RECYCLED ASPHALT PAVEMENT MIXTURES FOR ROAD CONSTRUCTION

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ABSTRACT:

Recycled Asphalt Pavement (RAP) is the largest recycled good inside the u. s. and eighty million tons ar recycled yearly, saving taxpayers about $1.5 billion bucks. This paper explores the possibility of utilizing 100 percent RAP materials in asphalt pavement. Asphalt mixtures are created 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 visualize the amount of effective binder available from RAP inside the asphalt plant. The 100% RAP combines have aged binder that can alter combine designs and interaction with virgin binder. In this study, to determine temperature cracking resistance and fatigue performance, samples were prepared exploitation a 100 percent RAP mix with no virgin binder and a 100 percent RAP mix with virgin asphalt binder to understand 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 attainable for field use if any virgin binder is else to attain the optimum asphalt content. Based on restricted take a glance at results, the low temperature grade weren't within correct limits but the beam fatigue testing results were acceptable. Based on compaction take a glance at results, additional heating is needed to extend the effectiveness of asphalt binder from RAP materials.

I INTRODUCTION

Recycling of existing asphalt pavement materials to produce new pavement materials results in considerable savings of material, money and energy. The specific benefits of recycling can be summarized as follows: (a) substantial savings over the use of new materials, (b) conservation of natural resources, (c) performance equal or even better than new materials, (d) pavement geometrics is maintained and (e) saving of considerable amount of energy compared to conventional construction techniques. The last benefit is very important due to the recent urgent need for reducing greenhouse gases that is, reducing carbon footprint thereby earning carbon for India.

The Asphalt Recycling and Reclaiming Association define five different types of recycling methods: (1) Cold Planning (2) Hot Recycling (3) Hot In Place Recycling (4) Cold-In-Place Recycling and (5) Full Depth Reclamation. Only hot recycling of asphalt pavements at a central plant will be discussed in this article in the context of 4-laning and 6-laning of India's state highways and national highways wherein road paving bitumen worth crores of rupees is being buried rather than recycled

National Highways Authority of India (NHAI), there are many projects of this nature which can save us hundreds of cores. The one-time cost of modifying an existing asphalt batch plant to do hot mix recycling in India is only 20 lakhs rupees.

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 is around 12% to 15%. The National Asphalt Pavement Association (NAPA) has set goals to increase the average RAP content throughout the country.

Objectives: The following are objectives of this study.

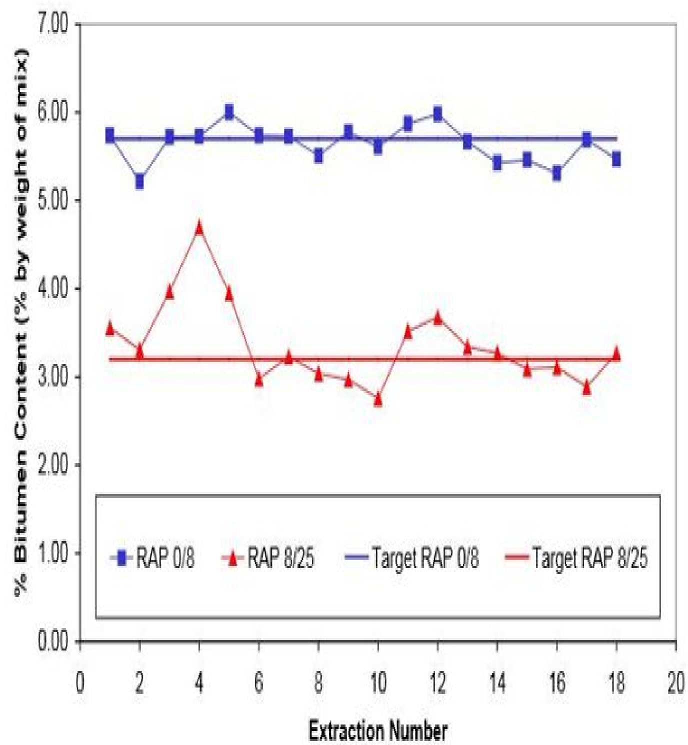
1. Determine the performance of local roadways built with typical RAP levels (less than 30 percent).
2. With the help of the asphalt industry, investigate the activation of RAP asphalt in a plant setting.
3. Based on objective #2, investigate the extent of RAP asphalt activation in a laboratory setting.
4. Develop high-RAP mixtures, and test them for low-temperature performance.

Scope: 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.

