Recycled Asphalt Binder Study

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16. Abstract

This research evaluated how the quantity and quality of recycled asphalt materials (RAM) affects the performance of the resultant binder blends by examining and understanding the interaction of their different components that included virgin binders with and without polymer modification, aged binder from RAM, and recycling agents (RAs). For this evaluation, rheological and chemical tests were conducted, which included PG grading, Multiple Stress Creep Recovery (MSCR), Linear Amplitude Sweep (LAS), Fourier Transform Infrared Spectroscopy (FTIR), and Gel Permeation Chromatography (GPC). Asphalt blends with different RAM contents were tested to investigate the effect of RAP/RAS binders on the properties of the blends. In addition, blends containing RAs were tested to assess the ability of the RAs to improve the properties of the blends. The project also included mixture performance testing to validate the binder results. Mixtures were tested for rutting resistance (Hamburg Wheel Tracking Test [HWTT]) after being subjected to short-term oven aging (STOA), and intermediate-temperature cracking resistance (Indirect Tensile Asphalt Cracking Test [IDEAL-CT]), and low-temperature cracking resistance (Disc-Shaped Compact Tension Test [DCT]) after being subjected to STOA plus long-term oven aging (LTOA). In addition, the dynamic modulus (|E*|) test was conducted at both STOA and LTOA conditions to assess the stiffness characteristics and aging resistance of the recycled mixtures with and without RAs. The binder results, indicated that the "type" of the recycled binder (i.e., RAP or RAS) played a more significant role affecting the rheological and chemical properties of asphalt binders than the "quantity" of the recycled binder when used as binder replacement. Due to the extremely high stiffness and poor relaxation properties, it is suggested that the addition of RAS as binder replacement be limited to 5% maximum. Additionally, petroleum-based RA (i.e., asphalt flux) is not recommended for use in recycled binder blends containing RAS and RAP plus RAS as binder replacement. Regarding mixture evaluation, HWTT and DCT results indicated that overall, the rejuvenated mixes had better rutting, moisture, and low-temperature cracking resistance than the control mixes. However, the rejuvenated mixes had reduced IDEAL-CT results than the control mixes, which indicated potentially increased susceptibility to intermediate-temperature cracking. Finally, the results of this research were used to develop a step-by-step guide to evaluate the quality of asphalt blends with high RAM contents in Wisconsin and to guide the use of RAs to produce RAM asphalt mixtures with balanced rutting and cracking performance.

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EXECUTIVE SUMMARY

This research evaluated how the quantity and quality of recycled asphalt materials (RAM) affects the performance of the resultant binder blends by examining and understanding the interaction of their different components that included virgin binders with and without polymer modification, aged binder from RAM, and recycling agents (RAs). For this evaluation, rheological and chemical tests were conducted, which included PG grading, Multiple Stress Creep Recovery (MSCR), Linear Amplitude Sweep (LAS), Fourier Transform Infrared Spectroscopy (FTIR), and Gel Permeation Chromatography (GPC). Asphalt blends with different RAM contents were tested to investigate the effect of RAP/RAS binders on the properties of the blends. In addition, blends containing RAs were tested to assess the ability of the RAs to improve the properties of the blends. The project also included mixture performance testing to validate the binder results. Mixtures were tested for rutting resistance (Hamburg Wheel Tracking Test [HWTT]) after being subjected to short-term oven aging (STOA), and intermediate-temperature cracking resistance (Indirect Tensile Asphalt Cracking Test [IDEAL-CT]), and low-temperature cracking resistance (Disc-Shaped Compact Tension Test [DCT]) after being subjected to STOA plus long-term oven aging (LTOA). In addition, the dynamic modulus (|E*|) test was conducted at both STOA and LTOA conditions to assess the stiffness characteristics and aging resistance of the recycled mixtures with and without RAs.

SUMMARY OF FINDINGS

Binder Performance Testing

- The addition of RAM to virgin binders significantly increased the stiffness of the resultant recycled binder blends, which improved the rutting resistance but decreased the fatigue resistance, thermal cracking resistance, and the stress relaxation property after Rolling Thin-Film Oven (RTFO) plus 40 hours of PAV oxidative aging. These effects became more pronounced as the RAM content increased.
- The incorporation of bio-based RA counterbalanced the aforementioned negative effects. The effectiveness of an RA was related to its chemical composition and its interaction with the type of recycled binder (i.e., RAP or RAS) used as binder replacement.
- Petroleum-based RA (i.e., an asphalt flux) behaved as a softener, restoring the properties of the recycled binders only by physical process. Furthermore, GPC results indicated that the chemical composition of this type of RA was similar to an asphaltic material. As a result, the additive was not effective in decreasing the cracking susceptibility of recycled asphalt blends containing RAS only and combination of RAP plus RAS binders. Therefore, petroleum-based recycling agent (i.e., asphalt flux) is not recommended for use in recycled binder blends containing RAS and RAP plus RAS as binder replacement.
- In general, it was observed that the "type" of the recycled binder (i.e., RAP or RAS) played a more significant role affecting the rheological and chemical properties of asphalt binders than the "quantity" of the recycled binder when used as binder replacement. Results have indicated that the addition of RAS as binder replacement should be limited to 5% maximum.
- ΔT_c parameter results indicated that recycled binder blends with up to 40% RAP binder replacement still met the threshold of -5°C after RTFO plus 40 hours of PAV aging. On the other hand, the addition of RAS between 15 and 25% binder replacement significantly increased the block cracking susceptibility of the resultant recycled binder blends.

- Recycled binder blends with 25% RAS binder replacement showed the highest reduction in the number of cycles to failure per unit increase in strain indicated by the LAS fatigue law |*B*|-parameter.
- The determination of the properties of the recycled binder blends at critical pavement temperatures by using standard testing equipment (i.e., Superpave DSR and BBR) is suggested as a more reliable approach to capture materials incompatibility and the potential inefficiency of recycling agents. Furthermore, this approach can guide the dosage selection of all the components within a recycled binder blend (i.e., virgin binder, RAM, and RA). Since the type (i.e., chemistry) of the RAs evaluated in this study influenced the aging susceptibility of each additive and its interaction with the virgin binder and RAM, an understanding of how the blending components impart the mixture performance properties is needed.

Mixture Performance Testing

- |E*| results showed mixed results for the rejuvenated mixes after STOA and LTOA when compared to the control mixes (with unmodified and modified binders). Some of the rejuvenated mixes showed higher stiffnesses while other showed lower stiffness at different frequencies for low, intermediate, and high temperatures.
- Similar to the |E*| results alone, |E*| Black Space diagram and G-R_m results also showed mixed results, with lower G-R_m values for some rejuvenated mixes while others showed higher values when compared to the control mixes.
- G-R_m aging ratios showed that the rejuvenated mixes had similar aging susceptibility as the control mixes with no RAs, with the exception of one rejuvenated mix.
- HWTT results showed that all of the rejuvenated mixtures at higher ABR showed better rutting and moisture susceptibility performance than the control mixtures.
- All of the rejuvenated mixes had lower IDEAL-CT CT_{index} values than the control mixes. However, only three mixes failed the preliminary minimum CT_{index} criterion of 40 recommended in WHRP project 0092-20-04. Two of these mixtures barely failed this criterion.
- All of the rejuvenated mixes at higher asphalt binder replacement (ABR) except one had higher DCT fracture energy values than the control mixes. In addition, all of the mixes exceeded the minimum fracture energy criterion of 300 J/m^2.

Validation of Binder Test Results with Mixture Performance Testing

Although the performance of asphalt mixtures with high RAM contents is typically assessed with respect to a “control” mix at a low RAM content, the goal of balanced mix design (BMD) is to “balance” the performance of the mixtures in terms of cracking resistance without compromising rutting resistance regardless of mixture composition. Therefore, when performing a BMD with RAs to compensate for high RAM materials used, the dosage should be selected to optimize the cracking and rutting performance of the rejuvenated asphalt mixtures.

In this study, the HWTT and DCT results of recycled asphalt mixtures with RAs exceeded the preliminary test thresholds recommended for Wisconsin mixtures in WHRP project 20-04, while the IDEAL-CT results showed that some of the recycled mixtures with RAs barely failed the preliminary CT_{index} criteria. Therefore, a BMD evaluation will likely require slight adjustments to the RA dosages selected based on the binder performance testing to provide the resultant asphalt mixtures with balanced rutting and cracking performance.

RECOMMENDATIONS

The results of this research were used to develop a step-by-step guide to evaluate the quality of asphalt blends with high RAM contents in Wisconsin, and to guide the use of RAs to produce recycled asphalt mixtures with balanced rutting and cracking performance. The design steps are summarized as follows:

1) Determine the high-temperature (HT) and the low-temperature (LT) performance grade (PG) of the component materials to be used for blending. Consider the research parameters and criteria for selection and approval of component materials presented in Table A.

Table A. Component Materials Selection and Proportioning Guidelines.

	Limits for Blend Component Material					
	Virgin Binder		RAP		RAS	
Dynamic Shear Rheometer (DSR) HT PG	Aging	Original and RTFO	Aging	RTFO	Aging	As Extracted
	≤ 64°C		≤ 82°C		≤ 160°C	
Bending Beam Rheometer (BBR) ΔT_c	Aging	RTFO plus 40 hours of PAV	Aging	RTFO	Aging	As Extracted
	≥ 0.0°C		≥ -3.0°C		N/A	

2) Determine the recycling agent (RA) dosage by targeting the low-temperature PG of -28°C (based on climatic requirements in Wisconsin) for the recycled binder blends after RTFO plus 40 hours of PAV aging.
   a. For bio-based recycling agents, an initial dosage of 5% per weight of total binder (i.e., virgin plus recycled binders) is recommended for low-temperature blending chart analysis, while an initial dosage of 20% per weight of total binder is recommended for petroleum-based (i.e., asphalt flux) recycling agents.
   b. Petroleum-based recycling agents (i.e., asphalt flux) are not recommended for recycled binder blends containing RAS binder only (i.e., without addition of RAP).
   c. The optimum recycling agent dosage can then be determined through the use of blending charts obtained from BBR testing of the recycled binder blend with RA, where the critical low-temperature grades for a recycled binder blend is plotted against the tested RA dosage.
3) Perform the rheological characterization of the recycled binder blend with RA at the dosage selected in Step 2, using standard test methods (AASHTO M320, AASHTO M332) and data analysis as indicated in Table B.

Table B. Guidelines for Rheological Characterization of Recycled Binder Blends with Recycling Agents at High and Low Temperatures.

High Temperature		
DSR HT PG	Aging	Original and RTFO
	Target Climate	
DSR MSCR $Jnr_{3.2}$ @ 58°C*	Aging	RTFO
	$\leq$ 4.5 kPa^{-1} for Standard (S) $\leq$ 2.0 kPa^{-1} for Heavy (H) $\leq$ 1.0 kPa^{-1} for Very Heavy (V) $\leq$ 0.5 kPa^{-1} for Extreme (E)	
Low Temperature		
BBR ΔT_c	Aging	RTFO + 40 hours of PAV
	$\geq$ -5.0°C	

*Considering the fact that the MSCR $\%Recovery_{3.2}$ parameter was found to be highly influenced by the creep compliance $Jnr_{3.2}$ of recycled binders, this parameter is not recommended for the characterization of recycled binder blend with recycling agent.

4) Conduct mixture performance tests to ensure compliance with the BMD performance criteria.
— For HWTT, samples are prepared from loose mix aged for four hours at 135°C (STOA).
— For IDEAL-CT and DCT, samples are prepared from STOA conditioned mix further aged for six hours at 135°C (LTOA).
   a. Prepare samples with the selected RA dosage and RAM proportion combination to conduct the IDEAL-CT test.
   b. Compare the IDEAL-CT results to the preliminary criterion developed in WHRP 0092-20-04 presented in Table C.
   c. If the IDEAL-CT criterion is satisfied, verify HWTT and DCT results using their corresponding criteria in Table C.
   d. If the IDEAL-CT criterion is not satisfied, increase the RA dosage and verify IDEAL-CT, DCT, and HWTT at the higher RA dosage.

Table C. Preliminary Threshold Criteria for BMD for Wisconsin Mixtures (*West et al., 2021*).

Traffic Level	HWTT (STOA)				Min. CT_{Index} (LTOA)	DCT Min. Fracture Energy (J/m^2) (LTOA)
	Min. Passes to 12.5 mm	Min. SIP (passes)	Max. CRD 20k (mm)	Min. SN (passes)		
High	15,000	9,000	6.0	2,000	40	300
Med	15,000		7.0			
Low	10,000		8.0			

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1. INTRODUCTION

The use of recycled asphalt materials (RAM), including reclaimed asphalt pavements (RAP) and recycled asphalt shingles (RAS), has significant economic and environmental benefits that include cost savings, conservation of natural resources, and reduction in energy consumption and emissions. The majority of new hot mix asphalt (HMA) mixes produced in the United States today contain a percentage of RAM. According to the most recent National Asphalt Pavement Association (NAPA) survey, the total estimated tons of RAP and RAS used in HMA in 2019 were 89.2 million tons and 921,000 tons, respectively *(Williams et al., 2020).*

Despite the pressing interest of highway agencies to increase the amount of RAP use in asphalt mixtures, it is recognized that as the percentage of RAP in the mix increases, the proportion of heavily oxidized binder increases, resulting in higher mixture stiffness and better rutting resistance; however, the mixes tend to become more susceptible to cracking and durability issues. Therefore, State Departments of Transportation (DOTs) limit the use of RAM in their asphalt mixtures. In addition, the performance of asphalt mixes containing RAM has been found to be dependent on the properties of their constitutive components as well as the degree of blending between recycled and virgin binders.

Highway agencies have specified the use of RAM based on the percentage of RAP and RAS by weight of the total mix, by weight of the aggregate, or by the binder replacement, but most have now adopted the asphalt binder replacement (ABR) concept (or recycled binder ratio [RBR]), given the fact that RAP and RAS contain significantly different amounts of asphalt binders. The asphalt binder content of RAP typically ranges between 5 to 6 percent, while RAS usually has a higher binder content of 20 to 30 percent. As presented in Equation 1, ABR is defined as the percentage of recycled asphalt binders from RAP and RAS by weight of the total binder content in the mix. It provides an overall indication of the binder contribution from RAM.

$$ABR = RAP_{BR} + RAS_{BR} = \frac{\%RAP * P_{b-RAP}}{P_{b-total}} + \frac{\%RAS * P_{b-RAS}}{P_{b-total}} \qquad \text{Equation 1}$$

where, RAP_{BR} = RAP binder replacement, RAS_{BR} = RAS binder replacement, $\%RAP$ = percentage of RAP by weight of the total mix, $\%RAS$ = percentage of RAS by weight of the total mix, $P_{b\text{-}RAP}$ = binder content of RAP, $P_{b\text{-}RAS}$ = binder content of RAS, and $P_{b\text{-}total}$ = total binder content of the mix.

The Wisconsin Department of Transportation (WisDOT) currently allows the use of recycled asphalt binders from fractionated reclaimed asphalt pavements (FRAP), RAP, and RAS in asphalt mixtures. The maximum allowable ABR for virgin asphalt binders is 40% in lower pavement layers and 25% in upper layers, but these values vary when RAP/FRAP and RAS are used alone or in combination, as presented in Table 1 *(WisDOT, 2021)*. Grade bumping of virgin binders is not required for mixtures with a total ABR lower than the maximum allowable values. In addition, WisDOT specifies that the RAS content, when used in combination with RAP/FRAP, shall not exceed 5% of the total weight of the aggregate blend. Previous research studies have shown that the inclusion of 20 to 30% of RAP by weight of the total mix has minimal effects on the long-term performance of asphalt pavements *(Shah et al., 2007; Li et al., 2008; Hajj et al., 2009; West et al., 2009).* However, it remains unclear whether a higher RAP content could be used without sacrificing pavement performance. In addition, mixtures with RAS should be handled with more caution because the recycled asphalt binders in RAS are much more heavily aged and susceptible to cracking than the binders in RAP.

Table 1. Maximum Allowable Percent Binder Replacement *(WisDOT, 2021)*.

RAM	Lower layers	Upper layer
RAP and FRAP in any combination	40	25
RAS alone	25	20
RAP, FRAP, and RAS combination	35	25

Several innovative technologies and engineering practices have been explored over the last decade to compensate for some of the negative characteristics of using high RAM contents and produce good performing mixtures. Some of these strategies include: mix design with higher asphalt binder content, the use of softer binders or polymer modified binders, and the incorporation of recycling agents (RAs). This project focused on the incorporation of recycling agents as a strategy to facilitate higher RAM contents.

RAs help mitigate the stiffening effect of RAP and RAS materials through uniform dispersion within the mix and diffusion into heavily aged recycled binders. RAs have been defined as organic materials with chemical and physical characteristics selected to restore the properties of aged asphalt in order to target specification limits *(Asphalt Institute, 1986).* For optimal restoration of the aged asphalt binder properties, consideration should be given not only to the viscosity-reducing capacity of the RA, but also to its chemical composition. Furthermore, the degree of diffusion of the RA into the aged binder is of the utmost importance, since it will allow changes in the intermolecular agglomeration and self-assembly of the asphalt polar micelles, affecting the overall performance properties of the recycled asphalt mixes.

Research studies have showed that most RA are able to partially restore the physical and chemical properties of the aged binders in RAM *(Epps et al., 2019; Zaumanis et al., 2014).* However, the effectiveness of RAs tends to diminish with aging *(Bahia et al., 2018).*

The performance of recycled mixtures with or without RAs in regard to rutting, fatigue cracking, and thermal cracking resistance is dependent of the amount of recycled materials used and the type and amount of RA used. In general, the literature review shows that for recycled mixes *(Mogawer et al, 2013; Xie et al., 2017; Tran et al., 2012):*

- Rutting resistance increases with an increase in RAP/RAS content but tends to decrease with the addition of RAs.
- Intermediate temperature cracking resistance decreases with an increase in the RAP/RAS content but may improve with the incorporation of RAs.
- Low temperature cracking resistance improves when the virgin binder grade is reduced to compensate for the increased stiffness of mixes with high recycled content. The use of RAs also tends to improve the low temperature properties of recycled mixtures.

This raises the question whether RA could improve the long-term cracking resistance of asphalt mixtures with RAM. Therefore, it is crucial to take into consideration the effect of oxidative aging and to assess how RAs affect the aged asphalt binders and what performance characteristics their recycled materials exhibit. More research is also needed to identify a systematic approach to determining the optimum dosage of RA.

1.1 Project Objectives

There are three main objectives in this study, as follows:

1. Understand how the quantity and quality of RAM affects the performance of resultant binders;
2. Validate resultant binder test results using mixture performance testing; and
3. Draft a binder and/or mixture testing procedure to evaluate the quality of RAM and fresh/virgin asphalt binder blending in Wisconsin.

To accomplish these objectives, NCAT worked with the project oversight committee (POC) to develop an experimental plan that included the evaluation of binder blends with high RAM contents with and without RAs, and performance tests with different combinations of virgin binders, RAM, and RAs. This project included the following tasks:

Task 1. Synthesis of Current Practice and Research. This task encompassed a detailed literature review addressing practices and recommendations for the use of RAM in asphalt mixes in different states around the country.

Task 2. Work Plan and Laboratory Testing. In this task, a laboratory experiment was designed to validate practices and recommendations for the use of RAM in Wisconsin.

Task 3. Interim Presentation and Project Memorandum. This task included the preparation of an interim web-meeting presentation with the POC and an interim report summarizing the results of Tasks 1 and 2. The interim report was submitted on March 27, 2019 and the presentation was made on April 24, 2019.

Task 4. Execution of Work Plan and Analysis of Results. Once approval from the POC was granted, the work plan was conducted and the results were analyzed.

Task 5. Develop a Testing Protocol to Evaluate Allowable RAM Binder Replacement Levels for Wisconsin Mixtures. The outcome of this task is a draft procedure to evaluate the quality and content of RAM in asphalt mixtures.

Task 6. Final Report. This task includes a final report documenting the findings of the study and project closeout activities.

2. EXPERIMENTAL PLAN

The experimental plan developed to meet the objectives of this project is presented in Figure 1. It includes evaluation of virgin and RAM binders, recycled binder blends, and mixtures with and without RAs. Rheological and chemical evaluation of recycled binder blends and mixture performance tests to evaluate rutting, intermediate temperature cracking, and low temperature cracking resistance were conducted. The testing plan was divided into three subtasks as presented in the following sections.

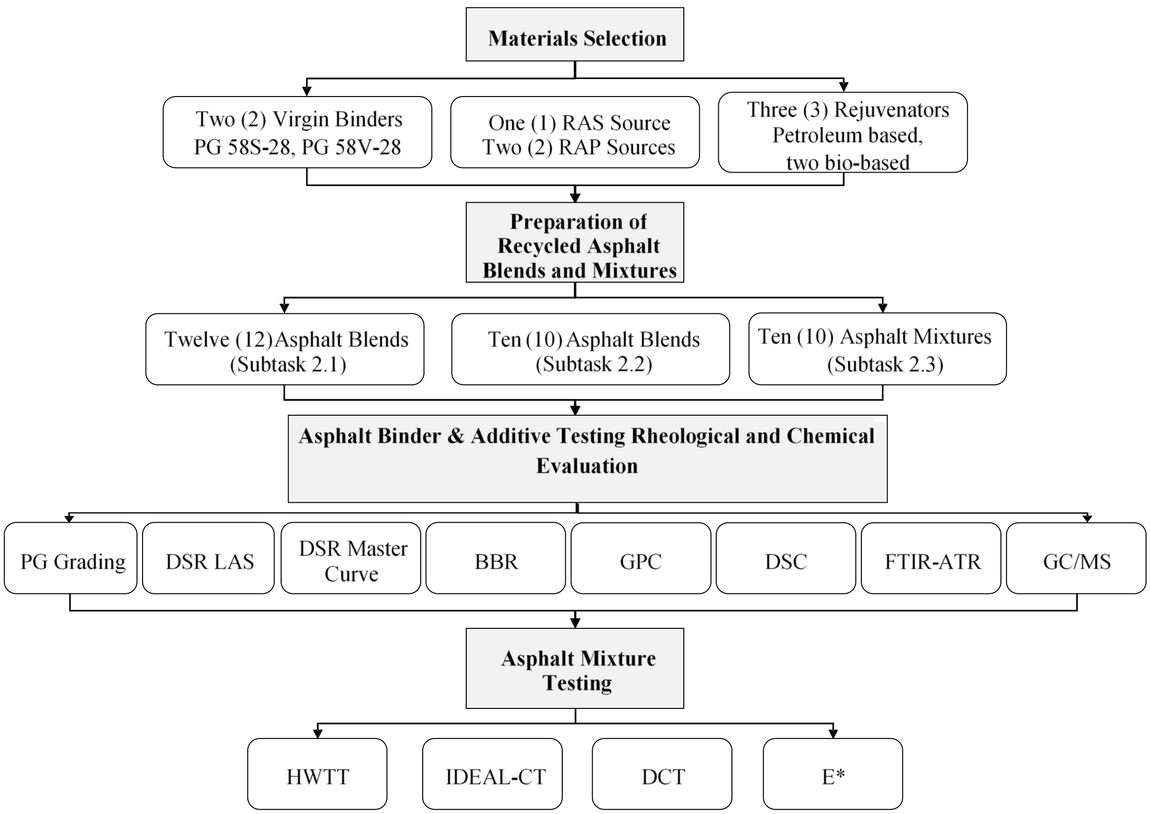


Figure 1. Proposed Testing Plan.

2.1 Subtask 2.1 Evaluation of RAM Effects on the Performance of Resultant Binders

The main objective of this subtask was to investigate the effects of RAP and/or RAS binder on the properties of the final binder blends through blending charts analysis. In order to develop applicable results for WisDOT, the following materials were selected: a virgin asphalt binder (PG 58S-28) and a polymer-modified binder (PMB) (PG 58V-28), two RAP materials, and one representative RAS representing typical materials used in Wisconsin. Binders from RAM samples were extracted, recovered, and blended with virgin binders at different proportions as presented in Table 2. A total of twelve asphalt blends were tested in Subtask 2.1.

Table 2. Testing Matrix for Subtask 1.

Factor	Description
Virgin Binders	Neat (PG 58S-28) and PMB (PG 58V-28)
RAM	Two RAP sources (RAP_1 and RAP_2), and one RAS source
Blending Ratio Neat/RAM and PMA/RAM	PG 58S-28 control PG 58S-28 + RAP_1 @ 20% and 40% ABR PG 58S-28 + RAS @ 15% and 25% ABR PG 58S-28 + RAP_1/RAS @ 20% and 35% ABR PG 58V-28 control PG 58V-28 + RAP_2 @ 20% and 40% ABR PG 58V-28 + RAS @ 15% and 25% ABR PG 58V-28 + RAP_2/RAS @ 20% and 35% ABR

Rheological Evaluation

The virgin binders and blended binders were evaluated for rheology characterization in accordance with the tests presented in Table 3 at high, intermediate, and low temperatures. The virgin and blended binders were subjected to different aging levels simulated in the Rolling Thin-Film Oven (RTFO, AASHTO T 240) and the Pressure Aging Vessel (PAV, AASHTO R 28). Since the hardening of asphalt binder during the service period of the pavement (long-term aging) is mainly due to oxidation, the effect of extended cycles of PAV aging (i.e., 40 hours) was investigated. The physical hardening behavior of the blended binders was evaluated with the extended Bending Beam Rheometer (BBR) testing in accordance with AASHTO TP 122 with samples conditioned at the Glass Transition Temperature (T_g) of each blend, since previous work has shown that the maximum rate of physical hardening occurs at the T_g temperature *(Tabatabaee et al., 2012)*.

Table 3. Rheology Testing for Materials Evaluation.

Property	Test Type	Standard	Testing		Research Parameter
			Conditions	Aging Level	
PG Grading	DSR	AASHTO M 320	@ High PG and Intermediate PG Temp.	Unaged and RTFO	$\lvert G^*\rvert/\sin(\delta)$
		AASHTO M 332	@ High PG Temp.	RTFO	$J_{nr3.2}$ and $\%R_{3.2}$
Intermediate Temp. Cracking Resistance	LAS	AASHTO TP 101	Frequency & Amplitude Sweep @ Intermediate PG Temp.	RTFO+40-hour PAV	Cycles to Failure (N_f)
	DSR Master-curve	AASHTO T 315	Frequency Sweep (0.1 to 30 Hz); Temp. range of 10-70°C	Unaged and RTFO+40-hour PAV	G-R
Low Temp. Cracking Resistance	BBR	AASHTO T 313	@ Low PG Temp.	RTFO+40-hour PAV	S, m-value and ΔT_c
		AASHTO TP 122	24 hrs of Conditioning @ Binder T_g Temp.	RTFO+40-hour PAV	Physical hardening behaviour

Chemical Evaluation

Since the aging behavior of blended binders is influenced by the chemical composition of the individual binders, chemical analysis was conducted to investigate the impact of RAM on the molecular distribution, thermal response and chemical composition of the resulting blends. Table 4 summarizes the tests conducted for chemical assessment of the asphalt blends.

Table 4. Chemical Characterization for Aging Evaluation.

Property	Test Type	Standard	Testing		Research Parameter
			Conditions	Aging Level	
MSD	GPC	N/A	1 mL/min @ 40°C	Unaged and RTFO+PAV	LMS, MMS and SMS molecules
Thermal Behaviour	DSC	N/A	Cooling range (165-90°C) @ 2°C/min. Heating range (-90-165°C) @ 2°C/min.	RTFO+PAV	T_g
Oxidative Aging Products	FTIR-ATR	N/A	Scans at region of 4000-650 cm^{-1}, resolution of 4 cm^{-1}	Unaged and RTFO+PAV	C=O

2.2 Subtask 2.2 Evaluation of the Effectiveness of Technologies in Compensating the Negative Aspects of RAM Binders

The objective of this subtask was to assess the ability of RAs to improve the performance properties of asphalt blends with high RAM content. Blending charts developed in Subtask 2.1 were used to guide the selection of the blended binders to be further modified with RA in order to restore the binder properties. Table 5 presents the testing matrix for this subtask. Ten asphalt blends were included in this evaluation. As shown in this table, the maximum allowable percent binder replacements currently allowed by WisDOT were selected to be tested in combination with the neat asphalt binder PG 58S-28 with three different RAs, two bio-based products (RA_1 and RA_2), and one petroleum based (RA_3). This table includes an additional blend with the polymer binder PG 58V-28, one ABR (40% RAP), and one RA (RA_1) added later in the project to assess the interaction between polymer-modified binders, recycled asphalt, and RAs. The selection of the two bio-based RAs used in this evaluation was based on a stand-alone (pre-screening) experiment conducted by the research team with five different products. The results of this experiment were submitted to the POC who made the final selection. After the addition of the RAs, the final blends were evaluated in accordance with the rheological tests described in Table 3 and Table 4.

Table 5. Testing Matrix for Subtask 2.2.

Factor	Description
Binder type, ABR and RAs	PG 58S-28 + RAP_1 @ 40% ABR + RA_1, RA_2, RA_3 PG 58S-28 + RAS @ 25% ABR + RA_1, RA_2, RA_3 PG 58S-28 + RAP_1/RAS @ 35% ABR + RA_1, RA_2 RA_3 PG 58V-28 + RAP_2 @ 40% ABR + RA_1

2.3 Subtask 2.3 Validate Resultant Binder Test Results using Asphalt Mixture Performance Testing

Materials and Mix Designs

The objective of this subtask was to validate the resultant binder test results using mixture performance testing. A total of ten mixtures were tested in Subtask 2.3 as presented in Table 6. Two different aggregates from Wisconsin, one gravel and one carbonate were included in the evaluation. Mixtures with Aggregate 1 used a PG 58S-28 and were designed to attain asphalt binder replacements of 20% RAP, 40% RAP, 25% RAS only, and a 35% RAP/RAS (30% from RAP and 5% from RAS) combination. Two additional mixes were prepared with Aggregate 1 using a PG 58V-28 with approximately 20% RAP and 40% RAP binder replacements. The 20% RAP mixes were treated as the "control mixes" for performance comparison in this study since 20% RAP is currently a typical RAP content in new mix designs. All the mixes prepared with Aggregate 1, with the exception of the 20%RAP mix were rejuvenated with RA_1. Mixtures with Aggregate 2 used a PG 58S-28 and were also designed to attain the same binder replacements as those with Aggregate 1. All of the mixes prepared with Aggregate 2, with the exception of the 20%RAP mixes were rejuvenated with RA_2. The RA dosage rates (by weight of total binder) along with the resultant binder PG grade for the unmodified binder and modified binder for all the blends are shown in Table 7. The RA dosages ranged from 2.1% to 5%, which were obtained by matching a climate low-temperature PG of -28ºC in Wisconsin after 40 hours of PAV aging. The approach to select the RA dosage for mixture performance testing will be further discussed in the next chapter.

