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Laboratory Evaluation of Asphalt Mixtures and Binders with Reclaimed Asphalt Shingle Prepared Using the Wet Process

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LABORATORY EVALUATION OF ASPHALT MIXTURES AND BINDERS WITH RECLAIMED ASPHALT SHINGLE PREPARED USING THE WET PROCESS

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For my father,

Rafael Maximiliano Alvergue Calderon.

Por siempre en mi corazon.

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TABLE OF CONTENTS

ABSTRACT

The objective of this study is to conduct a laboratory evaluation of asphalt mixtures and binders containing RAS prepared using the newly-developed wet process. In the proposed wet process, RAS material is blended with the binder at high temperature prior to mixing with the aggregates. The proposed wet process offers the potential to better control the Superpave Performance Grade (PG) of the binder blend, to stimulate chemical and physical interactions taking place in the blend between asphalt binder in shingles and virgin asphalt binder in the mix, and to reduce maintenance issues at the plant due to the high content of fines and fibers in RAS.

To achieve this objective, asphalt binder blends with 10%, 20%, and 30% RAS were prepared using the wet process, and asphalt mixtures with a nominal maximum aggregate size (NMAS) of 12.5mm were designed according to the Superpave design protocol. The mechanistic performance of asphalt mixtures containing RAS materials was evaluated as compared to conventional asphalt mixtures. Laboratory mixture testing evaluated the rutting performance, fracture performance, and low temperature resistance of the produced mixtures using the Hamburg Loaded-Wheel Tester (LWT), the Semi-Circular Bending (SCB) test, and the Thermal Stress Restrained Specimen Test (TSRST).

Results from the experimental program indicated that the proposed wet blending process allows a reduction of the virgin binder content with no detrimental effects on the laboratory performance of the mixture as compared to the conventional mixture without RAS. In addition, results suggested that the usage of RAS in its regular processed size, as processed by the recycling plant, is feasible with no foreseen adverse effects on the mixture performance.

The resistance of the binder blends with RAS to fatigue and permanent deformation was evaluated through the use of the newly developed Linear Amplitude Sweep (LAS) test and the Multiple Stress Creep Compliance (MSCR) test. The effect of using different RAS amounts, as well as binder with two different PG grades, was investigated. Results of the LAS test showed that an increase in RAS leads to an increase in the number of cycles to fatigue failure. This is the opposite of what would be expected. These results indicate that the LAS test may not be suitable for characterizing RAS-modified asphalt binders. With respect to permanent deformation, it was

found that the addition of RAS improved the performance of the blends by reducing the non-recoverable creep compliance and increasing elastic recovery.

1 INTRODUCTION

In the past 40 years, the increasing cost of asphalt cement, a petroleum-based product, has led to investigate methods to reduce the amount of virgin binder required to produce Hot Mix Asphalt (HMA) without negatively affecting its performance. In addition to rising costs, environmental concerns about the carbon emissions resulting from the production of asphalt binder have motivated research on decreasing the amount of asphalt used in HMA pavement. As one possible solution to this problem, state highway agencies have started to use recycled materials by incorporating them into the production of HMA. Among these materials, Recycled Asphalt Shingles (RAS) have been increasingly used by many states.

The use of RAS has been an innovation, which has gained popularity and acceptance within the past twenty years. Highway agencies, as well as contractors, have now included RAS within their HMA mixes in efforts to reduce virgin binder content, which translate into reduced costs. On average, most shingles contain an asphalt content ranging between 15 and 35% (Gevrenov, 2008). It has been estimated that savings could range between $1 and $2.80 per ton of HMA when using 5% shingles (CMRA, 2013). In addition, shingle waste is widely available. In the U.S., it is estimated that 11 million tons of tear-off scrap and 1 million ton of manufactured waste is generated annually (McGraw, 2007).

Current practices implemented in the recycling of asphalt shingles consist of dry blending RAS with the aggregates before the asphalt binder is added to the batch. Recently, a “wet process” has been introduced as a new approach where RAS material is ground to a fine particle size and blended with the binder at high temperature prior to mixing with the aggregates. This process aims to stimulate a more effective chemical interaction between asphalt binder in shingles and virgin asphalt binder in the mix (Salari, 2012).

1.1 Problem Statement

While binder containing RAS and prepared through the wet process has been evaluated, no research has been performed on the performance of asphalt mixtures prepared using this innovative approach. Laboratory tests should be performed on these classes of asphalt mixtures in order to predict their performance to different loading and environmental conditions. These tests would also provide an insight on how the asphalt mixture will perform when in service.

1.2 Research Objectives

The objective of this study is to conduct a laboratory evaluation of asphalt mixtures and binders containing RAS prepared using the wet process. Asphalt mixtures with a nominal maximum aggregate size (NMAS) of 12.5 mm were designed using the Superpave design methodology. Three mixture laboratory performance tests and two binder test methods were considered in this study. These methods include test methods for the mixture: the Hamburg Loaded-Wheel Tester (LWT), Semi-Circular Bending (SCB) test, Thermal Stress Restraining Specimen Test (TSRST), and for the binder: Multiple Stress Creep Recovery (MSCR), and Linear-Amplitude Sweep test methods. These tests were selected to assess the material's performance against permanent deformation, fracture resistance and fatigue cracking, and low-temperature thermal cracking.

1.3 Research Approach

In this thesis, a paper-format was used in which each chapter is considered a standalone work with minimal references to other parts of the study. This format hypothesizes that a technical paper will result or has resulted from each chapter; therefore, each chapter possesses its own conclusions and references. The research approach adopted in this study consisted of completing the following three main tasks:

Task 1: Literature Review

A comprehensive literature review was conducted to review the following topics:

1) Types and compositions of roofing shingle;

2) Current practice of RAS usage;

3) RAS binder characteristics and rheology;

4) Performance of asphalt pavements with RAS;

Task 2: Mix Design and Preparation

All the mixtures evaluated in this study consisted of the same mix design, designed according to AASHTO TP 28, "Standard Practice for Designing Superpave HMA" and in accordance with the Louisiana Standard Specifications for Roads and Bridges. The two asphalt binders used for this study for both mixture and binder performance, are PG 70-22M and PG 64-22. Tear-off RAS from Illinois, Texas, and South Dakota was used in this study. More details about the distribution of particle size of each source discussed in the subsequent chapters.

Task 3: Laboratory Experimental Testing

Asphalt mixture and binder performance was evaluated according to the following five tests:

1. Hamburg Loaded-Wheel Tester (AASHTO T 324):

Rutting performance of the mix was assessed using a Hamburg-type Loaded Wheel Tester (LWT). This test consists of rolling a 703 N (158 lb.) steel wheel across the surface of a slab that is submerged in 50°C water for 20,000 passes at 56 passes a minute. A maximum allowable rut depth of 6 mm at 20,000 passes at 50ºC was used. The rut depth at 20,000 cycles was measured and used in the analysis.

2. Semi-Circular Bending (SCB) Test (AASHTO TP 105):

Fracture resistance potential was assessed using the semi-circular bending (SCB). This test characterizes the fracture resistance of HMA mixtures based on fracture mechanics principals, the critical strain energy release rate, also called the critical value of J-integral, or J_c. This test consists of loading a semi-circular specimen till fracture failure under a constant cross-head deformation rate of 0.5 mm/min in a three-point bending load configuration. The load and deformation are continuously recorded and the critical value of J-integral (J_c) is then determined.

3. Thermal Stress Restrained Specimen Tensile Strength (AASHTO TP10):

Cracking performance at low-temperature was evaluated using the TSRST. This test determines the tensile strength and temperature at fracture of a specimen, which is cooled at a constant rate, while being restrained from contraction. From the resulting data, a relationship can be established between temperature at which fracture occurs and mixture characteristics.

4. Multiple Stress Creep Recovery (AASHTO TP 70):

In addition to using the LWT for evaluating mixtures' resistance to permanent deformation, the Multiple Stress Creep Recovery (MSCR) test was conducted on the RAS-modified binders to determine the effects of RAS on the binder rheological properties. MSCR is designed to identify the elastic response of a binder and the change in the elastic response at two different stress levels while being subjected to ten cycles of creep stress and recovery. The stress levels used are 0.1 kPa and 3.2 kPa. The creep portion of the test lasts for 1 s, which is followed by a 9-s recovery period.

5. Linear-Amplitude Sweep test (AASHTO TP 101):

In order to test the binder's resistance against fatigue damage, the Linear-Amplitude Sweep test uses cyclic loading (in shear) at increasing amplitudes in order to induce fatigue damage in the binder. The test consists of two main steps: a frequency sweep test and an amplitude test. Frequency sweep is conducted at low strain level to measure the property of the binder in the undamaged state. The amplitude sweep test consists of loading the binder in a cyclic mode while gradually increasing the strain level until it reaches 30%. The rate of damage accumulation in the binder is used to indicate fatigue performance of the asphalt binder. This test is performed using a Dynamic Shear Rheometer (DSR) at 25°C.

2 LITERATURE REVIEW

2.1 Recycling Alternatives in HMA

The increasing cost of asphalt cement in the past 40 years has led to investigate methods to reduce the amount of virgin binder required to produce HMA pavements without negatively affecting the performance. A wide variety of potentially recyclable materials have been considered. Included in this list is Reclaimed Asphalt Pavement (RAP), waste tire rubber and Recycled Asphalt Shingles (RAS). Although this study focuses on RAS, it is noted that not only recycling alternatives for pavement been developed, but new processes have been introduced in attempts to lower the energy required to produce HMA pavement. This modified process is referred to as Warm Mix Asphalt (WMA).

2.2 Production of Roofing Shingles

There are two types of asphalt shingles, which are used for roofing: organic and fiberglass. Organic shingles consist of a paper saturated with asphalt with a top coating of adhesive asphalt and embedded ceramic granules. Fiberglass shingles have a base layer of glass fiber reinforcing mat. Asphalt containing mineral fillers, is used to coat the mat to make it waterproof. These two types of shingles have different asphalt binder contents, as shown in Table 2-1.

Table 2-1: Typical Shingle Composition (Salari, 2012)

Material	Organic Shingles	Fiberglass Shingles
Asphalt Binder	30 – 35%	15 – 20%
Aggregate	30 – 50%	30 – 50%
Fibers/Mineral Fines	15 – 35%	20 – 35%

The production process for organic and fiberglass shingles are similar. Both are impregnated with asphalt, and then both sides are coated with two different types of asphalt. One type of asphalt is used to saturate the base, the other is applied as a coating. Since the shingles are expected to withstand high temperatures, both types of asphalt binders are "air-blown" to incorporate oxygen into the asphalt for higher viscosity and stiffness. Powdered limestone is added as a stabilizer and the topside is covered with crushed rocks and granules ranging from 0.3 to 2.36 mm as a way to protect the shingle from damage. The last step involves covering the bottom surface with fine sand (less than 0.425 mm) as a way of preventing shingles from adhering to one another during transportation (Salari, 2012).

The existence of asbestos in tear off shingles is a common concern, which is associated with the use of RAS. Asbestos was commonly used in roofing products up through the late 1970's. Manufacturers have not been able to track how many asbestos roofing shingles were sold or to what part of the U.S. they were shipped to (Stellmach, 2012). In spite of this, a survey aimed at testing shingles for asbestos, found that out of 27,000 shingle samples, only 1.5% contained asbestos (Salari, 2012). Any material containing greater than 1% asbestos by weight, is considered an "asbestos-containing" material by the U.S Environmental Protection Agency (EPA) and is therefore regulated as such. The Department of Environmental Quality (DEQ) prohibits the use RAS, which contains asbestos for any paving purpose. In addition, it is prohibited to grind any asbestos containing roofing waste since asbestos fibers could be released into the air (Stellmach, 2012). For this reason, asbestos testing is regularly done on tear-off shingles during the shingle processing stage. Regulation requirements vary from state to state, but in general, the process involves sampling each layer of shingle material, which is then sent to an asbestos testing laboratory (Zhou et al., 2011).

2.3 RAS Processing

The processing of RAS is the first key step to produce a quality RAS mix pavement. As shown in Figure 2-1, RAS processing consists of the following steps: collecting, sorting, grinding, screening, storing and an extra step of asbestos testing for tear-off RAS. Generally, manufactured RAS has received more attention for use in HMA since they contain fewer contaminants and contain asphalt, which is less oxidized. In addition, manufactured RAS does not require significant sorting, inspection, testing or separation of unwanted material but at the same time, the availability is limited since typically manufacturing facilities are located only in densely populated areas. Primary concerns with tear-off RAS include potential presence of asbestos, deleterious materials (metal, wood, plastic, etc.) and highly oxidized (stiff) asphalt. The advantage of tear-off RAS is that they are readily available through out the U.S. (Zhou et al., 2011).

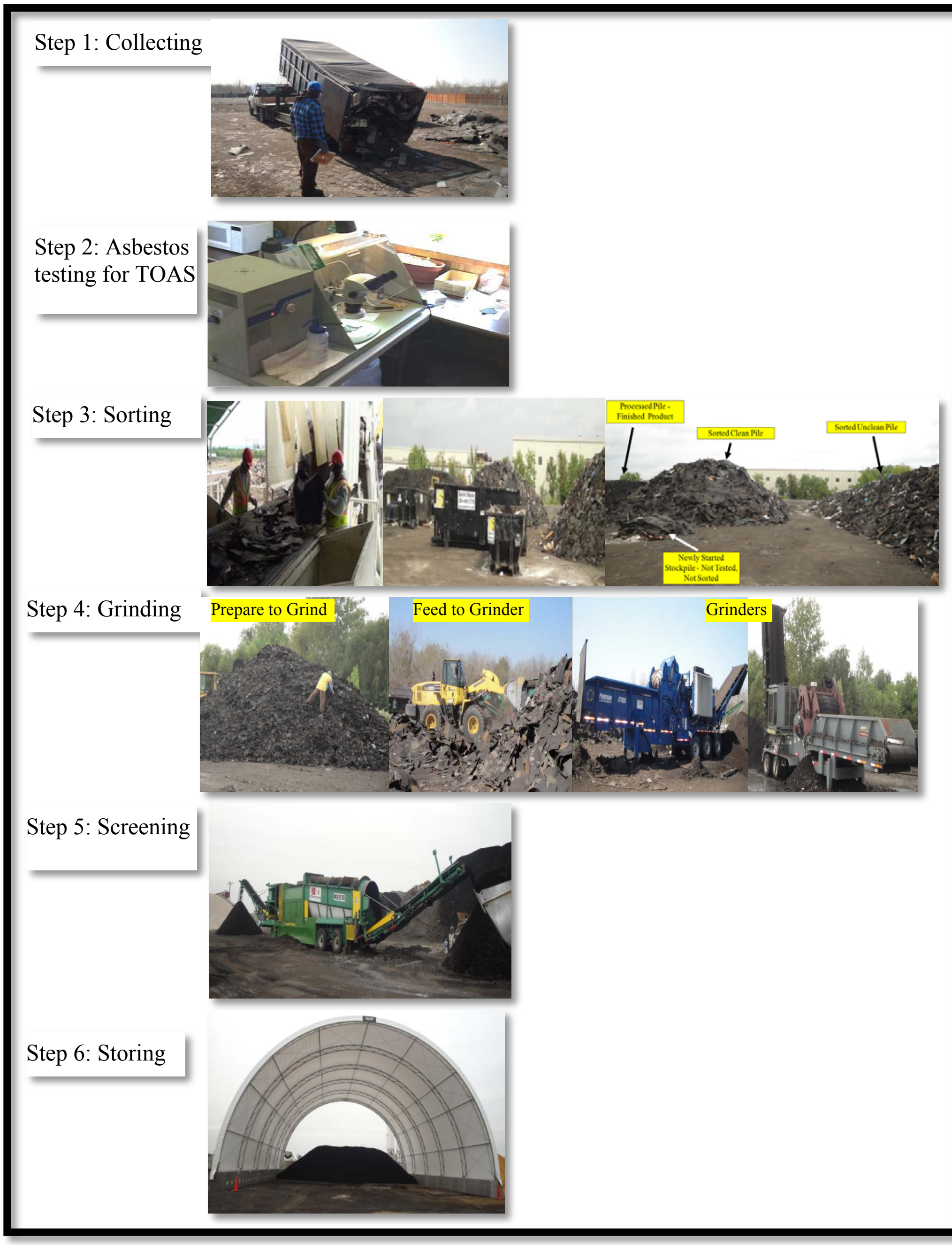

Figure 2-1: RAS Processing Steps

2.4 Use of RAS in Paving Applications

The use of RAS has been an innovation, which has gained popularity and acceptance within the past twenty years. Government agencies, as well as contractors, have now included RAS within their HMA mixes in efforts to reduce virgin binder content, which translates into reduced costs. These reduced costs are mainly due to two reasons. For DOT's and pavement contractors, a decrease in material cost is due to a reduction of virgin asphalt. For roofing contractors, lower disposal expenses are common since depositing waste at a recycler is more economical than at a landfill. Of course, other variables need to be accounted for such as acquirement, processing, and handling expenses. The actual cost of these varies from state to state. Some studies have estimated that savings could range between \$1 and \$2.80 per ton of HMA when using 5% shingles (Construction Materials Recycling Association, 2013). In addition, shingle waste is widely available. In the U.S., it is estimated that 11 million tons of tear-off scrap is generated annually, which is about ten times the amount of manufactured shingle scrap (McGraw et al., 2007).