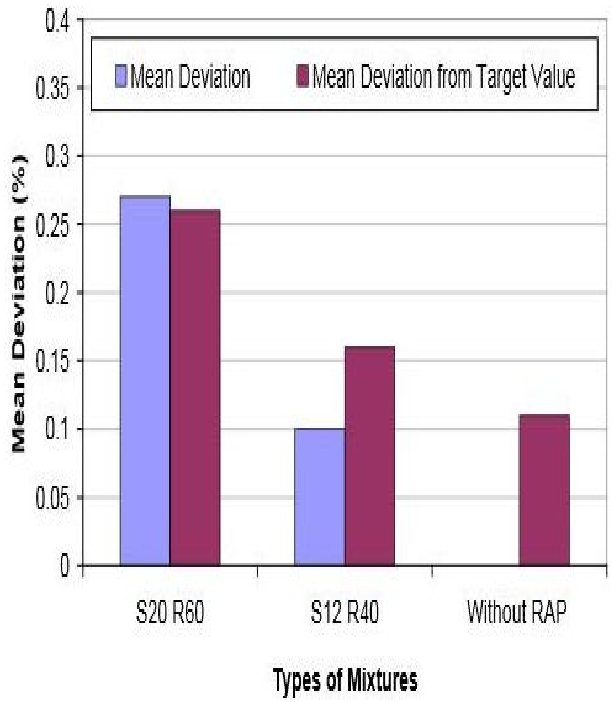
RAP VARIABILITY:

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 were 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.



FENIX project RAP gradations

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.'



Variability with 60%, 40% and no RAP mixes (Gonzalo 2009)

II LITERATURE REVIEW

Hansen (2013) was explained 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.

RAP in HMA paving mixtures per state

State	Average RAP Percent 2009	2010	2011	2012	State	Average RAP Percent 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%

Al-Quid was explained the 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 shows the nine samples that were made for testing. The first sets 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.

Nine separate samples for Complex modulus testing

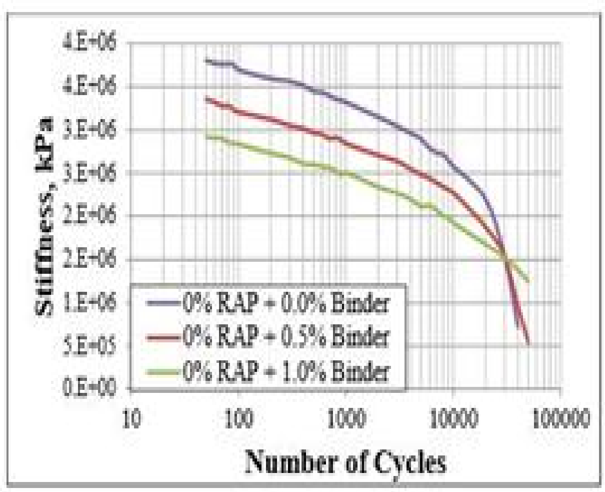
RAP Percentage	Specimen ID	Aggregates	Binder	RAP Binder/Total Binder (%)	Remarks
0 % RAP design	DI-SET AP-00	Virgin	Virgin	NA	
20% RAP design	DI-SET AP-20	Virgin and 20% RAP	Virgin	Unknown	
	DI-SET 0-20	Virgin and 20% recovered RAP	Virgin and recovered	0	0% working
	DI-SET 50-20	Virgin and 20 % recovered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

Carpenter (2006) stated that the age 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.

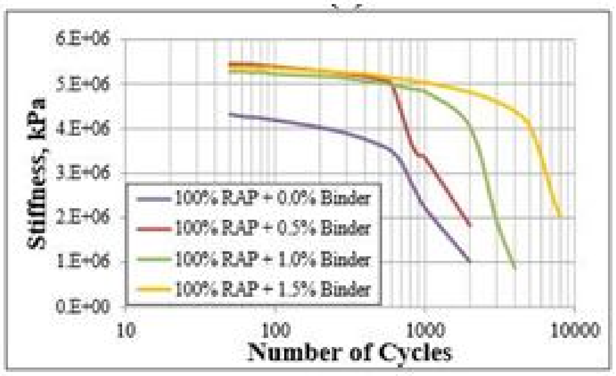
BARIACK, KATICHA AND FLINTSCH:

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 . 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.

Fatigue testing for 0% RAP



Fatigue testing for 100% RAP (Boriack 2013)



III LABORATORY TESTING OF RAP MATERIALS

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.

The materials should be selected by conducting 100% I-80 RAP, Fractionation tests and Asphalt Binder selected by PG Grading,Volumetric tests.