Table 6. Asphalt Mixtures Compositions for Subtask 2.3.

Factors	Description
Aggregate type + binder type + ABR with and without RAs	Agg.1 + PG 58S-28 +RAP_1 @ 20%ABR Agg.1 + PG 58S-28 + RAP_1 @ 40% ABR+RA_1 Agg.1+ PG 58S-28 + RAS @ 25% ABR+RA_1 Agg.1 + PG 58S-28 + RAP_1/RAS @ 35% ABR+ RA_1 Agg.2 +PG 58V-28 +RAP_2 @ 20%ABR Agg. 2 + PG 58V-28 + RAP_2 @ 40% ABR+RA_2 Agg.2 + PG 58S-28 +RAP_2 @ 20%ABR Agg.2 + PG 58S-28 + RAP_2 @ 40% ABR+RA_2 Agg.2 + PG 58S-28 + RAS @ 25% ABR+RA_2 Agg.2 + PG 58S-28 + RAP_2/RAS @ 35% ABR+ RA_2

Virgin aggregates along with recycled materials (RAP and RAS) were provided by two contractors Wisconsin. Along with the raw material, the contractors provided two WisDOT-approved job mix formula (JMF) (baseline mixes), which were modified to achieve the desired RAM content for research evaluation, but keeping a similar gradation. The existing mix designs provided by the contractors had 28.1% RAP by weight of the mix for Aggregate 1, and 10.1% RAP and 3.4% RAS by weight of the mix for Aggregate 2. These proportions correspond to 21.7% ABR for the Aggregate 1 and 23.1% ABR (8.2% from RAP and 14.9% from RAS) for Aggregate 2. One source of RAS material was used for all of the mixes with RAS.

Table 7. Recycling Agent Dosage Rates.

Base Binder	Binder Blend	Recycling Agent	Dosage Rate (%)	Resultant Binder PG (RTFO plus 40 hours of PAV)
PG 58S-28	25% ABR	RA_1	4.1	69.9-28.0
		RA_2	5.0	67.3-28.0
	35% ABR	RA_1	2.1	66.0-28.0
		RA_2	2.5	65.3-28.0
	40% ABR	RA_1	2.4	66.1-28.0
		RA_2	2.8	64.8-28.0
PG 58V-28	40% ABR	RA_1	3.0	71.6-28.1

All mixtures for this study were designed according to the Superpave asphalt mixture design methodology (AASHTO R35) to meet WisDOT specifications for medium traffic (1 to 8 million ESALs) with a nominal maximum aggregate size (NMAS) of 12.5 mm, as shown in Table 8. The optimum asphalt content was selected to achieve a regressed air voids of 3.0%. The regressed air voids approach is a practice that has been implemented by WisDOT. Table 9 and Table 10 show the cold feed percentages for each JMF.

Table 8. WisDOT Specifications for a 12.5 mm-NMAS Mix for Medium Traffic.

Parameter	WisDOT Spec
N_{design} gyration	75
Air voids content (V_a), %	4
Voids in mineral aggregates (VMA), %	>14.5
Voids filled with asphalt (VFA), %	70-76
Dust to binder (D/B) ratio	0.6-1.2

Table 9. Material Proportions of Aggregate 1 Blends.

Aggregate 1 Blend	5/8" x 3/8"	3/8" Bit	1/8" MS	5/8" Sand	3/4" RAP	RAS
20% ABR	20.0%	16.0%	17.0%	22.0%	25.0%	-
25% ABR	27.0%	27.0%	10.0%	30.0%	-	6.0%
35% ABR	20.0%	10.8%	17.0%	14.0%	37.0%	1.2%
40% ABR	18.0%	7.0%	18.0%	7.0%	50.0%	-

Table 10. Material Proportions of Aggregate 2 Blends.

Aggregate 2 Blend	5/8" Chip	3/8" Chip	Mfrd Dry	Mfrd Wash	Torp Sand	Dust	RAP	RAS
20% ABR	7.0%	20.0%	-	32.0%	16.0%	-	25.0%	-
25% ABR	7.5%	28.0%	29.0%	-	28.0%	1.0%	-	6.5%
35% ABR	10.0%	-	27.0%	-	22.0%	-	39.5%	1.5%
40% ABR	10.0%	20.0%	-	23.0%	14.0%	-	33.0%	-

Before mixing, the asphalt binder was preheated in an oven for three to four hours at 150 ±3 °C and 163 ±3 °C for the unmodified and polymer modified binder, respectively. RAP was preheated at 135 °C for at least an hour and half but not more than three hours. RAS was added without any preheating, and virgin aggregates were preheated overnight at 175°C. For all mixtures but those with RA, a low-speed shear mixer (200 rpm) was used to blend the RA into the base binders for 30 ±5 minutes prior to mixing with the aggregates and recycled materials. During mixing, preheated virgin aggregates were added in the bucket followed by preheated RAP or cold RAS. They were thoroughly mixed for two minutes before adding a heated asphalt binder. The blend was then moved to the rotary mixer and mixed until all the aggregates were coated with asphalt. For mixtures using both RAP and RAS, cold RAS was added to the hot aggregates followed by the preheated RAP. Asphalt mixtures prepared for volumetric mix design were conditioned for two hours at 135±3 ºC to simulate short-term aging and asphalt absorption by the aggregates per AASHTO R 30.

Table 11 and Table 12 show the JMF of the asphalt mixtures used in this study. The table shows the final ABR of the mixtures, which are within ± 2.5 % from the target values set for this project. All but two mixtures met the WisDOT requirements for a medium traffic (75 gyrations) 12.5 mm NMAS mix. Mixtures with 35% ABR and 40% ABR with Aggregate 2 material did not meet the dust-to-binder (D/B) ratio requirement of 0.6-1.2 due to the high RAP contents used. It is important to point out that these mix designs were conducted using aggregate stockpiles originally used for mixes with lower ABR provided by the Wisconsin contractors. As the ABR increases, the amount of fines in the mix increases, causing the D/B ratio to increase. Several aggregate blends were tried but they were not able to meet the D/B ratio requirement without sacrificing other volumetric requirements such as VMA. The trial mixes closer to meet the D/B ratio requirement and all the other volumetric requirements were presented to the POC for discussion. The POC approved to include these mixes for further testing. Although the existing mix design provided by the contractor using Aggregate 1 included an antistrip, it was decided and approved by the POC not to add antistrip agent in all the mixes evaluated in the study because of the concern that the antistrip could potentially affect the effectiveness of RAs due to incompatibility issues.

Table 11. Job Mix Formula for Aggregate 1 Mixtures.

Mixture Type	20%ABR	25%ABR	35%ABR	40%ABR
% Passing Sieve Size (in)				
3/4	100.0	100.0	100.0	100.0
1/2	95.5	95.7	95.0	94.7
3/8	84.8	83.9	83.8	83.7
#4	64.7	61.5	63.8	64.0
#8	51.9	48.9	51.6	51.7
#16	39.6	37.8	39.4	39.3
#30	28.4	26.8	28.5	28.7
#50	13.9	13.8	14.7	15.2
#100	6.4	7.3	7.2	7.5
#200	3.7	4.6	4.4	4.5
Mix Design Information				
Optimum AC% @ 4% V_a	5.5	5.5	5.3	5.1
VMA @ 4% V_a	15.3	15.6	15.0	14.7
VFA @ 4% V_a	74.1	74.5	73.5	73.0
D/B Ratio @ 4% V_a	0.67	0.83	0.84	0.90
VMA @ 3% V_a	15.3	15.2	14.9	14.6
Regressed AC% @ 3% V_a	5.9	5.7	5.6	5.4
V_{be} @ 3% V_a	12.3	12.2	11.9	11.6
ABR% Information @ 3% V_a				
RAP Content	25%	-	37%	50%
RAS Content	-	6%	1.2%	-
RAP ABR	19.1%	-	29.7%	41.7%
RAS ABR	-	26.2%	5.3%	-
Total ABR	19.1%	26.2%	35.0%	41.7%

Table 12. Job Mix Formula for Aggregate 2 Mixtures.

Mixture Type	20%ABR	25%ABR	35%ABR	40%ABR
% Passing Sieve Size (in)				
3/4	100.0	100.0	100.0	100.0
1/2	98.9	98.8	98.0	98.4
3/8	89.5	89.5	88.4	88.8
#4	67.4	64.5	68.6	70.1
#8	55.5	53.7	54.2	54.9
#16	35.8	37.5	37.6	36.6
#30	23.9	24.9	25.4	24.4
#50	12.1	11.9	12.6	13.3
#100	7.1	7.5	8.1	8.4
#200	5.2	5.3	5.7	6.3
Mix Design Information				
Optimum AC% @ 4% V_a	5.8	6.2	5.8	5.8
VMA @ 4% V_a	15.4	15.6	14.8	14.7
VFA @ 4% V_a	74.1	74.7	73.0	72.7
D/B Ratio @ 4% V_a	1.08	1.07	1.28	1.41
VMA @ 3% V_a	15.5	15.4	14.5	14.6
Regressed AC% @ 3% V_a	6.1	6.5	6.1	6.1
V_{be} @ 3% V_a	12.5	12.4	11.5	11.6
ABR% Information @ 3% V_a				
RAP Content	25%	-	39.5%	33%
RAS Content	-	6.5%	1.5%	-
RAP ABR	19.3%	-	29.3%	37.8%
RAS ABR	-	24.9%	6.1%	-
Total ABR	19.3%	24.9%	35.4%	37.8%

Asphalt Mixture Performance Tests

Table 13 presents the mixture performance tests conducted in this study. The loose mixtures for performance testing were subjected to two aging conditions: short-term oven aging (STOA) and long-term oven aging (LTOA), both at 135 °C. The loose asphalt mixtures were conditioned for STOA for four hours after mixing. For LTOA, the conditioned STOA loose asphalt mixtures were further aged for six hours but at a reduced layer thickness (less than ¾ to 1 inch thick) prior to compaction. The HWTT was conducted on STOA specimens to evaluate the rutting resistance and moisture susceptibility of the asphalt mixtures because asphalt mixtures are most vulnerable to these two distresses right after construction. IDEAL-CT and DCT tests were performed on LTOA mixtures considering that asphalt mixtures tend to be more susceptible to cracking after aging due to increased mix embrittlement and reduced relaxation properties. E* was conducted on both STOA and LTOA asphalt mixtures to evaluate the stiffness characteristics and aging resistance of the mixtures. All specimens for performance testing were prepared with a target air void content of 7.0±0.5 %.

Table 13. Proposed Mixture Performance Tests.

Mixture Property	Test	Aging Condition	Performance Parameter
Rutting Resistance	HWTT (AASHTO T324)	STOA	Passes to 12.5 mm, corrected rut depth (CRD)
Moisture Susceptibility			Stripping inflection point (SIP); stripping number (SN)
Intermediate Temp. Cracking Resistance	IDEAL-CT (ASTM D8225-19)	LTOA	CT_{Index}
Thermal Cracking Resistance	DCT (ASTM D7313)	LTOA	Fracture energy (G_f)
Viscoelasticity	E* (AASHTO TP132-19)	STOA and LTOA	E*/phase angle master curve and black space diagram
Aging Resistance			$G\text{-}R_m$ aging index

Test procedures and data analysis methodologies are briefly discussed in the following sections.

Dynamic Modulus (|E*|)

Dynamic modulus testing was performed in accordance with AASHTO TP132-19 using the IPC global® AMPT-PRO equipment on both STOA and LTOA mixture samples to evaluate the stiffness characteristics of the asphalt mixtures and their evolution with aging. Superpave Gyratory Compactor (SGC) specimens were compacted to 180 mm tall and 150 mm in diameter with an air void content of 8.0 %. From these specimens, four 38 mm diameter by 110 mm tall specimens were cored and saw-cut from the larger SGC specimens per AASHTO PP99-19. Three replicates of small specimens with 7.0 ± 0.5% air voids (were selected for testing for each mixture type and each aging condition. Specimens were tested at three temperatures (4, 20, and 35°C) and three loading frequencies (10, 1, and 0.1 Hz) at each testing temperature. The |E*| master curves were generated by fitting the |E*| values at various reduced frequencies using the sigmoidal function described in Equation 2.

$$\log|E*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma logtR}} \qquad \text{Equation 2}$$

Where |E*| is the dynamic modulus, t_r is the reduced time at the reference temperature, δ is the minimum value of |E*|, δ+α is the maximum value of |E*|, and β, γ are parameters describing the shape of the sigmoidal function.

Dynamic modulus and phase angle results using a temperature of 20°C and frequency of 5 Hz were analyzed in a Black Space diagram and with the mixture Glover-Rowe parameter ($G\text{-}R_m$) as determined using Equation 3. A lower $G\text{-}R_m$ value is desirable for asphalt mixtures with better resistance to block cracking. This approach has been proposed and used by a number of researchers to assess the effect of aging and RAs on the brittleness properties and cracking resistance of asphalt mixtures with high RAM (*Ogbo, et al., 2019*, *Epps Martin et al., 2019*).

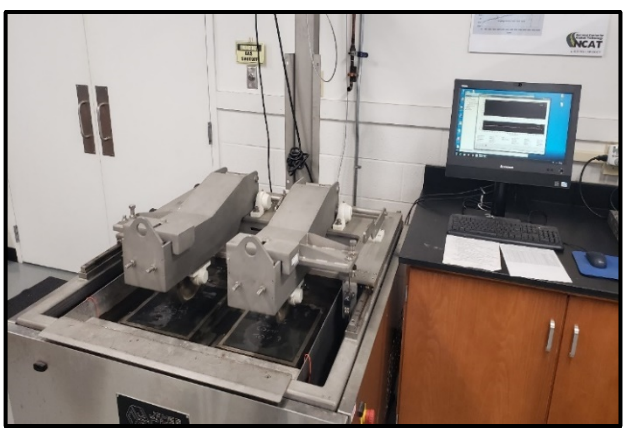
$$G\text{-}R_m = \frac{|E^*|\,(cos\phi)^2}{sin\phi} \text{ at 20°C and 5 Hz} \qquad \text{Equation 3}$$

Hamburg Wheel Tracking Test

The Hamburg Wheel Tracking Test (HWTT) was conducted to assess the rutting resistance and moisture susceptibility of the asphalt mixtures per AASHTO T324. Two sets of HWTT specimens were loaded with two steel wheels, each 158 ± 1 lbs. for 20,000 passes while submerged in a water bath maintained at a temperature of 46 °C. Two linear variable differential transformers on the side of the machine continuously recorded the relative vertical positions of the steel wheels, which were then translated into rut depth measurements.

Two rutting test parameters were used for HWTT data analysis: the number of passes to 12.5 mm rut depth, and the corrected rut depth (CRD), both at 20,000-wheel passes. The CRD_{20k} is a simplified version of the viscoplastic strain increment parameter ($\Delta\varepsilon^{vp}$) proposed by Yin et al. *(2014)* and represents the projected rut depth at 20,000 passes due to the permanent deformation of the mixture only. Stripping inflection point (SIP) and stripping number (SN) were used to evaluate the moisture damage potential of the mixtures. SIP is obtained by interpolating the intersection of two tangential lines that best fit the creep and stripping phase of the HWTT curve. SN was also proposed by Yin et al. *(2014)* and refers to the number of wheel passes at the onset of stripping. As compared to SIP, SN is less subjective because its determination is based on curve fitting of the entire rut depth curve instead of fitting two tangential lines for the creep phase and stripping phrase.

The HWTT setup is shown in Figure 2 (a) while Figure 2 (b) illustrates the determination of CRD_{20k} using the HWTT rut depth curve. For CRD_{20k}, a lower value is desired for asphalt mixtures with better rutting resistance; the opposite applies to SIP and SN for the evaluation of moisture resistance.



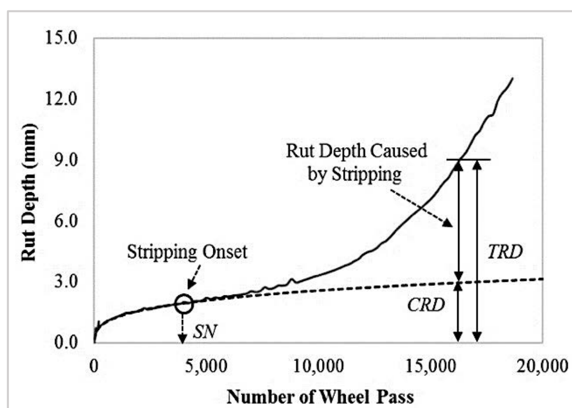


Figure 2. HWTT; (a) Test Equipment, (b) Data Analysis *(Yin et al. 2014)*

Indirect Tensile Asphalt Cracking Test

The Indirect Tensile Asphalt Cracking Test (IDEAL-CT) was used to evaluate the intermediate-temperature cracking resistance of the asphalt mixtures. The test was conducted in accordance with

ASTM D8225-19. Prior to testing, specimens were conditioned in an environmental chamber at 25 ±1.0°C for two hours ±10 minutes. During the test, a monotonic load was applied along a gyratory specimen at a constant displacement rate of 50 mm/min as shown in Figure 3(a). Equation 4 was used to calculate the cracking tolerance index (CT_{index}) from the load versus displacement curve. G_f is the failure energy obtained by dividing the work of fracture (the area under the load versus displacement curve) by the cross-sectional area of the sample. As illustrated in Figure 3(b), l_{75} is the displacement at 75% the peak load after the peak, and m_{75} is the slope of the tangent at 75% the peak load after the peak. A higher CT_{index} value is desired for asphalt mixtures with better cracking resistance at intermediate temperatures.

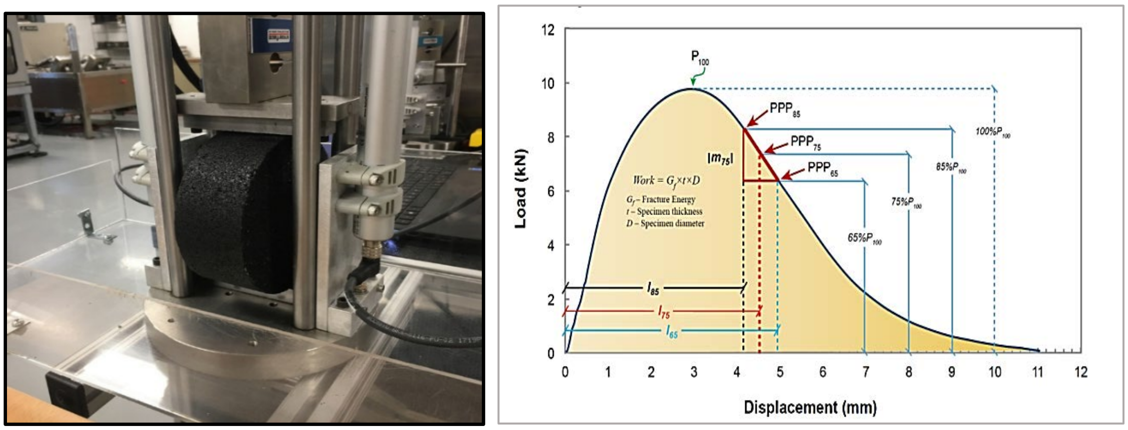


Figure 3. IDEAL-CT (a) Experiment Setup (b) Data Analysis.

$$CT_{index} = \frac{t}{62} * \frac{l_{75}}{D} * \frac{G_f}{|m_{75}|} * 10^6$$ Equation 4

Where

t = specimen thickness;
l_{75} = displacement at 75% of peak load;
D = specimen diameter;
G_f = fracture energy; and
$|m_{75}|$ = slope at 75% peak load.

Disc-shaped Compact Tension Test

The Disc-Shaped Compact Tension Test (DCT) was conducted in accordance with ASTM D7313-13 to assess the low-temperature cracking resistance of the asphalt mixtures. The test specimens were prepared by saw-cutting a 160 mm-high by 150 mm-diameter specimen compacted to 7.5% air void contents into two halves of 50±5 mm thick. The halved specimens were then trimmed to have a flat edge on one side of the specimen for knife gages. Then, a notch 62.5±2.5 mm long was saw-cut at the center of the flat edge, followed by coring two 1-inch diameter holes on each side of the notch. The final testing specimen had a target air void content of 7.0±0.5 %; and the number of replicates ranged from five to six specimens.

Since both asphalt binders had a low-temperature PG of -28 °C, the test was conducted at -18 °C for all binders, as ASTM D 7313-13 recommends running the test at 10°C above the low PG temperature of the asphalt binder. Tests were conducted by loading a DCT specimen in tension using metal rods that were inserted through core holes, as shown in Figure 4(a). A clip gage was installed over the crack mouth prior to the start of the test to control and record the crack mouth opening displacement (CMOD). The test was conducted in CMOD control mode with the clip gage opening at a constant rate of 0.017 mm/sec. The test was terminated when the load dropped below 0.1 kN. Figure 4(b) presents an example of the load versus CMOD behavior in the DCT test. For data analysis, the fracture energy (G_f) was calculated using Equation 5, where the area under the load-CMOD curve was determined through numerical integration using the trapezoidal rule. A higher G_f value is desired for asphalt mixtures with better resistance to low-temperature cracking.

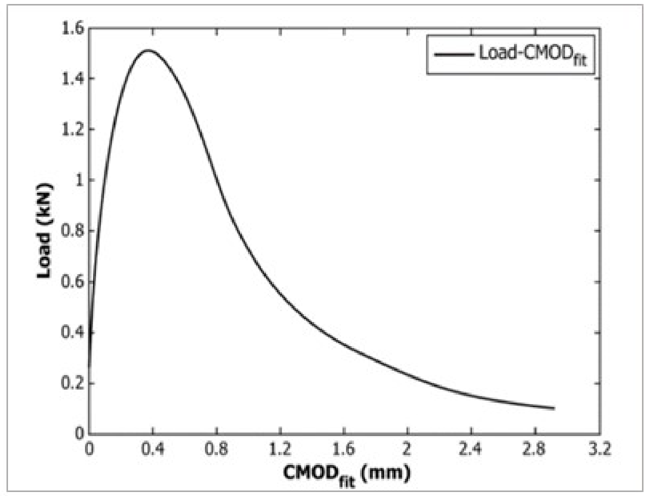


Figure 4. DCT (a) Experiment Setup (b) Data Analysis.

$$G_f = \frac{Area}{B*(W-a)}$$ Equation 5

Where

G_f = fracture energy (J/m^2);
Area = area under load-CMOD curve;
B = specimen thickness (m); and
W-a = initial ligament length (m).

3. ANALYSIS OF RHEOLOGICAL AND CHEMICAL RESULTS

This section presents the rheological and chemical testing results associated with the evaluation of how quantity and quality of RAM affects the performance properties of resultant binders. Such measurements will be used for examining and understanding the interaction of the different constituents (i.e., virgin binder, aged binder, polymer, and recycling agents) of the multi-component recycled binder blends. Due to the page limit of this report, the rheological and chemical parameters utilized for evaluation of the blended binders are described in detail in the literature review report, which is available upon request through WHRP. Furthermore, complete databases for both rheological and chemical analysis are available to the WisDOT. For simulation of oxidative aging, the base asphalt binders and the recycled binder blends were short-term aged in the Rolling Thin-Film Oven (RTFO, AASHTO T 240) followed by a single protocol of 40 hours in the Pressure Aging Vessel (PAV, AASHTO R 28) for simulation of long-term aging. The RAP recycled binders were only short-term aged in the RTFO, while the RAS recycled binder was not aged in laboratory.

3.1 Superpave Performance Grade Classification

The final PG classifications of all asphalt binders evaluated in this study are presented in Table 14. In summary, the addition of recycled binder to both the PG 58S-28 and PG 58V-28 base binders improved rutting resistance of the asphalt binders but decreased the fatigue resistance, the thermal cracking resistance, or stress relaxation property after RTFO plus 40 hours of oxidative aging in PAV oxidative aging. The incorporation of the three RAs counterbalanced these negative effects. With exception of the blends with 25% RAS binder replacement, the addition of RAs resulted in a decrease in the temperature at which the limiting fatigue parameter [$|G^*|.\sin(\delta)$] was satisfied based on AASHTO M320. Moreover, when the bio-based RAs were added, a restoration to the initial base binders' low temperature PG was achieved.

Table 14. PG Classification of Asphalt Binders at High and Low Temperatures.

Sample	T_{cont}, High, °C	T_{cont}, Intermediate, °C	T_{cont}, Low S, °C	T_{cont}, Low m-value, °C	T_{cont}, Low, °C	ΔT_c	PG HT	PG LT
PG 58S-28	60.3	16.8	-30.9	-30.7	-30.7	-0.2	58	-28
PG 58V-28	66.1	17.4	-30.6	-31.6	-30.6	1.0	64	-28
RAP_1	83.1	26.2	-25.9	-22.9	-22.9	-3.0	82	-22
RAP_2	86.4	27.1	-22.7	-21.1	-21.1	-1.6	82	-16
RAS	163.2	38.2	-24.9	27.7	27.7	-52.6	160	26
80% PG 58S-28 + 20% RAP_1	64.8	22.1	-28.9	-25.8	-25.8	-3.2	64	-22
60% PG 58S-28 + 40% RAP_1	69.5	24.3	-28.0	-23.2	-23.2	-4.8	64	-22
85% PG 58S-28 + 15% RAS	67.8	23.3	-29.5	-22.5	-22.5	-7.0	64	-22
75% PG 58S-28 + 25% RAS	77.0	25.1	-28.1	-17.0	-17.0	-11.2	76	-16
80% PG 58S-28 + 15% RAP_1 + 5% RAS	64.2	20.4	-29.6	-26.2	-26.2	-3.3	64	-22
65% PG 58S-28 + 30% RAP_1 + 5% RAS	67.8	23.6	-28.4	-24.5	-24.5	-3.9	64	-22
80% PG 58V-28 + 20% RAP_2	74.0	21.5	-28.2	-26.3	-26.3	-1.9	70	-22
60% PG 58V-28 + 40% RAP_2	75.8	24.3	-27.6	-23.8	-23.8	-3.7	70	-22
85% PG 58V-28 + 15% RAS	81.1	21.5	-31.2	-21.8	-21.8	-9.4	76	-16
75% PG 58V-28 + 25% RAS	86.1	25.1	-30.0	-19.1	-19.1	-10.9	82	-16
80% PG 58V-28 + 15% RAP_2 + 5% RAS	76.1	21.3	-28.2	-24.6	-24.6	-3.6	76	-22
65% PG 58V-28 + 30% RAP_2 + 5% RAS	76.4	24.6	-27.5	-22.9	-22.9	-4.6	76	-22
55% PG 58V-28 + 40% RAP_2 + 5% RA_1	68.8	17.1	-34.8	-30.9	-30.9	-3.9	64	-28
55% PG 58S-28 + 40% RAP_1 + 5% RA_1	62.3	16.5	-34.5	-33.3	-33.3	-1.1	58	-28
70% PG 58S-28 + 25% RAS + 5% RA_1	68.4	17.8	-35.3	-30.3	-30.3	-4.9	64	-28
60% PG 58S-28 + 30% RAP_1 + 5% RAS + 5% RA_1	63.5	15.5	-34.7	-33.0	-33.0	-1.6	58	-28
55% PG 58S-28 + 40% RAP1 + 5% RA_2	61.2	15.9	-33.6	-31.7	-31.7	-1.9	58	-28
70% PG 58S-28 + 25% RAS + 5% RA_2	67.3	19.2	-33.8	-28.0	-28.0	-5.8	64	-28
60% PG 58S-28 + 30% RAP_1 + 5% RAS + 5% RA_2	62.7	14.5	-33.8	-31.5	-31.5	-2.3	58	-28
40% PG 58S-28 + 40% RAP_1 + 20% RA_3	61.3	11.7	-32.4	-28.2	-28.2	-4.2	58	-28
55% PG 58S-28 + 25% RAS + 20% RA_3	67.6	17.0	-32.0	-19.3	-19.3	-12.8	64	-16
45% PG 58S-28 + 30% RAP_1 + 5% RAS + 20% RA_3	61.9	14.1	-32.6	-28.0	-28.0	-4.6	58	-28

To investigate if linear blending applies to blends of RAP, RAS, RAP+RAS (RAM), RAs and virgin binders, plots of the continuous grade temperature as a function of recycled binder content are shown in Figure 5 through Figure 8. As can be seen, for both the unmodified and modified base binders, a linear effect of increasing recycled binder replacement up to 40% was found for most of the high temperature continuous grade, the intermediate temperature continuous grade, and the low temperature continuous grades determined based on creep stiffness and m-value. When RAs were added to the recycled binder blends, the effects of these additives were found to be dependent on their chemical composition and was base binder and recycled asphalt material specific.

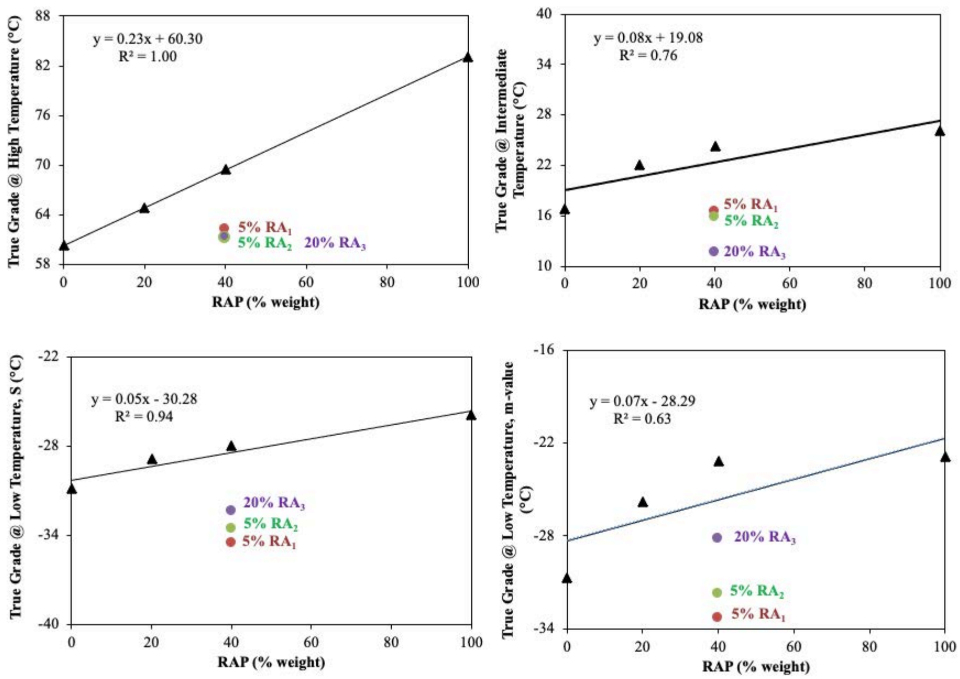


Figure 5. Effect of RAP Binder Replacement and RAs on Continuous Grade Temperatures for Recycled Binders containing a PG 58S-28 Binder.

