BURNS COOLEY DENNIS, INC.
GEOTECHNICAL AND MATERIALS ENGINEERING CONSULTANTS

Development of Laboratory Mix Design Procedures for RAP Mixes

Prepared for
Mississippi Department of Transportation

State Study No. 246
Project No. SPR-1(60) 106266 166000

Prepared by
L. Allen Cooley, Jr., Ph.D.
Kevin Williams, P.E.

Technical Report Documentation Page

1.Report No. FHWA/MS-DOT-RD-13-246	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Development of Laboratory Mix Design Procedures for RAP Mixes	5. Report Date December 31, 2013 6. Performing Organization Code BCD No. 120245
7. Author(s) L. Allen Cooley, Jr. and Kevin Williams	8. Performing Organization Report No. MS-DOT-RD-13-246
9. Performing Organization Name and Address Burns Cooley Dennis, Inc. Post Office Box 12828 Jackson, Mississippi 39236	10. Work Unit No. (TRAIS) 11. Contract or Grant No. SS-246
12. Sponsoring Agency Name and Address Mississippi Department of Transportation P.O. Box 1850 Jackson, MS 39215-1850	13. Type Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes
MDOT State Study 246
Project No. SPR-1(60) 106226 166000

16. Abstract:
The objective of this study was to evaluate the amount of blending that occurs between RAP and virgin asphalt binders in plant produced HMA in which RAP is incorporated. This objective was accomplished by testing plant produced mixture from three different on-going HMA projects. Two of the three projects incorporated 15 percent RAP while the third project incorporated 30 percent. Samples were brought back to the laboratory and subjected to a staged extraction/recovery process. Asphalt binder recovered from each stage was subjected to Dynamic Shear Rheometer testing in order to determine the high failure temperature using a criterion of 2.20 kPa.
Based upon the research approach, it was concluded that majority of asphalt binder was extracted and recovered from the first stage of washing. The amount of asphalt binder extracted/recovered from successive washes decreased, except for the last stage. For mixes containing 15 percent RAP, the asphalt binder was not significantly affected by the RAP though there was a slight increase in failure temperature through the staged washes, except for the last stage. The majority of the asphalt binder from the 30 percent RAP mixture was removed during the first stage of washing. The stiffness of the asphalt binder after Wash 1 was higher for this 30 percent RAP mix than for the 15 percent RAP mix; however, the increase in stiffness was not large. The increase in stiffness for successive washes was higher for the 30 percent RAP mix than for the 15 percent RAP mixes. Based upon these findings, it was concluded that partial blending between RAP and virgin asphalt binders when RAP is incorporated into plant produced HMA.

17. Key Words Hot mix asphalt, recycled asphalt pavement, black rock, asphalt binder, extraction, recovery	18. Distribution Statement Unclassified

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 31	22. Price

Form DOT F 1700.7 **(8-72)**

Reproduction of completed page authorized

NOTICE

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

CHAPTER 1 – INTRODUCTION AND OBJECTIVES

1.1 Introduction

Recycled Asphalt Pavement (RAP) is the most recycled material in the U.S. RAP has been routinely used in the production of hot mix asphalt (HMA) since the 1970's. Since the incorporation of RAP into HMA began, there has been a significant amount of research dealing with how RAP behaves when included within HMA. Historically, there have been three theories of how RAP behaves when included within HMA. The first is that the highly oxidized asphalt binder contained within the RAP essentially makes the RAP a "black rock". The second theory is that the asphalt binder within the RAP becomes fluid during the production and construction process and totally blends with the new, virgin asphalt binder. If this second theory is correct, the resultant asphalt binder after blending occurs is uniformly stiffer. The final theory is called "partial blending". This theory assumes that some portion of the RAP binder becomes fluid and partially blends with the new asphalt binder. In this instance, there is a zone of blended binder where the properties of the asphalt binder properties range from being similar to the virgin binder to the stiff binder coating the RAP (Figure 1). Also, a portion of the RAP particles are black rock.

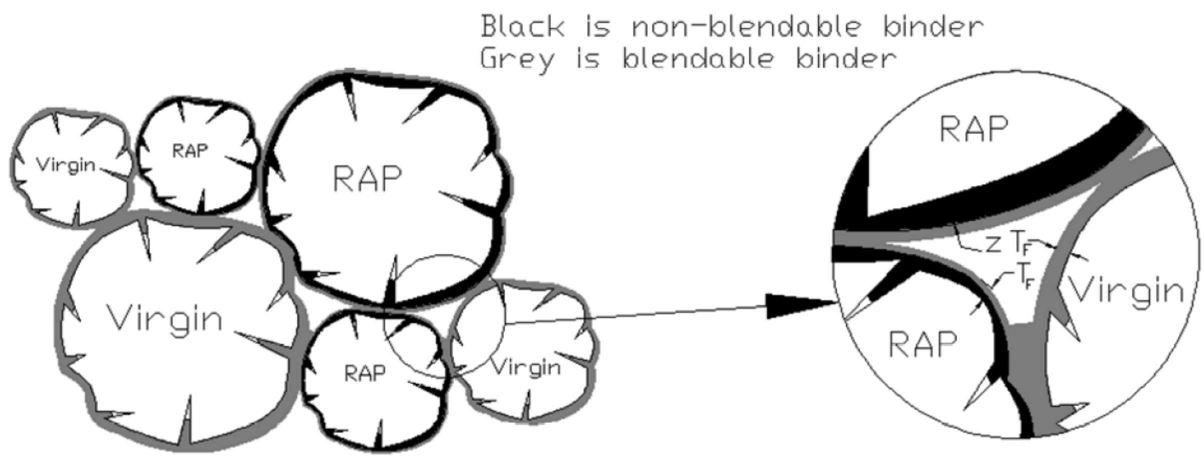

Figure 1: Varying Stiffness of Asphalt Binder Film (Partial Blending Theory)

The importance of determining the true mechanism of how RAP binder and virgin binder mix is two-fold. First, every ton of RAP binder that blends with the virgin binder reduces the virgin asphalt demand for the mixture. Figure 2 illustrates how the price of virgin asphalt binder has significantly increased from 2000 to 2011. On average, the price per ton of asphalt binder tripled since 2000 to 2011. Even though the current policy of MDOT is to keep some RAP for maintenance purposes, the trend of increasing virgin asphalt binder costs will likely cause MDOT to rethink this policy at some point, especially if it is determined that RAP binder does blend with the virgin binder and higher percentages of RAP can be used. The second important reason for determining the true mechanism of how RAP and virgin binders blend is performance. If RAP and virgin binder blend totally, then MDOT's current practices are okay. If RAP is a black rock, then MDOT is severely under-asphalting their mixtures, especially at higher RAP percentages.

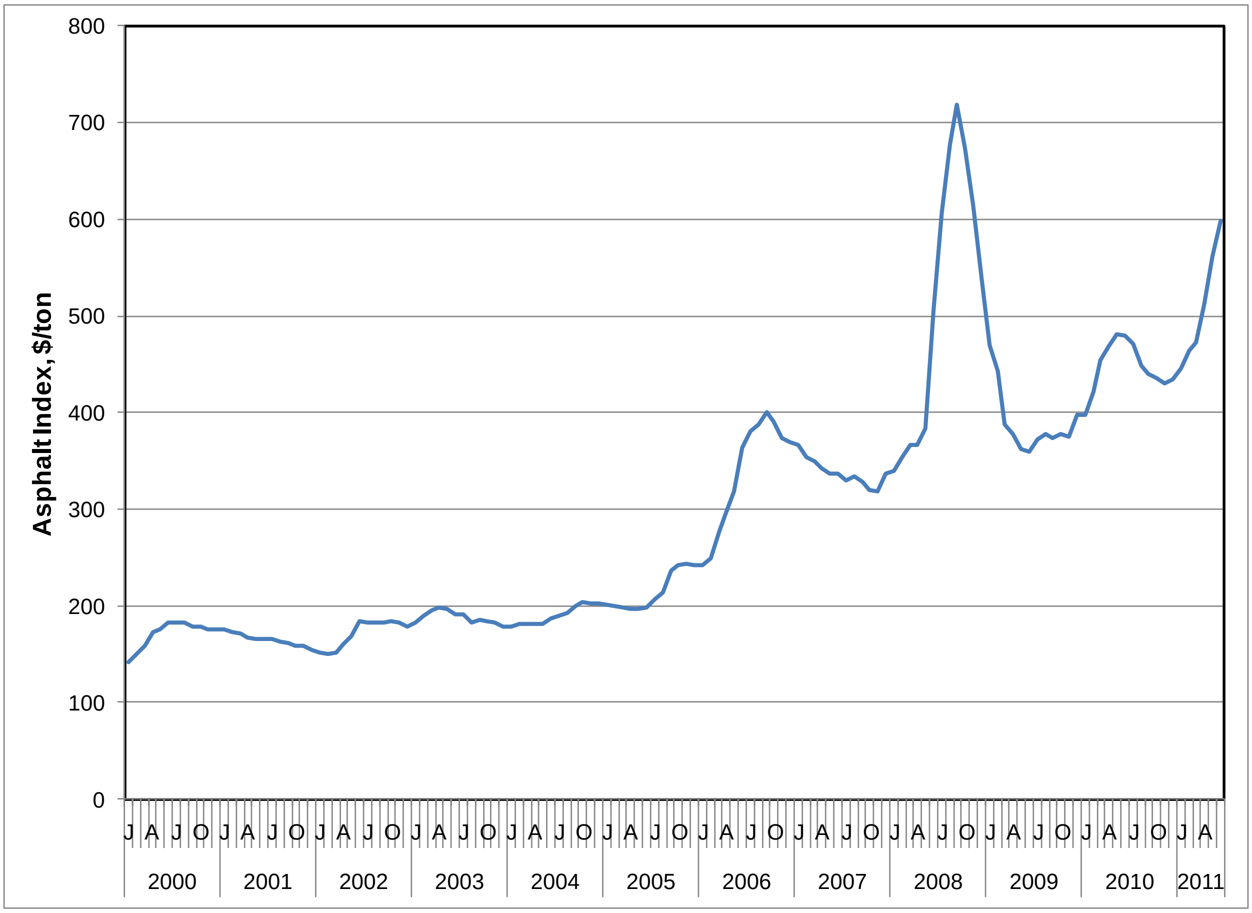

Figure 2: Monthly Asphalt Index Prices for PG 67-22

As stated above, there has been a significant amount of research conducted on the inclusion of RAP within HMA. The vast majority of this research has involved extracting all the asphalt binder from the RAP mix and testing the recovered asphalt binder (i.e., combination of aged RAP binder and virgin binder). Inherently, because of this methodology, the research is based upon total blending of the RAP and virgin binder and may or may not be applicable.

