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Feasibility of using 100% recycled asphalt pavement mixtures for road construction

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FEASIBILITY OF USING 100% RECYCLED ASPHALT PAVEMENT MIXTURES FOR ROAD CONSTRUCTION

by

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CERTIFICATE OF APPROVAL

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MASTER'S THESIS

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This is to certify that the Master's thesis of

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has been approved by the Examining Committee
for the thesis requirement for the Master of Science degree
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To my family, friends and professors who helped me throughout this experience

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ABSTRACT

Recycled Asphalt Pavement (RAP) is the largest recycled good in the United States and 80 million tons are recycled yearly, saving taxpayers about $1.5 billion dollars. This paper explores the possibility of utilizing 100% RAP materials in asphalt pavement. Asphalt mixtures are produced at 135°C in a typical asphalt plant. However, at 135°C, not all binder from RAP materials may not become effective for coating aggregates. The main objective of the study is to determine the amount of effective binder available from RAP in the asphalt plant. The 100% RAP mixes have aged binder that can alter mix designs and interaction with virgin binder. In this study, to determine low temperature cracking resistance and fatigue performance, samples were prepared using a 100% RAP mix with no virgin binder and a 100% RAP mix with virgin asphalt binder to achieve the optimum binder content of the mix. Second, to determine the effectiveness of binder from RAP materials, compaction tests were performed by heating RAP materials at various temperatures. It was found that 100% RAP mixes cannot be feasible for field use if additional virgin binder is added to reach the optimum asphalt content. Based on limited test results, the low temperature grade was not within proper limits but the beam fatigue testing results were acceptable. Based on compaction test results, additional heating is needed to increase the effectiveness of asphalt binder from RAP materials.

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CHAPTER 1. INTRODUCTION

RAP (Recycled asphalt pavement) has become the most common resource to produce new asphalt, and is currently the most recycled product in the United States. Recycling asphalt uses old resources to cut cost and materials for new asphalt pavement. RAP is being used more and more as technology with RAP has increased. However, there are strict specifications for RAP use which limits the amount that can be used for each mix design. Recent surveys have shown that the national average of RAP used in new mixes are around 12% to 15%. The National Asphalt Pavement Association (NAPA) has set goals to increase the average RAP content throughout the country.

Hot mix asphalt with RAP materials has been shown to have the same quality as hot mix asphalt without RAP in terms of rutting, raveling, and weathering and fatigue cracking. This recycled pavement has also been shown to age slower and is more resistant to water than normal hot mix asphalt. A recent study comparing the performance of recycled against virgin mixes based on LTPP data show that mixes with at least 30% RAP have similar results in pavement performance. With more demand of higher RAP mixes, further studies are needed to prove similar results to HMA mixes.

1.1 Objectives

The purpose of this research was to evaluate the performance of 100% recycled asphalt pavement in a beam fatigue test. The Specific gravity was also tested to gain more knowledge on how the recycled asphalt can be evaluated. These objectives were met by first fractionating the RAP material to minimize the dust content in the mixes. First, a literature review shows the performance properties with High-RAP content to evaluate the feasibility of later making mixes with 100% RAP. Extensive laboratory experiments were conducted to assess the properties of the recycled mix. The properties were evaluated using different specific gravity tests, and later put through a beam fatigue test to evaluate the performance property. Following fatigue testing, further tests were conducted to evaluate the mixing of aged binder with virgin binder.

1.2 Scope

The RAP was taken from Interstate 80 and was stored at L.L. Pelling. The RAP was fractionated at the #16 sieve in hopes of meeting Iowa DOT standards from dust content to VMA and VFA. 100% RAP with and without additional virgin binder were evaluated in this research effort. To address the impact of using only recycled asphalt pavement for future use, laboratory testing was conducted to address the following questions:

- The impact of 100% RAP on the Specific gravity to further understanding of the aggregate and aged binder,
- The impact of 100% RAP on the resistance to load responses through fatigue testing,
- The impact of aged binder along with the impact of aged binder mixing with virgin binder,
- The impact of preheating temperature of RAP materials for proper mixing.

1.3 Problem Statement

1.3.1 RAP Variability

One major factor that affects the mix design with high amounts of RAP materials, is the variability of the stockpiles. Stockpiles that are not fractionated or split into more specific sizes can vary from being too coarse or too fine. Binder contents have also been shown to vary in stockpiles that have not been split. Varying stockpiles can cause varying mix designs which could be detrimental to future projects in the field.

In a study by the Texas Transportation Institute (Zhou 2011), three RAP stockpiles owned by the DOT and eight privately owned stockpiles were investigated for varying samples. Seven separate RAP samples were collected from each stockpile and tested by using an ignition oven test. After extensive testing, all of the stockpiles being tested had consistent results with the other samples from each stockpile. As these tests proved to be acceptable, however, not every stockpile can be assumed to have the same results.

The FENIX Project ("Strategic Research on Safer and More Sustainable Roads") examines RAP variability and mechanically characterizes the properties of mixes with high-RAP content (Gonzalo 2009). A RAP variable analysis was conducted on coarser and finer RAP samples. The coarser RAP samples was shown to have a larger deviation from the average gradation than the finer samples. For the coarser RAP samples, it is proven that there is a higher variability in asphalt content and particle size. Figure 1-1 shows the extracted samples for the coarser and finer RAP mixes.

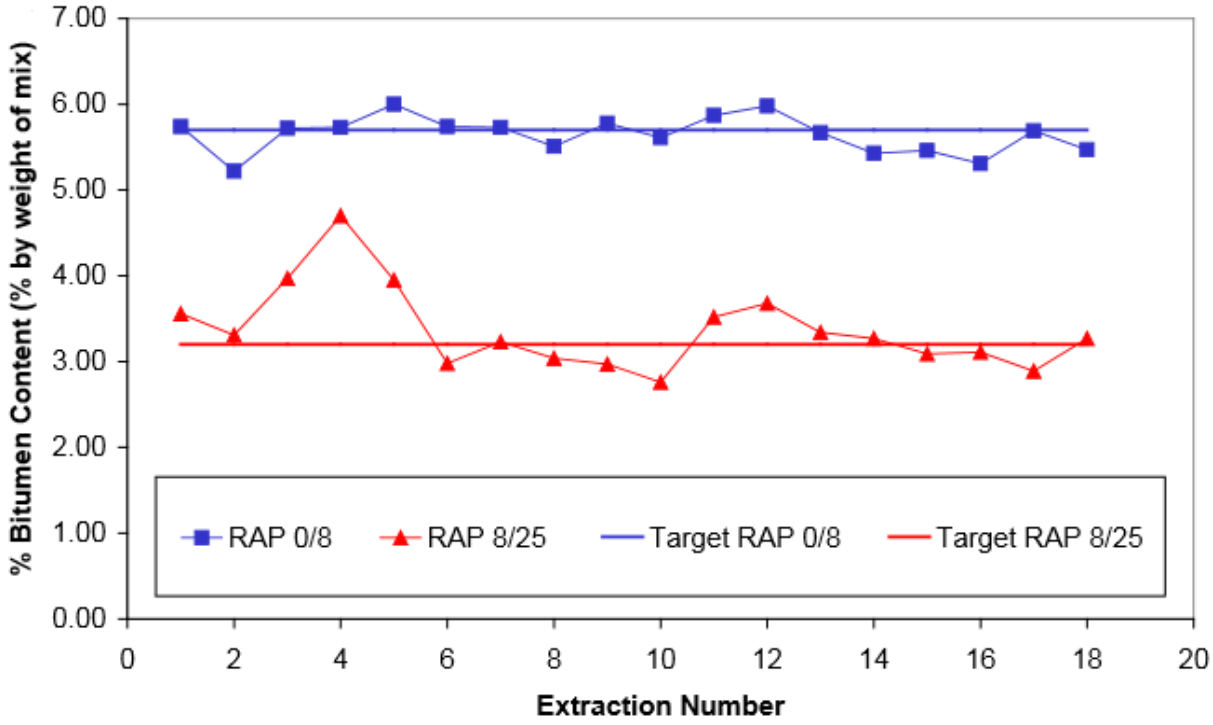

Figure 1-1. FENIX project RAP gradations (Gonzalo 2009)

The FENIX project continues on and tests the variability of mixes with 60% and 40% RAP with the mean deviation and the mean deviation from the target value. Figure 1-2 shows the results from the 60%, 40% and a mix without RAP for asphalt content. This figure shows

that with increased RAP content and the use of coarser RAP, the variability of mixture grading and asphalt content increases. Due to these findings, it is acknowledged that the ultimate way to reduce variability in RAP mixes, is to separate and stockpile each RAP in different material fractions.

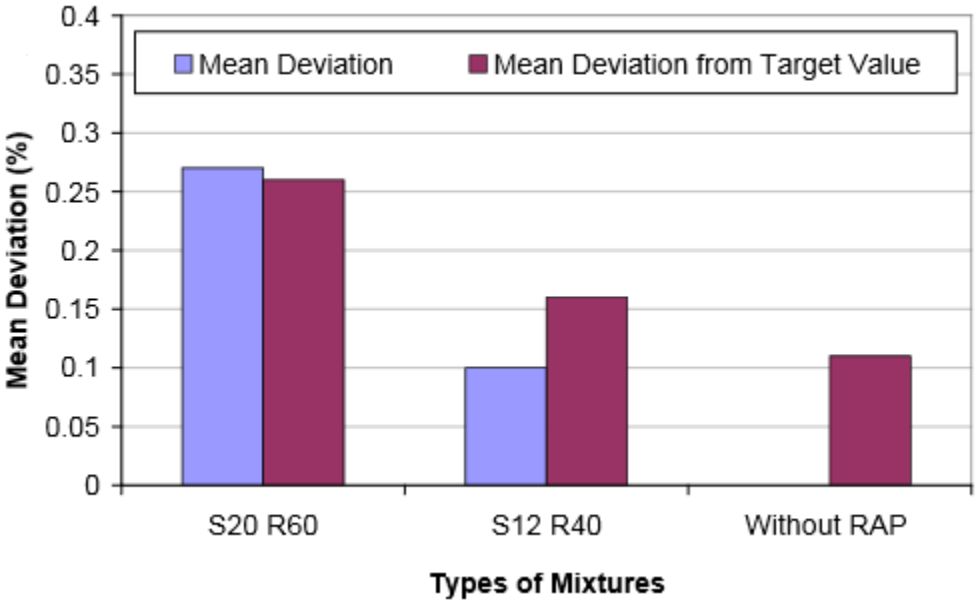

Figure 1-2. Variability with 60%, 40% and no RAP mixes (Gonzalo 2009)

From these findings, finer RAP samples have a smaller deviation of gradation, thus making the mixes more consistent for mix design. However, the fractionation of RAP to include coarser material is necessary due to the many guidelines needed to follow to be acceptable for field use. This presents a problem as to needing the coarser RAP but needing it to be more consistent to ensure similar mix designs.

1.3.2 Aged Binders Properties and Concerns

RAP binder is known to be significantly stiffer than virgin binder in HMA. There is standard aging during the first construction and throughout the service life of the pavement. After the pavement is removed from the field, due to the stockpiling of the materials, the RAP

ages further due to air exposure and can result in increased oxidation. This increased aging can result in an increase in the complex modulus of the mix when RAP binder is blended with the virgin binder (Al-Qadi 2009). An increase in the complex modulus may resist rutting, but has been shown to cause a decrease in fatigue life.

1.3.3 Proper Blending

Another concern can be with increased amount of RAP, proper blending may not occur due to the hardened state of the binder that may not break up during the mixing process. This will change the volumetric properties and aggregate structure of the RAP mixes. Selective absorption is shown to occur when the binder is stiffer/older than the binder that is added to the mix. An increased preheating time has been shown increase the mixing of the aged and virgin binder (Al-Qadi 2009). The properties of each RAP product is investigated before field use to ensure proper mixing.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

2.1.1 Importance of RAP

Throughout the country, the use of RAP is rising due to its environmental and economic advantages over the use of virgin aggregate and binder. There is a finite amount of resources throughout the world, making RAP the most economic choice for contractors and government officials. RAP also makes it possible to replace some of the binder that would be used in the mix already, making less need for as much virgin binder. Due to the aging of the RAP, it is also notably stiffer, which can lead to increased strength, rutting resistance, and moisture susceptibility (Al-Qadi 2009) than the softer virgin binders. However, the stiffness may lead to other problems, such as cracking, but there are many additives that can be combined with the RAP to alleviate this problem. RAP usage will continue to grow and will lead to a much more sustainable, and perpetual, transportation system throughout the country.

2.1.2 Current Use of RAP

The use of RAP has steadily increased throughout the country as it is more understood and studied. Currently, over 80 million tons of asphalt is recycling yearly, which saves about $1.5 billion tax dollars for new construction. Many states restrict the use of RAP to about 20 to 25% of the total mix by weight. As more research is conducted, the amount of RAP used will inevitably rise, until pavements with 100% RAP can be used exclusively. Until then, RAP usage is much lower, and Table 2-1 shows the current use of RAP for each state throughout the country (Hansen 2013).

Table 2-1. RAP in HMA paving mixtures per state (Hansen 2013)

State	Average RAP Percent				State	Average RAP Percent			
	2009	2010	2011	2012		2009	2010	2011	2012
Alabama	19%	25%	21%	22%	Montana	7%	8%	8%	10%
Alaska	5%	3%	13%	8%	Nebraska	NR	NR	30%	22%
Arizona	13%	5%	11%	14%	Nevada	6%	7%	10%	11%
Arkansas	10%	11%	10%	10%	New Hampshire	15%	18%	21%	19%
California	10%	19%	9%	16%	New Jersey	4%	17%	16%	16%
Colorado	19%	19%	24%	29%	New Mexico	NR	NR	18%	NR
Connecticut	15%	17%	13%	21%	New York	10%	11%	16%	13%
Delaware	20%	20%	NR	28%	North Carolina	20%	22%	24%	15%
Dist. of Columbia	NR	NR	NR	NR	North Dakota	NR	NR	11%	NR
Florida	24%	24%	30%	27%	Ohio	23%	24%	23%	24%
Georgia	19%	22%	23%	23%	Oklahoma	12%	13%	18%	12%
Hawaii	10%	9%	11%	14%	Oregon	26%	25%	24%	24%
Idaho	6%	10%	23%	28%	Pennsylvania	13%	13%	16%	16%
Illinois	18%	20%	16%	30%	Puerto Rico	0%	0%	2%	20%
Indiana	23%	24%	26%	23%	Rhode Island	11%	11%	8%	2%
Iowa	12%	17%	14%	15%	South Carolina	17%	20%	22%	24%
Kansas	18%	20%	20%	20%	South Dakota	12%	6%	18%	20%
Kentucky	9%	9%	9%	10%	Tennessee	20%	17%	14%	20%
Louisiana	18%	18%	18%	19%	Texas	11%	10%	13%	16%
Maine	13%	14%	15%	15%	Utah	19%	21%	25%	19%
Maryland	19%	21%	24%	22%	Vermont	21%	20%	17%	23%
Massachusetts	14%	14%	11%	16%	Virginia	21%	28%	26%	26%
Michigan	27%	30%	36%	34%	Washington	18%	16%	16%	15%
Minnesota	16%	19%	22%	20%	West Virginia	10%	11%	11%	12%
Mississippi	16%	17%	18%	19%	Wisconsin	15%	15%	16%	14%
Missouri	12%	12%	19%	19%	Wyoming	6%	5%	1%	2%

NR	= No Contractors Reporting
%	= 0–9%
%	= 10–14%
%	= 15–19%
%	= 20–29%
%	≥ 30%

2.2 Background

2.2.1 Importance of Fractionation (Rayya Hassan)

Fractionating has been used more frequently as of late for higher RAP mixes in hopes to lower the variability of the RAP. Fractionating RAP can help with having better control over the

input to the plant which leads to more control over mix designs and constant mixes (Hassan). RAP can be fractionated off however the plant desires to further control the mix design needs. (Al-Qadi et al, 2009) Laboratory mix designs are fractionated into four different stockpiles to ensure repeatable lab mixes and exceptional quality control (Al-Qadi 2009). Fractionating can be done however the company or contractor seems fit, but an increased amount of stockpiles can lead to more consistent mixes.