Coarse Aggregate Testing:

- Apparent Specific Gravity (Gsa)
- Bulk Specific Gravity (Gsb)
- Bulk SSD specific Gravity
- Water Absorption

Fine Aggregate Testing:

- Apparent Specific Gravity (Gsa)
- Bulk Specific Gravity (Gsb)
- Bulk SSD specific Gravity
- Water Absorption

Specific gravity of Gmm of RAP materials evaluated by using the AASTHO T 209 Procedure (Rice test), Corelok Vacuum Procedure and Gmm Test Procedures

- Gmb Testing

Beam Fatigue Testing

- Constant Strain vs. Constant Stress
- Beam Compaction
- Loading Device

Environmental Chamber

Control and Data Acquisition System

PG-Grade Testing:

- DSR Testing
- RFTO Aging
- PAV Aging
- BBR Testing

Specimen Moulds

Loading Frame with Environment Chamber

Control and Data Acquisition System

Aged Binder Blending:

- Compacting Testing
- Indirect Tensile Strength Testing

IV TEST RESULTS AND ANALYSIS

- **Specific gravity test:**

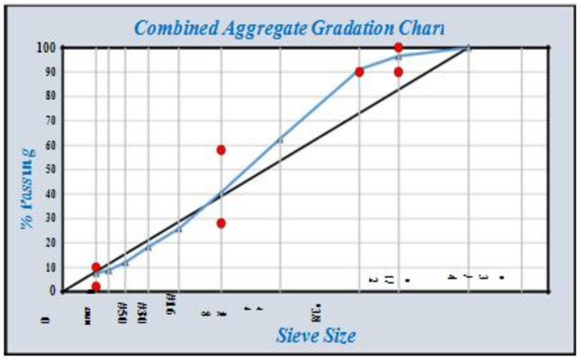
  RAP was fractionated at the ±16 sieve in hopes for the volumetric tests to become acceptable for the DOT regulations in the field. Specific gravity had to be found using experiments.

- **Fractionation Gradation:**

Resulting Gradation of Fractionated RAP

Sieve Size	Fractionated RAP		
	Frac. ≥ #16		
	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%		

Gradation of burnt off fractionated RAP

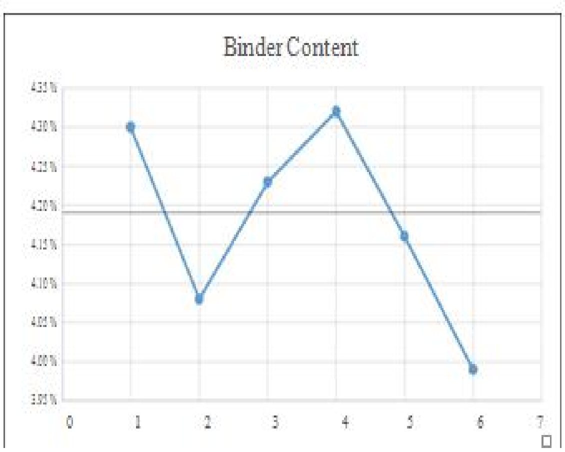


- **RAP Binder Content:**

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

Varying Binder Contents from Burn-off



- **Volumetric test results:**

The following properties can be determined from the volumetric tests. The properties are VMA, VFA, dust-Binder ratio and Film thickness.

Coarse Aggregate Results:

The following properties can be determined. Those are bulk specific gravity (Gsb), apparent specific gravity (Gsa) and water absorption.

Fine Aggregate results:

The following properties can be determined. Those are bulk specific gravity (Gsb), apparent specific gravity (Gsa) and water absorption.

Final Gsb, Absorption and Gsa results

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

- **Mix Design Results:**

Mix Design results for an 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

Mix Design results for 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

- **Gmm Test results:**

Gmm is known as the maximum theoretical specific gravity of the mix.

The Gsb and Gsa used for these experiments are 2.650 and 2.736, respectively.

Experiment Load 1 and 2 for 100% RAP Gmm

Sample ID	% AC	Dry Weight	H20 + Metal Bowl	Agg. In Metal bowl	Gmm	Avg. Gm	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 Gsa for both experiments is above Gsa should not be possible.

Experiment 3 for 100% RAP Gmm

Sample ID	% AC	Dry Weight	H20 + Metal Bowl	Agg. In Metal bowl	Gmm	Avg. Gmm	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		

Above table shows the same predicament with the Gsa being too high.

Experiment 4 for 100% RAP Gmm

Sample ID	% AC	Dry Weight	H20+ Metal Bowl	Agg. + Metal Bowl	Gm	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

The table shows the fourth experiment with new added binder at the same percentage by weight that they were before burn-off.