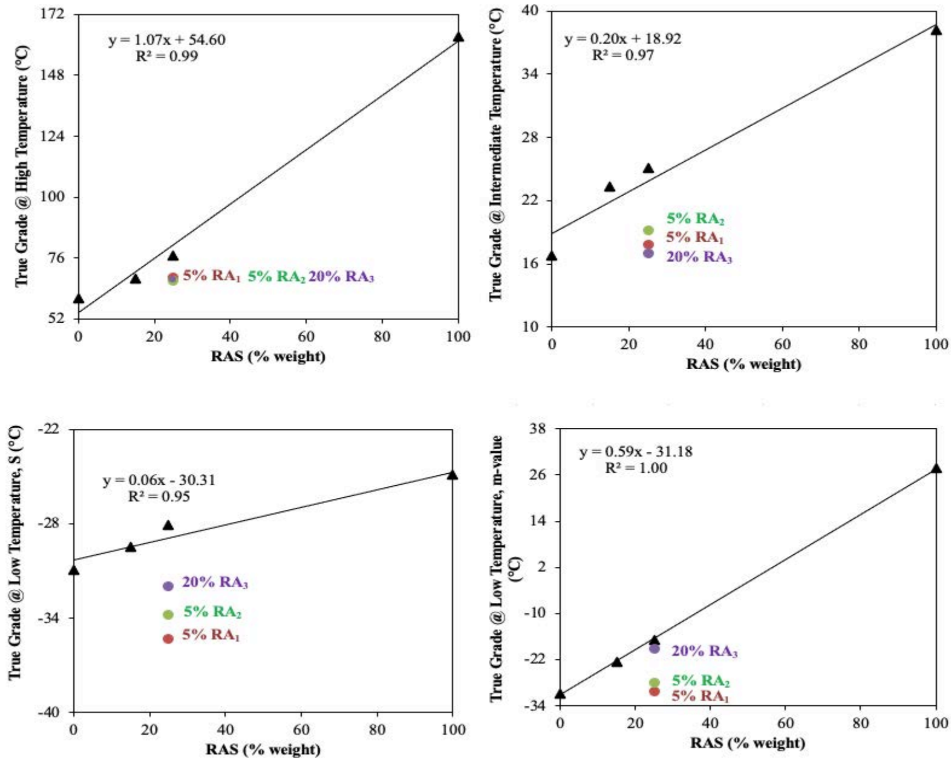


Figure 6. Effect of RAS Binder Replacement and RAs on Continuous Grade Temperatures for Recycled Binders containing a PG 58S-28 Binder.

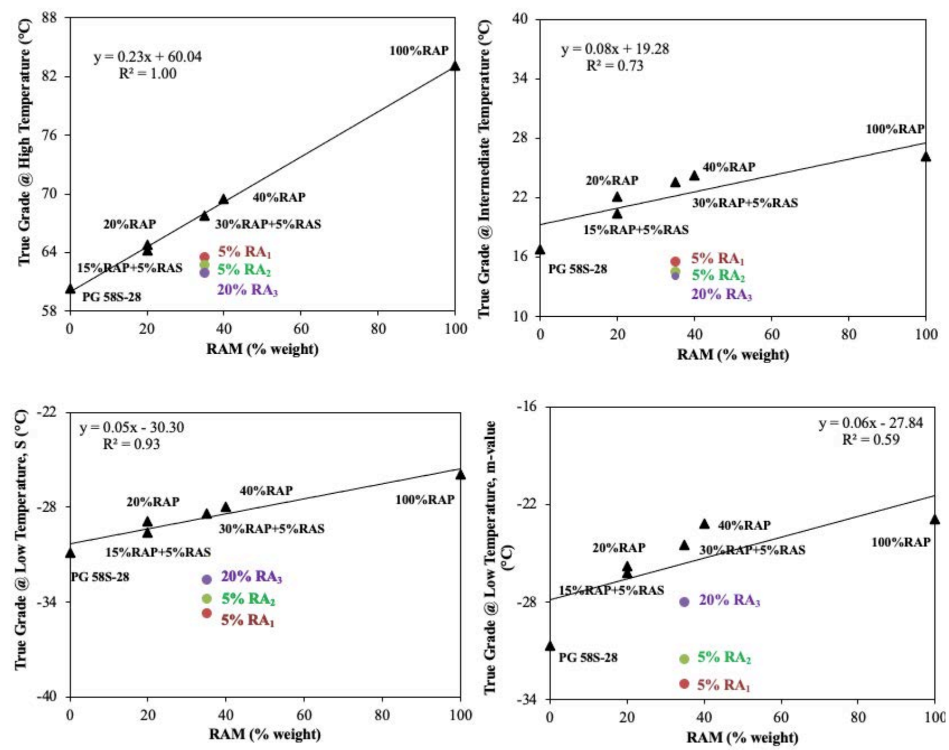


Figure 7. Effect of RAM Binder (i.e., RAP+RAS) Replacement and RAs on Continuous Grade Temperatures for Recycled Binders containing a PG 58S-28 Binder.

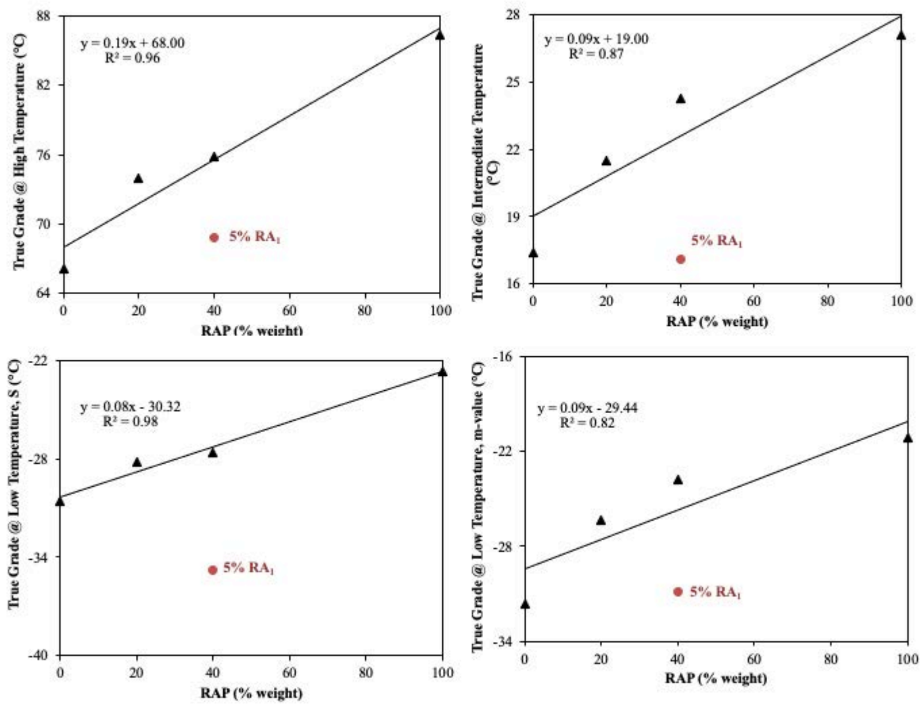
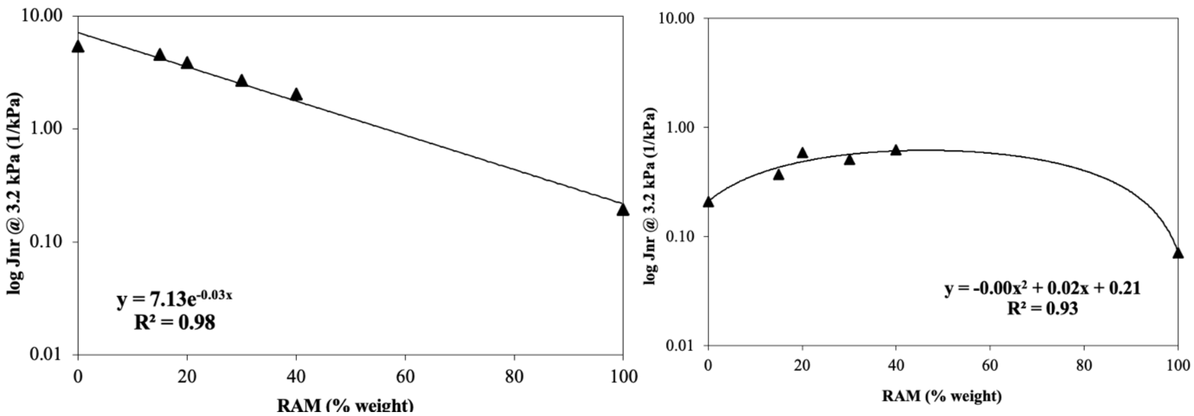


Figure 8. Effect of RAP Binder Replacement and RA_1 on Continuous Grade Temperatures for Recycled Binders containing a PG 58V-28 Binder.

3.2 High Temperature Performance in Terms of the Multiple Stress Creep and Recovery Test

MSCR testing was performed on all samples after RTFO oxidative aging. Although WisDOT specifies MSCR testing at 58°C, this temperature was found as rather low when considering the materials under investigation in this project (i.e., with the exception of the PG 58S-28 base binder, the binder blends presented high temperature grade at or above PG 64). Therefore, to better differentiate the rutting resistance of these materials, MSCR testing was conducted at 64°C.

To investigate if linear blending applies to blends recycled binder blends with and without RAs, the J_{nr} at 3.2 kPa, %Recovery, and percent difference in J_{nr} between the 0.1 and 3.2 kPa were plotted as a function of recycled binder content. The graphs were submitted to WHRP in a excel file. Results indicate that the MSCR testing parameters are dependent on the constituents of the binder blends (i.e., base binder type and percentage, recycled binder type and percentage, and RA type and dosage). For example, while for the PG 58S-28 base binder the J_{nr} at 3.2 kPa parameter showed a linear relationship on the log-linear scale presenting decreased values as the recycled binder content increased [Figure 9(a)], the relationship was non-linear for the PG 58V-28 base binder [Figure 9(b)]. The addition of RAs to the binder blends did not alter the log-linear relationship between J_{nr} at 3.2 kPa and recycled binder content (Figure 10).



(a) (b)

Figure 9. Effect of RAM Binder (i.e., RAP+RAS) Replacement on J_{nr} @ 3.2 kPa for Recycled Binders containing: (a) PG 58S-28 Binder, and (b) PG 58V-28 Binder

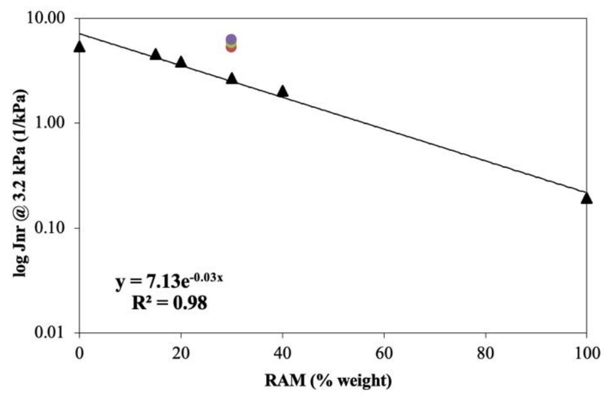


Figure 10. Effect of RAM Binder (i.e., RAP+RAS) Replacement and RAs on J_{nr} @ 3.2 kPa for Recycled Binders containing a PG 58S-28 Binder

As indicated in Figure 11, the effect of the recycled binder type plays a more important role in the J_{nr} than the recycled binder replacement content. As can be seen, the blends with 25% RAS recycled binder showed smaller J_{nr} values in comparison to 40% RAP recycled binder and 30% RAP + 5% RAS. Moreover, the RAs seem to have an effect on the overall magnitude of J_{nr}, by increasing it, and the effectiveness of each RA seemed to be related to both its chemical composition and its interaction with the recycled binder type.

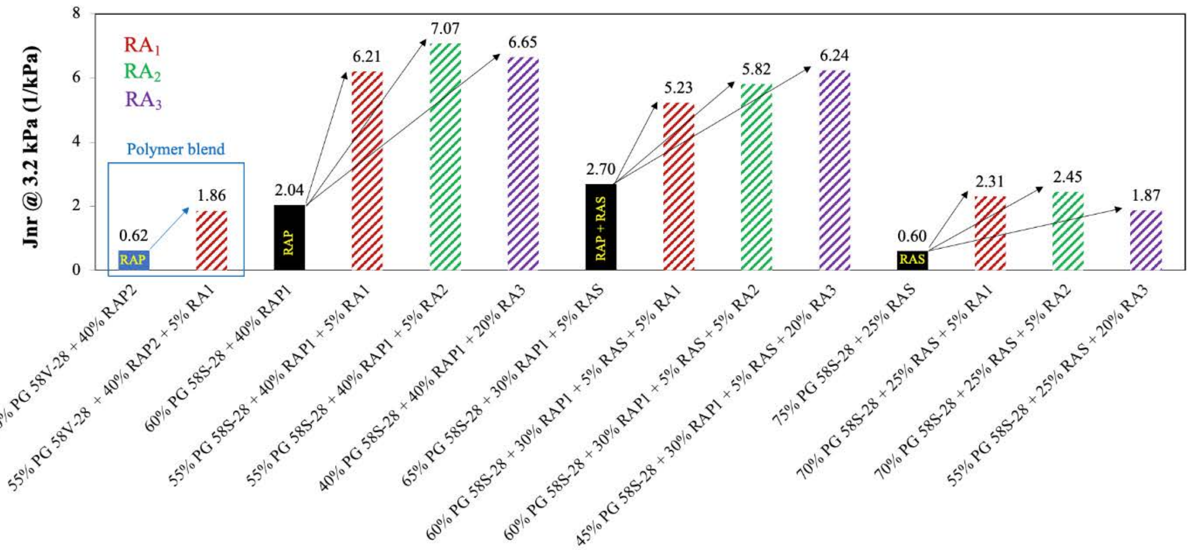


Figure 11. Effect of Binder Replacement and RAs on J_{nr} at 3.2 kPa and 64°C.

The behavior of the %Recovery parameter was found to be highly influenced by the creep compliance J_{nr} of the binders, regardless of the presence and content of polymer. For example, the RAS recycled binder showed extremely high recovery (i.e., 94.52%), when it is known that this behavior is due to the extremely low J_{nr} of the material (i.e., 0.00007671 kPa^{-1}). As expected, the addition of RAs did not affect the linear relationship between %Recovery and recycled binder replacement, and a decrease in the %Recovery was observed as the RAs were added to the binder blends. Among the blends with RAs, the 55% PG 58V-28 + 40% RAP_2 + 5% RA_1 blend showed the highest %Recovery due to the presence of polymer in the base binder (Figure 12).

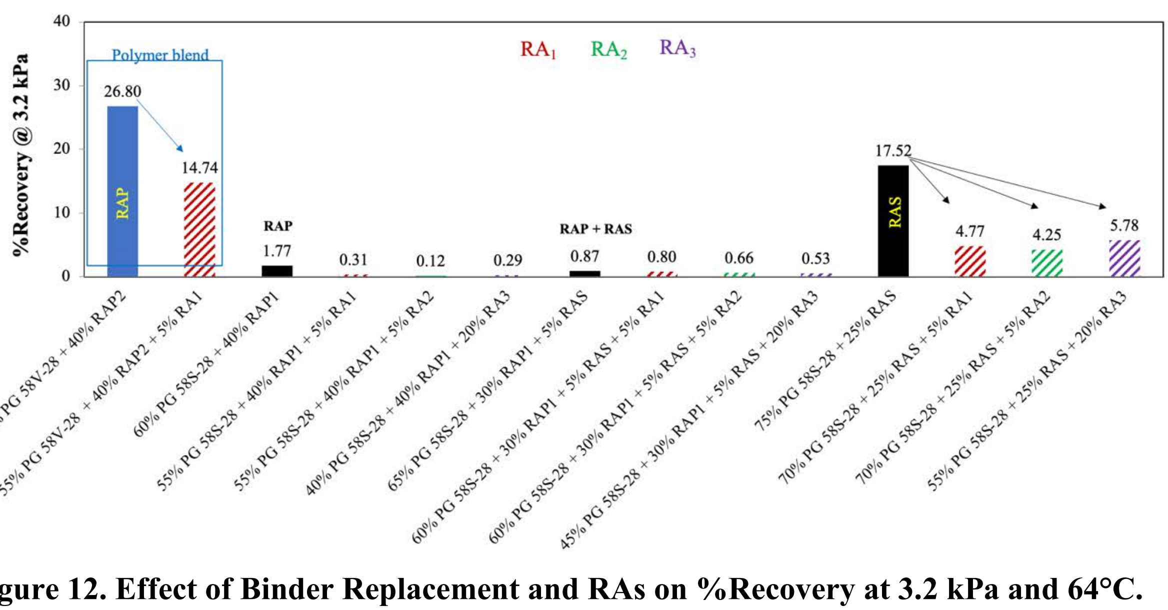


Figure 12. Effect of Binder Replacement and RAs on %Recovery at 3.2 kPa and 64°C.

Figure 13 illustrates the aforementioned relationship between J_{nr} and %Recovery, where %Recovery for a given binder blend is associated to the J_{nr} of the binder. Moreover, it can be seen that base binder type and percentage, recycled binder type and percentage, and RA type and dosage played a role in the overall MSCR results of the binders, which agreed with the findings of Bahia et al. *(2018).*

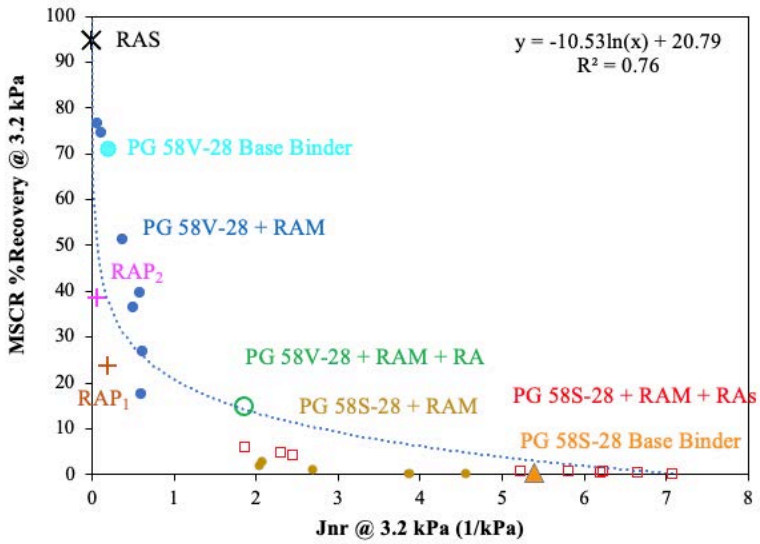


Figure 13. J_{nr} *versus* %Recovery at 64°C for all Evaluated Asphalt Binders.

3.3 Intermediate Temperature Performance in Terms of the Linear Amplitude Sweep Test

LAS testing was performed at 28°C after RTFO plus 40 hours of PAV aging for all the recycled asphalt binder blends. The relationship between the number of cycles to failure (N_f) and the recycled binder replacement was linear on a log-linear scale, indicating an exponential relationship between the decrease of N_f with increased recycled binder replacement. As indicated in Figure 14, the effect of increasing the recycled binder content on the N_f was more pronounced to the asphalt blends with a polymer modified base binder (PG 58V-28) than those containing an unmodified base binder (PG 58S-28). This behavior cannot be solely related to the nature of the recycled binder material. For example, despite the fact that RAP_1 and RAP_2 were obtained from different locations, the extracted binder from both RAPs had similar high temperature true grade (both 86.4°C) and intermediate temperature true grade (26.2°C and 27.1°C, respectively). When observing the LAS results for the binder blends with RAS, the behavior of the N_f parameter was found to be influenced by the presence of severely aged recycled binder (i.e., RAS). For example, all binder blends containing RAS only presented higher number of cycles to failure at 2.5% strain than the binder blends with RAP and RAP + RAS. These results could indicate that the LAS test is not applicable for non-conventional asphalt binders, such as highly oxidized recycled binders.

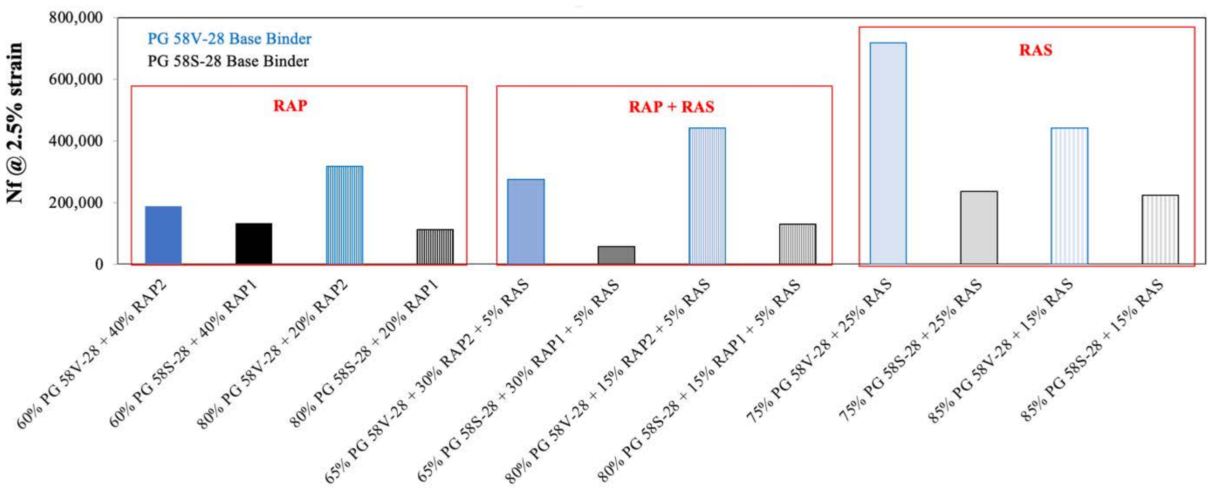


Figure 14. LAS Number of Cycles to Failure at 2.5% and 28°C for the RAM Blends.

When RAs were added to the asphalt blends, the general trend observed was an increase in the number of cycles to failure at 2.5% strain (Figure 15). However, this trend was perceived as being both binder blend (i.e., type and percentage of recycled binder) and RA type dependent, as can be seen that the addition of 5% RA_1 to the 55% PG 58S-28 + 40% RAP_1 blend slightly decreased its fatigue life, while the opposite behavior was observed when the same RA at the same dosage was added to both 60% PG 58S-28 + 30% RAP_1 + 5% RAS and 70% PG 58S-28 + 25% RAS blends. As previously observed for the recycled binder blends without RAs, the behavior of the N_f parameter was also found to be influenced by the presence of severely aged recycled binder (i.e., RAS) after incorporation of RAs, since all binder blends containing RAS only presented higher number of cycles to failure at 2.5% strain than the binder blends with RAP and RAP + RAS.

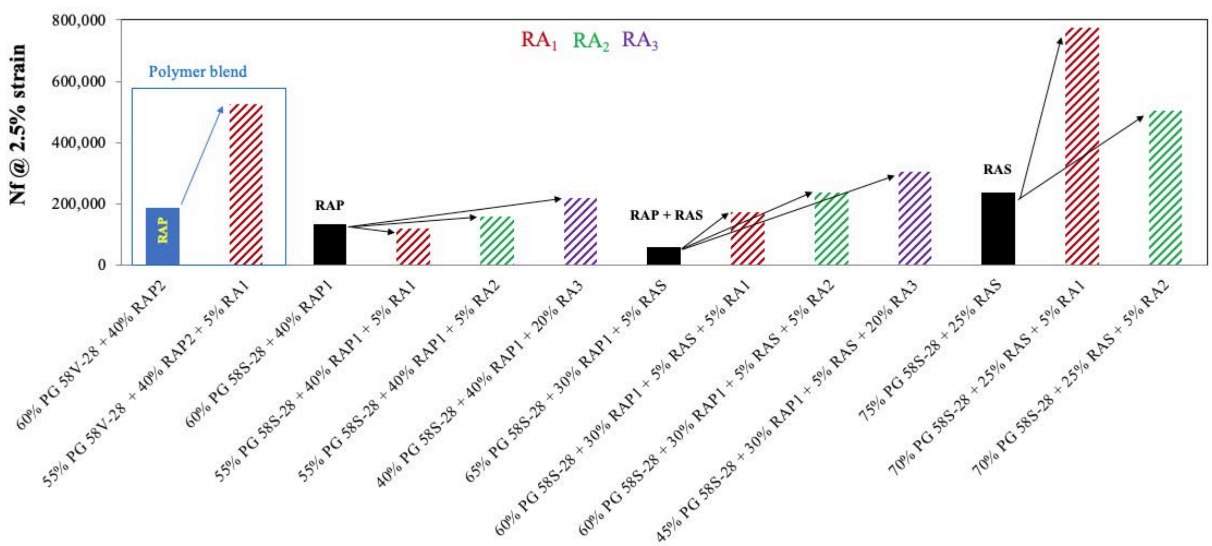


Figure 15. LAS Number of Cycles to Failure at 2.5% and 28°C after Addition of RAs.

Figure 16 presents the absolute value of the LAS fatigue law *B*-parameter, which is characteristically a negative number and indicates a reduction in the fatigue life with increased strain. A higher LAS fatigue law |*B*|-parameter indicates a higher reduction in the number of cycles to failure per unit increase in strain. As can be seen by smaller values of the LAS fatigue law |*B*|-parameter in Figure 8, the addition of RAs increased the fatigue resistance of the evaluated binders.

As can also be seen, binder blends with higher percentages of recycled binders that have experienced a higher level of oxidative aging (i.e., RAS) yielded the highest reduction in the number of cycles to failure per unit increase in strain. Overall, base binder type and percentage, recycled binder type and percentage, and RA type and dosage played a role in the fatigue resistance of the binders.

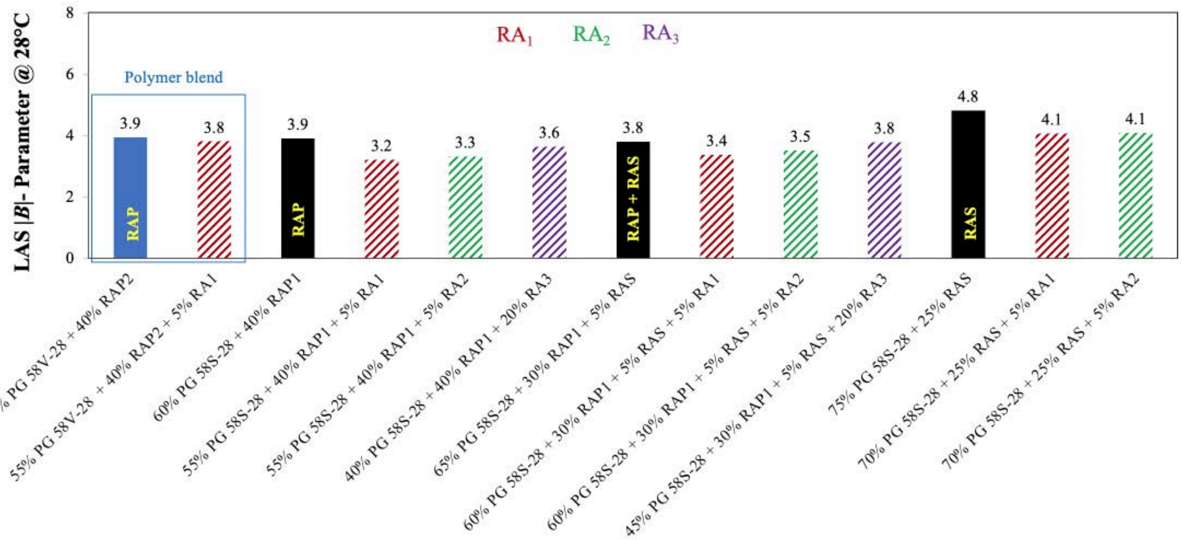
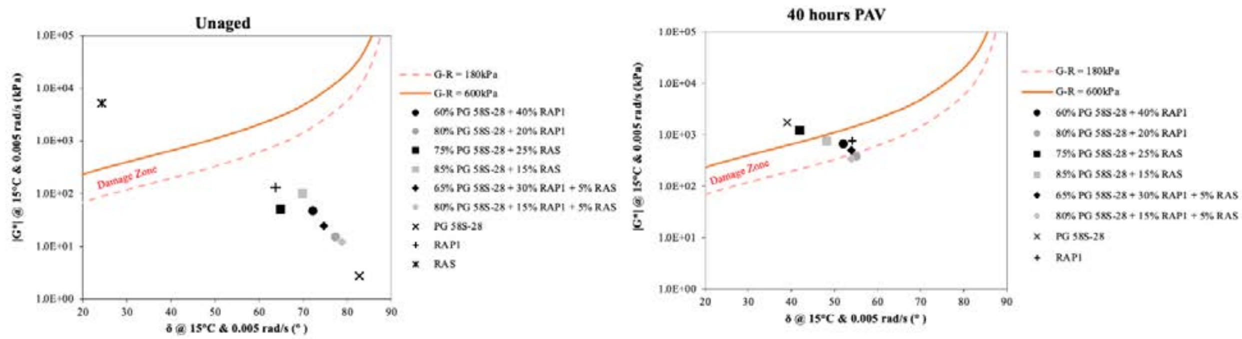


Figure 16. LAS |*B*|-Parameter Results at 28°C after Addition of RAs.

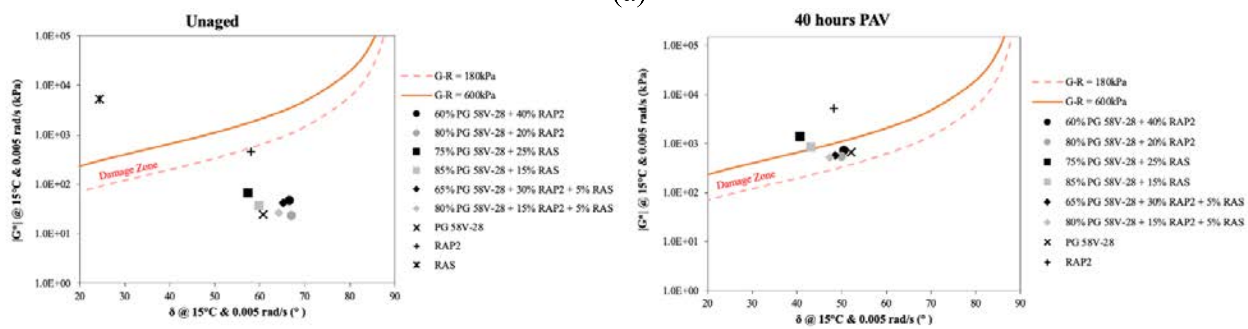
3.4 Glover-Rowe Parameter and Black Space Diagram

The Glover-Rowe (*G-R*) parameter considers both binder stiffness and embrittlement and offers an indication of the cracking potential at intermediate temperatures *(Rowe, 2011)*. The $|G^*|$ and δ at 15°C and 0.005 rad/s as well as the *G-R* parameter results of the base binders and recycled asphalt binder blends, at unaged and after RTFO plus 40-hour of PAV aging conditions, are were submitted to WHRP in an excel file. Overall, the blends of recycled asphalt binders consistently showed higher *G-R* parameters than the base binders, as expected. These results highlighted the binder stiffening effect due to the use of recycled asphalt materials. After RTFO plus 40-hour of PAV aging, with exception of the 80% PG 58S-28 + 20% RAP_1 and 80% PG 58S-28 + 15% RAP_1 + 5% RAS blends, all of the recycled asphalt binders' blends exceeded the preliminary *G-R* parameter criterion of 180 kPa for the damage onset of block cracking. However, debate exist in the validity of using the *G-R* thresholds for evaluating polymer modified binders.