RAS usage, from both manufacture and construction (tear-off) waste, increased from 1.1 million tons in 2010 to 1.2 million tons in 2011, an 8 percent increase. Assuming a conservative asphalt content of 20% for the shingles, this represents 380,000 tons (2.2 million barrels) of asphalt binder conserved (Hansen and Newcomb, 2011). The American Association of State Highway and Transportation Officials (AASHTO) have developed specifications and guidelines for designing HMA with addition of RAS. Among these are requirements for shingle aggregate gradation, performance grade (PG) of the virgin and RAS binder and relative reduction of the virgin asphalt binder due to replacement by RAS binder. The actual maximum quantity of RAS allowed is left at the discretion of the designer (McGraw et al., 2007). As of 2010, 26 states reported using RAS in their HMA mixes (Hansen and Newcomb, 2009). The majority of these states allow RAS quantities between 2.5% and 5%, but states such as Missouri and South Carolina allow between 5% and 8%, which are the highest amounts currently used in practice (Salari, 2012).

Most states are reluctant to use higher percentages of RAS, due to the stiffening effect, which has been found to be caused by the aged asphalt recovered from the shingles. Previous research has shown that mixes containing up to 5% RAS by weight, can perform adequately without any significant negative effects, but exceeding 5% may change the properties of the blended mixture significantly and adversely impact pavement performance (Button et al., 1995; Newcomb et al., 1993). The main distress, which is of most concern when using RAS modified pavement, is susceptibility to low temperature cracking due to the increase in stiffness of the blended binder (Williams et al., 2011; McGraw et al., 2007). Recently, new research has found that through a new approach of mixing finely ground RAS with virgin binder, the quantity of RAS could be incremented to a content of 20% or less by weighting of the binder, while raising or not influencing the PG high temperature grade and maintaining the low temperature grade of the virgin binder (Salari, 2012).

2.5 RAS Binder Characteristics

2.5.1 Methods of Incorporating RAS into Asphalt Mixture

In order to effectively use RAS, the material needs to be heated in order to activate the RAS binder and improve workability. The two most commonly used methods of incorporating RAS into mixtures are referred to as “dry” and “wet” method. The “dry” method consists of preheating RAS materials at the target mixing temperature, then mixing with the virgin aggregates. The “wet” method is done by superheating the virgin aggregate, in order to ensure heat transfer to the RAS, and then adding in the RAS which is at room temperature (Zhou et al., 2011).

Based on RAP mix design experience and some limited data on RAS mix design, researchers at the Texas Transportation Institute recommend a “dry” two step pre-heating process, which includes heating RAS overnight (12-15 hours) at 140°F, then preheating the RAS at the mixing target temperature for two hours, which is a common time for preheating virgin binder (Zhou et al., 2011).

Researchers at Louisiana State University evaluated a “wet” method in which RAS was ground to ultra-fine particles, and then blended at 180°C using a mechanical shear mixer rotating at a speed to 1500 rpm for 30 minutes. Results from rheological and stability testing indicated that this “wet” process could be used with a RAS modification content of 20% or less by weight of the binder (Salari, 2012).

2.5.2 Rheological Properties

HMA pavement deformation is closely related to the rheological properties of the asphalt binder. The addition of RAS into a HMA mix, either by a wet or dry process, has been shown to influence these properties. Moreover, tear-off and manufactured RAS have been found to affect the binder properties differently, since one (tear-off) contains asphalt which is much more oxidized (stiffer) than the other (manufacturer waste) (Salari, 2012).

Salari (2012) conducted a study on the effect of RAS binder mixing through a wet process as well as using different RAS types and quantities. Two unmodified binders, classified as PG 64-22 and PG 52-28, were blended with tear-off and manufactured RAS at percentages ranging from 10 to 40% by weight of the binder. Binder with RAS content up to 20% was found to either gain or maintain its high temperature grade. Both tear-off and manufactured shingles resulted in an increase in viscosity ranging from 3 to 130% when compared to the unmodified binder. In addition, samples made from tear-off showed a higher viscosity than those prepared from manufactured waste. RAS was shown to decrease the temperature susceptibility of the binder for temperatures within the range of 95 to 135°C. Binder modified with both types of RAS showed an increased susceptibility to thixotropy than the unmodified binder and it was found that as RAS content increased, thixotropy increased as well. Results from the High Pressure Gel Permeation Chromatography Analysis (HP-GPC) showed that binder with RAS had a higher content of High Molecular Weight (HMW) than the control unmodified binder. Taking into account all results, it was determined that RAS can be used through the ``wet" process at a modification content of 20% or less.

Past research (Wahhab et al., 1999; Lee et al., 2008; Salari, 2012) has shown that LMS is a good indicator of aging in asphalt binders. Zhao et al. (2013) conducted a study to investigate the correlation between rheological properties and of low molecular weight (LMW) fraction for a variety of different combinations of RAS and binder. Each sample was tested using a DSR and GPC to obtain the complex shear modulus (G*) and percentages of LMW. Results showed a positive correlation between percentage of LMW and G* at both 25°C and 64°C. As the percentage of LMW increased, G* increased as well.

You et al. (2011) performed a study on the low temperature performance of environmentally friendly HMA paving materials, including RAS from tear-off sources. The resistance to thermal cracking of mixtures containing 5 and 10% RAS was determined through the use of Superpave Bending Beam Rheometer (BBR) and the new Asphalt Binder Cracking Device (ABCD), which has been recently found to be a reliable tool in determining low temperature cracking resistance at in-field type conditions (Kim, 2013). Results from the BBR test showed that 10% RAS mixture had higher creep stiffness than that of the 5% mixture. In addition, the Superpave low temperature cracking maximum value of 300MPa was satisfied by both mixtures. Results from the ABCD test provided the same relation between RAS content and creep stiffness; as the RAS percentage increased, stiffness also increased. Both tests indicated that as RAS content increased, the binder became more susceptible to develop low temperature cracking.

Falchetto et al. (2012) evaluated the effect of both RAS and RAP on the low temperature properties of asphalt mixtures in order to determine if changes in mixture behavior are due to the addition of recycled material, or due to blending virgin and recycled binder. While most of the studies on the rheological properties of RAS/RAP modified binder have been performed using Superpave testing equipment, Falchetto et al. (2012) used microstructural analysis and modeling of rheological data obtained from mixtures. Samples were prepared using PG58-28 binder and different percentages of RAP and RAS (tear-off and manufactured). The maximum percentage of RAS used in any one mixture was 5% by weight of the mix. A Digital Image Processing (DIP) system was used to evaluate the changes in the material microstructure and it concluded that the recycled material added to the mixtures does not affect the microstructural spatial distribution of the aggregate phase.

In attempts to investigate the effect of different shingle sources and quantities on the binders final PG grading, Johnson et al. (2010) produced 17 different mixtures containing variable RAS (tear-off and manufactured) and RAP contents. Mixes were prepared using both PG 58-28 and PG 51-34. As with most of these studies, the RAS was treated as a fine aggregate and blended with the sand prior to heating and addition of the virgin binder (i.e., dry process). The asphalt binders were then extracted from the prepared mixtures using a centrifuge extraction method, which involved the use of toluene. The solvent was removed using the ASTM D5404-Rotovapor recovery process. The extracted binder was then graded using all the required Superpave binder testing equipment. Results showed an increase in both the high PG temperature grade and low PG temperature grade with an increase in RAP and/or RAS. Mixtures, which used PG 51-34 binder, were found to have a lower high temperature grade as well as a lower low temperature grade than those with the same level of RAS/RAP but with PG 58-28 binder. Tear-off RAS mixes showed slightly higher low-temperature grades than those of manufactured RAS, but mixes with both types of RAS at quantities of 3% shared the same PG grade. Only one case resulted in a difference in PG grade, when RAP quantity was increased to 25% and both tear-off and manufactured RAS was raised to 5%. In this case, tear-off RAS showed more stiffening, which changed the PG grade to PG 82-10, compared to PG 76-16 for the manufactured RAS mix. It was noted that this could have been due to variability of the testing or due to the material itself. These results suggested that binder stiffness is related to the new asphalt binder to total asphalt binder ratio. Plots were developed of the new binder to total binder ratio against the low and high temperature PG grade of the binder. Using a least squares linear regression, a stronger relationship was found using the high PG grade rather than the low PG grade (R^2 of 0.89 vs. 0.77). From the results, it was suggested that decreasing the proportion of new binder in the mixture will have an unfavorable effect on the durability of the mix if no other changes are made in effort to counter the stiffening effect of RAS/RAP.

The Dynamic Shear Rheometer (DSR) was used to test the samples at intermediate and high temperatures as a way to predict fatigue and rutting distresses. Complex modulus master curves were developed to show the relationship between stiffness and frequency (time) of mixtures with RAS. It was found that the 25% RAP mixture with 5% RAS was stiffer with tear-off RAS than with manufactured RAS as well as almost no difference at the 3% RAS level. At the 15% RAP level, there was little difference between tear-off RAS and manufactured RAS at both 5% and 3% levels.

More recently, Zhou et al. (2013) continued the investigation on the way tear-off and manufactured RAS affects binder properties differently. As previously found, manufactured RAS has much less of an impact on the properties of virgin-RAS binders than tear-off RAS, indicating that for mix design purposes, it is necessary to differentiate between the two types of RAS and to set different limits on maximum RAS replacement for each type. Additionally, it was said that RAS binder should be limited to a maximum of 30% replacement, in order to still be able to apply the linear blending chart, which is used for estimating the high and low PG temperature grades of the RAS binder blend.

In a recent study, Abbas et al. (2013) evaluated the effect of RAS on the chemical and physical properties of asphalt binder. Blends were prepared using PG 58-28 and varying RAS percentages (0%, 5%, 7% and 10%) from post-manufactured asphalt shingles. Physical properties were evaluated using the Rotational viscometer (RV), dynamic shear rheometer (DSR), multiple stress creep recovery (MSCR), and bending beam rheometer (BBR) tests. The Fourier transform infrared spectrometry (FTIR) and gel-permeation chromatography (GPC) tests were used to evaluate the chemical properties of the blends. It was reported that at high temperatures, addition of RAS resulted in an increase in $|G^*|$ and a decrease in the phase angle, meaning that an increased resistance to permanent deformation is expected. In contrary to the majority of previous studies, at intermediate temperatures, the fatigue cracking parameter showed no change with the addition of RAS. At low temperatures, addition of RAS resulted in a higher stiffness values and lower m-values, indicating that the material became more susceptible to thermal cracking. An aging index (G^* ratio of aged and unaged asphalt binders) was used an indication of the aging tendency of a binder when exposed to high mixing temperatures and high service temperatures. From these results, it was concluded that an addition of RAS will primarily affect aging of the binder in its long term performance but it will not cause a significant change in the short-term (production stage or pavement's early life). Similar to previous studies, results from GPC test showed that blends with RAS contained a higher percentage of LMS (large molecular size) but found no trend with respect to SMS (small molecular size) or MMS (medium molecular size).

2.6 Performance of RAS Mixtures

Newcomb et al. (1993) performed one of the earliest studies on the effect of both tear-off and manufactured RAS on mixture properties. Samples were made using 5% and 7.5% shingles and then tested to address the following factors: 1. Temperature susceptibility, 2. Moisture sensitivity, 3. Low temperature behavior, and 4. Permanent deformation characteristics. A repeated diametric loading was used to determine the resilient modulus in order to evaluate the temperature susceptibility of each mixture. Results indicated that asphalt mixtures modified with manufactured RAS were less temperature susceptible. Similar results were found for mixtures containing tear-off RAS but to a lesser degree. In addition, stiffness of the mixtures was adversely decreased when RAS content exceeded 5%. To evaluate moisture sensitivity, the Lottman procedure was performed, which consists of a comparison between unconditioned resilient moduli and tensile strengths to values after the samples were conditioned. It was determined that manufactured RAS did not significantly change the moisture susceptibility of the samples. On the other hand, samples with tear-off RAS were found to have an increased susceptibility to moisture damage. An indirect tensile test was used to measure the mixtures resistance to low temperature cracking. The parameters of interest from this test included the tensile strength and tensile strain at peak stress. Samples prepared with tear-off RAS were found to have a decreased strain capacity with the increase in RAS content. Core samples were retrieved from project sites built with RAS modified HMA, then subjected to the same tests as the laboratory samples. It was found that field mixtures produced similar results as the laboratory mixes with respect to temperature susceptibility, moisture sensitivity, and low temperature cracking, even though field mixtures did show a higher tensile strength than any of the laboratory samples.

Johnson et al. (2010) investigated the effect of both tear-off and manufactured RAS on mixtures, which also contained varying amounts of RAP. Samples were prepared with RAP ranging from 10% to 25% and RAS up to 5%. Each mixture was produced to meet the following design requirements: 4% air voids, minimum 14% voids in the mineral aggregate (VMA), 65-78% voids filled with asphalt (VFA). Each mixture was tested using the dynamic modulus test, Asphalt Pavement Analyzer (APA) and the Lottman test in order to test for stiffness, rutting and susceptibility to moisture. Field evaluations were then conducted on in-service RAS/RAP pavements in the area in order to help verify the laboratory test results. Results from the dynamic modulus test indicated that mixes with tear-off RAS were stiffer than mixes with manufactured RAS. The biggest difference between both sources was most apparent at the 5% RAS level. The

APA test applied loads cycles equivalent to 1,000,000 ESALS. From these results, it was concluded that tear-off mixtures provided better resistance to rutting than manufactured mixtures. This finding agreed with the dynamic modulus test results in that tear-off shingles provided a stiffer mix, which results in a greater resistance against rutting.

The Lottman test, for moisture sensitivity, compared the splitting tensile test of a control to those of moisture conditioned mixtures. By comparing TSR, which is the ratio of wet strength to dry strength of each sample, it was found that manufactured RAS mixes had higher TSR values, which suggests that tear-off shingles might be more susceptible to moisture damage.

As previously noted and as a way to help verify laboratory results, field evaluations were conducted on experimental project sites, which had been constructed using both tear-off and manufactured RAS at quantities of 5% by total weight. The evaluation of these project sites was conducted using 500 ft. long monitoring stations. Each station was visually rated for cracking (transverse, longitudinal, and joint) and rutting. Results for each project varied, as is often the case for field evaluations. Some projects showed that pavements with tear-off RAS performed the best. Others, that RAS sections were very brittle in appearance, and developed substantial reflective cracking after experiencing its first winter. Even though field evaluations contain many variables, it was suggested that there was no substantial difference between performance of tear-off RAS pavements and manufactured RAS pavements.