Experiment 5 for 100% RAP Gmm

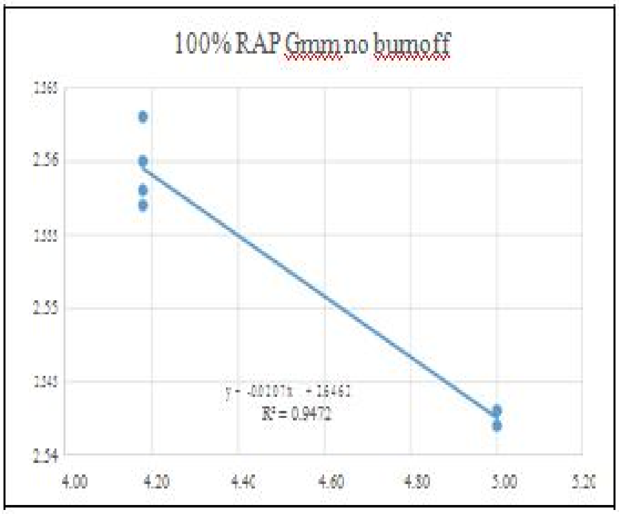
Sample ID	% AC	Dry Weight	H20 + Metal Bowl	Agg. In Metal bowl	Gmm	Avg. Gm	Gse
HMA 1	5.00	1995.3	7357.8	8567.9	2.541	2.543	2.754
HMA 2	5.00	1992.6	7339.3	8548.9	2.545		
HMA 3	5.00	2005.3	7357.4	8575.3	2.547	2.548	2.76
HMA 4	5.00	2002.2	7339.3	8556.2	2.55		
HMA 5	5.00	2004	7360.5	8578.5	2.55	2.543	2.754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

Above table shows the results for the fifth experiment where off RAP was replaced with new binder at 5% by weight.

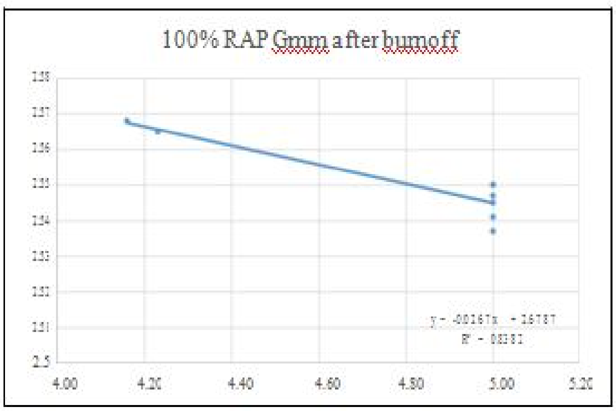
Corelok Experiment for 100% Gmm

Sample ID	Bag weights	Aggregate weight	Underwater	Gmm	Avg. Gmm	Gse
HMA1	73.9	1998.8	1207.7	2.552	2.5565	2.771
HMA2	73.1	1992.5	1206.5	2.561		

Graphs:



100% RAP Gmm with aged binder (Experiment 1,2 and 3)

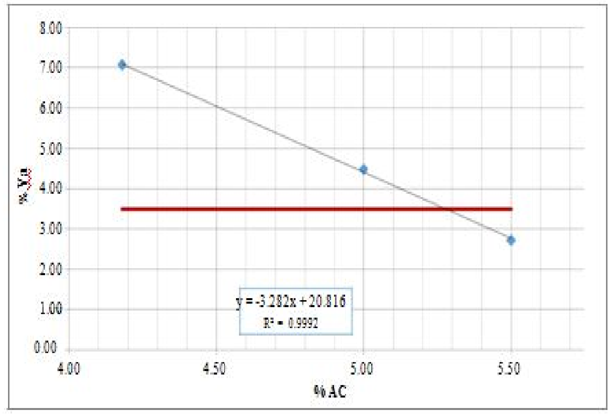


100% RAP Gmm with virgin binder after burn-off (experiment 4 and 5)

- **Gmb Test results**

The 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	



Optimum Binder Content for 3.5% air voids

- **Beam fatigue Test Results:**

Slab characteristics:

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

Beam characteristics:

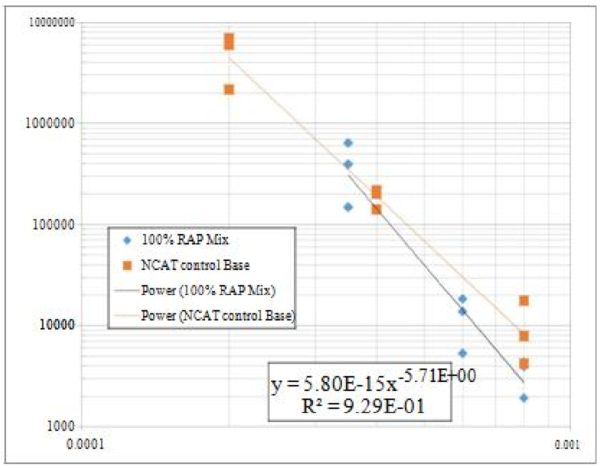
Beam Air Voids, Height and Width

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

- **Beam Fatigue Results;**

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%



Resulting Beam fatigue Curve

Percentage of fatigue resistance of NCAT control base vs. 100% RAP mix

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

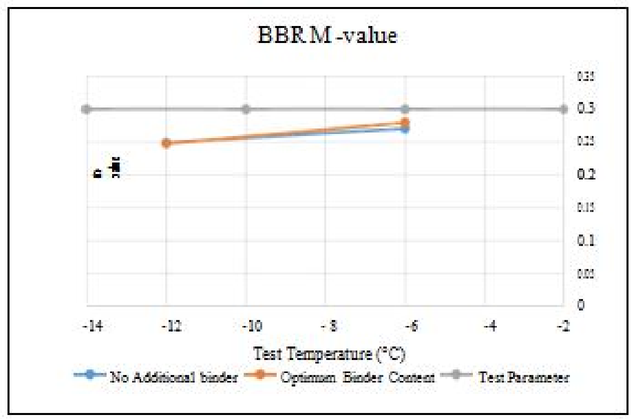
- **PG-Grading:**

DSR results

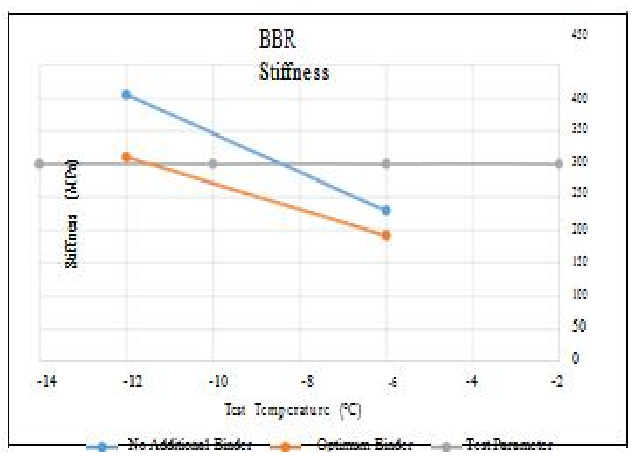
From the process of binder being aged, the chemical properties change, making the binder stiffer. This stiffness increases the higher PG-grade due to the need for higher temperatures to make the binder viscous. Due to this knowledge, the BBR was tested first to see the plausibility of higher a accessible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

BBR 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



BBR m-value results for both 100% Rap mixes with and without additional binder



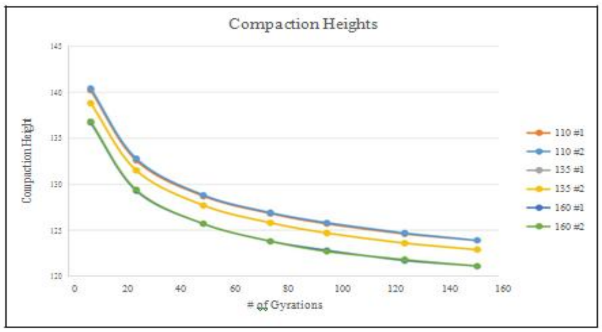
BBR Stiffness results for both 1005 RAP mixes with and without additional binder

- **Aged Binder Blending Results;**

Compaction test results

Compaction height 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



Compaction height for each sample

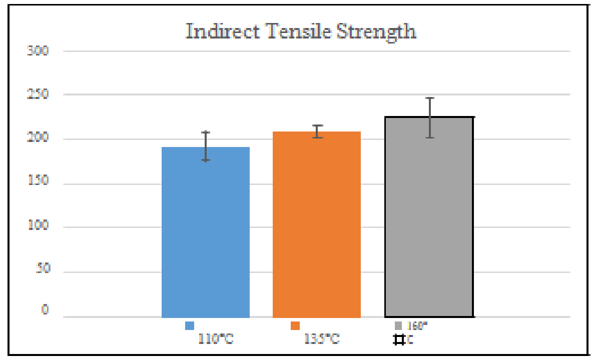
Percent of Compaction for each recorded gyration

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

- **Indirect Tensile Strength results:**

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	



Average tensile strength results for each temperature

V CONCLUSIONS

The following are conclusions:

i. 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.

ii. **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.

iii. **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.

iv. **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.

v. **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.

vi. 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.

vii. **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.

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