2.2.2 Benefits of Using Aged Binder

2.2.2.1 Superpave Mixtures Performance

Superpave mixes were tested with High-RAP for a comparison with HMA mixes (Sabahfar 2014). For the experiments, it was determined rutting performance and moisture resistance declined as the percentage of RAP increased and is highly influenced by the source of RAP. It shows that one source had higher cracking resistance with higher RAP percentages while the other source showed a decline. RAP with a stiffer binder grade may indicate that asphalt films rupture when it is presented with moisture conditioning at higher and freezing temperatures. It is proven that prior knowledge of the RAP and laboratory evaluation needs to be done before field use.

2.2.2.2 Working Binder in HMA

High-RAP mixes have been thought to have adverse effects on moisture susceptibility and indirect tensile strength (Al-Qadi 2009). To test this, binder from RAP was extracted and mixed at 0, 50% and 100% aged binder with extracted aggregate and virgin materials to replicate the effect of aged binder on mix performance. Along with the extracted binder, tests were used with 0%, 20%, and 40% RAP designs. One set for 20% RAP and 40% RAP used RAP from the stockpile without extracting the binder or aggregate. Nine total samples were made and had a varying amount of extracted binder from unknown, 0%, 7-8%, 15-16% and 31-32% by weight. Table 2-2 shows the nine samples that were made for testing. The first set of tests were volumetric with air voids, VMA and VFA. It is shown that air voids and VMA decreased with the increasing amount of RAP but was not affected by the amount of extracted binder in the mix.

The VFA of the mixes looked to increase with the increasing amount of RAP but there was not trend with the increasing amount of extracted binder. The complex modulus was then tested and it showed all mixes with 20% RAP had similar results proving the amount of extracted binder has no influence on the results. However, with the 40% RAP, a higher complex modulus is shown with the samples of no addition of extracted binder compared to the samples with the extracted binder. A higher complex modulus tells us that there is a higher rutting resistance but a lower fatigue cracking prevention.

Table 2-2. Nine separate samples for Complex modulus testing (Al-Qadi 2009)

RAP Percentage	*Specimen ID*	*Aggregates*	*Binder*	*RAP Binder/Total Binder (%)*	*Remarks*
0 % RAP design	D1-SET AP-00	Virgin	Virgin	NA	
20% RAP design	D1-SET AP-20	Virgin and 20% RAP	Virgin	Unknown	
	D1-SET 0-20	Virgin and 20% recovered RAP	Virgin and recovered	0	0% working
	D1-SET 50-20	Virgin and 20 % recovered RAP	Virgin and recovered	7-8	50% working
	D1-SET 100-20	Virgin and 20% recovered RAP	Virgin and recovered	15-16	100% working
40% RAP design	D1-SET AP-40	Virgin and 40% RAP	Virgin	Unknown	
	D1-SET 0-40	Virgin and 40% recovered RAP	Virgin and recovered	0	0% working
	D1-SET 50-40	Virgin and 40% recovered RAP	Virgin and recovered	15-16	50% working
	D1-SET 100-40	Virgin and 40% recovered RAP	Virgin and recovered	31-32	100% working

Along with these samples, other samples were “double bumped” with PG 58-28 binder to soften the mix. The results for these tests show that “double bumping” decreased the complex

modulus of both 40% RAP mixes. With the proper selection of additional binder, the performance can prove to excel with the older, stiffer binder from the RAP.

2.2.3 Interaction of aged and virgin binder

As binder from RAP materials become stiffer through time, the blend of old and virgin binders may not perform as expected. At higher percentages, the aged binder significantly changes the properties of the blend and may affect the binder grade (Hassan). Aged binder can also be affected by the level of moisture damage on the existing pavement prior to recycling and should not be recycled. However, it has been shown that RAP materials can actually provide a higher moisture resistance than virgin HMA since the aggregates are already coated with binder.

2.2.3.1 Binder Rejuvenators

Aged binder has shown to be much stiffer than virgin binder, so there is a need for a mixing agent or softer asphalt binder to be added to restore the rheological properties. Rejuvenating agents help restore the physical and chemical properties of the old binder. As binder loses many of its oil components during construction and service life, making the binder stiffer and less ductile, the rejuvenating agent can aid in restoring the aged binder. As rejuvenating agents are added to RAP, the agents surround to aged binder and slowly penetrates and softens the old binder. Also, it has been noted that the process does not just occur during mixing and construction, but over a longer period of time and will exert a large influence on the HMA properties (Al-Qadi 2009).

2.2.3.2 Blending of aged and virgin binder

Depending on the RAP content, certain binders need to be used. With RAP content up to 15% by weight, there is no required change in binder grade. For any mix with 16-25% RAP by weight, a softer binder of one increment is required. For any mix with a higher RAP content, blending charts should be created to determine the appropriate binder grade to be used (Hassan).

As noted above, it is believed that aged binder on RAP and virgin binder do not mix completely. This is a concern as it will affect all aspects of the asphalt with volumetric properties and the performance of the pavement. A study was conducted, NCHRP 9-12, that

tested three possible levels of interaction from no blending, total blending, and actual blending for two RAP contents of 10% and 40% (Al-Qadi 2007). Both RAP contents had the same overall gradation and overall asphalt binder content. After testing, the mixes with RAP content of 10% had the same cases 70% of the time where total blending was equal to actual blending. However, the mixes with 40% RAP content only had total blending 42% of the time.

It has been noted that HMA with recycled binder has better results from fatigue and rutting performance than the virgin HMA. However, if complete mixing does not occur, the softer virgin binder that is used for mixing will become the main binder filling the voids making the pavement softer than intended.

Another experiment was conducted to evaluate the effects of blending between RAP and virgin binders on SuperPaveTM grade (Stephens 2001). 11 mixes were made with the same gradation with 15% RAP and the same binder. A 12^{th} mix was made of virgin aggregate and binder with no RAP binder. Each mix was heated for a different amount of time from zero to 540 minutes. After mixing, each mix is gone through an indirect tensile strength test to assess whether each mix completely blended or not. The assumption that when the binders are completely blended, the indirect strength of the mix should increase. After testing, the results show that just adding RAP to the virgin mixes increases the strength, and as the preheating time increases, the strength of the mix greatly increases. This test proves that with certain preheating time, proper blending can occur and benefit the strength and endurance of the pavement.

2.2.4 Penetration and Viscosity

Aged binder that has been recovered from RAP has been shown to be more viscous with lower penetration values than that of virgin binders. These physical effects are caused from the chemical changes in the binder that occurs during ageing. The viscosity is initially increased due to the short term ageing during construction evaporates the lighter oil fractions due to the hot temperature. Next, during the in-service years, the long term ageing occurs through oxidation of the binder and results in water-soluble oxidation products that leach from the binder to increase

the viscosity further. As a result, more consideration needs to be put in when RAP is introduced to a mix and how further ageing during production can affect the mix (Carpenter 2006).

2.2.5 Beam Fatigue

Beam fatigue testing is used on HMA at intermediate pavement operating temperatures to characterize the fatigue life. This test is necessary to provide estimates of layer fatigue after repeated traffic loading. Each pavement is put under designed strains to cause fatigue failures after repeated loads. There are many ways to interpret the data given from beam fatigue testing such as maximum tensile stress, maximum tensile strain, fatigue curves, and even an endurance limit of the asphalt.

2.2.5.1 Endurance Limit

The fatigue endurance limit is shown to be the point where the strain in low enough on the asphalt, that there can be an infinite fatigue life. Normally, the strain levels can be around 70 microstrain to reach the point where the HMA can experience unlimited amount of load repetitions. The theory behind this states that HMA has an ability to recover consistently with a strain low enough. However, the pavement thickness need to create a strain low enough is not feasible in the field, so a 40-year life is designed.

2.2.5.2 Validating the Fatigue Endurance Limit

NCAT predicted the fatigue life through extrapolation of their findings for several fatigue tests (Timm 2012). They conducted beam fatigue tests with two beams each, at 800, 400, 200, 100, 70 and 50 micro-strain. Their tests had such low micro-strain levels, the tests were terminated after 50 million cycles. A shift factor of 10 was given to those samples, estimating they could last for a total of 500 million cycles, which estimated a 40-year life. Data from the 800 micro-strain to 200 micro-strain were also used to estimate the strain level that would result in a fatigue life of 50 million cycles. From their experiments, a strain level of 166 micro-strain was needed for the pavement to last for 50 million cycles.

2.2.5.3 NCAT fatigue testing

NCAT followed the AASHTO T321 procedure for an evaluation of mixture performance for nine beams (Timm 2012). Nine beams were used to complete a more complete analysis of the beam fatigue testing process. Three beams were each used at either 200, 400 and 800 microstrain. The data was then applied to a power model transfer function ($\varepsilon = \alpha_1 N^{\alpha_2}$) to show the number of cycles to failure compared to strain levels. Table 2-3 and Figure 2-1 show the results from their testing and Table 2-4 shows their resulting coefficients for the graph. The results from the beam fatigue tests uses the same procedure with nine beams and will be compared to the control group in the NCAT testing.

Table 2-3. NCAT Fatigue Resistance Results (Timm 2012)

NCAT Control Base	
Strain	Cycles to failure
0.0008	7890
0.0008	4260
0.0008	17510
0.0004	201060
0.0004	216270
0.0004	141250
0.0002	6953800
0.0002	5994840
0.0002	2165480

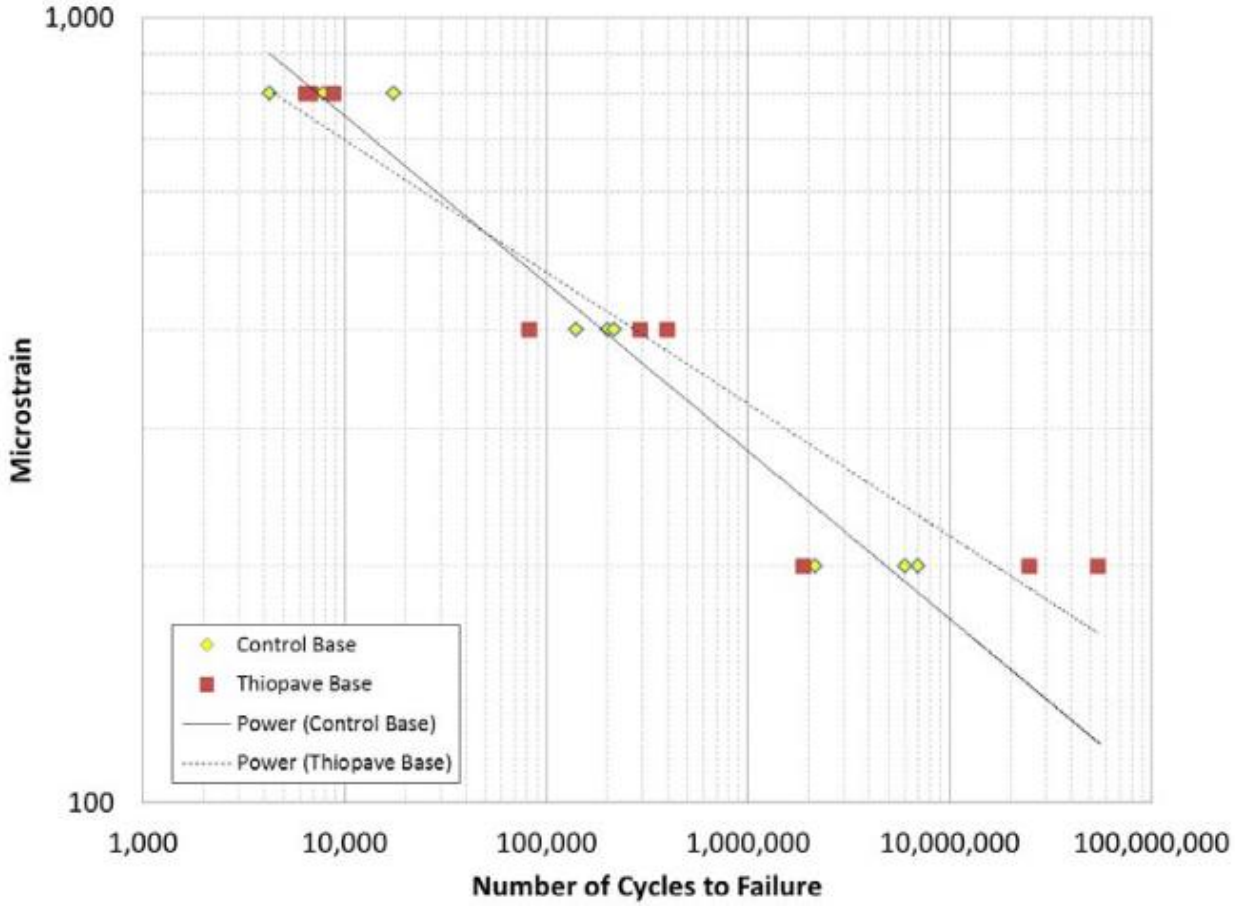

Figure 2-1. NCAT multiple test results (Timm 2012)

Table 2-4. NCAT coefficient results (Timm 2012)

Mixture	AASHTO T321		
	α1	α2	R^2
Control Base	5374.2	-0.214	0.969
Thiopave Base	3290.7	-0.168	0.914

2.2.5.4 100% RAP fatigue testing (Boriack, Katicha, Flintsch)

A following fatigue test with 100% RAP with and without the addition of virgin binder was conducted to determine the feasibility of use in the field (Boriack 2013). The 100% RAP had an asphalt content of 5.77% before the addition of .5%, 1%, and 1.5% virgin binder by weight. The mixes were tested at a constant strain of 400 micro-strain. A mix design was not conducted to determine the optimum binder content for the experiments. However, it shows that with additional binder, the fatigue resistance increased with the increase in virgin binder added. Figure 2-2 and 2-3 shows the comparison of 0% RAP and 100% RAP with and without additional binder. The results show that with additional binder, the 100% RAP mixture still cannot perform to the same level as the 0% RAP mix.