Ozer et al. (2012) performed a study on the effect of RAS quantities on mechanical properties of asphalt mixtures, which contain high binder replacement levels (RAP and RAS). Mixtures were made using two asphalt binders: 1. PG 46-34 with 2.5%, 5% and 7.5% tear-off RAS and 2. PG 58-28 with 7.5% tear-off RAS only. In addition, Fractionated Recycled Asphalt Pavement (FRAP) was also added to all mixes, resulting in a total asphalt binder replacement level varying from 43% to 64% for different levels of RAS. The complex modulus test indicated that when RAS was increased, the modulus increased significantly, at both high temperatures and low loading speeds. In addition, the slopes of the master curves decreased, indicating a lower capability of relaxation with increments in RAS content. Mixtures were evaluated for permanent deformation resistance using the Hamburg Wheel Tracking Test (WTT). It was found that usage of RAS significantly improved resistance against rutting at high pavement temperatures.

Resistance to fracture at low temperatures (0°C and -12°C) was tested using the Semi Circular Bending Beam (SCB) and Disc Compaction Tension Test (DCT). Testing was done on RAS mixes and field cores retrieved from project sites shortly after construction and 1 year after construction. At the testing temperature of -12°C, no significant difference was found between lab-compacted mixes for any level of RAS. At 0°C testing, fracture energy of samples with 2.5% RAS was significantly higher than the rest. Samples with PG 46-34 binder were found to have higher fracture energy, indicating that a softer virgin binder aids in counteracting the effects of the RAS asphalt binder, which tends to be stiffer. Fatigue testing was done using both the Texas Transportation Institute Overlay Test (ITT) (to predict resistance against reflective cracking) and the Push-Pull Fatigue Test. Results from ITT, showed that mixes with PG 46-34 and 2.5% RAS provided the highest cycles to failure. Similar results were obtained from the Push-Pull test, which determined that samples with PG 46-34 and 2.5% RAS performed the best with respect to number of cycles to failure. From these results, Ozer et al. (2012) suggests using very soft binders when making mixes with high asphalt binder replacement levels, in order to obtain favorable pavement performance.

Williams et al. (2011) investigated the effect of adding 5% tear-off RAS into mixtures containing Fractionated Reclaimed Asphalt Pavement (FRAP) quantities ranging in between 25% and 50%. Two types of samples were tested, laboratory produced and field samples obtained from a field demonstration project conducted by the Illinois Tollway in the summer of 2009. The mixtures were tested for dynamic modulus, flow number, tensile strength ratio, beam fatigue, and disc compaction tension test (DCT). It was found that at lower percentages of FRAP, RAS seemed to have the most influence on the high temperature properties of the mixture. With respect to rutting resistance, mixtures with more than 40% recycled materials (35% FRAP and 5% RAS) showed no significant improvement. The flow number test results showed that the mixture with 25% RAP and no RAS, had the greatest strain accumulation and consequently the least resistance to rutting. It was noted that when 5% FRAP was replaced with RAS, the strain accumulation significantly decreased. Based on the fatigue test results, it was concluded that using RAP and RAS at the percentages tested, did not negatively affect the fatigue cracking resistance. The Tensile Strength Ratios (TSR) showed no correlation between amount of recycled material and TSR values, so it was suggested that mixes which use the same quantities of RAS and RAP as the mixtures which were tested, would be result in a durable pavement even if subjected to a freeze-thaw environment. It was concluded that mixtures containing 35% RAP , 5% RAS and produced with a PG 58-22 binder may result in pavement with a favorable level of crack resistance, while pavements with more than 40% recycled material may be much more prone to cracking.

More recently, Williams et al. (2013) conducted testing on the field performance of HMA with RAS. The study, which consisted in collecting representative samples from field projects in seven states, aimed at investigating a variety of different factors of asphalt mixes containing RAS. Among these, the difference between fine grind RAS and coarse grind RAS, effect of different RAS percentages, difference between post-manufacturer and post-consumer RAS, and the performance difference between laboratory and plant produced RAS mixes. Testing included dynamic modulus, flow number, four point bending, and SCB test. Results from the dynamic modulus test and flow number test indicated that, for all projects, addition of RAS improved resistance against rutting. Pavement condition surveys also confirmed this finding, since no measurable amount of wheel path deformation was found in the corresponding pavements. Mixes containing RAS from four out of six states showed slightly higher resistance to fatigue cracking, tested using the four point bending beam test. Overall, it was suggested that mixes with RAS should perform as well as HMA without RAS, with respect to fatigue performance. The low temperature fracture energy, from the SCB test results, was compared from each project to evaluate resistance against fracture. The only statistical difference found between fracture energies, corresponded to a mix with 0% RAS, which had a statistically lower fracture energy than a mix with 4% RAS. Taking into account all results, it was concluded that mixes containing RAS have the same resistance to fracture than mixes without RAS, in other words, addition of RAS does not have a negative effect in HMA with regard to fracture resistance.

Where most studies focus on the use of RAS at low percentages (2.5 to 5%), Ozer et al. (2013) evaluated the effects of higher asphalt binder replacement (up to 7.5% RAS) on a mixtures properties. The experimental program consisted of testing laboratory mixed specimen and field cores for fracture, fatigue, modulus, and permanent deformation. With respect to the complex modulus test, results showed that RAS influenced the value of the complex modulus, mainly at high temperature/low frequency. When comparing the complex modulus for the mixtures, as the RAS percentage increased, the modulus increased as well. However, when comparing the modulus at low temperatures/high frequencies, there was no clear difference between mixes with varying percentages of RAS. By evaluating the slopes of the complex modulus master curves, the relaxation potential of the mixes were assessed. Mixes with 7.5% RAS and the highest PG grade (PG 58-28) showed the lowest slope, indicating small relaxation potential, and mixes with 2.5% RAS and the lowest PG grade (PG 46-34) showed the highest slope, indicating the highest relaxation potential. These findings reiterated the importance of choosing soft binders when working with RAS. As multiple studies concluded before, results from the wheel track test showed an increase in permanent deformation resistance with an increase in RAS. Results from SCB testing (fracture energy values) showed no statistical difference between mixes with varying RAS percentages at -12°C, but a difference was evident when tested at 0°C, since specimen with 2.5% RAS had significantly higher fracture energy than the rest of the samples. The effect of using a binder with lower PG grade was also visible since it caused an increase in fracture energy.

2.7 Current Practice of RAS Usage

AASHTO has developed specification MP 15-09, which allows both tear-off and manufactured RAS to be included in HMA as an additive. In addition, AASHTO included recommendations for usage of RAS in order to provide additional guidance for designing pavements containing recycled material (McGraw et al., 2007).

Important specifications included in the AASHTO standard include:

1. Final RAS product must be sized and screened such that 100 percent passes a 0.5-in sieve screen.
2. The mixture of HMA and RAS should satisfy gradation and volumetric specifications mentioned in M 323.
3. The maximum addition of RAS is left as an option to the contractor. This maximum quantity allowed, varies from state to state. Table 4-2 provides a summary of how much RAS is allowed by some states.
4. If the quantity of RAS recycled binder exceeds 75% by weight of the total HMA mix (both recycled and virgin binder). The combination of the two binders needs to be

evaluated through performance grading to ensure that the final blend complies with the specified grade requirements.

5. A limit is set on the amount of deleterious material allowed in the RAS. Materials such as wood, plastic and paper should be less than 1.5% by weight, with the others less than 3% retained on sieve No. 4.

AASHTO PP 53-09 provides additional guidance on designing HMA pavement with RAS. Specific guidance includes: design considerations, determining shingle aggregate gradation, how to determine the performance grade (PG) and percentage of the virgin asphalt binder, and how to estimate the contribution of the shingle asphalt binder to the final blended binder. To estimate the contribution of RAS binder to the final blended binder, AASHTO PP 53-09 uses

$$F_c = \frac{P_{bv} - P_{bvr}}{P_{sr} P_{br}} \tag{4-1}$$

and

$$\Delta = P_{bv} - P_{bvr}, \tag{4-2}$$

where F_c is the estimated factor of shingle asphalt availability in percentage, P_{bv} is the binder content of a mix without RAS in percentage, P_{bvr} is the binder content of same mix with RAS in percentage, P_{sr} is the amount of RAS used in mix in percentage, P_{br} is the percentage of shingle asphalt in RAS, and Δ is the amount of shingle asphalt working as binder in blended binder.

The quantity, Δ, is calculated after performing two mix designs, one with RAS and another without. A positive value of Δ indicated that RAS contributes to the asphalt content of the mix. In contrast, a negative value indicates that RAS material is absorbing virgin asphalt, so additional virgin asphalt should be added (Salari, 2012). The shingle asphalt availability factor is calculated as

$$F = \frac{1+F_c}{2}, \tag{4-3}$$

while the quantity of shingle asphalt calculated to be active in the final blend is given as

$$P_{brf} = \frac{F P_{sr} P_{br}}{P_{bbf}}, \tag{4-4}$$

where P_{brf} is the percentage of shingle asphalt in total blend and P_{bbf} is the amount of total binder blend in mix with RAS.

The PG grade of the virgin binder is required in order for the blend of RAS asphalt and virgin asphalt meet the desired performance grade. This PG grade can be calculated in terms of critical temperatures as follows

$$T_{bv} = T_{br} - \frac{T_{br} - T_{bbf}}{1 - P_{brf}}, \quad (4\text{-}5)$$

where T_{bv} is the critical temperature of virgin asphalt (°C), T_{br} is the critical temperature of shingle asphalt (°C), T_{bbf} is the desired critical temperature of blend (°C), and T_{brf} is the percent of shingle asphalt in total blend.

As previously mentioned, AASHTO guidelines leave it up the contractor to decide the maximum allowed quantity of RAS to be included in HMA pavements. Table 2-2 provides a summary of states, which allow usage of RAS in HMA pavement (Construction Materials Recycling Association, 2013).

Table 2-2: Maximum percentage by total weight of allowable RAS per state

State	Tear-off (%)	Manufactured (%)
Alabama	3	5
Missouri	7	7
South Carolina	3-8	3-8
Texas	5	5
Florida	n/a	5
Georgia	n/a	5
Indiana	n/a	5
Maryland	n/a	5
Michigan	n/a	5
New Jersey	n/a	5
North Carolina	n/a	5
Pennsylvania	n/a	5

2.8 Summary

The increasing cost of asphalt cement in the past 40 years has led to investigate new methods to reduce the amount of virgin binder required to produce HMA pavements without negatively affecting pavement performance. In this chapter, we have reviewed the role of RAS as one possible solution to decrease the amount of required virgin binder. The “dry" method, which consists of treating RAS like aggregate, was found to be the most common method of incorporating the RAS into the HMA mix. A new “wet” method, which consists of combining finely ground RAS with virgin binder at high temperatures, is a recent approach, which has produced promising results and may be used for incorporating RAS into asphalt mixtures.

It is noted that the majority of DOT's attempt to incorporate both RAP and RAS simultaneously into their HMA mixes; consequently, most studies evaluated the rheological properties of asphalt modified with recycled binder from both RAP and RAS. The majority of studies conclude that the asphalt recovered from both sources is highly oxidized and has a stiffening effect on the overall mix. To overcome this, the two most common solutions given were to use a soft conventional binder for mixing or to reduce the binder replacement ratio. In addition, even though there is a much greater amount of tear-off RAS available, most DOT's seem to prefer usage of manufactured shingle scrap. This is most likely due to findings, which indicate that at ratios of 5% or greater, tear-off RAS stiffens the mix considerably, which is desirable for rutting but not for low temperature cracking.

Performance of RAS mixtures subjected to mechanistic testing has been mixed. Most studies concluded that the use of 5% to 7% RAS improved resistance to rutting at high temperatures but some studies found that mixtures with more than 40% recycled material (35% RAP and 5% RAS) showed no significant improvement. The most common concern about HMA mixes modified with RAS is susceptibility to low temperature cracking. Most findings indicate that a mixture's strain capacity at low temperatures is decreased, with the increase in RAS content. Furthermore, it is suggested that pavements with more than 40% recycled material may be much more prone to low temperature cracking.

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3 LABORATORY EVALUATION OF ASPHALT MIXTURES WITH RECLAIMED ASPHALT SHINGLE PREPARED USING THE WET PROCESS[1]

3.1 Abstract

The objective of this study is to conduct a laboratory evaluation of asphalt mixtures containing RAS prepared using the newly-developed wet process. In the proposed wet process, RAS material is blended with the binder at high temperature prior to mixing with the aggregates. The proposed wet process offers the potential to better control the Superpave Performance Grade (PG) of the binder blend, to stimulate chemical and physical interactions taking place in the blend between asphalt binder in shingles and virgin asphalt binder in the mix, and to reduce maintenance issues at the plant due to the high content of fines and fibers in RAS. To achieve this objective, asphalt binder blends were prepared using the wet process and an asphalt mixture with a nominal maximum aggregate size (NMAS) of 12.5mm was designed according to the Superpave design protocol. The mechanistic properties of asphalt mixtures containing RAS materials were evaluated as compared to conventional asphalt mixtures. Laboratory testing evaluated the rutting performance, fracture performance, and low temperature resistance of the produced mixtures using the Hamburg Loaded-Wheel Tester (LWT), the Semi-Circular Bending (SCB) test, and the Thermal Stress Restrained Specimen Test (TSRST). Based on the results of the experimental program, it was determined that the use of RAS through the wet process allows the reduction of the virgin binder content with no adverse effects on the laboratory performance of the mixture as compared to the conventional mixture with no RAS. Results also indicated that the blending of RAS directly with its regular processed size at the recycling plant with no additional processing in the wet process is feasible with no foreseen adverse effects on the mixture performance. However, it is recommended that the RAS be processed to the finest processing size possible at the recycling facility to stimulate chemical and physical interaction between recycled and virgin materials. Based on these results, additional work is needed to

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[1] This chapter previously appeared as Alvergue, A., M.A. Elseifi, L.N. Mohammad, S.B. Cooper, and S. Cooper III, *Laboratory Evaluation of Asphalt Mixtures with Reclaimed Asphalt Shingle Prepared Using the Wet Process*, Journal of the Association of Asphalt Paving Technologists, 2014 (in press). It is reprinted by permission of Association of Asphalt Paving Technologists.

simulate plant operations using the newly-developed wet process. Further, research is needed on the shingle asphalt binder availability factor and its variation for the dry and wet recycling processes.

3.2 Introduction

In recent years, considerable attention has been given to using recycled asphalt shingles (RAS) in asphalt pavement construction. The Environmental Protection Agency (EPA) estimates that 170 million tons of construction and demolition (C&D) debris is generated every year with asphalt shingles making up to 15% of this waste (1). Recycling of asphalt shingles in asphalt paving mixtures is a promising approach for technical, economical, and environmental reasons. From an economic perspective, the use of RAS reduces the consumption of asphalt binder, a petroleum-based product, eases the disposal cost of shingle waste in landfills; and reduces energy consumption during processing and manufacturing of virgin materials. The disposal fee of waste shingles in landfills can reach $90 to $100 per ton in the neighborhoods of large cities (2) and even up to $200 or higher in select California metropolitan areas. From an environmental perspective, the use of RAS reduces emissions of harmful by-products during processing and manufacturing of virgin materials, reduces consumption of virgin materials, and diminishes consternation of the public over emissions.