Burns Cooley Dennis, Inc. (BCD) has recently conducted some limited internal laboratory research to investigate the three theories of how RAP behaves within HMA. Figure 3 illustrates this research for a 20 percent RAP mix. This figure depicts the stiffness of asphalt binder that has been extracted from RAP mixes in stages. The process entailed laboratory mixing of the 20 percent RAP dense graded mix. After cooling, the mixture was placed into a large bowl. Trichloroethylene (TCE) was then placed into the large bowl to just cover the RAP mixture. The mix was soaked in the TCE for three minutes after which the solvent and asphalt binder was decanted from the bowl. This process was continued for a total of four stages (or washes).

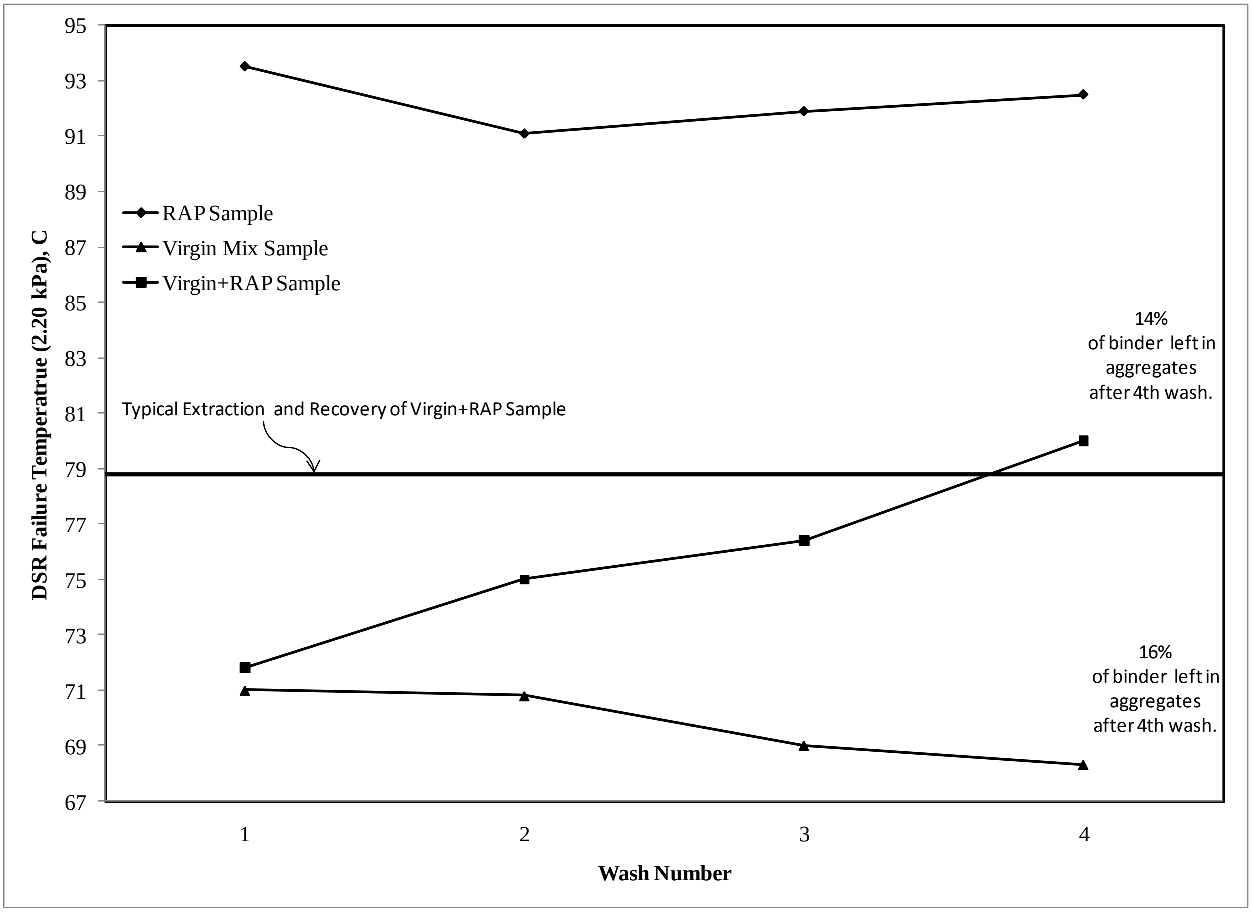

Figure 3: Results from Staged Extractions of Virgin and RAP Mixes

After completion of the four stages of extraction, the asphalt binder was recovered for each individual stage. This resulted in four extracted and recovered samples of asphalt binder. These samples of asphalt binder were then tested in the Dynamic Shear Rheometer (DSR) to evaluate stiffness. This process was also followed for a 100% RAP sample and a virgin mix sample.

As shown in Figure 3, the results are very interesting. The stiffness of the asphalt binder extracted and recovered from the first wash of the virgin plus RAP mix was almost identical to the stiffness of the asphalt binder extracted from the virgin mix. As the number of washes increased, the difference in asphalt binder stiffness between the virgin plus RAP mix and virgin mix increased. This seems to infer that the partial blending theory is closer to correct.

Additional data that was obtained was the mass of asphalt binder that was extracted and recovered from each wash. This data combined with the original mass of mix and the asphalt content of the material remaining after the four washes allowed representative asphalt contents to be calculated for each stage. Taking another step, the percentage of total asphalt extracted and recovered could be calculated. This data is presented in Table 1.

Table 1: Percentage of Total Asphalt Removed and DSR Failure Temperature

Stage	100% RAP		Virgin Mix		20% RAP Mixture	
	% AC	DSR, °C	% AC	DSR, °C	% AC	DSR, °C
Wash 1	31.4	93.5	62.9	71.0	64.0	71.8
Wash 2	10.2	91.1	14.1	70.8	15.0	75.0
Wash 3	6.9	91.9	5.0	69.0	4.5	76.4
Wash 4	4.3	92.5	2.1	68.3	2.2	80.0
Remaining in Agg.	47.3	N/A	16.0	N/A	14.3	N/A

Of particular interest in Table 1 are the data for the virgin and 20% RAP mixes after Wash 1. Roughly 63 percent of the asphalt binder within the RAP mix had a similar stiffness as the virgin mix. Combining Figure 3 and Table 1, this data is a strong argument that in a laboratory setting only partial blending occurs when RAP is added within an HMA mixture.

The implication of these results is that only a portion of the RAP binder blends with the virgin binder. Therefore, a portion of the RAP binder does not blend with the virgin binder. Historically, this portion that does not blend with the virgin binder has been credited to the mix as contributing to the durability of the mix. If the results presented above are true for field produced mixes, then we have potentially under-asphalted our mixes. This may explain why mixes with higher RAP contents have historically shown a higher potential for premature cracking.

As stated above, the vast majority of research conducted on RAP has made the assumption that the RAP binder and virgin binder blend totally. Based upon the above data and discussion, this is likely not true. Therefore, research is needed to further investigate the amount of blending that occurs. However, a bigger need is to develop a method of preparing RAP mixes in the laboratory that simulates the properties of plant produced RAP mixes. Until laboratory mixing methods are developed that produce RAP mixtures similar to those that are produced in the plant, any laboratory performance testing conducted on the mixes is useless. For example, a significant amount of research was conducted during the development of Superpave on the short-term aging procedure. The short-term aging procedure was developed specifically to result in a laboratory mix that simulates HMA at the paver. The key components of the short-term aging procedure were to age the asphalt binder within the mix similar to the aging that occurs through the plant and for asphalt absorption to take place. The addition of the short-term aging procedure within Superpave has greatly enhanced our ability to design and characterize dense-graded mixes. Unfortunately, incorporation of RAP was not included in the Superpave research.

Ideally, there are four steps required for MDOT to accurately include RAP within HMA, no matter the percentage. These steps are illustrated in Figure 4. As discussed above, the first step has to be to develop laboratory methods for incorporating RAP into HMA that results in mix that is similar to plant produced mix. Once the appropriate laboratory methods are determined, work is needed to characterize RAP mixes in the laboratory, again no matter the percentage. Key pavement performance characteristics should be considered when characterizing the RAP mixes, including: rutting, cracking, and moisture damage. After evaluating the mixes, the mix design methodology for RAP mixes should be refined in the third step. The final step of the process should be to build a number of pavement test sections and monitor their performance.