Figure 17 presents the *G-R* parameter results on a Black Space diagram for the recycled binder blends, where the binder $|G^*|$ at 15°C and 0.005 rad/s is plotted on the y-axis *versus* δ at the same condition on the x-axis at both unaged and 40-hour PAV aged conditions. The bold and dashed curves in the figure represent the two preliminary *G-R* parameter criteria of 180 kPa and 600 kPa for the onset of block cracking and visible surface cracking, respectively.



(a)



(b)

Figure 17. |*G| and *δ* results on a Black Space diagram of: (a) Recycled Binder Blends for PG 58S-28 Binder, and (b) Recycled Binder Blends for PG 58V-28 Binder.**

Figure 17 shows that as aging increases for the same binder, the |*G**| and *δ* data migrate from the lower right corner [i.e., low stiffness (|G*|) and high ductility (*δ*)] to the upper left corner [i.e., increased stiffness (|G*|) and increased brittleness (*δ*)] of the Black Space diagram. It can be seen that the aging susceptibility of the base binder PG 58S-28 was higher than the RAP_1 recycled binder, emphasizing that the aging behavior of recycled binder blends is influenced by the chemical composition of the individual binders. Regardless of the base binder, the addition of 25% RAS binder replacement exceeded the preliminary *G-R* parameter criterion of 600 kPa after long-term aging. The blends with 15% RAS binder replacement were located on the 600 kPa limit. As a result, the RAS blends were located above or on the top of the "cracking damage zones" on the Black Space diagram. Moreover, for the base binder PG 58S-28, the blends with 20% RAP and 15% RAP + 5% RAS did not reach the damage zone. On the other hand, all recycled binder blends containing the base binder PG 58V-28 were located within the damage zone, with exception of the blends with 25% and 15% RAS replacement, as previously mentioned. Another interesting observation from these Black Space diagram plots is the fact that these analyses could capture the presence of polymer in the base binder PG 58V-28, as all blends are shifted to the left (i.e., towards lower phase angles) in comparison to same blends prepared with the base binder PG 58S-28.

Figure 18 presents the Black Space diagram plots for the |*G**| and *δ* data after addition of RAs, for investigation of the potential binder rejuvenation of these additives. As can be seen, the addition of the three RAs to the recycled binder blends decreased the stiffness of all blends, before and after PAV aging. Moreover, for the unaged blends, it can be seen that this decrease in stiffness was followed by an increase in the phase angle (δ). However, after long-term aging in PAV, the decrease in |*G**| for the binder blends rejuvenated with RA_3 was not accompanied by an increase in *δ*. This behavior is attributed to the fact that RA_3 acted as a softener to the recycled binders due to its petroleum-based nature, restoring the properties of the binders solely by physical process

(Bajaj et al., 2020). After long-term aging, all recycled binder blends rejuvenated with RA_1 were located below the damage zone and thus, are not likely to experience premature block cracking in the field.

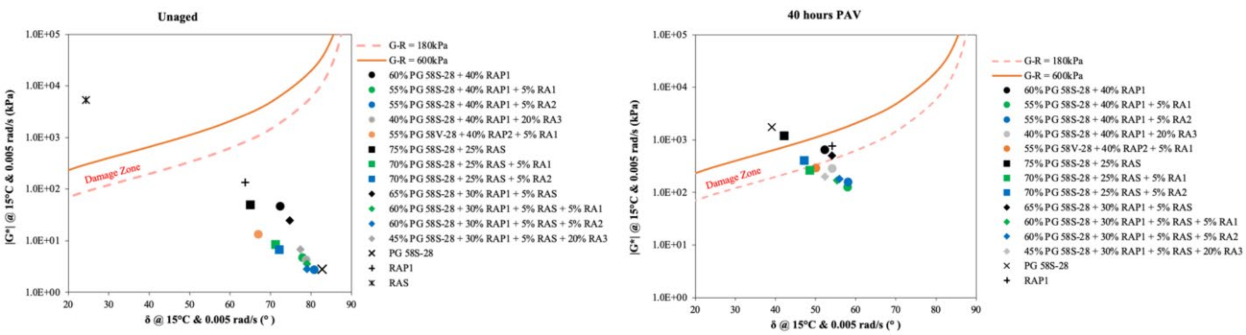


Figure 18. |*G| and *δ* Parameter Results on a Black Space Diagram of Recycled Binder Blends After Addition of RAs.**

An aging index in terms of *G-R* was determined to evaluate the effect of RAs on the aging behavior of the recycled binder blends. For each binder, the *G-R* Aging Index was calculated as the fraction of the *G-R* parameter of the RTFO plus 40-h PAV-aged sample over that of the unaged sample. As shown in Figure 19, for both base binders (i.e., PG 58S-28 and PG 58V-28), the addition of the three RAs increased the *G-R* Aging Index of all the recycled binder blends, indicating increased susceptibility to oxidative aging.

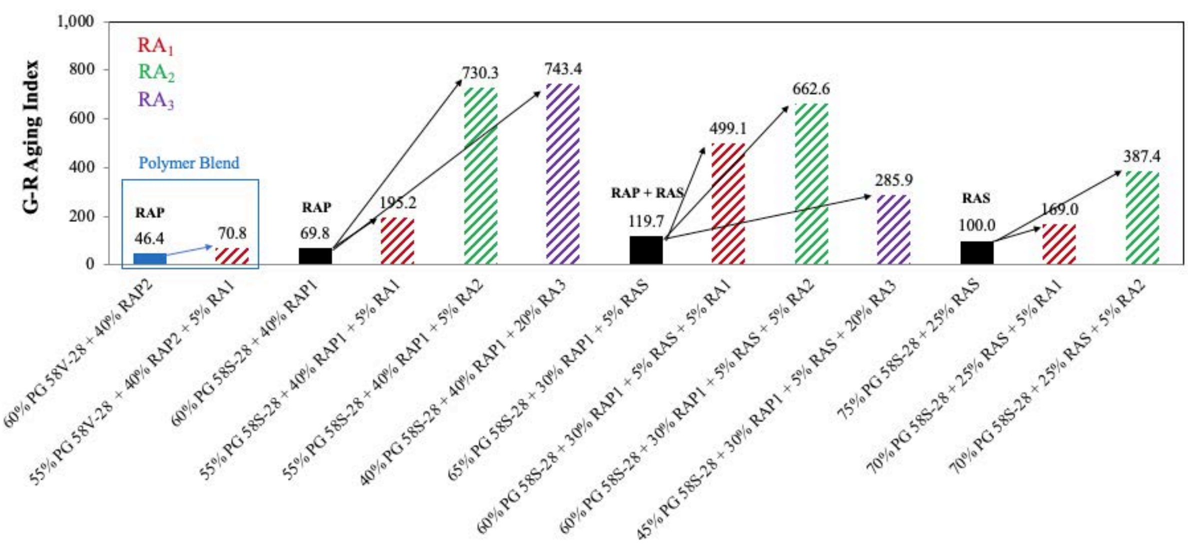


Figure 19. *G-R* Aging Index Results.

3.5 ΔT_c Parameter

ΔT_c ($\Delta T_c = T_{c,S} - T_{c,m}$) is the difference between the continuous low temperature binder grade measured via the BBR creep stiffness (related to stresses in an asphalt pavement due to thermal contraction) and m-value (related to the ability of an asphalt pavement to relieve these stresses). It has been suggested that asphalt binders with low (i.e., more negative) ΔT_c have less ductility and reduced relaxation properties than asphalt binders with higher (less negative or positive) ΔT_c. A minimum ΔT_c threshold of -5°C after RTFO plus 40 hours of PAV aging has been suggested to minimize the risk of age-related block cracking *(Anderson et al., 2011).*

As shown in Figure 20, the aging susceptibility evaluated in terms of the ΔT_c parameter of the blends containing the base binders (PG 58S-28 and PG 58V-28) and the RAP_1 and RAP_2 recycled binders was influenced by the chemical composition of the individual binders. As the RAP binder replacement increased from 20 to 40%, the ΔT_c parameter became more negative.

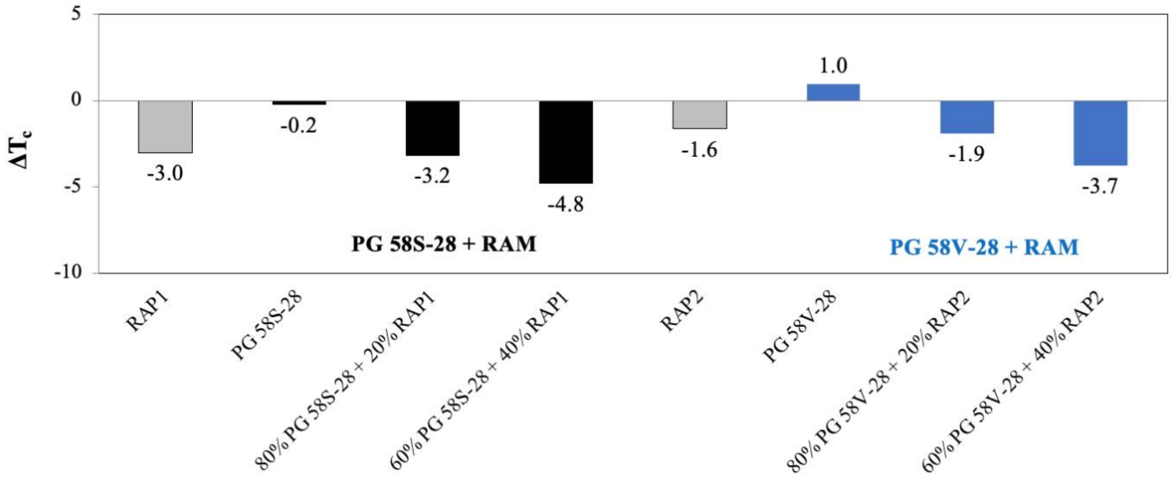


Figure 20. Effect of RAP Binder Replacement on ΔT_c after RTFO plus 40 hours PAV Aging.

Figure 21 shows the ΔT_c values of binder blends with recycled material. Considering the aforementioned limits established for the ΔT_c parameter, it can be seen that the addition of RAS between 15 and 25 percent binder replacement increased the block cracking susceptibility of the resultant binder blends. Moreover, the results in Figure 11 indicated that it is possible to have up to 40 percent of RAP binder while still meeting the ΔT_c threshold of -5°C after RTFO plus 40 hours of PAV aging.

ΔT_c is intended to provide an indication of loss of ductility, indicating when the asphalt binder cannot relax the stresses fast enough to prevent breaking. Figure 22 shows that after addition of the bio-based RAs (i.e., RA_1 and RA_2), the stress relaxation of the recycled binder blends improved as indicated by less negative ΔT_c values, with exception of the blend with the polymer modified binder. Figure 23 presents the overall change in ΔT_c after addition of the RAs. As can be seen, among the three RAs, RA_1 showed the greatest improvement in the binder cracking susceptibility regardless of the recycled binder type and percentage, while RA_3 had the least improvement. Note that RA_3 is a petroleum-based RA. Moreover, RA_3 increased the block cracking susceptibility of recycled asphalt blends containing RAS binder as indicated by more negative ΔT_c values. All recycled binder blends were found to be “m-controlled” (i.e., failure potentially controlled by inadequate stress relaxation).

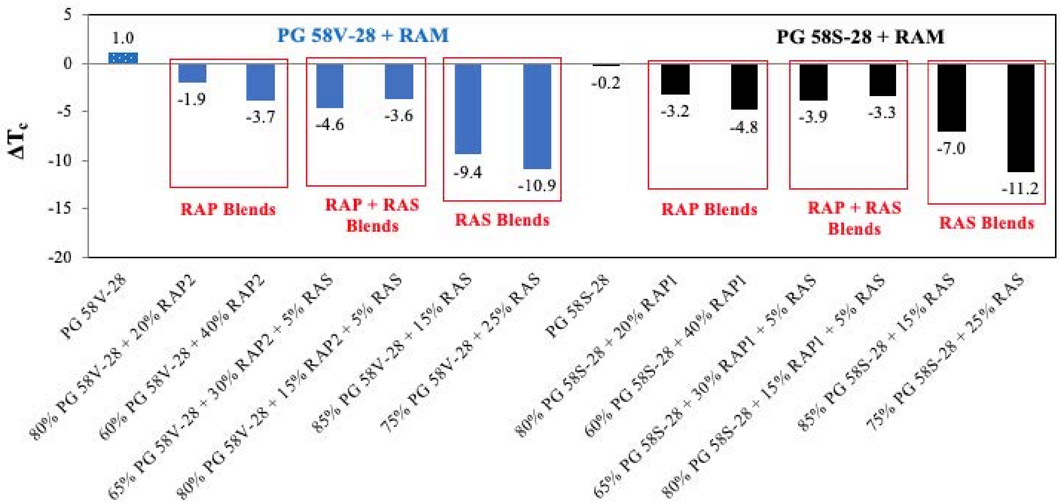


Figure 21. Effect of Binder Replacement on ΔTc after 40 hours of PAV Aging.

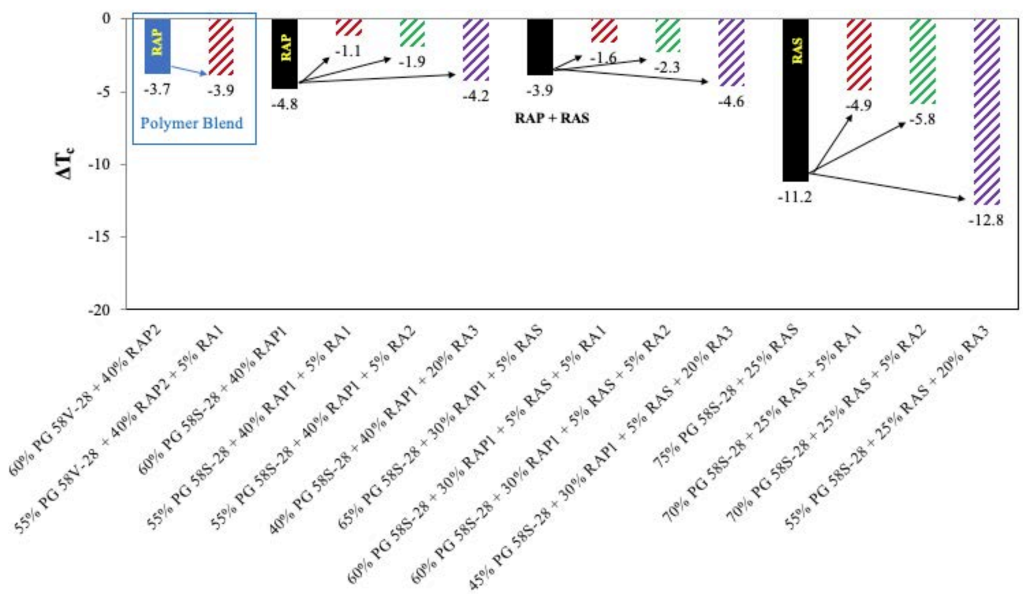


Figure 22. Effect of Binder Replacement on ΔTc after Addition of RAs.

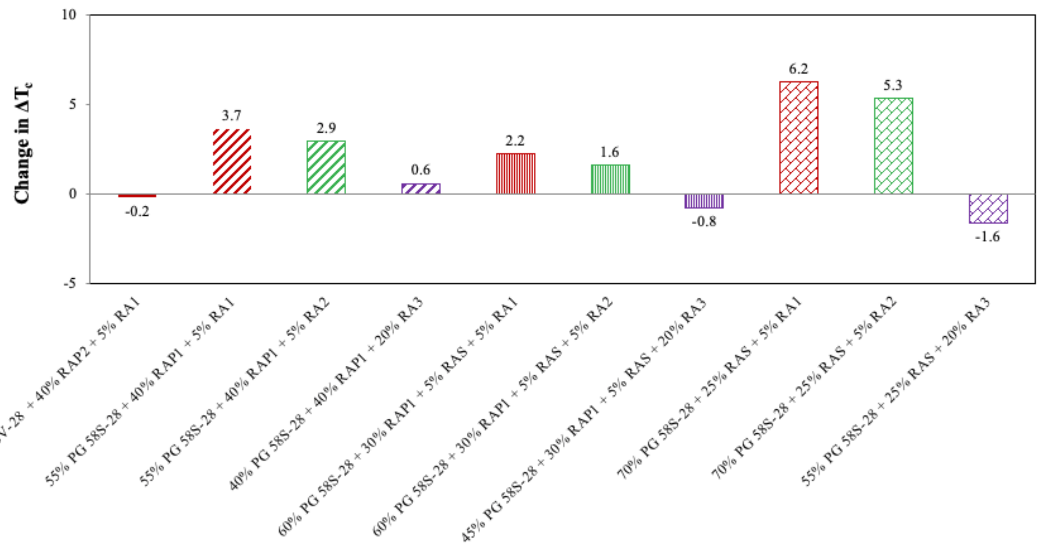


Figure 23. Change in ΔT_c after Addition of RAs.

3.6 Low Temperature Performance in Terms of Thermal Response

To evaluate the physical hardening behavior (i.e., the thermo-reversible relaxation process taking place in the glass transition region) of the recycled binder blends, extended Bending Beam Rheometer (BBR) testing was performed in accordance with AASHTO TP 122. The selected extended conditioning test temperature was the Glass Transition temperature (T_g) of each recycled binder blend containing RA, since previous work has shown that the maximum rate of physical hardening occurs at the T_g temperature (Tabatabaee et al., 2012). Differential Scanning Calorimetry (DSC) was used to measure the T_g temperature of the rejuvenated blends after RTFO plus 40 hours of PAV aging. The T_g and extended BBR test results are presented in Table 15.

Table 15. T_g and Creep Stiffness of Rejuvenated Binder Blends After Oxidative Aging.

Recycled Binder Blend	T_g, °C	After 1-h of BBR conditioning at T_g Temperature	After 24-h of BBR conditioning at T_g Temperature	S/S_0
		S_0, MPa	S, MPa	
55% PG 58S-28 + 40% RAP_1 + 5% RA_1	-18.2	145	184	1.3
55% PG 58S-28 + 40% RAP_1 + 5% RA_2	-19.3	183	195	1.1
60% PG 58S-28 + 30% RAP_1 + 5% RAS + 5% RA_1	-9.4	46	55	1.2
60% PG 58S-28 + 30% RAP_1 + 5% RAS + 5% RA_2	-5.2	34	35	1.0
70% PG 58S-28 + 25% RAS + 5% RA_1	-14.5	69	120	1.7
70% PG 58S-28 + 25% RAS + 5% RA_2	-11.1	86	90	1.0

The T_g has been considered as a characterization parameter that helps to determine the process and aging level of asphalt binders, as researchers have shown that the T_g of asphalt influences its low-temperature cracking *(Tabatabaee et al., 2012*). Moraes and Bahia *(2015)* showed that oxidative aging and an increase in asphaltenes content shift the T_g of binders towards higher temperatures, increasing the susceptibility of the binder to cracking and durability issues due to the ductile-to-brittle transition behavior. Thus, the effectiveness of RAs on lowering the T_g of recycled binder blends is of interest. As can be seen, the bio-based RA_1 shifted the T_g of the blends towards lower temperatures than the bio-based RA_2, with exception of the 55% PG 58S-28 + 40% RAP_1 + 5% RA_1 blend, for which RA_2 was slightly more effective.

Asphalt physical hardening rate depends on the chemical composition of the asphalt binder, and thus, the addition of RAs could influence this thermal behavior. A hardening index (S/S_0) defined as the ratio of the creep stiffness [i.e., S(60)] after 24 hours of isothermal conditioning at the T_g temperature to the initial stiffness measurement after 1 hour of isothermal conditioning at the T_g temperature is generally used to show the rate at which physical hardening occurs at different isothermal conditions *(Tabatabaee et al., 2010)*. As indicated in Table 15, the overall increase in S/S_0 (i.e., hardening index) was slightly higher for the recycled binder blends containing RA_1. These results could be an indication that the physical hardening rate for RA_1 was higher than for RA_2. However, results should be interpreted with caution due to the limited number of replicates evaluated per sample.

3.7 Correlation Between Rheological and Chemical Testing

Since the aging behavior of recycled blended binders is influenced by the chemical composition of the individual binders, chemical analyses were performed to investigate the impact of RAM on the chemical composition and molecular distribution of the resulting blends. The rheological evaluation of the recycled asphalt binder blends yielded answers towards the viscoelastic properties of these materials; however, it did not give insights into what was occurring on the molecular level. Therefore, chemical analyses were performed to link the stress-strain response of the blended binders to chemical changes occurring within the material.

The change of chemical structure of asphalt binders can be obtained by the calculation of functional and structural indices of some groups from Fourier Transform Infrared (FTIR) spectra, since with oxidative aging the absorbance bands representing oxygen containing functionalities (e.g., carbonyl groups) of asphalt increases *(Milton et al., 1998)*. Figure 24 shows the absorption spectrum carbonyl (C=O) area before and after the addition of RAs. As can be seen, the general trend is that after long-term aging, the C=O area decreased with the addition of RAs. An exception occurred with the 45% PG 58S-28 + 30% RAP_1 + 5% RAS + 20% RA_3 blend, where the petroleum-based additive RA_3 increased the C=O area of the recycled binder blend. It was also observed that the reduction in C=O area due to the addition of RAs was dependent on the RA type (i.e., composition), where the imparted reduction of the carbonyl-containing compounds varied between the recycled binder blends.

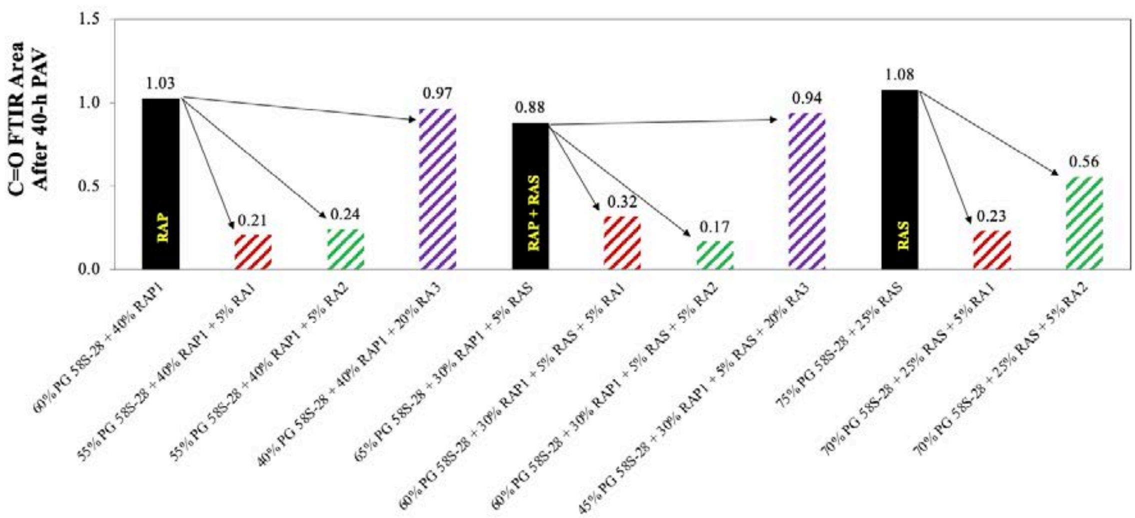


Figure 24. Effect of Binder Replacement and RAs on C=O Area for PG 58S-28 Binder.

The previously discussed *G-R* parameter supports the presented FTIR-ATR carbonyl area data (Figure 25), where a reasonable correlation ($R^2 = 0.68$) was observed between the *G-R* parameter and C=O area results for the binder blends rejuvenated with the bio-based RA_1 and RA_2. Thus, when characterizing recycled binder blends after rejuvenation and exposure to long-term oxidative aging, a higher *G-R* parameter can be indicative of the addition of RAs with higher aging susceptibility. RA_3 was excluded from this analysis since it has a different nature as being a petroleum-based (i.e., asphalt flux) additive.

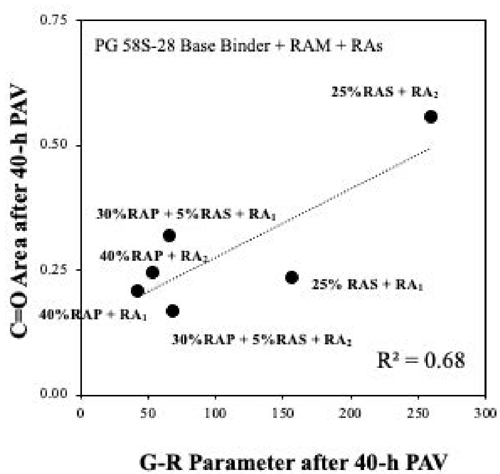


Figure 25. *G-R* parameter *versus* C=O Area for Binder Blends Rejuvenated with Bio-Based RAs.

Gel Permeation Chromatography (GPC) was used to determine the molecular size distribution (MSD) (analogous to a sieve analysis on a smaller scale) of the recycled binder blends, before and after oxidative aging. As can be seen in Figure 26, the GPC chromatographic profiles (i.e., chromatograms) of the recycled binder blends with bio-based recycling agents differs significantly from the chromatograms obtained for the blends with the petroleum-based additive. This is a clear indication of the different chemical composition between these two types of RAs.

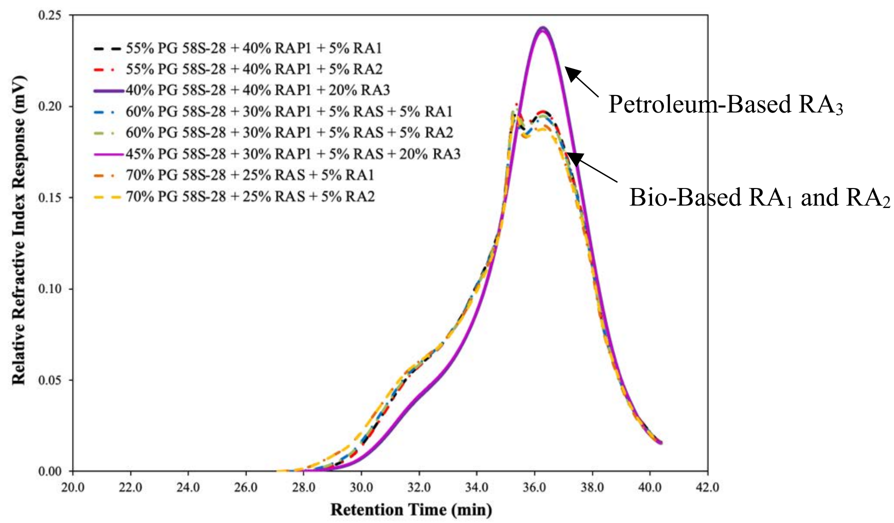


Figure 26. GPC Chromatograms of Binder Blends Rejuvenated with Petroleum-Based and Bio-Based RAs.

From a GPC chromatogram it is possible to calculate M_w (weight-average molecular weight), M_n (number-average molecular weight), and M_z (z-average molecular weight), among others molecular weight parameters. M_w is related to tensile strength of the asphalt binder, while M_n is usually related to brittleness and flow properties, and M_z is related to elongation and flexibility (*Lobo and Bonilla, 2003)*. Figure 27 shows the relationship between M_z and the MSCR parameters J_{nr} and %Recovery at 3.2 kPa. As can be seen, recycled binder blends with higher values of M_z were associated with lower creep compliance and higher %Recovery values. Moreover, a clear distinction among the recycled binder blends with and without polymer can be made.

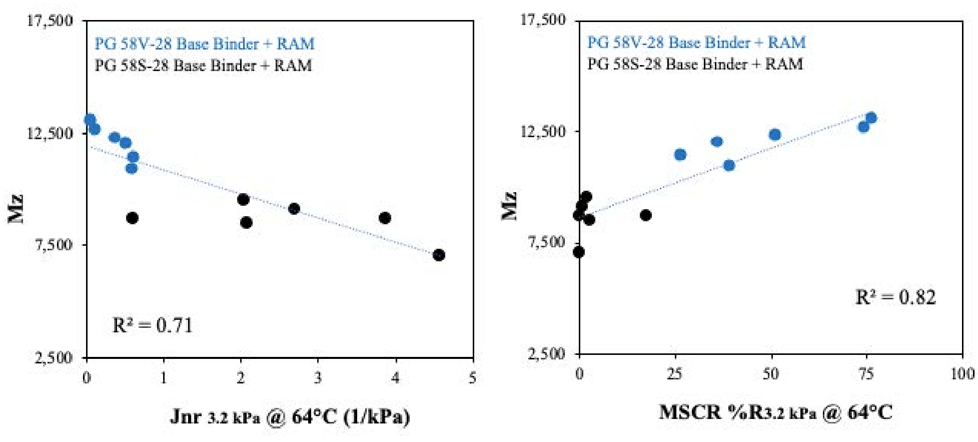
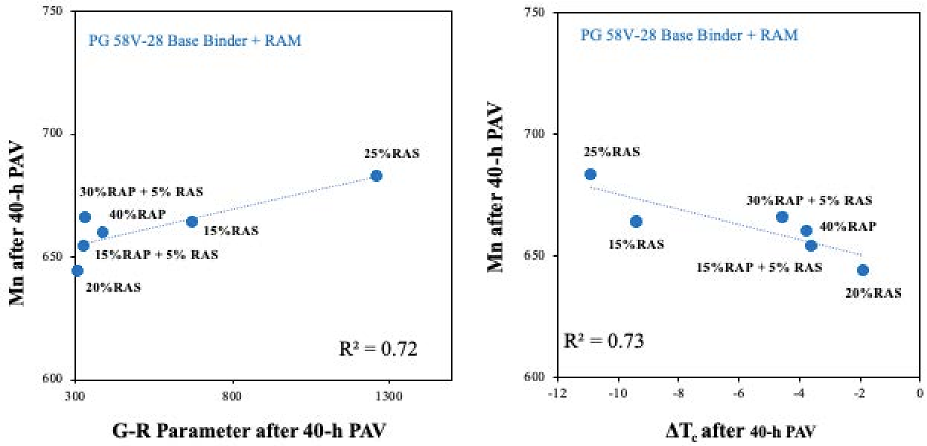


Figure 27. (a) J_{nr} at 3.2 kPa *versus* M_z. (b) %Recovery at 3.2 kPa *versus* M_z.

