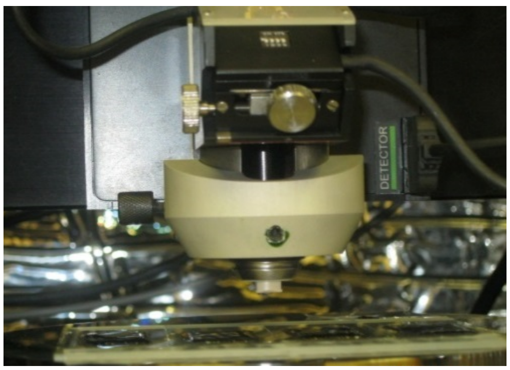
Fundamental Evaluation of the Interaction between RAS/RAP and Virgin Asphalt Binders



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16. Abstract

A comprehensive laboratory testing program was conducted in this research project to examine the blending between reclaimed asphalt pavement (RAP)/recycled asphalt shingles (RAS) and virgin asphalt binders and to evaluate the factors that may affect fatigue and low-temperature cracking as well as moisture-induced damage in asphalt mixtures prepared using these materials. This project included two parts: a binder study and a mixture study. In the binder study, atomic force microscopy (AFM) was utilized to characterize the micro-mechanical properties of the interfacial zone that develops between the RAP/RAS binders and the virgin asphalt binders. Three virgin asphalt binders with different performance grades (PG 58-28, PG 64-28, and PG 64-22), three RAP sources, as well as manufacturing waste and tear-off RAS were used in this project. A new sample-preparation procedure was developed to simulate the blending between the RAS/RAP and the virgin asphalt binders that occurs during asphalt mixture production. The micro-structure, stiffness and the adhesive properties along the blending zone were evaluated for different combinations of RAP/RAS binders and virgin binders. In the mixture study, several asphalt mixtures were used to evaluate the effect of the incorporation of RAP and/or RAS on the mix performance, including a control mixture (no RAP or RAS), a mixture containing 30% RAP, a mixture containing 5% tear-off RAS, and a mixture containing 20% RAP and 3% tear-off RAS. All mixtures were designed to meet ODOT specifications for Item 442 (Superpave) Type A for heavy traffic intermediate course asphalt mixes. The resistance of the asphalt mixtures to fatigue cracking was evaluated using the semi-circular bend (SCB) and the indirect tensile strength (IDT) tests. The SCB test was performed using the Illinois Method and the Louisiana Method. In addition the potential for low-temperature cracking was evaluated using the asphalt concrete cracking device (ACCD), and the susceptibility of the asphalt mixtures to moisture-induced damage was evaluated using the AASHTO T 283 (modified Lottman) test.

The AFM test results indicated that blending occurred to a varying degree between the RAP binders and the virgin binders for all RAP-virgin binder combinations. The average modulus of the blending zone depended on the properties of the RAP and the virgin binders. For all binders, a reduction in the adhesive bonding energy was also observed in the blending zone due to the presence of RAP. However, the adhesive properties of the blending zone were significantly higher than those in the RAP binders. Statistical analysis also indicated that the stiffness of the interface blending zone is affected by the properties of the RAP and virgin asphalt binders, while the adhesive properties of the interface blending zone is primarily affected by those of virgin binder used. A linear regression model was developed to predict the modulus and adhesive bonding energy of the blending zone in terms of RAP and virgin binder properties. The validation of the regression models suggested that these models can serve as a viable tool in selecting the virgin binder to be used in a RAP mixture based on the properties of the RAP binder. Finally, the AFM imaging and force spectroscopy experiments revealed very limited to no blending between manufacturing waste or tear-off RAS materials and the virgin binders considered. The asphalt mixture test results also showed that the use of tear-off RAS in intermediate asphalt mixes significantly reduced their resistance to low-temperature and fatigue cracking as well as moisture damage, which can be attributed to the limited blending observed in the AFM experiments between the RAS and the virgin asphalt binders.

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TABLE OF CONTENTS

List of Figures

List of Tables

Fundamental Evaluation of the Interaction between RAS/RAP and Virgin Asphalt Binders

Executive Summary

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Based on the findings of this study, it was recommended to lower the maximum percentage of RAS currently allowed in Item 401.04 in ODOT specifications to 3 percent by dry weight of

mix. In addition, the assumed 18 percent available RAS binder specified by ODOT was recommended to be lowered to 10 percent when designing asphalt mixes with RAS. It was also recommended that the mix design process for asphalt mixes with 0.3 or more RAP binder ratio or contain RAS include evaluating their fatigue cracking resistance using the SCB test. Finally, it was recommended to use a proper RAP sampling method in developing the job mix formula of asphalt mixes containing RAP.

1. Project Background

In response to the significant rise in prices of raw asphalt materials and the increasing demands for environment-friendly paving mixtures, the asphalt mixture producers and the Ohio Department of Transportation (ODOT) increased the use of the readily available recycled materials such as Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS), both being used individually or together, in flexible pavement mixtures. Though the potential benefits are high, using RAS and higher amounts of RAP in new paving mixtures present a concern that the resultant mixture may be more prone to load and non-load associated cracking and adhesion/cohesion failures during the service life of the pavement. This is due to the fact that asphalt binder contained in the RAP is significantly oxidized/hardened due to aging. Increased aging has been shown to contribute to the reduction of the adhesive and cohesive properties as well as the stress relaxation capacity of the binder, which is a root cause of decreased cracking resistance of the mixture. This problem is further enlarged when RAS is used in conjunction with RAP in producing asphalt mixtures. Recycled binders from RAS are substantially stiffer and have different rheological properties than virgin or modified asphalt binders since they are heavily air-blown during shingle production.

Previous studies reported the development of an interfacial blending zone between RAP and virgin asphalt binders (Nazzal et al. 2015, Nahar et al. 2014). These studies indicated that the properties of this zone might dictate the performance of the RAP asphalt mixture. At the current time, the interaction between RAS and virgin asphalt binders is unclear. Determining the type of interaction between RAS and virgin asphalt binders and examining the properties of their interfacial zone is imperative for understanding the fracture performance of asphalt mixtures containing RAS and to identify the factors that affect this performance. Furthermore, it will help identifying if poor or no blending occurs between the RAS and virgin asphalt binders, which will result in limited contribution of the RAS binder leading to mixtures that are more susceptible to different types of distresses.

This project aims at examining the interaction between the RAS/RAP and different types of virgin asphalt binders and evaluating the properties of the interfacial zone between these binders and their relation to the fracture performance of asphalt mixtures containing RAP and RAS materials. This will be achieved by using different Atomic Force Microscopy (AFM) techniques to study the interaction between RAS/RAP and virgin asphalt binders and evaluate the adhesive and cohesive properties of the interfacial zone between these binders and their relation with the fatigue cracking resistance, low-temperature cracking resistance, and moisture damage susceptibility of mixtures containing RAS and RAP materials. As such, this research will help in maximizing the effective use of RAS and RAP materials in construction of pavements in Ohio. In addition, it will help in extending the service life and durability of asphalt pavements in Ohio while reducing their costs and improving their environmental impacts.

2. Research Context

The main objective of this project is to study the interfacial zone between the RAS/RAP and virgin asphalt binders and evaluate the properties of this zone that affect the fatigue cracking and moisture damage resistance of mixtures containing RAP and RAS materials. Specific objectives of this project include:

- Determine the type of interaction between the RAS (manufacturing waste / tear-off RAS), RAP and different types of virgin asphalt binders commonly used in construction in Ohio.
- Evaluate the adhesive properties of the interfacial zone between the RAS/RAP and virgin asphalt binders and examine their relation with the fracture resistance of mixtures containing RAP and RAS materials.
- Determine the type of interaction between the RAS (manufacturing waste / tear-off RAS) and the RAP binders.

This study included conducting the following tasks to achieve the outlined objectives:

Task 1. Conduct Literature Review
Task 2. Material Selection and Design of Experimental Test Matrix
Task 3. Prepare and Submit Interim Report
Task 4. Securing Material and Sample Preparation
Task 5. Study the Micro-Structure of Interfacial Zone between RAS, RAP and Virgin Asphalt Binders
Task 6. Evaluate the Micro-Mechanical Properties and Moisture Damage Resistance of the Interfacial Zone between the RAS/RAP and Virgin Asphalt Binders
Task 7. Evaluate the Fatigue Resistance and Moisture Damage of Asphalt Mixtures with RAS and RAP
Task 8. Conduct Data Analysis
Task 9. Prepare Final Report

A summary of the comprehensive literature review performed in this study is presented in Appendix A. Previous studies showed that the inclusion of RAP/RAS materials in asphalt mixes affects their performance by changing the rheological properties of the final binder blend and stiffening it (e.g. Zhao et al. 2015, Rad 2013). All laboratory and field studies reported that the addition of RAS and RAP enhanced the rutting performance of asphalt mixtures (e.g. Zhang et al. 2016, Aurangzeb, 2012, Al-Qadi et al. 2015, McDaniel et al. 2012). However, conflicting results were reported regarding the cracking performance of RAS/RAP mixtures (e.g. Al-Qadi et al. 2015, Mogawer et al. 2012, McDaniel et al. 2012, Behnia et al. 2011). While some laboratory studies showed that RAS and RAP did not significantly affect the low-temperature and fatigue cracking performance of asphalt mixtures (e.g. McDaniel et al. 2012, Aurangzeb, 2012, William et al. 2013), other studies reported that mixtures containing RAS (particularly tear-off RAS) and RAP might adversely affect the fatigue cracking performance (Cooper et al. 2014, Al-Qadi et al. 2015). These results can be explained by differences in the properties of the evaluated mixtures (such as the binder type) as well as the laboratory test procedures used in these studies. Differences in testing temperature, loading rate, aging level of samples and test parameter used had significant influence on the obtained test results.

Most previous studies have only used macro-scale methods for evaluating the performance of RAP/RAS mixtures and studying the blending between RAP/RAS and virgin asphalt binders. However, the interaction and blending between the aged RAP/RAS binders and the virgin asphalt binder occur at the micro-scale level; therefore, the evaluation of blending should be completed at the same scale. Few studies have been conducted during the past few years to study the blending between the RAP/RAS and virgin binders at the micro-scale level (Nahar et al. 2014). The results of those studies indicated that an interfacial blending zone develops between RAP and virgin asphalt binders. However, those studies did not consider the effect of the RAP/RAS and the virgin asphalt binders' properties on the characteristics of that blending zone.

3. Research Approach

Previous research work has focused only on the macro-scale properties of the composite binder in RAS/RAP mixtures; however, the typical thickness of an asphalt binder coating aggregates in an asphalt mixture is in the order of a few microns (Nazzal et al. 2014, Nazzal et al. 2015, Nazzal et al. Nahar et al. 2014). In addition, the interfacial blending zone between RAP and virgin asphalt binders was reported to be few hundred microns (Nahar et al., 2014). The properties of this zone might dictate the response of RAP/RAS mixtures and help in predicting the performance of such mixes. Therefore, there is a great need to study the mechanical properties of that zone and evaluate the effect of RAP/RAS and virgin asphalt binders on the cracking performance of RAS/RAP mixtures. Appendix B provide details about the laboratory testing program that was conducted to achieve the objectives of this study. The following subsections summarize the research approach that was pursued in this study.

3.1 Testing Program

3.1.1 Materials

The testing plan developed in this study included the different types of RAP, RAS, and virgin asphalt binders. RAP materials were selected from seven different resurfacing projects in Ohio. Table B.2 presents the information for the RAP material obtained in this study. Manufacturing waste and tear-off RAS were considered in this study. In addition, three types of virgin asphalt binders were selected, which included asphalt binders meeting specifications for PG 58-28 (neat), PG 64-28 (PPA modified), and PG 64-22 (neat). These three PG binder grades are typically used in high RAP and RAS mixes for ODOT. All three binders were obtained from the Shelly Company. The binder of each RAP material was extracted and recovered in accordance with AASHTO T164 and AASHTO R59, respectively. Trichloroethylene (TCE) was the solvent used for extraction of all RAP binders. In addition, toluene was also used for extraction of the binder from one RAP material (RAP-IR-270) to evaluate the effect of the extraction solvent on the blending between the RAP binder and the virgin asphalt binders. The performance grade was determined for each recovered RAP in accordance with AASHTO M320 and are shown in Table B.3. Based on the obtained results, four recovered RAP binders with different performance grades were selected in this study: RAP-IR-70, RAP-US33, RAP-IR-270TCE, and RAP-IR-270Tol. The manufacturing waste RAS considered in this study was obtained from Shelly asphalt plant in Kent, Ohio and has been used in previous paving projects in northeastern Ohio. The tear-off RAS was obtained from Roof to Road (one of ODOT's approved RAS suppliers) processing facility in Columbus, Ohio. The binder from both types of RAS materials was extracted and recovered following AASHTO T164 and AASHTO R59. While TCE was used for extracting the tear-off RAS, TCE and toluene were used for the extraction of the manufacturing waste RAS binder. The high temperature performance grade was determined for each of the recovered RAS in accordance with AASHTO M320 and are presented in Table B.5.

3.1.2 Micro-Scale Testing

One of the micro-scale techniques that has received increasing attention for examining the behavior of asphalt materials is the AFM. In this study, an Agilent 5500LS AFM system was used to study the blending between RAP/RAS and virgin binders. To achieve that, AFM samples were prepared using a procedure that was developed by the researchers to simulate the interaction between the RAP/RAS binders and virgin asphalt binders that occurs in an asphalt mixture during its production. This procedure involved casting a thin film of each asphalt binder at the edge of a microscopic slide separately. The thickness of the prepared samples was controlled by placing a specific amount of asphalt in between four strips of thermal tape and allowing it to spread in the defined area by heating the sample at 154°C. The thickness was measured to ensure that it was the same for all of the casted binders. The RAP binder was then placed on a metal plate and heated on a hot plate at a temperature of 154°C for 30 sec, which was done to simulate the heating of RAP with aggregates before adding the virgin binder. Immediately after, the virgin and RAP binders slides were combined together. The assembly of the two slides was then heated on top of a hot plate for a period of 3 minutes at 154°C. This resulted in melting and spreading of the binders on both sides creating a thin film with a diffused interfacial zone in the middle as shown in Figure 1.

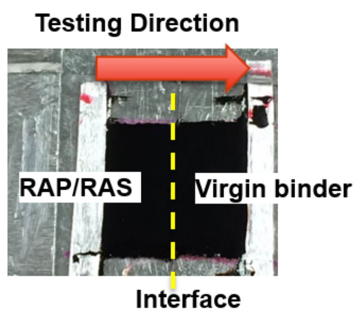

Figure 1. AFM Testing of Samples

At least two samples of each of the RAP/RAS and virgin asphalt binders combinations shown in Table B.6 were prepared. AFM tapping mode imaging and force spectroscopy experiments were performed on the prepared samples by testing a straight line with a length ranging from 5 to 8 mm over the sample surface. As shown in Figure 1, each testing line starts at the RAP/RAS-binder zone and goes toward the blending zone and then the virgin binder zone. The spacing between the tested points was typically higher in the RAP and virgin binder zones but drastically decreased as the blending zone was being approached to capture any changes in the properties of the binder. The spacing between tested points within the blending zone varied between 5 to 30 μm. At least two lines of data were collected for each sample.

The AFM tapping mode imaging experiments were used to characterize the micro-structure and viscoelastic domains of the interfacial zone between the RAP/RAS and virgin binders and compare it to those of the RAP/RAS and the virgin asphalt binders. The phase images were post-processed to evaluate the blending between RAP/RAS and virgin asphalt to quantify the extent of the interfacial zone between the RAS/RAP and the different virgin asphalt binders.

AFM force spectroscopy experiments were also conducted to measure the micro-scale stiffness as well as the adhesive properties of the RAS/RAP and virgin binders as well as the interfacial zone between them. The force spectroscopy test results were analyzed to determine the elastic modulus and the bonding energy of the interfacial zone and compared it to those of the RAS, RAP and virgin asphalt binders. The reduced elastic modulus, $E_{reduced}$, was calculated using Equation 1 which is based on Sneddon's modification of the Hertzian model for the indentation of a flat, soft sample by a stiff tip (Fischer-Cripps 2006):

$$E_{reduced} = \frac{\pi}{2}\frac{F}{\delta^2 \tan(\alpha)} \quad (1)$$

$$\delta = z - d \quad (2)$$

where F is the measured force, δ is the indentation depth, α is the half-opening angle of the AFM tip, d is the cantilever deflection, and z is the piezo-driver displacement.

The total bonding energy needed to separate the tip from the asphalt sample, Ebonding, was estimated using Equation 3. This equation represents the area under the force-distance curve in the retraction region where the force is less than zero (Pauli et al. 2013), as indicated by the shaded portion of Figure B.5.

$$E_{bonding} = \int_{z_o}^{z_1} F dz \approx \frac{\Delta z}{2N}\sum_{i=1}^{N}[F(z_{i+1}) + F(z_i)] \quad (3)$$

Analysis of Variance (ANOVA) and post-ANOVA Least Square Mean analyses (LSM) were conducted using Statistical Analysis Software (SAS) on the obtained AFM test results in order to evaluate the effects of RAP/RAS and virgin asphalt properties on the blending zone that develops between these binders. In addition, a regression analysis was conducted to develop a model that can predict the interfacial blending zone properties based on the properties of the RAP and virgin asphalt binders.

3.1.3 Macro-Scale Testing

Macro-scale tests were conducted on a 19-mm intermediate course mixture to evaluate the effect of the RAS/RAP materials on its fracture performance and durability. The mixture selected in this study was used in construction of intermediate course layer in a resurfacing project on Interstate Route 270 (IR 270). The mixture included using PG 64-28 binder, limestone aggregates, natural sand, and 25% of RAP-IR270 processed using ODOT 401.04 Method 2. Plant-produced samples of intermediate course mixtures were collected during the construction. In addition, the same aggregates, RAP (IR-270 RAP), and binder used in producing the field mixes were obtained. Several asphalt mixes were designed, which included: a control mixture (no RAP), a mixture with 30% RAP-IR270, a mixture with 5% tear-off RAS, and a mixture with 3% tear-off RAS and 20% RAP-IR270. It is noted that as a part of this study, the effect of RAP sampling on obtained mixture design was evaluated by using two mixtures with the same RAP materials that were processed using two different methods. In the first method, the RAP material was split one time using a dual splitter that provides two samples of relatively homogeneous gradations of the RAP material. In the second method, the RAP material was split four more times to receive eight different sampling quadrants, which significantly increased the gradation uniformity used in the mixtures. As shown in Table 1, the two RAP methods resulted in different mixtures with different RAP binder replacement ratios. It is also noted that the mix design for the considered 5% RAS mixture showed that the RAS contributed 0.6% to the asphalt mix; such that only 12% RAS binder was available in the mixture. Therefore, this study also included evaluating a mix with 5% RAS assuming 18% RAS binder was available (A 5% RAS mix with 3.8% virgin asphalt content).

The resistance to fatigue cracking, low-temperature cracking, and moisture-induced damage were evaluated. The propensity of the asphalt mixtures to fatigue cracking was evaluated using the semi-circular bend (SCB) tests and indirect tensile strength. Two methods of the SCB test were used in this study: the Illinois Method (AASTHO TP 124) and the Louisiana Method (ASTM D8044). The low-temperature cracking potential was assessed using the asphalt concrete cracking device (ACCD). Finally, the susceptibility of the asphalt mixtures to moisture-induced damage was evaluated using AASHTO T 283 (modified Lottman test). All tested samples were prepared with air voids of 7 ± 0.5%. In addition, SCB and ACCD tests were conducted on short-term and long-term aged samples. The short-term aging involved placing the loose mixture for four hours at a temperature of 135^{o}C before compacting the samples. The long-term aging was conducted according to AASHTO R30 and involved placing the samples in an environmental chamber for 5 days at 85^{o}C.

Table 1. Tested Mixture Properties

	270 Field	Control	30% RAP-1	30% RAP-2	5% RAS	5% RAS	20% RAP& 3% RAS
Virgin Binder Content	3.3	4.7	2.9	3.3	4.1	3.8	3.1
Total Binder Content	4.7	4.7	4.7	4.7	4.7	4.7	4.7
RAP/RAS replacement ratio	0.28	0.00	0.38	0.30	0.13	0.19	0.34
% RAP	25	0	30	30	0	0	20
% RAS	0	0	0	0	5	5	3

ANOVA and post ANOVA LSM statistical analyses were conducted on the obtained macro-scale test results to statistically compare the performance and the durability of considered asphalt mixtures. The results of ANOVA and post ANOVA LSM were used to identify the test methods that are sensitive enough to detect differences in the cracking performance and durability between the control mixture and the different RAS and RAP mixes.

4. Research Findings and Conclusions

Appendices A, B and C present a detailed summary of the literature review, testing program, and analyses of tests conducted in this study, respectively. The following subsections provide a summary of the main findings and conclusions that were made based on the results obtained in this study.

4.1 Micro-Scale Test Findings

- The results of the AFM imaging and force spectroscopy experiments conducted on the different RAP and virgin binder combinations indicated that the RAP binders blended with virgin binders in a blending zone with varying size.
- The blending zone characteristics varied based on the virgin binder and RAP binder being used. The highest and lowest stiffness values were achieved when using PG 64-22 and PG 58-28 virgin asphalt binders, respectively.
- The bonding energy of the blending zone was lower than the virgin binder grade and higher than RAP binders, which indicated that the RAP binder adversely affected the adhesive properties of the blended binder.
- The results of statistical analyses conducted on the obtained AFM results indicated that the stiffness properties of the RAP binder and the virgin binder significantly affected the reduced modulus of the blending zone. However, the adhesive characteristics of the blending zone were mainly affected by the virgin binder being used.
- Linear regression models were developed to accurately predict the reduced modulus and bonding energy of the blending zone in terms of the properties of the RAP and virgin binder used in the mixture.
- The validation of the developed models suggested that these models could serve as a viable tool to determine the virgin binder that should be used in a RAP mixture, based on the properties of the RAP binder.
- The results of the AFM imaging and force spectroscopy experiments conducted on manufacturing waste and tear-off RAS showed that very limited to no blending occurred between the RAS binder and the virgin asphalt binders.
- The type of RAS (i.e. manufactured waste or tear-off) did not affect the AFM test results.

4.2 Macro-Scale Test Findings

4.2.2 Mix Design

- The assumption that the effective binder content of RAS in an asphalt mixture is 18% of the RAS weight is inaccurate.
- The RAP sampling method can significantly affect the mix design parameters, which might adversely affect the performance of a RAP mixture.

4.2.1 Fatigue Cracking Resistance

- The SCB and IDT tests results showed that the use of 5% RAS significantly reduced the fatigue cracking resistance of the intermediate course asphalt mixes considered in this study; particularly for long-term aged samples.
- The use of 3%RAS and 20% RAP in the intermediate course asphalt mix considered in this study significantly reduced its Flexibility Index and normalized Fracture Energy computed using the SCB-IL test results.
- The results of the SCB and IDT tests are attributed to the limited blending between the RAS and virgin asphalt binders that was observed in the AFM experiments.
- The increase in the RAP recycled binder ratio (RBR) in an asphalt mixture reduces its resistance to fatigue cracking.
- The Flexibility Index and normalized Fracture Energy computed from SCB-IL test, the J integral computed from SCB-LA test, and the toughness index computed from IDT test were

sensitive enough to capture the effect of RAS on the fatigue cracking performance of intermediate course asphalt mixes.