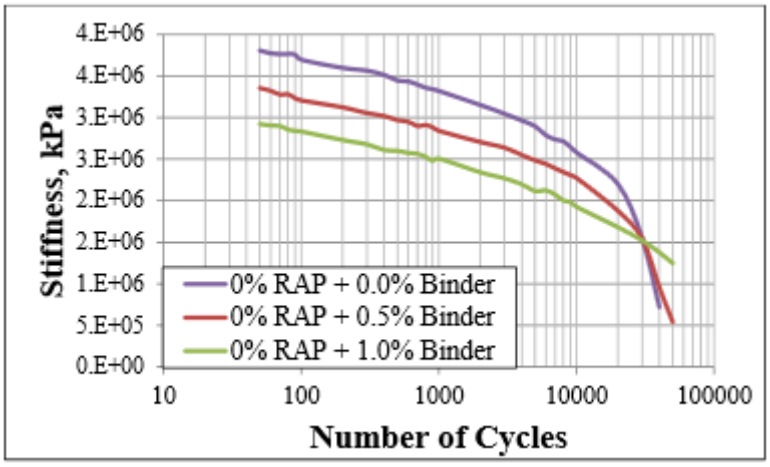

Figure 2-2. Fatigue testing for 0% RAP (Boriack 2013)

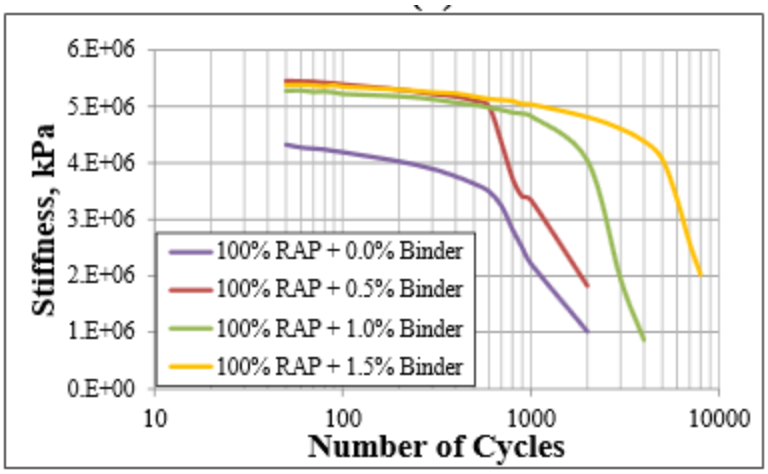

Figure 2-3. Fatigue testing for 100% RAP (Boriack 2013)

The fatigue resistance for the 100% RAP has a smaller initial decline but becomes much steeper at the end of the test compared to the 0% RAP. However, the 100% RAP has a higher initial stiffness, but declines much faster and does not have the same results and mixes with much less RAP.

CHAPTER 3. LABORATORY TESTING OF RAP MATERIALS

3.1 Materials

The RAP being tested is taken from Interstate 80, and has been supplied from LL Pelling Company. This RAP was mixed with PG 58-28 asphalt binder. This binder grading was used as it is needed to "double bump" the aged binder.

3.1.1 100% I-80 RAP

The purpose of these experiments is to find how suitable a mix with 100% recycled material with additional virgin binder is compared to traditional hot mixes used today. A series of experiments were conducted with aged binder without any additional virgin binder, and mixes with the addition of virgin binder to reach the mixes optimum binder content.

3.1.2 Fractionation

The RAP material used was a fractionated blend at the #16 sieve to decrease the amount of fine materials. With these gradations, the Pelling Company performed multiple burn-offs to determine the binder content in the RAP material. After six separate burn-offs, the binder content was estimated to be 4.18% by weight.

3.1.3 Asphalt Binder

The only asphalt binder used for this study was PG 58-28 to bump the stiffer aged binder to a softer blend. PG 58-28 is an unmodified binder. Recommended HMA mixing and compaction temperatures for PG 58-28 are shown to be between 295 and 306 F and 271-281 °F, respectively.

3.1.3.1 PG Grading

Binder becomes stiffer as it ages and more viscous creating a higher PG-grading then when the first mix was made. The lower PG grade of the old binder and the new binder was found before and after the addition of the PG 58-28 binder. The PG 58-28 is added to create a softer and more workable blend of asphalt binder.

3.2 Volumetric Tests

Volumetric testing must be used on potential mix designs as the DOT has certain guidelines to follow to be allowed for field use. The most crucial of the parameters include a VMA of at least 14%, a VFA between 70 and 80%, a dust-binder ratio between .6 and 1.4, and a film thickness between 8 and 13 μm.

The VMA is known as Voids in the Mineral Aggregate which is the volume of void space between the aggregate particles of a compacted paving mixture. This volume of space is expressed as a percent of the total volume and includes air voids and the effective asphalt content. An excessive VMA will cause low mixture stability and a low VMA will result in a poor mix with the binder and will not coat the aggregate completely.

The VFA is known as voids filled with asphalt and represents the volume of effective asphalt binder. The dust-binder ratio is simply the amount of dust in the mix compared to the amount of binder. It is measured by the amount of aggregate passing the #200 sieve divided by the amount of effective binder. The film thickness of a mix design is found as the ratio of the quantity of binder to the surface area of the aggregate.

3.2.1 Mix Design

The Mix design of the 100% RAP was fractionated at the #16 sieve to attempt to remove as much dust content as possible without removing an excessive amount of aggregate. Some dust particles will remain attached to larger pieces due to binder but will eventually break off when heating and mixing occurs. Multiple tests were used on the fractionated RAP after burnoff to determine the Gsb, Bulk specific gravity of the aggregate, and Gsa, apparent specific gravity of the aggregate. With these figures, all of the above equations can be solved to find the different volumetric properties of the mix design.

3.2.1.1 Coarse Aggregate Testing

After the RAP burnoff, the remaining aggregate is split into coarse and fine aggregates for bulk specific gravity testing. The coarse aggregate (≥ #4 sieve) specific gravity follows the AASHTO T85 standards. The coarse aggregate is weighed at three different conditions: Oven-

dried, saturated surface dry (water filled in the pores), and while it is underwater. These three measurements can then be used to calculate the apparent specific gravity (Gsa), bulk specific gravity (Gsb), and bulk SSD specific gravity.

To begin, the coarse aggregate must be soaked in water at room temperature for 15 to 19 hours. The coarse aggregate is then removed from the water and rolled out onto an absorbent towel until all the visible water is removed. This aggregate is weighed to obtain the saturated surface dry (SSD) condition. Following, the aggregate is placed back in water at a temperature of 23 ±1.7°C and weighed after all entrapped air is removed, for the saturated weight. Lastly, the aggregate is placed into an oven at 110 ±5°C until thoroughly dry to be weighed once again.

3.2.1.2 Fine Aggregate Testing

The fine aggregate specific gravity testing follows the standards that are given in the AASHTO T84. Similar to the coarse aggregate testing, the fine aggregate is tested to obtain the Oven-dried, saturated surface dry (water filled in the pores), and saturated weights. With all three measurements from the coarse and fine aggregate, the results can be used to calculate the apparent specific gravity (Gsa), bulk specific gravity (Gsb), and bulk SSD specific gravity.

For these experiments, a 500 mL pycnometer flask is needed along with a 1000 gram sample that has soaked in water for 15 to 19 hours. The 500 mL flask must be first weighed with water filled to a set level that will remain constant throughout the experiment. The sample is then laid on a smooth surface to be air dried until the saturated surface dry condition is found. This condition can be found by filling a mold of a frustum of a cone with the fine aggregate and tamped 25 times on top of the mold to compress the fine aggregate in the mold. The metal tamper, should weigh 340 ±15 grams with a face 25 ±3 mm in diameter, should be dropped 5 mm above the aggregate. After 25 drops, remove the mold vertically to judge the slumping of the fine aggregate. The aggregate has reached the saturated surface dry once 25 to 75% of the top diameter of the cone slumps.

After SSD condition is found, 500 grams of the aggregate is weighed and placed into the pycnometer flask along with water filled to around the neck of the flask. The flask is then rolled

and agitated for 15 to 20 minutes to remove all entrapped air. After all the air is removed, fill the rest of the flask to the set level that was determined earlier to be weighed. The water and aggregate is then carefully removed into a pan making sure all the aggregate is removed from the flask. The water and aggregate is oven dried at 110 ±5°C and weighed when the aggregate has cooled all the water has been removed.

3.2.2 Gmm of RAP materials

The objective of these experiments is to find a common Gmm for 100% RAP that could be used when designing mix designs for future projects in the field. The Gmm is the maximum specific gravity of the sample and is used to find and set certain air voids for compacted samples. Air voids are designed to be between 7% and 3%, and they are targeted to be around 4%. Once the voids are higher than 8%, air and moisture can permeate the pavement and the durability of the pavement is lost. When the air voids are less than 3%, there is not enough room within the asphalt to expand and contract with the weather causing the asphalt to become unstable. The specific gravity of the fractionated RAP was evaluated using the AASHTO T 209 Procedure (Rice test) and the Corelok Vacuum Procedure. Due to fluctuating results, the two procedures were modified slightly to help determine a true maximum specific gravity.

The Gmm is used to calculate the Gse, also known as the effective specific gravity. The Gse is the volume of the aggregate particles plus the void volume that is filled with water during the testing minus the void volume that absorbs the asphalt. This calculated Gse needs to fall in between the apparent specific gravity (Gsa) and the bulk specific gravity (Gsb).

3.2.2.1 AASHTO T 209 Procedure

The Gmm of asphalt mixtures is generally measures using the AASHTO T 209 procedure, also known as the rice test. For this procedure, the RAP was heated for two hours at 135°C, then mixed and broken up as well as possible. After the RAP is cooled, it is then measured and placed in the metal bowl. Water is then filled well above all of the material in the bowl. The metal bowl is then placed on the orbital shaker while the top is sealed to the vacuum. The shaker is set at 225-250 rpm and the vacuum is set at constant around 30 mm Hg for 15

minutes to remove all the entrapped air in the sample. After 15 minutes, the shaker and the vacuum are shut off and the sample sits in water for an additional 10 minutes to ensure all the air is removed from the sample. When 10 minutes is over, water is carefully added to the metal bowl, as to not add any unwanted air, to the brim. The metal lid is then carefully placed on top to ensure a good water tight seal before being weighed again.

3.2.2.2 Corelok Vacuum Procedure

A less used procedure to determine Gmm of mixes is the Corelok Vacuum procedure. Even though it is used less, it is claimed to be more accurate as it decreased the amount of air absorbed by the binder in the mix. Samples of fractionated RAP were heated in an oven at 135°C for two hours. Then the same as the last experiments, the sample is broken up as well as possible and cooled. After the RAP cooled sufficiently, 2000 grams is measured out and placed in the special channel bag. This bag is then placed with the rough side done inside another bag which is then placed in the Corelok machine. With the Corelok machine set on "Program 2" and making sure the channel bag is not touching the seal bar, the machine is closed to start the vacuum process. After the bags are completely sealed, place the bags under water that is set at 25°C. Making sure the entire bag is under water, the bag is cut open. After water has entered the bags, allow some time to make sure the water makes it in every part of the bag. The bags are then placed on a scale under the water which is then used to find the Gmm.

3.2.2.3 Gmm Test Procedures

The AASHTO T 209 procedure was used to evaluate the Gmm of the samples that were made. Different mixing temperatures and newer binders were used for each test for comparative reasons. The fractionated RAP was then tested using the same procedure with the binder content being 4.18% by weight. The Gsa and Gsb for the fractionated RAP was calculated to be 2.741 and 2.652, respectively. Table 4-6 shows the results of the rice test for this RAP. As can be seen, the Gse is right at the Gsa. This may seem positive, but the Gse is wanted to be closer to the Gsb even though it does fit in the range. More experiments using different mixing temperatures and new binders were further conducted.

The second experiment used the same AASHTO T 209 procedure with a new mixing temperature of 150 C. This was done in hopes to break up further binder that may have been in the larger pieces of the RAP. Table 4-6 shows the results of the rice test for this RAP and the previous experiment.

In hopes of lowering the Gse to more desirable results, the third experiment for the fractionated RAP returned the temperature to 135 C, but added virgin PG 58-28 binder to total 5% binder by weight. This was done in hopes that bumping the aged binder of the RAP would help with the absorption and stiffness of the aged binder. Table 4-7 shows the results of the third experiment for the fractionated RAP.

The fourth experiment consisted of two samples that had new binder added to them after the L.L. Pelling Co. had burnt off the existing binder. The estimated binder content in the two samples were 4.16% and 4.23% by weight. For this experiment, new PG 58-28 binder was added at the same asphalt content that the samples had before they were burnt off. Table 4-8 shows the results of this rice test procedure.

The fifth experiment took six more burnt-off samples from L.L. Pelling and added new PG 58-28 binder at 5% by weight. 5% asphalt content was used as this is the normal asphalt content used when determining the Gmm of a mix. Table 4-9 shows the results of the samples with 5% binder content.

The sixth and final experiment conducted was using Corelok vacuum procedure in hopes to better extract any air that could be trapped with the binder. The theory as of now for the Gmm being so high is that there is air currently still in the RAP material that isn't being vacuumed out properly. Two samples were put together with added PG 58-28 binder to bring the asphalt content up to 5% by weight. Table 4-10 shows the results for the Corelok vacuum procedure. This procedure gave the highest Gse of all the experiments.

3.2.3 Gmb Testing

Along with these testing results, the bulk specific gravity needs to be found to help determine the optimum binder content of the mix. The testing for bulk specific gravity followed

the AASHTO T 166 standards. A sample is compacted according to the AASHTO T 312 standards before any of the testing can begin. Following the compaction of the sample, it must be cooled to 25 ±5°C and then weighed. Next, the sample is submerged in water at a temperature of 25 ±1°C, suspended on a scale, for 3 to 5 minutes. When the sample has been weighed after the time, remove the specimen from the water and blot until visibly dry with a damp towel. Weigh the sample and record the final saturated surface dry condition of the sample.

3.3 Beam Fatigue Testing

The objective for these experiments were to determine the fatigue behavior of the aged binder with a double bump of PG 58-28 binder with a constant strain analysis. AASHTO T321 uses a constant strain test determine fatigue performance. The first step of the procedure is to compact asphalt slabs with air voids of 7 $\pm$ 1%, which are then later cut into beams that can be used for the experiment.

3.3.1 Constant Strain vs. Constant Stress

In constant strain mode, the strain is maintained constant while the stress is allowed to vary. In constant stress mode, the opposite occurs as the strain is maintained constant and the strain is allowed to vary. The constant strain test is chosen because this mix would be a thin top layer of asphalt that would be less than 5 inches. Experience has shown, that thinner HMA pavements generally perform closer to a constant strain mode in the field. The constant strain mode is much more widely used as it is thought to provide more accurate results comparable to field observations.