Following these steps should result in RAP mixes that will perform as well as virgin mixes, no matter the percentage of RAP.

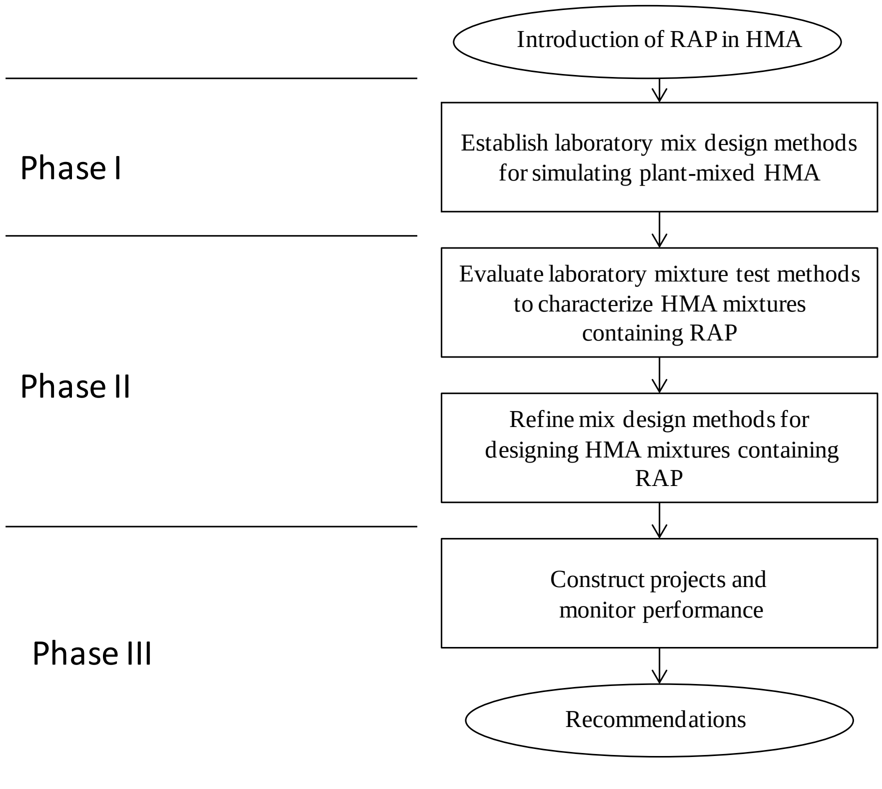

Figure 4: Steps to Accurately Include RAP within MDOT HMA

1.2 Objective

The objective of this study was to evaluate the amount of blending that occurs between RAP and virgin asphalt binders in plant produced HMA in which RAP is incorporated. Answers to this question will then be the first step in accomplishing Phase 1 within Figure 4.

CHAPTER 2 – RESEARCH APPROACH

2.1 Research Approach

As described above, the objective of this research was to evaluate the amount of blending that occurs between RAP and virgin asphalt binder. To accomplish this objective, three tasks were required. The following sections describe the work accomplished in each task.

2.1.1 Task 1 – Literature Review

The literature review conducted within this task provided an overview of current activities being conducted around the nation related to RAP. Topics covered included characterization of RAP materials, blending of RAP and virgin asphalt binders, and methods of designing HMA containing RAP.

2.1.2 Task 2 – Field Work

This task was to entail visiting four ongoing HMA field projects that utilized RAP within the HMA. However, due to time constraints only three field projects were visited. At each of the field projects, HMA samples were obtained at three locations, including: slat conveyor leading from drum mixer to storage silo, truck, and paver. Two to four samples were obtained from each location throughout a day's production.

2.1.3 Task 3 – Testing of Field Produced Material

Testing on the plant-mixed material involved conducting staged extractions to evaluate the varying stiffness of the asphalt binder coating the aggregates. As illustrated within Figure 5, a sample was covered with TCE for two minutes and the mixture of solvent and asphalt binder decanted. A total of five stages of extraction were conducted. The last stage was designed to remove the remaining asphalt from the aggregates as the remaining aggregates were soaked within TCE for an extended time period. The mixture of solvent/asphalt binder obtained within the first four stages was recovered using a rotary evaporator (rotovapor) recovery process. Materials recovered from each stage of extraction were used to determine the DSR failure temperature using a criterion of 2.20 kPa.

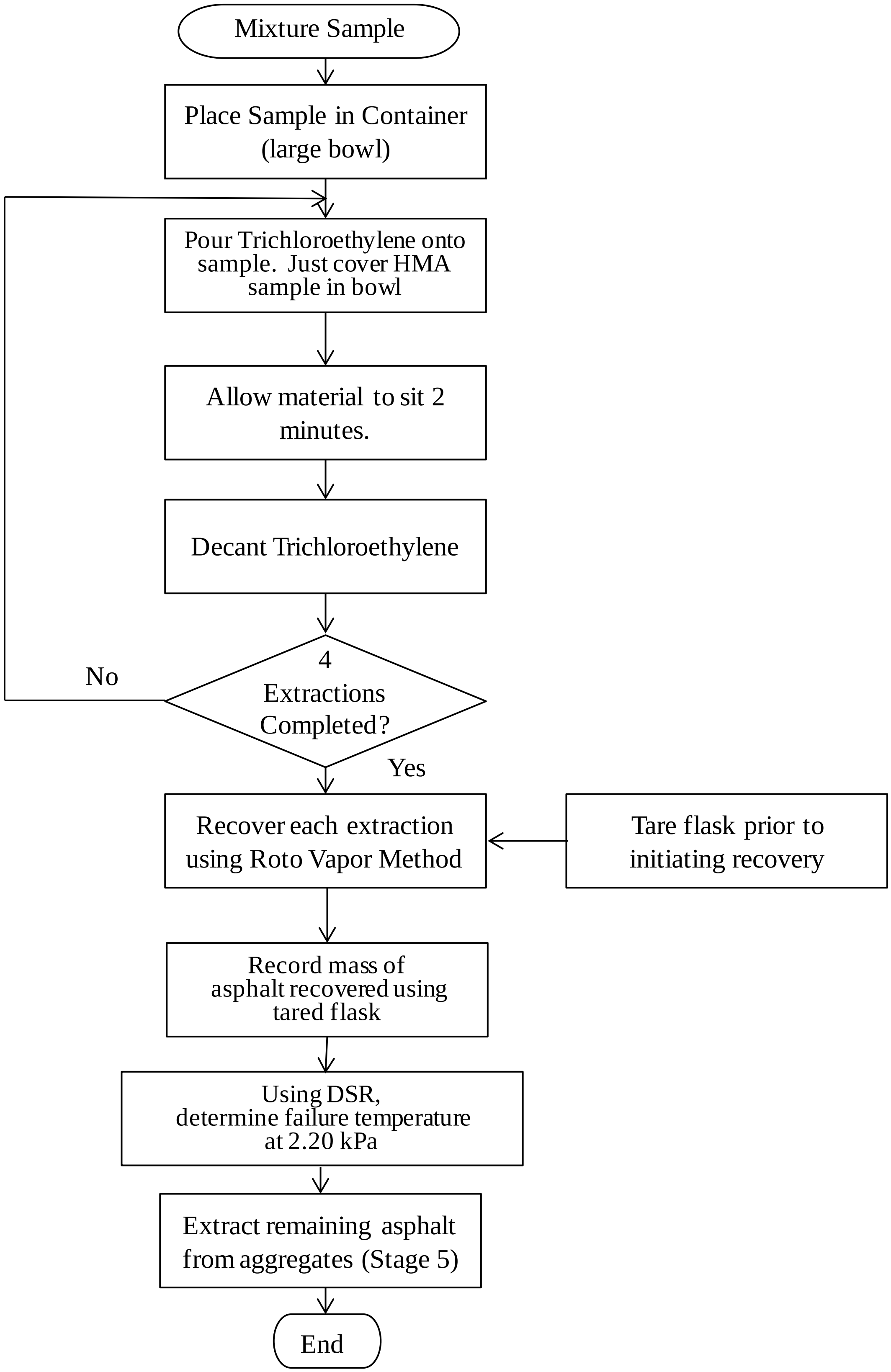

Figure 5: Staged Extraction of RAP Mixes

CHAPTER 3 – LITERATURE REVIEW

3.1 Introduction

In 2011, the Federal Highway Administration (FHWA) estimated that over 90 percent of the highway and roads within the US were constructed with hot mix asphalt (Copeland, 2011). As these pavements age and fulfill their intended performance life, there will always be a need to maintain, rehabilitate, or reconstruct these pavements. In many instances, cold planing is used to remove a layer of HMA that has become distressed. Cold planing is the removal of an existing pavement to a desired depth (ARRA, 2001). After an asphalt pavement has been removed, one option is to recycle the material back into an HMA in the form of recycled asphalt pavement (RAP).

Because of the vast mileage of HMA pavements within the US and the continual need for maintenance/rehabilitation, the FHWA developed the following policy for recycled materials (Wright, 2001):

> *"The same materials used to build the original highway system can be re-used to repair, reconstruct and maintain them. Where appropriate, recycling of aggregates and other highway construction materials makes sound economic, environmental, and engineering sense."*

As described in the above FHWA quote, the recycling of HMA pavements can provide economical and environmental benefits. Copeland (2011) stated that RAP is a useful alternative to virgin aggregates during the production of HMA. The use of RAP minimizes the tonnage of virgin aggregates that must be bought. Copeland (2011) also states that the amount of virgin asphalt binder that must be purchased is reduced. Both virgin aggregates and virgin asphalt binder are non-renewable resources, so the use of RAP also provides an environmental benefit. Additionally, the use of RAP reduces the amount of construction debris that must be placed in landfills (Copeland, 2011).