Recycling of scrap shingles in asphalt mixtures is not new and has been considered since the late 1980s (3). However, with the recent significant rise in asphalt binder prices, interest has peaked during the past 5 years. RAS originates from two main sources: 10 million tons of asphalt shingles come from C&D debris (tear-off scrap shingles [TOSS]) and one million tons originates from asphalt shingle manufacturers (manufacturing shingle waste [MSW]. Over 1.2 million tons of RAS was used in HMA in 2010 by 15 states agencies, which currently allow its use in asphalt paving construction. Currently, around 15 states allow RAS content in asphalt mixes ranging from 2 to 7.5% using a dry blending process in which RAS is added similar to Reclaimed Asphalt Pavement (RAP).

Current practices implemented in the recycling of asphalt shingles consist of dry blending RAS with the aggregates before the asphalt binder is added to the batch similar to RAP. State highway agencies allow the reduction of virgin asphalt binder in the mix by the percentage of asphalt binder that is assumed to be released from RAS and is expected to blend with the virgin asphalt binder. AASHTO PP 53-09 estimates the contribution of RAS to the overall asphalt binder in the mixture by calculating an availability factor (F_c) (4). However, research studies have reported that the air-blown asphalt binder used in RAS is very stiff and aged and may inadequately blend with the virgin asphalt binder during HMA production (5).

In 2010, Elseifi and co-workers introduced a new approach to recycle asphalt shingles in asphalt paving construction in which RAS is ground to ultra-fine particle sizes (more than 80% passing sieve No. 200 (0.075 mm)) and blended with asphalt binder through a wet process (5). In the proposed wet process, the ground recycled material is blended with the binder at high temperature prior to mixing with the aggregates. The proposed wet process offers the potential to better control the Superpave Performance Grade (PG) of the binder blend, to stimulate chemical and physical interactions taking place in the blend between asphalt binder in shingles and virgin asphalt binder in the mix, and to reduce maintenance issues at the plant due to the high content of fines and fibers in RAS. The idea behind the proposed method was motivated by the successful recycling of scrap tires in HMA using a wet process to create what is commonly known as Asphalt Rubber (AR) or Crumb Rubber Modifier (CRM). The use of RAS through the proposed wet process is expected to act as a partial binder replacement but also as a binder extender due to the presence of fillers, rubber, and fibers in the processed RAS material.

3.3 Objective and Scope

The objective of this study is to conduct a laboratory evaluation of asphalt mixtures containing RAS prepared using the newly-developed wet process. To achieve this objective, asphalt binder blends were prepared using the wet process and an asphalt mixture with nominal maximum aggregate size (NMAS) of 12.5mm was designed according to the Superpave design protocol. A suite of laboratory tests was conducted to capture the mechanistic behaviors of asphalt mixtures against major distresses and to compare it to the control mixture prepared with virgin materials. Laboratory testing evaluated the rutting performance, fracture resistance, and thermal cracking resistance of the produced mixtures using the Hamburg Loaded-Wheel Tester (LWT), the Semi-Circular Bending (SCB) test, and the Thermal Stress Restraining Specimen Test (TSRST), respectively.

3.4 Background

Asphalt shingles are the most popular roofing materials in the US making up to two-thirds of the residential roofing market (1). They are manufactured as two main types (6): organic and fiberglass. Organic shingles are composed of 30 to 35% asphalt, 5 to 15% mineral fiber, and 30 to 50% mineral and ceramic-coated granules with their market share diminishing over time since the introduction of fiberglass shingles. Fiberglass shingles are the most popular type because of their lower asphalt contents and thus lower cost. Fiberglass shingles consist of 15 to 20% asphalt, 5 to 15% felt, 15 to 20% mineral filler, and 30 to 50% mineral and ceramic-coated granules. While fiber glass shingles have a fiberglass reinforcing backing that is coated with asphalt and mineral fillers, organic shingles have a cellulose-felt base made with paper.

Asphalt binder content (AC) for different RAS sources sampled from recycling centers around the country was measured according to AASHTO T 164-11 – Test Method B (7). As shown in Figure 3-1, AC content in TOSS ranged from 24% to 31% with an average content of 26.6% and a coefficient of variation (COV) of 8.9%. Results show that the AC content in the virgin shingle source (SHIN) was 20.4%, which matched closely to the content provided by the shingle manufacturer. The noticeably lower AC content in the virgin shingle source as compared to the RAS from TOSS was expected because shingles lose surface granules during service, and therefore, have higher AC content than virgin shingles.

A recent study synthesized the best practices for the use of RAS in HMA in terms of RAS processing, characterizing the processed RAS (binder content, gradations, and performance grade [PG]), RAS mix design, production, and field construction (8). Processing of scrap shingles for use in HMA consists of five main steps: (1) Collecting of RAS and ensure that the recycled material is of high quality; (2) Asbestos testing for TOSS. The EPA does not allow any asbestos containing materials, greater than 1% asbestos, to be used in roadway construction. Asbestos testing is occasionally conducted during recycling and processing of TOSS based on the Polarized Light Microscopy (PLM) method, which can detect an asbestos content of 1%; (3) Sorting for TOSS, to remove various debris such as nails, wood, and insulation; (4) Grinding, in which RAS is processed to be ground to a uniform particle size ranging from 2.35 to 12.5 mm;

(5) Screening, in which oversized pieces are removed to ensure uniform gradation of the RAS material.

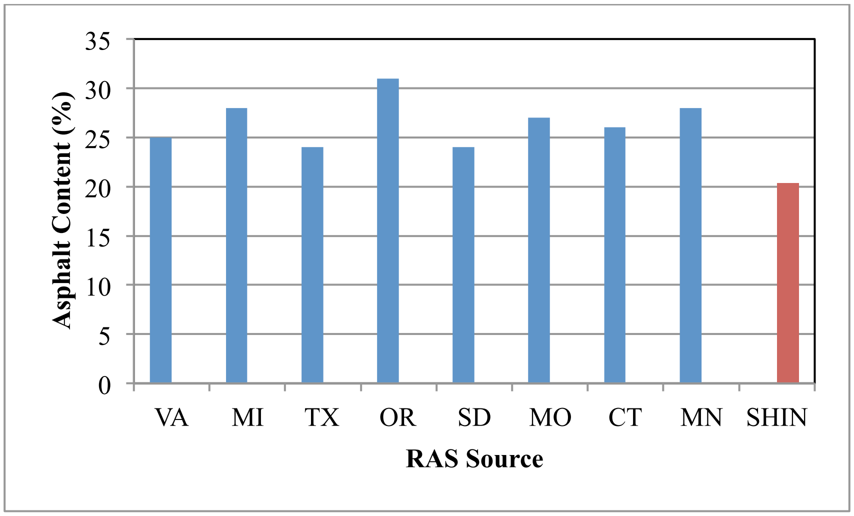


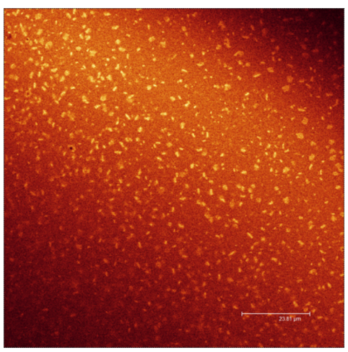
Figure 3-1: Variation of AC content in RAS sources (7)

3.4.1 Asphalt Binder in RAS

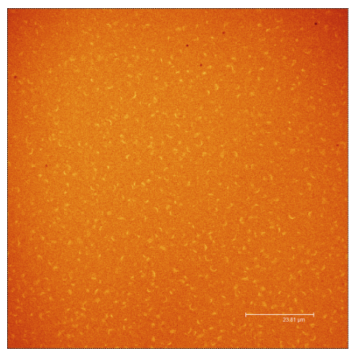
Air blown asphalt is typically used in the manufacturing of asphalt shingles; this type of asphalt binder has a greater viscosity than conventional asphalt binder used in HMA. A recent study measured rheological properties of the extracted RAS binders as well as their final PG based on laboratory testing (5, 9). Binders in RAS were very stiff and brittle and could not be graded at low temperatures even when tested at 0°C (5). In addition, the extracted binders were too stiff at 135°C for testing using the rotational viscometer. This stiff behavior was expected as the binder used in shingle manufacturing and present in RAS materials is an air-blown asphalt binder with stiff characteristics and low elongation properties. RAS binders extracted from different recycling centers around the country were graded as PG 118 + - xx using the Superpave binder specification system.

This study also used Confocal Laser-Scanning Microscopy (CLSM) in a fluorescence mode to analyze the microstructure of virgin shingle binder as compared to neat asphalt binder used in road construction (5). Figure 2 presents a comparison between the images of PG 52-28 pure binder and the air-blown asphalt binder (SHIN) used in the manufacturing of shingles. As shown in these images, a continuous phase is observed, in which the wax crystals (light-colored particles) are dispersed. The size of the wax particles ranged from 4 to 8 microns with a flake shape, which is in agreement with the findings of past research (10). The size and relative concentration of wax crystals were greater in the air-blown asphalt binder than in the PG 52-28 binder, Figure 5-2. The concentration and morphology of wax particles is believed to have an impact on the binder performance (10). Therefore, the higher concentration of wax crystals in the air-blown asphalt may cause this binder to be stiffer and more brittle than the soft PG 52-28 binder, which showed lower concentration of wax molecules.

Research work in TFP-5 (213) has shown that field mixtures with the base asphalt binder grades for requisite locations and RAS can yield different performances (11). For example, a mix consisting of a virgin asphalt binder grade of PG 58-28 with 5% RAS in northern Iowa can have different performance than a mix with a PG 64-22 with 3% to 5% RAS in the southern portions of the Midwest (Indiana and Missouri).



(a) SHIN



(b) 52-28

Figure 5-2: CLSM Images of (a) Pure Air-Blown Asphalt Binder and (b) Pure Asphalt Binder (52-28) (5)

3.4.2 Performance of Asphalt Mixtures with RAS

While the use of RAS in asphalt mixture is expected to provide economic benefits to the asphalt industry, research results on the performance of HMA with RAS have been mixed. The main difference between HMA with RAP and RAS is that the binder used in RAS is an air blown asphalt, which has stiff characteristics and low elongation properties, and the binder content of RAS is ~5 times more than that in RAP. Button et al. (1996) evaluated the influence of adding 5 to 10% of asphalt shingles on the mechanical properties of asphalt mixtures as compared to untreated mixes (12). The use of RAS resulted in a decreased tensile strength and creep stiffness of the mixture but it improved the mix resistance to moisture damage (probably due to the higher mixing temperatures). Zhou et al. (2012), using the TTI Overlay Tester, predicted that HMA with RAS will exhibit poor cracking resistance (8).

Maupin (2010) evaluated the use of RAS in the production of HMA and WMA in Virginia (13). In total, five mixes (three surface mixes and two base mixes) were produced and installed by three asphalt contractors. Both mixes were sampled during production, and their performance was evaluated in the laboratory. RAS content ranged from 4 to 5%; however, one surface mix was produced with 18% RAP and 2% RAS. Laboratory testing included volumetrics, rut testing using an Asphalt Pavement Analyzer (APA), fatigue using a four-point flexural beam test, and grading of the binder recovered through extraction. Results of rut testing indicated that the mixes would perform satisfactorily on high traffic conditions. Similarly, the mixes were expected to perform satisfactorily against fatigue failure. Testing of the recovered binders showed that the high-temperature grade of the binder was increased due to RAS by one to three grades and that the low-temperature grade deteriorated one grade on five of the six mixtures.

Johnson et al. (2010) studied the effects of RAP and RAS on the HMA mixture properties. A matrix of laboratory-produced mixtures that incorporated RAS, which included both TOSS and MSW, was tested for both asphalt binder and mixture properties at high and low temperatures (14). Stripping and thermal cracking tests were performed on laboratory and field specimens. They conducted field performance survey of RAS/RAP mixtures used in Minnesota was also conducted to supplement laboratory evaluation. Binder extraction and performance grading (PG) of RAS/RAP HMA mixtures showed a strong correlation between the virgin binder content and the high and low PG temperatures. Mixture testing showed a correlation between virgin binder content and dynamic modulus values at a high test temperature. These results provide justification for the current 70% minimum virgin binder criterion. Mixture and binder testing indicated that increasing RAP in RAS mixtures increased the total stiffness of the mixture. The asphalt binder contained in TOSS is typically stiffer than that contained in MSW; however, the age of the processed RAS needs to be considered. Decreasing the shingle content to 3% minimized the differences between MSW and TOSS. Plant-produced mixtures were found to have lower modulus values than comparable lab-produced mixtures. The authors recommended a new mix design procedure that more closely simulates plant production of RAP/RAS mixtures should be developed, including investigation of using softer binder or softening agents to allow more recycled materials to be used in RAP/RAS mixes.

You et al. (2011) evaluated the effect of a WMA additive (Sasobit), RAS, RAP, and Bio-asphalt on the low-temperature properties of asphalt binders containing varying percentages of these environmentally friendly additives as estimated by the bending beam rheometer (BBR) stiffness and the asphalt binder cracking device (ABCD) tests (15). Two levels of RAS concentrations (5% and 10% by weight of the virgin asphalt binder) in a typical Michigan asphalt binder (PG 52-34) were evaluated. The BBR stiffness results at -34ºC showed higher stiffness for the binder with the higher RAS content, but less than the 300-MPa Superpave criterion indicating that the addition of RAS up to 10% would not harm the low-temperature performance of asphalt pavement. On the other hand, the ABCD cracking temperature results showed the binder with 10% RAS cracked at -41.0ºC, which is much warmer than the cracking temperature of the binder with 5% RAS at -47.8ºC.

3.5 Experimental Program

3.5.1 Proposed Wet Process

Conventional practices of dry blending tear-off asphalt shingles with the aggregates before asphalt binder is added to the batch are often criticized due to the variability observed in the asphalt content of RAS and the unknown final PG grade of the binder. A new approach was introduced to recycle asphalt shingles in asphalt paving construction in which RAS is ground to ultra-fine particle sizes and blended with asphalt binder at high temperature and shear through a wet process (5). During HMA production, the binder blend (virgin binder + ultra-fine RAS) would be added to the dry aggregates at high temperature similar to conventional production. The proposed wet process for recycling asphalt shingle consists of the following four main steps:

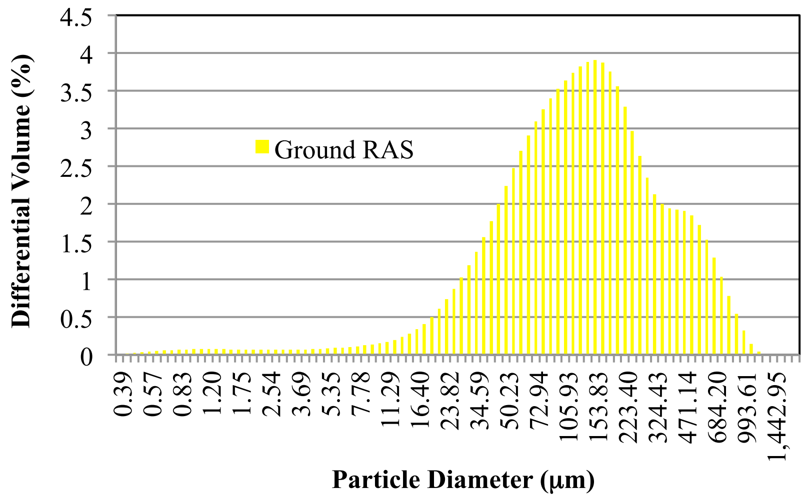
- **Step 1:** Remove non-shingle debris from the recycled material;
- **Step 2:** Ground RAS to a uniform particle size such that 80% passes sieve No. 200;

- **Step 3:** Blend ground RAS with virgin asphalt binder at a mixing temperature from 180 to 200°C for 30 minutes and with continuous mechanical agitation; and
- **Step 4:** Use RAS-modified asphalt binder in production of HMA.