3.3.2 Beam Compaction

According to different compaction methods, the rolling wheel compaction method was deemed to most likely represent the field conditions which is represented by performance testing. The rolling wheel applies a vertical pressure while a movable table moves back and forth as shown in Figure 3-1. The movable table holds a steel mold with dimensions of 15 in. x 8.25 in. x 7.375 in. The asphalt and mold is heated to 135°C before being placed in the machine. 30

separate metal bars are then placed on top of the leveled asphalt in the mold before the wheel is lowered on top of the mold and movable table. The movable table moves back and forth as the wheel slowly increases pressure to level the metal bars on top of the asphalt. Figure 3-2 shows the resulting asphalt slab still in the mold.

Air voids are controlled through using the Gmm of the mix already knowing the volume of the slab after the compaction. The air voids are checked after compaction to ensure to meet the AASHTO T321 standards of the test. The first two slabs are compacted to ensure proper air voids for future slab compactions. Once the desired air voids of 7 ± 1 % are obtained, each slab can be cut into 3 separate and equal beams that can be used for the fatigue testing. Each beam used met the AASHTO standards for the dimensions of 380 ± 6 mm in length, 63 ± 6 mm in width and 50 ± 6 mm in height.

Figure 3-1. The rolling wheel Compactor

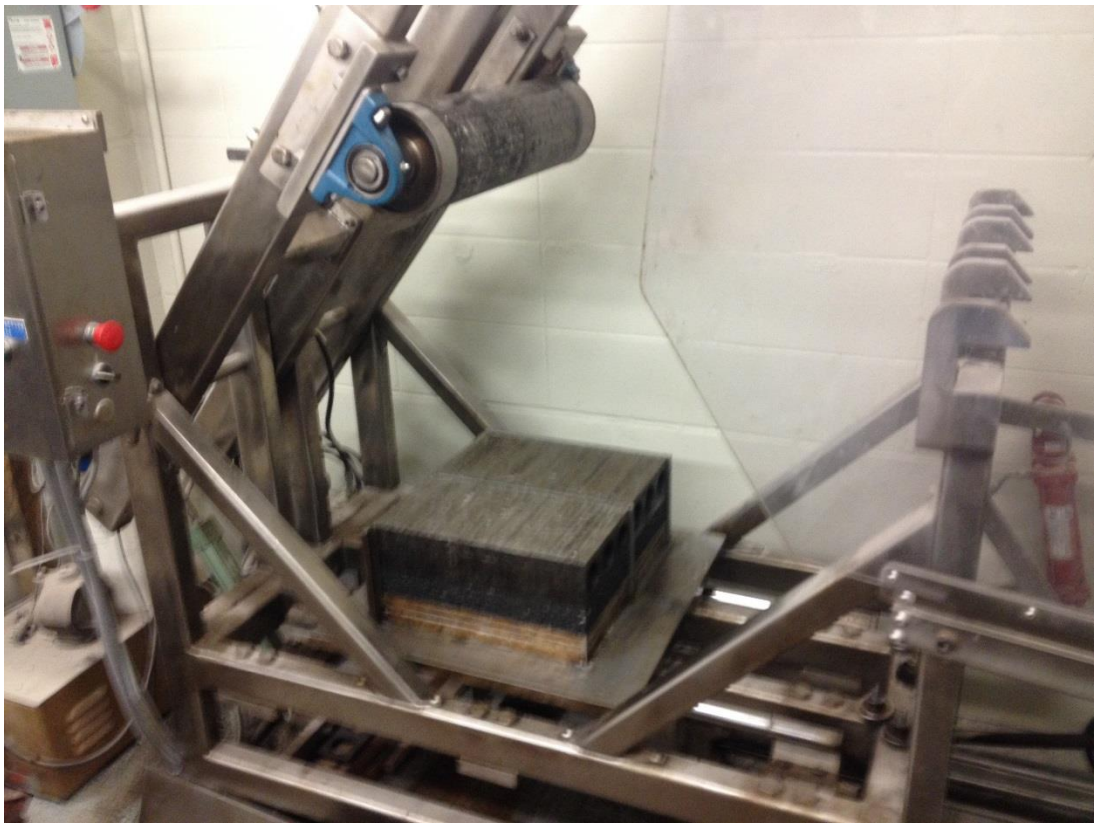

Figure 3-2. Resulting Compacted slab

3.3.3 Loading Device

This test system includes a closed-loop, computer controlled loading component that will adjust and apply a load on the beam to remain at a constant strain. The loading device subjects the beams to four-point bending and can regulate the output waveform to equal the input waveform giving the device particular control. A Linear Variable Displacement Transformer is used to measure the deflection of the center of the beam.

3.3.4 The Environmental Chamber

The environmental chamber holds the Loading device and all beams needed to be tested. All tests were conducted according to AASHTO T321 with a constant temperature of 20.0 ±

.5°C before and during testing. The beams to be tested on were kept in the environmental chamber from two hours before and kept until after the test was completed. Figure 3-3 shows the Loading Device located inside the Environmental Chamber.

Figure 3-3. Loading Device in the Environmental Chamber

3.3.5 Control and Data Acquisition System

The Control and Data Acquisition System is attached to the Loading Device and measures the deflection of the beam specimen, computes the strain in the beam, and adjusts the load to hold the constant strain. The CDAS also records load cycles, applied loads, beam

deflections and computes initial and final stiffness where the beam will fail. The beam, under constant strain testing, is considered to have failed after a 50% reduction in the initial stiffness.

3.3.6 Testing Conditions

The procedure followed the AASHTO T321 guidelines for a constant strain analysis. Each beam was stored in the chamber for two hours before testing to reach the required test temperature. The following parameters for each beams was used:

- Mode of Loading: Constant-Strain
- Wave shape: Haversine
- Load Pulse Width: 10 Hz
- No rest period
- Temperature: 20°C

Three beams were used for each constant strain setting to ensure consistent results, as RAP can have a high variability. The strain levels were set at 350, 600 and 800 micro-strain to generate a fatigue curve for the material.

3.4 PG-grade Testing

Two separate samples were made to determine the PG grading of the binders for each mix. The first sample is of 100% aged binder from the Interstate 80 RAP. The next mix is the optimum binder content of the completely recycled mix with the addition of PG 58-28 binder. Aged binder becomes stiffer and less viscous than its virgin counterpart. Each mixture has additional PG 58-28 binder added to the mix to help the aged binder of the RAP become softer and more viscous. As a result, each mixture will potentially have varying PG grades. Tests for PG grading include DSR testing of the un-aged and aged mixture and BBR testing with PAV aged material. Since it can be predicted the stiffer binder will have a higher PG-grading than virgin binders, BBR testing will be conducted first. If BBR test results show to be promising, DSR testing will occur. It is noted that even though the RAP binder has already been aged, the binder must be aged again for these procedures. This is due to the wanted findings of the feasibility for future road construction.

3.4.1 DSR testing

DSR (Dynamic Shear Rheometer) is used to characterize the viscous and elastic behavior of asphalt binder at medium to high temperatures. DSR testing includes a sample of .04 inch thick and 1 inch diameter of the testing binder that is sandwiched between two circular plates. The bottom plate is stationary while the upper plate oscillates at 10 rad/sec which simulates traffic speed of about 55 mph, to produce a shear action on the sample. Each sample is heated to certain temperatures that are specified for each performance grade and is used to find the high temperature PG grade. These tests are conducted on the un-aged, RTFO aged and PAV aged binder samples. After the tests are conducted, the binders rutting preventing and fatigue cracking prevention can be calculated.

3.4.2 RFTO Aging

Rolling Thin-film oven testing simulates the aging that occurs during the mixing and construction phase of the asphalt. The RTFO aging follows the standards of AASHTO T240-09 throughout the testing. The test uses an oven being heating at 163°C with a rotating wheel with holsters with an air jet positioned at the lowest point of the wheel. The air jet blows heated air at a rate of 4000 ± 300 mL/min. into the center of each holster while the wheel is rotating. Figure 3-4 shows the oven suitable for the RTFO aging. Each holster holds a glass tube that has been measured beforehand. Each glass tube holds 35 ± .5 grams of the asphalt binder to be tested on. Immediately after pouring the sample into the glass tubes, the glass tubes must be laid horizontally to create a layer of binder around the entire tube. These tubes are then left at room temperature horizontally for 60 to 180 minutes. After cooling, the glass tube are placed in the holsters of the rotating wheel while being sure the oven stays close to testing temperature. The rotating wheel is set to rotate at a rate of 15 ± .2 rpm. The desired temperature of 163°C has to be reached before the first 10 minutes of the test or it is discontinued. If the temperature is reached, the test is run for a total of 85 minutes. When the test has been run, mass changes in the binder are recorded, then collected for further testing of BBR and PAV aging.

Figure 3-4: RTFO Oven

3.4.3 PAV Aging

Following the RTFO aging, the remaining binder not being tested on is put through a pressure aging vessel (PAV) to simulate in-service aging from 5-10 years. The PAV aging followed the AASHTO R28-12 standards throughout the entire testing. The pressure vessel is designed to hold a temperature between 90-110°C and holds a constant pressure of 2.1 ± .1 MPA. The pressure vessel is shown in Figure 3-5. This vessel contains a pan holder capable of holding 10 stainless steel pans in a horizontal position that allows each pan to be stacked on top of each other. After RTFO aging, each pan is filled with 50 ± .5 grams of binder to be aged further. Each pan is placed in the pan holder and then put in the vessel where the aging takes

place for 20 hours. During the 20 hours ± 10 minutes, the asphalt is being forced to oxidize under the pressure and temperature in the vessel.

Figure 3-5: Pressure aging vessel

After the aging process, the binder is collected and put into separate containers to be placed in the degasser. Since air has been forced into the binder for so long, the degasser is used to remove all the remaining air that is within the binder. The degassing oven is set to 170 ± 5°C. The binder is placed in the oven without the vacuum for 15 ± 1 min followed with the vacuum

set at 15 ± 2.5 kPa for 30 ± 1 min. Figure 3-6 shows the degassing oven. Following the degassing procedure, the BBR testing can now be started.

Figure 3-6: Degassing Oven

3.4.4 BBR testing

BBR (Bending Beam Rheometer) is used to provide a measure of low temperature stiffness and relaxation properties of the binder samples. For this procedure, a small asphalt beam is simply supported in a cold liquid bath. A load is then applied to the center of the beam with the deflection being measured against time. This test uses PAV aged asphalt binder and

determines the binder's resistance to low temperature cracking and the resulting low temperature PG grade.

When the PAV aged binder has been fully degassed, the BBR procedure can be set up. Specimen molds must be made for each test and each binder being tested on. These molds are tested by measuring the flexural creep stiffness.

3.4.4.1 Specimen Molds

Aluminum flat stock is assembled with strips of plastic coated in petroleum jelly are assembled to create the beam specimens used for the test. The molds are carefully put together to ensure there are no air bubbles under the plastic to ensure the thickness of the beam molds are consistent. The aged binder is then poured into each mold to create a beam with the dimensions of 6.35±.05 mm thick, 12.7±.05 mm wide and 127±2 mm long. Figure 3-7 shows the aged binder in the mold after the top had been scraped to make an even width throughout the beam. The molds with the binder are then cooled for 45 to 60 minutes before the top is scraped off with a heated spatula. The beams are then put in an ice bath, just prior to the testing, for 5 to 10 minutes before being removed from the molding to ensure the binder is stiff enough to be de-molded properly.

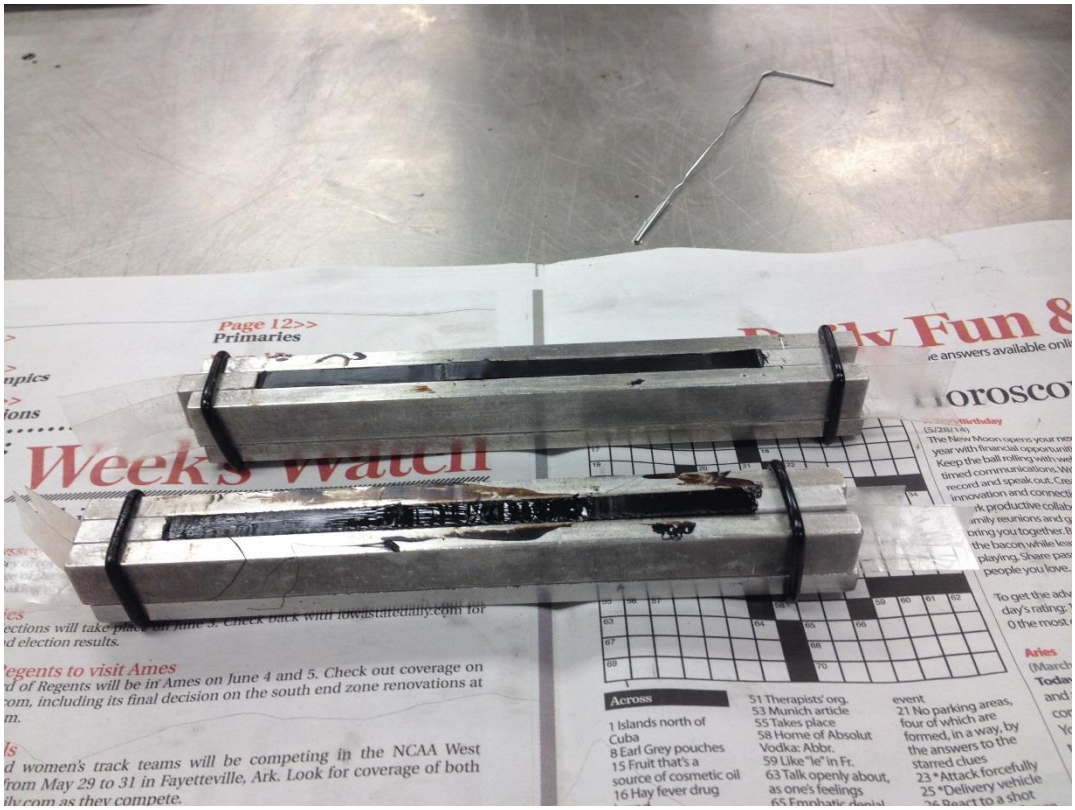

Figure 3-7: BBR Binder molds

3.4.4.2 Loading Frame with Environment Chamber

The loading frame consists of a set of sample supports, with a blunt- nosed shaft (with a 6.25 ± .3 mm spherical contact point) that applies a pressure on the mold at midpoint. A constant load is set on the beam specimen with a transducer measuring the deflection of the specimen. The loading system can apply a contact load of 35 ± 10 mN to the beam specimen and maintain a test load of 980 ± 50 mN. The Linear Variable Differential Transducer (LVDT) is capable of measuring a linear movement of ≤ 2.5μm with a range of 6 mm, to measure the deflection of the beam specimen.

This loading frame is within a controlled temperature fluid bath that can maintain temperatures from -36 and 0 ±.1°C. The bath is agitated by a fan and circulates throughout the chamber with a circulating bath unit to maintain constant temperature throughout the

environment. Once temperatures are reached, the beam specimens are placed inside for 60±5 minutes to ensure thorough cooling of the beam, before testing can begin.