3.2 Characterizing RAP Properties

Recycled asphalt pavement materials are comprised primarily of two components: aged asphalt binder and aggregates. Proper characterization of these components is vital for properly designing an HMA mix containing RAP, especially when using higher percentages of RAP. Generally, the first test conducted on RAP materials is to determine the asphalt binder content. Three methods are generally used: ignition oven, reflux and chemical extraction. West et al (2013) state that research has shown the ignition oven is the most accurate method for determining the asphalt binder content. They also state that the solvent method does not always remove all of the binder from the RAP.

After removal of the asphalt binder, the aggregate properties are evaluated. Unfortunately, both of these methods can affect the properties of the recovered aggregates. Prowell and Carter (2000) evaluated the effect of the ignition oven on several aggregate types and properties used within Virginia. Aggregate properties evaluated included, coarse aggregate angularity, fine aggregate angularity, flat/elongated, sand equivalency, aggregate bulk specific gravity, and gradation. Of these properties, Prowell and Carter (2000) indicated that only the sand equivalency and aggregate bulk specific gravity changed after removing asphalt binder with the ignition oven. No significant change was observed for the other aggregate properties. A similar study was conducted in Arkansas (Hall, 2004) that evaluated the effect of the ignition oven on gradation and the bulk specific gravity of the aggregates. Hall (2004) stated that there was very little change in the gradation of the aggregates after determining asphalt content using the ignition oven. Hall (2004) also stated that minimal differences occurred with the bulk specific gravity of the aggregates after ignition testing. West et al (2013) concluded that both the ignition oven and chemical extraction can be used to determine the gradation and aggregate consensus properties. They recommended the use of either the ignition oven or solvent extraction to remove the aged asphalt binder and then conducting the specific gravity and absorption tests in order to determine the bulk specific gravity of the RAP aggregates. However, the ignition oven may significantly affect the measured bulk specific gravity of some aggregate mineralogical types. West et al (2013) did state that both methods of removing the asphalt binder from the RAP aggregates will likely lead to small errors in the measured bulk specific gravity values.

The other material to be evaluated during characterization of RAP materials is the aged asphalt binder. Some agencies require the extraction and recovery of the aged asphalt binder for mix design purposes. In these instances, chemical extraction is required since the ignition oven incinerates that asphalt binder. Recovery methods used to recover the asphalt binder from the solvent have included both the rotary evaporator and Abson method. It should be pointed out, however, the the Abson method has been criticized as causing additional aging within the asphalt binder (Burr, et al, 1991). After recovery of the asphalt binder, typical asphalt binder tests are conducted to characterize the material. Tests may include viscosity tests, Superpave binder tests, penetration tests, etc.

Another property commonly used to characterize RAP materials is the theoretical maximum specific gravity test. This test is generally used, along with the asphalt binder content, to calculate the effective specific gravity of the RAP aggregates.

3.3 Blending of Virgin and RAP Asphalt Binder

Likely the biggest controversy related to the use of RAP materials within HMA has been how much, if any, blending occurs between the RAP asphalt binder and the virgin asphalt binder. There are three theories that have been put forth about the amount of blending that occurs during the production and construction of HMA containing RAP. The first theory is that no blending occurs between the two asphalt binders. This theory is commonly called the "black rock" theory. In essence the RAP particles are black colored aggregates. A second theory is that total blending occurs between the RAP binder and the virgin binder. In this scenario, the blending of the two binders results in a new binder with different properties than either of the two binders. Finally, the third theory is that only partial blending occurs between the RAP binder and virgin binder.

During NCHRP 9-12, McDaniel and Anderson (2001) conducted a large research study on the inclusion of RAP within HMA mixes. One of the research objectives of this large study was to experimentally investigate the three theories of how the RAP binder and virgin binder blend. The researchers created three scenarios within the laboratory. For the first, the black rock scenario, the researchers extracted the binder from the RAP materials and used the remaining aggregates within an HMA mixture. For the second, the asphalt binder was extracted and recovered from the RAP materials and blended with the virgin asphalt binder. This totally blended asphalt binder was then added to a mix containing virgin aggregates and the recovered aggregates combined with virgin aggregates from the RAP materials. The final scenario was titled the "actual practice." Within this scenario, heated RAP materials were mixed with virgin asphalt binder and virgin aggregates. Numerous tests were conducted in the laboratory to evaluate HMA using the three scenarios. A comparison of the mix test results indicated that the actual practice and the total blending scenarios yielded the most similar results. Therefore, McDaniel and Anderson (2001) concluded that the addition of RAP resulted in a scenario more closely related to total blending.

Huang et al (2005) conducted a study with a novel concept to look at how much blending takes place between a RAP binder and a virgin binder. Huang et al (2005) tried to remove the layers of asphalt binder within an HMA mix containing RAP through staged extractions. The RAP containing HMA was initially soaked in trichloroethylene (TCE) for 3 minutes and the solution decanted from the mix. Following the recovery of the solvent/asphalt solution after the first TCE soak, they conducted an additional three extractions for a total of four stages. For the last stage, the authors extracted all of the asphalt binder from the remaining materials. Each of the solvent/asphalt mixtures were recovered from the various stages and tested. The recovered asphalt from the first stage had the lowest viscosity. Asphalt binder from each successive stage became stiffer. Huang et al (2005) used this data to suggest that partial blending occurred between the RAP asphalt binder and the virgin asphalt binder.

Bonaquist (2007) documented a method of determining the effective grade of asphalt binder within an HMA containing RAP and/or recycled asphalt shingles using the Hirsch model. The process entailed using dynamic modulus test results along with volumetric inputs to predict a shear moduli of the "effective" binder within the specimen. A shear modulus master curve was then developed for the specimen. Next, the asphalt binder was removed from the mix using solvent extraction and then recovered. The recovered asphalt binder from the mix was tested in the Dynamic Shear Rheometer to determine the binder shear moduli. Again, a master curve was developed using the measured shear moduli. The predicted asphalt binder shear moduli was then compared to the measured shear moduli using master curves. When the predicted and measured shear moduli master curves overlap it was inferred that the recycled and virgin asphalt binders were completely blended. Bonaquist (2007) found that there is not much blending between the asphalt binder within asphalt shingles and the virgin asphalt binder. However, RAP mix data suggested that RAP and virgin binder are well blended.

Nahar et al (2013) used an innovative approach to evaluate the extent of blending between RAP and virgin binders. Atomic force microscopy indicated that four distinct zones related to the asphalt binder. Within the first zone, RAP binder was observed without any blending. The next zone was a blended zone where the RAP binder and the virgin binder blended. The third zone was titled a transition zone in which the blended binder was transitioning to the virgin binder. The third zone totally consisted of virgin asphalt binder.

3.4 Designing HMA Mixtures Containing RAP

Currently, AASHTO guidelines for the inclusion of RAP materials follow the recommendations of McDaniel and Anderson (2001). They provide step-by-step procedures for how to handle RAP materials during mix design. The primary part of this study was recommendations on how RAP is handled based upon the percentage of RAP incorporated within the mix. As the percentage of RAP increases, the specified asphalt binder grade is changed. If the RAP content is less than 15 percent, no specific changes are required. For mixes containing from 15 to 25 percent RAP, the virgin asphalt binder should be one full grade lower than for a comparison virgin mix. Blending charts are recommended for mixes in which 25 percent or more RAP is incorporated into the mix.

Within a recently completed National Cooperative Highway Research Program study (West, et al, 2013), recommendations were provided for high RAP content mixes. Within this study, high RAP content mixes were defined as mixes with more than 25 percent RAP. The authors recommended that selection of the virgin binder as one of the following: allowing a maximum ratio of RAP binder to total binder content or determining the high and low critical temperatures for the resultant blend of asphalt binder. The latter option entails using the properties of the RAP binder and virgin binder to mathematically blend the materials such that an appropriate blend of RAP and virgin asphalt binder are attained.

CHAPTER 4 – METHODS AND MATERIALS

4.1 Test Methods

Test methods used within this project included determining the asphalt content (P_b) of the samples using the ignition oven, extracting asphalt binder from loose mix, recovering the extracted asphalt binder using a rotary vapor device and evaluating the stiffness of the recovered asphalt binder using the Dynamic Shear Rheometer (DSR). The asphalt content of the different samples was determined in accordance with AASHTO T308. Loose HMA mix was placed into an ignition furnace and heated to a temperature that ignites the asphalt binder. The asphalt binder content was calculated by determining the difference in mass between the initial HMA sample and the mass of remaining aggregates. An aggregate correction factor was determined for each of the projects using stockpiled materials sampled at each respective field project.

Asphalt binder from the loose mixture samples from each of the field projects was extracted using Method A of AASHTO T164. Trichloroethylene was used to cover the loose HMA materials within the centrifuge bowl. The centrifuge was then allowed to revolve until the extract was not darker than a light straw color. A high-speed centrifuge was then utilized to remove any mineral matter within the asphalt binder/solvent solution.