- The acceptable values for Flexibility Index reported in other studies should be re-evaluated for intermediate course mixes.
- Tests for evaluating the fracture properties of asphalt mixtures with RAP and/or RAS should be performed on long-term aged samples.

4.2.2 Moisture Damage Resistance

- The intermediate course asphalt mix with 30% RAP and 0.3 RAP RBR had slightly lower tensile strength ratio (TSR) than the control mix with virgin materials. However, the TSR value was significantly lowered when the RAP RBR was increased to 0.38.
- The use of RAS in the considered intermediate course asphalt mixes significantly reduced their TSR. The asphalt mixture with 5% RAS had the lowest TSR value, which was lower than the minimum value of 80% required by ODOT. This suggests that the use of RAS might reduce the moisture damage resistance of asphalt mixtures.

4.2.3 Low-Temperature Cracking Resistance

- The ACCD test results showed that the RAP did not significantly reduce the low-temperature cracking resistance of the considered intermediate asphalt mixture.
- The use of RAS in the considered asphalt mixtures significantly reduced their low-temperature cracking resistance.

5. Recommendations for Implementation

The following recommendations are made based on the findings of this study:

- The maximum percentage of RAS currently allowed in Item 401.04 in ODOT specifications should be lowered to 3 percent by dry weight of mix.
- The assumed 18 percent available RAS binder specified by ODOT should be lowered to 10 percent when designing intermediate course asphalt mixes with RAS.
- An alternative method needs to be explored for processing and incorporating RAS in asphalt mixtures.
- The RAP RBR should be reported for intermediate course mixes as part of the job mix formula submitted to ODOT by contractors.
- Item 401.04 in ODOT specifications should include a maximum limit for the RAP RBR.
- The mechanical properties of a RAP binder should be evaluated and used in designing intermediate mixes with RAP RBR of 0.3 or more.
- The mix design process for asphalt mixes with 0.3 or more RAP RBR or contain RAS should include evaluating their fatigue cracking resistance using the SCB test. Both SCB-IL and SCB-LA tests are sensitive enough to detect the effect of RAP and RAS on the susceptibility of asphalt mixtures to fatigue cracking. Future research should evaluate the correlation between the SCB test results and field performance of asphalt mixes.
- A proper RAP sampling method should be utilized to ensure the gradation uniformity of the RAP material used in developing the job mix formula of asphalt mixes containing RAP.

6. References

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Appendix A Literature Review

A.1 Introduction

In response to the increased cost of asphalt mixtures and the Federal Highway Administration's policy to increase environmental stewardship (FHWA 2015), there has been a growing interest to increase the amounts of Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) used in asphalt mixtures. RAP is typically obtained from pavement resurfacing by surface milling or from pavement reconstruction activities that involve full-depth removal, while RAS is obtained from two sources: post-manufactured asphalt shingles (factory rejects and cut-outs that are discarded as scrap) and post-consumer asphalt shingles (weathered shingles that are removed when a new roof is installed on a building). The former is typically referred to as "manufacturer scrap," while the latter is generally referred to as "tear-offs."

A survey conducted by National Asphalt Pavement Association (NAPA) reported that more than 71.9 million tons of RAP and 1.9 million tons of RAS were used in new asphalt mixtures in 2014, which resulted in more than $2.6 billion in savings (Hansen et al. 2014). The use of RAP and RAS also conserves non-renewable natural resources (both asphalt and aggregates) and reduces the energy and emissions needed to obtain them. In addition, using RAP and RAS also reduces the amount of construction debris placed into landfills (Copeland et al. 2011).

RAP is normally introduced in asphalt paving mixtures at substitution rates of 10 to 50 percent or more (depending on state specifications) (FHWA 2015). Because RAS contains a much stiffer asphalt binder than is generally used in asphalt pavements, most state highway agencies typically permit contractors to use no more than 5% of RAS in asphalt mixtures, while others specify that only post-manufactured asphalt shingles can be used.

Despite all of the potential economic and environmental benefits of incorporating higher percentages of RAP and RAS in asphalt mixtures, the use of these materials presents a concern that the resulting mixture may be more prone to load and non-load associated cracking and failures during the service life of the pavement structure. This is due to the fact that the asphalt binder contained in the RAP and RAS is oxidized due to aging. Increased asphalt binder aging has been shown to contribute to the reduction of the adhesive and cohesive properties as well as the stress relaxation capacity of the binder, which are the root causes for the decreased cracking resistance of asphalt mixtures. This problem is magnified when RAS is used in conjunction with RAP in the preparation of asphalt mixtures.

Current asphalt mix design methods assume that there will be thorough blending between the aged (oxidized) asphalt binder in RAP and/or RAS and the virgin asphalt binder that is incorporated into the asphalt mixture. As a result, a softer grade virgin binder is generally used to negate the effect of the RAP and RAS binders so that the resulting asphalt mixture would have properties appropriate for prevailing climatic and traffic conditions. However, a few studies showed that there is actually a narrow adhesion interface where the aged and virgin binders combine (Nazzal et al. 2014, Nahar et al., 2013). This suggests that the aged and virgin asphalt binders do not actually blend to produce a new asphalt binder with acceptable performance properties. Moreover, recent experience across the nation suggests that the maximum allowable limits for RAP and RAS may be too high and may exceed what is desired for performance, especially for RAS.

Though the potential benefits are high, using RAS and higher amounts of RAP in new paving mixtures presents a concern that the resultant mixture may be prone to more load and non-load associated cracking and adhesion/cohesion failures. During the past few years laboratory and field studies have been conducted to evaluate the properties of binders in RAS/RAP mixtures and examine the performance of these mixtures to identify the factors that affect this performance.

A.2 Macro-Scale Studies on RAP Mixes

In general, laboratory studies reported that the use of RAP in asphalt mixtures improves their rutting resistance (e.g. Zhang et al. 2016, Al Qadi et al. 2015, Li et al. 2008, Zhao et al. 2012). There was no consensus on the effect of RAP on resistance to fatigue cracking, as it depended on different factors. Zhang et al. (2016) used the indirect tensile strength (IDT) test to evaluate the thermal and fatigue cracking resistance of laboratory-produced and field-produced mixes with different RAP contents ranging from 0% to 50%. The results of their study indicated that mixes with a low percentage of RAP (17% RAP) had similar fatigue performance to those of the control mix without RAP. In addition, for mixes with more than 17% RAP, the effect of RAP on fatigue cracking depended on the target performance grade (PG). Mogawer et al. (2012) used the overlay tester (OT) device to examine the fatigue cracking resistance of asphalt mixes with up to 40% RAP. Their results indicated decreasing resistance to cracking with increasing RAP content. In all mixes except the one with 40% RAP, cracking resistance was improved when using a softer PG virgin binder. McDaniel et al. (2012) used the push-pull test to evaluate mixes with 0%, 15%, 25%, and 40% RAP. The results of their study indicated that mixes with 40% RAP exhibited the highest fatigue resistance followed by the mixes without any RAP. Furthermore, the mixes with 15% and 25% RAP had similar fatigue performance. In addition, Aurangzeb et al. (2012), Al-Qadi et al. (2015), and Tabaković et al. (2010) used flexural beam fatigue to test mixtures with different RAP contents that ranged between 0% and 50%. They concluded that the addition of RAP slightly improved the fatigue resistance of asphalt mixes. It is worth noting that recent studies indicated that the flexural beam fatigue test is highly variable and might not detect the effect of RAP on fatigue cracking performance (Zhou et al. 2017, Martin et al. 2015). In general, laboratory studies indicated that using up to 20% RAP did not significantly affect the fatigue cracking resistance of asphalt mixes.

Zhang et al. (2016) found no significant effect of the RAP on low-temperature performance of asphalt mixes. Li et al. (2008) used the semi-circular bend (SCB) test to evaluate the low-temperature cracking resistance of ten mixes with varying RAP contents that ranged between 0 and 40%. Mixes with 20% RAP had comparable fracture resistance to the control mixtures. However, mixes with 40% RAP had significantly lower low-temperature fracture resistance. Behnia et al. (2011) used the disk-shaped compact tension test to assess the effect of RAP on the low-temperature fracture properties of asphalt mixes and to evaluate the effect of reducing the virgin binder grade to compensate for the increased stiffness of mixes with high RAP contents. The results of their study indicated that mixes with 30% RAP with a softer binder had acceptable low-temperature fracture properties compared to the mixes without RAP. Hajj et al. (2014) used the thermal stress restrained specimen test (TSRST) to evaluate thermal cracking of mixes with 0%, 15%, and 50% RAP. The results of their study indicated that mixes with 0% and 15% RAP exhibited similar TSRST fracture temperatures. However, mixes with 50% RAP had lower thermal cracking resistance.

A.3 Macro-Scale Studies on RAS/RAP Mixes

Many research studies have also been conducted in recent years to quantify performance of mixtures containing RAS and RAP. Kriz et al. (2014) used AASHTO M320 to evaluate the blending efficiency of RAP binders. From this study, it was concluded that AASHTO M323 Superpave mixture design does not accurately predict the blend limitation performance temperatures. This issue points to the need for more technical blending evaluation. Rad (2013) found that using dynamic shear rheometer (DSR) is a suitable approach to determine the blending efficiency between RAP and virgin binders. Ghabchi et. al (2016) conducted a study that tested eight Superpave surface mixes, four using a PG64-22 virgin binder and four using a PG70-28 virgin binder. Each set of four contained a control mix with no RAP or RAS, 30% RAP, 5% RAP 5% RAS and 6% RAS. The dynamic modulus, creep compliance and ITS tests were performed on all mixes. It was found that the mixes with 30% RAP and a RAP/RAS blend had better fatigue resistance than the mix with only 6% RAS. Mixtures with RAS were found to have the highest stiffness as compared to RAP and control mixes. The indirect tensile strength increased as the RAP and RAS contents increased, with the 6% RAS having the highest strength. The toughness index (TI) values did not show a good trend with the ITS values for the PG 70-28 mixes but showed a reasonable trend for the PG 64-22 mixes. The 6% RAS mix had the lowest TI value of about 0.35 and the control mix had the highest of about 0.7.

Reinke et al. (2014) evaluated the effects of using RAS on asphalt mixture and binder properties. This study included laboratory mixture testing and field cores evaluation. The laboratory mixtures were produced with 20% RAS RBR and were compared to control asphalt mixtures produced using virgin binders PG 58-28 and PG 52-34. Tests to evaluate mixture performance included Hamburg wheel tracking and OT tests. The OT test was performed on unaged and aged samples. Most of the unaged RAS mixes performed well under the OT test; however, similar to the virgin binder mix, significant degradation occurred after aging. The results also suggested that the presence of RAS may cause rapid aging of the binders in asphalt mixtures, which may adversely affect the low-temperature and relaxation properties of the binders and the mixtures as well. The field part of this study included constructing four test sections with different levels of RAP and RAS. Three cores were collected from each section two months after construction. The first core was left unaged, the second core was subjected to 5 days of aging at 85°C, and the third core was subjected to 10 days of aging at 85°C. The asphalt binder was extracted and recovered from these cores prior to being tested using the Dynamic Shear Rheometer (DSR) and the Bending Beam Rheometer (BBR) in order to examine the effect of aging on the four field sections. The results of these tests showed that mixtures containing RAS had a faster deterioration rate in stiffness and binder properties for mixtures containing RAS than for mixtures containing RAP only.

Cooper et al. (2014) evaluated the laboratory performance of asphalt mixtures containing tear-off RAS, manufacturer waste RAS, and no RAS using the dynamic modulus, semi-circular bending, TSRST, and Hamburg wheel tracking tests. The dynamic modulus test indicated that the HMA mixtures with RAS have better resistance to permanent deformation at 54.4°C. The mixture containing manufacturer waste RAS had comparable dynamic modulus ratios to the one with no RAS at 25°C; however, mixes with tear-off RAS exhibited lower ratio; indicating more susceptibility to fatigue cracking. The RAS-containing asphalt mixtures showed better performance with regard to rutting in the Hamburg wheel tracking test and comparable moisture susceptibility to asphalt mixtures prepared with no RAS. Finally, thermal stress restrained specimen tensile strength test results indicated that there was no significant difference in low-temperature cracking performance between the different mixtures.

Zhou et al. (2014) evaluated the impact of tear-off and manufacturer waste RAS on engineering properties of asphalt mixes. The results of their study indicated that adding RAS generally increased the optimum asphalt content (OAC) of HMA mixes with higher OAC corresponding to higher RAS content. In addition, the RAS did not have any significant influence on the dynamic modulus of HMA mixes, but improved their resistance to rutting and moisture damage measured by Hamburg Wheel Tracking device test. The results of the Texas Overlay tester indicated that the RAS mixes exhibited very poor cracking resistance as compared to those without RAS with either PG 64-22 or PG 70-22, even though the RAS mixes have higher OAC. This paper also explored two approaches for improving cracking resistance of RAS mixes in the laboratory and the field. Laboratory test results clearly indicated that both using soft binder and increasing design density can improve cracking resistance of RAS mixes. When considering rutting resistance of RAS mixes, using a soft binder is superior to decreasing design air voids. The effectiveness of decreasing design air voids was confirmed through two field test sections on US 87 near Amarillo, Texas. Four additional test sections were constructed using soft asphalt binders on FM 973, near Austin, Texas. These sections are still being monitored.

Wu et al. (2013) investigated the performance of hot mix asphalt with and without RAS based on the evaluation of field cores drilled from four experimental pavement sections that were constructed in 2009 in King County of Washington State. The performance of the asphalt mixtures were evaluated in term of rutting, fatigue and thermal cracking resistance using different laboratory test. The Hamburg wheel tracking test results suggested that mixtures with RAS exhibited better rutting resistance than mixtures without RAS. The indirect tensile strength test results at low and intermediate temperatures showed that the fatigue and thermal cracking resistance of the mixtures is not significantly affected by the addition of RAS. Finally, the field performance evaluation conducted in this study indicated excellent conditions for all test sections after three years of service.

William et al. (2013) conducted a study as part of a pooled fund program to comprehensively evaluate the effect of RAS, RAS source, the use of RAS in combination with RAP and WMA on pavement performance. Field demonstration projects were constructed in different states. These projects included RAS asphalt mixtures sections in addition to several control sections with traditional binder that either contained RAP or no recycled materials to provide comparisons between RAS mixtures and control mixtures. Binders were extracted and recovered from asphalt mixtures collected from the field demonstration projects and were tested to evaluate the change in binder properties. Laboratory tests were performed on field-produced lab-compacted asphalt mixtures. The results of the binder tests indicated the low-temperature grade for binders in the RAS mixtures increased by 1.9°C for every 1% increase in RAS content. However, for every 1% increase in RAP content, the low-temperature grade increased by 0.3°C only. The asphalt binder test results were not consistent with the asphalt mixture test results. The RAS asphalt mixtures performed well in the bending beam fatigue and SCB tests, and in some cases the RAS mixtures exhibited better fatigue cracking resistance than the control mixtures with no RAS.

Williams et al. (2011) reported the results of another study to characterize the effects of tear-off RAS on the laboratory performance of HMA and its compatibility with fractionated recycled asphalt pavement (FRAP). In this study, a field demonstration project was conducted by the Illinois Tollway on the Jane Addams Memorial Tollway (I-90). Eight mix designs containing zero or five percent RAS and varying percentages of FRAP were developed and placed in the pavement shoulder. The dynamic modulus, flow number, modified Lottman, beam fatigue, and disk compact tension tests were conducted on field-produced laboratory-compacted samples of each of the placed mixes. The flow number and dynamic modulus test results indicated that the mixes containing five percent RAS with less than 40 percent FRAP exhibited an increased resistance to permanent deformation. In addition, the beam fatigue test results showed that these mixes had satisfactory fatigue cracking performance. The disk compact tension results showed that the low-temperature fracture resistance decreased in the Tollway mixes with the addition of recycled materials. Mixtures containing 40 to 50 percent FRAP did not meet the lower recommended energy limit of 350 J/m^2; suggesting that it might have the higher susceptibility to low-temperature cracking. The modified Lottman indicated that mixes with FRAP and RAS at the percentages tested exhibit acceptable levels of durability in a freeze-thaw environment. Finally, Williams et al. (2013) suggested that the fibers in the RAS materials might have contributed to the improved performance of the RAS asphalt mixtures.

Johnson et al. (2010) evaluated the effect of incorporating RAS in asphalt mixtures through a laboratory and field study. The laboratory part included designing and testing field-produced laboratory-compacted samples as well as laboratory-produced and laboratory-compacted mixtures containing no RAS, tear-off, manufacturer waste RAS at three or five percent with either zero, 15, or 30 percent RAP. The asphalt mixtures were found more homogenous with the finer ground tear-off RAS. In addition, tear-off RAS required slightly more asphalt binder than manufacturer waste RAS. Dynamic modulus tests showed that mixtures with tear-off RAS were stiffer than those with manufacturer waste RAS. This difference was most pronounced at the 5% RAS content, and was apparent regardless of the used RAP percentage. Dynamic modulus tests also demonstrated that the stiffening effect of tear-off RAS alone appears to be much greater than RAP alone. The softening effect of using a softer grade (PG 51-34) binder was also apparent in the reduced stiffness and different (smoother) shape of the master curve. The Lottman test results indicated that the tear-offs RAS are more susceptible to moisture damage than manufacturer waste RAS. The results of tests performed on binders extracted and recovered of considered asphalt mixtures indicated that the low-temperature grade of these binders was warmer with the addition of RAP and/or RAS suggesting an increase in thermal cracking potential. The field part of this study included evaluating several experimental test sections that were constructed with mixtures that contain tear-offs and manufacturer waste RAS. These projects demonstrated the performance benefits of using a softer grade binder confirmed the results of the laboratory part of this study. In some cases, the RAS mixtures visually appeared to be more brittle with more severe cracking. In addition, there was little difference in field performance between tear-off and manufacturer waste RAS mixtures.

In summary, most of the previous studies showed that the inclusion of RAP/RAS materials in asphalt mixes affects their performance and changes the rheological properties of the final binder blend and stiffens it. All laboratory and field studies reported that the addition of RAS and RAP enhanced the rutting performance of asphalt mixtures. However, conflicting results were reported regarding the cracking performance of RAS/RAP mixtures. While some laboratory studies showed that RAS and RAP did not significantly affect the low-temperature and fatigue cracking performance asphalt mixtures; other studies reported that the mixtures containing RAS (particularly tear-off RAS) have poor fatigue cracking performance. These results can be explained by differences in the properties of evaluated mixtures (such as binder type) as well as the laboratory tests procedures used in these studies. Differences in testing temperature, loading rate, aging level of samples and test parameter used had significant influence on the obtained test results.

A.4 Micro-Scale Testing for Blending and Diffusion between Recycled and Virgin Binders

Few studies used micro-scale techniques to evaluate the blending between virgin and RAP binders. Some researchers used computer tomography (CT) and scanning microscopy (Mohajeri et al. 2014 & Rinaldini et al. 2014) while others used atomic force microscopy in evaluating the interface or the blending zone between RAP and virgin binders (Nahar et al. 2014; Nazzal et al. 2014; Nazzal et al. 2015). Additionally, Gel permeation chromatography (GPC) and Fourier transform infrared spectroscopy (FTIR) was utilized in evaluating the blending between RAP and virgin binders (Bowers et al. 2014 & Zhao et al. 2015).

Mohajeri et al. (2014) used nano-indentation, nano-computed tomography (nano-CT) scanning and optical microscopy to study the interface zone between reclaimed asphalt binder and virgin binder. Nano-indentation results indicated that there is a blending zone between the simulated virgin binder aggregates and RAP aggregates, which was due to the huge difference in modulus values. The nano-indentation results showed a constant change in the modulus within the virgin binders zone, which was attributed to the different domains within that binder. Nano-tomography also indicated the presence of a blending zone between a column of soft (virgin) and hard (RAP) binders. Optical microscopy was successful in evaluating the interface between the binder and aggregates, but it failed to differentiate between the soft and hard binder.

Rinaldini et al. (2014) used computer tomography (CT) and environmental scanning electron microscopy (ESEM) to investigate the blending between RAP and virgin asphalt material within an asphalt mixture at a micro-scale level. CT images showed that the blending between virgin bitumen and RAP is dependent on the location within the mixture. Some SEM images revealed the presence of micro crack at some locations between the virgin and RAP binders around the aggregates surface. The micro crack might indicate incomplete blending and weak adhesion that may lead to larger cracks within the pavement. SEM images at other locations revealed a possible blend between the RAP and virgin binders. The extent of the blend could not be seen using SEM, but further analysis using energy-dispersive X-ray spectroscopy (EDX) revealed that there is good blending between RAP binder and virgin binder. Overall, the results indicated that the blending between RAP and virgin materials is not homogeneous within the mixture. Some locations showed good blending, while others showed poor blending identified by the presence of micro cracks.

Nahar et al. (2014) evaluated the blending zone between RAP and virgin binder by testing the microstructure of this zone using AFM. The material used included extracted RAP binder and a soft virgin binder. DSR was used to characterize the rheological properties for these two binders in addition to their blend. To test the blending zone using the AFM, 15 grams of RAP binder was applied on one side of a metal sample and on the other side 15 grams of virgin binder was added; the metal sample was heated for 40 seconds at 130 ^{o}C on a hot plate. This created a thin film of interfacial zone in the middle of the sample that was assumed to simulate the blending zone. The AFM images showed a blending zone between RAP binder and virgin binder. Thus, if aggregates covered with RAP bitumen and virgin bitumen come together in an asphalt mixture, they may form a blending zone. The extent of this blending zone is a function of time and temperature. The properties for the bitumen in the blended bitumen were in between that of the virgin and RAP binder in terms of microstructure size and microstructural shape. Accordingly, the DSR results revealed that the mechanical properties of the blended binder were in between the virgin and RAP binder; indicating that there is a relation between the mechanical properties and the microstructure of the blended zone. The authors concluded that the mixing between RAP and virgin binder lead to a new material as no traces of the virgin binder or the RAP binder microstructure was found in the blending zone images.

Nazzal et al. (2014) used AFM to evaluate the nano-mechanical properties of RAP, virgin binder, and composite binder containing 33.6% RAP binder and 66.4% virgin binder. The results indicated that the composite binder had a significantly lower modulus compared to RAP binder and was more like the virgin binder. Additionally, the presence of the RAP in the composite binder adversely affected the binder adhesion properties. In another study, Nazzal et al. (2015) investigated the effects of rejuvenators on the nano-mechanical properties of the interfacial blending zone that forms between RAP and virgin asphalt binders in a high RAP content mixture using AFM techniques. This was done by heating a small amount of each binder side-by-side to create an interfacial blending zone in middle. The results showed that the blending zone between RAP and virgin binder was stiffer than the virgin binder and resembled the RAP binder. The addition of rejuvenators was found to significantly decrease the stiffness of the blending zone and improve its adhesive properties.