3.4.4.3 Computer-Controlled Data Acquisition

The data acquisition measures loads to the nearest 2.5 mN, beam deflection to the nearest 2.5μm, and bath temperature to the nearest .1°C. The system senses the time when the contact load on the beam becomes more than zero, which is then referred to the start of the beam testing. This system records the load and deflection throughout the testing time of 240 seconds. Figure 3-8 shows the entire system, the loading frame with the environment chamber attached to the computer-controlled data acquisition, for the BBR testing.

Figure 3-8: BBR Test System

3.4.4.4 Calibrating Items

The calibration of the loading frame is achieved using two separate stainless steel beams and different standard masses. The thick beam (6.4±.1 mm by 12.7±.25 mm by 127±5 mm) is used for compliance measurement and load cell calibration. The thin beam (1.3±.3 mm by 12.7±.1 mm by 127±5 mm) is used for an overall system check. This beam has a reported set of measurements elastic modulus from the manufacturer.

The standard masses are used for load cell calibration and the verification of the load cell calibration. Four 100±.2 gram masses are used for the calibration of the load cell and two or more of the masses are used for a daily overall system check. This system has to be calibrated for every temperature change.

3.4.4.5 Testing Conditions

Testing was conducted on RAP binder that had no additional virgin binder, and RAP binder with the addition of PG 58-28 binder. The addition of binder was calculated using the optimum binder content from the volumetric properties of the RAP. This addition of virgin binder was mixed in with the RAP before the extraction of the binder. Two beams of each binder were tested at temperatures of -12 and -6°C.

3.5 Aged Binder Blending

As stated above, another major factor with the use of RAP is the uncertainty with the mixing of aged binder with virgin binder. This was tested by varying the time the RAP was preheated from 0 to 540 minutes, and the effect of the indirect tensile strength (Stephens 2001). A comparable experiment was conducted using altered preheat temperatures of 110, 135, and 160°C. The preheat time remained constant at two hours.

The compaction testing and indirect tensile strength testing are conducted at the different temperatures in hopes to show the current preheat temperature of 135°C does not fully extract the aged binder into the mix. The compaction testing hopes to show more compactibility for the higher temperatures to show the aged binder is more viscous and can cover the aggregate more

thoroughly. Similarly, the indirect tensile strength goes off of the compaction testing in hopes to show a higher tensile strength with a higher preheat temperature. If these experiments prove to be true, 100% blending cannot be assumed after mixing with the current heating temperature.

3.5.1 Compaction Testing

The first experiment to test the binder blending was to examine the different compaction heights of each RAP mix at the different temperatures. Six similar samples of fractionated 100% RAP were made for the experiment. Two of each sample were preheated at the different temperatures for two hours before mixing. After mixing, the samples were placed back in the oven to reach the desired temperature again before being compacted. Each mold for compaction was heated at similar temperatures of each RAP mix. The compaction was set for the n-max of 152 gyrations as in accordance to the 10 million ESAL desired setting for the mix. Heights throughout the compaction were recorded along with the calculated air voids after the specimens were cooled. Each specimen was compacted for target air voids of 4%.

3.5.2 Indirect Tensile Strength Testing

Similar to the compaction testing, six similar 100% RAP mixes were made, with two being tested at each preheating temperature. The compaction process followed the standards for the AASHTO T 312 with an n-design of 96 gyrations for each sample. Following compaction, the indirect tensile strength procedure followed the standards from the ASTM D 6931 with the exception with the mold diameter used being 100 mm instead of 150 mm. The dimensions of each specimen were recorded as well as the force for the specimen to fail.

3.5.2.1 Compression Testing Frame

The compression testing frame used for the indirect tensile strength test is a Master Loader HM-3000. The load frame holds each specimen and raises it to a stationary bar to exert a force across the specimen. The HM-3000 reads the amount of force and flow peak during the marshal test when the specimen fails. The final force is recorded and used to determine the indirect tensile strength. Figure 3-9 shows the compression frame used for the testing.

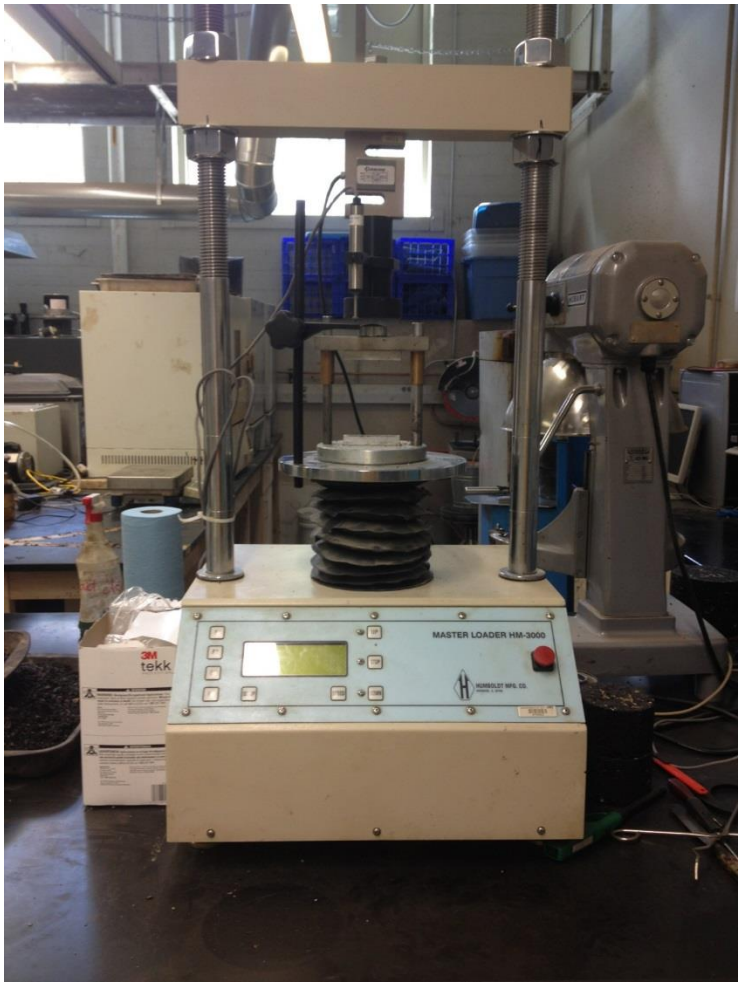

Figure 3-9. Compression Frame for ITS test

CHAPTER 4. TEST RESULTS AND ANALYSIS

4.1 Specific Gravity Test Results

RAP was fractionated at the #16 sieve in hopes for the volumetric tests to become acceptable for the DOT regulations in the field. Specific gravity had to be found using experiments mentioned above to determine the many properties that goes into the design of asphalt.

4.1.1 Fractionation Gradation

The first step for the mix design is to sieve the RAP at the #16 sieve and discard smaller sizes. The resulting percentages of each sieve size are measured and then taken to be burnt off to measure the resulting gradation. Table 4-1 shows the gradation of the fractionated RAP before and after the burn-off. Figure 4-1 also shows the gradation of the burnt off RAP after the gradation along with the maximum density line and high and low points for the ½", 3/8", #8 and #200 sieve.

Table 4-1. Resulting Gradation of fractionated RAP

	Fractionated RAP		
	Frac. ≥ #16		
Sieve Size	RAP Matl.	Recovered Aggregate	
	% Ret.	Mass Ret.	% Ret.
1 1/2 inch	0.0%	0.0	0.0%
1 inch	6.80%	0.0	0.00%
3/4 inch	7.87%	0.0	0.00%
1/2 inch	15.59%	50.9	3.54%
3/8 inch	10.59%	76.4	5.32%
No. 4	27.26%	410.3	28.55%
No. 8	19.13%	315.0	21.92%
No. 16	12.76%	212.9	14.81%
No. 30	0.0%	107.2	7.46%
No. 50	0.0%	91.6	6.37%
No. 100	0.0%	46.6	3.24%
No. 200	0.0%	17.2	1.20%
Pan	0.0%	109.2	7.60%
Binder Content (%)	4.18		
Total Sample Size (g)	1437.3		
% of RAP Blend	100%		
% Removed/Left Over	100.00%		

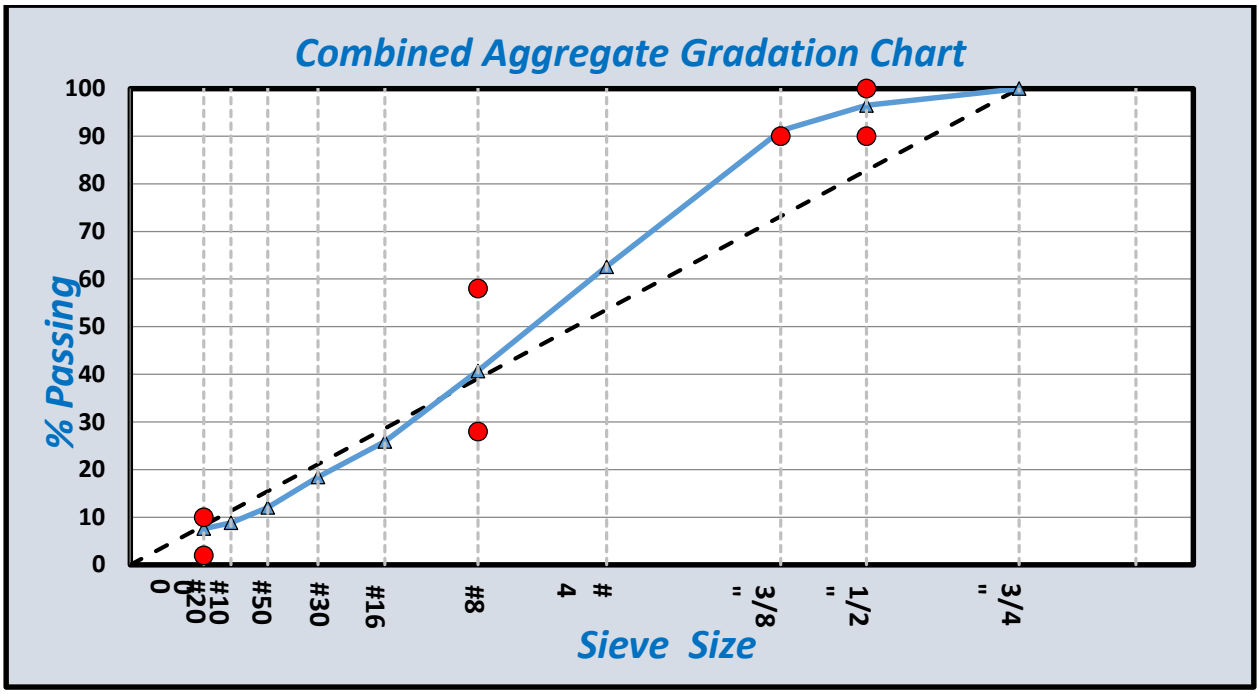

Figure 4-1. Gradation of burnt off fractionated RAP

4.1.2 RAP Binder Content

Along with finding the gradation of the fractionated RAP after the burn-off, the binder content of the RAP was also found. Six samples were taken to be burnt off to determine the average binder content. Table 4-2 shows the results for the average binder content of the fractionated RAP. It can be seen that there is a significant variability with the binder contents further as shown in Figure 4-2.

Table 4-2. Fractionated RAP binder content

Binder Content	
1	4.30%
2	4.08%
3	4.23%
4	4.32%
5	4.16%
6	3.99%
Average	4.18%
Std. Dev.	0.128841

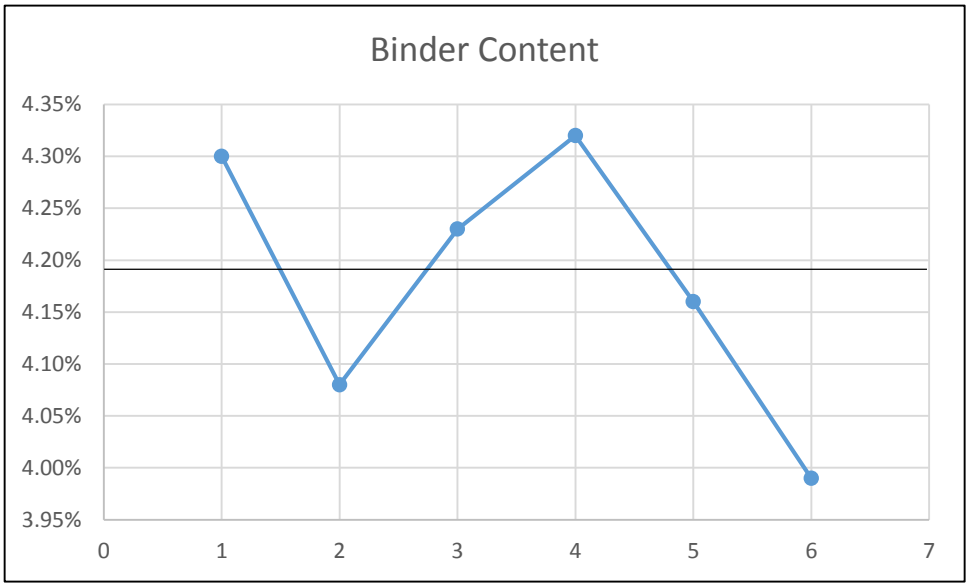

Figure 4-2. Varying Binder Contents from Burn-off

4.1.3 Volumetric Test Results

The following properties can be determined from the volumetric tests: VMA, VFA, Dust-Binder ratio, and Film thickness. These formulas shown below to calculate the different properties.

$$VMA = \left(1 - \frac{G_{mb}(1-P_b)}{Gsb}\right) * 100 \quad \text{Eq. 1}$$

Where: Gmb = bulk specific gravity of the compacted sample

Gsb = bulk specific gravity of the aggregate in the mix

Pb = asphalt content in the mix by weight

$$VFA = \frac{V_{be}}{V_{be}+V_V} \quad \text{Eq. 2}$$

Where: Vbe = Volume of the effective asphalt binder

Vv = Volume of the total voids

$$Dust - Binder\ ratio = \frac{\%<\#200}{P_{be}} \quad \text{Eq. 3}$$

Where: Pbe = Effective binder by weight in mix

$$Film\ Thickness = 10 * (\frac{P_{be}}{A_s}) \quad \text{Eq. 4}$$

Where: As = Surface area of the aggregate

4.1.3.1 Coarse Aggregate Results

Before the volumetric properties can be obtained, the coarse aggregate results are used to find the following properties: bulk specific gravity (Gsb), apparent specific gravity (Gsa), and absorption.

$$Gsb = \frac{A}{(B-C)} \quad \text{Eq. 5}$$

Where: A = Weight of oven dry sample in air

B = Weight of saturated surface dry sample in air

C = Weight of saturated sample in water

$$Gsa = \frac{A}{(A-C)} \quad \text{Eq. 6}$$

$$Absorption = \left(\frac{(B-A)}{A}\right) * 100 \quad \text{Eq. 7}$$

4.1.3.2 Fine Aggregate Results

Along with the coarse aggregate results, the fine aggregate results are found and combined with the coarse aggregate results. The following properties are found: bulk specific gravity (Gsb), apparent specific gravity (Gsa), and absorption.

$$Gsb = \frac{A}{(B+S-C)} \quad \text{Eq. 8}$$

Where: A = Weight of oven dry sample

B = Weight of flask filled with water

C = Weight of flask with aggregate and water

S = Weight of saturated surface dry sample (500 g.)

$$Gsa = \frac{A}{(B+A-C)} \quad \text{Eq. 9}$$

$$Absorption = \left(\frac{(S-A)}{A}\right) * 100 \quad \text{Eq. 10}$$

Following the calculations for both coarse and fine aggregate, both calculations for each criteria is multiplied by the percent of it occupies in the total mix and then combined. After the burn off, 37.4% of the mix was coarse (≥ #4 sieve) and 62.6% was fine. After the calculations, the Gsb, absorption, and Gsa results are shown in table 4-3.