The rotary evaporator was used in accordance with AASHTO T319 to recover the asphalt binder from the solution. The rotary evaporator system distills the solution under vacuum to remove the trichloroethylene. By determining the mass of the flask used to catch the recovered asphalt binder before the test, the amount of recovered asphalt binder was determined.

After recovery of the asphalt binder using the rotary evaporator, the stiffness of the recovered asphalt binder was determined using a DSR in accordance with AASHTO T315. Within this test, a thin film of asphalt binder is placed between two circular plates. The lower plate is fixed and the upper plate oscillates back and forth at 10 rad/sec. The stiffness of the asphalt binder is then determined for the test temperature at which the asphalt binder is tested.

4.2 Materials

Materials used during this project were plant produced HMA. A total of three field projects were tested. Hot mix asphalt produced for projects ranging from Interstates to low volume highways were included. Table 2 presents a summary of the HMA mixes produced for the three projects.

Table 2: HMA Properties of the Three Field Projects

	Project 1	Project 2	Project 3
Mix Type	HT 9.5 mm	ST 9.5 mm	HT 19 mm
	Gradation Information		
1 in.	100	100	100
¾ in.	100	100	99
½ in.	100	100	87
⅜ in.	93	96	76
No. 4	69	68	50
No. 8	41	43	34
No. 16	28	29	26
No. 30	20	20	20
No. 50	12	11	11
No. 100	9	7	7
No. 200	6.6	5.2	5.5
Property	Mix Information		
Pb	6.2	5.5	4.5
VMA	15.4	15.6	13.4
VFA	74	73.9	70.1
Gmm	2.315	2.466	2.372
Gsb	2.472	2.65	2.511
Pba	0.77	0.42	0.23
Pbe	5.43	5.08	4.27
D/B	1.22	1.02	1.29
Gse	2.522	2.680	2.526
Gb	1.032	1.04	1.034
PG Grade	PG 67-22	PG 67-22	PG 67-22
% RAP	15	15	30

Two of the three projects used High-Type (HT) HMA mixes while the third project used a Standard-Type (ST). Two of the three projects had a 9.5 mm nominal maximum aggregate size (NMAS) gradation while one was a 19.0 mm NMAS. All three of the projects utilized a PG 67-22 asphalt binder. Two of the three incorporated 15 percent RAP while the third incorporated 30 percent RAP.

CHAPTER 5 – TEST RESULTS AND ANALYSIS

5.1 Test Results

As stated previously, samples of loose HMA were obtained at three different locations along the production and construction process. Samples labeled as "Plant" samples were obtained from the slat conveyor leading from the drum to the storage silo. "Truck" samples were obtained from the backs of trucks similar to how typical quality control/quality assurance samples are obtained within Mississippi. The final sample type was labeled as "Paver" samples and was obtained from the paver.

The first test conducted on the different samples was to determine the asphalt content using the ignition oven. Asphalt binder calibration factors were developed for each of the three projects using aggregates from each respective project. Table 3 presents the average asphalt binder contents for each of the projects, by sample location, determined using the ignition oven. Also included within Table 3 is the asphalt binder content from the job mix formula (JMF). For Projects 1 and 2, the average asphalt binder content for the samples was slightly less than the JMF, while for Project 3 the asphalt binder content was approximately equal to the JMF.

Table 3: Average Asphalt Binder Content – Ignition Oven

		Average Asphalt Binder Content		
Project	JMF	Plant	Truck	Paver
1	6.2	5.98	5.86	5.92
2	5.5	5.44	5.16	5.23
3	4.5	4.43	4.52	4.60

Asphalt binder contents were also determined during the extraction of asphalt binder process. Table 4 presents the average asphalt binder contents, by sample location, determined during the extraction testing. Comparing Table 3 and Table 4, the average asphalt binder contents determined during ignition oven testing were always higher. This suggests that some asphalt binder was left within the aggregates during the extraction process. The differences in asphalt binder content obtained from the ignition oven and extractions are presented within Table 5. This table shows that the difference in asphalt binder contents between the two methods seems to be relatively constant for a given project. However, the magnitude of the differences were not always similar and may be related to aggregate type. Projects 1 and 3 were predominantly gravel mixes while Project 2 contained a significant amount of limestone.

Table 4: Average Asphalt Binder Content - Extractions

		Average Asphalt Binder Content		
Project	JMF	Plant	Truck	Paver
1	6.2	5.49	5.40	5.53
2	5.5	5.15	4.92	4.97
3	4.5	4.02	3.86	4.19

Table 5: Difference in Asphalt Binder Contents - Ignition Oven and Extraction

Project	JMF	Average Asphalt Binder Content		
		Plant	Truck	Paver
1	6.2	0.49	0.46	0.39
2	5.5	0.29	0.24	0.26
3	4.5	0.41	0.66	0.41

Recall that the staged extraction process included five different washes. After each stage, the mass of material recovered was determined. The total amount of asphalt binder recovered was used to calculate the asphalt contents presented within Table 4. Another method of evaluating the data was to calculate the percentage of recovered asphalt binder obtained during each wash. By determining the mass of asphalt binder per stage and dividing by the total amount of asphalt recovered, a percent of asphalt binder recovered per wash was obtained. Results of this testing are presented within Tables 6 through 8 for Projects 1 through 3, respectively.

Table 6: Percent Total Asphalt Binder Retained per Wash - Project 1

Wash Number	% of Total Asphalt Binder Retained per Wash		
	Plant Samples	Truck Samples	Paver Samples
1	53.8	56.1	57.3
2	22.8	18.8	21.7
3	9.3	7.6	7.3
4	4.7	4.4	3.9
5	9.5	13.0	9.7

Table 7: Percent Total Asphalt Binder Retained per Wash - Project 2

Wash Number	% of Total Asphalt Binder Retained per Wash		
	Plant Samples	Truck Samples	Paver Samples
1	53.9	57.4	56.4
2	19.8	23.3	22.1
3	10.7	8.3	8.5
4	5.9	4.1	5.4
5	9.6	7.0	7.6

Table 8: Percent Total Asphalt Binder Retained per Wash - Project 3

Wash Number	% of Total Asphalt Binder Retained per Wash		
	Plant Samples	Truck Samples	Paver Samples
1	60.4	58.8	58.1
2	17.3	18.5	17.9
3	10.8	6.7	6.9
4	4.5	5.4	5.9
5	7.0	10.6	11.2

As shown within Tables 6 through 8, the percentage of asphalt binder retained per wash consistently decreases from Wash 1 to Wash 4. However, the percent asphalt binder retained per wash always increases from Wash 4 to Wash 5. In all instances, the percent asphalt binder retained during Wash 1 is significantly higher than the other stages. In fact, the percentage retained within Wash 1 is generally 2.5 to 3 times more than the percentage retained from Wash 2.

Samples recovered from each stage were tested within the DSR to determine the high failure temperature. Because the mix had been through production and the aging that takes place within the drum, a failure criterion of 2.20 kPa was used for defining the high failure temperature. Tables 9 through 11 present the average failure temperatures for each sample location and stage for Projects 1 through 3, respectively.

Table 9: High Failure Temperatures - Project 1

Wash Number	High Failure Temperature, °C		
	Plant Samples	Truck Samples	Paver Samples
1	71.8	72.6	72.4
2	75.5	74.1	75.0
3	74.3	74.3	74.9
4	79.5	75.7	72.9

Table 10: High Failure Temperatures - Project 2

Wash Number	High Failure Temperature, °C		
	Plant Samples	Truck Samples	Paver Samples
1	70.8	70.9	71.1
2	73.0	72.7	73.1
3	71.4	73.0	72.5
4	75.5	73.8	69.7

Table 11: High Failure Temperatures - Project 3

Wash Number	High Failure Temperature, °C		
	Plant Samples	Truck Samples	Paver Samples
1	74.3	74.8	74.7
2	77.7	77.1	77.1
3	80.9	79.9	76.3
4	80.3	83.5	80.3

As shown within Tables 9 through 11, the failure temperatures are generally lowest for asphalt binder recovered from the first stage. Subsequent failure temperatures generally increase as more and more asphalt binder is removed from the mix.

5.2 Analysis of Test Results

The primary objective of this study was to evaluate how much blending of RAP asphalt binder and virgin asphalt binder takes place for HMA mixes incorporating RAP materials. The research approach was developed using the different stages of extraction/recovery (Figure 5) in order to evaluate the three scenarios of how RAP asphalt binder and virgin asphalt binder blend within plant produced HMA. Recall, the three scenarios of asphalt blending within HMA incorporating RAP are total blending, partial blending and black rock. Entering into the study, it was assumed that if total blending occurs, then the stiffness of the asphalt binder extracted and recovered from each stage would be similar. If the RAP acts as a black rock, it was assumed that the stiffness of the extracted/recovered asphalt binder would be similar through the first three to four stages and then become much stiffer within the final stages. This was assumed because the virgin asphalt binder would be coating the RAP particles. As the virgin asphalt binder was removed during the initial stages, the aged RAP binder would remain for the latter stages. Finally, if partial blending occurred it was assumed that the stiffness of the extracted/recovered asphalt binder would increase with successive stages. During the initial stages, the blended binder would likely be more similar to the virgin asphalt binder. In later stages, the blended asphalt binder would be closer to the aged RAP binder. The concept of partial blending was illustrated within Figure 1.

Another goal of the analysis was to evaluate whether the amount of asphalt binder blending, if observed, changed through the production and construction process. Comparing the stiffness obtained at each of the sampling locations for a given project would allow a determination of whether the RAP and virgin asphalt binders blended more from the plant to the paver.