Bowers et al. (2014) used GPC and FTIR to evaluate the blending efficiency between RAP binders in asphalt mixtures. The staged extraction method was used to evaluate binder layers within the RAP and virgin binder asphalt mixture blend. In the staged extraction, a specific amount of the asphalt mixture was placed in a basket and was immersed into trichloroethylene (TCE) beaker for 30s, 1 min or 3 min; the basket of the asphalt mixture was then removed and placed in another beaker with clean TCE; this was repeated two more times. In the fourth time, the asphalt mixture was not removed until all asphalt binder was removed from the aggregates. The asphalt binder was then extracted from each beaker using Rotoevaporation. GPC results revealed that the percentage of larger molecular size (LMS) differed for each extracted layer. While the first asphalt layers obtained from the first beaker in the staged extraction process had similar LMS (%) to the virgin binder than the RAP binder, the fourth layer that was obtained from the forth TCE beaker had the highest LMS (%) and was more similar to RAP binder than virgin binder. Although the fourth layer had the highest LMS (%), it did not reach the LMS (%) obtained from the RAP binder. This indicates that some blending occurred within that layer. FTIR showed similar results to GPC, where the carbonyl indices percentage increased consistently from the outermost layer to the innermost layer. Hence, from the GPC and FTIR results the authors concluded that blending does occur between RAP and virgin binder in the asphalt mixture; however, based on the test results obtained from the various layers, blending was not uniform.

Zhao et al. (2015) conducted a similar study using the staged extraction method to evaluate blending and diffusion in high RAP mixtures. The extracted binders were tested using GPC from which LMS (%) for each binder was quantified. The mixtures were prepared with coarse virgin aggregate (retained on sieve #4) and fine RAP aggregates passing sieve #8. This was done to easily distinguish the two types of aggregates. Staged extraction for the course aggregates showed a relatively small change in LMS (%) between the outmost layer to the innermost layer. Thus, the virgin aggregates had a relatively homogenous, well blended asphalt coating. However, for the fine RAP aggregates, the LMS (%) increased from the outermost binder layer to the innermost binder layer. Binders extracted from the outer two layers had statistically similar LMS (%) to the binders extracted from the virgin coarse aggregates. This indicates that the RAP aggregates were coated by a nonhomogeneous binder and that part of the RAP binder surrounding the aggregates was un-mobilized; resulting in a stiffer innermost layer.

A.5 References

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Appendix B Testing Program

This appendix provides a description of all the materials that were used in this research study. In addition, it also provides a description of the employed testing experiments and approaches as well as the preparation procedures developed and used to prepare representative samples for these experiments.

B.1 Materials

B.1.1 Virgin Asphalt Binder

Three different virgin asphalt binders meeting the specifications for PG 58-28 (neat), PG 64-28 (PPA modified), and PG 64-22 (neat). These three PG binder grades are typically used in high RAP and RAS mixes for ODOT. All three binders were obtained from the Shelly Company. Binders with different performance grades were used to evaluate the effect of binder properties on the blending with the RAP and RAS materials. PG 58-28 was the softest grade used, PG 64-28 was the intermediate grade, and PG 64-22 was the stiffest binder. All obtained binders were tested in accordance with AASHTO M320. Table B.1 presents the continuous grade and performance grade obtained for each binder.

Table B.1. Performance and Continuous Grade of the Considered Binders

Binder	Continuous Grade	Performance Grade
PG 58-28	CG 58.5-29.8	PG 58-28
PG 64-28	CG 64.9-30.6	PG 64-28
PG 64-22	CG 66.7-22.0	PG 64-22

B.1.2 Reclaimed Asphalt Pavement (RAP)

RAP materials were obtained from seven different resurfacing projects within Ohio. Table B.2 presents the information of the RAP material obtained. The binder was extracted and recovered from each of the obtained RAP materials in accordance with AASHTO T164 and AASHTO R59. The performance grade was determined for each of the extracted and recovered RAP in accordance with AASHTO M320. Trichloroethylene (TCE) was the solvent used for extraction of all RAP binders. In addition, Toluene was also used for extracting the binder from one RAP material (RAP-IR-270) in order to evaluate the effect of the extraction solvent on the blending of RAP binder and virgin asphalt binders. Table B.3 presents the high- and low-temperature grades for the extracted and recovered RAP binders. Based on the obtained performance grades, four extracted and recovered binders with different rheological properties were selected in this study: RAP-IR-70, RAP-US33, RAP-IR-270TCE, and RAP-IR-270Tol. It is noted that the selected RAP materials were subjected to different aging and environmental conditions through their service life, which resulted in the differences in the properties of the extracted and recovered binders.

B.1.3 Reclaimed Asphalt Shingles (RAS)

Different types of RAS materials were also considered in this study. This included a manufacturing waste RAS and tear-off RAS. The manufacturing waste RAS was obtained from the Shelly company asphalt plant in Kent, Ohio and has been used in paving projects in northeastern Ohio. The tears-off RAS was obtained from Roof to Road (one of ODOT's approved RAS suppliers) processing facility in Columbus, Ohio. The binder from both types of RAS materials was extracted and recovered according to AASHTO T164 and AASHTO R59. While TCE was used for extracting the binder from tear-off RAS, TCE and Toluene were used in the extraction of binder from manufacturing waste RAS. Table B.4 presents the high temperature performance grade that was determined for each of the recovered RAS binders in accordance with AASHTO M320.

Table B.2 Information of the Obtained RAP Materials

RAP ID	Date RAP was Obtained	Project No.	Original Project No. *	Roadway*	RAP Mixture Info.		
					Aggregate	Binder	RAP %
Comp.	Aug., 2015	Yard RAP plant	-	Multiple	LS	NA	-
SR 7	Aug.,2015	302-14	88-03	SR 7	Gravel	NA	10
IR-70	Sep., 2015	11-0386	98-0440	IR70	LS	PG 67-28	10
IR-90	Nov., 2015	625-12	229-05	IR-90	Slag	PG 70-22	10
US 33-2015	Oct., 2015	269-15	349-02	US 33	LS	PG 70-22	10
US 33-2014	Oct., 2015	16-14 & 455-13	-	US 33	-	-	-
IR-270	June, 2016	8035-15	-	IR-270	LS	PG70-22	

Table B.3 Performance Grade of the RAP Materials

RAP ID	Extraction Solvent	Continuous High Temperature Grade, °C	Continuous Low-Temperature Grade, °C
Composite	TCE	81.2	-19.8
SR 7	TCE	96.8	-13
IR-70	TCE	83.5	-19.1
IR-90	TCE	80.2	-20.6
US 33	TCE	90	-16.1
US 33-2014	TCE	89	-19.2
IR-270-TCE	TCE	78.1	-23.5
IR-270-Tol	Toluene	79.7	-23.1

Table B.4 Performance Grade of the RAS Materials

RAS ID	Extraction Solvent	Source	Continuous High Temperature Grade, °C
Tear-off-TCE	TCE	Tear-off from Roof to Road	163.9
M.W.-TCE	TCE	Manufacturing Waste obtained from Shelly Company	143.2
M.W.-Tol	Toluene		145.2

B.1.4 Mixtures

To evaluate the effects of the RAS/RAP materials on the fracture performance, a mix that was used in construction of intermediate course layer in a resurfacing project on interstate highway 270 (IR 270) was selected. The considered asphalt mixture had a ¾-inch (19-mm) nominal maximum aggregate size (NMAS) and was designed to meet ODOT specification for Item 442 Type A for heavy traffic intermediate mixtures. The selected mixture included PG 64-28 asphalt binder. The aggregate blend of the original mixture used in the field included: limestone aggregates, natural sand, manufactured sand, and 25% of RAP-IR270 that was processed using ODOT 401.04 Method 2. Plant produced samples of intermediate course mixtures were collected during the construction. In addition, the same aggregates, RAP (RAP-IR-270), and the binder used in producing the field mixes were obtained.

Several asphalt mixes were designed and produced in the lab to evaluate the effects of RAP, RAS and their combination. These included: control mixture (no RAP), control mixture with 30% RAP, control mixture with 5% tear-off RAS, control mixture with 3% tear-off RAS and 20% RAP. The aggregate gradation of all lab produced mixes were maintained as close as possible to that of the field produced mix by adjusting the percentages of the virgin aggregate in the mix. The ratio between the percent manufactured sand and natural sand was also maintained as possible for each mix to eliminate performance variability from sand angularity. Figure B.1 presents the aggregate gradations of all designed mixes.

Superpave mix design was performed according to ODOT specifications for Item 442 to determine the optimum asphalt content for the different considered mixes. This process involved evaluating the volumetric properties of mixtures prepared with at least three different asphalt contents ranging between 2.5 to 5.0 percent. Two samples were prepared for each asphalt binder content. Mixing and compaction temperatures of 153°C and 145°C, respectively, were used for all considered mixtures. Some of the prepared mixture was left loose and was used to determine the mix maximum specific gravity. The maximum specific gravity G_{mm}, mix bulk specific gravity G_{mb}, VTM, VMA, VFA, % G_{mm} @ N_{design}, and % G_{mm} @ $N_{initial}$ were computed for the prepared samples. The data were then analyzed to select the optimum asphalt binder content that corresponds to an air void of 4 percent. A summary of the mix design results for the designed mixtures is presented in Table B.5. It is noted that as a part of this study, the effect of RAP sampling on the mixture design and performance parameters was examined. To this end, two mixtures with 30% RAP were designed using two sampling methods. In the first mixture, the RAP material used was split one time using a dual splitter that provides two samples of relatively homogeneous gradations of the RAP material. The RAP material used in the second RAP mixture was split four more times to receive eight different sampling quadrants, which significantly increased the gradation uniformity used in the mixtures. As noticed in Table B.5, although the same amount of RAP was used in the two mixtures the first mixture required 0.4% less virgin asphalt binder content than the second (2.9% as compared to 3.3%). This indicates that there was higher RAP binder replacement ratio in the first RAP mixture. Asphalt binder content analysis of the used RAP-IR 270 showed that the fine portion of RAP (passing sieve number 4) had much more asphalt binder than the coarse portion of the same RAP. Thus, the first method of sampling RAP resulted in a material with more fine portion and higher asphalt binder content than the one in produced in the field. This indicates the importance of using a representative RAP sample when performing the mix design in the laboratory. It is noted that the mix design for 5% RAS mixture showed that the RAS contributed 0.6% to the asphalt mix; such that 12% RAS binder was available. This study also included evaluating mixes with 5% RAS that assumed 18% RAS binder was available.

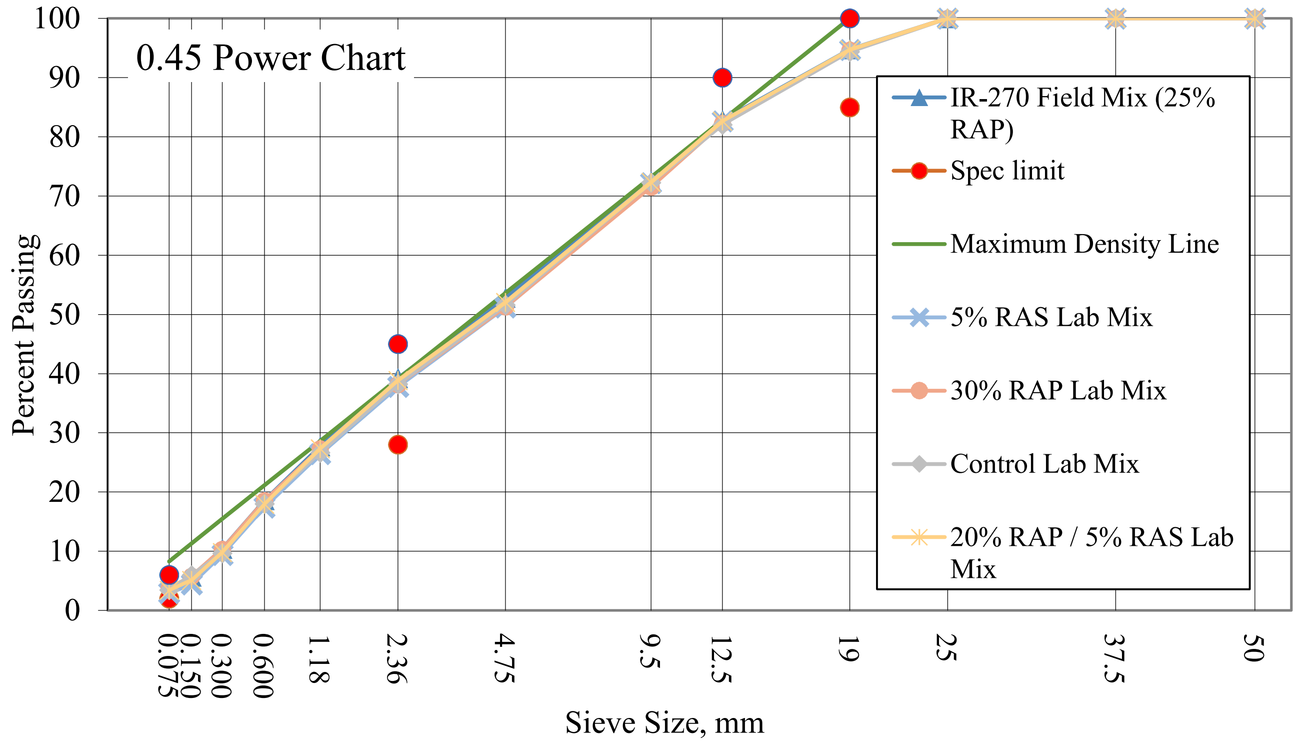


Figure B.1 Gradations of the Mixes Evaluated In this Study

Table B.5 Tested Mixture Properties

	270 Field	Control	30% RAP-1	30% RAP-2	5% RAS	5% RAS	20% RAP 3% RAS
Virgin Binder Content	3.3	4.7	2.9	3.3	4.1	3.8	3.1
RAP/RAS replacement ratio	0.28	0.00	0.38	0.30	0.13	0.19	0.34
G_{mm}	2.482	2.484	2.495	2.471	2.464	2.476	2.478
% 57s	23	28	23	23	28	28	24
% #8s	15	26	14	14	26	26	18
% Man. Sand	22	25	18	18	23	23	15
% Nat. Sand	15	21	15	15	18	18	20
% RAP	25	0	30	30	0	0	20
% RAS	0	0	0	0	5	5	3

B.2. Micro-Scale Experiments

Atomic Force microscopy (AFM) was used in this study to better understand the blending between RAP/RAS binders and virgin asphalt binders. AFM is a flexible high-resolution scanning probe microscopy technique, which uses a laser-tracked cantilever with a sharp underside tip (probe) to raster over while interacting with the sample. AFM is an ideal tool for measuring nano and micro-scale forces within a composite material (Beach et al. 2002; Nguyen et al., 2005). It has become increasingly useful when testing engineering materials such as visco-elastic asphalt binders to understand nano-mechanical properties (Nazzal et al. 2013). Modern AFM systems can accurately map a particular force in various imaging modes with nanometer resolution or track the dependence of different components as a function of tip-surface distance with sub-nanometer resolution. The following subsections provide a detailed description of the experiments conducted in this study.

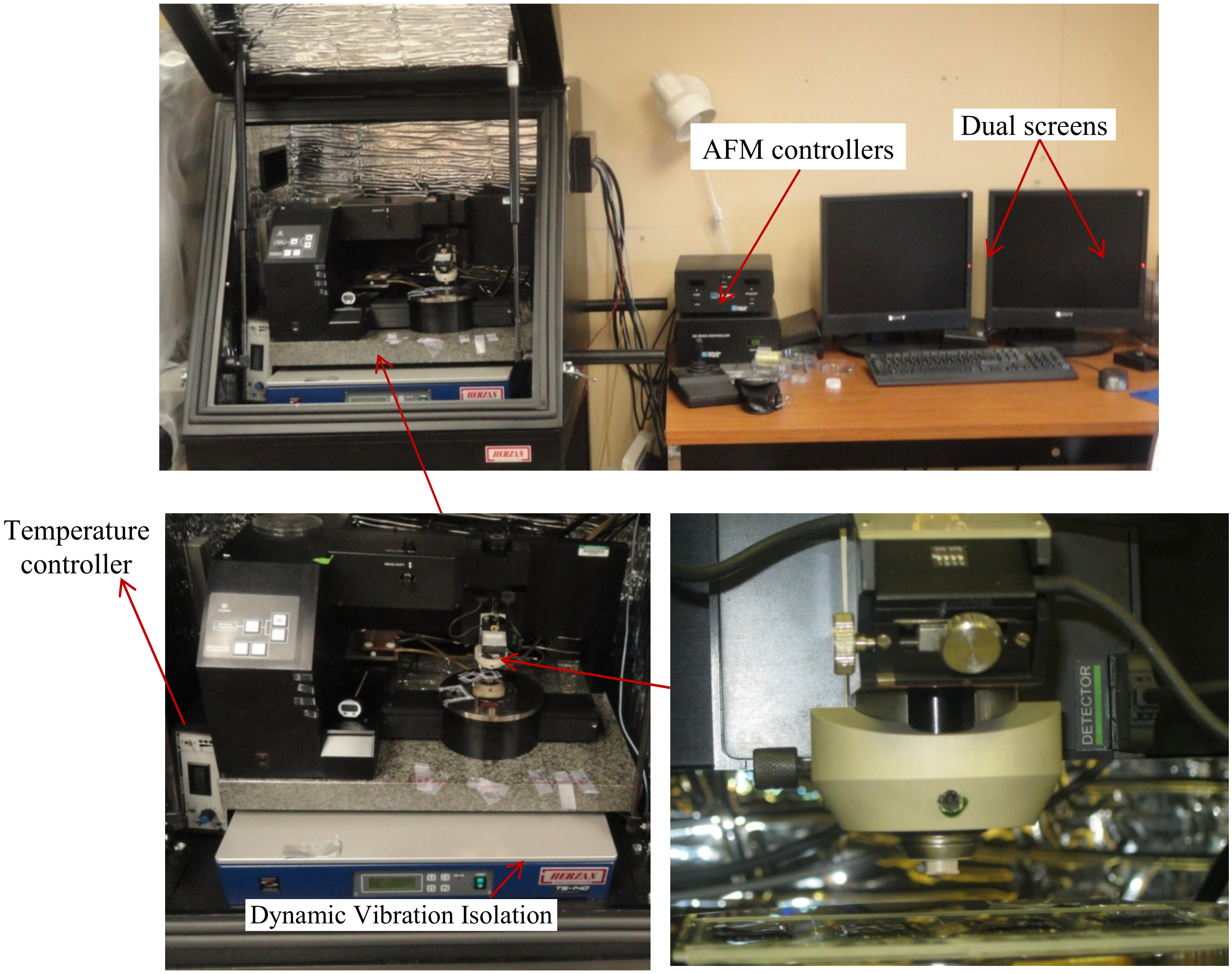
B.2.1 AFM Specimen Preparation

AFM samples were prepared using a procedure developed in this study to simulate the interaction between RAP and virgin binders that occurs in an asphalt mixture during its production. The procedure involved placing a pre-determined amount of binder on a glass microscope slide that was broken in half and tightly attached together at the opposite ends using aluminum tape. The weight of each binder was determined by multiplying the specific gravity of the binder by the volume of the constraint on the slide. Once the proper weight was placed on the confined glass slide, the samples were heated on a hot plate for a specific time and temperature. The RAP and virgin binders were soft enough to heat at 153°C for 5 minutes to spread and ensure developing a smooth surface for testing. However, the RAS binders were much stiffer and required a longer heating time of two hours with a higher temperature of 210°C for tear-off RAS and 170°C for manufactured waste RAS, along with added weight on top of the sample to spread the binder over the surface. A small piece of Teflon paper was placed between the weight and the RAS binder to prevent the binder from sticking to the weight. After the slides with different binders were prepared, they were allowed to cool down to room temperature. The tape longitudinal to the slide was removed and the two halves of the slide were separated. The edges of the slides were finely cleaned to ensure optimal blending without contamination. The slides with recycled materials (RAP or RAS) were then heated on a hot plate for 30 seconds at 153°C, which was done to simulate the heating of RAP with aggregates before adding the virgin binder. After this, the slide with the virgin binder was quickly pressed against the edge of the recycled binder slide. Immediately after the virgin and RAP binders slides were combined together, the assembly of the two slides was heated on top of a hot plate for a period of 3 minutes at 153°C. This resulted in melting and spreading of the binders on both sides; creating a thin film with a diffused interfacial zone at the middle. Figure B.2 shows pictures taken during preparation of one of the RAP and virgin asphalt binder's combination. Once the samples were prepared, they were stored in a refrigerator to prevent any further diffusion between the binders until tested.

B.2.2 AFM Testing Experiments

An Agilent 5500LS AFM (Figure B.3) was used to perform all the AFM experiments in this study. Two AFM techniques were used in this study: AFM force spectroscopy and AFM imaging. Force spectroscopy experiments were performed at a temperature of 24 ± 1 °C to measure the elastic modulus and bonding energy for the different RAP/RAS and virgin binder combinations shown in Table B.6. In these experiments, the tip penetrates the sample surface to a specific indentation depth and then is retracted away from the sample surface. The selected indentation depth was around 0.3 μm, which is less than 10% of the sample thickness to minimize any boundary effects from the glass slide. The force spectroscopy tests were conducted at a constant test duration of 2 seconds for all indentation experiments. Micromasch HQ:NSC19/AL BS tips were used for all tested samples. The cantilever for these tips had an average frequency of 90 kHz, a force constant ranging from 1.5 to 2 N/m, a length of 125± 5 μm, a width of 22.5± 3 μm, and a thickness of 1± 0.5 μm.

Figure B.2 AFM Sample Preparation



Agilent 5500LS AFM **AFM Scanner**

Figure B.3 AFM Testing Setup

Force spectroscopy experiments were performed for each sample combination by testing different points along a straight line over the sample surface. As shown in Figure B.4, testing started at the RAP or RAS binder zone towards the interface and into the virgin binder zone. The spacing between the tested points was typically higher in the RAP and virgin binder zones but drastically decreased as the blending zone is approached to capture any changes in the properties of the binder. The spacing between tested points within the blending zone varied between 5 to 30 µm. At least two replicate samples were tested for each RAP/RAS and virgin binder combination, and two lines of data were collected for each sample.