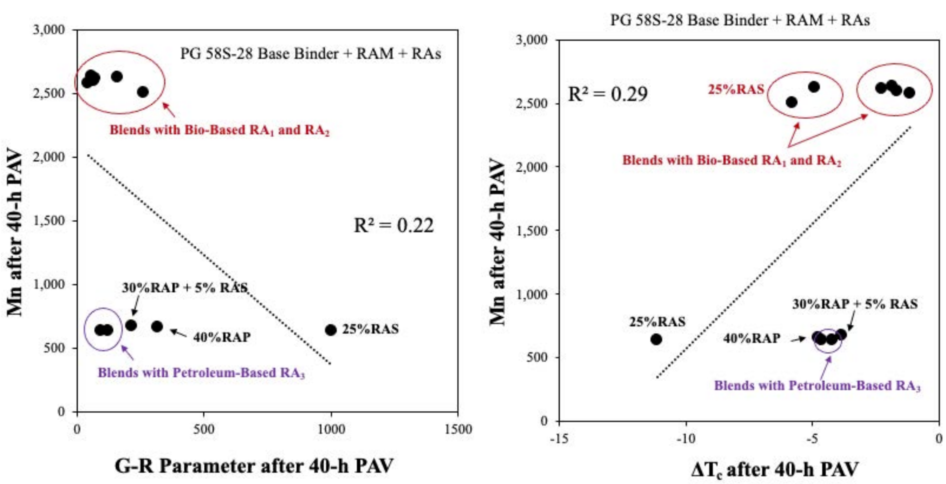
Figure 28 shows the relationship between M_n and the two cracking parameters *G-R* and ΔT_c after long-term aging. A good explanation for these two cracking indicators can be obtained when evaluating the M_n (number-average molecular weight) of the recycled binder blends, since aging resulted in a shift towards higher M_n, increasing the brittleness of the binders and thus the likelihood of cracking. Moreover, recycled binder blends with higher content of severely aged RAM material (i.e., 25% RAS), showed higher tendency for cracking.



(a) (b)

Figure 28. Effect of RAM Binder Replacement for PG 58V-28 Binder in Terms of: (a) *G-R* parameter *versus* M_n. (b) ΔT_c *versus* M_n.

When correlating M_n with *G-R* and ΔT_c of the recycled binder blends containing RAs (Figure 29), it was observed that the type of RA played a role on the cracking susceptibility of the recycled blends. While the bio-based RAs behaved somewhat similarly in terms of M_n, the petroleum-based RA behaved similar to the recycled blends with higher percentage of RAM (i.e., 40% RAP and 30% RAP + 5% RAS), indicating that the composition of RA_3 is similar to an asphaltic material. After aging, RA_3 behaved as a recycled binder.



(a) (b)

Figure 29. Effect of RAM Binder Replacement and RAs for PG 58S-28 Binder in Terms of: (a) *G-R* parameter *versus* M_n. (b) ΔT_c *versus* M_n.

3.8 Optimum Recycling Agent Dosage Determination for Mixture Performance Evaluation

The optimum recycling agent dosages for mixture performance testing were determined through the use of blending charts obtained from DSR and BBR testing of the recycled binder blends with each RA. In this analysis, the critical high- and low-temperature for a recycled binder blend is plotted against the tested RA dosage. As indicated in the binder section, for the bio-based RA_1 and RA_2 a dosage of 5% per weight of total binder (i.e., virgin plus recycled binders) was utilized for the blending chart analysis. For the optimum dosage determination of each RA, two methods were experimented by the research team as indicated as follows:

a) Target "20% RAP-BR" Grade (i.e., match the DOT control blend) (Figure 30)
b) Target "PG xx-28" Grade (i.e., match the virgin binder) (Figure 31)

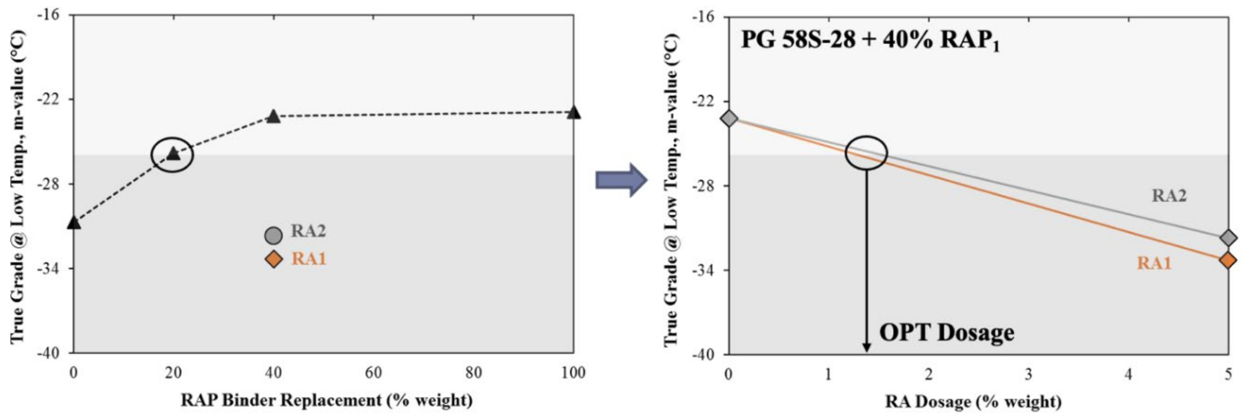


Figure 30. Example of Optimum Recycling Agent Dosage Determination by Targeting the "20%RAP-BR" Grade.

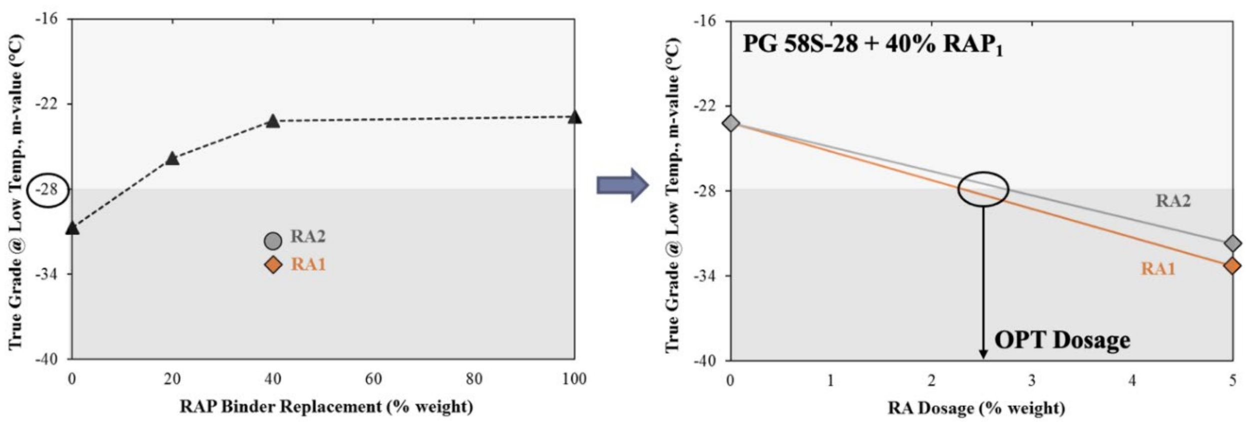


Figure 31. Example Optimum Recycling Agent Dosage Determination by Targeting the "PG xx-28" Grade.

By linear interpolation between 0 and 5% RA dosage, the optimum RA_1 and RA_2 dosage for each recycled binder blend was determined following the two aforementioned methods, and the results are presented in Table 16. After consideration, the research team decided to select the optimum dosage obtained by targeting the "PG xx-28" Grade which is in general the more conservative method.

Table 16. Optimum Recycling Agent Dosages for Mixture Performance Evaluation.

Recycled Binder Blend	RA	Optimum RA Dosage		
		Method 1: Match "20% RAP-BR" Grade (DOT Control)		Method 2: Match "PG xx-28" Grade
		HT	LT	
PG 58S-28 + 40% RAP_1	RA_1	3.3	1.3	2.4
	RA_2	2.8	1.5	2.8
PG 58S-28 + 25% RAS	RA_1	7.1	3.3	4.1
	RA_2	6.3	4.0	5.0
PG 58S-28 + 30% RAP_1 + 5% RAS	RA_1	3.5	0.8	2.1
	RA_2	2.9	0.9	2.5
PG 58V-28 + 40% RAP_1	RA_1	1.3	1.8	3.0

4. ASPHALT MIXTURE PERFORMANCE TESTING RESULTS AND COST BENEFIT ANALYSIS

For IDEAL-CT and DCT test results, analysis of variance (ANOVA) and Tukey's honest significant difference (HSD) test were used to assess the statistically significant differences in the mean values of the performance test results (multiple groups). ANOVA shows whether the differences in the mean values of the groups are statistically significant and Tukey's HSD indicates the exact groups with mean values that are significantly different. Furthermore, a paired t-test was used to assess the statistical significance difference among the mean values of two of the groups. All inferential tests were conducted with a significance level (α) of 0.05.

Since WisDOT is working toward the implementation of Balanced Mixture Design (BMD), the results of HWTT, IDEAL-CT, and DCT were compared with the preliminary BMD for Wisconsin mixtures proposed in the ongoing project WHRP 0092-20-04 "Balanced Mixture Design Implementation Support" *(West et al., 2020)*. These preliminary performance criteria are presented in Table 17.

Table 17. Preliminary Threshold Criteria for BMD for Wisconsin Mixtures (*West et al., 2020*).

Traffic Level	HWTT (STOA)				Min. CT $_{Index}$ (LTOA)	DCT Min. Fracture Energy (J/m^2) (LTOA)
	Min. Passes to 12.5 mm	Min. SIP (passes)	Max. CRD 20k (mm)	Min. SN (passes)		
High	15,000	9,000	6.0	2,000	40	300
Med	15,000		7.0			
Low	10,000		8.0			

4.1 Dynamic Modulus (|E*|)

Figure 32 and Figure 33 present the |E*| results for samples of mixtures with Aggregate 1 and Aggregate 2 after STOA and LTOA at 1Hz for comparison purposes. For mixtures with Aggregate 1 and the PG58S-28 binder, the |E*| results of the rejuvenated mixtures (25% ABR, 35% ABR, and 40% ABR) at both aging conditions showed higher stiffnesses than the 20% ABR mix at all three test temperatures (except for the 25% ABR mixes with lower stiffness). For the mixes with the PMB, the rejuvenated mix (40% ABR-PMB) shows similar stiffness as the 20% ABR-PMB mix at all temperatures. Similar trends were observed at the other frequencies. For mixtures with Aggregate 2 and the PG 58S-28 binder, the |E*| results of the rejuvenated mixes (25% ABR, 35% ABR, and 40% ABR) at both aging conditions showed lower stiffness than the 20% ABR mix with a similar trend at the other frequencies.

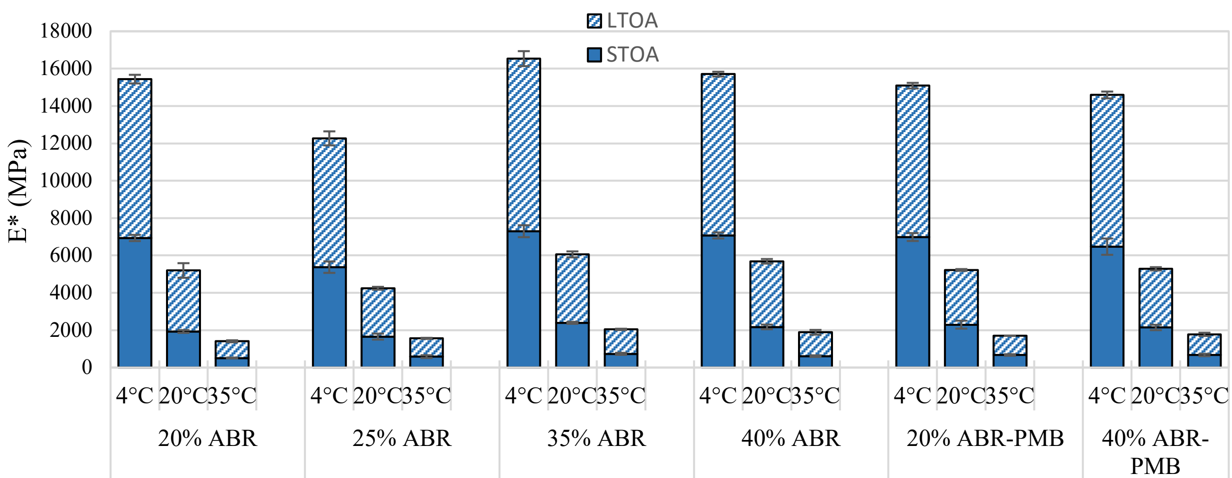


Figure 32 E* Stiffness at 4, 20, 35ºC and 1 Hz for STOA and LTOA Aggregate 1 Mixtures.

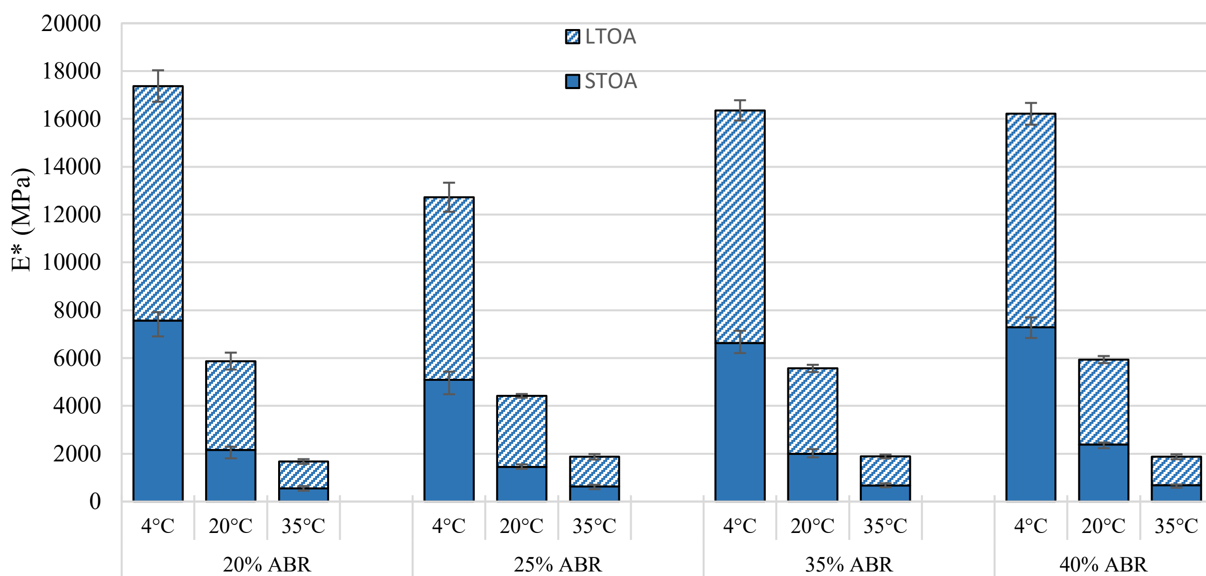


Figure 33 E* Stiffness at 4, 20, 35ºC and 1 Hz for STOA and LTOA Aggregate 2 Mixtures.

Figure 34 presents the |E*| Black Space diagram for the Aggregate 1 mixes with the PG 58S-28 binder and PMB after STOA and LTOA. From Figure 34, the mixtures are located more towards the bottom right corner after STOA, but with the increase in aging level after LTOA the points moved to the top left corner, indicating an increase in stiffness (|E*|) and a reduction in relaxation properties (ϕ). After STOA, the 20% ABR mix with the PG 58S-28 binder is located closer to the bottom right corner when compared to the rejuvenated mixes. The rejuvenated mixes with 35%ABR and 40% ABR show similar |E*| as the 20% ABR but have lower ϕ, while the rejuvenated mix with 25%ABR shows lower |E*| and lower ϕ than the 20% ABR mix. In comparison, the 20% ABR mix with the PMB shows slightly higher |E*| and lower ϕ than the 40% ABR mix. After the LTOA, similar trends are observed for the mixes with the PG 58S-28 binder; however, for the mixes with the PMB, the 40%ABR mix shows a slight increase in |E*| but the same ϕ compared to the 20% ABR mix.

Figure 35 presents the |E*| Black Space diagram for the Aggregate 2 mixes with the PG 58S-28 binder after STOA and LTOA. After STOA, the mixtures are located more towards the bottom right corner, but with the increase in the aging level after LTOA, the points move to the top left corner as expected. After STOA, the 25% ABR mix is located closer to the bottom right when compared to the other mixes, the rejuvenated mix with 35% ABR has similar location in the Black Space diagram as the 20% ABR mix, while the 40% ABR mixes show similar |E*| but lower ϕ than the 20% ABR mix. After LTOA, the 25% ABR rejuvenated mix showed lower |E*| and lower ϕ than the other mixes. The 20% ABR mix shows a similar location in the Black Space diagram than the other two rejuvenated mixes.

Figure 36 presents the G-R_m parameters for the Aggregate 1 mixes with the PG 58S-28 binder and PMB after STOA and LTOA. For the mixes with the PG 58S-28 binder, the 25% ABR mix shows the lowest values (after STOA and LTOA), followed by the 20% ABR, 40% ABR, and 35% ABR mixes, respectively. However, based on the G-R_m aging ratios (G-R_m after LTOA divided by G-R_m after STOA) presented in Figure 38, all the rejuvenated mixes have similar aging susceptibility as the 20% ABR mix. For the mixes with PMB, the G-R_m after STOA is slightly higher for the 20% ABR mix when compared to the rejuvenated mix with 40% ABR, while the opposite trend is observed after LTOA; nevertheless, they are expected to have similar block cracking resistance. In addition, PMB mixes show relatively lower aging ratios than the mixes with the PG 58S-28 binder, which indicates the improved aging resistance due to polymer modification.

Figure 37 presents the G-R_m parameters for the Aggregate 2 mixes with the PG 58S-28 binder after STOA and LTOA. The results show lower values for the rejuvenated mixes compared to the 20% ABR mix after STOA and LTOA (except for the 40% ABR mix after STOA). However, the 25% ABR mix shows higher a G-R_m aging ratio than the 20% ABR mix and the other two rejuvenated mixes (35% ABR and 40% ABR).

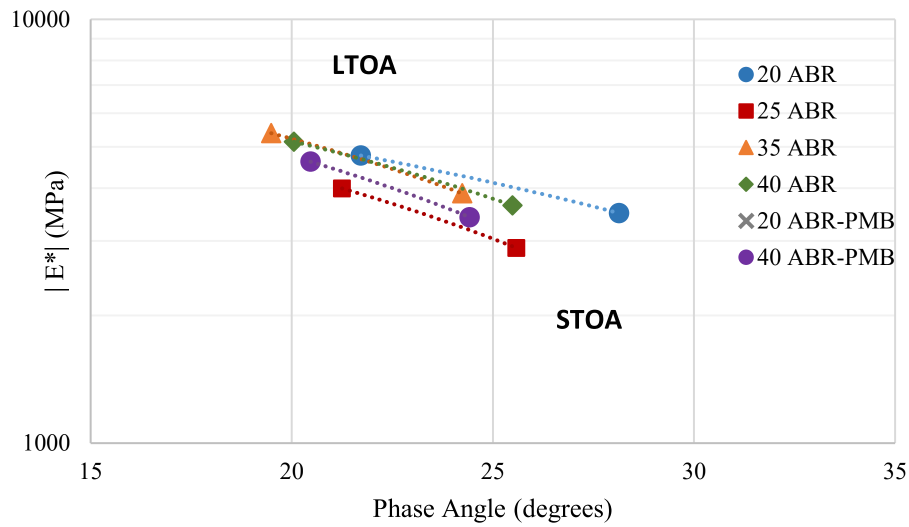


Figure 34 |E*| Mixture Black Space for Aggregate 1 Mixtures After STOA and LTOA (5Hz, 20ºC).

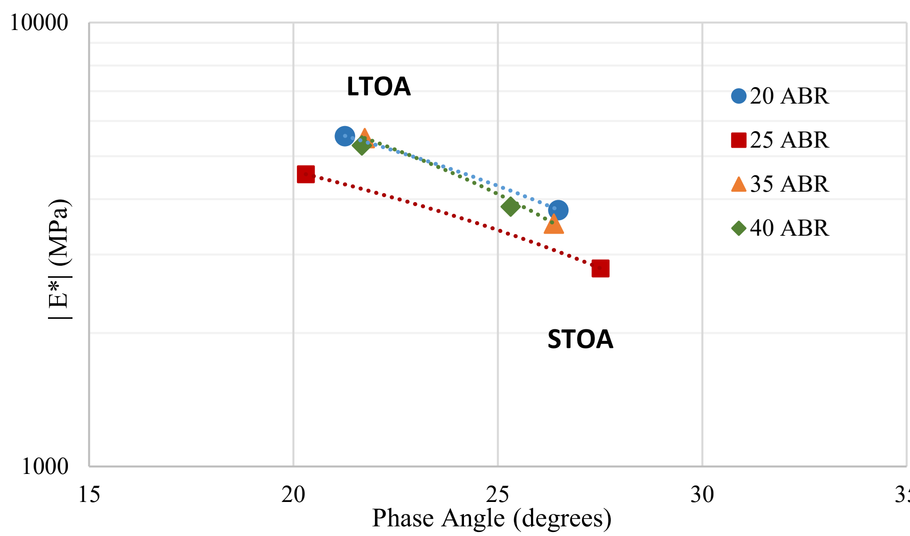


Figure 35 |E*| Mixture Black Space for Aggregate 2 Mixtures After STOA and LTOA (5Hz, 20ºC).

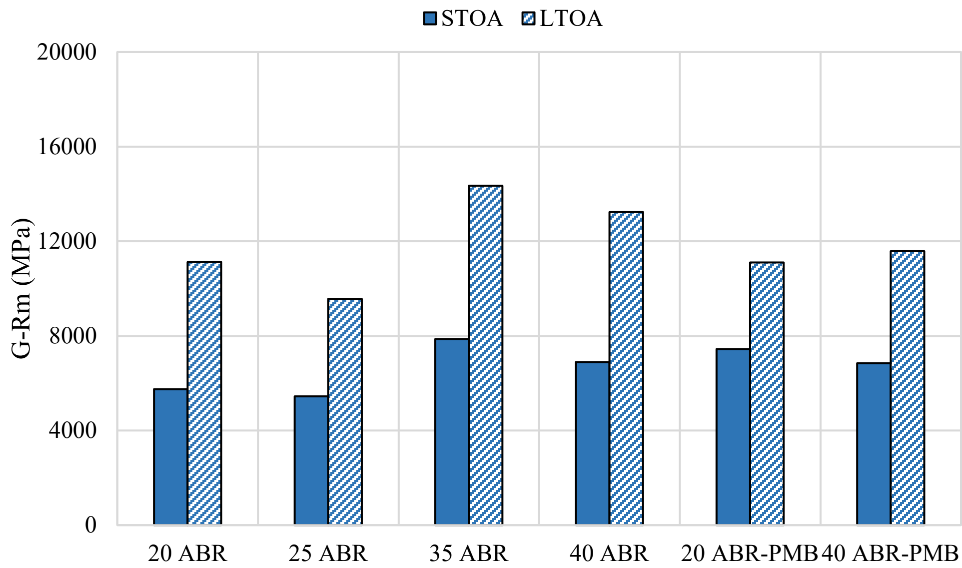


Figure 36 G-R$_m$ Results for Aggregate 1 Mixtures After STOA and LTOA (5Hz, 20^{o}C).

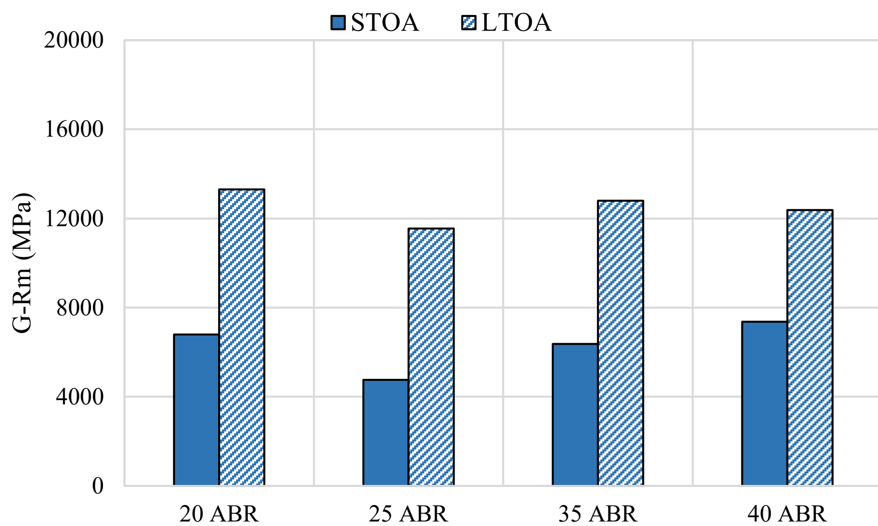


Figure 37 G-R$_m$ Results for Aggregate 2 Mixtures After STOA and LTOA (5Hz, 20^{o}C).

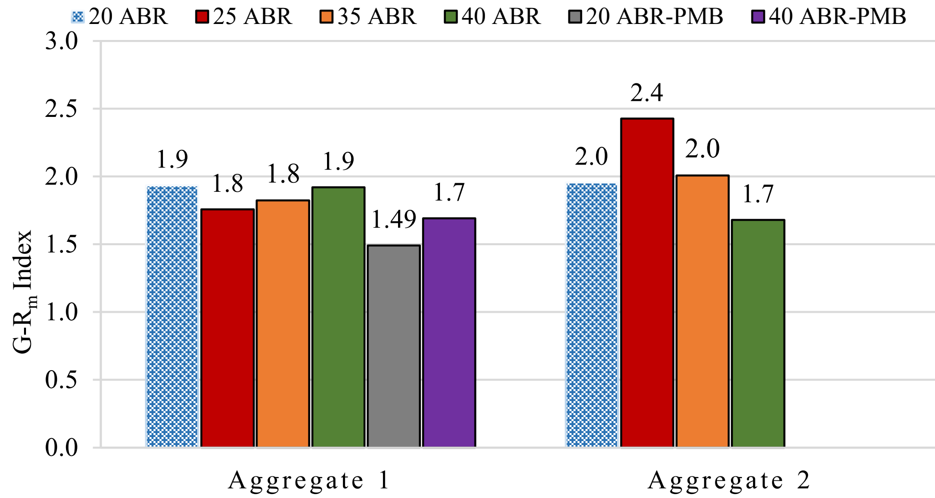


Figure 38. G-R_m Aging Ratio for all the Mixtures with Aggregate 1 and Aggregate 2.

4.2 Hamburg Wheel Tracking Test (HWTT)

Figure 39 and Figure 40 present the HWTT rut depth curves for the mixes prepared with Aggregate 1 and Aggregate 2, respectively. In general, all of the rejuvenated mixtures with Aggregates 1 and the PG 58S-28, and mixtures with Aggregate 2 performed better compared to the 20% ABR mixtures without RAs. As expected, asphalt mixtures with the PMB (20% ABR-PMB and 40% ABR-PMB) also performed better compared to those with the PG58S-28 binder; the two PMB mixtures show similar rutting performance. All of the Aggregate 1 mixtures with the PG 58S-28 binder exhibited a stripping phase while the PMB mixes showed no stripping potential. For Aggregate 2 mixtures, all four mixtures showed stripping potential following a similar trend.

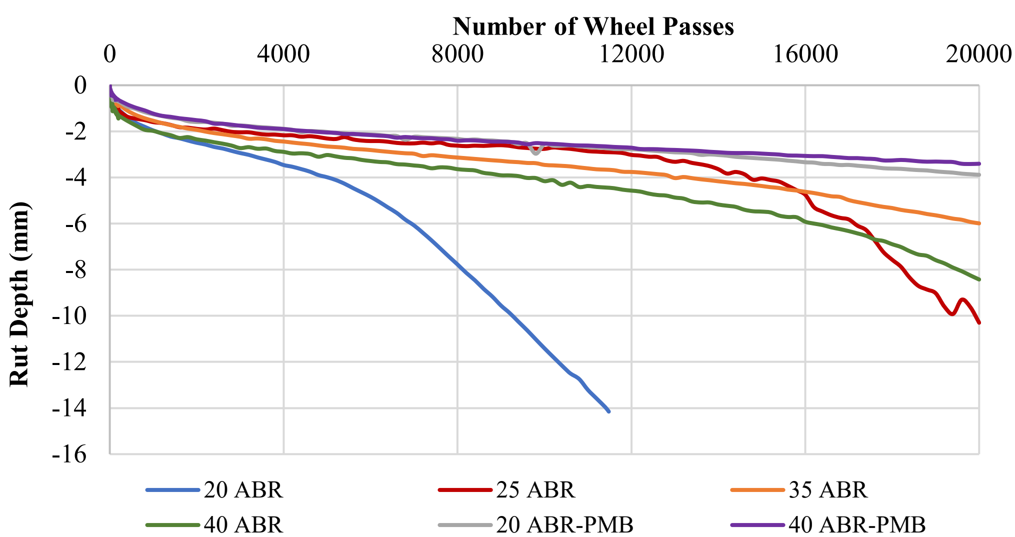


Figure 39. HWTT Rut Depth Curves for Aggregate 1 Mixtures.