Initial analysis of the data was conducted to determine whether differences occurred in asphalt binder stiffness between each stage of extraction/recovery. Figure 6 illustrates the average DSR failure temperature for each sampling location and stage. After Wash 1, the failure temperature for all three sample types was approximately 72ºC. After Wash 1, a gradual trend existed of increasing stiffness from Wash 1 to Wash 4. Overall, the data suggests that the largest increase in stiffness was between Washes 1 and 2. However, a spike (large increase) in stiffness does occur going from Wash 3 to Wash 4 of the Plant samples. It's unclear whether this spike is testing related or whether, possibly, the aged asphalt binder from a conglomerate of RAP material was affected during Wash 4. As discussed above, the stiffness of the extracted/recovered asphalt binder after Wash 5 was much lower than for Washes 1 through 4. Based on the data, it does not appear that the sampling location significantly affected the stiffness of the extracted/recovered asphalt binder. The trend for the Plant, Truck and Paver samples appear to be similar except as noted for the Plant sample at Wash 4.

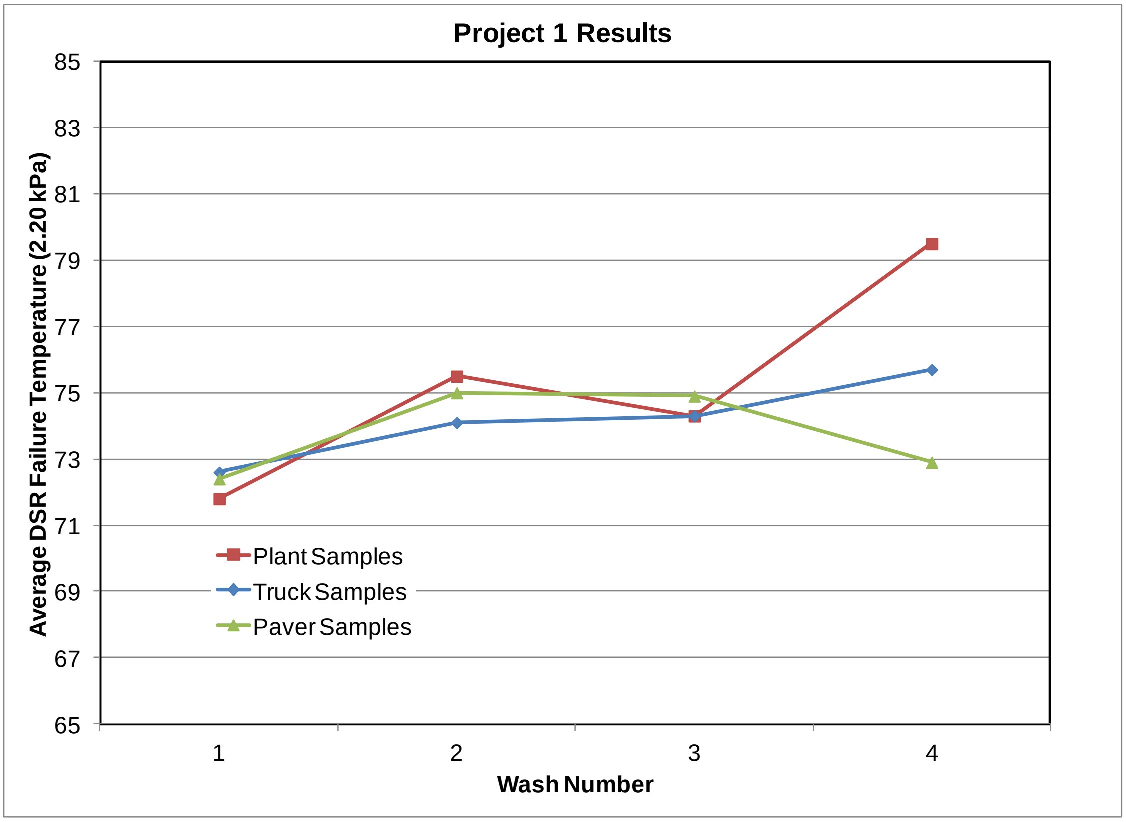

Figure 6: Average DSR Failure Temperatures for Project 1

Figure 7 presents the DSR failure temperatures for each stage from Project 2. The failure temperature after Wash 1 was again consistent; however, for Project 2 the failure temperature was approximately 71ºC. An increase in stiffness occurred for all three sample locations from Wash 1 to Wash 2. From Wash 2 to Wash 3, the extracted/recovered asphalt binder stiffness stayed approximately the same. A similar spike in stiffness was observed for the Plant samples for Wash 4. Again, the stiffness of the Truck samples increased for the Wash 4 testing. The data again suggests that the sampling location did not significantly affect results.

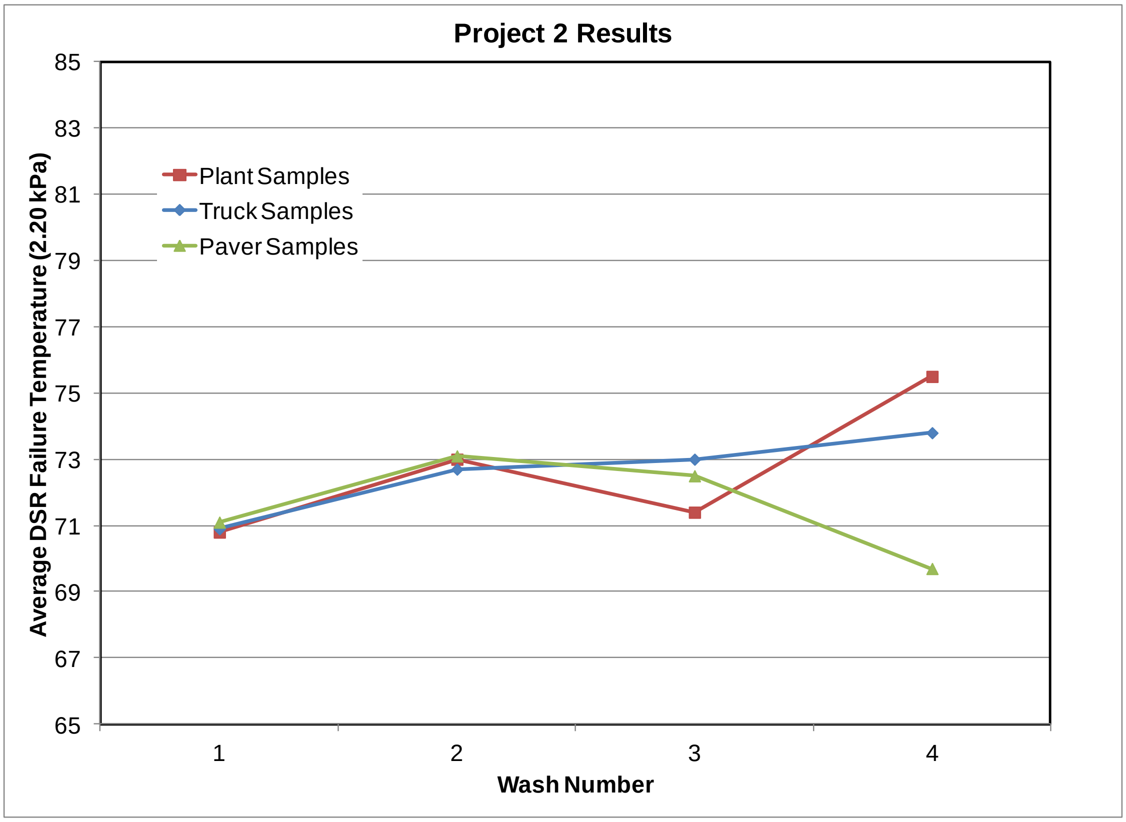

Figure 7: Average DSR Failure Temperatures for Project 2

Figure 8 illustrates the various DSR failure temperatures for Project 3. Again, similar stiffness's were observed for all three sample types for Wash 1. After Wash 1, the extracted/recovered asphalt binder stiffness for Wash 1 was approximately 74ºC. This is slightly higher than for Projects 1 and 2. Recall that Project 3 was the only one of the three projects in which 30 percent RAP was incorporated into the HMA. Projects 1 and 2 utilized 15 percent RAP. A trend of increasing stiffness with washing stage is shown on Figure 8. The increase in asphalt binder stiffness from Wash 1 to Wash 2 is much higher for Project 3 than those observed for Projects 1 and 2. The stiffness continued to increase from Wash 3 to Wash 4 for the Plant and Truck sample locations. It is unclear why the Paver sample location did not show the same increase; however, the stiffness did increase again from Wash 3 to Wash 4. Similar to Project 1, the stiffness of the extracted/recovered asphalt binder for Wash 5 significantly decreased compared to the other stages.