Table 4-3. Final Gsb, Absorption and Gsa Results

G_{sb}	ABS, %	G_{sa}
2.650	**1.190**	**2.736**

4.1.3.3 Mix Design Results

The mix design results were determined for both binder contents of no additional binder and the optimum binder content. It was foreseen that the RAP without additional virgin binder would not pass any of the credentials, but the optimum binder was more hopeful. Table 4-4 shows the mix design results for the RAP with no additional binder, and Table 4-5 shows the results for the optimum binder content.

Table 4-4. Mix Design Results for no additional binder

Mixture Property	Value	Specification
Target Air Voids (%)	3.50%	----
Optimum Asphalt Content (%)	4.18%	----
RAP (% Dry Mix Weight)	100.0%	----
RAP (% Total Aggregate)	100.0%	----
Agg. Bulk Spec. Gravity (G_{sb})	2.650	----
Max. Specific Gravity (G_{mm})	2.557	----
Binder Abs. (P_{ba} % DWA)	1.18	----
Effective Binder (P_{be} % TWM)	3.05	----
Bulk Specific Gravity (G_{mb})	2.468	----
VMA (%)	10.8	14.0% Min.
VFA (%)	67.5	70% - 80%
Dust-Binder Ratio	2.49	0.6 -1.4
Film Thickness, µm	4.90	8.0 - 13.0

Table 4-5. Mix Design Results for the Optimum binder content

Mixture Property	Value	Specification
Target Air Voids (%)	3.50%	----
Optimum Asphalt Content (%)	5.28%	----
RAP (% Dry Mix Weight)	100.0%	----
RAP (% Total Aggregate)	100.0%	----
Agg. Bulk Spec. Gravity (G_{sb})	2.650	----
Max. Specific Gravity (G_{mm})	2.515	----
Binder Abs. (P_{ba} % DWA)	1.18	----
Effective Binder (P_{be} % TWM)	4.16	----
Bulk Specific Gravity (G_{mb})	2.427	----
VMA (%)	13.2	14.0% Min.
VFA (%)	73.6	70% - 80%
Dust-Binder Ratio	1.83	0.6 -1.4
Film Thickness, µm	6.68	8.0 - 13.0

4.1.3.4 Gmm Test Results

Gmm is known as the maximum theoretical specific gravity of the mix and can be found with the following formula.

$$Gmm = \frac{A}{(A+D-E)} \quad \text{Eq. 11}$$

Where: A = Weight of broken up aggregate

D = Weight of water filled container

E = Weight of aggregate, and water in container

The results of each experiment are given in the tables below. The Gsb and Gsa used for these experiments are 2.650 and 2.736, respectively. Table 4-6 shows the results from the first and second experiment.

Table 4-6. Experiment 1 and 2 for 100% RAP Gmm.

Sample ID	% AC	Dry Weight	H20 + Metal Bowl	Agg. In Metal bowl	G_{mm}	Avg, G_{mm}	Gse
HMA 1	4.18	2489.8	7357.8	8874.3	2.558	2.557	2.732
HMA 2	4.18	2497.2	7357.8	8878.3	2.557		
HMA 1 150C	4.18	2483.8	7357.4	8872.1	2.563	2.561	2.737
HMA 2 150C	4.18	2489.1	7357.4	8874.1	2.560		

As is shown from the table, the Gse for both experiments is above Gsa which should not be possible. Table 4-7 shows the results from the third experiment.

Table 4-7. Experiment 3 for 100% RAP Gmm.

Sample ID	% AC	Dry Weight	H20 + Metal Bowl	Agg. In Metal bowl	G_{mm}	Avg, G_{mm}	Gse
HMA 1	5.00	2010.4	7357.8	8577.7	2.543	2.543	2.754
HMA 2	5.00	2007.4	7339.3	8557.1	2.542		

Table 4-7 shows the same predicament as the table above with the Gse being too high. Table 4-8 shows the fourth experiment with new added binder at the same percentage by weight that they were before burn-off.

Table 4-8. Experiment 4 for 100% RAP Gmm.

Sample ID	% AC	Dry Weight	H20+ Metal Bowl	Agg. + Metal Bowl	G_{mm}	Gse
HMA 1	4.16	1982.1	7357.8	8568	2.568	2.744
HMA 2	4.23	1971.8	7357.6	8560.8	2.565	2.744

As can be seen, the results still aren't exactly where we would like them. Table 4-9 shows the results for the fifth experiment where burnt off RAP was replaced with new binder at 5% by weight.

Table 4-9. Experiment 5 for 100% RAP Gmm.

Sample ID	% AC	Dry Weight	H20 + Metal Bowl	Agg. In Metal bowl	G_{mm}	Avg, G_{mm}	Gse
HMA 1	5.00	1995.3	7357.8	8567.9	2.541	2.543	2.754
HMA 2	5.00	1992.6	7339.3	8548.9	2.545		
HMA 3	5.00	2005.3	7357.4	8575.3	2.547	2.548	2.76
HMA 4	5.00	2002.2	7339.3	8556.2	2.55		
HMA 5	5.00	2004	7360.5	8578.5	2.55	2.543	2.754
HMA 6	5.00	2005.6	7360.5	8575.6	2.537		

With even higher Gse numbers, the last chance for promising results was to use the Corelok procedure, which is shown in Table 4-10.

Table 4-10. Corelok Experiment for 100% RAP Gmm.

Sample ID	Bag weights	Aggregate weight	Underwater	Gmm	Avg, Gmm	Gse
HMA 1	73.9	1998.8	1207.7	2.552	2.5565	2.771
HMA 2	73.1	1992.5	1206.5	2.561		

Figure 4-3 and 4-4 show the resulting Gmm for the samples that had RAP binder included, and the Gmm for the samples with virgin binder added after the binder burnoff, respectively. These two figures show the linear regression to find the variability in the mixes. Both figures show a small variability with the Gmm's meaning the samples can be assumed to be consistent throughout the experiments for determining airvoids. The linear regression in Figure 4-3 will be used to determine the Gmm at varying binder contents, as the 100% RAP mixes tested on has RAP binder present. With the findings, the Gmm for 100% RAP with no additional binder was found to be 2.557 and the 100% RAP mix with additional virgin binder to achieve 5.00% total binder content was 2.543.

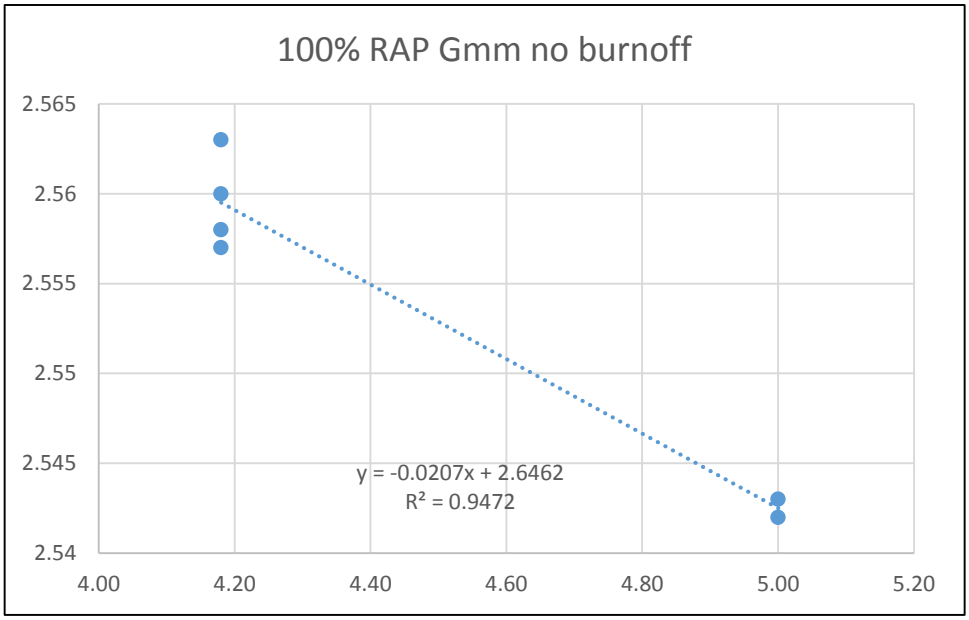

Figure 4-3. 100% RAP Gmm with aged binder (Experiment 1, 2 and 3)

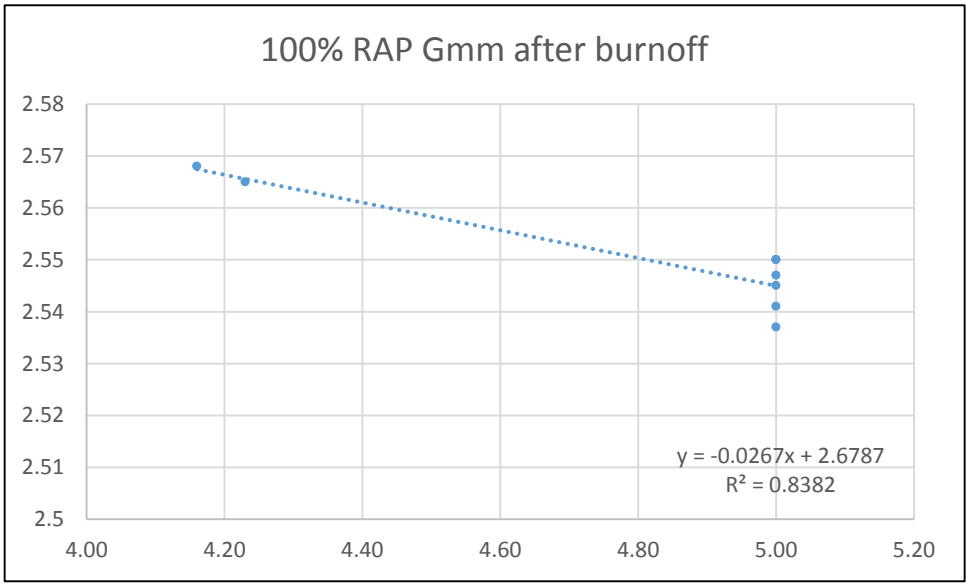

Figure 4-4. 100% RAP Gmm with virgin binder after burnoff (Experiment 4 and 5)

4.1.3.5 Gmb Test Results

The Gmb is helpful, along with the Gmm, to find the air voids of compacted samples. It is important to find the air voids of the samples, so the optimum binder content can be determined for further testing. The Gmm changes with the asphalt content so it is necessary to find the Gse also to calculate different Gmms for each asphalt content. The Gmb formula is shown below.

$$Gmb = \frac{A}{(B-C)} \quad \text{Eq. 11}$$

Where: A = Weight in grams of specimen in air

B = Weight in grams of saturated surface dry

C = Weight in grams in water

To find the optimum binder content of the 100% RAP mixture, samples were compacted with 4.18% (no additional virgin binder), 5%, and 5.5% binder by weight. The mixtures were compacted at 96 gyrations according to the standards for 10 million ESAL designs. Each Gmb is then used to calculate the air voids to find the optimum binder content. The air voids for the optimum binder content is set to 3.5% air voids. Normally, air voids are set to 4%, but 3.5% is used because RAP is stiffer and will result in a higher fatigue resistance. Table 4-11 shows the average Gmbs of the mixtures, and Figure 4-5 shows the linear regression for the 3.5% air void objective.

Table 4-11. Average Gmb of each binder content

Sample ID	A	C	B	G_{mb}	Avg, G_{mb}
H1, 4.18%	4922.4	2903.2	4977.8	2.373	2.377
H2, 4.18%	4920.1	2904.2	4972.9	2.378	
H1, 4.18%	4893.3	2892	4949	2.379	
H1, 5.0%	4864.9	2873.5	4877.7	2.427	2.431
H2, 5.0%	4865.0	2878.7	4877.0	2.435	
H1, 5.5%	4792.8	2833.5	4798.7	2.439	2.439
H1, 5.5%	4794.7	2837	4803.4	2.438	

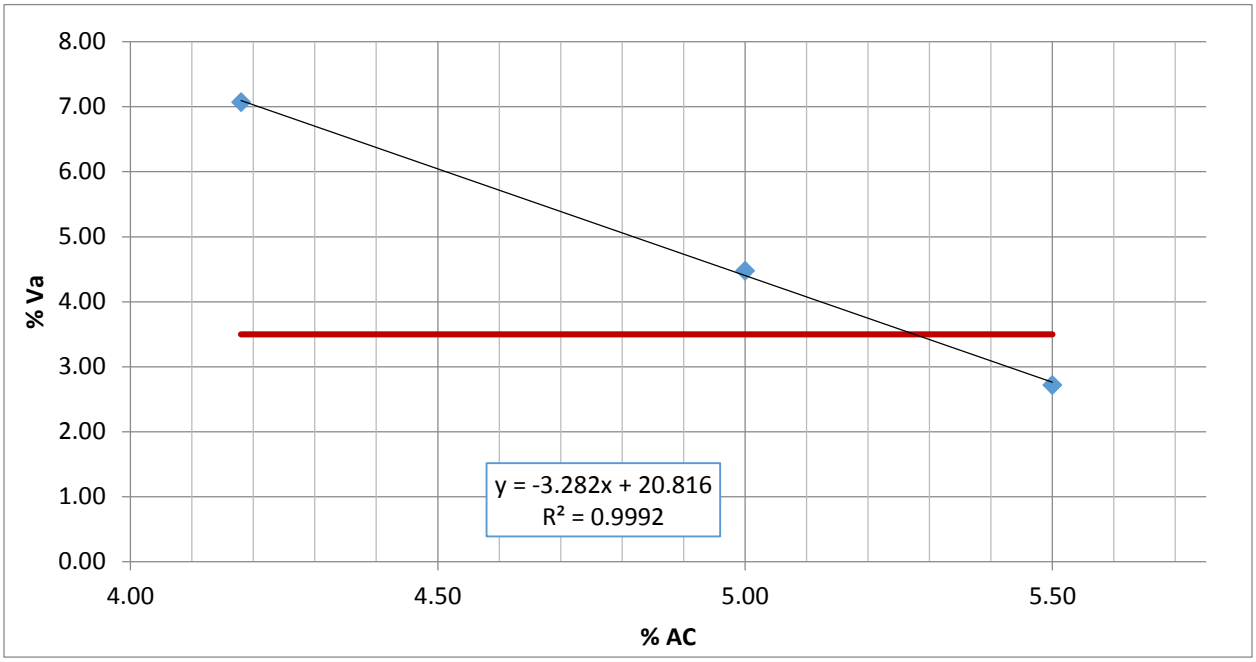

Figure 4-5. Optimum Binder Content for 3.5% air voids

Showing the regression line and an R-squared value of .9992, the optimum binder content can be calculated to 5.28% binder by weight.