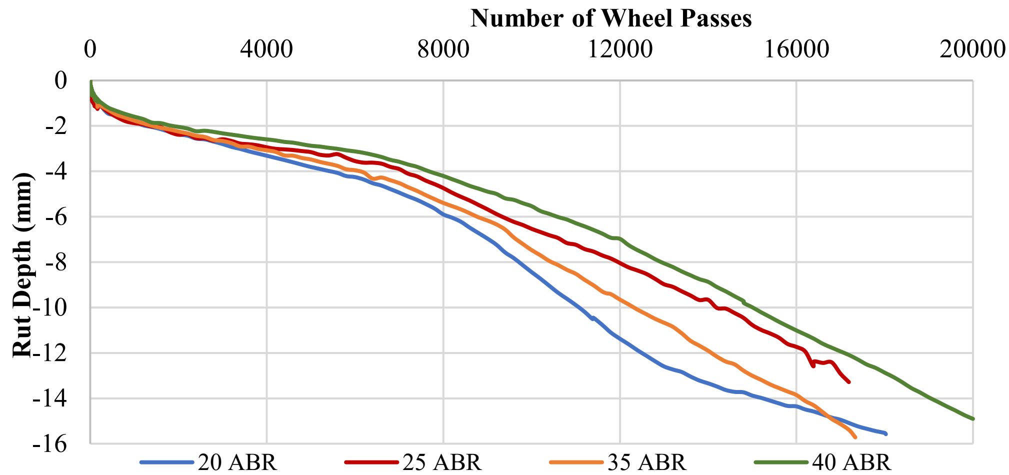


Figure 40. HWTT Rut Depth Curves for Aggregate 2 Mixtures.

Figure 41 presents the number of passes to 12.5 mm rut depth. For Aggregate 1 mixes with the PG58S-28, the 20%ABR mix only reached 10,600 passes while all of the other rejuvenated mixes reached more than 20,000 passes. For Aggregate 2 with the PG 58S-28, the 20% ABR and the 35% ABR mixes reached less than 15,000 passes, while mixes with 40% ABR and 25% ABR reached more than 15,000 passes. A preliminary threshold criterion of 15,000 passes to 12.5 mm for medium traffic level has been recommended as part of the ongoing WHRP project 0092-20-04 *(West et al., 2020)*. Based on this criterion, the 20% ABR mixtures with Aggregate 1 and Aggregate 2 and the 35% ABR mixtures with Aggregate 2 failed the criterion marginally; all of the other mixtures exceeded the minimum requirement.

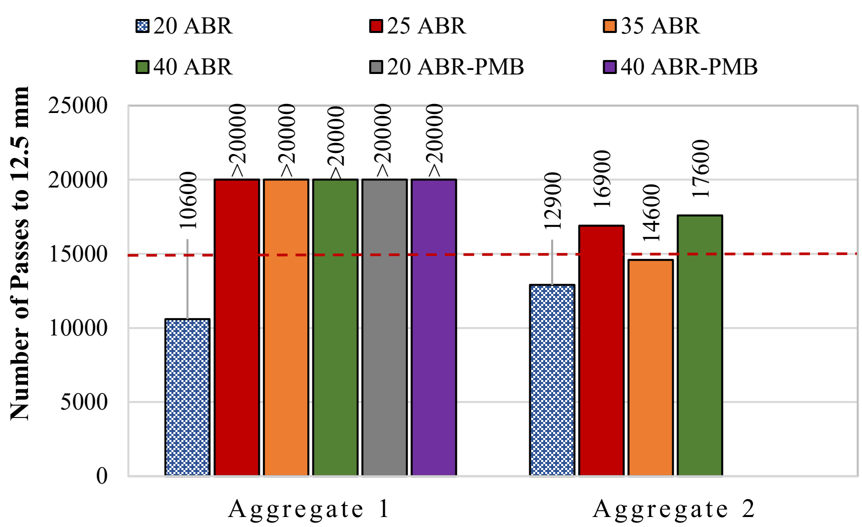


Figure 41. Number of Passes to 12.5 mm.

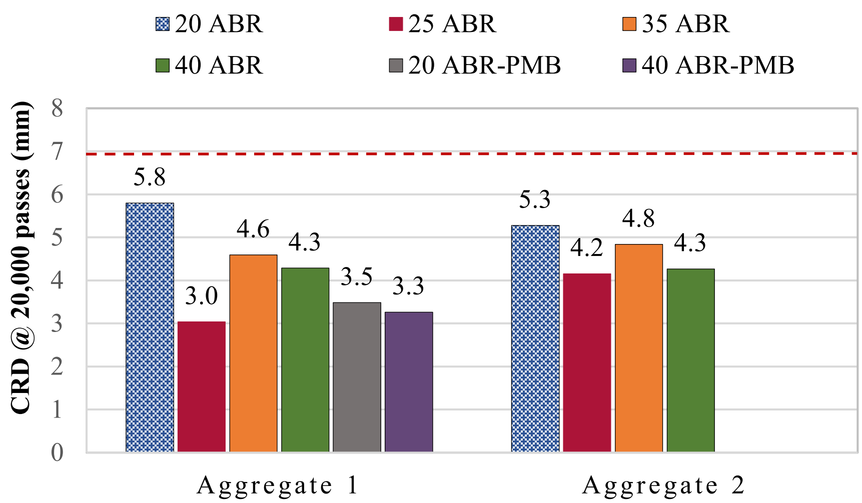


Figure 42. CRD HWTT Results.

The CRD results at 20,000-wheel passes for all of the asphalt mixtures are shown in Figure 42. As mentioned previously, a lower CRD value indicates a more rutting resistant mixture. For mixtures with Aggregate 1 and 2, the 20% ABR mixture had a higher CRD than the rejuvenated mixtures; 5.8 mm and 5.3 mm for Aggregate 1 and Aggregate 2, respectively, followed by the 35% ABR mixtures, with 4.6 mm for Aggregate 1 and 4.8 mm for Aggregate 2. Mixtures with RAS only (25% ABR) showed better rutting resistance than the other rejuvenated mixes (35% ABR, and 45 % ABR); 3.0 mm and 4.2 mm for Aggregate 1 and Aggregate 2, respectively. The PMB mixtures had a CRD of 3.5 mm and 3.3 mm for the 40% ABR-PMB mixture and the 20% ABR-PMB mixture, respectively. A maximum CRD at 20,000 passes of 7.0mm for medium traffic level mixtures has been recommended as a preliminary criterion in the ongoing WHRP project 0092-20-04. None of the mixes exceeded this maximum CRD criterion.

The moisture susceptibility potential of the mixtures is presented in Figure 43 and Figure 44 using the SIP and SN parameters, respectively. A lower SIP or SN number indicates that the mixture is more susceptible to moisture damage. A minimum SIP of 9,000 and SN of 2,000 have been recommended as preliminary criteria in the ongoing WHRP project 0092-20-04. For Aggregate 1 mixtures with the PG 58S-28 binder, the SIP numbers shown in Figure 43 are higher for all the rejuvenated mixes compared to the 20% ABR mix, while the PMB mixtures exhibited SIP of 17,400 and more than 20,000 for the 20% ABR and 40% ABR mixtures, respectively. For Aggregate 2 mixtures, the 25% ABR showed lower SIP when compared to the other mixes (20% ABR, 35% ABR, and 40% ABR). Three mixes failed the minimum SIP of 9000, the 20%ABR mixes with the PG 58S-28 binder, and the 25% ABR mix with Aggregate 2. From Figure 44, SN for Mixtures with Aggregate 1 are higher for the rejuvenated mixes compared to the 20% ABR mix. On the other hand, for mixtures with Aggregate 2, the 35% ABR mixtures showed lower SN than all the other mixtures. When compared to the preliminary criterion for SIP (minimum of 9000 passes) all the mixes met the criterion, except for the 20% ABR mixes with PG 58S-28 binder, and the 25% ABR mix with Aggregate 2. In addition, all the mixtures met the criterion for SN (minimum of 2000 passes) except the 20% ABR with Aggregate 1.

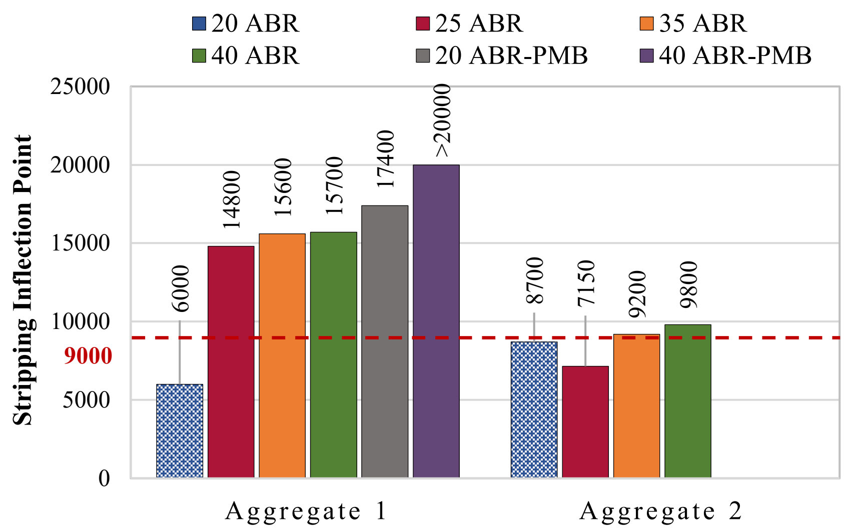


Figure 43. SIP HWTT Results.

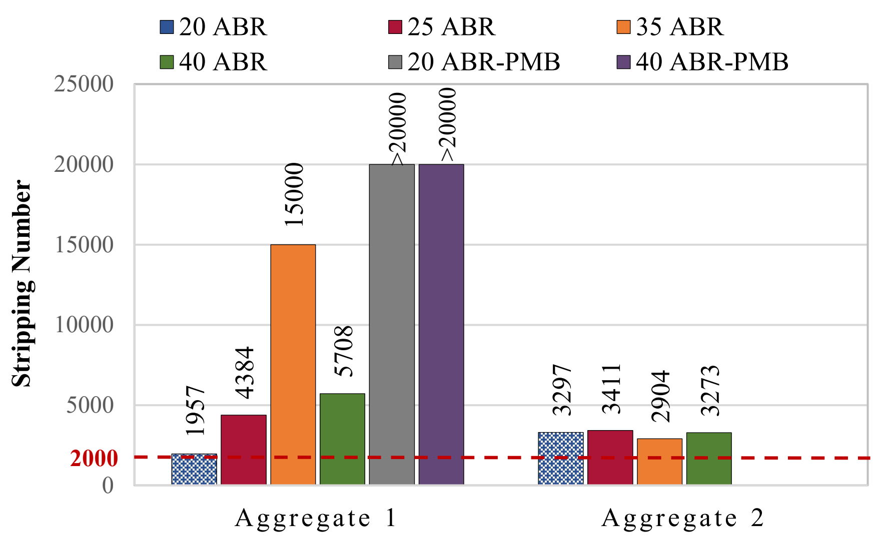


Figure 44. SN HWTT Results.

4.3 Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

Figure 45 and Figure 46 present the average IDEAL-CT load versus displacement curves for the Aggregate 1 and Aggregate 2 mixtures, respectively. For the Aggregate 1 mixtures, the 20% ABR-PMB mix/mixture had the highest peak load of all the mixes but a relatively steep post peak slope. On the other hand, the 20% ABR mixes with the PG 58S-28 binder had a relatively low peak load but one of the lowest post peak slope among all the mixes. For the Aggregate 2 mixtures, the 20% ABR mixture with the PG 58S-28 binder had the highest peak load with post peak slope almost identical to the post peak slope of the 25 % ABR mixture. In contrast, the 40% ABR mix had the same peak load as the 20% ABR mixture, but the steepest post peak slope among all the mixes.

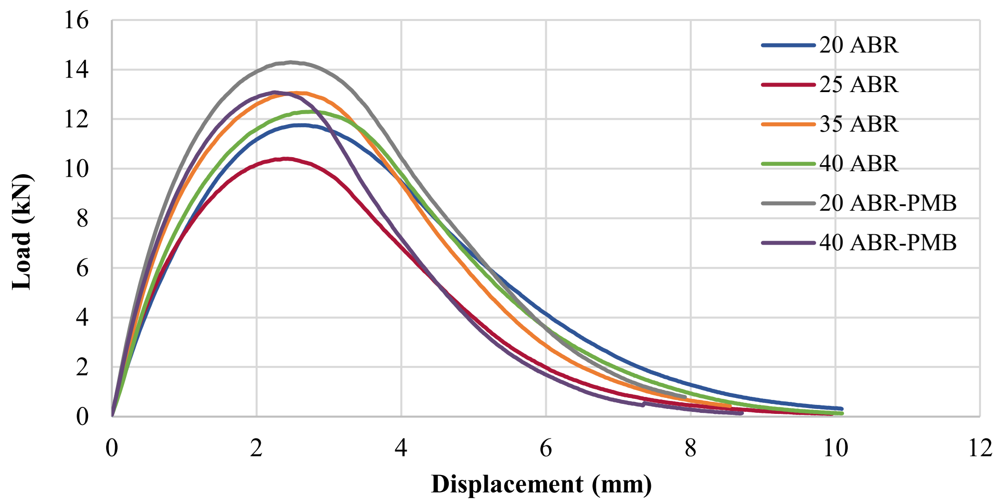


Figure 45. Load-displacement curves for Aggregate 1 Mixtures.

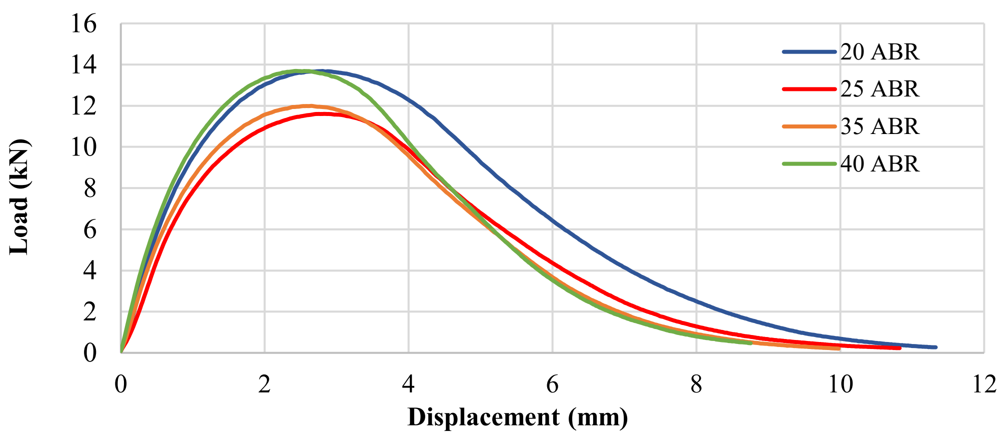


Figure 46. Load-Displacement Curves for Aggregate 2 Mixtures.

The CT_{index} of the mixtures with Aggregates 1 and 2 are shown in Figure 47. As presented in this figure, for the Aggregate 1 mixtures, the 20% ABR mixture with the PG 58S-28 binder had a higher CT_{index} than the 20% ABR control mixture with the PMB, indicating that the polymer modification had a negative effect on the CT_{index} results. However, these results should be interpreted with caution because the current IDEAL-CT procedure per ASTM D8225-19 may not be able to appropriately demonstrate the benefits of polymer modification on improving the cracking resistance of asphalt mixtures. Note that the test is conducted at a single temperature and loading rate and requires the calculation of CT_{index} based on the fracture energy and post-peak slope of the load-displacement data. Asphalt mixtures with better cracking resistance require higher fracture energy and more moderate post-peak slopes for toughness and flexibility considerations, respectively. However, polymer modification typically provides increased binder stiffness and elasticity, which have opposing impacts on the CT_{index} value. If CT_{index} is falsely more sensitive to changes in the post-peak slope than fracture energy, then PMB mixtures will have lower CT_{index} values, indicating reduced cracking resistance, than the unmodified mixtures. However, in this case, the CT_{index} is predominately governed by the overall mixture stiffness; as a result, the test would always favor the use of softer binders without appropriately considering their toughness and relaxation properties.

The 20% ABR mixes with Aggregates 1 and 2 had higher CT_{index} values than the rejuvenated mixes. These results indicate that when CT_{index} was used as the cracking performance indicator, the RA dosages used were not enough to produce rejuvenated mixes with similar cracking performance as the 20% ABR mixes. For Aggregate 1 mixtures, ANOVA showed that the differences of the mixtures' CT_{index} results are statistically significant. According to Tukey's HSD for Aggregate 1 mixtures, statistical differences exist between the 20% ABR vs. 25% ABR mixes and the 20% ARB vs. 35% ABR mixes, but there is no statistical difference between the 20% ABR and the 40% ABR mixes. The paired t-test on mixtures with the PMB binder showed that the CT_{index} results are statistically significant. ANOVA conducted on the CT_{index} results of Aggregate 2 mixes showed that they are statistically significantly different. Tukey's HSD showed that the mean differences exist between the 20% ABR vs 25% ABR, 35% ABR, and 40% ABR mixes. If these results are evaluated as part of a BMD approach, all of the Aggregate 2 mixtures exceeded the proposed minimum CT_{index} criterion of 40, while Aggregate 1 mixtures with 25% ABR and 35% ABR with PG 58S-28 binder barely failed this criterion. In addition, the 40% ABR-PMB mixture also failed the minimum CT_{index} requirement.

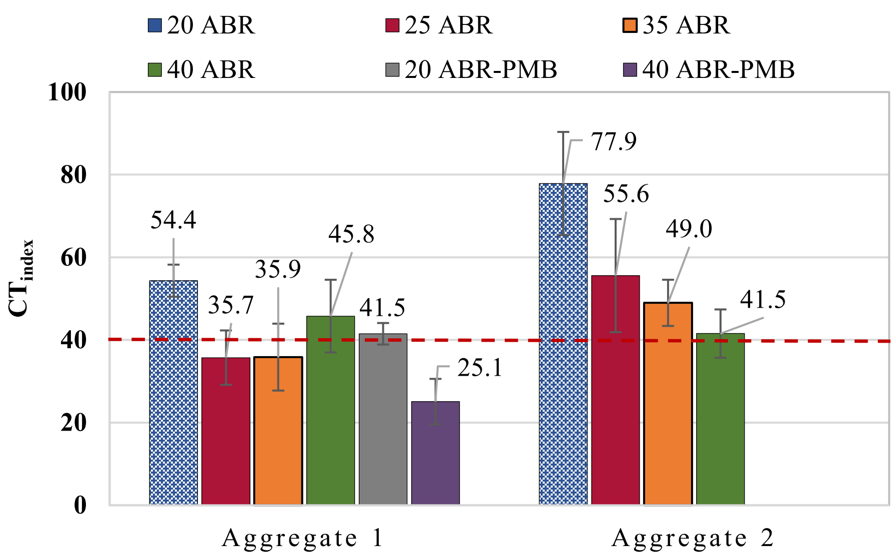


Figure 47. CT_{index} Results.

4.4 Disc-shaped Compact Tension (DCT) Test

Fracture energy results of the DCT test are shown in Figure 48. Higher fracture energy values are indicative of better resistance to thermal cracking. The mean fracture energy values of the rejuvenated mixtures were higher than the 20% ABR mixtures with Aggregate 1 and Aggregate 2, with the exception of the 40% ABR mix with Aggregate 2. In addition, the 20% ABR mixture with the PMB had higher fracture energy than the 20% ABR with the PG 58S-28 binder.

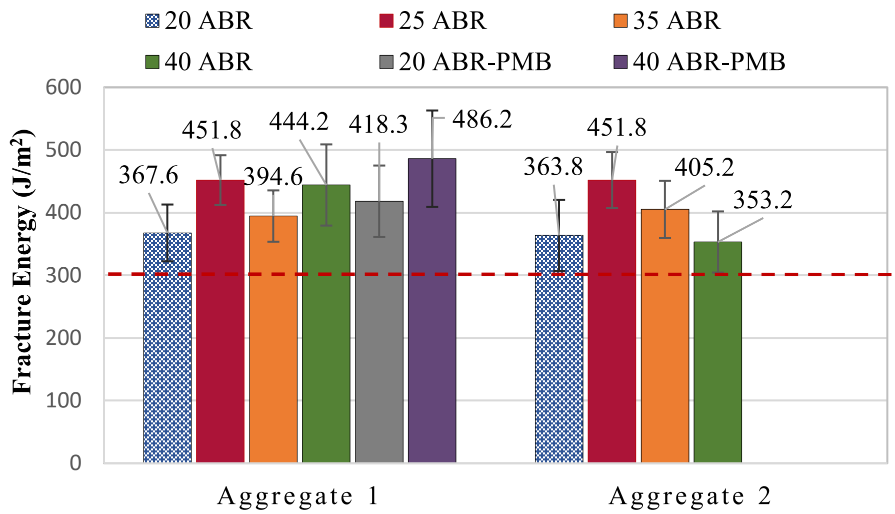


Figure 48. DCT Fracture Energy Results.

ANOVA conducted on Aggregate 1 mixtures with unmodified binder showed that the mean values of the fracture energy are statistically significantly different. For asphalt mixtures with Aggregate 1 and PMB, the paired t-test showed that the fracture energy values are not statistically significant. For Aggregate 2 mixtures, ANOVA showed that the fracture energy values were different. The differences of the mean values were between 20% ABR vs 25% ABR, and the 25% ABR vs. 40% ABR. These results indicate that the mixes with high recycled material content with the selected recycling agent dosages are expected to have better or equivalent thermal cracking resistance as the 20% ABR mixes. In addition, all the mixtures met the preliminary minimum fracture energy criterion of 300 J/m^2 recommended for BMD evaluation in WHRP project 0092-20-04.

4.5 Cost Benefit Estimates Associated with the Use of High RAM Content Mixtures

A simple cost analysis was conducted to identify the likely cost changes associated with the high RAM content mixes used in this study. This analysis considered the cost of materials only. The representative cost associated with each material was based on information gathered from different sources, as summarized in Table 18. It is worth noting that the cost of RA varies greatly from product to product and is market dependent. Table 19 summarizes the cost savings or additions for the different mixes with and without RAs. Although all the high RAM content mixes in this study use RAs, the cost of the mixes without RAs was also calculated for comparison purposes. As shown in Table 19, with respect to the 20% ABR mixes, the 40% ABR rejuvenated mixes yielded cost savings of 11% to 15%, while the 35% ABR rejuvenated mixes yielded cost savings of 8% to 11%. The addition of RAs to these mixes increased the cost of the non-rejuvenated mixes by approximately 5% to 6%. The 25% ABR rejuvenated mixes yielded additional costs of 7% to 10% with respect to the 20% ABR mixes, suggesting that there is no economic incentive when the maximum allowable percentage of RAS is used in combination with RAs.

Table 18. Representative Cost of Materials.

Material	Representative Cost, $/Ton	Reference/Source
Virgin Asphalt	500	Williams et al., 2020
Virgin Aggregate	10.8	Williams et al., 2020
RAP	9.0	WAPA, 2020
RAS	30.0	WAPA, 2020
Rejuvenator	1,650	Rejuvenator Suppliers, 2020

Table 19. Material Cost for Mixes in the Study.

Mix Type	Material Costs, $ton		Cost Difference of 20% ABR Mixes-High RAM mixes, $/ton (% cost difference)	
	Aggregate 1	Aggregate 2	Aggregate 1	Aggregate 2
20% ABR	32.4	34.3	-	-
40% ABR	25.6	28.8	6.8 (21)	5.5 (16)
40% ABR+RA	27.5	30.7	4.9 (15)	3.6 (11)
35% ABR	27.8	28.9	4.6 (14)	5.5 (16)
35% ABR+RA	29.8	30.6	2.6 (8)	3.7 (11)
25% ABR	30.8	34.0	1.6 (5)	0.3 (1)
25% ABR+RA	34.6	37.7	-2.2 (-7)	-3.4 (-10)

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Project WHRP 0092-19-04 evaluated how the quantity and quality of RAM affects the performance of the resultant binder blends by examining and understanding the interaction of their different components (virgin binders with and without polymer modification, aged binder from RAM, and RAs). For this evaluation, rheological and chemical tests were utilized. Twelve asphalt blends with different RAM contents were tested to investigate the effect of RAP/RAS binders on the properties of the blends. In addition, ten blends containing three different RAs were tested to assess the ability of the RAs to improve the properties of the blends. The project also included mixture performance tests for ten asphalt mixtures to help validate the binder results.

The results of this study are summarized below.

Binder Testing

The effects of the addition of RAM and RAs in the overall behavior of the resultant recycled binder blends are summarized in Table 20 and described as follows.

Table 20. Effects of RAM and RAs in the Behavior of the Resultant Recycled Binder Blends.

<table>
<tr><th>Temperature Range</th><th>Test Type</th><th>Research Parameter</th><th>RAM Binder Replacement</th><th>Addition of RAs</th></tr>
<tr><td rowspan="3">High-Temperature</td><td>PG</td><td>True Grade</td><td>Increased linearly with increasing ABR.</td><td>Decreased.</td></tr>
<tr><td rowspan="2">MSCR</td><td>J_{nr} @ 3.2 kPa</td><td>Recycled binder type played a more significant role on J_{nr} results than ABR content.</td><td>Increased.</td></tr>
<tr><td>%R @ 3.2 kPa</td><td colspan="2">Highly influenced by the creep compliance J_{nr} of the binders.</td></tr>
<tr><td rowspan="3">Intermediate-Temperature</td><td rowspan="2">LAS</td><td>N_f</td><td>Decreased due to presence of RAS.</td><td>Increased.</td></tr>
<tr><td>Fatigue law \|B\|-parameter</td><td>RAS yielded greater reductions in N_f per unit increase in strain in comparison to RAP.</td><td>Increased.</td></tr>
<tr><td>Master Curve</td><td>G-R @ 15°C and 0.005 rad/s</td><td>RAS blends were located inside the “cracking damage zones”.</td><td>Decreased.</td></tr>
<tr><td rowspan="2">Low-Temperature</td><td rowspan="2">PG</td><td>True Grade</td><td>Increased linearly with increasing ABR.</td><td>Decreased.</td></tr>
<tr><td>ΔT_c</td><td>Recycled binder blends with up to 40% of RAP ABR met the threshold of -5°C after RTFO plus 40-hour PAV aging. RAS binder blends between 15 and 25% ABR failed the threshold and thus, are expected to be susceptible to block cracking.</td><td>Improved (less negative ΔT_c values) with addition of bio-based RAs. Opposite was observed with addition of petroleum-based RA.</td></tr>
</table>

Performance Grading

- The addition of RAM to virgin binders significantly increased the stiffness of the resultant recycled binder blends, which improved the rutting resistance but decreased the fatigue resistance, thermal cracking resistance, and stress relaxation property after RTFO plus 40-hour PAV oxidative aging. This effect became more pronounced as the RAM content increased.

- The incorporation of bio-based RAs counterbalanced the aforementioned detrimental effects. The effectiveness of RA was related to its chemical composition and its interaction with the type of recycled binder (i.e., RAP or RAS) used as binder replacement.

— Petroleum-based RA (i.e., an asphalt flux) behaved as a softener, restoring the properties of the recycled binders only by physical process. Therefore, petroleum-based recycling agent (i.e., asphalt flux) is not recommended for use in recycled binder blends containing RAS and RAP plus RAS as binder replacement.

MSCR

— J_{nr} and %Recovery MSCR testing parameters were found as dependent on the constituents of the binder blends (i.e., base binder type and percentage, recycled binder type and percentage, and RA type and dosage).

— The effect of the recycled binder type played a more significant role on the MSCR J_{nr} results than the recycled binder replacement content.

— The addition of RAs increased the MSCR J_{nr} of recycled binder blends; and the effectiveness of each RA was related to its chemical composition as well as its interaction with the recycled binder type.

— %Recovery parameter was found to be highly influenced by the creep compliance J_{nr} of the binders, regardless of the presence and content of polymer.

LAS

— The effect of increasing the recycled binder content on the number of cycles to failure was more pronounced to the asphalt blends with the polymer modified base binder.

— When RAs were added to the asphalt blends, the general trend observed was an increase in the number of cycles to failure. This trend was perceived as being both binder blend (i.e., type and percentage of recycled binder) and RA type dependent.

— The N_f parameter was found to be influenced by the presence of severely aged recycled binder (i.e., RAS). For example, all binder blends containing RAS only presented higher number of cycles to failure at 2.5% strain than the binder blends with RAP and RAP + RAS. These results could indicate that the LAS test is not applicable for evaluating the fatigue resistance of non-conventional asphalt binders, such as highly oxidized recycled binders.

— The LAS fatigue law |B|-parameter indicated that binder blends with higher percentages of heavily oxidized recycled binders yielded greater reductions in the number of cycles to failure per unit increase in strain. Overall, base binder type and percentage, recycled binder type and percentage, and RA type and dosage played a role in the fatigue resistance of the recycled binder blends.

G-R Parameter and Black Space Diagram

— G-R parameter results highlighted the binder stiffening effect due to the use of recycled asphalt materials, where the blends of recycled asphalt binders consistently showed higher G-R parameters than the base binders, as expected.

— The addition of RAs to the recycled binder blends decreased the stiffness of all blends, before and after aging. For the unaged blends, this decrease in stiffness was followed by an increase in the phase angle (δ). After long-term aging in PAV, the decrease in |G*| for the binder blends rejuvenated with the petroleum-based RA was not accompanied by an increase in δ. This behavior was attributed to the fact that the petroleum-based RA acted as a softener to the recycled binders, restoring the properties of the binders solely by physical process.

ΔTc Parameter

- ΔT_c parameter results indicated that recycled binder blends with up to 40% RAP binder replacement still met the threshold of -5°C after RTFO plus 40 hours of PAV aging. On the other hand, the addition of RAS between 15 and 25% binder replacement significantly increased the block cracking susceptibility of the resultant recycled binder blends.

Correlation Between Rheological and Chemical Testing

FTIR

- The reduction in C=O area was dependent on the RA type (i.e., composition). For recycled binder blends with RAs, higher *G-R* parameter was associated to RAs with higher aging susceptibility.

GPC

- Recycled binder blends with higher values of M_z were associated with lower creep compliance and higher %Recovery values.
- *A*ging resulted in a shift towards higher M_n, increasing the brittleness of the binders and thus the likelihood of cracking as indicated by higher *G-R* and more negative ΔT_c values.
- While the bio-based RAs behaved somewhat similarly in terms of M_n, the petroleum-based RA behaved similar to the blends with higher percentage of RAM (i.e., 40% RAP and 30% RAP + 5% RAS).
- GPC results indicated that the chemical composition of this type of RA was similar to an asphaltic material.

Mixture Performance Testing

The approach used to select the RA dosage for mixture performance testing in this project was to target the low-temperature PG of -28°C for the recycled binder blends after RTFO and 40-hour PAV aging considering the Wisconsin climate. The results of the performance tests are summarized as follows.

Dynamic Modulus (|E*|)

- |E*| results showed mixed results for the rejuvenated mixes (25% ABR, 35% ABR, and 40% ABR) after STOA and LTOA when compared to the 20% ABR mixes (with unmodified and modified binders). Some of the rejuvenated mixes showed higher stiffnesses while other showed lower stiffness at different frequencies for low, intermediate, and high temperatures.
- Similar to the |E*| results alone, |E*| Black Space diagram and $G\text{-}R_m$ results also showed mixed results, with lower $G\text{-}R_m$ values for some rejuvenated mixes while others showed higher values when compared to the control mixes.
- $G\text{-}R_m$ aging ratios showed that the rejuvenated mixes had similar aging susceptibility as the 20% ABR mixes with no RAs, with the exception of the 25% ABR mix with Aggregate 2.