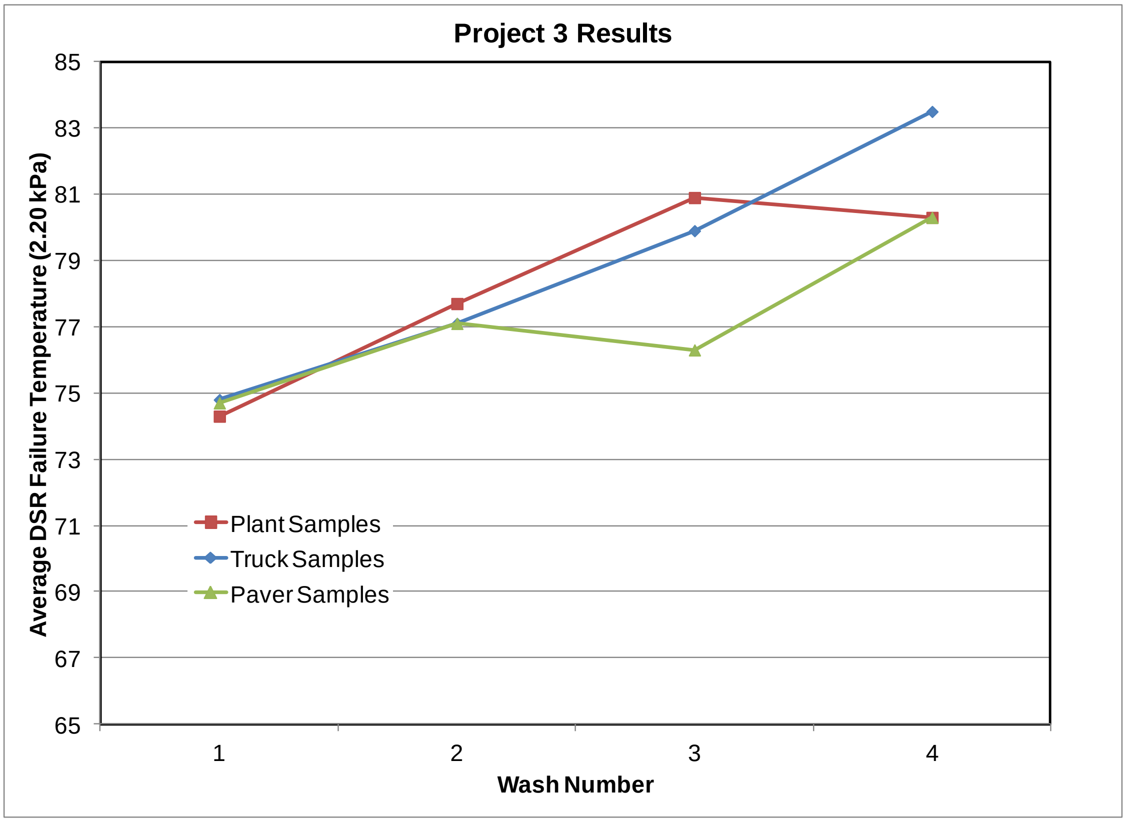

Figure 8: Average DSR Failure Temperatures for Project 3

The data illustrated in Figures 6 through 8 and discussed above suggests that partial blending between the RAP and the virgin binder takes place when RAP is incorporated into HMA. This observation is based on the increase in extracted/recovered asphalt binder stiffness through the staged process. Comparing Figures 6 and 7 to Figure 8 suggests that as the percentage of RAP incorporated into HMA increases, the resulting effect on partial blending changes. Figures 6 and 7 show only slight increases in stiffness from Wash 1 to Wash 4; however, Figure 8 shows a much higher increase in stiffness. Recall that Projects 1 and 2 incorporated 15 percent RAP while Project 3 incorporated 30 percent RAP. For Projects 1 and 2, the average failure temperature for Wash 1 was 71 to 72°C while for Project 3 the average failure temperature was 74°C. Whether this 2 to 3°C increase in average failure temperature is significant is unclear. The biggest difference between mixes containing 15 and 30 percent RAP was observed within the Wash 3 and Wash 4 data. In both of these instances, the average failure temperature for Projects 1 and 2 was approximately 5 to 7ºC less than the average failure temperature for Project 3.

Just looking at the absolute data presented in Figures 6 through 8 doesn't provide a clear picture of how the partial blending really affects the asphalt binder within an HMA mix. Figure 9 presents a pie chart that illustrates how much asphalt binder was obtained from each stage of the extraction/recovery process. This chart shows the percentage of asphalt binder that was extracted/recovered from each Wash. Superimposed onto the pie chart is the average failure temperature associated with the percentage of asphalt binder extracted/recovered. Because

Projects 1 and 2 both incorporated 15 percent RAP and Figures 6 and 7 suggested similar characteristics, Figure 9 is the average of all data from Projects 1 and 2.

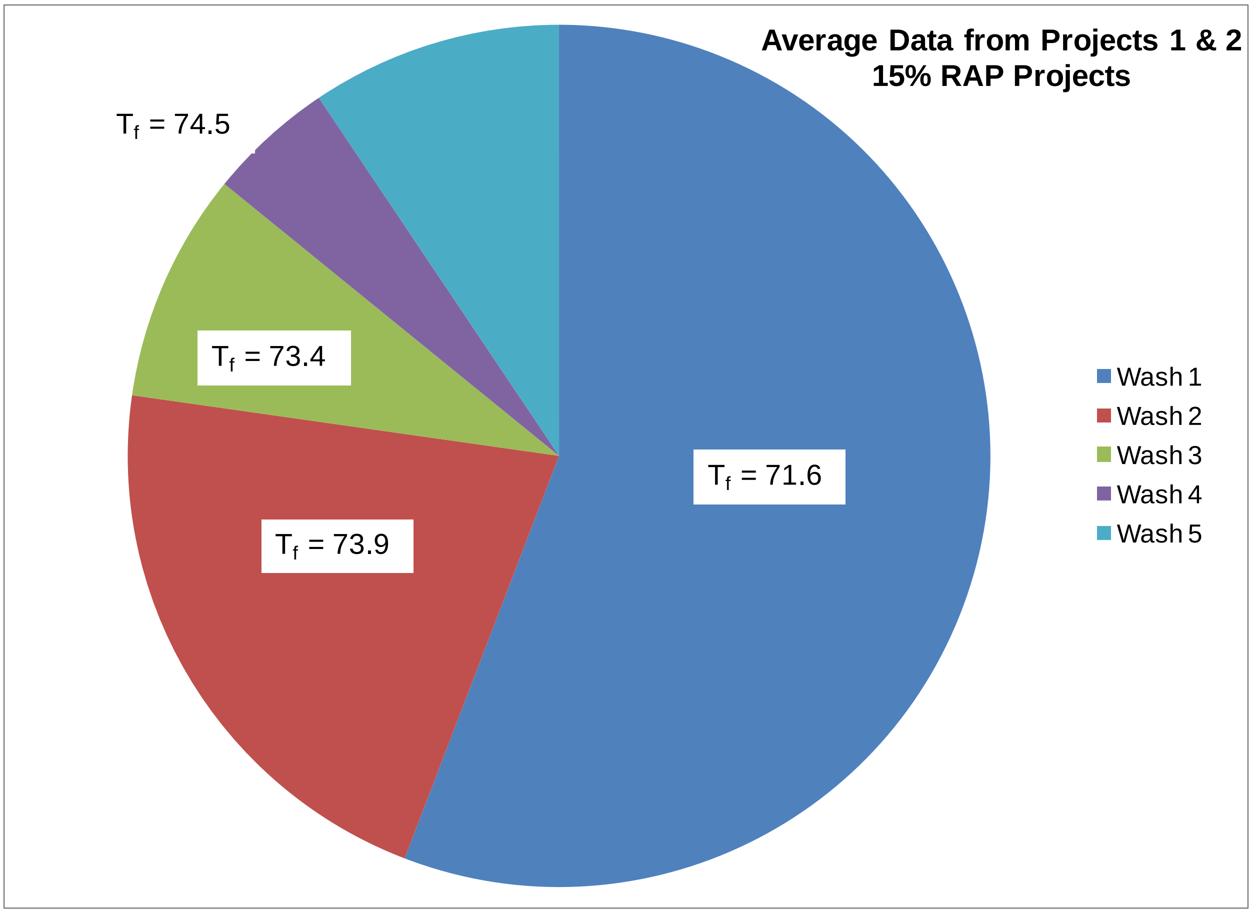

Figure 9: Percentages of Recovered Asphalt Binder and Average Failure Temperatures - 15 Percent RAP Projects

Figure 9 shows that the majority (56 percent) of asphalt binder was recovered during Wash 1. The average failure temperature for Wash 1 was 71.6ºC. Since the virgin asphalt binder used within the HMA mixes for Projects 1 and 2 was a PG 67-22, Figure 9 suggests very little blending took place for the material represented within Wash 1. For Wash 2, the average percentage of asphalt binder recovered was 21 percent and the average failure temperature was 73.9ºC. The increase in the average failure temperature suggests more blending between the RAP and virgin asphalt binders. However, the failure temperature of 73.9ºC still does not suggest a significant increase in binder stiffness. The average failure temperature for Wash 3 was 73.4ºC. This is very similar to Wash 2. The average failure temperature for Wash 4 was 74.5 ºC which is a slight increase over Washes 3 and 4. However, only 5 percent of the recovered binder is represented in Wash 4. From a big picture standpoint, Figure 9 suggests that when 15 percent RAP is incorporated into an HMA mixture, minimal effect occurs to the properties of the asphalt binder within the mix. This observation supports many previous researchers.