Table B.6 The RAP/RAS Virgin Asphalt Binder Combinations Tested Using AFM

Combination	Binder from Recycled Materials	Virgin Binder
1	RAP-IR70	PG 58-28
2	RAP-IR70	PG 64-28
3	RAP-IR70	PG 64-22
4	RAP-US33	PG 58-28
5	RAP-US33	PG 64-28
6	RAP-US33	PG 64-22
7	RAP-IR270-TCE	PG 64-28
8	RAP -IR270-Tol	PG 64-28
9	Tear-off RAS	PG 58-28
10	Tear-off RAS	PG 64-28
11	Tear-off RAS	PG 64-22
12	Manufacturing Waste RAS-TCE	PG 64-28
12	Manufacturing Waste RAS-Tol	PG 64-28

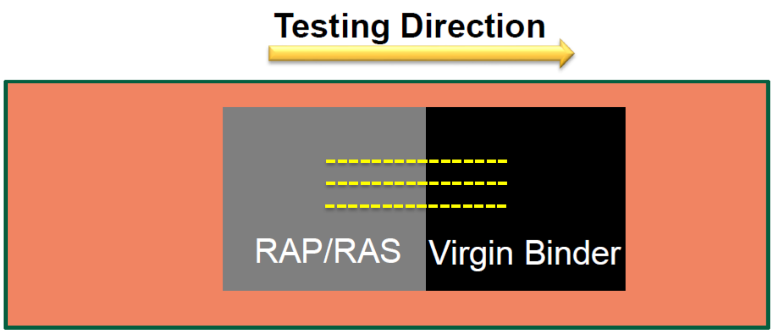


Figure B.4 AFM Testing of Samples

The outcome of a single indentation in a force spectroscopy experiment is a force-distance curve similar to that presented in Figure B.5. The curve is divided into two parts: the approaching part and the retracting part. At first, the tip starts approaching the sample surface, as the tip gets closer to the surface, the force between the tip and the sample starts to increase slightly. As soon as the tip contacts the surface, a significant increase in the deflection of the cantilever occurs. The tip will then continue to penetrate the sample to the pre-selected indentation depth. The maximum observed positive force is reached at the maximum indentation point. The tip is then retracted from the sample surface until it overcomes the adhesive forces between the tip and asphalt and completely snaps off the asphalt sample.

The force spectroscopy test results were analyzed to determine the reduced elastic modulus of the asphalt binder and the total energy needed to separate the tip from the asphalt sample. The reduced elastic modulus, $E_{reduced}$, was calculated using Equation B.1, which is based on Sneddon's modification of the Hertzian model for the indentation of a flat, soft sample by a stiff tip (Fischer-Cripps 2006):

$$E_{reduced} = \frac{\pi}{2} \frac{F}{\delta^2 \tan(\alpha)} \tag{B.1}$$

$$\delta = z - d \tag{B.2}$$

where F is the measured force, δ is the indentation depth, α is the half-opening angle of the AFM tip, d is the cantilever deflection, and z is the piezo-driver displacement.

The total bonding energy needed to separate the tip from the asphalt sample, $E_{bonding}$, was estimated using Equation B.3. This equation represents the area under the force-distance curve in the retraction region where the force is less than zero (Pauli et al. 2013), as indicated by the shaded portion of Figure B.5.

$$E_{bonding} = \int_{z_o}^{z_1} F dz \approx \frac{\Delta z}{2N} \sum_{i=1}^{N} [F(z_{i+1}) + F(z_i)] \tag{B.3}$$

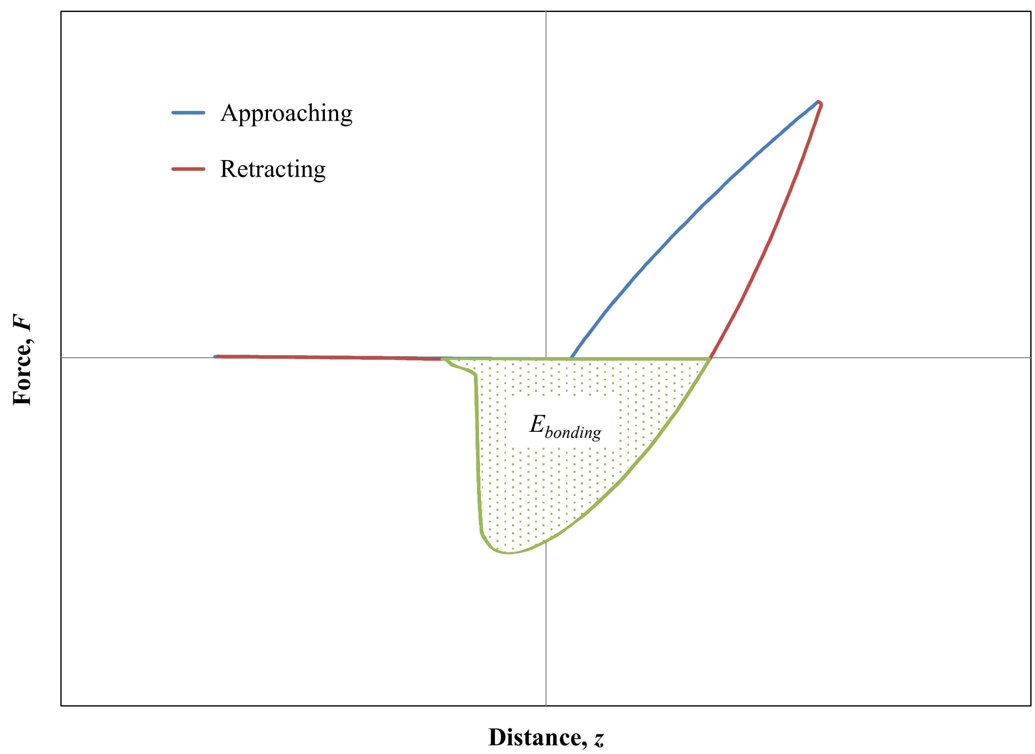


Figure B.5 Typical Force-Distance Curve Obtained In A Force Spectroscopy Experiment

AFM tapping mode images were obtained during the testing of different samples. At least two images were obtained within each of the three zones: RAP/RAS binder zone, blending zone, virgin binder zone. Tapping mode was utilized rather than contact mode to prevent damage to the relatively soft binder material. This was performed by setting a pre-determined frequency for the cantilever tip to oscillate. The oscillating tip was scanned across the surface of the binder, while the change in amplitude produced a topographical and phase imagery of the binder surface. Image dimensions were taken between 6 and 10 µm to obtain high quality resolution. A phase shift will result from this procedure due to the lag between the piezo signal and tip.

B.3 Macro-Scale Experiments

Three different tests were performed on the different mixtures considered in this study to evaluate their fatigue and low-temperature cracking resistance. All samples for these tests compacted to a target air void of 7 ± 0.5%.

B.3.1 Semi-Circular Bending (SCB) Test

The SCB test was conducted on each mixture to evaluate fatigue cracking performance at an intermediate temperature of 25°C. The SCB tests were performed according to the Illinois SCB test Method (AASHTO TP 124-16: *Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperatures)* and the Louisiana SCB test Method (ASTM D8044-16: *Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures*). An Instrotek© Auto SCB, Figure B.6 was used to conduct all SCB tests. Both SCB test methods are discussed in the following subsections in detail.

B.3.1.1 *Illinois Method*

In the Illinois SCB Method (SCB-IL), mixture samples were compacted with 150 mm diameters and heights of 150 mm. All samples made were in full compliance with AASHTO TP 124-16. A cutting jig was used to cut each sample in half and trim the ends to obtain a thickness of 50 ± 1 mm thickness. Each 50-mm thick sample was then cut in half to create the semi-circular shape. A notch depth of 15 mm and width of 2.5 mm was cut into the center of the sample, as shown in Figure B.7. The SCB-IL test was conducted on at least four short-term aged samples and four long-term aged samples. The short-term aging involved placing the loose mixture for four hours at a temperature of 135°C before compacting the samples. The long-term aging was conducted according to AASHTO R30 and involved placing the samples in an environmental chamber for 5 days at 85°C. All short-term aged and long-term aged samples were conditioned for at least 3 hours at 25°C before testing. The SCB-IL was performed by loading the sample monotonically to failure at a constant cross-head deformation rate of 50 mm/min. Load and vertical deformation was recorded until failure. The main output of the SCB-IL is the load versus deformation plot, Figure B.8. From this plot, the Fracture Energy (G_F) and the Flexibility Index (FI) are calculated, using the Equations B.4 and B5, respectively. The Fracture Energy represents the energy needed to propagate a crack through the pavement layer, whereas the Flexibility Index identifies brittle mixes that are prone to pre-mature cracking (Al-Qadi et al. 2015).

$$G_F = \frac{W_f}{Area_{lig}} \text{ x } 10^6 \qquad \text{(B.4)}$$

Where:

- G_F = Fracture Energy (Joules/m^2)
- W_f = work of fracture, or area beneath load vs. displacement curve up to peak load (Joules)
- $Area_{lig}$ = ligament area, ligament thickness x length (mm^2)

$$FI = \frac{G_F}{|m|} \text{ x } A \qquad \text{(B.5)}$$

Where:

- $|m|$ = absolute value of slope at inflection point
- A = unit conversion (0.01)

Figure B.6 Instrotek© Auto SCB Testing Equipment

Figure B.7 Illinois SCB Sample Preparation And Testing Equipment

B.3.2.1 Louisiana Method

The Louisiana SCB (SCB-LA) test also quantifies the propensity of asphalt mixtures to cracking. However, the test is conducted on samples that are 150 mm in diameter and 57 mm in thickness. Samples at three different notch depths (25.4 mm, 31.8 mm, and 38.1 mm) need to be tested in the SCB-LA method. At least four samples should be tested for each notch depth. The SCB-LA test was conducted by loading the sample monotonically to failure at a constant cross-head deformation rate of 0.5 mm/min rate. The Fracture Energy needed to cause failure was determined for each sample by computing the area under the load versus displacement curve up to the peak load. The critical strain energy release rate (J_c) was calculated by fitting Equation B.6 the average strain energy per thickness of the sample with each notch depth.

$$J_c = \frac{-1}{b}\left(\frac{dU}{da}\right) \tag{B.6}$$

Where

b = the sample thickness (m)

a = sample notch depth (m)

U = strain energy up to peak load of failure (kJ)

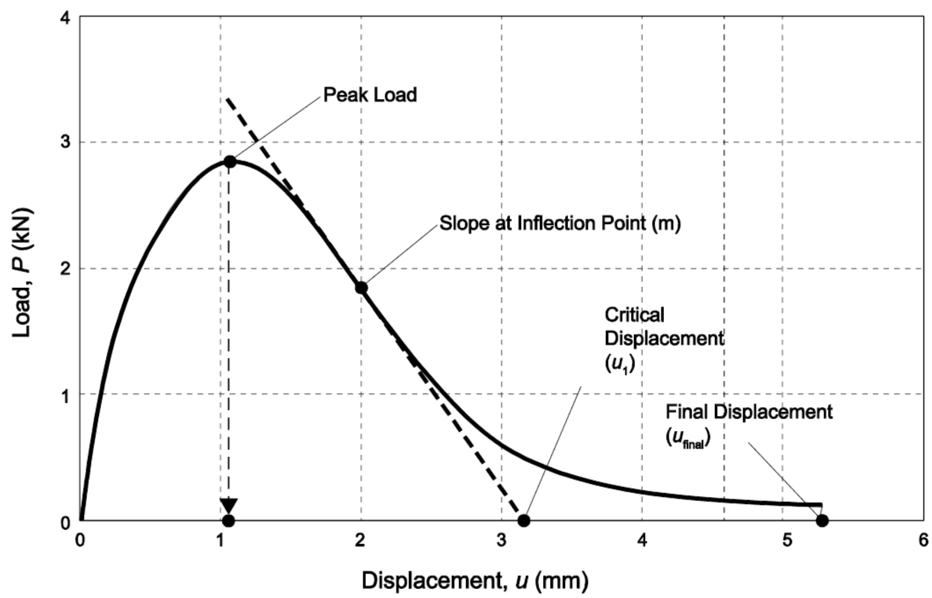


Figure B.8 Plot of Load vs. Displacement Obtained from Illinois SCB Test (Al-Qadi et al. 2015)

B.3.2 Indirect Tensile Strength (IDT) Test

The IDT test was conducted in accordance with AASHTO T245 at 25°C on at least three cylindrical samples 150 mm in diameter and 95 mm thickness. A deformation rate of 50 mm/min was used. The load as well as the vertical and lateral deformations were continuously recorded. The indirect tensile strength is computed using Equation B.7. In addition, the toughness index (TI), which is a parameter that describes the toughening characteristics in the post-peak region, was also calculated using Equation B.8.

$$\mathrm{ITS} = \frac{2P}{\pi DT} \tag{B.7}$$

P: is the peak load, lb

D: is the specimen diameter, in

T: is the specimen thickness, in

H_t: is horizontal deformation at peak load, in

$$\mathrm{TI} = \frac{A_{3\%-P}}{(3\% - \varepsilon_p) * \mathrm{Stress}_{peak}} \tag{B.8}$$

Where:

$A_{3\%-p}$: is the area under stress-strain curve between the peak lateral strain and a lateral strain value of 3%

ε_p: is the lateral strain at peak stress in %

Stress_{peak}: maximum stress value obtained.

B.3.4 AASHTO T283

The moisture susceptibility of designed mixtures was evaluated using the AASHTO T283 test procedure modified according to the standard practices implemented in the State of Ohio. At least six samples 6 inch (150 mm) in diameter and 3.9 inch (95 mm) in height were prepared for each mixture. The samples were then divided into two groups. The first group, control samples, was wrapped with Saran-Wrap and stored at room temperature for testing in the dry condition. In addition, the second group was conditioned. The conditioning procedure involved partially saturating the samples to a level between 70 to 80 percent in a water bath under a 2.9 psi (20 kPa) vacuum pressure for approximately two to three minutes. The partially saturated samples were then wrapped and placed in a plastic bag, and 10 ml of water was added to the bag. The samples were then subjected to a freezing cycle by placing them for 16 hours in an environmental chamber at a temperature of 0°F (–18°C). After the freezing cycle, the samples are thawed in a water bath at 140°F (60°C) for about 24 hours. Finally, the samples were conditioned for 2 hours in a water bath at a temperature of 77°F (25°C) before testing.

The indirect tensile strength test was conducted on the dry and conditioned wet samples. The tensile strength ratio (TSR) was then computed as the ratio between the average indirect tensile strength of the wet conditioned specimens to average indirect tensile strength of the dry unconditioned specimens. The TSR ratio is a measure of the resistance of the asphalt mixture to moisture damage. The higher the TSR ratio of an asphalt mixture, the better its resistance to moisture-induced damage.

B.3.5 Asphalt Concrete Cracking Device (ACCD)

This test was conducted to evaluate the low-temperature cracking resistance of mixtures considered in this study. In this test, a 60-mm (2.3-inch) diameter inner core of the prepared 6 inch (150 mm) specimen was first cored out. A 22.4-mm (0.88-inch) long-notch was then introduced at the outer surface of the sample to control the location of the crack. The test specimen and the ACCD ring were heated for 60 minutes at 65°C, and the tapered end of the heated ACCD ring was placed in the center hole of the heated test sample. The sample with the ACCD ring was placed in an environmental chamber (Figure B.9). As the temperature decreased, the contraction of the asphalt mix specimen was restrained by the ACCD ring, developing tensile stress within the test specimen and compressive stress within the ACCD ring. Four samples can be typically tested at the same time. The temperature and strain of each ACCD ring were continuously recorded until failure. The temperature corresponding to the maximum slope of the ACCD strain-temperature curve was considered as the onset on thermal cracking. The point at which the slope of the strain-temperature curve equals to eighty percent of the maximum slope after the onset of cracking is defined as the ACCD cracking temperature. The ACCD was performed on short-term and long-term aged specimens.

Figure B.9 ACCD Test Setup

Appendix C Test Results And Data Analysis

C.1 Introduction

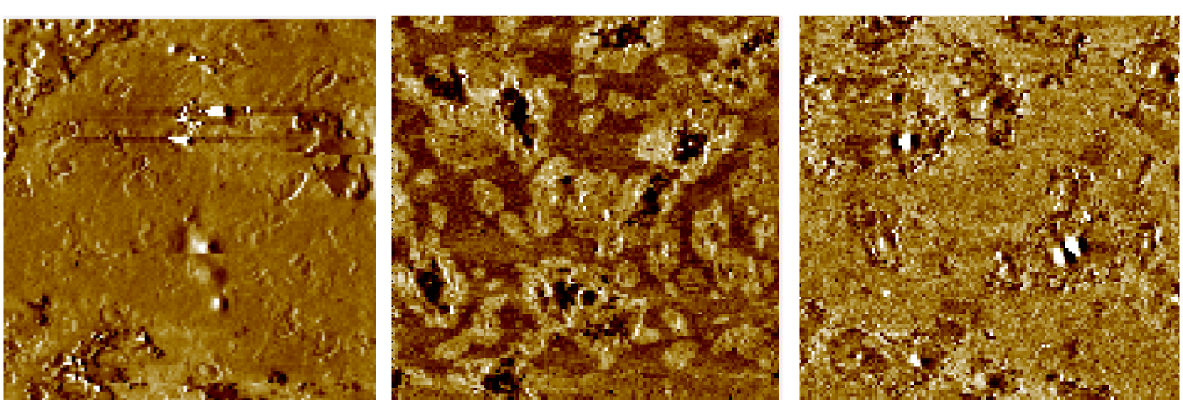
This appendix presents the results of the different AFM experiments and macro-scale tests that were conducted in this study. A comparison between the results obtained in macro-scale tests and AFM experiments is also provided. The chapter is divided into several sections. The layout of each section includes first the presentation and discussion of the test results. This is followed by summarizing the outcome of the statistical analyses that were conducted on the experimental data.

C.2 AFM Imaging Results

Tapping mode imaging was performed on different samples considered in this study. High quality images were obtained for the extracted and recovered RAP/RAS binder, blending zone and virgin asphalt binders to qualitatively evaluate the blending between those binders.

C.2.1 RAP Samples

AFM images were obtained during the testing of the different types of extracted and recovered samples. In general, there were no significant differences between RAP binders considered in this study. Figures C.1a-c present representative phase images of the RAP, interfacial blending zone, and virgin asphalt binder (PG 64-28) that were obtained for the TCE extracted RAP- IR-270 samples. It is clear that the micro-structure of the RAP binder is different from that of the virgin asphalt binder; such that the size of "bee-like" structure in the considered RAP binders is significantly smaller than that for the virgin asphalt binder. This may be attributed to the aging of the RAP binder, which may have resulted in obstructing the movement of asphalt molecule chains, and in preventing the crystallization of microcrystalline waxes and waxy molecules. Figures C.1b shows the images of the interfacial zone that develops between the RAP and virgin asphalt binders. It is clear that the micro-structure of the interfacial zone is different from both the RAP and virgin asphalt binder and is affected by those binders. The "bee-like" structure of interfacial zone was larger than that of the RAP asphalt binder but much smaller than that of the virgin binder. In addition, the phase contrast between dispersed domains and flat matrix observed for the virgin binder seems to be inverted. Hence, Figures C.1a-c clearly suggest that there was some blending at the interface between the RAP and virgin binders, which occurred at the micro-scale level in a fairly uniform manner.

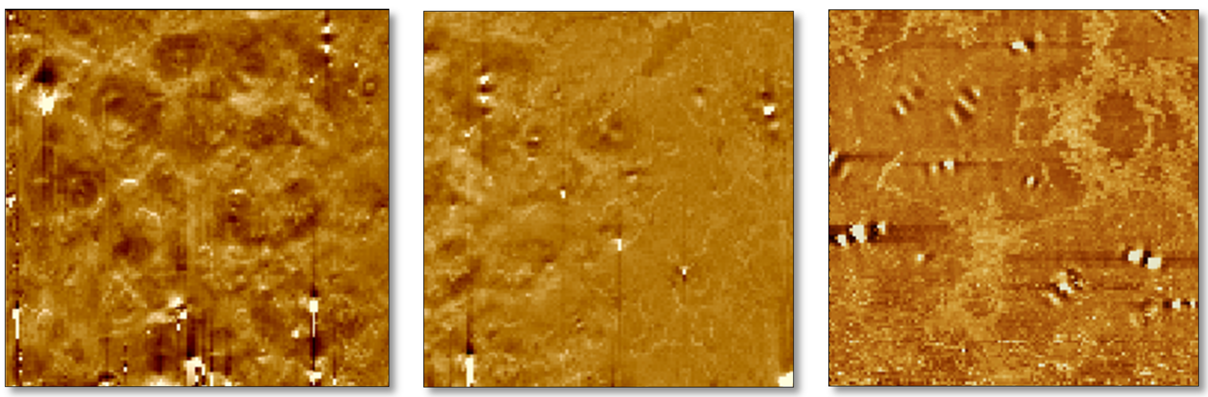


a) **b)** **c)**

Figure C.1 AFM Phase Imaging IR-270 RAP TCE Recovered + PG64-28 a) RAP Binder b.) Blending Zone c) Blending Zone d) Virgin Binder

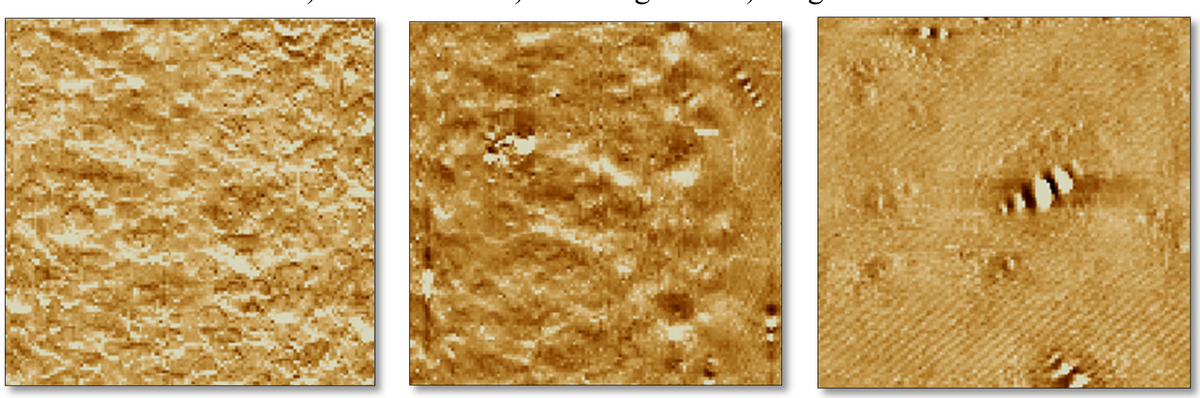
C.2.2 RAS Samples

AFM images were also obtained for the manufacturing waste and tear-off RAS binder samples. Figures C.2a-c show the phase images for tear-off RAS and PG64-28 virgin asphalt binder samples. It is clear that the tear-off RAS binder (Figure C.2a) had different micro-structure than the virgin asphalt binder (Figure C.2c). Figure C.2b presents the image taken at the interface between the tear-off RAS and PG64-28 virgin asphalt binder. A clear distinction between the tear-off RAS and virgin binder is observed within the interface image, which indicates that no blending occurred between the two binders. This was also observed in the images for tear-off RAS and PG64-22 virgin asphalt binder samples shown in Figure C.3b. Representative phase images for the tear off RAS and PG58-28 virgin asphalt sample are shown in Figures C.4a-c. The image of the interfacial zone shown in Figure C.4b suggests that the zone contained tear-off RAS and virgin asphalt domains that did not blend. This image suggest that for PG 58-28 binder diffused into the RAS binder but complete blending did not occur.



