures. Finally, state agencies and contractors should conduct cost analyses to determine if adding additional binder, a softer binder, or using a WMA technology would provide the most cost-effective solution when similar results are seen as options.

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APPENDIX A
AGGREGATE PROPERTIES

TABLE A.1 Aggregate Gradations for 10% RAP Mixture

Sieve Size (mm)	Sieve Size (Inches)	Percent Passing					
		Columbus Granite 7's	Columbus Granite 89's	EAP Limestone 8910's	Shorter Natural Sand	Unprocessed RAP	Total Blend
19.0	3/4"	100.0	100.0	100.0	100.0	100.0	100.0
12.5	1/2"	95.2	100.0	100.0	100.0	100.0	98.5
9.5	3/8"	51.8	99.5	99.5	100.0	99.2	84.3
4.75	#4	7.4	31.9	99.4	99.5	83.1	47.4
2.36	#8	1.8	4.9	90.0	89.3	64.3	32.7
1.18	#16	1.1	2.6	65.4	70.0	49.5	24.4
0.600	#30	1.0	2.0	47.8	38.7	34.9	16.0
0.300	#50	0.9	1.6	36.1	14.0	22.4	9.7
0.150	#100	0.8	1.2	27.5	4.4	14.9	6.3
0.075	#200	0.6	0.8	20.2	0.8	9.5	4.1
Cold Feed (%)		**32**	**31**	**13**	**14**	**10**	**--**

TABLE A.2 Aggregate Gradations for 25 Percent RAP Mixture

Sieve Size (mm)	Sieve Size (Inches)	Percent Passing					
		Columbus Granite 7's	Columbus Granite 89's	Columbus Granite M10's	Shorter Natural Sand	Unprocessed RAP	Total Blend
19.0	3/4"	100.0	100.0	100.0	100.0	100.0	100.0
12.5	1/2"	95.2	100.0	100.0	100.0	100.0	98.5
9.5	3/8"	51.8	99.5	100.0	100.0	99.2	84.7
4.75	#4	7.4	31.9	99.3	99.5	83.1	50.6
2.36	#8	1.8	4.9	88.6	89.3	64.3	35.6
1.18	#16	1.1	2.6	70.5	70.0	49.5	27.4
0.600	#30	1.0	2.0	53.5	38.7	34.9	18.7
0.300	#50	0.9	1.6	36.8	14.0	22.4	11.4
0.150	#100	0.8	1.2	23.0	4.4	14.9	7.0
0.075	#200	0.6	0.8	13.2	0.8	9.5	4.1
Cold Feed (%)		**31**	**24**	**10**	**10**	**25**	**--**

TABLE A.3 Aggregate Gradations for 50 Percent RAP Mixture

Sieve Size (mm)	Sieve Size (Inches)	Percent Passing					
		Columbus Granite 7's	Columbus Granite 89's	Shorter Natural Sand	Coarse (+#4s) RAP	Fine (-#4s) RAP	Total Blend
19.0	3/4"	100.0	100.0	100.0	100.0	100.0	100.0
12.5	1/2"	95.2	100.0	100.0	99.7	100.0	98.5
9.5	3/8"	51.8	99.5	100.0	97.3	100.0	84.6
4.75	#4	7.4	31.9	99.5	41.0	100.0	44.7
2.36	#8	1.8	4.9	89.3	23.7	79.3	30.2
1.18	#16	1.1	2.6	70.0	19.4	58.3	23.1
0.600	#30	1.0	2.0	38.7	15.4	41.2	15.9
0.300	#50	0.9	1.6	14.0	10.7	24.6	9.3
0.150	#100	0.8	1.2	4.4	7.5	16.0	5.8
0.075	#200	0.6	0.8	0.8	5.1	10.6	3.7
Cold Feed (%)		**30**	**10**	**10**	**35**	**15**	**--**

TABLE A.4 Consensus Aggregate Properties

Consensus Property	Columbus Granite 7's	Columbus Granite 89's	EAP Limestone 8910's	Columbus Granite M10's	Shorter Natural Sand	Unprocessed RAP	Coarse (+#4s) RAP	Fine (-#4s) RAP
Bulk Specific Gravity (Gsb)	2.661	2.610	2.819	2.707	2.614	2.708	2.636	2.674
Absorption (%)	0.9	1.5	0.5	0.3	0.2	0.5	1.1	0.4
Crushed Faces (%)	100	100	N/A	N/A	N/A	N/A	97.2	N/A
Uncompacted Void Content	N/A	N/A	48.4	50.2	45.8	46.6	N/A	45.8
Sand Equivalence	N/A	N/A	78	72	81	89	N/A	86
Flat and Elongated Particles (%) **	0	0	N/A	N/A	N/A	NA	0	N/A

** - 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	4	Average	StDev
10	Opt	67-22	221	433	657		437	218
	Opt + 0.25%	67-22	4201	2176	3516		3298	1030
	Opt + 0.50%	67-22	786	1259	2360		1980	1218
	Opt + WMA	67-22	1249	2279	1092	1676	1574	531
	Opt	58-28	3461	2084	1756		2023	1105
25	Opt	67-22	104	151	67	111	108	34
	Opt + 0.25%	67-22	101	394	502	60	264	217
	Opt + 0.50%	67-22	245	114	181	214	189	56
	Opt + WMA	67-22	622	263	203		294	231
	Opt	58-28	312	138	614		278	250
50	Opt	67-22	244	186	120		183	62
	Opt + 0.25%	67-22	155	787	179	1368	622	577
	Opt + 0.50%	67-22	216	382	621	1846	766	739
	Opt + WMA	67-22	289	438	30	136	233	178
	Opt	58-28	950	765	626		780	163

APPENDIX C
ASPHALT PAVEMENT ANALYZER RESULTS

TABLE C.1 APA Results

%RAP	Binder Content	Binder Grade	Rut Depth, mm							
			1	2	3	4	5	6	Average	COV, %
10	Opt	67-22	1.41	1.79	2.43	1.79	2.38	2.40	2.04	0.43
	Opt + 0.25%	67-22	1.26	2.81	3.12	1.32	4.46	3.58	2.76	1.27
	Opt + 0.50%	67-22	1.97	2.47	2.78	3.17	2.64	3.05	2.68	0.43
	Opt + WMA	67-22	1.74	2.44	2.36	2.84	1.80	3.02	2.37	0.52
	Opt	58-28	5.28	3.68	4.76	2.76	4.43	3.80	4.12	0.89
25	Opt	67-22	3.00	2.03	2.72	2.17	3.57	2.55	2.67	0.56
	Opt + 0.25%	67-22	2.21	2.71	3.02	2.81	3.82	3.52	3.02	0.58
	Opt + 0.50%	67-22	1.36	1.77	2.41	1.39	1.85	1.93	1.79	0.39
	Opt + WMA	67-22	1.77	1.57	2.19	1.86	1.98	2.48	1.98	0.32
	Opt	58-28	2.43	2.79	3.32	3.03	4.95	3.18	3.28	0.87
50	Opt	67-22	2.24	1.97	2.19	2.26	2.35	2.46	2.25	0.17
	Opt + 0.25%	67-22	1.65	1.43	1.38	1.57	2.16	2.42	1.77	0.42
	Opt + 0.50%	67-22	2.92	2.29	3.14	2.97	2.52	2.76	2.77	0.31
	Opt + WMA	67-22	2.05	1.72	2.87	2.02	2.97	3.34	2.50	0.65
	Opt	58-28	2.34	2.32	3.02	2.25	3.48	3.31	2.79	0.55