Figure 10 illustrates the percentage of extracted/recovered asphalt binder per Wash and the average failure temperatures for the 30 percent RAP mixture (Project 3). Similar to the 15 percent RAP mixes, the majority of the asphalt binder was recovered during Wash 1. A slightly higher percentage of asphalt binder was recovered for the 30 percent RAP mix than the 15 percent RAP mixes (59 percent to 56 percent). Also, a slight increase in the average failure temperature was observed (71.6°C to 74.6°C). Recall that a PG 67-22 asphalt binder was also used as the virgin asphalt binder for Project 3. The failure temperature of 74.6°C does suggest some minimal amount of blending likely occurred to the materials removed during Wash 1. However, Figure 9 shows that roughly 60 percent of the asphalt binder within the mixture had minimal blending. The percentage of material extracted/recovered during Wash 2 was 18 percent and the average failure temperature increased to 77.3°C. Thus, some additional blending did occur to the asphalt binder recovered during Wash 2. Though the percentage of material extracted/recovered during Wash 3 became stiffer (failure temperature increased to 79.0°C), this fraction of asphalt binder represented only 8 percent of all the asphalt binder removed from the HMA. Only 5 percent of the asphalt binder was recovered from Wash 4. The average failure temperature did increase to 81.4ºC.

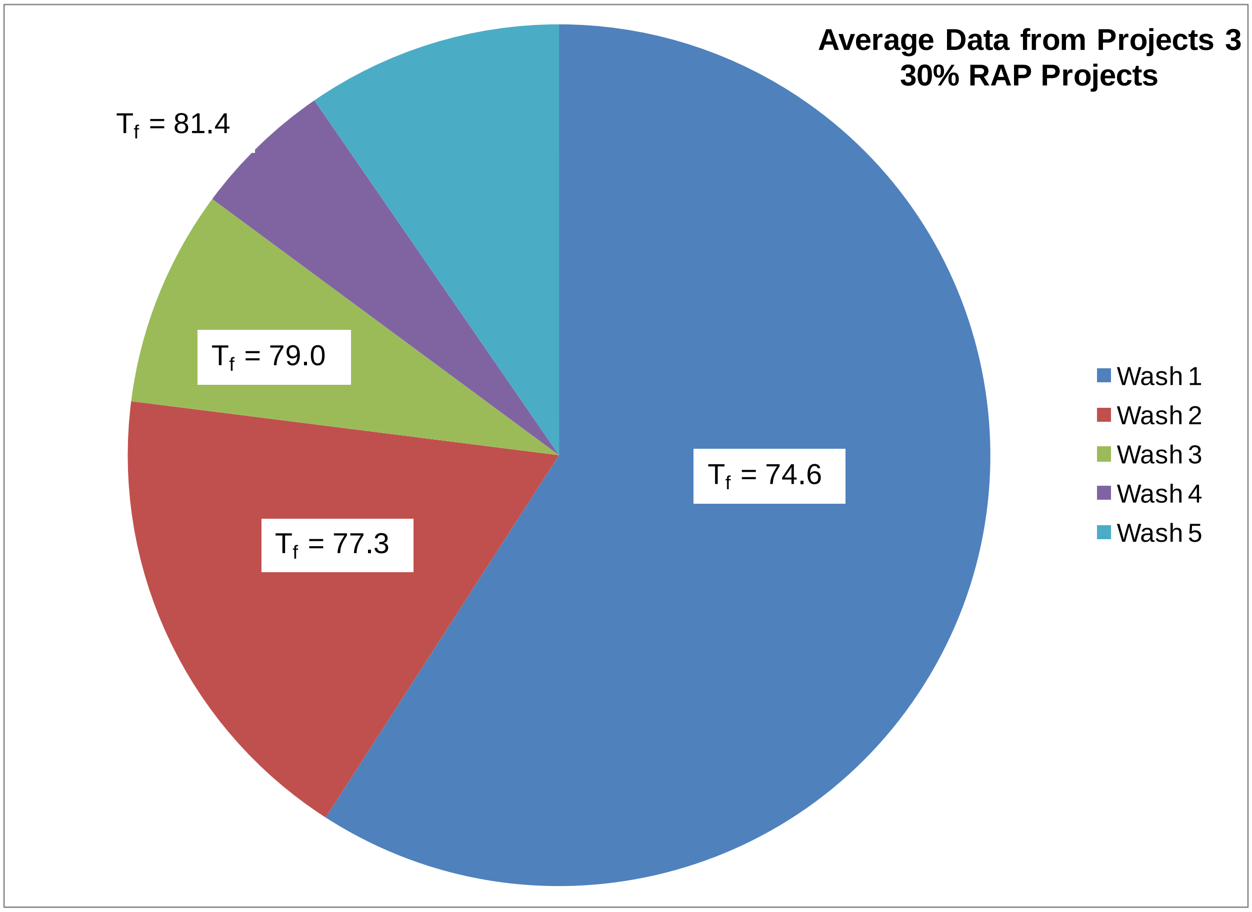

Figure 10: Percentages of Recovered Asphalt Binder and Average Failure Temperatures - 30 Percent RAP Project

Figure 10 strongly suggests that only partial blending occurs when RAP is added to HMA mixes. As layers of asphalt binder are removed, the asphalt binder becomes stiffer. However, from a performance point of view, it is unclear how the partial blending affects HMA properties such as volumetrics and/or performance properties. Figure 10 suggests that only a small portion of the asphalt binder is significantly affected by blending of the RAP and virgin asphalt binders. The question arises as to whether the incorporation of RAP into laboratory mixes containing 30 percent RAP follows a similar trend as observed for this plant produced HMA. Another question is whether the addition of more or less RAP would change how much blending occurs and whether the same proportions of asphalt binder stiffness would occur.

CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The objective of this study was to evaluate the amount of blending that occurs between RAP and virgin asphalt binders in plant produced HMA in which RAP is incorporated. Answers to this question will be the first step in accomplishing Phase 1 shown within Figure 4. The objective of this study was accomplished by testing plant produced mixture from three different on-going HMA projects. Two of the three projects incorporated 15 percent RAP within the HMA while the third project incorporated 30 percent. Samples were obtained at three locations during the production and construction process. These samples were brought back to the laboratory and subjected to a staged extraction/recovery process. Based upon the research approach for this project, the following conclusions are provided.

- Asphalt binder content measurements for HMA determined using the ignition oven are generally higher than asphalt binder contents determined using solvent extraction.
- The difference in measured asphalt contents between the ignition oven and solvent extraction appear to be aggregate type dependent.
- Failure temperatures measured using the DSR were relatively consistent within each stage for mixes containing 15 percent RAP.
- Failure temperatures measured using the DSR were higher for mixes containing 30 percent RAP.
- The stiffness of the blended asphalt binder generally increased for each stage for all mixes containing RAP. The asphalt binder recovered in each stage for the 30 percent RAP mixes increased at a greater rate than mixes containing 15 percent RAP.
- For mixes containing 15 percent RAP, the majority of the asphalt binder within the mix was not significantly affected by the aged RAP asphalt binder.
- For mixes containing 30 percent RAP, the majority of the asphalt binder within the mix was not significantly affected by the aged RAP asphalt binder. The RAP asphalt binder significantly affected 5 to 13 percent of the total asphalt binder extracted. Another 18 percent was affected ; however, the failure temperature was similar to a PG76-XX asphalt binder.
- The theories of RAP behaving as a black rock and total blending of RAP and virgin asphalt binders were proven false. The data explicitly shows that partial blending takes place between RAP and virgin asphalt binders.

6.2 Recommendations

Based upon the above conclusions for this project, the following recommendations are provided:

- Because partial blending between RAP and virgin binder was found during this study, additional research is needed to establish a laboratory method for inclusion of RAP materials into HMA that best simulates the amount of partial blending that takes place in plant produced HMA containing RAP.

REFERENCES

Asphalt Recycling and Reclaiming Association (ARRA) (2001). “Basic Asphalt Recycling Manual. Asphalt Recycling and Reclaiming Association. 2001.

Bonaquist, R. (2007). “Can I Run More RAP?” Hot Mix Asphalt Technology, Vol. 12, No. 5. National Asphalt Pavement Association. Lanham, Maryland. September/October 2007.

Burr, B. L. et al. (1991). Asphalt Hardening in Extraction Solvents.” Transportation Research Record 1323. Transportation Research Board of the National Academies. Washington, D.C. 1991.

Copeland, A. (2011) “Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice.” Report No. FHWA-HRT-11-021. Federal Highway Administration. McLean, Virginia. April 2011.

Hall, K.D. (2004). “Using a Single Test to Determine Specific Gravity and Absorption of Aggregate Blends.” Transportation Research Record 1874. Transportation Research Board of the National Academies. Washington, D.C. 2004.

Huang, B., et al. (2005). “Laboratory Investigation of Mixing Hot Mix Asphalt with Reclaimed Asphalt Pavement.” Transportation Research Record 1929. Transportation Research Board of the National Academies. Washington, D.C. 2005.

McDaniel, R.S. and R.M. Anderson (2001) “Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method.” National Cooperative Highway Research Program Report No. 452. Transportation Research Board. Washington, D.C. 2001.

Nahar, S.N., et al. (2013). “First Observation of the Blending Zone Morphology at the Interface of Reclaimed Asphalt Binder and Virgin Bitument.” Transportation Research Record 2370. Transportation Research Board of the National Academies. Washington, D.C. 2013.

Prowell, B. and C. Carter. (2000). “Evaluation of the Effect on Aggregate Properties of Samples Extracted Using the Ignition Furnace: Interim Report.” Virginia Transportation Research Council. April 2000.

West, R., J.R. Willis, and M. Marasteanu. (2013). “Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content.” National Cooperative Highway Research Program Report No. 752. Transportation Research Board. Washington, D.C. 2013.

Wright, Jr., F. (2001). “FHWA Recycled Materials Policy.” Federal Highway Administration. Obtained from: http://fhwa.dot.gov/legsregs/directives/policy/recmatpolicy.htm. Washington, D.C.