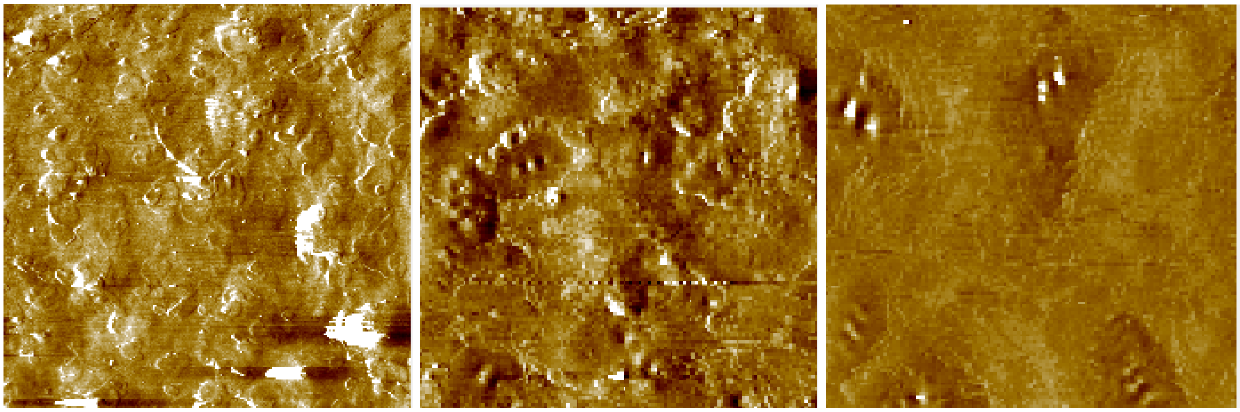
a) **b)** **c)**

Figure C.2 AFM Phase Imaging Tear-off RAS + PG64-28:
a) RAS Binder b.) Blending Zone c) Virgin Binder



a) **b)** **c)**

Figure C.3 AFM Phase Imaging Tear-off RAS + PG64-22:
a) RAS Binder b.) Blending Zone c) Virgin Binder



a) b) c)

Figure C.4 AFM Phase Imaging Tear-off RAS + PG58-28:
a) RAS Binder b.) Blending Zone c) Virgin Binder

C.3 Results of Force Spectroscopy Experiments

The results of force spectroscopy experiments were analyzed to determine the reduced modulus and bonding energy for RAP/RAS aged binders, virgin binders, and interface zone between these binders. The following sections summarize the obtained results.

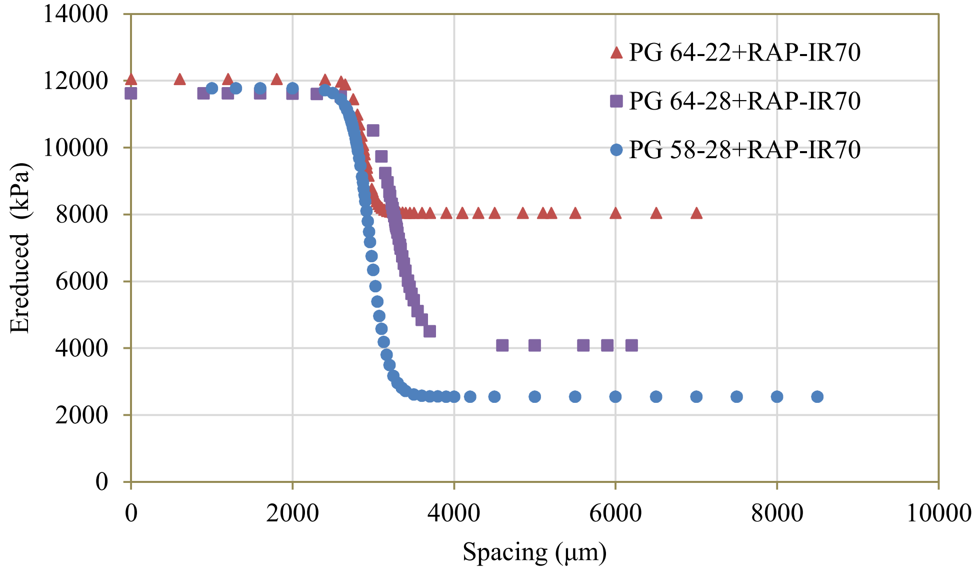
C.3.1 RAP Samples-Reduced Modulus and Bonding Energy Curves

The values of the reduced modulus and bonding energy were plotted with the distance along the sample where the blending occurred. Figures C.5a,b present the typical reduced modulus and bonding energy curves obtained from force spectroscopy experiment for the combinations of RAP-IR70 and all virgin binder, respectively. From Figure C.5a, the curve for any combination starts with the reduced modulus of RAP binder where the slope of the curve is constant and the modulus is high. Once the blending zone is approached, a gradual decrease in the modulus values occurs and the slope of the curve starts to drop until it reaches an asymptote representing the virgin binder reduced modulus. Similarly, Figure C.5b shows the variation of the bonding energy with distance across the samples for RAP-IR70 and virgin binders. The curve showed opposite behavior to that of the reduced modulus curve. The curve starts with the low bonding energy values for the RAP binder. The bonding energy starts to increase when the blending zone is reached as shown by the sharp increase in the slope curve, and finally it reaches constant values over the virgin binder, which had much higher bonding energy than RAP binder. Similar behavior was observed for the other combinations of RAP and virgin binders.

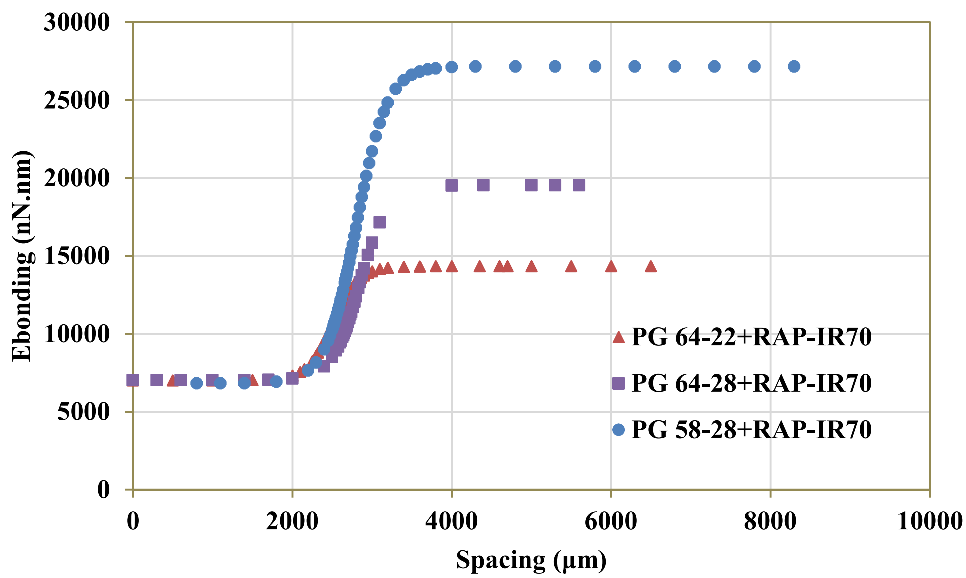
C.3.2 RAP Samples-Average Reduced Modulus of The Different Zones

The average values of the reduced moduli for RAP binder, blending interfacial zone, and virgin asphalt binder were computed for the different RAP-virgin binder combinations. Figures C.6a,b present the computed values for RAP-IR70 and RAP-US33 combinations, respectively. The error bars associated with the bar chart represents the standard deviation. It is clear that the RAP-US33 had a higher modulus value as compared to RAP-IR70, which is in agreement with the high temperature performance grade obtained from the DSR test results. Furthermore, the two RAP binders had a higher modulus as compared to the virgin binder. In general, the indentation modulus of the blending zone depended on the virgin binder PG grade and the RAP source. The blending zone for each combination, the modulus of blending zone between RAP-IR70/RAP-

US33 and PG 58-28 moduli was different than those of RAP and virgin binders, and was in between them. A similar behavior was observed for the PG 64-28; however, the modulus of the blending zone between both RAP binders and PG 64-28 was closer to the RAP binder than it was to the virgin binder. The blending zone between the RAP binders and PG 64-22 showed slightly different behavior based on the RAP binder being used. For RAP-IR70, the modulus of the blending zone was between those of the RAP and virgin binder moduli but slightly closer to the virgin binder PG 64-22. However, for the RAP-US33 sample the modulus of the blending zone was closer to that of PG 64-22 and lower than that the RAP binder.



(a)



(b)

Figure C.5 (a) Typical Reduced Modulus For RAP-IR70 And Virgin Binder Sample (B) Typical Bonding Energy Values For RAP-IR70 And Virgin Binder Sample

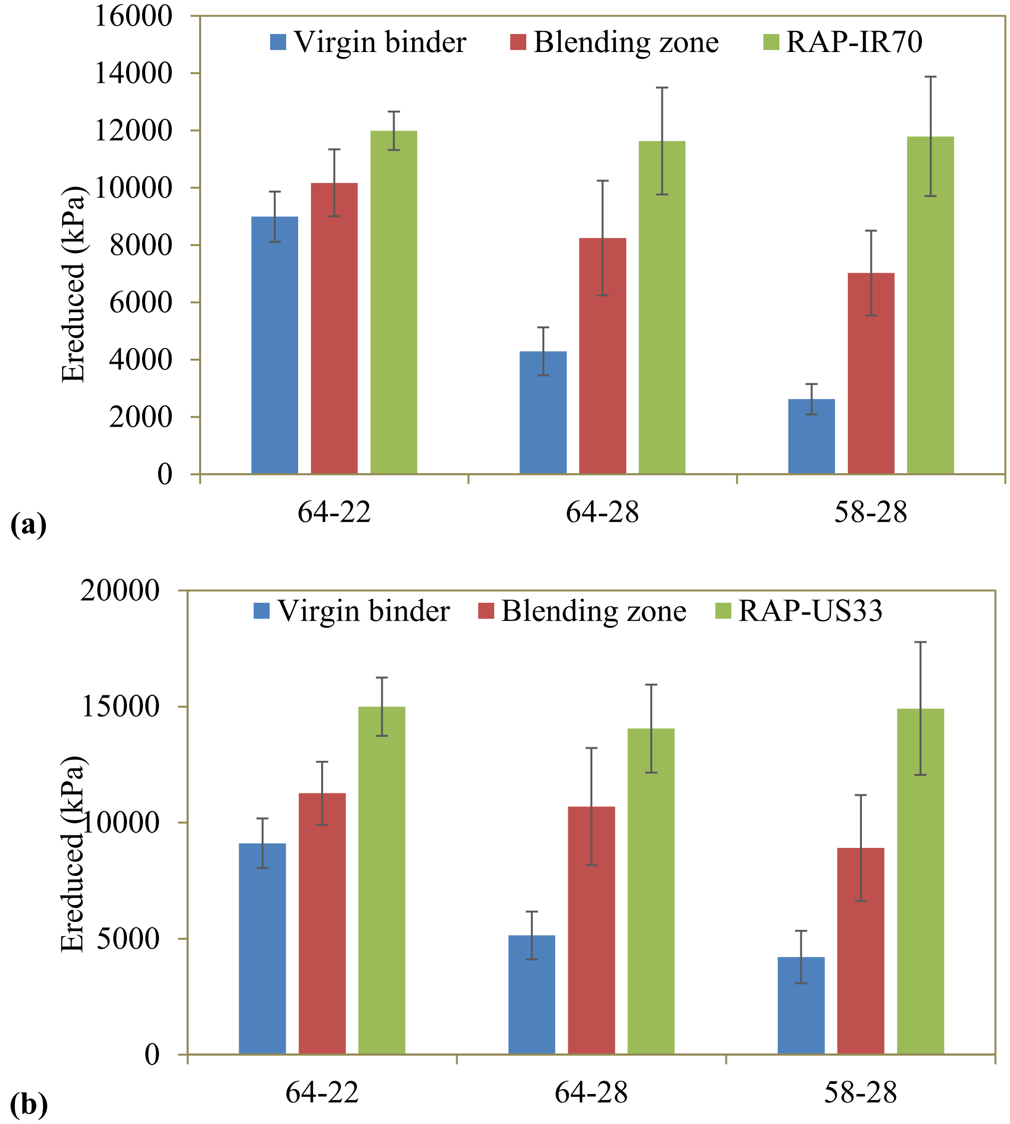


Figure C.6. Average Reduced Modulus Values For (a) RAP-IR70 and Virgin Binder Combinations (A) RAP-US33 And Virgin Binder Combinations

In general, the moduli for the three blending zones between RAP-US33 and virgin binders were higher than the blending zones with RAP-IR70. This is expected since RAP-US33 had a higher modulus than RAP-IR70. The results indicate that some blending occurred between the RAP and the virgin binders. The high standard deviations in the blending zones between RAP and PG 58-28/PG 64-28 indicate that two phases occurred with the blending zones, one that resembles the RAP binder and another phase that resembles the virgin binder.

To further evaluate the effect of RAP and binder properties on the blending zone, Analysis of Variance (ANOVA) and post-ANOVA Least Square Mean analyses (LSM) were conducted using Statistical Analysis Software (SAS). Table C.1 presents the ANOVA and post-ANOVA analyses for the reduced modulus data. At 95% confidence level (P-value < 0.05), the RAP binder, virgin binder type, and their interaction had significant effect on the reduced modulus of the blending zone. The grouping of the blending zone data was determined using the post-ANOVA

LSM analyses. The groups in Table C.1 are listed in descending order with the letter "A" assigned to the highest mean followed by the other letters in appropriate order. Based on the reduced modulus data, the blending zone between US33 and PG 64-22 binders had the highest modulus while RAP-IR70 and PG 58-28 had the lowest modulus. US33 and virgin binder combinations had the highest modulus with the exception of RAP-US33 and PG 58-28, which had a lower modulus than that for RAP-IR70 and PG 64-22 binders.

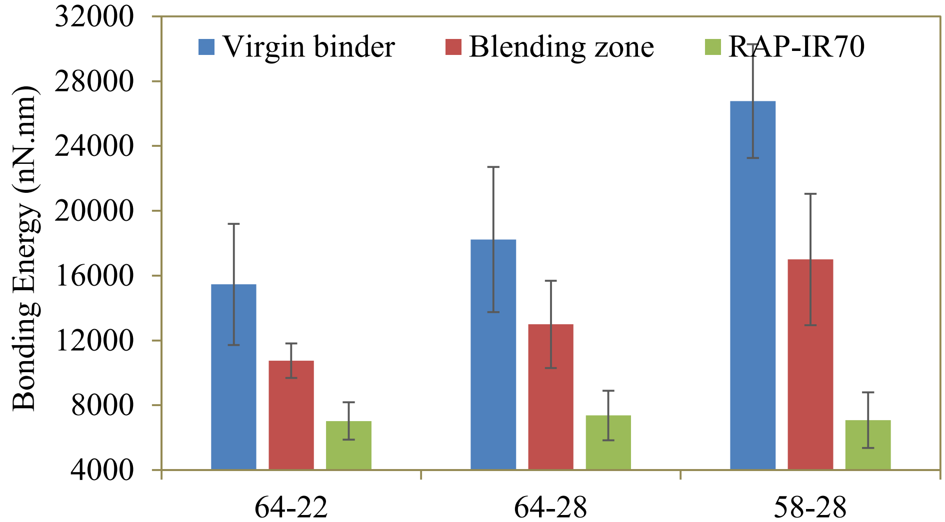
Table C.1 Results of ANOVA Tests for Reduced Modulus of the Blending Zone

Effect	**F-value**	**P-value**	
RAP binder	65.64	<.0001	
Virgin binder	48.91	<.0001	
RAP binder*Virgin binder	7.47	0.0006	
Results of Post ANOVA Analyses -Grouping Of Binder			
Combination	**$E_{reduced}$ (nN.nm)**	**Standard Error**	**Letter Group**
US33 + PG64-22	11270	377.88	A
US33 + PG64-28	10691	466.36	A
IR70+ PG64-22	10176	355.28	B
US33 + PG58-28	8907.78	469.99	B
IR70 + PG64-28	8248.20	594.49	C
IR70 + PG58-28	7997.67	334.96	C

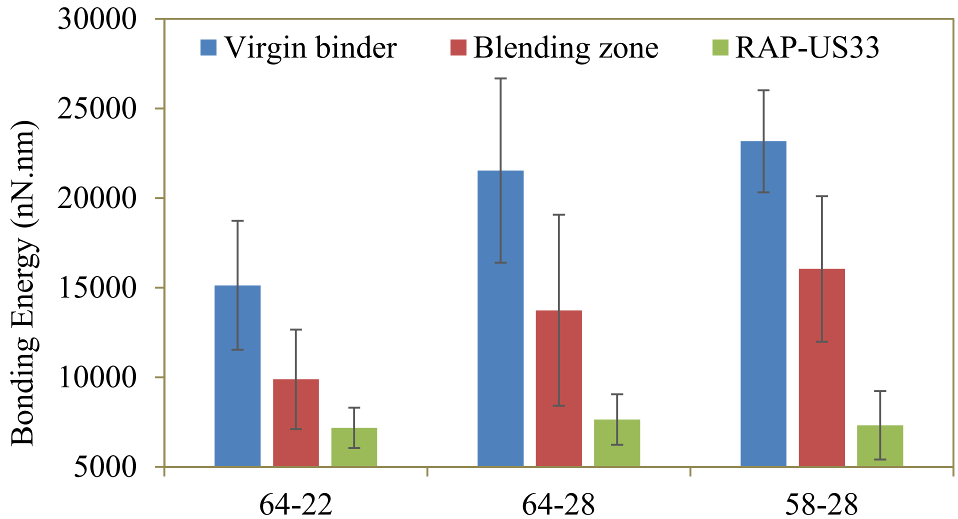
C.3.3 RAP Samples Average Adhesive Bonding Energy of The Different Zones

The average adhesive bonding energy values for the three zones in each RAP/virgin binder combination were calculated. Figures C.7a,b show the results of RAP-IR70 and RAP-US33 combinations, respectively. The adhesive bonding energy of the blending zone was lower than that for the virgin binder. However, the blending zone had a higher bonding energy than both RAP binders. Notably, the bonding energy for RAP-IR70 and RAP-US33 were very similar although their reduced moduli were different. Thus, the blending zone adhesive properties were determined by the virgin binder properties rather than the RAP binder properties. This is evident from the bonding energy values for each combination, the bonding energies for the combination of RAP-IR70/RAP-US33 and PG 58-28 were very similar, as were the other combinations. Similar to the results of the reduced modulus, the high error bars in the blending zone of RAP binders and PG 58-28/PG 64-28 data indicate the presence of more than one zone within the blending zone.

ANOVA and ANOVA-LSM were conducted to statistically evaluate the results in Figures C.7a,b. Table C.2 presents the results of ANOVA and post-ANOVA analyses. At a 95% confidence level (P-value < 0.05), only the virgin binder type had significant effect on the bonding energy of the blending zone. The grouping of the blending zones grouping based on the adhesive bonding energy data showed that the blending zone between RAP and PG 58-28 had the highest bonding energy, followed by RAP and PG 64-28 combinations and RAP and PG 64-22.



(a)



(b)

Figure C.7. Average Adhesive Bonding Energy Values For: (a) RAP-IR70 and virgin binder combinations (a) RAP-US33 and virgin binder combinations

C.3.4 Interfacial Blending Zone Prediction Model

A linear regression analysis was performed to develop models that can relate the blending zone properties (i.e. reduced modulus and bonding energy of the bending zone) to the properties of the RAP and the virgin asphalt binders considered. The results of these analyses resulted in models shown in Equation C.1 and Equation C.2. It is noted that excellent correlations with a high coefficient of determination (R^2) were obtained. This is also clear in Figures C.8a,b, which compare the models prediction to measured values for the blending zone reduced modulus and bonding energy, respectively. The model coefficients in Equation C.1, suggest that the reduced modulus of the blending zone is more affected by the RAP binder properties. However, Equation C.2 suggests that the bonding energy of the blending zone primarily depends on the virgin asphalt binder properties, as indicated by the much smaller coefficient for the bonding energy of the RAP binder.

Table C.2 Results of ANOVA Tests for the Bonding Energy of the Blending Zone

Effect	**F-value**	**P-value**	
RAP binder	0.55	0.4604	
Virgin binder	89.66	<.0001	
RAP binder*Virgin binder	2.10	0.1234	
Results of Post ANOVA Analyses -Grouping Of Binder			
Combination	**Bonding energy estimate (nN.nm)**	**Standard Error**	**Letter Group**
IR70 + PG58-28	16730	377.88	A
US33 + PG58-28	16046	466.36	A
US33 + PG64-28	13739	355.28	B
IR70 + PG64-28	12989	469.99	B
IR70+ PG64-22	10754	594.49	C
US33 + PG64-22	9887.51	334.96	C

$$E= 0.508\ E_{RAP} + 0.456\ E_{VB} \tag{C.1}$$

Where
E: reduced modulus of the bending zone
E_{RAP}: reduced modulus of the RAP binder
E_{VB}: reduced modulus of the virgin binder

$$BE = 0.146BE_{RAP} + 0.614BE_{VB} \tag{C.2}$$

Where
BE: bonding energy of the blending zone
BE_{RAP}: bonding energy of the RAP binder
E_{VB}: bonding energy of the virgin binder

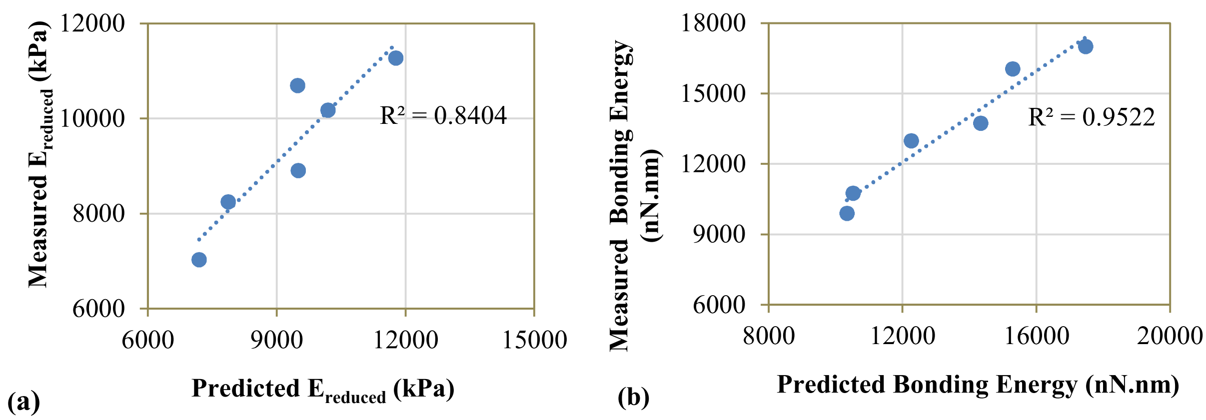


Figure C.8. (a) Predicted reduced modulus vs. measured reduced modulus (b) Predicted bonding energy vs. measured bonding energy

C.3.5 Blending Level Based on Virgin/RAP Binder Concentration

The aforementioned AFM force spectroscopy results for the blending zone indicate that blending between RAP and virgin binders occurred. However, the degree of blending between the two binders within the blending zone needs to be quantified. Rad (2013) estimated the stiffness of the blending zone between two binders based on the stiffness and concentration of the given binders (Equation C.3). This was originally presented by Arrhenius (1887) for the viscosity of the blend instead of the stiffness.

$$E_{blend} = \frac{E_A^{\alpha} . E_B}{E_B^{\alpha}} \tag{C.3}$$

Where, E is the stiffness of blended asphalt binders, E_A and E_B are the stiffness for binder A and binder B in the blend, and α is the concentration of binder A.