4.2 Beam Fatigue Test Results

4.2.1 Slab Characteristics

To begin the beam fatigue testing, slabs had to be compacted with air voids being 7 ± 1%. The first two slabs that were compacted were used to determine the proper amount of material needed for proper air voids. Table 4-12 shows the resulting air voids of each slab which were calculated using the Eq. 1 shown below. As can be seen, the first two slabs compacted did not meet the air void criteria, so they were discarded from further experiments.

$$\boldsymbol{Air\ Voids} = \frac{(\boldsymbol{Gmm - Gmb})}{\boldsymbol{Gmm}} * \mathbf{100} \qquad \text{Eq. 12}$$

Table 4-12. Slab air void contents

	Dry Wt.	Sub Wt.	SSD Wt	Gmb	Gmm	Air Voids
Sample 1	9263.5	5451.4	9303.5	2.405	2.5369	5.21
Sample 2	9556.1	5664.1	9589.3	2.435	2.5369	4.03
Sample 3	8785	5105.5	8859.6	2.340	2.5369	7.76
Sample 4	8899.9	5176.5	8951.5	2.358	2.5369	7.07
Sample 5	8891.6	5203.7	8998.6	2.343	2.5369	7.64

4.2.2 Beam Characteristics

Each slab that had adequate air voids were then cut into three separate beams that could be used for testing. After each beam was cut, the air voids had to be found for each beam to ensure they had proper air voids. Along with the air voids, the height and width was taken three times of each beam for later calculations. Table 4-13 shows the resulting air voids along with each height and width. As can be seen, each beam has acceptable air voids and can proceed to be used in the fatigue testing.

Table 4-13. Beam Air Voids, Height and Width

Sample	Height	Width	Gmb	Air Voids
1-1	48.2	56.5	2.359	7.00
1-2	48.4	66.4	2.363	6.85
1-3	48.3	60.4	2.351	7.33
2-1	48.2	64.0	2.371	6.54
2-2	48.3	64.9	2.378	6.26
2-3	48.5	59.2	2.364	6.80
3-1	48.7	58.0	2.350	7.38
3-2	48.7	60.5	2.371	6.56
3-3	48.5	49.6	2.349	7.41

4.2.3 Beam Fatigue Results

Following the beam fatigue tests, the strain was plotted against the amount of the load cycles each beam went through. Three beams were used for each strain setting of 800, 600 and 350 micro-strain. For each test, the initial flexural stiffness is recorded after 50 load cycles and failure is set to when the stiffness of the beam reaches 50% of that value. Table 4-14 shows the number of load cycles to failure (Nf) with the constant strain. The resulting beam fatigue curve is shown in Figure 4-6 compared to the NCAT control base (Timm 2012).

Table 4-14. Beam Fatigue Results

IA - 100% RAP					
Beam	Microstrain	Strain	Nf	Initial Flexural Stiffness (Mpa)	Voids
1	800	0.0008	1940	5760	6.54%
2	800	0.0008	3940	5256	7.38%
3	800	0.0008	4380	4520	7.33%
4	600	0.0006	18360	6488	6.56%
5	600	0.0006	5320	5507	7.41%
6	600	0.0006	13790	7237	6.26%
7	350	0.00035	147490	6356	7.00%
8	350	0.00035	640410	7413	6.80%
9	350	0.00035	396420	6995	6.85%

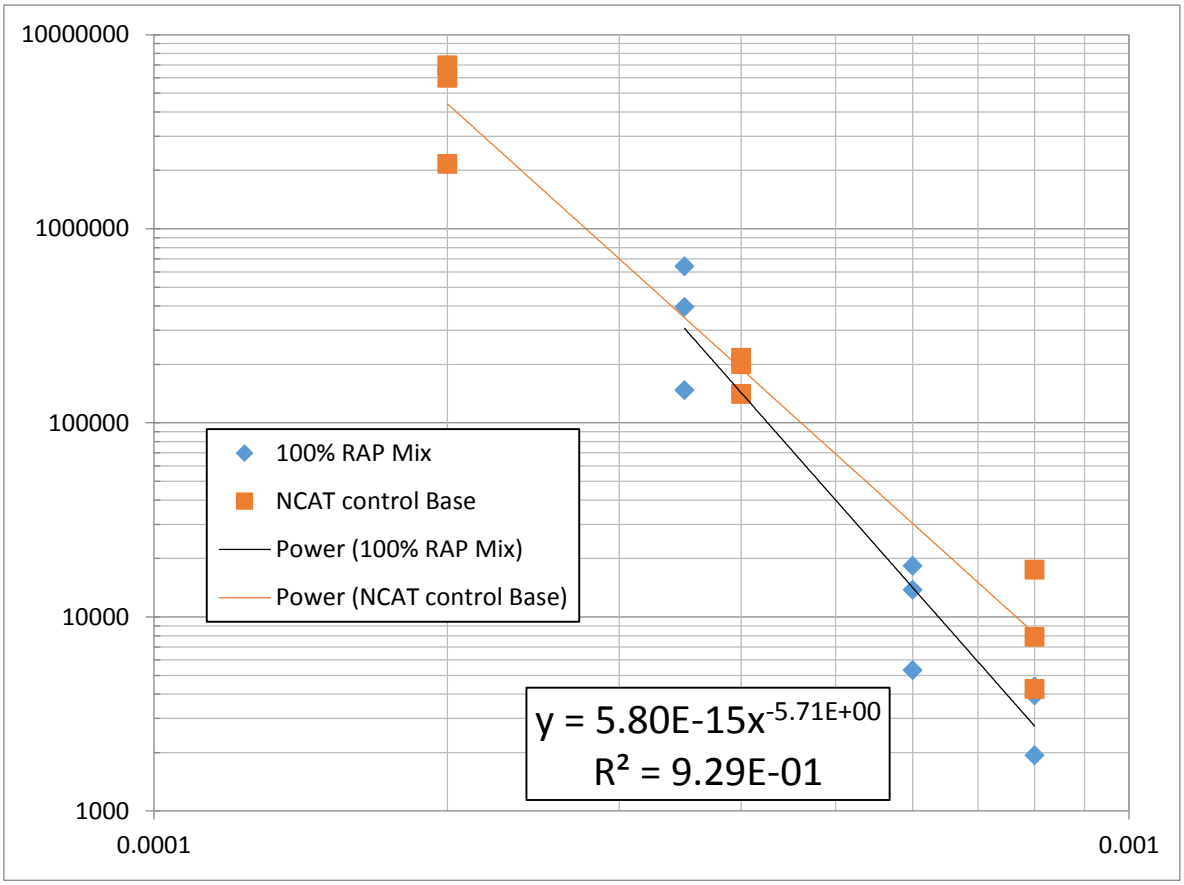

Figure 4-6. Resulting Beam Fatigue Curve

The percentage difference between the average fatigue life of the NCAT control base and that of the 100% RAP mix were calculated to fully realize the 100% RAP results. Calculated percentage differences are shown in Table 4-15. The fatigue life for the 100% RAP mix was extrapolated from the equation found from the graph for comparison reasons. The fatigue life of the NCAT control base had a 65.4% and 21.3% longer life for the strain levels of 800 and 400 με, respectively. However, at 200 με, the 100% RAP mix lasted for 52.2% longer than the NCAT control base.

Table 4-15. Percentage of fatigue resistance of NCAT control base vs. 100% RAP mix.

Strain level	800 με	400 με	200 με
Percent Change in Fatigue Life	65.4%	21.3%	-52.2%

4.3 PG-grading

4.3.1 DSR Results

From the process of binder being aged, the chemical properties change, making the binder stiffer. This stiffness increases the higher PG-grade due to the need for higher temperatures to make the binder viscous. Due to this knowledge, the BBR was tested first to see the plausibility of higher a accessible upper temperature. After the BBR results, the DSR was not deemed necessary due to the failing of the BBR testing.

4.3.2 BBR Test Results

During the BBR testing, the measured stiffness and deflection is recorded after 60 seconds to determine the lower PG-grade of the binder. Both the aged binder and optimum binder content were tested two separate time for the m-value and stiffness at -12 and -6°C. Table 4-16 shows the results for each binder content at each temperature. For the binder to be passed, the m-value and stiffness must be greater than .3 and less than 300 MPa, respectively, after 60 seconds in the test. Figure 4-7 and 4-8 show the resulting BBR tests, for m-value and stiffness, respectively, along with the necessary parameters to pass each test.

Table 4-16. BBR Test Results

100% RAP Mix	Temperature	m-value	Stiffness (Mpa)
No Additional Binder	-12	0.252	363
		0.246	448
	-6	0.268	241
		0.274	217
Optimum Binder	-12	0.245	314
		0.251	307
	-6	0.283	187
		0.277	196

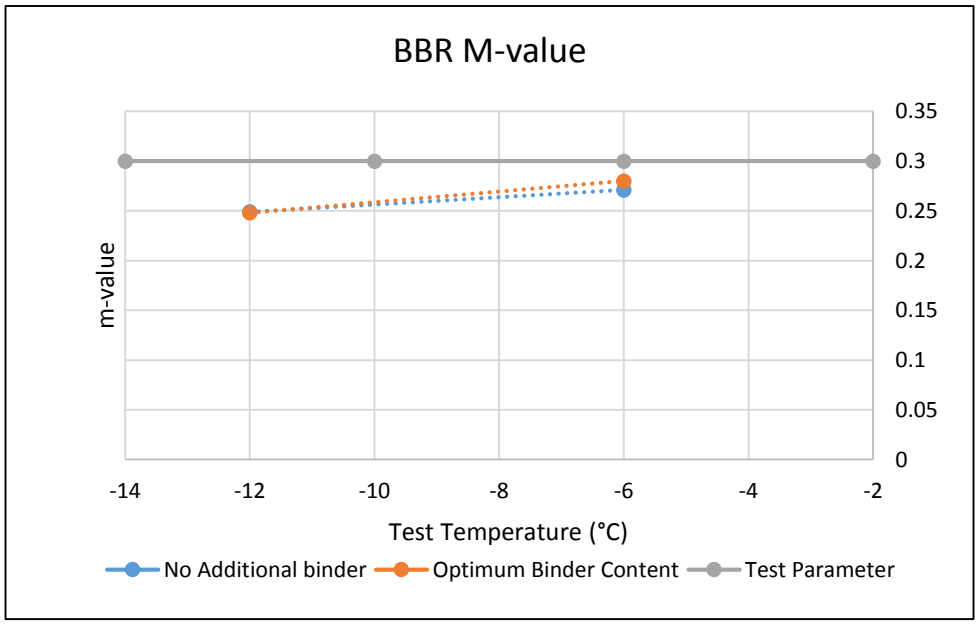

Figure 4-7. BBR m-value Results for both 100% RAP mixes with and without additional binder

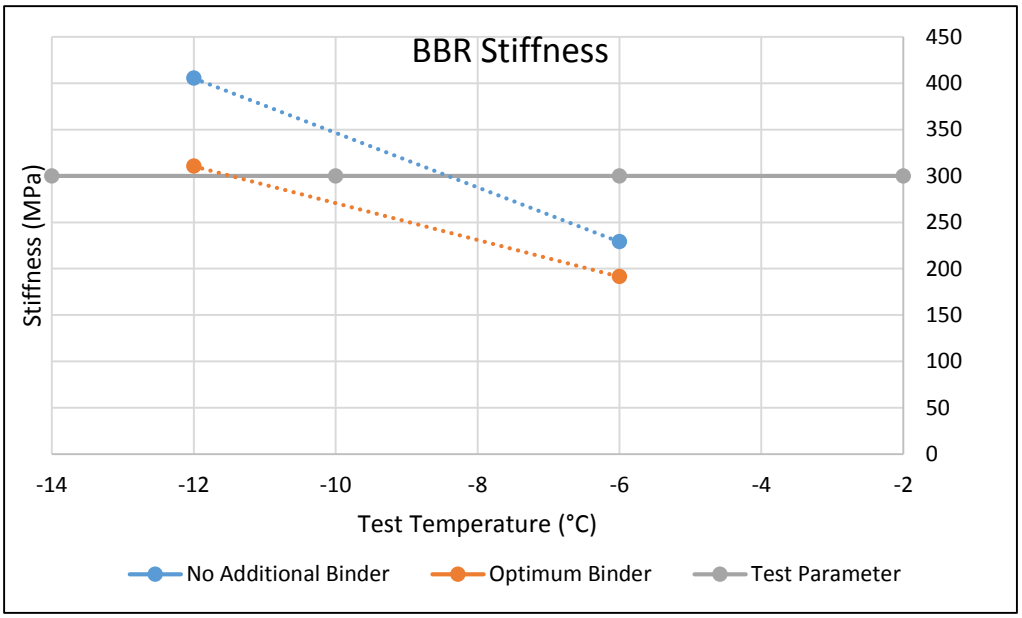

Figure 4-8. BBR Stiffness Results for both 100% RAP mixes with and without additional binder

4.4 Aged Binder Blending Results

Currently, the practice of associating RAP into mixes assumes a 100% blend of the aged binder and virgin binder. However, with the stiffness of the aged binder in the RAP, that should not always be assumed until it is proven. These following tests hoped to help with the understanding of the temperatures needed to ensure proper blending.

4.4.1 Compaction Test Results

The compaction testing was able to show the importance of preheat temperature to ensure proper blending of all the available binder in mixes. After compaction, the results were used to calculate the actual compaction by comparing the compaction of 160°C to that of the normally used temperature of 135°C. Equation 12 shows the formula used to determine the actual compaction when 135°C is used. Table 4-17 and Figure 4-9 shows the compaction of each sample throughout the compaction process.

$$\%\ Compaction = \frac{Height_{160} - Height_{135}}{Height_{135}} \qquad \text{Eq. 12}$$

Table 4-17. Compaction heights for different temperatures.