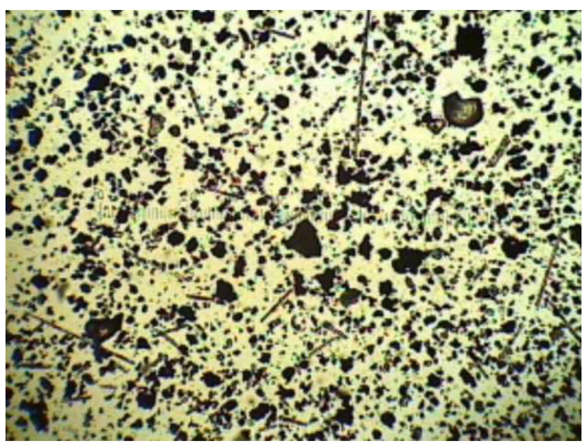
While the original process recommended grinding the RAS to ultra-fine particle size (Step 2), the present study also considered blending the RAS directly with its regular processed size at the recycling plant with no additional processing. This modification was made upon discussion with practitioners in order to improve the cost-effectiveness of the wet process as compared to the currently-used dry method. Asphalt blends were prepared using two sources of RAS materials. These sources of RAS were sampled from C&D processing plants and consisted of tear off shingles from Illinois and from Texas. While the RAS from Illinois was used directly in blend preparation without grinding (92% passing No. 8 - 2.35 mm); the RAS from Texas was ground to ultra-fine particle sizes. RAS materials were ground to an ultra-fine particle size distribution at room temperature using a Pulva-Sizer® hammer mill. The utilized milling machine was equipped with a rotor assembly and hammers running at a high rotational speed of 9,600 rpm. Figure 5-3 compares RAS materials prior to and after grinding.

Figure 5-3: RAS Materials before and after Grinding

The particle size distribution of the ground RAS was characterized using laser diffraction. The ground RAS was analyzed using a Beckman Coulter Particle Size Analyzer (LS13 320) operated on a wet mode. Approximately 1g of ground RAS was wetted with 26 drops of a solution of glycerol and water followed by 20 sec of bath sonication. Results of the particle size analysis using laser diffraction are presented in Figure 5-4a for the ground RAS materials. As shown in this figure, the mean particle sizes were 201.0 μm with a standard deviation approximately equal to the mean of the distribution indicating that the particle size distribution is heavily weighted far from the mean. As more practice is gained with the grinding process, it is expected that the ground shingle size would be more uniform with more than 80% passing sieve No. 200 (0.075 mm). Microscopic details of the ground shingles are presented in Figure 5-4b.



(a)



(b)

Figure 5-4: (a) Laser Diffraction Particle Size Analysis for the Ground RAS and (b) Microscopic Details of RAS after Grinding (26.6 µm per division)

Rheological properties and stability of the prepared asphalt blends were evaluated (5). A polymer-modified binder that is classified as PG 70-22 was blended with the ground RAS materials at a modification content ranging from 10 to 40% by weight of the binder. The blends were prepared by mixing 500 g of asphalt binder with the corresponding content of RAS at a mixing temperature of 180°C using a mechanical shear mixer rotating at a speed of 1500 rpm for 30 minutes. The mixing temperature, blending time, and shear rate speed were selected by trying different blending conditions until a homogeneous blend was obtained (5). Based on the results of the experimental program, the proposed wet process would generally improve or not influence the high temperature grade of the binder but it may reduce the low temperature grade of the binder especially at high RAS contents. Table 5-1 presents the Superpave PG grading of the blends utilized in the present study, which are the blends prepared at a RAS content of 20% by weight of the binder. As shown in this table, the high temperature grade of the binder was increased by one for both RAS sources and the low temperature grade was decreased by one grade in case of the Illinois RAS source, which was used with its regular processed size.

Table 5-1: Superpave PG Testing of the Binder Blends

Binder Testing	Spec	Test Temp	PG 70-22	PG 70 +20%Texas	PG 70 +20%Illinois
Test on Original Binder					
Dynamic Shear, G*/Sin(δ), (kPa), AASHTO T315	1.00^{+}	70°C	1.46	2.60	2.96
	1.00^{+}	76°C	0.769	1.36	1.60
Tests on RTFO					
Dynamic Shear, G*/Sin(δ), (kPa), AASHTO T315	2.20^{+}	70°C	3.21	5.65	6.21
	2.20^{+}	76°C	1.64	2.83	3.17
Tests on (RTFO+ PAV)					
Dynamic Shear, G*Sin(δ), (kPa), AASHTO T315	5000^{-}	28°C	2750	4050	4245
BBR Creep Stiffness, (MPa), AASHTO T313	300^{-}	-6°C	81.8	117	109
		-12°C	188	196.7	209
Bending Beam m-value AASHTO T313	0.300^{+}	-6°C	0.377	0.345	0.341
		-12°C	0.319	.305	0.297
Actual PG Grading			**PG 70-22**	**PG 76-22**	**PG 76-16**

The compatibility and stability of the prepared blends were evaluated using the cigar tube test (ASTM D 7173-05) for the blends prepared with the ground RAS materials. The cigar-tube test showed that the use of a RAS content of 20% or less was acceptable with levels of separation less than 20%. At high RAS content of 40%, stability and workability of the blends will not be favorable given the high level of separation. Based on these results, a 20% RAS content was selected in preparation of the asphalt mixes in this study.

3.5.2 Asphalt Mixture Design

Table 5-2 presents a description of the prepared asphalt mixtures. All the mixtures evaluated in this study consisted of the same mix design. A 12.5 mm Superpave mixture meeting LADOTD specifications ($N_{initial}$ = 8-, N_{design} = 100-, N_{final} = 160-gyrations), was designed according to AASHTO R 35, "Standard Practice for Designing Superpave HMA" and Section 502 of the 2006 Louisiana Standard Specifications for Roads and Bridges (16). It is worth noting that the RAS content is expressed by weight of the binder in the wet process while it is expressed by weight of the mix in the dry process.

Table 5-2: Description of the Evaluated Mixes

Mixture Abbreviation	Description
64CO	Conventional 12.5mm HMA mixture with PG 64-22
70CO	Conventional 12.5mm HMA mixture with polymer-modified PG 70-22M
70WI	HMA mixture with PG 70-22M HMA containing 20% RAS[1] from Illinois without grinding using the wet process
70WT	HMA mixture with PG 70-22M HMA containing 20% RAS[1] from Texas ground to ultra-fine particle size using the wet process
70DT	HMA mixture with PG 70-22M HMA containing 5% RAS[2] from Texas prepared using the dry blending process

[1] by weight of the binder; [2] by weight of the mix

As shown in Table 5-3, the optimum asphalt binder content was determined based on volumetric (VTM = 2.5 - 4.5 percent, VMA ≥ 12%, VFA = 68% -78%) and densification (%G_{mm} at $N_{initial}$ ≤ 89, %G_{mm} at N_{final} ≤ 98) requirements. Gravel and granite aggregates and coarse natural sand were used in mix preparation. Gradation of the RAS material used in the binder blend was measured and was used in adjusting the gradation of the composite blend. Similarly, the binder content in the RAS was measured and was used in adjusting the total asphalt content in the mixture. The AC content was determined to be 28.6% and 27.2% in the Texas and Illinois RAS sources, respectively. When the wet process is used and since the RAS is blended with the virgin binder at high temperature and high shear rate, it is assumed that the total asphalt content in the RAS will actively contribute to the mix. In this study, the performance of two mixtures containing RAS prepared using the wet process was compared to a control mix with 0% RAS (70CO prepared with polymer-modified PG 70-22M) and a mix prepared with 5% RAS using the dry blending process (70DT).

For the mixture containing the RAS from Illinois and prepared using the wet process (70WI), the virgin binder content was reduced from 5.3% to 4.6% by total weight of mix. This represents an 8.0% reduction in virgin asphalt binder content as compared to the conventional mixture 70CO. For the mixture containing the RAS from Texas and prepared using the wet process (70WT), the virgin binder content was reduced from 5.3% to 4.8% by total weight of the mix. This represents a 7.7% reduction in virgin asphalt binder content as compared to the conventional mixture 70CO. For the mixture containing 5% RAS and using the dry blending process, the virgin binder content was reduced from 5.3% to 4.8%, representing a 9.4% reduction in virgin asphalt binder content and an availability factor of 35.7% as defined in AASHTO PP53-09 (4). Results shown in Table 3 also show a slight reduction in the total AC in the mixes prepared with the wet process to achieve the required volumetrics (from 5.3% to 5.2% and 5.0%). This may be due that when the wet process is used; the RAS material is expected to act as a partial binder replacement but also as a binder extender due to the presence of fillers, rubber, and fibers in the processed RAS material.

Table 5-3: Mix Designs of the Asphalt Mixtures

Mix ID / Parameter	70CO	70DT	70WI	70WT
% G_{mm} at N_{ini}	88.8	88.9	88.9	88.2
% G_{mm} at N_{max}	97.0	96.9	97.1	96.9
Air Voids %	4.0	4.0	4.0	4.0
VMA %	13.3	14.0	14.0	13.5
VFA %	70	71	73	78
Total %AC	5.3	5.3	5.0	5.2
%AC (Virgin)	5.3	4.8	4.6	4.8
Gradation – Sieve Size (mm)				
19.0	100	100	100	100
12.5	97	97	97	97
9.5	85	86	85	85
4.75	63	64	63	63
2.36	44	45	44	44
1.18	32	32	31	32
0.600	24	24	23	24
0.300	17	17	17	17
0.150	8	9	8	8
0.075	5.3	5.2	5.4	5.4
Binder Replacement (%)	N/A	9.4	8.0	7.7

3.5.3 Laboratory Testing

Laboratory performance testing evaluated the rutting performance, fracture resistance, and thermal cracking resistance of the prepared asphalt mixtures using the Hamburg LWT, SCB test, and TSRST. Table 5-4 presents the test factorial conducted for the four mixtures evaluated in this study and the number of specimens tested. Triplicate specimens were considered for each test except for the LWT where two specimens were tested. All specimens were compacted to an air void level of 7 ± 1%. Results of the tests presented in Table 5-4 had a coefficient of variation that was less than 15%. Mixture aging for SCB test and TSRST was performed according to AASHTO R30-02 (2010) by placing compacted specimens in a forced draft oven for five days at 85°C. A brief description of each of the test methods considered in the experimental program is presented.

Table 5-4: Experimental Test Factorial

Mixture Variables	**LWT**	**TSRST**	**SCB**
Mixture ID	Unaged	Aged	Aged
64CO	2	3	3
70CO	2	3	3
70DT	2	3	3
70WI	2	3	3
70WT	2	3	3

3.5.4 Loaded Wheel Tracking (LWT) Test

Rutting performance of the mix was assessed using a Hamburg-type Loaded Wheel Tester (LWT), manufactured by PMW, Inc. of Salina, Kansas. This test was conducted in accordance with AASHTO T 324, “Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)." This test is considered a torture test that produces damage by rolling a 703 N (158 lb.) steel wheel across the surface of a slab that is submerged in 50°C water for 20,000 passes at 56 passes a minute. A maximum allowable rut depth of 6 mm at 20,000 passes at 50ºC was used. The rut depth at 20,000 cycles was measured and used in the analysis (17).

3.5.5 Semi-Circular Bending (SCB) Test

Fracture resistance potential was assessed using the semi-circular bending (SCB) approach proposed by Wu *et al.* (18). This test characterizes the fracture resistance of HMA mixtures based on fracture mechanics principals, the critical strain energy release rate, also called the critical value of J-integral, or J_c. Figure 5-5 presents the three-point bend load configuration and typical test result outputs from the SCB test.

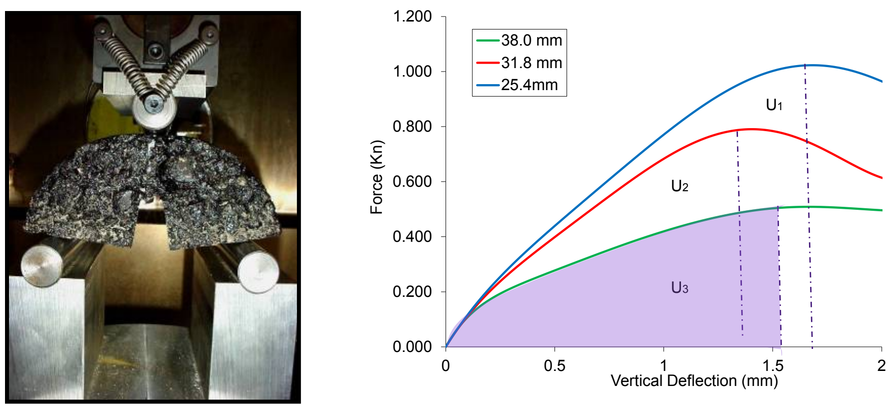


Figure 5-5: The Semi-Circular Bending Test

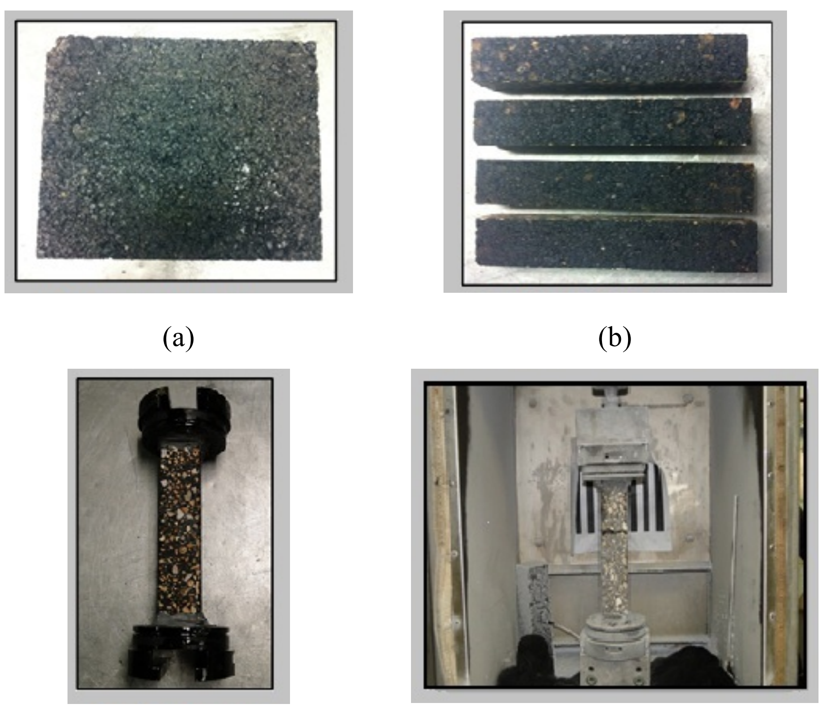
To determine the critical value of J-integral (J_c), semi-circular specimens with at least two different notch depths need to be tested for each mixture. In this study, three notch depths of 25.4 mm, 31.8 mm and 38 mm were selected based on an a/r_d ratio (the notch depth to the radius of the specimen) between 0.5 and 0.75. Test temperature was selected to be 25°C. The semi-circular specimen is loaded monotonically till fracture failure under a constant cross-head deformation rate of 0.5 mm/min in a three-point bending load configuration. The load and deformation are continuously recorded and the critical value of J-integral (J_c) is determined using the following equation (18)

$$J_c = \left(\frac{U_1}{b_1} - \frac{U_2}{b_2} \right) \frac{1}{a_2 - a_1}, \tag{5-1}$$

where b is the sample thickness (m), a is the notch depth (m), and U is the strain energy to failure (kJ).

3.5.6 Thermal Stress Restrained Specimen Test (TSRST)

Low-temperature cracking performance was assessed using the TSRST, which was used to study changes in the binder's glass transition temperature and how it may affect the mix performance in terms of low temperature cracking. This test was conducted according to AASHTO TP 10, "Standard Test Method for Thermal Stress Restrained Specimen Tensile Strength (TSRST)." Triplicate specimens 50 mm thick x 50 mm wide x 254 mm long were used. The specimen is glued at the ends to two aluminum platens, see Figure 5-6. The test device then cools the beam specimen while restraining it from contracting. As the temperature drops, thermal stresses build up until the specimen fractures (19).