HWTT

- All of the rejuvenated mixtures at higher ABR showed better rutting and moisture susceptibility performance than the 20% ABR control mixtures.

- Only three mixtures failed the criterion of 15,000 passes to 12.5 mm, the 20% ABR mixtures, and the 35% ABR mix with Aggregate 2.
- None of the mixes exceeded the maximum CRD criterion of 7.0mm.
- Three mixes failed the minimum SIP of 9000, the 20%ABR mixes with the PG 58S-28 binder, and the 25% ABR mix with Aggregate 2.
- All the mixtures met the minimum criterion for SN of 2000 passes, with the exception of the 20 % ABR with Aggregate 1.

IDEAL-CT

- All of the rejuvenated mixes at higher ABR had lower CT_{index} values than the 20% ABR control mixes. However, only three mixes failed the preliminary minimum CT_{index} criterion of 40 recommended in WHRP project 0092-20-04. Two of these mixtures barely failed this criterion.

DCT

- All of the rejuvenated mixes at higher ABR except one had higher fracture energy values than the 20% ABR control mixes. In addition, all of the mixes passed the minimum fracture energy criterion of 300 J/m^2 proposed in WHRP project 0092-20-04.

It is important to emphasize that the long-term aging procedure used to characterize the cracking resistance of asphalt mixes in this study, and previously recommended in other WHRP project (Bahia, 2018), is more aggressive, but is expected to better simulate the field aging of asphalt pavements in Wisconsin than the standard long-term aging procedure in AASHTO R30 (i.e., conditioning of compacted specimens for 5 days at 85°C). This aging procedure is crucial for evaluating the long-term cracking resistance of high RAM content mixtures with RAs because some of these additives could significantly affect the aging characteristics of the rejuvenated binders and mixtures.

Although the performance of asphalt mixtures with innovative materials and high RAM contents is typically assessed with respect to a “control” mix at a low RAM content, the goal of BMD is to “balance” the performance of the mixtures in terms of cracking resistance without compromising rutting resistance regardless of mixture composition. Therefore, when performing a BMD with RAs to compensate for high RAM materials used, the dosage selected should aim to optimize the cracking and rutting performance of the rejuvenated asphalt mixture.

In this study, HWTT and DCT results exceeded the required thresholds preliminary recommended for mixtures in Wisconsin, while IDEAL-CT results showed that some of the recycled mixtures with RAs barely failed their corresponding performance requirements. Therefore, a BMD evaluation will likely require slight adjustments to RAs dosage rates to provide optimized mixtures.

5.2 Recommendations for Implementation

Proposed Guidance to Evaluate Asphalt Blends with High RAM Contents and Determine RA Dosage

The results of this research were used to develop a step-by-step guide to evaluate the quality of asphalt blends with high RAM contents in Wisconsin, and to determine the use of appropriate recycling agent dosages to produce mixtures with optimized performance.

As the recycled binder replacement level is increased, the likelihood of incomplete blending of the recycled and virgin binders is enhanced. Consequently, the inherent non-linearity in the properties being measured is escalated due to differences in the chemistry of the components when considering recycled binder blends with RAs and further aging. Thus, an understanding of how the blending components impart the mixture performance properties is needed. To that end, steps 1-3 of the proposed design guide are suggested to capture materials incompatibility and the potential inefficiency of recycling agents by determining the properties of the recycled binder blends at critical pavement temperatures with standard testing equipment (i.e., Superpave DSR and BBR). Furthermore, this approach can guide the dosage selection of all the components within a recycled binder blend (i.e., virgin binder, RAM, and RA).

The four proposed design steps are as follows.

1) Determine the high-temperature (HT) and the low-temperature (LT) performance grade (PG) of the component materials to be used for blending, considering that one failing and one passing test temperature per AASHTO M320 must be obtained. Consider the research parameters and criteria in Table 21 for selection and approval of component materials.

Table 21. Component Materials Selection and Proportioning Guidelines.

	Limits for Blend Component Material					
	Virgin Binder		**RAP**		**RAS**	
DSR HT PG	Aging	Original and RTFO	Aging	RTFO	Aging	As Extracted
	≤ 64°C		≤ 82°C		≤ 160°C	
BBR ΔT_c	Aging	RTFO plus 40 hours of PAV	Aging	RTFO	Aging	As Extracted
	≥ 0.0°C		≥ -3.0°C		N/A	

2) Determine the recycling agent (RA) dosage by targeting the low-temperature PG of -28°C (based on climatic requirements in Wisconsin) for the recycled binder blends after RTFO plus 40 hours of PAV aging.
   a. For bio-based recycling agents, an initial dosage of 5% per weight of total binder (i.e., virgin plus recycled binders) is recommended for low-temperature blending chart analysis, while an initial dosage of 20% per weight of total binder is recommended for petroleum-based (i.e., asphalt flux) recycling agents.
      i. As indicated in Figure 49, for the bio-based RA_1 and RA_2 evaluated in this study, the dosage of 5% per weight of total binder was able to restore to -28°C the low-temperature PG of the recycled binder blends after RTFO plus 40 hours of PAV aging, which exceeded the low-temperature PG of the 20% RAP control blends (i.e., -22°C). In the case of the petroleum-based RA_3, the dosage found for restoration of the low-temperature PG of the recycled binder blends after aging was 20% per weight of total binder.

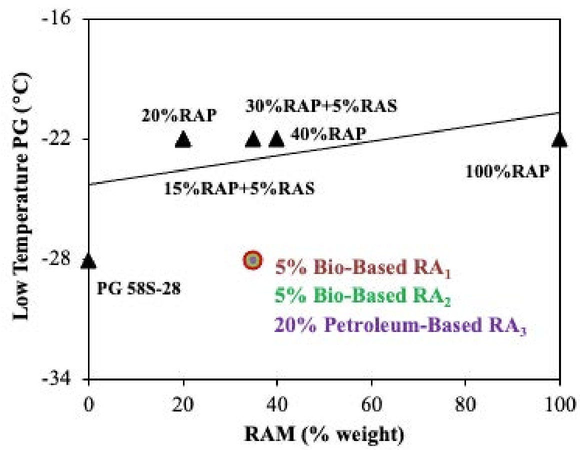
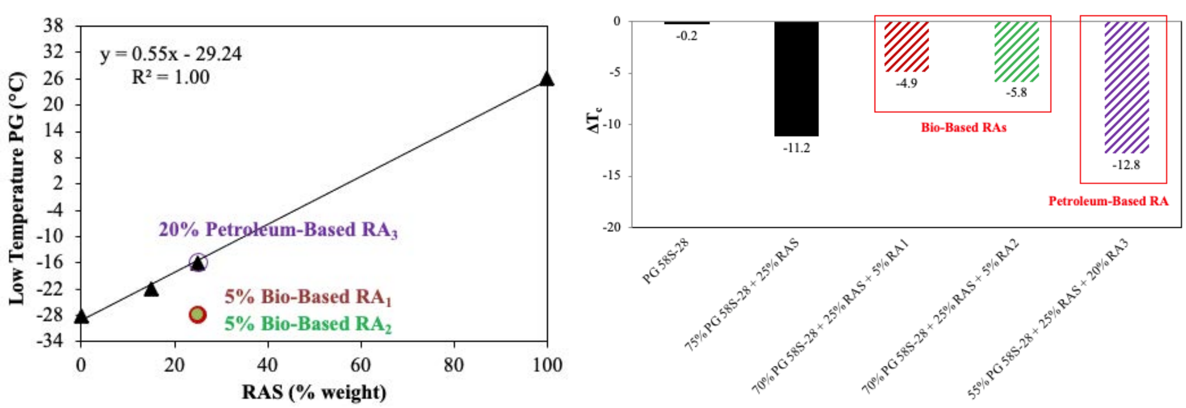


Figure 49. Effect of RAM Binder (i.e., RAP+RAS) Replacement and RAs on the Low-Temperature Performance Grade of the PG 58S-28 Binder.

b. Petroleum-based recycling agents (i.e., asphalt flux) are not recommended for recycled binder blends containing RAS binder only (i.e., without addition of RAP).

  i. As indicated in Figure 50(a), adding 20% petroleum-based RA_3 by weight of total binder was only able to restore the low-temperature PG of the recycled binder blend with 25% RAS to -16°C after RTFO plus 40 hours of PAV aging. Moreover, this addition did not mitigate the brittleness of the recycled binder blend; on the contrary, it increased its cracking susceptibility as indicated by a more negative ΔTc of -12.8°C [Figure 50(b)].



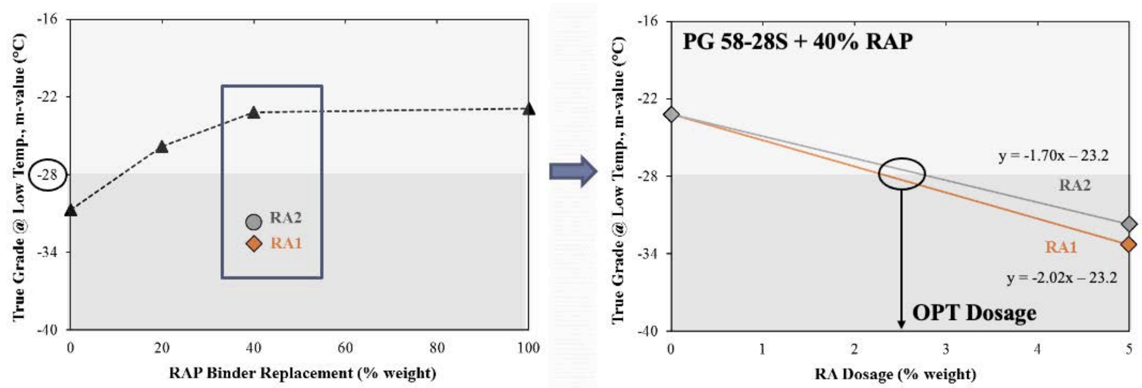
(a) (b)

Figure 50. Effect of RAS Binder Replacement and RAs on the: (a) Low-Temperature Performance Grade, and (b) ΔT_c of the PG 58S-28 Binder.

c. The optimum recycling agent dosage can then be determined through the use of blending charts obtained from BBR testing of the recycled binder blend with RA. In this analysis, the critical low-temperature for a recycled binder blend is plotted against the tested RA dosage.

  i. Figure 51 illustrates the determination of the optimum dosage for the bio-based RA_1 and RA_2 considering the recycled binder blend PG 58S-28 + 40% RAP. Please note that the optimum dosage for both additives (i.e., 2.4% for RA_1 and

2.8% for RA_2) was obtained by linear interpolation between 0 and 5% RA dosage.



Method	Recycled Binder Blend	Optimum Dosage RA_1	Optimum Dosage RA_2
Target "PG xx-28" Grade	PG 58S-28 + 40% RAP_1	2.4 %	2.8 %

Figure 51. Example of Optimum Recycling Agent Dosage Determination.

3) Perform the rheological characterization of the recycled binder blend with recycling agent at the dosage selected in Step 2, using standard test methods (AASHTO M320, AASHTO M332) and data analysis as indicated in Table 22.

Table 22. Guidelines for Rheological Characterization of Recycled Binder Blends with Recycling Agents at High and Low Temperatures.

High Temperature		
DSR HT PG	Aging	Original and RTFO
	Target Climate	
DSR MSCR $Jnr_{3.2}$ @ 58°C*	Aging	RTFO
	≤ 4.5 kPa^{-1} for Standard (S) ≤ 2.0 kPa^{-1} for Heavy (H) ≤ 1.0 kPa^{-1} for Very Heavy (V) ≤ 0.5 kPa^{-1} for Extreme (E)	
Low Temperature		
BBR ΔT_c	Aging	RTFO + 40 hours of PAV
	≥ -5.0°C	

*Considering the fact that the MSCR $\%Recovery_{3.2}$ parameter was found to be highly influenced by the creep compliance $Jnr_{3.2}$ of recycled binders, this parameter is not recommended for the characterization of recycled binder blend with recycling agent.

a. Whenever possible, the *G-R* parameter criteria of 180 kPa and 600 kPa in a Black Space diagram with $\delta_{15°C, 0.005\ rad/s}$ *versus* $|G^*|_{15°C, 0.005\ rad/s}$ can be used as an indication of the effect of RAs on the cracking potential of recycled binder blends at intermediate temperature, as shown in Table 23. This evaluation is recommended as optional due to the fact that the current DSR procedure for determination of the G-R parameter is time consuming because it requires a temperature-frequency sweep test with master-curve generation and complicated shifts. Furthermore, debate exist in the validity of using the *G-R* thresholds for evaluating polymer modified binders.

Table 23. Guidelines for Rheological Characterization of Recycled Binder Blends with Recycling Agents at Intermediate Temperature.

Intermediate Temperature		
DSR G-R in Black Space Diagram @ 15°C, 0.005 rad/s	Aging	RTFO plus 40 hours of PAV
	≤ 600 kPa	

4) Conduct mixture performance tests to ensure compliance with the BMD performance criteria.
— For HWTT, samples are prepared from loose mix aged for four hours at 135°C (STOA).
— For IDEAL-CT and DCT, samples are prepared from STOA conditioned mix further aged for six hours at 135°C (LTOA).
   a. Prepare samples with the selected RA dosage and RAM proportion combination to conduct the IDEAL-CT test.
   b. Compare the IDEAL-CT results to the preliminary criterion developed in WHRP 0092-20-04 presented in Table 24.
   c. If the IDEAL-CT criterion is satisfied, verify HWTT and DCT results using their corresponding criteria in Table 24.
   d. If the IDEAL-CT criterion is not satisfied, increase the RA dosage and verify IDEAL-CT and HWTT at the higher RA dosage.

Table 24. Preliminary Threshold Criteria for BMD for Wisconsin Mixtures. (*West et al., 2020*).

Traffic Level	HWTT (STOA)				Min. CT Index (LTOA)	DCT Min. Fracture Energy (J/m^2) (LTOA)
	Min. Passes to 12.5 mm	Min. SIP (passes)	Max. CRD 20k (mm)	Min. SN (passes)		
High	15,000	9,000	6.0	2,000	40	300
Med	15,000		7.0			
Low	10,000		8.0			

Recommended Changes to WisDOT Standard Specifications

- It is recommended to add a new section 460.2.4.5, “Recycling Agents” to read: Recycling agents can be used to help meet the performance test requirements of mixes containing high RAM contents. Petroleum-based (i.e., asphalt flux) recycling agents are not allowed in mixtures containing RAS only or combination of RAP plus RAS as binder replacement.
- It is suggested that this new section 460.2.4.5 includes the recommended step-by-step guide provided above for the evaluation of component materials, RA dosage selection, and performance characterization of recycled binder blends and mixtures with RAs.

REFERENCES

1. Anderson, M., Gayle, K., Douglas, H., and Philip, B. *Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking*. Journal of the Association of Asphalt Paving Technologists, Volume 80, 2011.
2. Asphalt Institute. *Asphalt Hot-Mix Recycling*. The Asphalt Institute Manual, Series No. 20 (MS-20), 1986.
3. Bajaj, A., Martin, A., King, G., Glover, C., Kaseer, F., Arámbula-Mercado, E. *Evaluation and Classification of Recycling Agents for Asphalt Binders*. Construction and Building Materials, Vol. 260, 2020.
4. Bahia, H., H. Sadek, M. Z. Rahaman, and Z. Lemke. *Field Aging and Oil Modification Study*, WHRP Project 0092-17-04, 2018.
5. Bahia, H., Swiertz, D., Kilger, A. *Modified Binder (PG+) Specifications and Quality Control Criteria*. Project WHRP (0092-14-20) TPF-5(302) Extension Final Report, 2018.
6. Epps Martin, A., F. Kaseer, E. Arámbula-Mercado, A. Bajaj, L. Garcia Cucalon, F. Yin, A. Chowdhury, J. Epps, C. Glover, E.Y. Hajj, N. Morian, J. Sias Daniel, M. Oshone, R. Rahbar-Rastegar, C. Ogbo, and G. King. *Evaluating the Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios*, NCHRP Research Report 927. Transportation Research Board, Washington, D.C., 2019.
7. Hajj E., P. Sebaaly, and R. Shrestha. *Laboratory Evaluation of Mixes Containing Recycled Asphalt Pavement (RAP).* International Journal of Road Materials and Pavements Design, Vol. 10, No. 3, 2009.
8. Li, X., M. Marasteanu, C. Williams, and T. Clyne. *Effect of RAP (Proportion and Type) and Binder Grade on the Properties of Asphalt Mixtures*. Transportation Research Record: Journal of the Transportation Research Board, No. 2051, pp. 90-97, 2008.
9. Lobo, H., and Bonilla, J. *Handbook of Plastics Analysis*. CRC Press, June, 2003.
10. Milton, L., J. M. Chaffin, R. R. Davison, C. J. Glover, and J. A. Bullin. Changes in Corbett Fraction *Composition during Oxidation of Asphalt Fractions*. Transportation Research Record: Journal of the Transportation Research Board, No. 1638, pp. 40-46, 1998.
11. Mogawer, W. S., Booshehrian, A., Vahidi, S., & Austerman, A. J. *Evaluating the effect of rejuvenators on the degree of blending and performance of high RAP, RAS, and RAP/RAS mixtures*. Road Materials and Pavement Design, 14(sup2), pp. 193-213, 2013.
12. Moraes, R., and Bahia, H. *Effect of Mineral Fillers on the Oxidative Aging of Asphalt Binders: A Laboratory Study Using Mastics*. Transportation Research Record: Journal of the Transportation Research Board, No. 2506, pp. 19-31, 2015.

13. Ogbo, C., F. Kaseer, M. Oshone, J. Sias and A. Epps-Martin. *Mixture-based rheological evaluation tool for cracking in asphalt pavements*. Road Materials and Pavement Design, Vol. 20, sup1, 2019.
14. Rejuvenator Suppliers, email communication with suppliers, 2020.
15. Rowe, G. M. Prepared Discussion for the AAPT Paper by Anderson et al. *Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking*. Journal of the Association of Asphalt Paving Technologists, Vol. 80, pp. 649-662, 2011.
16. Shah A., R. McDaniel, G. Huber, and V. Gallivan. *Investigation of Properties of Plant-Produced Reclaimed Asphalt Pavement Mixtures*. Transportation Research Record: Journal of the Transportation Research Board, No. 1998, pp. 103-111, 2007.
17. Tabatabaee, H., Magnifico, S., Velasquez, R., and Bahia, H. *Investigation of Low Temperature Cracking in Asphalt Pavements*. National Pooled Fund Study, Phase II, Task 2 - Expand Phase I Test Matrix with Additional Field Samples Subtask on Physical Hardening, 2010.
18. Tabatabaee, H., Velasquez, R., and Bahia, H. *Predicting Low Temperature Physical Hardening in Asphalt Binders*. Journal of Construction and Building Materials, Vol. 34, pp. 162-169, 2012.
19. Tran, N., Taylor, A., and Willis, R. *Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents*. Rep. No. 12-05, National Center for Asphalt Technology (NCAT), Auburn, AL, 70 pp, 2012.
20. West, R., A. Kvasnak, N. Tran, B. Powell, and P. Turner.. *Testing of Moderate and High RAP Content Mixes: Laboratory and Accelerated Field Performance at the National Center for Asphalt Technology Test Track*. Transportation Research Record: Journal of the Transportation Research Board, No. 2126, pp. 100-108, 2009.
21. West. R., F. Yin, C. Rodezno and A. Taylor. *WHRP 0092-20-04 BMD Implementation Support*, Panel Update Meeting, June 17, 2020.
22. Williams, B.A., J.R. Willis, and J. Shacat. *Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2019*. Information Series 138, National Asphalt Pavement Association, Greenbelt, MD, 2020.
23. Wisconsin Asphalt Pavement Association, email communication with WAPA member, 2020.
24. WisDOT, 2021, *Standard Specifications*. Section 4602.5-Hot Mix Asphalt Pavements.
25. Xie, Z., Tran, N. Julian, G., Taylor, A., and Davis Blackburn, L. *Performance of Asphalt Mixtures with Recycled Contents Using Rejuvenators and Warm-Mix Additive: Field and Lab Experiments*. *Journal of Materials in Civil Engineering*, Vol. 29, Issue 10, 2017.
26. Yin, F., Arambula, E., Lytton, R., Martin, A. E., & Cucalon, L. G. *Novel method for moisture susceptibility and rutting evaluation using Hamburg wheel tracking test*. Transportation Research Record, 2446(1), 1-7, 2014.
27. Zaumanis, M., R. Mallick, and R. Frank. *Evaluation of Different RAs for Restoring Aged Asphalt Binder and Performance of 100 % Recycled Asphalt*. Materials and Structures, 14 p, 2014.

APPENDIX A

TASK 1 LITERATURE REVIEW

Wisconsin Highway Research Program

Recycled Asphalt Binder Study

Literature Review-Task 1

Wisconsin Highway Research Program
<u>LIMITED USE DOCUMENT</u>

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1 Background

The use of recycled asphalt materials (RAM), including reclaimed asphalt pavements (RAP) and recycled asphalt shingles (RAS), has significant economic and environmental benefits that include cost savings, conservation of natural resources, and reduction in energy consumption and emissions. Today, the majority of new hot mix asphalt (HMA) mixes produced in the United States contain a certain percentage of RAM. According to the most recent National Asphalt Pavement Association (NAPA) survey, the total estimated tons of RAP and RAS used in HMA in 2017 were 76.2 million tons and 944,000 tons, respectively (Williams et al., 2017).

There is a general agreement among the asphalt pavement industry that the stiffness and rutting resistance of asphalt mixes containing RAM increases with increasing RAM content; however, the mixes tend to become more susceptible to cracking and durability issues due to the heavily aged asphalt binders in RAM, which are stiffer and more brittle than virgin asphalt binders. Over the years, the performance of asphalt mixes containing RAM has been found dependent on the properties of their constitutive components as well as the degree of blending between recycled and virgin binders.

1.1 Degree of Blending between Recycled and Virgin Binders

The degree of blending between recycled and virgin binders has a significant effect on the volumetric and performance properties of asphalt mixes (Copeland, 2011). If the degree of blending is overestimated, the mix will not have enough asphalt binder (or is too "dry") and thus becomes more susceptible to cracking and durability related distresses. On the other hand, underestimating the degree of blending will yield mixes with excessive asphalt binder and increased susceptibility to deformation and bleeding issues (Copeland, 2011; Coffey et al., 2012). Therefore, establishing a good understanding of the degree of blending between recycled and virgin binders is important to ensure the satisfactory performance of asphalt mixes containing RAP and RAS materials.

In the Superpave mix design method, the total binder content of an asphalt mix is a function of the virgin binder content and the "active" recycled binder content in RAP and RAS materials. There are three approaches for determining the amount of "active" asphalt binder in recycled materials (Stroup-Gardiner, 2016). The first is the "full blending" approach, which assumes that 100% of the asphalt binders in RAP and RAS materials are "active" and contribute to the total binder content. The second is the "black rock" approach, which assumes that none of the RAP and RAS binders is "active". The third approach assumes somewhere in between the first two approaches, where a portion of the recycled binders in RAP and RAS materials are "active". This approach is commonly referred to as the "partial blending" approach. Regardless of which approach is used, the total binder content of an asphalt mix containing RAP and RAS materials can be determined using Equation 1.

$$TAC = \text{Virgin } AC + FRAP * AC_{RAP} * RAP\% + FRAS * AC_{RAS} * RAS\% \qquad \text{(Equation 1)}$$

Where,

TAC = total asphalt binder content;
Virgin AC = virgin asphalt binder content;
AC_{RAP} = RAP asphalt binder content;
AC_{RAs} = RAS asphalt binder content;
RAP% = percent of RAP in mix;

RAS% = percent of RAS in mix;
FRAP = RAP binder availability factor, 0 to 1; and
FRAS = RAS binder availability factor, 0 to 1.

The use of F_{RAP} and F_{RAS} parameters in Equation 1 allows the discrimination among the three approaches; F_{RAP} and F_{RAS} are assumed to be 1 when the "full blending" approach is used, 0 when the "black rock" approach is used, and somewhere in between 0 and 1 when the "partial blending" approach is used. There was a belief among the asphalt industry that the recycled binders in RAP and RAS materials could fully blend with the virgin binder and form a uniform recycled binder blend at an elevated temperature during production. In other words, all the RAP and RAS binders were assumed to be effectively "active" for contributing to the total binder content of the mix, as indicated in the "full blending" approach. However, over the years, asphalt researchers and practitioners have recognized that the interaction between recycled and virgin binders in asphalt mixes is much more complicated than anticipated, and that in most cases, a full blending between recycled and virgin binders does not occur. Therefore, the "partial blending" approach is now believed as the most appropriate approach for use in designing asphalt mixes containing RAP and RAS materials.

A number of research studies have been conducted to evaluate the degree of blending between recycled and virgin binders. In general, these studies indicate that the degree of blending is primarily governed by the physical dispersion and chemical diffusion between the recycled materials and virgin binder during production. Mix components and production factors that have been found to impact the degree of blending include the recycled binder content, gradation of recycled materials, relative difference in stiffness between recycled and virgin binders, and mix production temperature. The experimental or analytical methods used in these studies to determine the degree of blending between recycled and virgin binders can be generally grouped into eight categories:

1. Preparation of Coarse-Aggregate, Fine RAP Mix
2. Preparation of Gap-graded Mixes
3. Volumetric Analysis
4. Comparing Measured and Predicted Asphalt Mixture Dynamic Modulus
5. Use of Titanium Dioxide in Virgin Binder as a Tracer
6. Use of Artificial Glass Beads in Virgin Aggregate as a Tracer
7. Staged Solvent Extraction
8. Other Methods

1.1.1 Preparation of Coarse-Aggregate, Fine-RAP Mix

This method was first developed by Huang et al. (2005) and has been used in numerous studies since (Shirodkar et al., 2011; Yu et al., 2017; Gottumukkala et al., 2018). The method requires the preparation of a RAP mix using fine RAP materials (i.e., passing a No. 4 sieve) and coarse virgin aggregates (i.e., retained on a 9.5mm sieve). After mixing, the loose mix is separated into two fractions using a No. 4 sieve. As shown in Figure 1, the finer fraction corresponds to a blend of fine RAP materials and virgin binder, and the coarser fraction is a blend of virgin aggregate, virgin binder, and a portion of RAP binder. The asphalt binder of each fraction is then extracted, recovered, and tested to determine the properties. This method assumes that if a full blending between RAP and virgin binders occurs, the properties of the recovered asphalt binders from the two fractions would be the same; otherwise, the recovered binder from the finer RAP fraction would be stiffer and more brittle than that recovered from the coarser aggregate fraction due to the presence of a higher percentage of RAP binder.

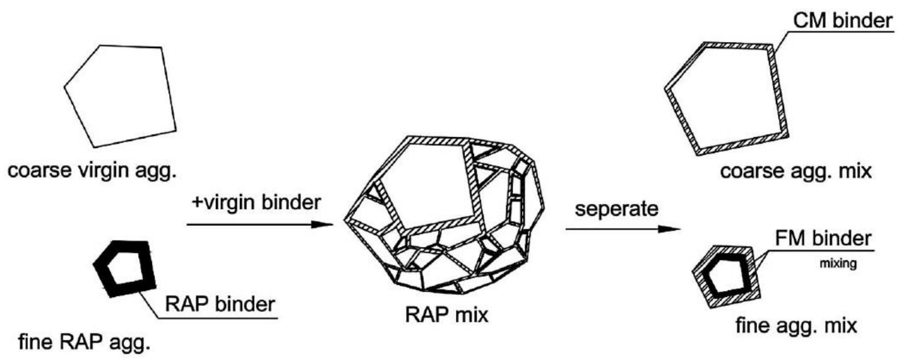


Figure 1 Schematic Illustration of the Preparation of Gap-graded RAP Mix (Yu et al., 2017)

Shirodkar et al. (2011) adopted this method and used the Dynamic Shear Rheometer (DSR) |G*|/sinδ parameter to estimate the degree of blending for a 25% RAP mix and a 35% RAP mix. The 25% RAP mix used a PG 70-28 virgin binder and the 35% RAP mix used a softer PG 58-28 virgin binder. Test results showed that the 20% RAP mix had a 70% degree of blending, which was lower than that of the 30% RAP mix (i.e., 96%). The improved degree of blending between RAP and virgin binders in the 30% RAP mix was attributed to the use of a softer virgin binder.

Yu et al. (2017) followed this method and used two DSR rutting parameters and two DSR fatigue parameters to evaluate the degree of blending between RAP and virgin binders. The two selected rutting parameters were DSR |G*|/sinδ and J_{nr} from the Multiple Stress Creep Recovery (MSCR) test, and the two fatigue parameters were |G*|sinδ and fracture energy from a fatigue monotonic test. Three RAP mixes with 20%, 40%, and 60% RAP were tested. The study found that the degree of blending of these mixes varied from 20% to 85% and that the results were not sensitive to specific rutting or fatigue parameters (Table 1). In addition, the study observed that the addition of recycling agents (RA), also known as rejuvenators, greatly improved the degree of blending of the 60% RAP mix. Finally, the study proposed a modified concept of binder blending chart for use in designing high RAP asphalt mixes that considered the actual degree of blending between RAP and virgin binders.

Table 1 Summary of Blending Ratio Results (Yu et al., 2017)

Blending Ratio	Rutting Parameters		Fatigue Parameters	
	G*/sinδ	MSCR Jnr	G*sinδ	Fracture Energy
20% RAP	36.2%	32.9%	21.2%	20.9%
40% RAP	83.0%	84.0%	81.6%	84.8%
60% RAP	73.5%	73.7%	63.6%	71.4%

Gottumukkala et al. (2018) adopted this method and used the difference in the softening point, penetration, and DSR G*/sinδ parameter of the two recovered binders to determine the degree of blending between RAP and virgin binders. Four RAP mixes containing two RAP contents and two virgin binders were tested. The study found the degree of blending of these mixes varied from 16% to 87% depending on the virgin binder type and RAP content.

1.1.2 Preparation of Gap-Graded Mixes

This method was developed by Kaseer et al. (2019) as part of the National Cooperative Highway Research Program (NCHRP) project 09-58. The method requires the preparation and testing of two gap-graded asphalt mixes with specific sizes of virgin aggregates and RAP materials. As shown in Figure 2, a virgin mix is prepared by mixing virgin binder and gap-graded virgin aggregate blends consisting of 3/8”, #4, #8, and #30 fractions. The RAP mix is prepared in the same manner as the virgin mix, except for replacing the #4 fraction of virgin aggregates with the same size of RAP materials. After mixing, both mixes are separated into three fractions using 3/8” and #4 sieves, and the binder content of each fraction is determined using the ignition oven. Finally, the difference in the binder content of the #4 fractions between the two virgin and RAP mixes is used to estimate the availability of RAP binder and determine the degree of blending between RAP and virgin binders. The assumption behind this method is that if a full blending between RAP and virgin binders occurs, all of the RAP binder would be “active” and the #4 fractions of the two mixes would have the same binder content; otherwise, the #4 fraction of the RAP mix would have a higher binder content than that of the virgin mix due to the presence of “inactive” RAP binder.