Temperature		Gyrations						
		8	25	50	75	96	125	152
110 C	1	140.2	132.6	128.7	126.8	125.7	124.6	123.9
	2	140.4	132.8	128.8	126.9	125.8	124.7	123.9
135 C	1	138.8	131.5	127.7	125.8	124.7	123.6	122.9
	2	138.9	131.5	127.7	125.7	124.7	123.6	122.9
160 C	1	136.7	129.3	125.7	123.8	122.8	121.7	121.1
	2	136.8	129.4	125.7	123.8	122.7	121.8	121.1

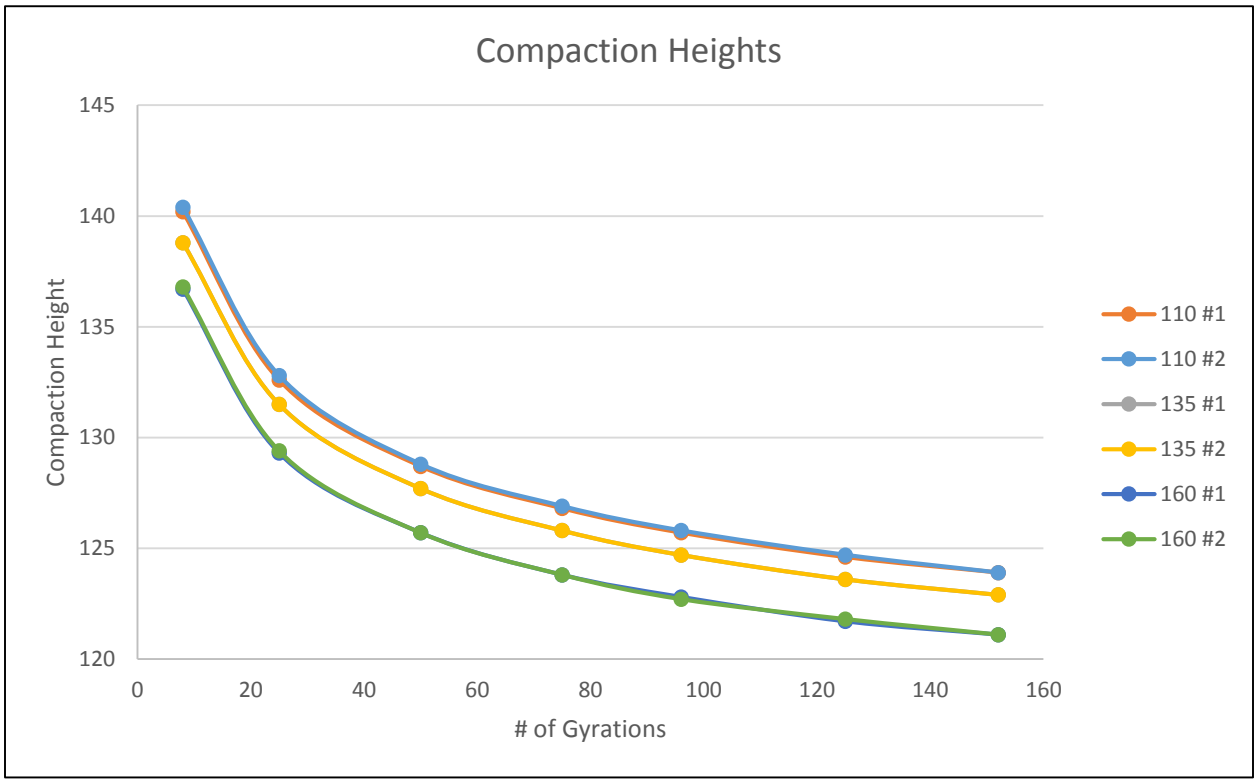

Figure 4-9. Compaction heights for each sample

With the results shown, it can easily be seen the compaction is greater as the temperature increases. The percentage of potential compaction compared to the normally used temperature of 135°C is shown in Table 4-18.

Table 4-18. Percent of Compaction for each recorded gyration

	Gyrations						
	8	25	50	75	96	125	152
% Compaction Improvement	-1.51%	-1.63%	-1.57%	-1.55%	-1.56%	-1.50%	-1.46%

4.4.2 Indirect Tensile Strength Results

Following the promising results from the compaction test, the indirect tensile strength test was hoping to also prove that higher temperatures would lead to higher tensile strength results. The indirect tensile strength was calculated using the following formula.

$$S_T = \frac{2F}{3.14(h*d)} \quad \text{Eq. 13}$$

Where: S_T = Indirect Tensile Strength (psi)

F = Total applied vertical load at failure (lb)

h = Height of specimen (inches)

d = Diameter of specimen (3.937 inches)

Table 4-18 shows the resulting tensile strength of each compacted specimen along with the average for each preheating temperature. Figure 4-10 shows the increase in tensile strength as the temperature is increased.

Table 4-19. ITS results for each preheating temperature.

Sample	Height (in)	Diameter (in)	Force (lb)	ITS (psi)	Avg. ITS (psi)
110 #1	2.590	3.937	3260	203.6352	192.2041077
110 #2	2.590	3.937	2894	180.7731	
135 #1	2.580	3.937	3245	203.4838	208.2149956
135 #2	2.574	3.937	3388	212.9461	
160 #1	2.530	3.937	3749	239.7341	224.3404415
160 #2	2.535	3.937	3274	208.9468	

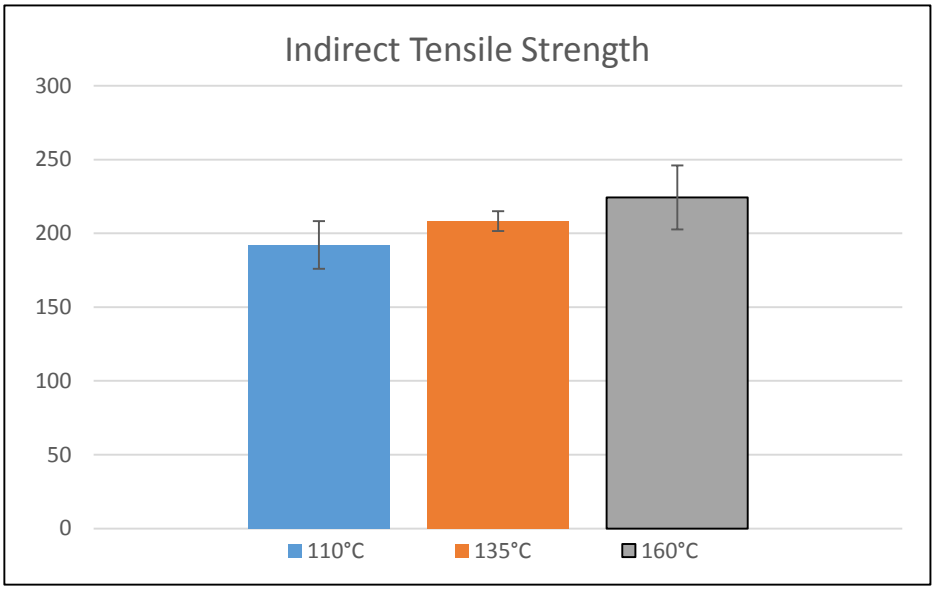

Figure 4-10. Average tensile strength results for each temperature

CHAPTER 5. SUMMARY OF FINDINGS

5.1 Conclusions

5.1.1 General Conclusions

As can be seen throughout the results, the 100% RAP at the optimum binder content tended to perform well. The 100% RAP without any virgin binder had worse mix design results than the optimum binder content along with worse BBR testing results. It can be noted that rejuvenators or polymer modifiers could be a more economical choice for the RAP mix, as a large amount of virgin binder was needed for the optimum binder content.

The mixing of RAP has always been an issue when it comes to complete mixing or partial mixing with virgin materials. With the findings for compaction and tensile strength tests, it can be noted that RAP needs to be heated for longer or at a higher temperature before mixing can occur. Mixing RAP at the current temperature can be assumed that only 65% of the aged binder is being mixed with the virgin material. As said above, a rejuvenator could help loosen the aged binder and help with the mixing process.

5.1.2 Specific Gravity

After significant lab work was done, it is safe to assume that the binder content of the fractionated RAP varies considerably. The first procedure for the Gmm showed promising results, but it cannot be confidently considered the solution due to the varying binder contents. This is due to a number of factors from how small the samples are and the amount of binder that is within the larger pieces. Even when the RAP is split into smaller sieve sizes, the amount of binder in the larger pieces influences the entire sample greatly. Another factor that could be detrimental to the results is the partial blending that can occur due to the stiffer binder.

Fractionated RAP is important as it is used in the higher RAP samples that are being placed in the roads due to the fact it has a lower dust content. Fractionated RAP in the field has a higher dust content due to fines stuck on larger aggregate but has a substantially larger sample to balance out the binder content. The lab work has a more precise extraction of fines because of

the smaller samples, but that is detrimental to the results as the larger pieces influence the binder content more, causing higher variation of binder content.

5.1.3 Beam Fatigue Results

The beam fatigue results for the 100% RAP show positive results for a potential of higher RAP usage. Comparing results with the NCAT control base, as discussed in the literature review, the results look very similar with fatigue resistance. The average number of cycles for each micro-strain was taken from the NCAT results and compared to the extrapolated results from the 100% RAP results. The NCAT results had a higher amount of cycles for strains of 800 and 400 micro-strain, but the 100% RAP far surpassed the NCAT for the magnitude of 200 micro-strain.

To compare results from the earlier experiments mentioned in the literature review (Boriack 2013), the number of cycles for 400 micro-strain is calculated using the Nf = K1x^K2 model found in the current experiments. The calculated cycle number for a micro-strain of 400 comes to over 146,000 cycles, which surpasses the findings for their 0% RAP fatigue resistance. As mentioned earlier, a mix design was not mentioned to infer one was not conducted, so results could have been greater if one was done. However, with the unfavorable results from the literature review, it does show that with an increased amount of virgin binder, the fatigue resistance does increase substantially. As these were good experiments, it should be noted that perhaps the same results could come from rejuvenators or polymer modifiers to be even more economically efficient with the same performance.

5.1.4 PG- Grading

Following the PG-grade experiments, it is apparent that just adding virgin binder does not soften the aged binder adequately enough for field use. The BBR testing showed promising results for stiffness, but failed at the m-value for -6°C. Due to this, DSR testing was not conducted but could be safely assumed the higher temperature grade would be above 88°C. As mentioned earlier, rejuvenators or polymer modifiers may need to be used to soften the aged binder further to ensure promising results.

5.1.5 Aged-Binder Blending

The results shown from the compaction test and the indirect tensile strength test, it is apparent that 100% blending cannot be assumed with the current preheating temperature that is used. Due to the stiffer binder grade of the aged binder, a higher temperature is needed to soften the binder to allow for proper blending.

The compaction test results show the higher temperature allows more compaction, which can be understood that there were more fines and more effective binder in the mix. More fines were in the mix as a result of the more viscous binder allowing the finer particles to separate from the larger aggregate in the mix. With more fines, and more effective binder, the smaller spaces in the compacted samples can be filled, allowing for a better compaction rate. With the results, it can be hypothesized that with the current preheating temperature of RAP, a 65% blending occurs when virgin binder is introduced to the mix.

The results from the indirect tensile strength test also prove of better blending as the preheating temperature is increased. As the more viscous binder in the RAP is mixed and compacted, the increase in effective binder allows for better coating of the aggregate. Being thoroughly coated, the aggregate can bond further, causes the specimen to have an increase in tensile strength.

5.2 Recommendations for Further Study

The objective of this research was to create a better understanding of 100% RAP mixes, along with the pavement performance properties such as fatigue resistance and tensile strength. These experiments were meant to find feasibility of being able to use 100% RAP mixes in the field, to create a truly sustainable pavement. In an effort to find this, the materials were identified along with mix designs to find the interaction with aged and virgin binder, the fatigue resistance, and the potential mixing ability of RAP products.

Some further tests need to be conducted to bring a better understanding of 100% RAP mixes. Rejuvenators and polymer modifiers could be used to reduce the amount of virgin binder needed in the mixes, as they would soften the aged binder more than just virgin binder. Further

testing should occur with the addition of these rejuvenators, such as PG-grading, fatigue resistance and rutting resistance to find the true value of these rejuvenators. Once these tests are run, the cost benefit ratio can be compared to just using virgin binder to find the most economical way to lay 100% RAP mixes.

REFERENCES

Al-Qadi, I. L., S. H. Carpenter, G.L. Roberts, H. Ozer, Q. Aurangzeb, *Investigation of Working Binder in Hot-Mix Asphalt Containing Recycled Asphalt Pavements*, Illinois Center of Transportation, Paper Number 09-1262, March 2009.

R. Hassan, *Feasibility of Using High RAP Contents in Hot Mix Asphalt,* Swinburne University of Technology

Al-Qadi, I. L., S. H. Carpenter, Mostafa Elseifi, *Reclaimed Asphalt Pavement- A Literature Review*, Illinois Center for Transportation, Research Report FHWA-ICT-07-001, March 2007

E. Denneman, M. Dias, S. Malone, Y. Choi, E. Woodall, R. Urquhart, *Maximising the Re-use of Reclaimed Asphalt Pavement: Binder Blend Characterisation*, Austroads Ltd, Austroads Publication No. AP-T245-13, August 2013

D.H. Timm, M. M. Robbins, J. R. Willis, N. Tran, A. J. Taylor, *Evaluation of Mixture Performance and Structural Capacity of Pavements Utilizing Shell Thiopave*, National Center of Asphalt Technology, NCAT Report 12-07, August 2012.

B. D. Prowell, E. R. Brown, R. M. Anderson, J. S. Daniel, A. K. Swamy, H. V. Quintus, S. Shen, S. H. Carpenter, S. Bhattacharjee, S. Maghsoodloo, *Validating the Fatigue Endurance Limit for Hot Mix Asphalt*, National Cooperative Highway Research Program, NCHRP Report 646, February 2010.

S. H. Carpenter, *Fatigue Performance of IDOT Mixtures*, Illinois Center for Transportation, Research Report FHWA-ICT-07-007, July 2006.

P. Boriack, S. W. Katicha, G. W. Flintsch, *A Laboratory Study of the Effect of High RAP and High Asphalt Binder Content on the Stiffness, Fatigue Resistance and Rutting Resistance of Asphalt Concrete*, Transportation Research Board, August 2013

I. L. Al-Qadi, Q. Aurangzeb, S. H. Carpenter, W. J. Pine, J. Trepanier, *Impact of High RAP Content on Structural and Performance Properties of Asphalt Mixtures*, Illinois Center for Transportation, Research Report FHWA-ICT-12-002, June 2012

F. Zhou, S. Hu, G. Das, T. Scullion, *High RAP mixes Design Methodology with Balanced Performance*, Texas Department of Transportation, Report FHWA/TX-11/0-6092-2, November 2011

V. V. Gonzalo, P. J. Felix, M. R. Rodrigo, M. Adriana, *Experimental Study of Recycled Asphalt Mixtures with High Percentages of Reclaimed Asphalt Pavement,* Transportation Research Board, November 2009

N. Sabahfar, S. R. Aziz, M. Hossain, G. Schieber, *Evaluation of Superpave Mixtures with High Percentages of Reclaimed Asphalt Pavement,* Transportation Research Board, January 2014

Stephens, J. E., J. Mahoney, and C. Dippold, *Determination of the PG Binder Grade to Use in a RAP Mix*, Report No. JHR 00-278, Connecticut Department of Transportation, Rocky Hill, CT, 2001

"Aggregate Specific Gravity" 13 August 2007. http://www.pavementinteractive.org, 7 July 2014

Hansen, K. R. and A. Copeland, *Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage:2009-2012*, Federal Highway Administration, Washington D.C., December 2013