A similar approach was used in this study to determine the concentration of virgin binder in the interface blending zone based on reduced modulus and bonding energy values of the virgin and RAP binders. The computed concentrations of the virgin binder within the blending zone are presented in Table C.3. It is clear that the stiffness properties for the blending zone between RAP-IR70/RAP-US-33 and PG 64-28/PG 58-28 was influenced primarily by the RAP binder. While, the bonding properties for the blending zone between RAP-IR70/RAP-US-33 and PG 64-28/PG 58-28 was influenced mainly by the virgin binder presented in each blend. On the other hand, the blending zone properties between PG 64-22 and any RAP binder in this study was equally influenced by both the virgin and RAP binder in the blend. This was valid from both the stiffness and bonding energy data for these combinations.

Table C.3. Virgin Binder Concentration in the Blending Zone

Combination	**α based on $E_{reduced}$**	**α based on bonding energy**
RAP-IR70 + PG 64-22	0.5702	0.5396
RAP-IR70 + PG64-28	0.3452	0.6262
RAP-IR70 + PG58-28	0.3448	0.6585
RAP-US33 + PG64-22	0.5726	0.4291
RAP-US33 + PG64-28	0.2720	0.5661
RAP-US33 + PG58-28	0.4074	0.6812

C.3.5 Effect of RAP Extraction Solvent On Blending

To develop a better understanding of the effect of solvent used for extracted RAP binder on blending between aged recycled and virgin binders, force spectroscopy experiments were performed on samples prepared using the binders extracted using TCE (the main solvent used in this study) and toluene from the RAP material obtained from Interstate highway 270 (IR-270 RAP) and PG 64-28 virgin asphalt binder. Figures C.9 and C.10 present the variation of the reduced modulus and bonding energy with the distance along the RAP-IR270-PG 64-28 samples, respectively. It is clear that for both recovered RAP binders the blending occurred and they had similar blending zone size. However, the toluene-recovered RAP binder had a higher reduced modulus value than the TCE-recovered RAP binder. In addition, the TCE-recovered RAP binder had a slightly higher adhesive bonding energy value than the toluene-recovered RAP binder. These results demonstrate that the solvent used for extraction of the RAP binder might affect the stiffness and adhesive properties of the extracted and recovered binder; however, the solvent seems not to influence the blending of the RAP binders with the virgin asphalt binder.

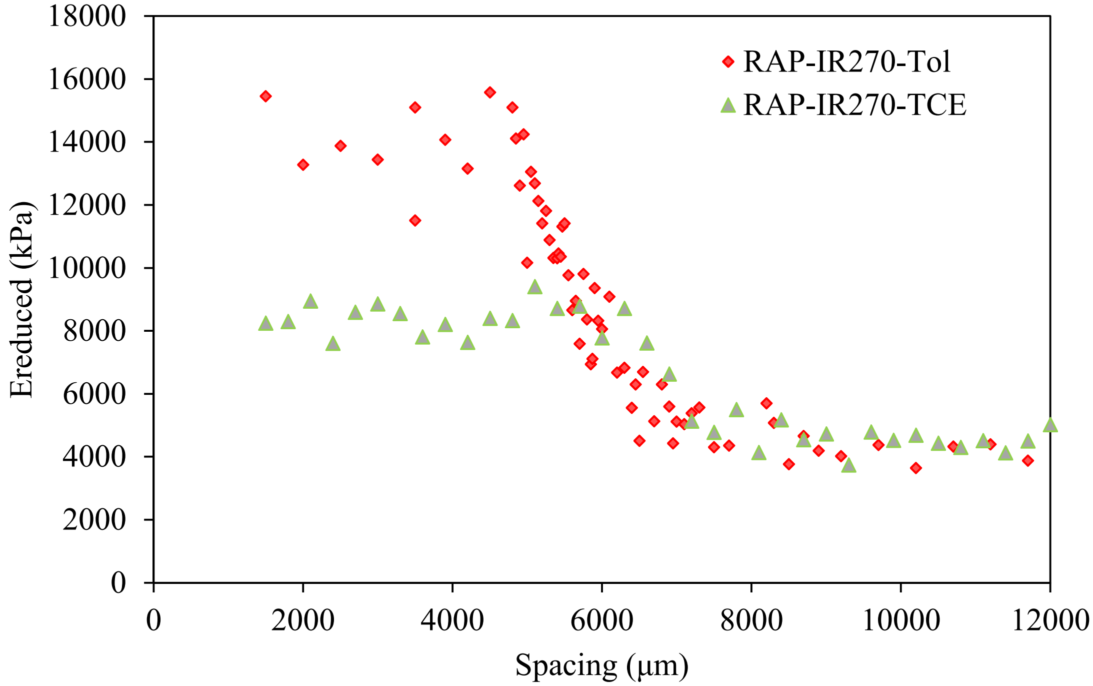


Figure C.9 Typical Reduced Modulus Curve for Toluene and TCE-Recovered RAP Blended Binders

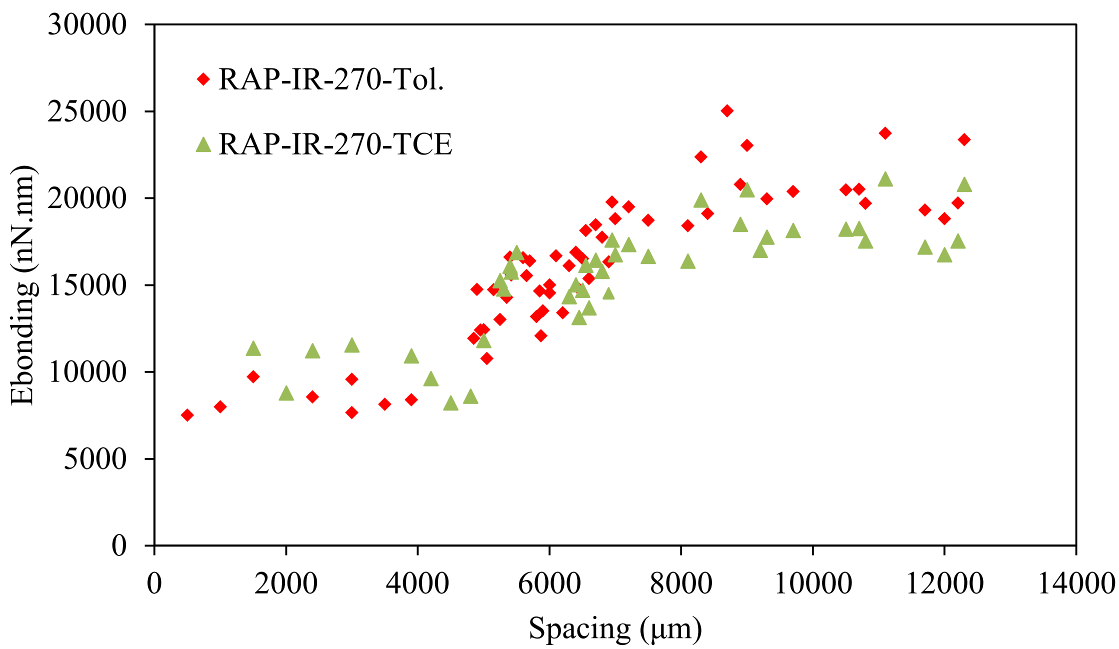


Figure C.10 Typical Bonding Energy Curve for Toluene and TCE-Recovered RAP Blended Binders

C.3.6 Validation Interfacial Blending Zone Prediction Model

The data obtained from testing the different combinations of the RAP-270 and PG 64-28 was used to evaluate the accuracy of the prediction of the interfacial blending zone model developed in this study and shown in Equations C.1 and C.2. Tables C.4 and C.5 present the results of this evaluation. It is clear that the developed models can accurately predict the properties of the interfacial blending zone based on the properties of the RAP and virgin asphalt binders. This suggests that the models developed in this study can be used to evaluate the properties of the binder blend in mixes with any RAP and virgin asphalt binder combination. Thus, these models can serve as a tool to determine the virgin binder that should be used in a RAP mixture, based on the properties of the RAP binder.

Table C.4 Developed Model Prediction of Bonding Energy for RAP Samples

Sample	BE_{RAP}	BE_{VB}	BE_{BZ}	$BE_{predicted}$	% Error
IR-270 RAP Toluene Recovered + PG64-28	7,814	19,585	13,978	13,166	5.8%
IR-270 RAP TCE Recovered + PG64-28	10,501	19,500	14,914	13,506	9.4%

Table C.5 Developed Model Prediction of Bonding Energy for RAP Samples

Sample	E_{RAP}	E_{VB}	E_{BZ}	$E_{predicted}$	% Error
IR-270 RAP Toluene Recovered + PG64-28	14,478	4,385	9,048	9,354	3.4%
IR-270 RAP TCE Recovered + PG64-28	8,248	4,449	6,124	6,219	1.6%

C.3.5 RAS Samples-Reduced Modulus and Bonding Energy Curves

Force spectroscopy was conducted on samples prepared using binders extracted and recovered from tear-off and manufacturing waste RAS were blended with the PG 64-28 virgin binder used in this study. The values of the reduced modulus and bonding energy were computed and plotted with the distance along the samples where the blending occurred. Figures C.11 and C.12 present typical reduced modulus and bonding energy curves, respectively, obtained from force spectroscopy experiment for the combinations of tear-off RAS with PG 64-28 and PG 64-22 virgin binders. Figure C.11 shows that the reduced modulus curve starts with high values for tear-off RAS followed by an immediate drop in the values upon reaching the interface and the virgin asphalt binder. The bonding energy curves showed similar behavior to those observed in reduced modulus curves; however, those curves started with much lower bonding energy values for tear-off RAS that significantly increased upon reaching the interface with the virgin asphalt binder. It is clear that interfacial zone was very small (less than 5 μm) and no blending occurred between the tear-off RAS and PG 64-28 and PG 64-22 virgin asphalt binders. This confirms the results obtained from the AFM images presented in Figures C.2 and C.3. The lack of blending between the virgin binders and RAS binders at mixing temperatures are thought to contribute to poor fatigue cracking resistance at intermediate temperatures.

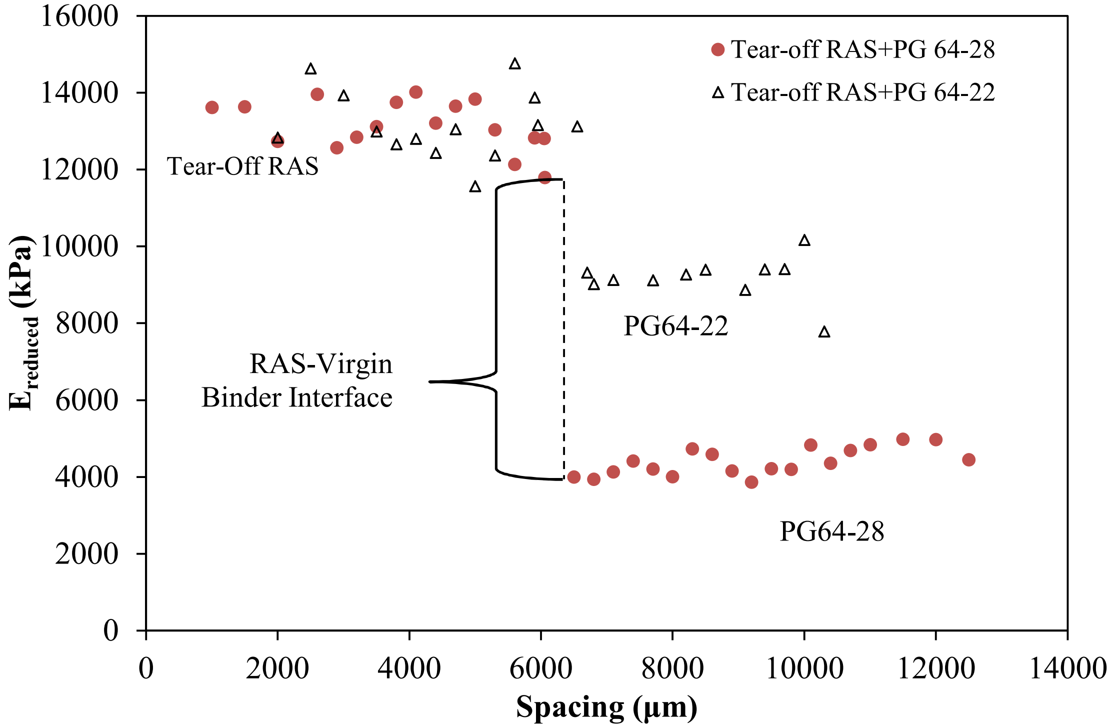


Figure C.11 Typical Reduced Modulus Curve for Tear-Off RAS-Virgin Binders Combinations

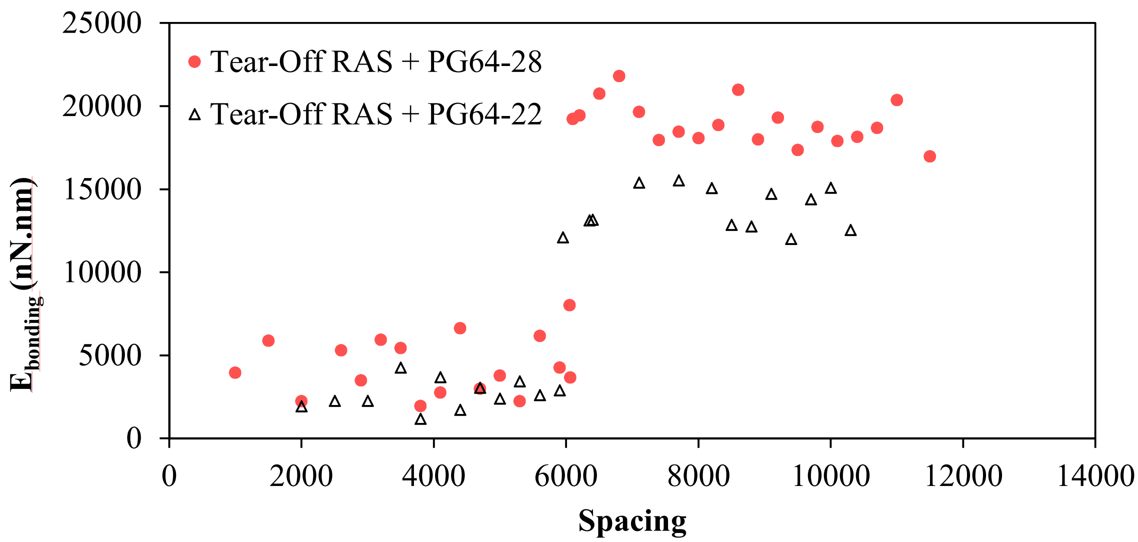
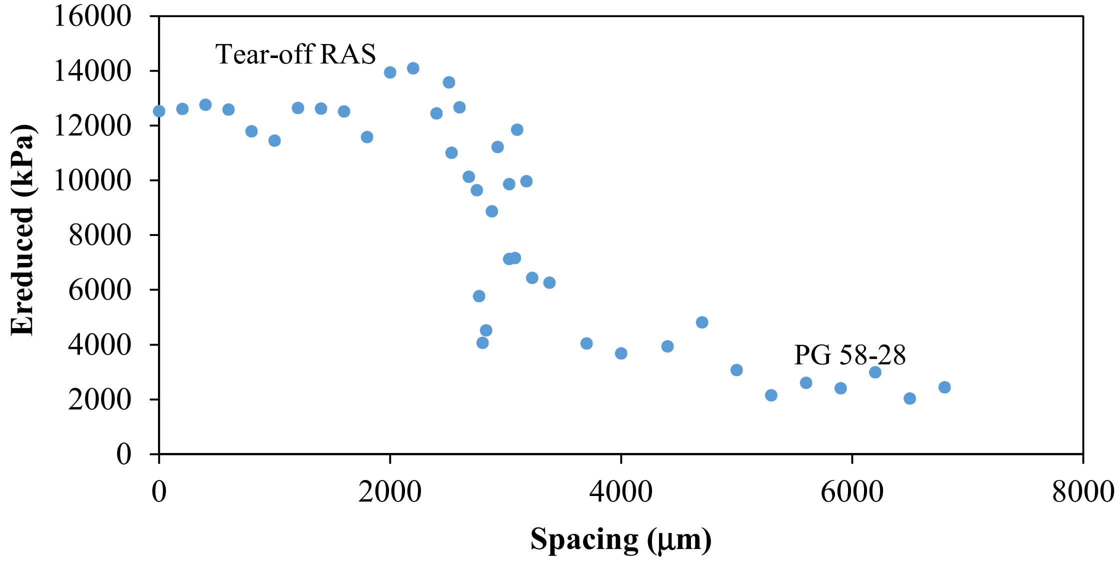
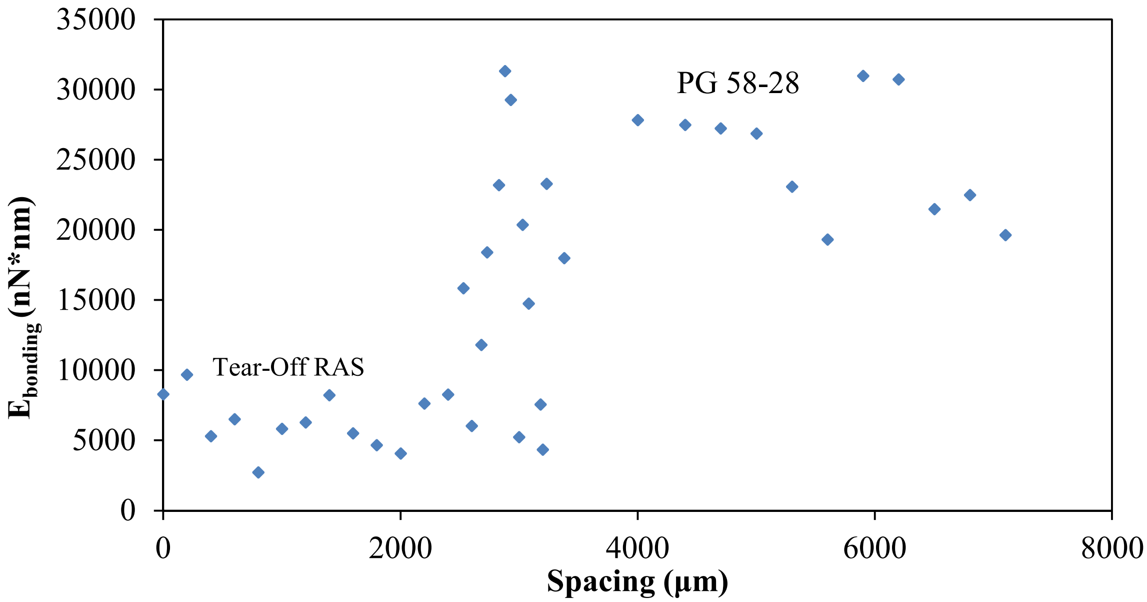


Figure C.12 Typical Bonding Energy Curve for Tear-Off RAS-Virgin Binders Combinations

Figures C.13a,b present the typical reduced modulus and bonding energy values obtained from force spectroscopy experiment for the combinations of tear-off RAS and the softer virgin asphalt binder PG58-28, respectively. It is clear from curves in both of these figures that a larger blending zone developed when using a PG 58-28 binder with the tear-off RAS as compared to PG 64-28 and PG 64-22 binders. This might be explained by the lower viscosity and better diffusion of the PG 58-28 as compared to the PG 64-28 and PG 64-22 binders. However, both figures are indicating very scattered values within the interfacial zone; such that high and low reduced modulus and bonding energy were obtained within that zone. This suggests that limited blending occurred in the interfacial zone. These results confirm the results obtained from the AFM images in Figures C.4.