(a) (b)

(c) (d)

Figure 5-6: TSRST specimen preparation: (a) Compact (b) Cut (c) Glue and (d) Test

3.6 Results and Analysis

3.6.1 Rutting Performance

Figure 5-7 presents the final rut depths for the evaluated mixtures as measured by the Hamburg Loaded Wheel Tracking Test, AASHTO T 324. All mixtures passed the Louisiana rut depth specification of 6.0 mm at 20,000 passes. The RAS-modified mixtures were compared to their conventional counterpart mixture using an Analysis of Variance (ANOVA) at 95% confidence level (α=0.05). The letters displayed in the figure represent the statistical grouping associated with the rut depths. The letter A is assigned to the mixture with the best performing rut depth. The letter B is assigned to a mixture if a significant difference exists between the means of the two mixtures. The mean rut depths of the conventional mixture containing PG 70-22 were reduced with the addition of RAS from Texas, either through the dry or the wet process. However, a slight increase in mean rut depth was observed with the addition of the RAS from Illinois. Nevertheless, the rutting performance of the mixtures containing RAS was acceptable as compared to the conventional mixture prepared with virgin materials and in light of the maximum rut depth specified in the LWT test.

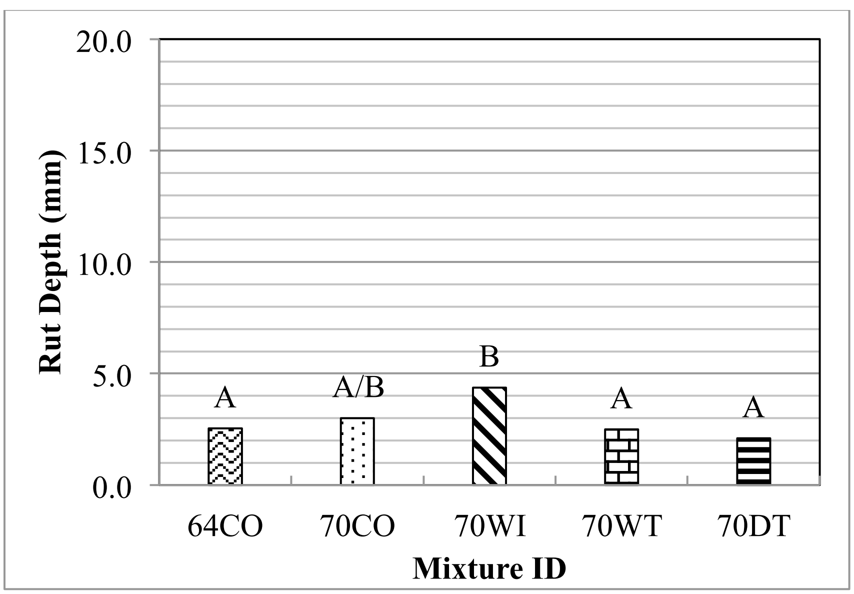


Figure 5-7: Loaded Wheel Tester Results

3.6.2 Intermediate Temperature Cracking

Figure 5-8 presents a comparison of the critical strain energy (J_c) data for the mixtures evaluated in this study. High J_c values are desirable for fracture-resistant mixtures. A threshold of a minimum J_c of 0.50 to 0.65 kJ/m^2 is typically used as a failure criterion for this test. As shown in this figure, the use of RAS caused a slight decrease in the critical strain energy given that RAS-binder modified HMA mixtures possessed stiffer properties than that of the conventional mixture and had slightly lower binder content. Given that the cracking resistance is mainly controlled by the binder in the mixture, it is likely that the use of RAS increased the brittleness of the binder at intermediate temperature. Nevertheless, statistical comparisons show that the cracking performance of the asphalt mixtures was not significantly affected by the use of RAS either through the dry or the wet processes.

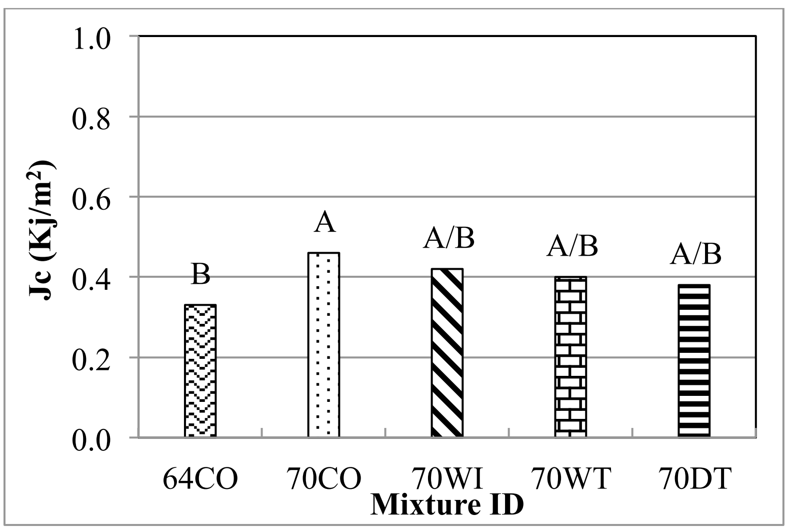


Figure 5-8: SCB Cracking Test Results

3.6.3 Low Temperature Cracking

Figure 5-9 presents a comparison of the fracture temperature of the mixtures using TSRST test. All mixtures exhibited a critical fracture temperature higher than the low temperature grade of the binder (-22°C). In addition, results indicate that the mixes with RAS had a slightly higher fracture temperature when compared to the conventional mixtures with the same binder PG grade. This behavior was expected given that the RAS-binder modified HMA mixtures possessed stiffer properties than that of the conventional mixture and had slightly lower binder content than the conventional mixture. However, statistical comparisons showed there were no significant differences observed due to the addition of RAS for the low temperature properties.

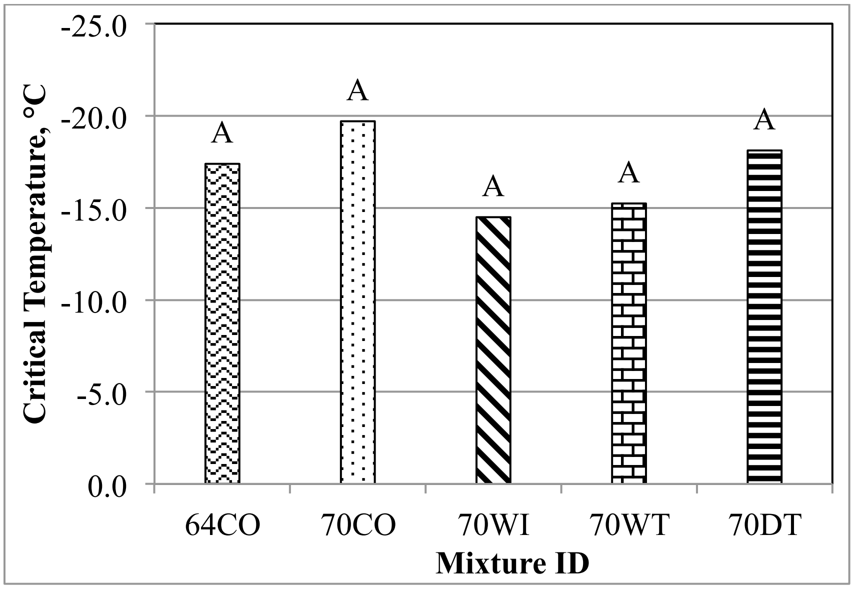


Figure 5-9. TSRST Test Results – Fracture Temperature

3.7 Summary of the Results

The tests evaluated and presented in this paper were selected to capture the laboratory performance of the mixtures prepared with RAS either through the wet or dry processes as compared to conventional mixes. Table 5-5 summarizes the ranking of the five mixtures as predicted from the different test methods. The letter A was assigned to the best performer followed by the other letters in appropriate order. A double letter designation, such as A/B, indicates that the difference in the means is not clear-cut, and that the results could fall in either category.

With the need to reduce natural resources consumption (materials and energy) and to improve the economic competitiveness of asphalt paving construction, the use of RAS materials through the dry or wet processes is promising. Results presented in Table 5-5 indicate that the use of RAS in the mixture is expected to provide comparable laboratory performance against rutting and intermediate and low temperature cracking.

Table 5-5. Summary of Test Results

Mixture	**Test**		
	Rutting	**Fatigue**	**Low Temp.**
	LWT	**SCB**	**TSRST**
64CO	A	B	A
70CO	A/B	A	A
70WI	B	A/B	A
70WT	A	A/B	A
70DT	A	A/B	A

While the moisture sensitivity of the prepared mixtures was not directly evaluated in this study, none of the mixtures stripped in the LWT test or reached the stripping inflection point (SIP). This is indicative that the moisture resistance of the RAS-modified asphalt mixtures is expected to be acceptable.

By comparing the performance of the two mixes prepared using the wet process (i.e., 70WI vs. 70WT), it appears that the mix prepared with RAS ground to ultra-fine particle sizes outperformed the mix prepared with RAS used directly with its regular processed size at the recycling plant. Yet, the use of RAS with no additional processing in the wet process is feasible. Further, it is noted that the RAS used from Illinois was processed at the recycling facility to a fine uniform particle size (92% passing No. 8 - 2.35 mm). RAS is usually processed at the recycling facilities to a uniform particle size ranging from 2.35 mm to 12.5 mm. Therefore, it is recommended that the RAS be processed to the finest processing size possible in order to stimulate chemical and physical interactions between virgin and RAS materials.

3.8 Summary and Conclusions

The objective of this study is to conduct a laboratory evaluation of asphalt mixtures containing RAS prepared using the newly-developed wet process. The advantages of the proposed wet process are expected to be better control the Superpave Performance Grade (PG) of the binder blend, to stimulate chemical and physical interactions taking place in the blend between asphalt binder in shingles and virgin asphalt binder in the mix, and to reduce maintenance issues at the plant due to the high content of fines and fibers in RAS.

To achieve the objectives of this study, asphalt binder blends were prepared using the wet process and an asphalt mixture with nominal maximum aggregate size (NMAS) of 12.5mm was designed according to the Superpave design protocol. The mechanistic properties of asphalt mixtures containing RAS materials were evaluated as compared to Louisiana's conventional asphalt mixtures. A suite of laboratory tests were conducted to capture the mechanical behavior of the mixtures against major distresses. Laboratory testing evaluated the rutting performance, fracture performance, and low temperature resistance of the produced mixtures using the Hamburg loaded-wheel tester, the semi-circular bending test, and the TSRST test, respectively. Based on the results of the experimental program, the following findings and conclusions may be drawn:

- The use of RAS through the wet process allowed the reduction of the virgin binder content by a percentage of 7.7 and 8.0%. For the mixture prepared using the dry blending process, the virgin binder content was reduced by 9.4%.
- With respect to rutting performance, the mean rut depths of the conventional mixture containing PG 70-22M were reduced with the addition of RAS from Texas, either through the dry or the wet process. However, a slight increase in meant rut depth was observed with the addition of the RAS from Illinois. Yet, the rutting performance of the mixture containing RAS was predicted to be satisfactory as compared to the conventional mixture prepared with virgin materials and in light of the maximum rut depth specified in the LWT test.

- The mixes containing RAS exhibited similar intermediate temperature fracture resistance as compared to conventional mixes. The results for the mixes prepared with PG 70-22M binder were statistically equivalent.
- With respect to low temperature performance, all mixtures exhibited a critical fracture temperature higher than the low temperature grade of the binder (-22°C). Yet, statistical comparisons show there are no significant differences observed from the addition of RAS for the low temperature properties.
- While the mix prepared with RAS ground to ultra-fine particle sizes outperformed the mix prepared with RAS used directly with its regular processed size at the recycling plant, the use of RAS with no additional processing in the wet process is feasible. However, it is recommended that the RAS be processed to the finest processing size possible at the recycling facility in order to stimulate chemical and physical interaction between recycled and virgin materials.

Based on these results, additional work is needed to simulate plant operations using the newly-developed wet process. Further, research is needed on the shingle asphalt binder availability factor, its variation for the dry and wet recycling processes, and the effects of non-bituminous components in the shingles on the binder diffusion mechanism.

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4 LABORATORY EVALUATION OF ASPHALT BINDERS WITH RECLAIMED ASPHALT SHINGLE PREPARED USING THE WET PROCESS

4.1 Abstract

The objective of this study is to conduct a laboratory evaluation of asphalt binder blends containing RAS prepared using the newly-developed wet process. In the proposed wet process, RAS material is blended with the binder at high temperature prior to mixing with the aggregates. The proposed wet process offers the potential to better control the Superpave Performance Grade (PG) of the binder blend, to stimulate chemical and physical interactions taking place in the blend between asphalt binder in shingles and virgin asphalt binder in the mix, and to reduce maintenance issues at the plant due to the high content of fines and fibers in RAS. The resistance of the RAS blends against fatigue and permanent deformation was evaluated and compared to that of conventional binder. The effect of using different RAS amounts, as well as binder with two different PG grades, was also investigated. Laboratory testing included the newly developed Linear Amplitude Sweep (LAS) test and the Multiple Stress Creep Compliance (MSCR) test. Results of the LAS test showed that an increase in RAS leads to an increase in the number of cycles to fatigue failure. This is the opposite of what would be expected. These results indicate that the LAS test may not be suitable for characterizing RAS-modified asphalt binders. With respect to permanent deformation, it was found that the addition of RAS improved the rutting performance of the blends by reducing the non-recoverable creep compliance and increasing elastic recovery.

4.2 Introduction

In the past 40 years, the increasing cost of asphalt cement, a petroleum-based product, has led to investigate innovative methods to reduce the amount of virgin binder required to produce Hot Mix Asphalt (HMA) pavements without negatively affecting the performance. In addition to rising costs, environmental concerns about carbon emissions resulting from the production of asphalt binder have also motivated research on decreasing the amount of asphalt used in HMA. As one possible solution to this problem, highway agencies have started to use recycled materials incorporating them into the HMA pavements. Among these materials, Recycled Asphalt Shingles (RAS) have been increasingly used by many states.

The use of RAS has been a promising approach, which has gained popularity and acceptance within the past twenty years. Highway agencies, as well as contractors, have now included RAS within their HMA mixes in efforts to reduce virgin binder content, which translate into reduced costs. On average, most shingles contain an asphalt content ranging between 15 and 35% (Gevrenov, 2008). It has been estimated that savings could range between $1 to $2.80 per ton of HMA when using 5% shingles (Construction Materials Recycling Association, 2013). In addition, shingle waste is widely available. In the U.S., it is estimated that 11 million tons of tear-off scrap and 1 million ton of manufactured waste is generated annually (McGraw, 2007).

Current practices implemented in the recycling of asphalt shingles consist of dry blending RAS with the aggregates before the asphalt binder is added to the batch. Recently, a "wet process" has been introduced as a new approach where RAS material is ultra ground to a fine particle size and blended with the binder at high temperature prior to mixing with the aggregates. This process aims to stimulate a more effective chemical interaction between asphalt binder in shingles and virgin asphalt binder in the mix (Salari, 2012).

4.3 Objective and Scope

The objective of this study is to test the performance of asphalt binder blends containing RAS, prepared using the wet process, for resistance against fatigue damage and permanent deformation. The effect of using different RAS amounts, as well as binder with two different PG grades, was investigated. The Multiple Stress Creep Compliance (MSCR) test was used to predict the resistance to permanent deformation and to identify the elastic response in the binder. The newly developed, Linear Amplitude Sweep (LAS) test, was used to test the binder's resistance to fatigue damage due to cyclic loading.