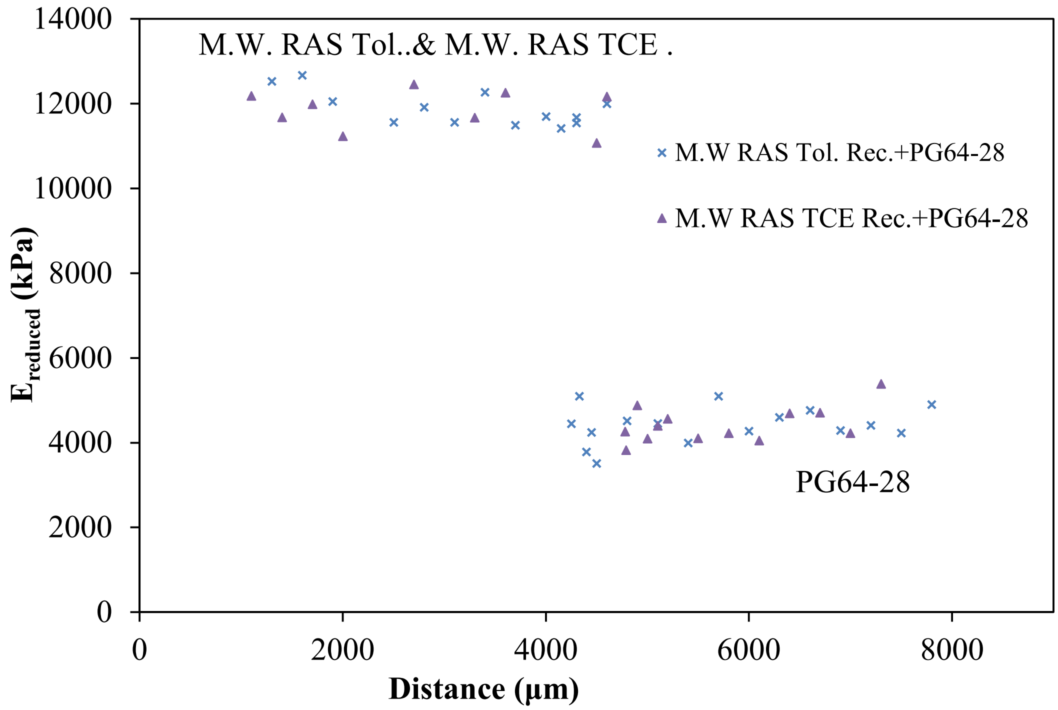
(a)



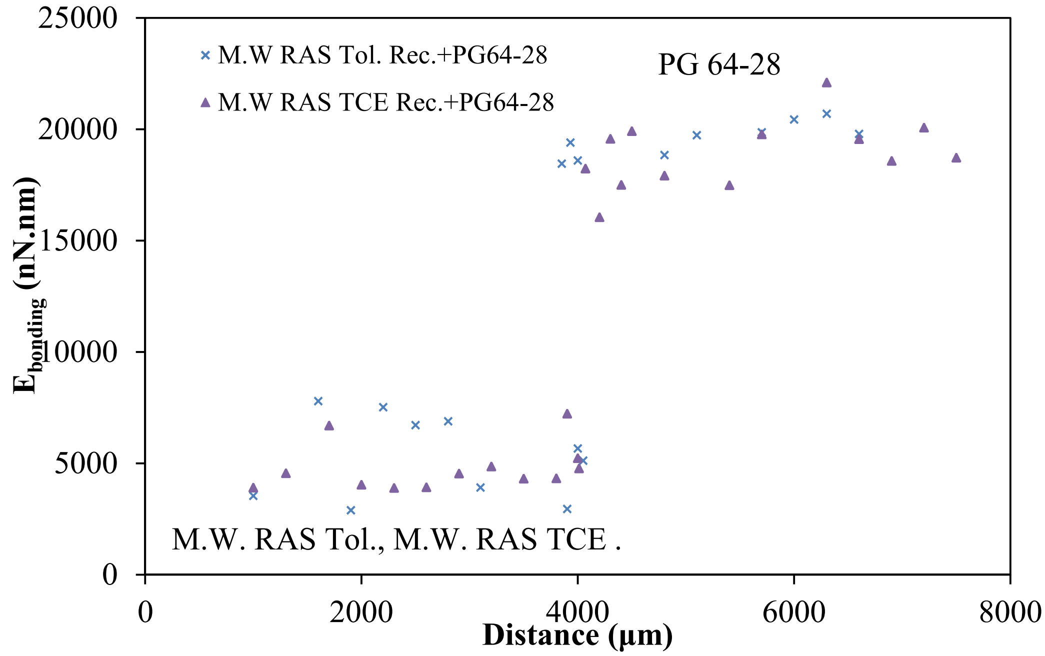
(b)

Figure C.13 (a) Typical Reduced Modulus Curve for Tear-off RAS and PG 58-28 Binder Samples (b) Typical bonding energy Curve for Tear-off RAS and PG 58-28 Binder Samples

Figures C.14a,b present typical reduced modulus and bonding energy curves, respectively, that were obtained for manufacturing waste RAS and PG 64-28 samples. It is clear that there is no sign of blending between the manufacturing waste RAS and the PG 64-28 binders. Both toluene and TCE recovered manufactured waste RAS binders had very similar reduced modulus and bonding energy values. These results suggest that the extraction solvent did not affect the properties of the recovered manufacturing waste RAS binder.



(a)



(b)

Figure C.14 (a) Typical Reduced Modulus Curve for Manufacturing Waste RAS and PG 64-28 Binder sample (b) Typical Bonding Energy Curve for Manufacturing Waste RAS and PG 64-28 Binder Sample

C.4 Results of Macro-scale Testing

C.4.1 Illinois SCB Test Results

The Flexibility Index (FI) and Fracture Energy (FE) values were calculated based on the results obtained from the SCB-IL tests performed on control mixes as well as the short-term and long-term aged RAP/RAS mixtures considered in this study. Figure C.15 shows the average Flexibility Index values for the different mixes. The short-term aged control virgin mix had slightly higher flexibly index than the short-term field produced mix with 25% RAP. In addition, all short-term aged lab produced RAP/RAS mixes had much lower Flexibility Index average values than the short-term aged control mix. The mix with 20% and 3% RAS had the lowest Flexibility Index value. The Flexibility Index values of all mixes significantly dropped due to long-term aging. However, the largest decrease in Flexibility Index values was observed for mixes with RAS. This suggests that the effect of RAS is more pronounced with aging. In general, the same trend was observed in long-term aged mixes as the short-term aged mixes; such that the control mix had the highest Flexibility Index value and the mix with RAP and RAS had the lowest values.

Figure C.16 presents the average Fracture Energy values computed for the different mixes considered. In general, the short and long-term aged control virgin mix had similar Fracture Energy values to the short and long-term aged lab produced mixes with 30% RAP, but higher values than mixes with RAS or RAS and RAP mixes. The lowest Fracture Energy values were for the 5% RAS with 3.8% asphalt content (i.e. 5% RAS mixture assuming 18% of RAS binder is available) and the 30% RAP 3.3% AC mixtures. It is worth noting that using a higher asphalt binder content in RAS helped in improving the Fracture Energy values; however, this improvement was less pronounced for long term-aged mixes. As shown in Figure C.16, the field mixture had the highest Fracture Energy values, which is explained by differences in producing the mixes in the field and lab.

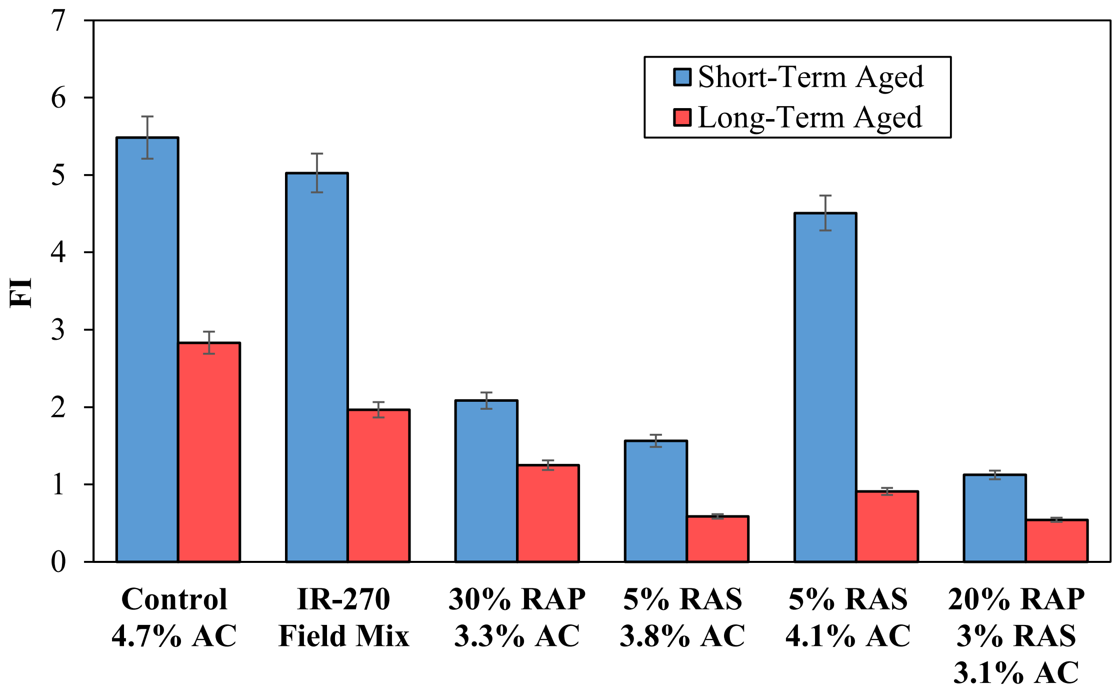


Figure C.15 Flexibility Index Results from Illinois SCB Test

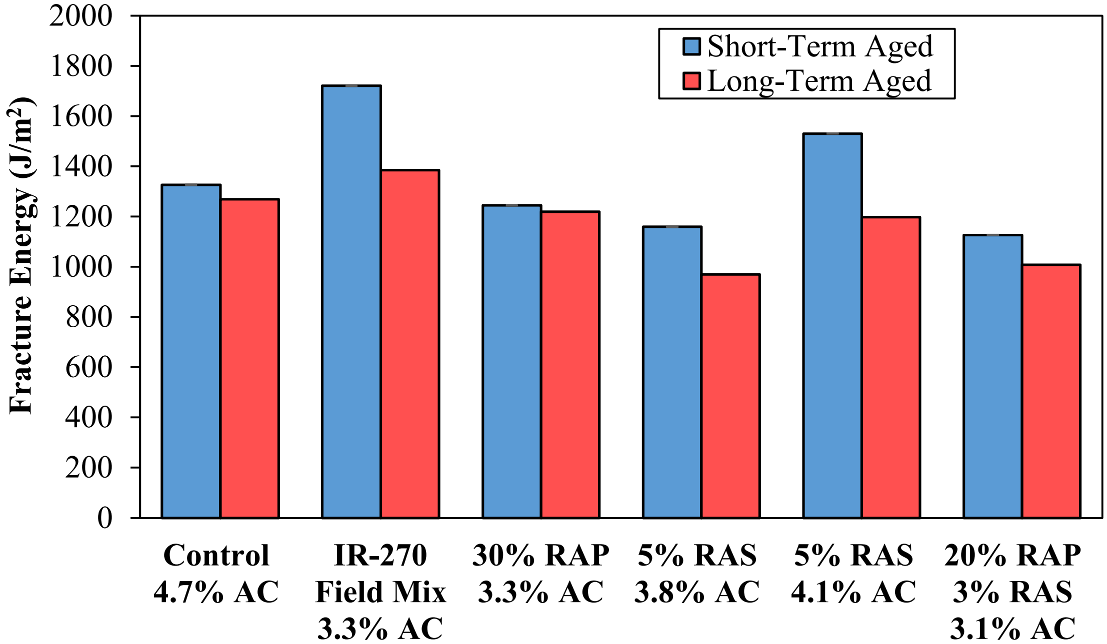


Figure C.16 Fracture Energy Values from SCB-IL Test

Since the Fracture Energy is a function of the peak load and displacement, the Fracture Energy values were normalized based on the peak loads for each mixture. Figure C.17 presents the average normalized Fracture Energy values for all mixtures considered. The normalized Fracture Energy provided a better parameter to evaluate the fracture properties of mixes; particularly that the brittle mixes will have higher peak loads resulting in higher Fracture Energy values even though it fails at a much smaller strain. The short and long-term aged control mix with only virgin materials had slightly higher values than field mix with 25% RAP and lab mix with 30% RAP. In addition, the use of RAS in the considered mixes resulted in significantly lowering the normalized Fracture Energy values especially for long-term aged mixes. The normalized Fracture Energy values of short and long-term aged RAS mixtures increased when using higher virgin binder content (4.1% instead of 3.8% virgin binder). The 20% RAP 3% RAS 3.1% AC mixture showed very similar results as the RAS 3.8% AC both unaged and aged, which were the lowest values of all mixtures.

An ANOVA and Post ANOVA-LSM statistical analysis was conducted on the SCB-IL results. Table C.6 presents the result of the ANOVA. At a 95% confidence level (p-value < 0.05), the mixture and the aging condition had a significant effect on Flexibility Index and normalized Fracture Energy. In addition, the mixture and conditioning interaction had significantly affected on Flexibility Index but not the Fracture Energy. The significance of the interaction indicates that the aging effect was different among the considered mixes. This may be attributed to the greater decrease in the Flexibility Index of mixes with RAS due to long-term aging. Table C.7 shows the grouping of the Flexibility Index values of long-term aged mixes based on the results of post-ANOVA. The control had statistically similar Flexibility Index values to those with RAP only. However, it had statistically higher values than those with RAS. Based on the results, the control, field and RAP mixtures were grouped the highest, while the mixtures containing RAS all grouped significantly lower. Table C.8 presents the grouping of the normalized Fracture Energy values of long-term aged mixes based on the results of post-ANOVA. The ranking of considered long-term aged mixes based on normalized Fracture Energy was similar to that obtained based on the flexibility index. The only difference was that to RAS mixture with higher AC% was statistically similar values as the RAP mixtures but lower than the control mixtures.

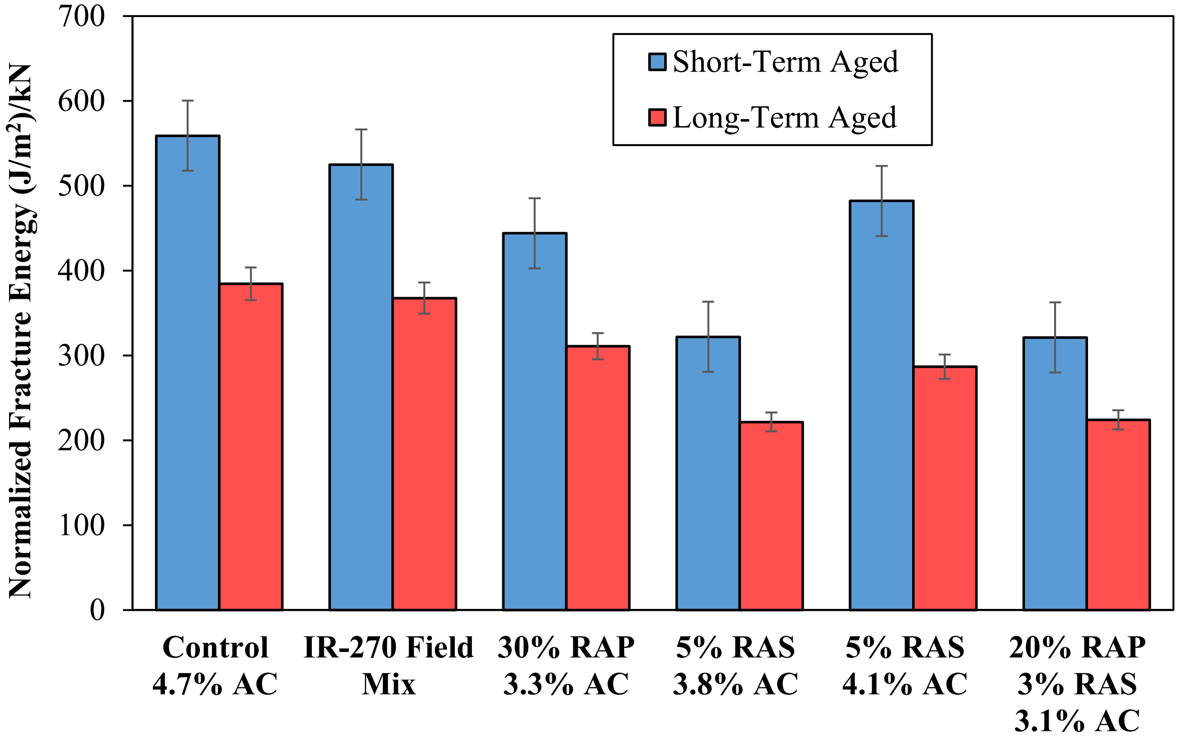


Figure C.17 Normalized Fracture Energy Values from SCB-IL Test

Table C.6 ANOVA Test of Fixed Effects for SCB-IL Test

	Results of Flexibly Index		Results of Normalized Fracture Energy	
Effect	F Value	P-value	F Value	P-value
Mixture	11.57	<.0001	14.31	<.0001
Aging Condition	36.73	<.0001	50.43	<.0001
Mixture* Aging Condition	2.55	0.0448	1.13	0.3614

Table C.7 Post-ANOVA Grouping of Long-Term Aged Mixtures based on Flexibility Index

Mixture	**FI Estimate**	**Standard Error**	**Letter Group**
Control	2.8325	0.3319	A
IR-270 Field	1.9650	0.3319	AB
30% RAP (3.3% AC)	1.4200	0.4693	AB
5% RAS (4.1% AC)	0.9125	0.3319	B
5% RAS (3.8% AC)	0.5875	0.3319	B
20% RAP& 3% RAS	0.5433	0.3832	B

Table C.8 Post-ANOVA Grouping of Long-Term Aged Mixes based on Normalized Fracture Energy

Material	Estimate	Standard Error	Letter Group
Control	388.39	20.4234	A
IR-270 Field	368.35	20.4234	AB
30% RAP (3.3% AC)	367.02	28.8830	AB
5% RAS (4.1% AC)	286.76	20.4234	BC
20% RAP& 3% RAS	223.81	23.5829	C
5% RAS (3.8% AC)	222.34	20.4234	C

C.4.2 Louisiana SCB Test Results

The SCB-LA test was performed in accordance with the ASTM Standard Test Method for "Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures". Only long-term aged samples were tested using this method to evaluate the fracture resistance of mixtures with recycled materials at aged conditions. The slope of the linear fit for each notch depth was found to be very sensitive to the peak loading of each sample, which was more variable than the Illinois method due to the slower loading rate. Figure C.18 presents the average calculated J integral value (J_{1c}) values for the considered mixes. The control mixture with had the much higher critical fracture resistance values as compared to mixes with RAP and/ or RAS. In addition, the mixture with RAS only had significantly lower fracture resistance values as compared to other mixtures with RAP. This result confirms those obtained in the SCB-IL test results, which indicated the inclusion of 5% RAS in the mixture had the most significant effect on the mixture's intermediate temperature fatigue cracking resistance at aged conditions.

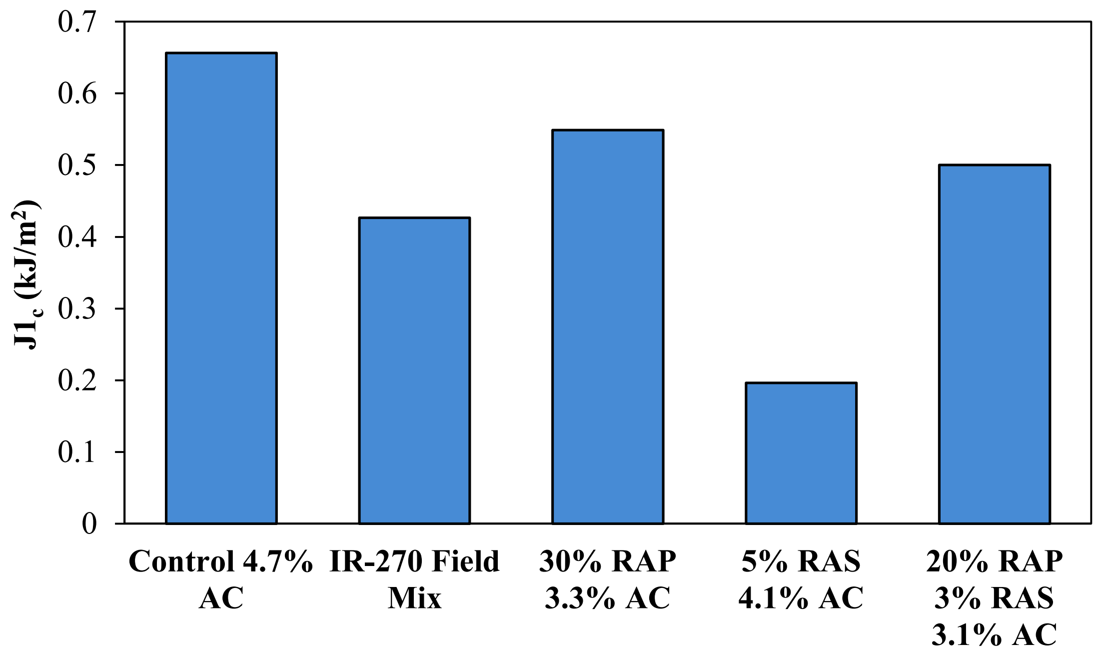


Figure C.18 J-Integral Results for Long-Term Aged Samples

C.4.3 Indirect Tensile Strength Test Results

The toughness index and indirect tensile strength were computed for the different mixtures tested. Figure C.19 presents the average the toughness index values. The mixtures with RAP only had similar toughness index to that of the control mixture with virgin materials only. However, mixtures with RAS had lower TI values particularly the one with 5% RAS. Figure C.20 shows the average indirect tensile strength (ITS) values of dry samples. It is clear that the inclusion of recycled materials (RAP/RAS) had significantly increased the ITS values of the mixture considered. The highest values were obtained when using RAP and RAS in the mixture. It is worth noting that the field-produced mixture had higher ITS than the lab-produced mixes.

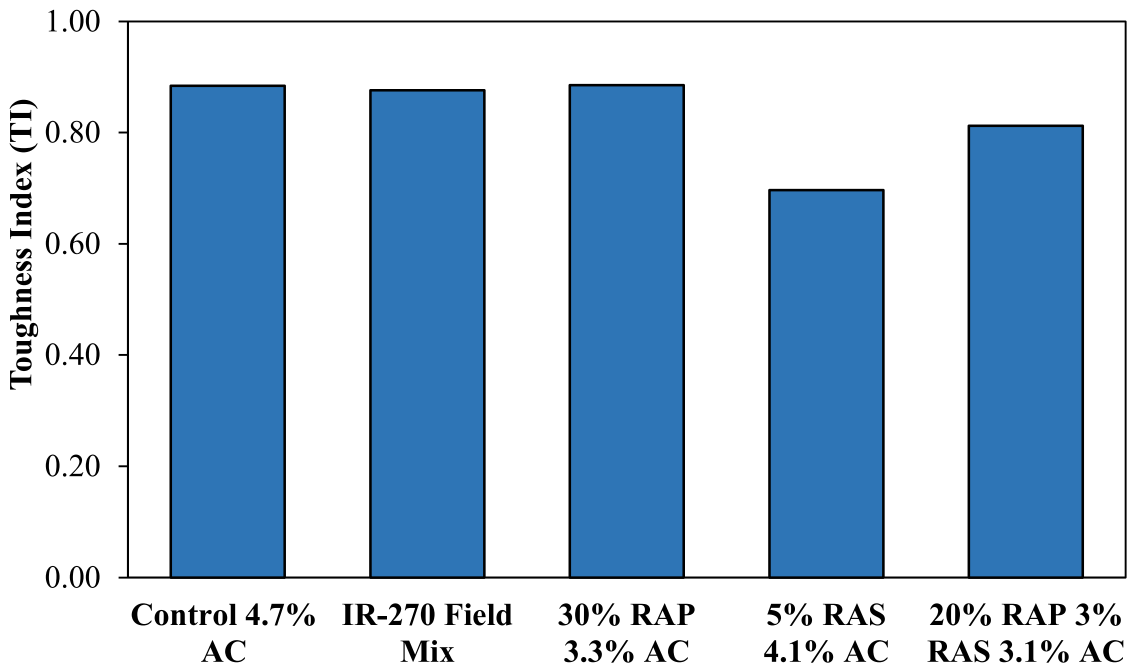


Figure C.19 Toughness Index Results from IDT Test

C.4.4 AASHTO T283 Test Results

Figure C.20 compares the average ITS values of dry and wet conditioned samples. It is clear that the ITS of all mixtures dropped due to conditioning; however, the largest decrease in the ITS was observed for mixtures that included RAS. This can be also observed in Figure C.21, which presents the tensile strength ratio (TSR). The lab control virgin mix had higher TSR value than mixes with RAP and or RAS. In addition, the mixture with 5% RAS had the lowest TSR, which was lower than the minimum TSR value of 80% required by ODOT. This suggest that the use of RAS might reduce the moisture damage resistance of asphalt mixtures.

C.4.5 ACCD Test Results

The Asphalt Cracking Concrete Device (ACCD) test was performed on all mixtures in this study. Figure C.22 presents the average cracking temperature value obtained in the conducted ACCD tests. It is clear that the long-term aging resulted in reducing the low-temperature cracking of all considered mixes; however, mixtures that had 20% RAP and 3% RAS had the largest reduction due to long-term aging (6 °C difference between short-term and long term aged samples). In general, the lab control mix had similar cracking temperature values as the lab mixture with

30% RAP. However, the mixes that included RAS had warmer cracking temperature; particularly long-term aged samples. This indicates that the inclusion of RAS in asphalt mixtures might result in reducing the low-temperature cracking resistance of asphalt mixtures. While the addition of 0.3% of virgin binder to 5% RAS to asphalt mixture improved the low-temperature cracking short-term aged samples, it did not have any improvement on long-term aged samples.

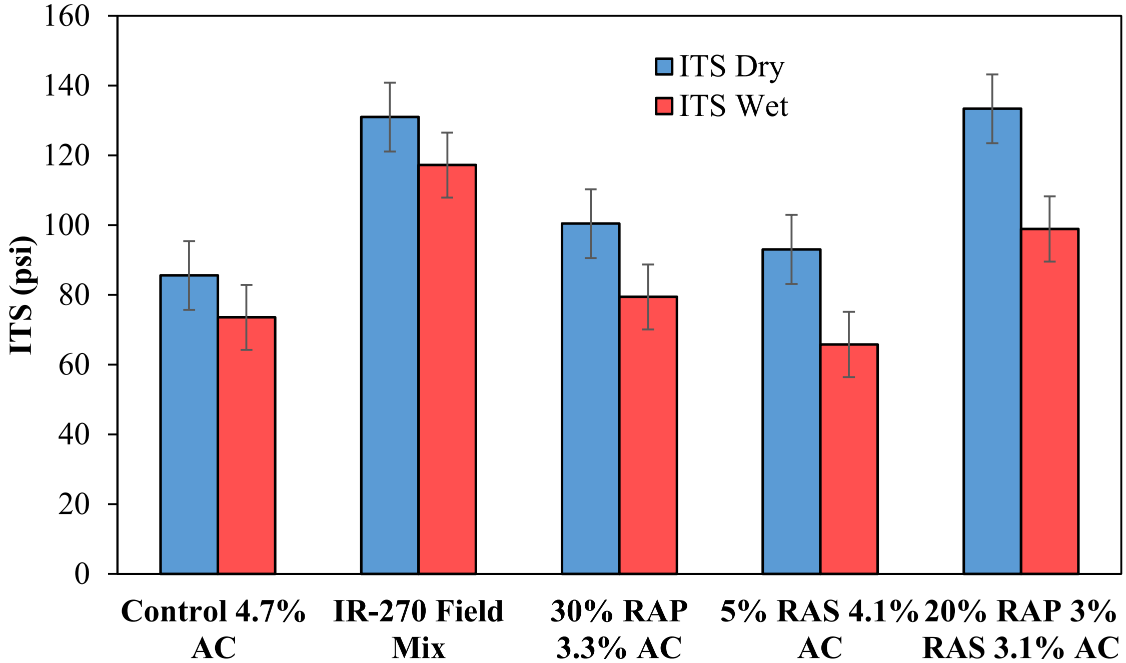


Figure C.20 Indirect Tensile Strength Results for Conditioned and Dry Samples

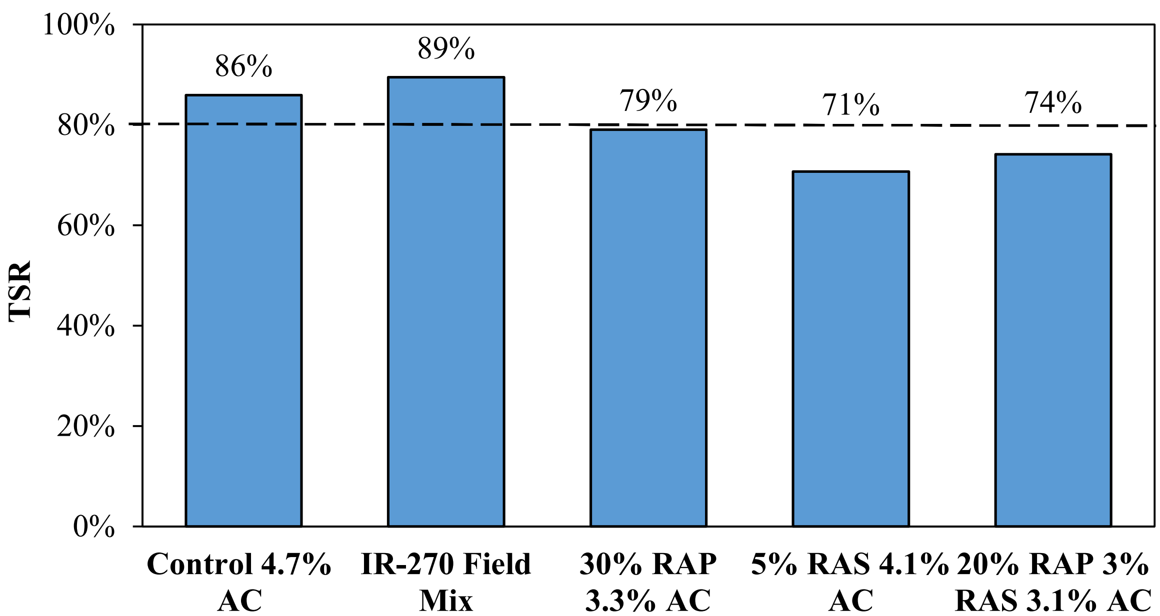


Figure C.21 Tensile Strength Ratio Results

Another ANOVA analysis was conducted on the results of the ACCD test to evaluate the effect of material type, aged conditions and their interaction. Table C.9 presents the results of this analysis. At a 95% confidence level (p-value < 0.05) the material type and aged condition had significant effects on the cracking temperature. Table C.10 provides the grouping results of long-term aged mixtures based on ACCD cracking temperature. It is noted that all mixtures that contain RAS had statistically warmer cracking temperature than the control mixture with virgin materials. This suggests that the RAS might significantly reduce the low-temperature racking resistance of asphalt mixtures.

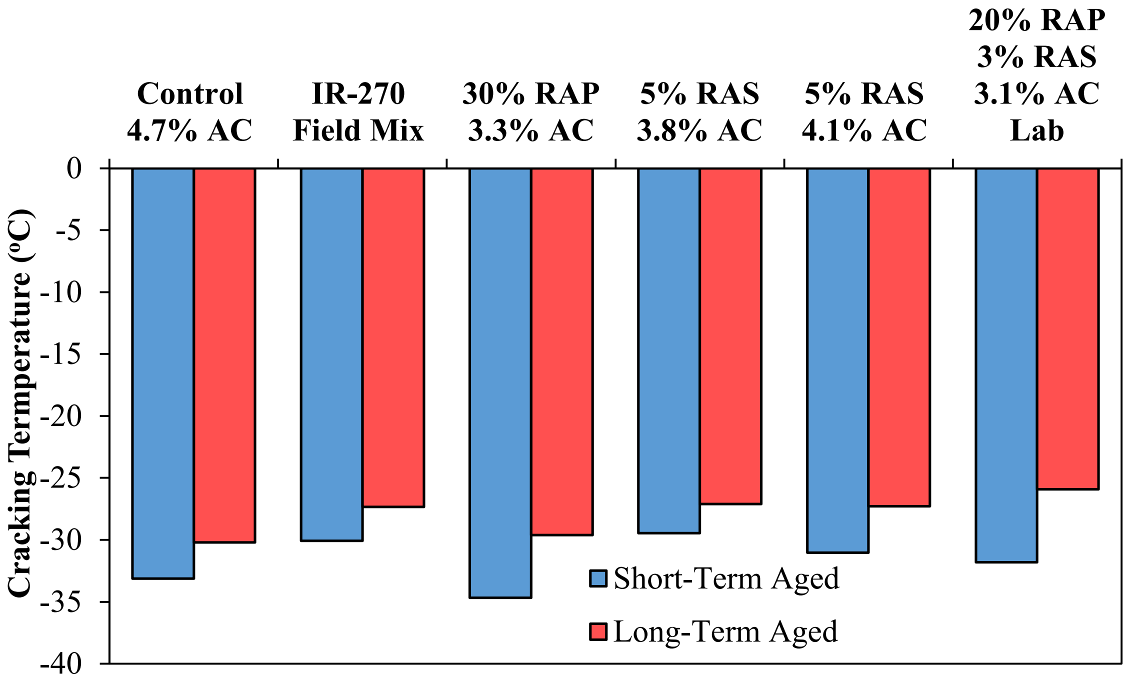


Figure C.22 Results of ACCD Test

C.4.6 Effect of RAP Sampling Efforts during Mixture Design on Laboratory Performance

As part of this study, the effect of RAP sampling during mixture design on the performance of mixtures with 30% RAP was examined. To this end, the performance of two mixtures with the same RAP content and source (RAP-IR 270) but with different contribution of aged RAP binder was evaluated. Figures C.23 and C.24 presents the average Flexibility Index and normalized Fracture Energy values obtained from the SCB-IL test results, respectively. It is clear, that mixtures with higher RAP binder ratio resulted in lower Flexibility Index and normalized Fracture Energy for long-term samples. Figure C.25 presents the average critical fracture parameter obtained in SCB-LA test conducted on long-term aged samples. It is clear that the mixture with higher RAP binder ratio had lower J integral. These results suggest that the higher RAP binder ratio resulted in reducing the resistance of the considered mixture to fatigue cracking. This confirms the AFM test results, which indicated that the RAP binder lowered the adhesive properties of the RAP and virgin asphalt binder blend in an asphalt mixture.

Figure C.26 presents the results of the AASHTO T283 on 30% RAP mixtures with different RAP sampling methods. The mixture with higher RAP binder ratio had higher wet and dry ITS values than the one with lower ratio. The higher ITS values for that mixture may be attributed to the higher amount of the aged and stiffer RAP binder in the mixture. However, the mixture with higher RAP binder ratio experienced much more reduction in the ITS value due to moisture conditioning as indicated by the TSR value shown in Figure C.27. This indicates that this mixture is more susceptible to moisture damage, which can be attributed to the lower adhesive properties of the RAP binder measured in the AFM force spectroscopy tests.

Figure C.28 presents the average cracking temperature obtained from the ACCD tests conducted on the 30% RAP mixtures with different RAP sampling methods. The mixture with higher RAP binder ratio had slightly warmer cracking temperature than the one with lower RAP binder ratio. This might be explained by the increase in the content of RAP binder in the mixture, which has poorer adhesive and low-temperature properties than the virgin asphalt binder.

Table C.9 ANOVA Results for ACCD Test of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Mixture	5	24	9.30	<.0001
Aging Condition	1	24	63.08	<.0001
Mixture*Aging Condition	5	24	1.78	0.1542

Table C.10 Post-ANOVA Grouping of ACCD Results Based on Material Type

Material	Estimate	Standard Error	Letter Group
20% RAP& 3% RAS	-25.9133	0.4766	A
5% RAS(3.8% AC)	-26.8400	0.5837	AB
5% RAS(4.1% AC)	-27.2900	0.5837	AB
IR-270 Field	-27.3475	0.4127	AB
30% RAP(3.3% AC)	-29.6050	0.5837	BC
Control	-30.1967	0.4766	C

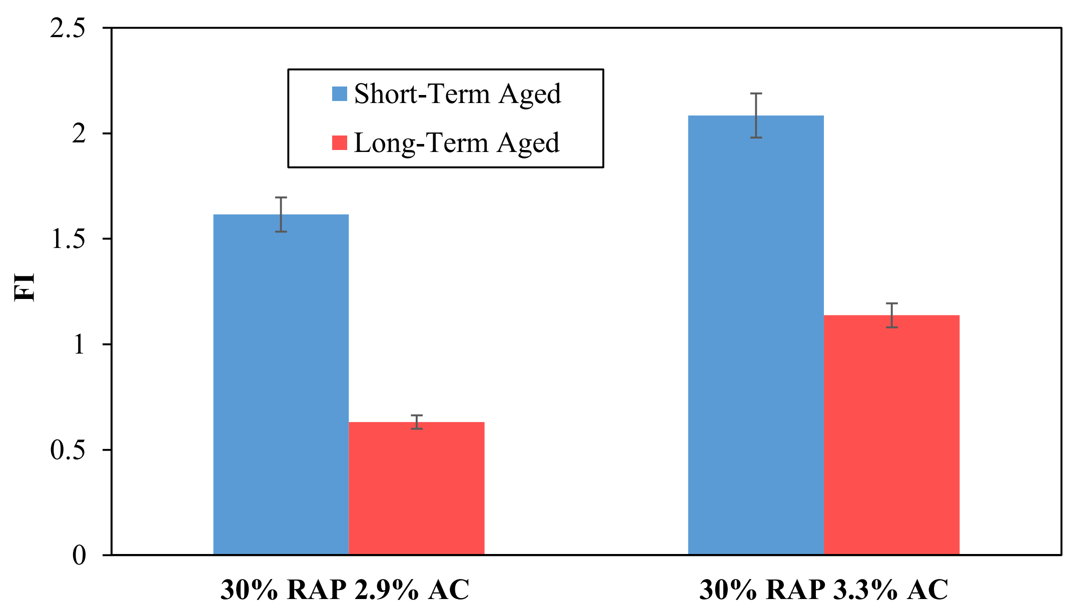


Figure C.23 Flexibility Index Values for Mixtures with Different RAP Sampling Methods

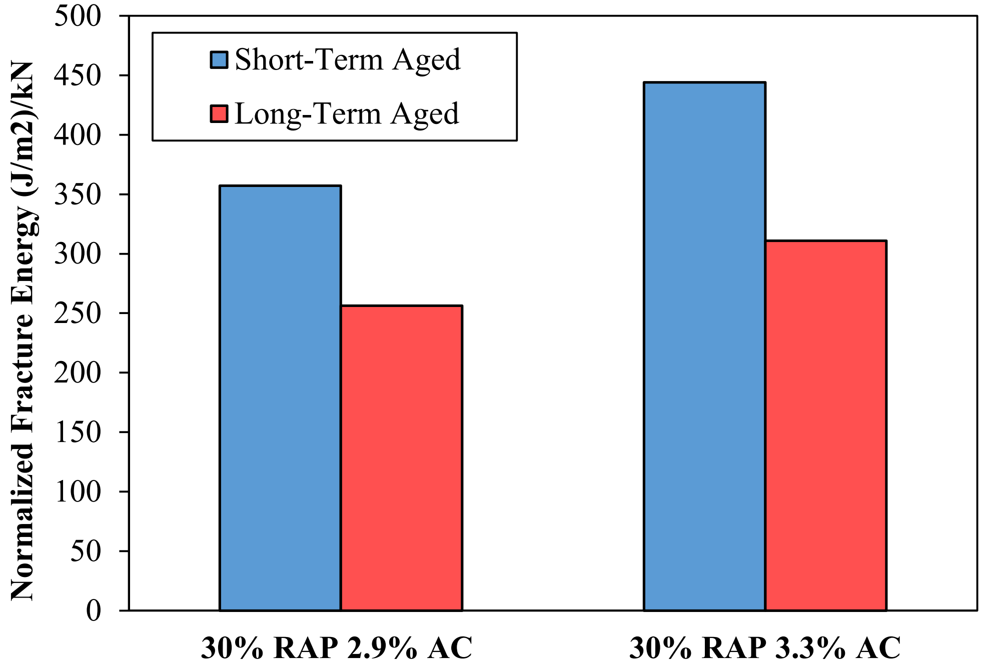


Figure C.24 Normalized Fracture Energy Values for Mixtures with Different RAP Sampling Methods

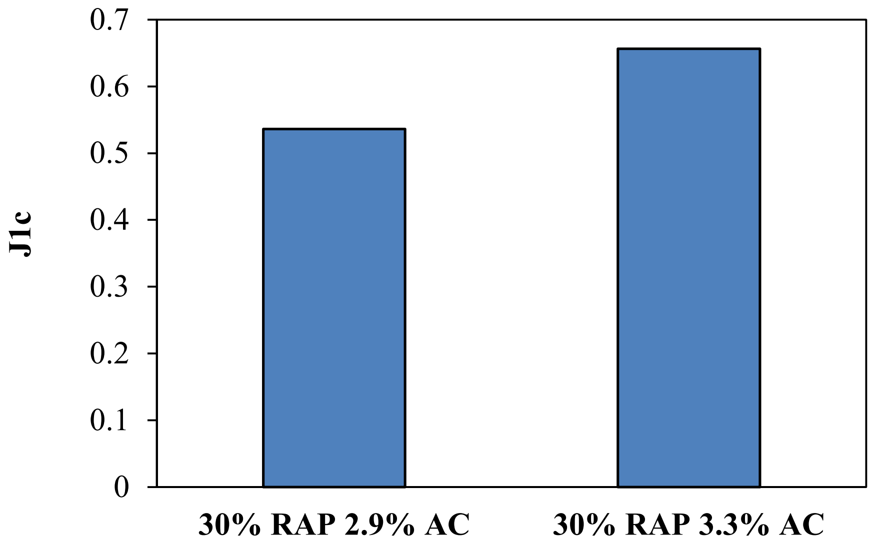


Figure C.25 J Integral Values from for Mixtures with Different RAP Sampling Methods

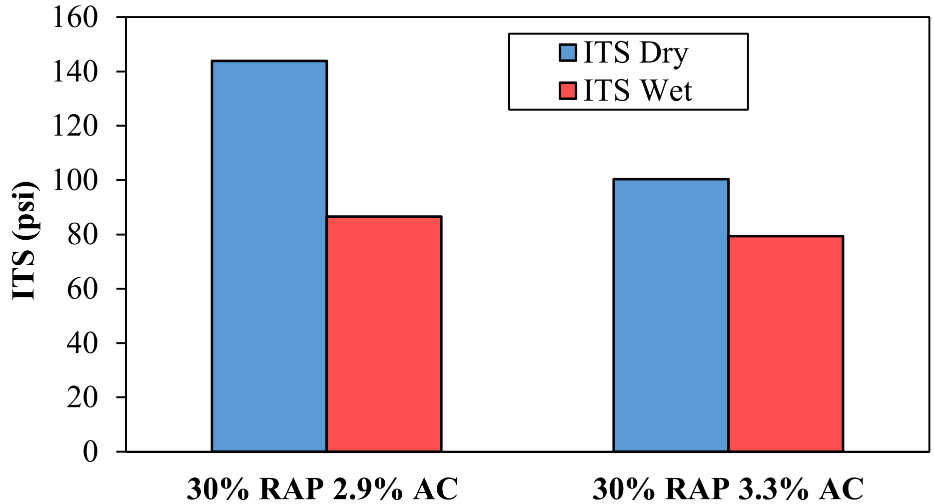


Figure C.26 ITS Values from for Mixtures with Different RAP Sampling Methods

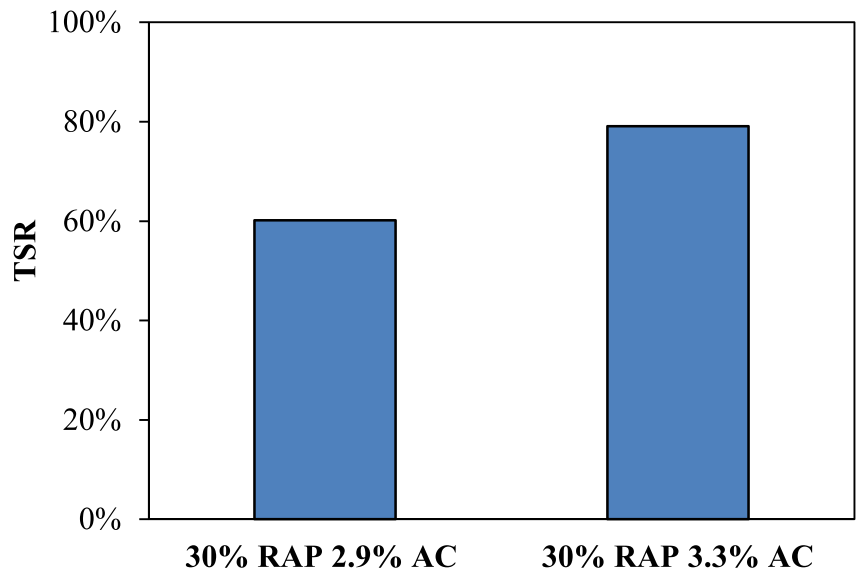


Figure C.27 TSR Values for Mixtures with Different RAP Sampling Methods

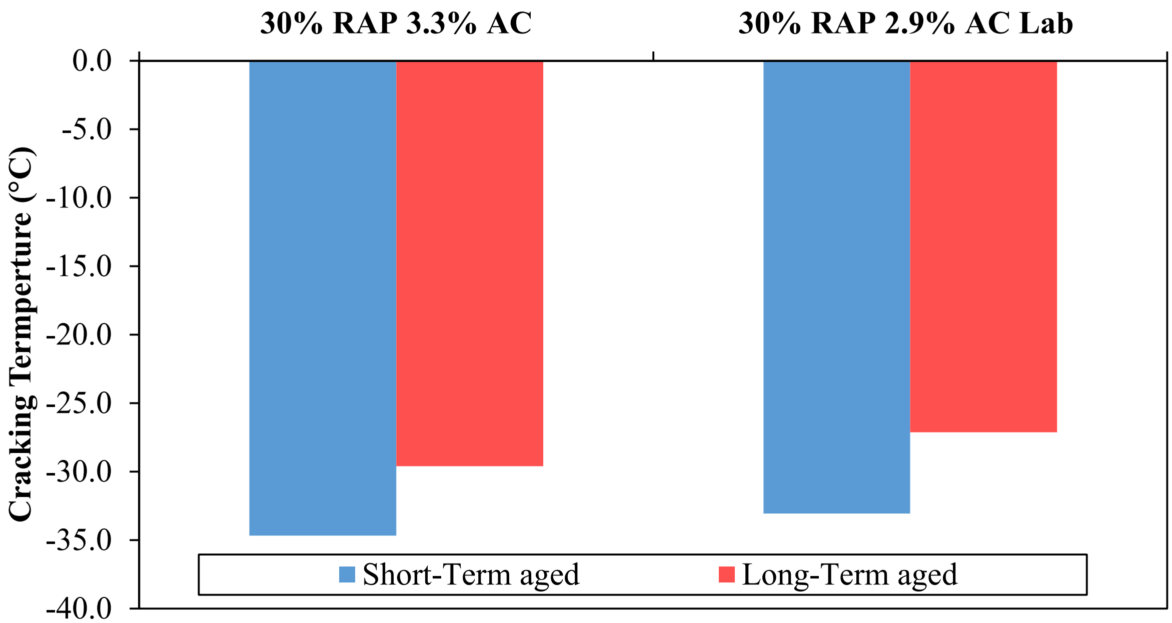


Figure C.28 ACCD Cracking Temperature for Mixtures with Different RAP Sampling Methods