4.4 Background

There are two types of asphalt shingles, which are used for roofing: organic and fiberglass. Organic shingles consist of a paper saturated with asphalt with a top coating of adhesive asphalt and embedded ceramic granules. Fiberglass shingles have a base layer of glass fiber reinforcing mat. Asphalt containing mineral fillers, is used to coat the mat to make it waterproof. These two types of shingles have different asphalt binder contents. Organic shingles are generally composed of 15-35% Fibers/Mineral Fines, 30-50% aggregate, and contain 30-35% asphalt. Fiberglass shingles have 20-35% Fibers/Mineral Fines, 30-50% aggregate, and contain a lower percentage of asphalt ranging between 15-20%. RAS usage, from manufacture and construction (tear-off) waste, increased from 1.1 million tons in 2010 to 1.2 million tons in 2011; an 8% increase. Assuming a conservative asphalt content of 20% for the shingles, this represents 380,000 tons (2.2 million barrels) of asphalt binder conserved (Hansen and Newcomb, 2011).

4.4.1 Current Practice of RAS Usage

The American Association of State Highway and Transportation Officials (AASHTO) has developed specifications and guidelines for designing HMA with addition of RAS. Among these are requirements for shingle aggregate gradation, performance grade (PG) of the virgin and RAS binder and relative reduction of the virgin asphalt binder due to replacement by RAS binder. The actual maximum quantity of RAS allowed is left at the discretion of the designer (McGraw et al., 2007).

As of 2010, 26 states reported using RAS in their HMA mixes (Hansen and Newcomb, 2009). The majority of these states only allow RAS quantities between 2.5% and 5%, but states such as Missouri and South Carolina allow between 5% and 8%, which are the highest amounts currently used in practice (Salari, 2012). Most states are reluctant to use higher percentages of RAS, due to the stiffening effect, which has been found to be caused by the aged asphalt recovered from the shingles. Previous research has shown that mixes containing up to 5% RAS by weight, can perform adequately without any significant negative effects, but exceeding 5% may change the properties of the blended mixture significantly and adversely impact pavement performance (Button et al., 1995; Newcomb et al., 1993). The main distress, which is of most concern when using RAS modified pavement, is susceptibility to low temperature cracking due to the increase in stiffness of the blended binder (Williams et al., 2011; McGraw et al., 2007).

In a recent study, Abbas et al. (2013) evaluated the effect of RAS on the chemical and physical properties of asphalt binder. Blends were prepared containing varying RAS percentages (5%, 7% and 10%) from post manufacture shingles. Physical properties were evaluated using the

Rotational viscometer (RV), dynamic shear rheometer (DSR), multiple stress creep recovery (MSCR), and bending beam rheometer (BBR) tests. It was reported that at high temperatures, addition of RAS resulted in an increase in G* and a decrease in the phase angle, meaning that an increased resistance to permanent deformation is expected. In contrary to majority of previous studies, at intermediate temperatures, the fatigue cracking parameter showed no change with the addition of RAS. At low temperatures, addition of RAS resulted in a higher stiffness values and lower m-values, indicating that the material became more susceptible to thermal cracking. An aging index ($|G^*|$ ratio of aged and unaged asphalt binders) was used an indication of the aging tendency of a binder when exposed to high mixing temperatures and high service temperatures. From these results, it was concluded that an addition of RAS will primarily influence aging of the binder in its long-term performance but it will not cause a significant change in the short-term (production stage or pavement's early life).

4.4.2 Incorporating RAS into Mix

In order to effectively use RAS, the material needs to be heated in order to activate the RAS binder and improve workability. The two most commonly used methods of incorporating RAS into mixtures are referred to as "dry" and "wet" method. The "dry" method consists of preheating RAS materials at the target mixing temperature, then mixing RAS with the virgin aggregates (Zhou et al., 2011).

Recently, researchers at Louisiana State University proposed a new "wet" approach. This new method consists of blending finely ground RAS (more than 80% passing sieve No. 200 – 0.075 mm) with virgin binder at a high temperature of 180°C prior to mixing the blend with the aggregates. Results from rheological and stability testing indicated that using this "wet" process, the quantity of RAS could be incremented to a content of 20% or less by weight of the binder, without influencing the PG high temperature grade and maintaining the low temperature grade of the virgin binder (Salari, 2012).

4.4.3 Linear Amplitude Sweep Test

The current binder characterization for fatigue performance, as required by the Superpave PG system, relies on the measurement of $|G^*|\sin\delta$ which, at intermediate temperature, is required to be less than 5000 kPa in order for the binder to show reasonable resistance against fatigue cracking. Deacon et al. (1997) found that $|G^*|\sin\delta$ had a satisfactory correlation with the fatigue resistance of thin (2 in. or less) asphalt-bound layers. Since then, researchers have questioned the validity of this parameter as it is stiffness-based and is measured under conditions of low shearing strain. Further, it was suggested that the SHRP binder fatigue specification is not appropriate for controlling fatigue in most asphalt pavements.

In an NCHRP report on the characterization of modified asphalt binders in Superpave mix design, Bahia et al. (2001) made emphasis on the need for new testing protocols and parameters for predicting the fatigue damage behavior of a binder, based on the concept of damage accumulation. The LAS test, which is based on viscoelastic continuum damage mechanics (VECD), was developed to provide the number of cycles at which a 35% reduction in initial modulus is reached. More recently, the current Superpave fatigue parameter, $|G^*|\sin\delta$, has been criticized as having a poor correlation with field performance and for not taking into account pavement structure or traffic loading since the binder is subjected to very few loading cycles and the measurement is made at a specific strain level. LAS has shown promising field validation when comparing the measured fatigue life (N_f) to measured cracking in test pavement sections constructed as part of the LTTP program (Hintz et al., 2011).

4.4.4 Multiple Stress Creep Recovery Test

The multiple stress creep recovery (MSCR) test was conducted in this study to effects of RAS on the binder rutting resistance. In this test, the dynamic shear rheometer is used to apply a constant shear stress for 1 sec. followed by a 9-sec. rest period. This test was recently introduced to characterize the binder rutting resistance at high temperatures. It was reported to correlate well with the mixture rutting performance as measured by accelerated pavement testing. It can also be used to determine the stress dependency of polymer modified binders. Two performance parameters have been suggested to evaluate the binder performance at high temperature. The non-recoverable creep compliance (J_{nr}) normalizes the strain response of the binder to stress as follows:

$$J_{nr} = \frac{\varepsilon_{nr}}{\sigma} \qquad (6\text{-}1)$$

where J_{nr} = non-recoverable creep compliance (1/kPa), ε_{nr} = non-recoverable strain at the end of the rest period, and σ = constant stress applied in the creep phase of the test (kPa).

The percentage recovery at the end of the recovery period is also determined as follows:

$$\varepsilon_r = \frac{\varepsilon_1 - \varepsilon_{10}}{\varepsilon_1} x100 \tag{6-2}$$

where ε_r= percentage recovery, ε_1 = strain at the end of the creep phase (after 1 sec.), and ε_{10} = strain at the end of the recovery period (after 10 sec.).

The test is conducted for 10 consecutive load cycles, and the average non-recoverable creep compliance and percentage recovery is calculated over these 10 cycles. For acceptable performance, it is desirable to use a binder with a low, non-recoverable creep compliance and high percentage recovery. At high temperature, two standard stress levels are typically used (100 Pa and 3200 Pa) to determine the stress dependency of the binder. The stress dependency is predicted by calculating the percentage difference in the binder response at the two stress levels as follows:

$$\varepsilon_{r-difference} = \frac{\varepsilon_{r100} - \varepsilon_{r3200}}{\varepsilon_{r100}} x100 \tag{6-3}$$

where $\varepsilon_{r-difference}$= percentage difference in recovery between 100 Pa and 3200 Pa, ε_{r100} = percentage recovery at 100 Pa, and ε_{r3200} = percentage recovery at 3200 Pa.

Figure 6-1 presents typical test results obtained from the MSCR test.

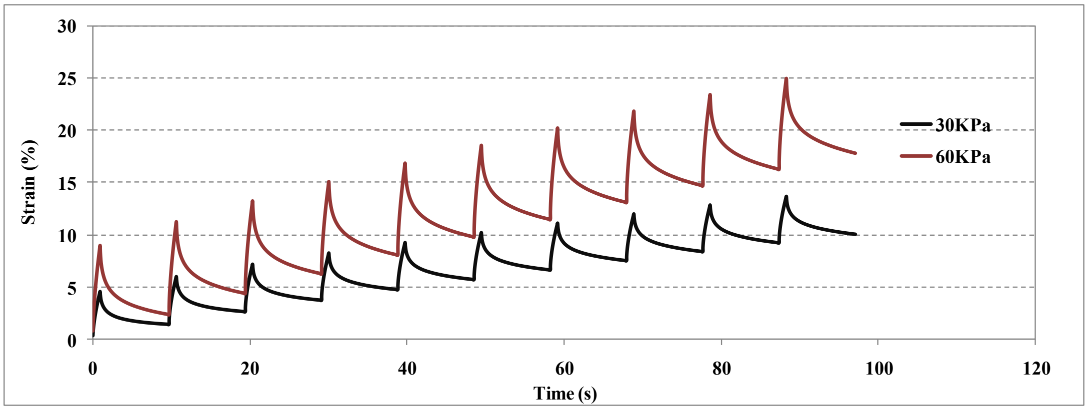

Figure 6-1: Typical test results obtained from the multiple stress creep recovery test

4.5 Experimental Program

4.5.1 Test Materials

The objective of this study was to conduct a laboratory evaluation of asphalt binder containing RAS, prepared using the wet process. Two binders, classified as PG 64-22 and PG 70-22M (Polymer-modified) according to Superpave specifications were selected as the base binders. Table 6-1 provides a summary of the materials subjected to testing.

Two sources of RAS consisting of tear-off shingles from South Dakota and Texas were obtained from C&D processing plants. RAS materials were ground to an ultra-fine particle size distribution at room temperature using a Pulva-Sizer® hammer mill with high rotational speed of 9,600 rpm. RAS from Texas and South Dakota consisted of a particle size in which 80% passed sieve No. 200 (0.075 mm). Asphalt binder blends of PG 64-22 and PG70-22M were prepared with RAS modification rates of 10, 20 and 30%, by weight of the binder. These modification levels were selected based on the results of the original test program, which showed that these contents kept separation levels below 20%, which is essential to ensure workability and stability of the blends (Salari, 2012). The blends were prepared by mixing the asphalt binder with the corresponding content of RAS at a mixing temperature of 180°C using a mechanical shear mixer rotating at a speed of 1500 rpm for 30 minutes.

Table 6-1. Description of the Test Materials

Binder Abbreviation	RAS Content (%)	RAS Source	Description
64CO	0	N/A	Conventional PG 64-22 binder with no shingle
70CO	0	N/A	Conventional PG 70-22M binder with no shingle
SD610	10	South Dakota	PG 64-22 binder with 10% RAS
SD620	20	South Dakota	PG 64-22 binder with 20% RAS
SD630	30	South Dakota	PG 64-22 binder with 30% RAS
TX610	10	Texas	PG 64-22 binder with 10% RAS
TX620	20	Texas	PG 64-22 binder with 20% RAS
TX630	30	Texas	PG 64-22 binder with 30% RAS
SD710	10	South Dakota	PG 70-22M binder with 10% RAS
SD720	20	South Dakota	PG 70-22M binder with 20% RAS
SD730	30	South Dakota	PG 70-22M binder with 30% RAS
TX710	10	Texas	70-22M binder with 10% RAS
TX720	20	Texas	70-22M binder with 20% RAS
TX730	30	Texas	70-22M binder with 30% RAS

4.5.2 Laboratory Testing

Linear Amplitude Sweep - LAS

In order to test the binder's resistance to fatigue cracking, the LAS test uses cyclic loading (in shear) at linearly increasing amplitudes in order to accelerate fatigue damage. The rate of damage accumulation in the binder is used as an indicator of fatigue performance of the asphalt binder. An Anton Paar MCR 302 rheometer with parallel plate configuration was used to perform the test at an intermediate temperature of 25°C. Two replicate specimens were tested at each temperature for each binder blend. All of the binder samples were first short-term aged using the Rolling Thin Film Oven (RTFO). Sample geometry consisted of an 8-mm diameter and a 2-mm thickness. Samples were first tested using a frequency sweep to determine their linear rheological properties. The frequency sweep consists of applying a load of 0.1±0.01 percent stain over a range of frequencies from 0.2-30 Hz. Immediately after, samples were subjected to a series of oscillatory load cycles in strain-controlled mode at a frequency of 10 Hz. Strain is increased linearly from zero to 30% over the course of 3,100 cycles of loading. The binder fatigue parameter N_f is calculated using the following equation:

$$N_f = A_{35}(\gamma_{max})^B \tag{6-4}$$

where A and B are coefficients based on the materials properties. The analysis of results is based on the viscoelastic continuum damage (VECD) approach, which is regularly used to model the fatigue behavior of asphalt binders and mixtures. The entire testing process was completed following AASHTO TP 101.

Multiple Stress Creep Recovery (MSCR)

The MSCR test was conducted according to AASHTO TP 70 "Standard Method of Test for *Multiple Stress Creep Recovery* (*MSCR*) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)". This analysis aims to predict the binder resistance against permanent deformation and repeated loading. MSCR is designed to identify the elastic response in a binder and the change in the elastic response at two different stress levels while being subjected to ten cycles of creep stress and recovery. The stress levels used are 0.1 kPa and 3.2 kPa. The creep portion of the test lasts for 1 s, which is followed by a 9-s recovery. Two performance parameters are used to characterize the material's response after ten cycles at each stress level:

Non-recoverable creep compliance J_{nr} and percent recovery, ε_r. Two replicate specimens were tested at the high temperature grade of the base binder (70°C and 64°C), for each binder blend. All of the binder samples were first short-term aged using the Rolling Thin Film Oven (RTFO). Sample geometry consisted of an 8-mm diameter and a 2-mm thickness.

4.6 Results and Analysis

Table 6-2 provides a summary of all the results from the LAS test.

Table 6-2: LAS Results

Sample	N_f at 2.5% Strain		N_f at 5.0% Strain	
	Sample 1	Sample 2	Sample 1	Sample 2
64CO	14,751	15,031	2,348	2,391
TX610	17,793	15,445	2,584	2,206
TX620	21,077	19,674	2,797	2,614
TX630	24,979	27,068	2,929	3,153
SD610	18,674	18,915	2,672	2,706
SD620	21,057	23,780	2,675	3,021
SD630	28,909	31,227	3,089	3,334
70CO	27,382	29,912	4,031	4,380
TX710	35,591	36,399	4,650	4,721
TX720	44,122	33,277	5,262	3,942
TX730	36,408	40,576	4,036	4,498
SD710	40,810	41,546	5,241	5,342
SD720	43,915	44,641	5,288	5,358
SD730	53,982	63,835	5,771	6,856

Figures 6-2 and 6-3 provide a comparison of cycles to failure, grouped by the original base binder and testing strain level. These results imply that an increase in RAS corresponds to an increase in the number of cycles to failure of the sample, for both PG 64-22 and PG 70-22M based binders. This is the opposite of what would be expected. These results indicate that the

LAS test may not be suitable for characterizing RAS-modified asphalt binders. Other researchers have expressed similar concerns when analyzing the results of the LAS test. The PG 70-22M base binders showed improved resistance to fatigue damage as compared to the PG 64-22. This finding is consistent with past research, which has showed that polymer modified binders are more resistant to fatigue damage since they exhibit a higher elastic recovery.

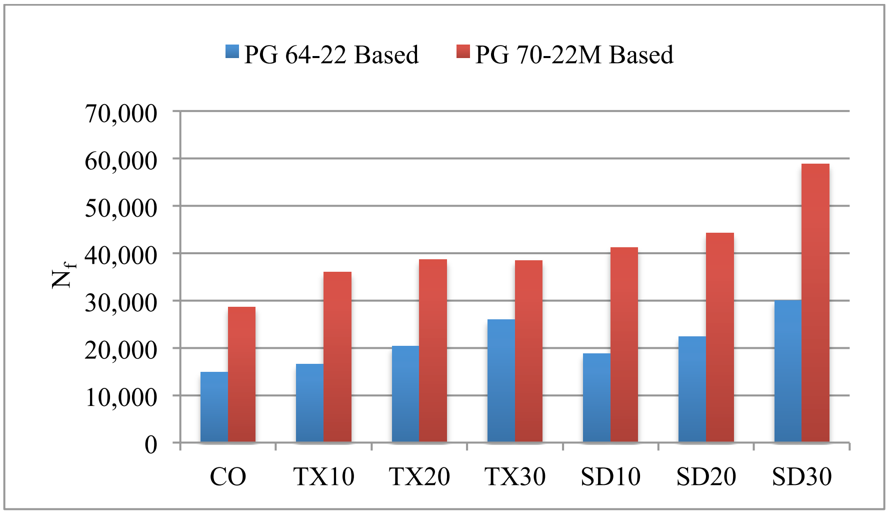

Figure 6-2: N_f at 2.5% Strain – LAS

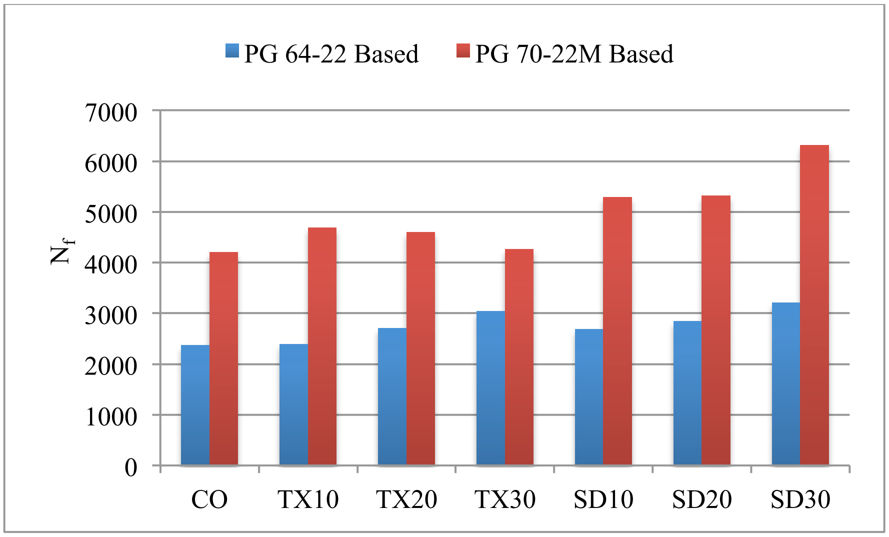

Figure 6-3: N_f at 5.0% Strain – LAS

Table 6-3 provides a summary of the results from the MSCR test. Figures 6-4 and 6-5 provide a comparison of the percent recovery for all samples, at both stress levels 0.1 kPa and 3.2 kPa.

Table 6-3: MSCR Results

Sample	Avg. %Recovery ε_r at 0.1 kPa	Avg. %Recovery ε_r at 3.2 kPa	Jnr at 0.1 kPa (kPa^{-1})	Jnr at 3.2 kPa (kPa^{-1})	Jnr %diff (0.1kPa)	Jnr %diff (3.2kPa)
64CO	3.46	0.68	2.19	2.37	8.5	7.8
TX610	6.04	1.78	1.51	1.67	10.4	9.4
TX620	9.57	2.99	1.12	1.28	14.4	12.4
TX630	12.32	6.06	0.72	0.81	11.4	10.2
SD610	6.35	1.76	1.55	1.71	10.0	9.1
SD620	9.14	3.54	1.04	1.15	10.2	9.28
SD630	16.41	8.69	0.47	0.53	10.6	9.5
70CO	25.58	10.62	1.95	2.71	38.6	27.7
TX710	27.56	13.67	1.41	1.85	30.7	23.5
TX720	30.21	16.87	1.00	1.27	27.6	21.6
TX730	24.58	13.89	0.94	1.16	22.5	20.1
SD710	26.75	12.95	1.37	1.78	30.1	23.1
SD720	28.23	14.86	1.05	1.34	26.5	20.95
SD730	32.70	18.95	0.67	0.86	27.7	21.7

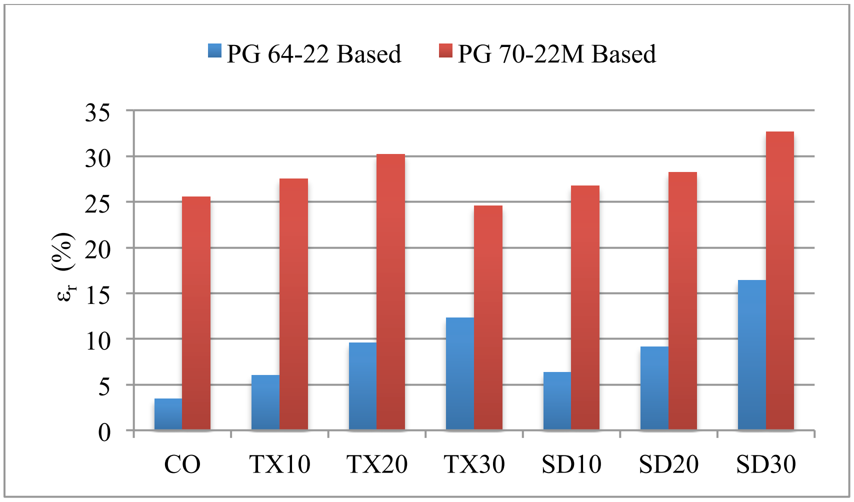

Figure 6-4: ε_r (%) at 0.1 kPa

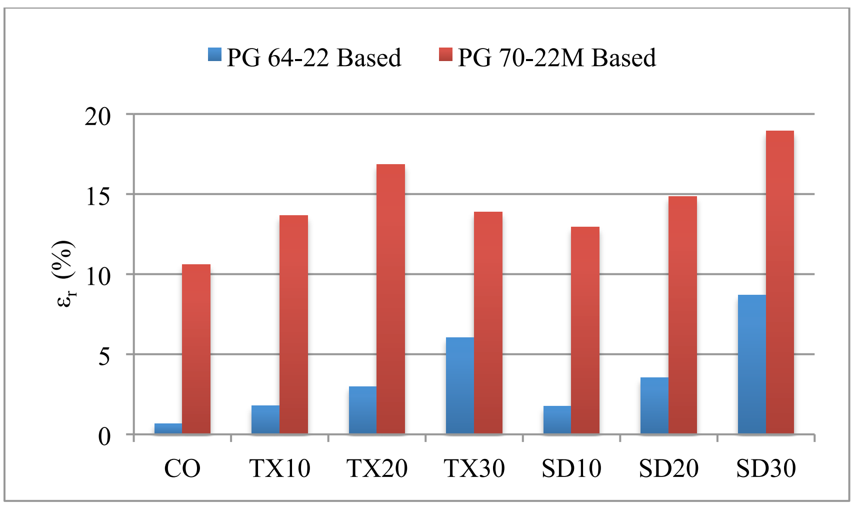

Figure 6-5: ε_r (%) at 3.2 kPa

At both stress levels and for all samples, the addition of RAS increased the recovery ability of the sample. PG 70-22M based binders showed a much higher percent recovery than those samples based on PG 64-22. Again, this is mainly due to the fact that the polymer modified samples have an increased ability for elastic recovery. However, even when comparing PG70-22M conventional binder with PG70-22M binder with RAS at any quantity, the increase in recovery is still evident. This is in contradiction of what was expected as the use of RAS should decrease the recovery ability of the binder blends.

Figures 6-6 and 6-7 provide a comparison of the non-recoverable creep compliance at both stress levels of 0.1 kPa and 3.2 kPa.

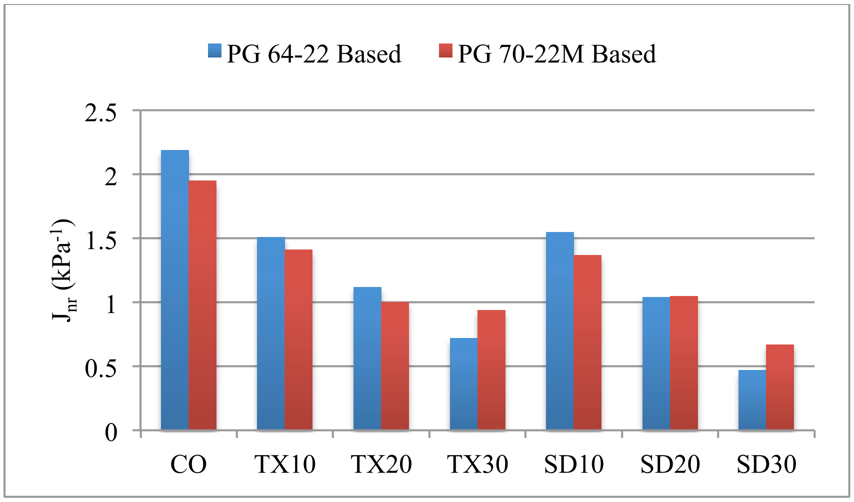

Figure 6-6: J_{nr} at 0.1 kPa

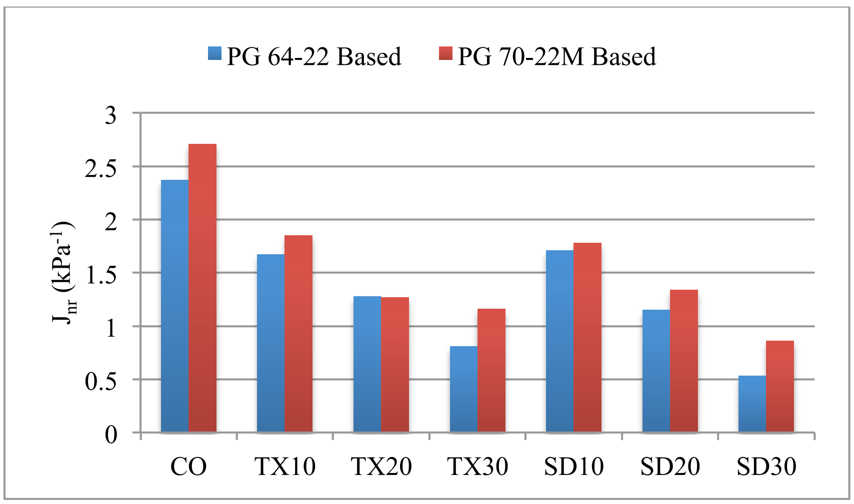

Figure 6-7: J_{nr} at 3.2 kPa

For all the tested binders and blends at both 0.1 kPa and 3.2 kPa, the addition of RAS demonstrated a reduction in J_{nr} values when compared to the conventional binder, which suggest an increased resistance to rutting. For the stress level of 0.1 kPa, the majority of PG 70-22M samples showed a higher reduction in J_{nr} than those based on PG 64-22, with the exception of the SD30 sample. At the 3.2 kPa stress level, the J_{nr} values of all binders and blends increased slightly due to a much higher stress level, but the overall reduction in J_{nr} when compared to the conventional binder, is still evident. It is also noted that at this higher stress level, the PG 64-22 based samples showed a higher reduction in J_{nr} when compared to J_{nr} values of PG 70-22M based samples, at the same RAS level.

4.7 Summary and Conclusions

The objective of this study was to conduct a laboratory evaluation of the behavior of shingle modified asphalt binders prepared using the wet process. The effects of varying shingle content and two different base binders were investigated. The influence of adding finely ground shingle on the binder's resistance to fatigue cracking and permanent deformation was evaluated at intermediate and high temperature using the newly developed LAS test and MSCR test, respectively. Based on the results of the experimental program, the following conclusions may be drawn:

- With respect to the LAS test, an increase in RAS corresponds to an increase in the number of cycles to failure of the sample, for both PG 64-22 and PG 70-22M based binders. Furthermore, the PG 70-22M based binders showed the highest resistance against fatigue damage for all the RAS quantities and both strain levels. Results of the LAS test showed that an increase in RAS leads to an increase in the number of cycles to fatigue failure. This is the opposite of what would be expected. These results indicate that the LAS test may not be suitable for characterizing RAS-modified asphalt binders.
- With respect to resistance against permanent deformation:
    - MSCR results indicate that for all the tested binders and blends at both 0.1 kPa and 3.2 kPa, the addition of RAS demonstrated a reduction in J_{nr} values when compared to the conventional binder, which suggest an increased resistance to rutting.
    - PG 70-22M based binders showed a much higher percent recovery than those samples based on PG 64-22.

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5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

With Respect to the Performance of Asphalt Mixtures containing RAS, blending through the wet process allowed the reduction of the virgin binder content by a percentage of 7.7 and 8.0%. The rutting performance was improved for those mixtures containing PG 70-22M and RAS from Texas. Mixtures containing RAS from Illinois observed a minor increase in mean rut depth, but when compared to the conventional mixture prepared with virgin materials, it was still found to produce satisfactory results by being below the maximum rut depth specified in the LWT test. With respect to low and intermediate temperature performance, TSRST and SCB testing indicated that mixes containing RAS exhibited similar results when compared to that of conventional mixes. The low temperature performance of mixtures with RAS has been of concern in the past, but in our study, three statistical comparisons showed that there were no statistically significant differences observed from the addition of RAS for the low temperature properties.

With Respect to the Performance of Asphalt Binders containing RAS, Results of the LAS test showed that an increase in RAS leads to an increase in the number of cycles to fatigue failure. This is the opposite of what would be expected. These results indicate that the LAS test may not be suitable for characterizing RAS-modified asphalt binders. MSCR testing, which evaluated the high temperature permanent deformation resistance, indicated that when compared to conventional binder, for both the PG 64-22 and PG 70-22M, the addition of RAS reduced creep compliance values, suggesting an increased resistance to rutting. The percent recovery of each binder was increased by the addition of RAS, in which binders based on PG 70-22M showed the highest ability for recovery.

5.2 Recommendations

Based on the evaluation presented in this study,

- The use of RAS through the wet process could provide a feasible way of lowering production costs by reducing the amount of virgin binder in HMA.

- For best results, it is strongly recommended that RAS be ground to the finest particle size possible, either by the recycling plant or by separate contractor, since this will lead to enhanced chemical and physical interactions between virgin and RAS materials.
- With respect to the LAS test, further evaluation should be performed on binders modified with recycled materials, as our results were in contradiction to what was expected.
- With respect to RAS replacement ratios, RAS within the range of 10% and 30% replacement by weight of the binder can provide suitable results. It is important to keep in mind that the PG grade of the base binder is a key factor in the performance of the mixture. Therefore, it is recommended that mixes with higher RAS replacement levels be paired with softer, or polymer modified, binders.
- The use of rejuvenators in combination with the wet process needs to be evaluated in future research.

APPENDIX

Letter of permission from AAPT to include Alvergue, A., M.A. Elseifi, L.N. Mohammad, S.B. Cooper, and S. Cooper III, *Laboratory Evaluation of Asphalt Mixtures with Reclaimed Asphalt Shingle Prepared Using the Wet Process*, Journal of the Association of Asphalt Paving Technologists, 2014 (in press) as Chapter 3.

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VITA

Alejandro Alvergue was born in February 1989, in Knoxville, Tennessee. He began his studies in El Salvador, and later completed high school in Lake Charles, Louisiana. He studied as an undergraduate at Louisiana State University, obtaining his Bachelor of Science in Civil Engineering in December 2012. He was admitted to the graduate school of Louisiana State University in January 2013, where he worked as a research assistant under Dr. Mostafa Elseifi and completed his research successfully in May 2014. He is expected to receive a Master of Science in Civil Engineering degree in summer of 2014.