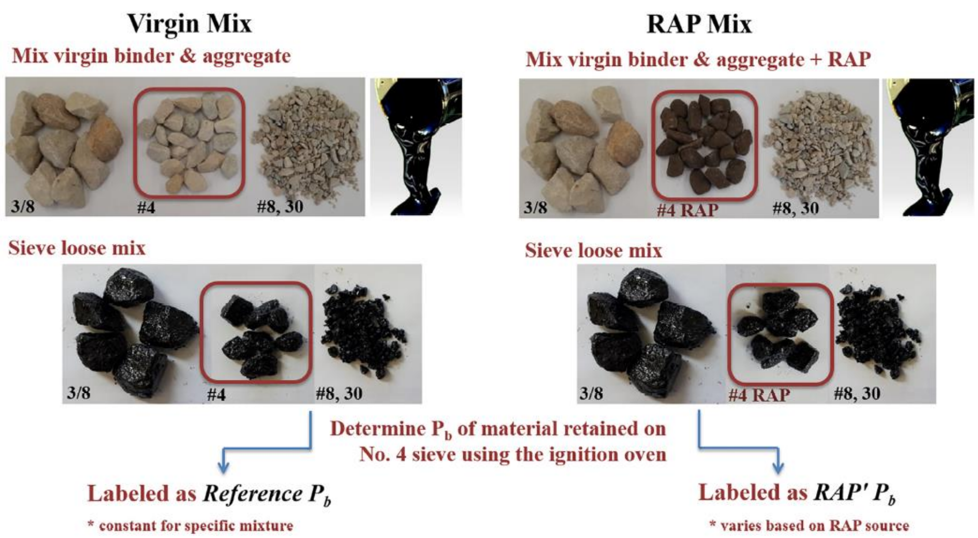


Figure 2 Illustration of the Preparation of Gap-graded Virgin and RAP Mixes (Kaseer et al., 2019)

Kaseer et al. (2019) verified this method using laboratory-produced artificial RAP materials with various aging conditions and found the RAP binder availability was sensitive to the aging condition of artificial RAP. The study also found that the RAP binder availability was dependent on RAP source and mixing temperature. Generally, the RAP binder availability increased as the stiffness (i.e., high-temperature performance grade) of the extracted RAP binder decreased and the mixing temperature increased. As shown in Figure 3, a RAP source from Wisconsin had a binder availability of 80.6% at 140°C, which further increased to 93.8% at 150°C. Furthermore, the study found that the use of recycling agents improved the RAP binder availability while extending the short-term mix conditioning time had no significant effect.

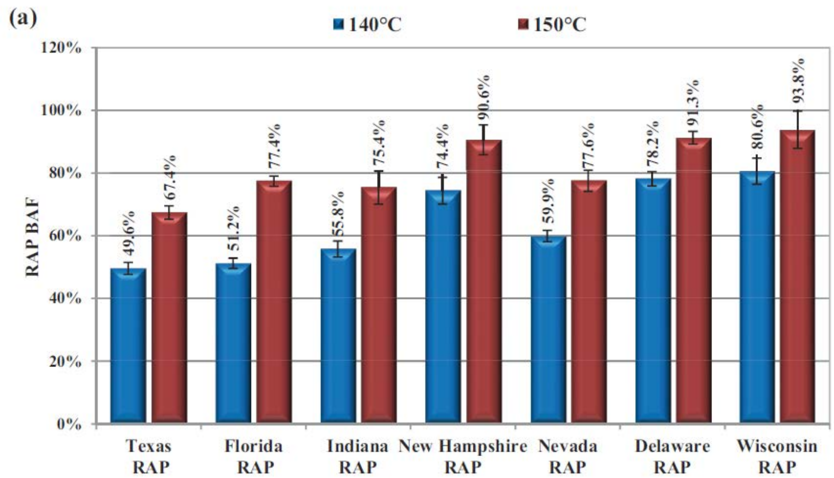


Figure 3 Binder Availability Results of RAP Materials from Different Sources (Kaseer et al., 2019)

1.1.3 Volumetric Analysis

This method was first introduced by Coffey et al. (2013), which was primarily based on the volumetric analyses of two companion RAP asphalt mixes. One mix was prepared with ignited RAP aggregates composing 25% of the mix and the other mix was prepared with 25% RAP under an assumption of 70% degree of blending between RAP and virgin binders. The amount of virgin binder required to achieve a 4.0 percent air voids at 75 gyrations for both mixes was determined and the difference was used to estimate the degree of blending between RAP and virgin binders. The study tested three RAP materials from different sources in New Jersey and found that the degree of blending between RAP binders and a PG 70-28 virgin binder was in the range of approximately 85% to 90%. The study also recommended that for RAP materials with such a high degree of blending, the "full blending" approach could be used to design recycled asphalt mixes without compromising their rutting and fatigue performance.

1.1.4 Comparing Measured and Predicted Asphalt Mixture Dynamic Modulus

This method was developed by Bonaquist (2005) to evaluate the degree of blending by comparing the measured dynamic modulus (E*) of recycled asphalt mixes versus the predicted E* from rheological testing of as-recovered asphalt binders. During solvent extraction and recovery, recycled and virgin binders are forced to blend together and achieve a full blending condition. The complex modulus (G*) master curve of the as-recovered binders is input into the Hirsch model to predict the mix E* with an assumption of 100% degree of blending. The relative difference between the measured and predicted E* indicates the actual degree of blending between recycled and virgin binders in asphalt mixes containing RAP and RAS materials.

Booshehrian et al. (2013) adopted this method on five plant-produced RAP asphalt mixes in New York and found most of them exhibited a good degree of blending. Similar findings were also reported by Mogawer et al. (2012) for 18 plant-produced RAP mixes in New Hampshire, New York, and Vermont. The study also found that plant discharge temperature had a significant effect on the degree of blending between RAP and virgin binders.

1.1.5 Use of Titanium Dioxide in Virgin Binder as a Tracer

Castorena et al. (2016) introduced the use of energy dispersive X-ray spectroscopy (EDS) scanning electron microscopy (SEM) to qualitatively evaluate the degree of blending between RAP and virgin binders. In this method, titanium dioxide power is pre-blended into the virgin binder prior to the preparation of asphalt mixes, which allows the delineation of RAP and virgin binders in the EDS mapping. During testing, the locations of RAP binder and virgin binder are determined by comparing the carbon EDS maps and titanium EDS maps. Because titanium dioxide is present only in virgin binder, areas with carbon but no titanium correspond to RAP binder while areas with carbon and titanium indicate the presence of virgin binder, possibly blended with RAP binder, as shown in Figure 4. The study demonstrated the effectiveness of the proposed EDS SEM method using two high RAP mixes and found that the preprocessing of RAP and short-term mix conditioning improved the degree of blending between RAP and virgin binders.

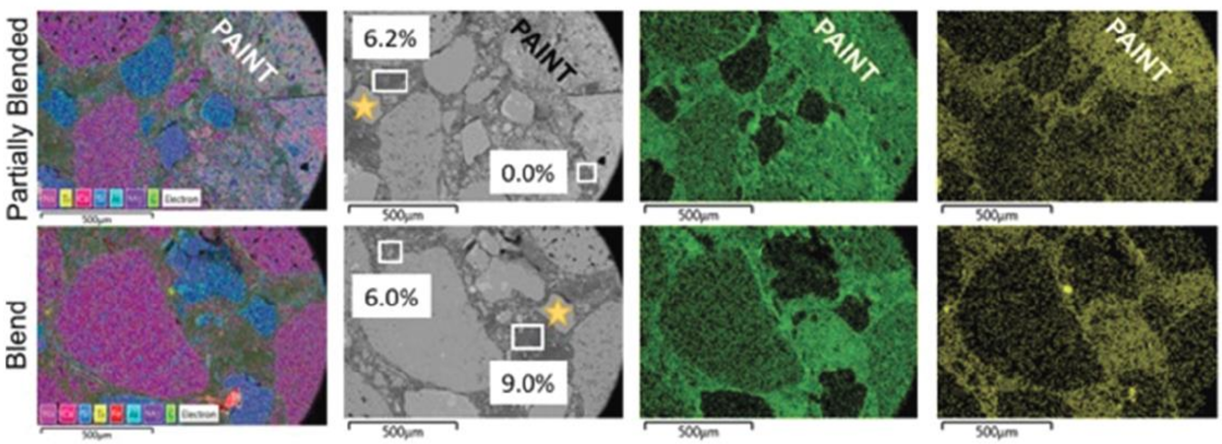


Figure 4 Examples of EDS SEM Images for Quantifying the Degree of Blending between RAP and Virgin Binders (Castorena et al., 2016)

A more recent study by Jiang et al. (2018) adopted the EDS SEM method described above and proposed the use of element mass ratio of titanium over sulfur (Ti:S) as an index to quantify the degree of blending between RAP and virgin binders. Four asphalt mixes with 0%, 15%, 30%, and 50% RAP were tested. The effect of mix aging and the use of recycling agents on the degree of blending between RAP and virgin binders was evaluated. As shown in Figure 5, the degree of blending varied from 40 to 100% among the RAP mixes tested. In general, the degree of blending decreased as the RAP content in the mix increased. In addition, loose mix aging for 12 hours at 135°C prior to compaction and the use of recycling agents greatly improved the degree of blending between RAP and virgin binders.

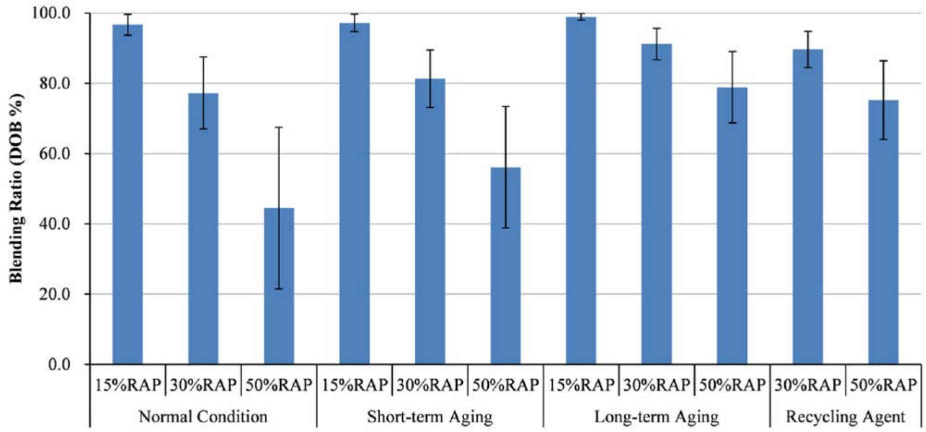


Figure 5 Summary of Degree of Blending Results from EDS SEM Analysis (Jiang et al., 2018)

1.1.6 Use of Artificial Glass Beads in Virgin Aggregate as a Tracer

This method was first developed by Mohajeri et al. (2015), which requires the use of borosilicate glass beads to replace a small percentage of virgin aggregates. A normal mixing procedure is used to prepare asphalt mixes by mixing virgin binder, virgin aggregate, glass beads, and RAP materials. After mixing, the glass beads are collected from the loose mix (Figure 6) and the asphalt binder coated on the surface of the glass beads is extracted, recovered, and tested.

Figure 6 Glass Beads; (a) Before Mixing, (b) After Dry Blending with RAP only, (c) After Normal Mixing with Virgin Binder, Virgin Aggregate, and RAP

In a study by Sreeram et al. (2018), the recovered binder from the glass beads was characterized through Fourier Transform Infrared Spectroscopy (FTIR) analysis to determine the normalized carbonyl (C=O) area and sulfoxide (S=O) area. The virgin binder was tested to provide the baseline data for the "black rock" scenario and the pre-blended RAP and virgin binder blend was tested to simulate the "full blending" scenario. The RAP blending efficiency was calculated based on the relative difference in the FTIR results among the recovered binder from the glass beads, the virgin binder, and pre-blended RAP and virgin binder blend. The study found that the RAP blending efficiency was highly dependent on the mix production temperature, as shown in Figure 7. Specifically, RAP mixes produced at 165°C had an average blending efficiency of approximately 60%, which was 20% higher than that of RAP mixes produced at 135°C. In addition, the study found that the use of WMA technologies greatly improved the RAP blending efficiency at a reduced production temperature.

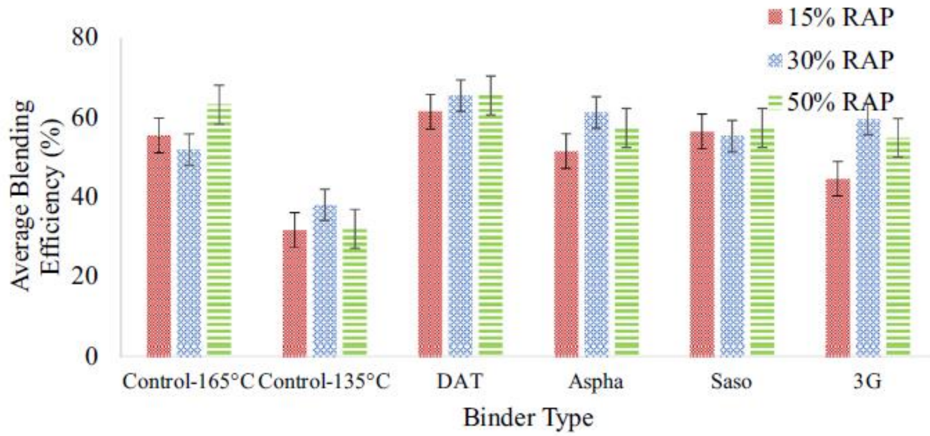


Figure 7 Effect of Production Temperature and WMA Technologies on RAP Blending Efficiency (Sreeram et al., 2018)

1.1.7 Staged Solvent Extraction

This method was first developed by Zearly (1979) to assess the diffusion of asphalt binders with different aging conditions. An aggregate particle was first coated with an age-hardened binder and then with a soft binder to create a two-layer binder coated sample. The sample was eluted in trichloroethylene (TCE) three consecutive times and the penetration of the asphalt binder recovered from each TCE solvent was measured. The difference in the penetration results provided an indication of the degree of diffusion between the age-hardened and soft binders. Later, the staged solvent extraction method was used to investigate the diffusion of rejuvenators into recycled binders and evaluate the degree of blending between RAP and virgin binders (Carpenter and Wolosick, 1980; Noureldin and Wood, 1987; Huang et al., 2005).

In a study by Bowers et al. (2014), 25gof loose mix particles of a RAP mix were submerged into TCE solvent for four consecutive times; the first for 30 seconds, the second for 1 minute, the third for 3 minutes, and the fourth for a period required to dissolve all the asphalt binder on the aggregate particles. The four-asphalt binder/TCE solvents were constituted as four layers. Asphalt binder from each layer was then recovered through rotary evaporation and tested in Gel Permeation Chromatography (GPC) and FTIR to determine its molecular size distribution and formation of carbonyl and sulfoxide functional groups. The relative difference in the GPC and FTIR results among the four layers indicated the degree of blending between RAP and virgin binders. If full blending occurs, the properties of asphalt binders recovered from the four layers would be the same; otherwise, the inner layers would have more heavily aged RAP binder than the outside layers. The study found that blending between RAP and virgin binders occurred within all layers, but the blending was not completely uniform.

1.1.8 Other Methods

A study by Yousef Rad et al. (2014) used DSR testing to estimate the rate of diffusion of virgin binder into RAP binder. A laboratory sample preparation procedure was developed to simulate the contact blending between RAP and virgin binders. As shown in Figure 8, the procedure required the preparation, assembling, and testing of two thin wafers made of RAP and virgin binders. The concept behind the procedure is that at an elevated temperature, the two in-contact binders will start blending at the interface boundaries, leading into a gradient of fresh binder into the RAP binder. As a result, the resultant sample represents a composite binder blend consisting of a layer of virgin binder and multiple layers of RAP binder with different concentrations of diffused virgin binder. Fick's law calculations were performed to analyze the DSR results of the resultant binder sample and determine the diffusion rate of virgin binder into RAP binder. The study found that the chemical composition of virgin binder and temperature had an effect on the diffusion rate and that only limited blending occurred between RAP and virgin binders at temperatures below 100°C.

Figure 8 Preparation of RAP and Virgin Binder Wafer Samples for Contact Blending Analysis (Yousef Rad et al., 2014)

Nazzal et al. (2017) developed a laboratory sample-preparation procedure for simulating the blending between RAP/RAS and virgin binders in recycled asphalt mixes. As shown in Figure 9, the procedure required casting a thin film of recycled and virgin binders at the edge of a microscopic slide separately. Each slide was heated on a hot plate at 154°C for 30 seconds and then placed next to each other. The assembly of the two slides on top of a hot plate allowed the RAP/RAS and virgin binders to create a thin film of blended binder with a diffused interfacial zone in the middle of the two slides. Atomic Force Microscopy (AFM) tapping mode imaging and force spectroscopy experiments were then conducted to characterize the micro-structure and viscoelastic domains of the interfacial zone between the RAP/RAS and virgin binders. The phase images were processed to evaluate the blending between the two binders. The study found that the degree of blending in the interfacial zone varied for different combinations of RAP and virgin binders and that very limited to no blending occurred between RAS and virgin binders.

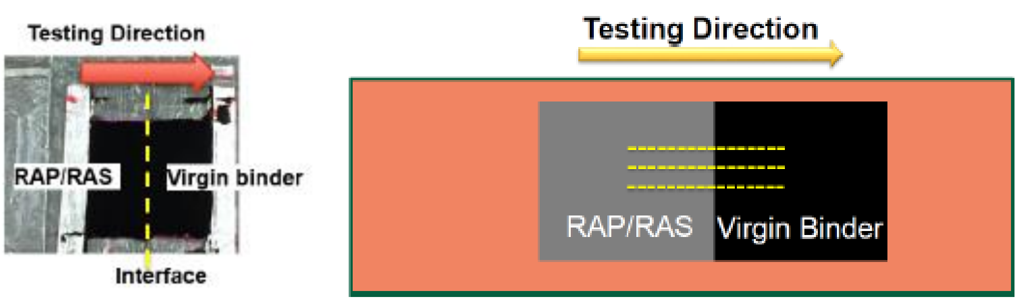


Figure 9 Proposed Sample-Preparation Procedure for Simualting the Blending between RAP/RAS and Virgin Binders (Nazzal et al., 2017)

1.1.9 State Agency Practice

A few state highway agencies have made changes to their asphalt mix design specifications to address the partial blending between RAP/RAS and virgin binders in recycled asphalt mixes. Typically, a discount factor is used to reduce the amount of "active" recycled binders in RAP and RAS. For example, the Georgia Department of Transportation (DOT) and South Carolina DOT require a discount factor of 60% and 75%, respectively, for both RAP and RAS asphalt binders. Additionally, Illinois DOT and Iowa DOT specify a discount factor of 85% and 67%, respectively, for RAS asphalt binders.

1.2 Cold Weather State Specifications and Practices for Use of Recycled Materials

This section describes several cold weather states' specifications on use of recycled materials in HMA mixes. Table 2 provides a list of promising policies and practices that have been implemented by these agencies for improving the performance of asphalt mixes containing RAP and RAS materials.

Table 2 List of Promising Agency Policy and Practice for Improving the Performance of RAP and RAS Asphalt Mixes

Agency Policy and Practice	Implementation by WisDOT?	Implementation by Other States?
Adjust or bump the virgin binder grade	Yes	IA, IL, MI, MO, MN, VA
Specify a maximum allowable RAS percent or RAS binder replacement	Yes	IA, IL, IN, MN, NE, OH, VA
Regress design air voids to increase total asphalt binder content	Yes	MI
Require a discount factor for asphalt binder contents in RAP and RAS	No	IA, IL
Require a minimum virgin asphalt binder content	No	OH
Require mixture performance testing	No	IA, IL, MN, MO, VA
Use asphalt rejuvenators	Yes	MO, VA

Wisconsin. Wisconsin DOT allows the use of RAP, fractionated RAP, and RAS in HMA mixes. Table 3 summarizes the maximum allowable percent binder replacement from RAP and RAS, where binder replacement is defined as the percentage of recycled asphalt binders from RAP and RAS by weight of the total asphalt binder in the mix (Equation 2). As shown in Table 3, more recycled materials are permitted in lower layer mixes than upper layer mixes. For mix design, if the amount of recycled materials is below the maximum limits in Table 3, no change in the virgin binder grade is needed; otherwise, the contractor is required to provide test results indicating that the resultant binder meets the performance grade originally specified for the project (in this case, rejuvenators can be used as an asphalt binder modifier). For production, the contractor is required to use the asphalt binder content corresponding to 3.0 regressed air voids at the design gyration instead of the JMF binder content corresponding to 4.0 design air voids. This practice is often referred as to the regressed air voids approach.

$$\text{Binder Replacement, \%} = \frac{(RAP\% * AC_{RAP}) + (RAS\% * AC_{RAS})}{TAC} \qquad \text{(Equation 2)}$$

Where,

$RAP\%$ = percent of RAP by weight of the mix;
AC_{RAP} = asphalt binder content in RAP;
$RAS\%$ = percent of RAS by weight of the mix;
AC_{RAS} = asphalt binder content in RAS; and

TAC = total asphalt binder content.

Table 3 WisDOT Maximum Allowable RAP and RAS Binder Replacement Limits

Recycled Asphaltic Material	Lower Layers	Upper Layer
RAS if used alone	25	20
RAP and FRAP in any combination	40	25
RAS, RAP, and FRAP in combination [1]	35	25
[1] When used in combination the RAS component cannot exceed 5 percent of the total weight of the aggregate blend.		

Illinois. Illinois DOT allows the use of RAP, pre-consumer RAS, and post-consumer RAS in HMA mixes. Table 4 shows the maximum allowable binder replacement from RAP and RAS (Equation 2). Binder course mixes and leveling course mixes allow the highest amount of recycled materials, followed by surface coarse mixes and then polymer modified mixes, respectively. When RAP or RAS is used alone, the maximum allowable binder replacement limits in Table 4 are reduced by 10 percent. No more than 5 percent RAS by weight of the mix is allowed when RAS is used alone or in combination of RAP. For all Superpave mixes, when the binder replacement exceeds 15%, the virgin binder grade is adjusted by lowering both the high-temperature and low-temperature grades by 6°C. For mix design, only 85 percent of the asphalt binder from RAS is assumed "active" and can be considered in the total asphalt binder content (i.e., FRAS = 0.85). In addition to volumetric requirements, mixture performance testing using the Hamburg Wheel Track Test (HWTT) and the Illinois Flexibility Index Test (I-FIT) are required for asphalt mix design and production.

Table 4 Illinois DOT Maximum Allowable RAP and RAS Binder Replacement Limits

HMA Mixtures/ N_{design}	Binder/Leveling Binder	Surface	Polymer Modified
30L	50	40	30
50	40	35	30
70	40	30	30
90	40	30	30
4.75mm N-50	-	-	40
SMA N-80	-	-	30

Indiana. Indiana DOT allows the use of RAP, pre-consumer RAS, and post-consumer RAS in HMA mixes. The maximum allowable binder replacement, as defined in Equation 2, is 25 percent for all surface, intermediate, and base course mixes. No more than 3 percent RAS by the weight of the mix is allowed. In addition, the RAS binder replacement cannot exceed 15 percent of the total asphalt binder content in the mix.

Iowa. Iowa DOT allows the use of RAP, pre-consumer RAS, and post-consumer RAS in HMA mixes. Table 5 presents the maximum allowable RAP percent limits, which vary as a function of mix designation, aggregate quality, and RAP classification. The maximum allowable RAS content is 5 percent by weight of total aggregate and is considered part of the maximum allowable RAP percentage. For mix design, only 67 percent of the asphalt binder from RAS is assumed "active" and can be considered in the total asphalt binder content (i.e., FRAS = 0.67). Grade bumping is required to select the grade of the virgin binder.

Table 5 Iowa DOT Maximum Allowable RAP Percent Limits

Mix Designation	Aggregate Quality Type	Unclassified RAP	Classified RAP
HMA ST S	A	0%	Limited by binder replacement
HMA ST I	B	10%	No limit
HMA ST B	B	10%	No limit
HMA HT S	A	0%	Limited by binder replacement
HMA HT I	A	0%	No limit
HMA HT B	B	10%	No limit
HMA VT S	A	0%	Limited by binder replacement
HMA VT I	A	0%	No limit
HMA VT B	B	10%	No limit

For mixes containing RAP only, when RAP binder replacement exceeds 20 percent of the total asphalt binder content, the virgin binder grade is adjusted by lowering both the high and low temperature PG grade by 6°C while maintaining the AASHTO M332 traffic designating letter. When RAP binder replacement exceeds 30 percent, the binder grade is selected based on the mix fracture energy results from the Disk-Shaped Compact Tension Test (DCT). The resultant mix is required to meet the following minimum DCT fracture energy criteria: 690 J/m^2 for Very High Traffic (VT) designation, 460 J/m^2 for High Traffic (HT) designation, and 400 J/m^2 for Standard Traffic (ST) designation.

For mixes containing both RAP and RAS, when the binder replacement is between 15 and 25 percent of the total asphalt binder content, the virgin binder grade is adjusted by lowering both the high and low temperature PG grade by 6°C while maintaining the AASHTO M332 traffic designating letter. When the RAP and RAS binder replacement exceeds 25 percent, the virgin binder grade is selected with the requirement of passing the above-mentioned DCT fracture energy criteria.

Michigan. Michigan DOT allows the use of RAP, pre-consumer RAS, and post-consumer RAS in HMA mixes. When Superpave High Stress mixes are used as leveling or surface course, up to 27 percent RAP or RAP and RAS binders by weight of the total asphalt binder is allowed. For mix design, if the RAP and RAS binder replacement is less than 17 percent of the total asphalt binder content, no adjustment to the virgin binder grade is required. Alternatively, the virgin binder grade can be selected using a blending chart according to AASHTO M 323. If RAP is used alone and the RAP binder replacement is between 18 and 27 percent, the virgin binder grade is adjusted by lowering the low temperature grade by 6°C or can be selected using a blending chart. If RAP and RAS are used in combination and the combined binder replacement is between 18 and 27 percent, the virgin binder grade is selected using a blending chart. If the RAP and RAS binder replacement exceeds 27 percent, the use of a blending chart is required to select the virgin binder grade. For production, the total asphalt binder content is increased to achieve a 3.0% regressed air voids at the design number of gyrations.

Minnesota. Minnesota DOT allows the use of RAP and RAS in HMA mixes. Table 6 presents the maximum allowable binder replacement from RAP and RAS. For wearing and non-wearing course mixes containing a PG 58(S, H, V, E)-34 virgin binder, up to 20 percent RAP and RAS binder replacement is allowed. For mixes containing a PG 58(S, H, V, E)-28, PG 52-34S, PG 49-34, or

PG 64S-22 virgin binder, the maximum recycled binder replacement is 30 percent or 35 percent. Alternatively, a blending chart can be used to select the virgin binder grade and verify compliance with the specified binder grade. For design of wearing course mixes, DCT testing is required in addition to volumetric analysis; the minimum DCT fracture requirement for wearing course mixes with a traffic level designation of 2-3 and 4-5 is 450 J/m^2 and 500 J/m^2, respectively.

Table 6 Minnesota DOT Maximum Allowable RAP and RAS Binder Replacement Limits

Specified Asphalt Grade	Recycled Material		
	RAS Only	RAS + RAP	RAP Only
PG 58X[1]-28, 52S-34, 49-34, 64S-22 (Wear)	30	30	30
PG 58X[1]-28, 52S-34, 49-34, 64S-22 (Non-Wear)	30	30	35
PG 58X[1]-34(Wear & Non-Wear)	20	20	20

[1]X=S, H, V, E

Missouri. Missouri DOT allows the use of RAP, pre-consumer RAS, and post-consumer RAS in HMA mixes. When RAP is used alone, mixes with more than 30 percent virgin effective binder replacement from RAP are acceptable provided that the resultant binder meets the binder performance grade specified in the contract. When RAP and RAS are used in combination and the effective virgin binder replacement does not exceed 30 percent, no change in the virgin binder grade (i.e., PG 64-22) is needed. When the effective virgin binder replacement exceeds 30 percent but is below 40 percent, the PG 64-22 virgin binder needs to be replaced with a softer PG 58-28 or PG 52-28 binder or to be modified with a rejuvenator provided that the resultant binder meets a PG 58-28 binder requirement. Missouri DOT currently requires DCT testing for the evaluation of thermal cracking resistance of asphalt mixes containing RAP and RAS.

Nebraska. Nebraska DOT allows the use of RAP, pre-consumer RAS, and post-consumer RAS in HMA mixes. Table 7 presents the minimum and maximum allowable RAP contents for different mix types. The maximum allowable RAS content is 5 percent for mainline mixes and 10 percent for shoulder mixes. In addition, the maximum binder replacement from pre-consumer RAS and post-consumer RAS is 60 percent and 35 percent, respectively, regardless of RAP content.

Table 7 Nebraska DOT Minimum and Maximum Allowable RAP Contents

Asphaltic Concrete Type	Minimum RAP Content	Maximum RAP Content
SPS	0	65
SPR	0	55
SPH	0	35
SLX	20	35
SRM	35	65

Ohio. Ohio DOT allows the use of RAP, pre-consumer RAS, and post-consumer RAS in HMA mixes. The maximum allowable RAP percent by weight of the mix varies from 10 percent for polymer surface course mixes to 55 percent for base coarse mixes, as shown in Table 8. When RAS is used alone, no more than 5 percent RAS by weight of the mix is permitted. When RAP and RAS are used in combination, no more than 3 percent RAS is allowed. The asphalt binder content of RAS (i.e., AC_{RAS}) is assumed to be 18.0 percent for mix design. Surface course mixes require a PG 70-22 virgin binder while intermediate or base courses allow the use of PG 58-28 and PG 64-28 virgin binders, depending upon the RAP and RAS percent used. For a mix design containing 26 to 30 percent RAP, the contractor may use a blending chart to determine the grade of virgin binder to use. Ohio DOT has a requirement on the minimum virgin binder content for mixes for different applications (Table 8).

Table 8 Ohio DOT Maximum Allowable RAP and RAS Limits

Method 1 – Standard RAP/RAS Limits				
Asphalt Mix Application	**% RAP by Weight of Mix, Max.**	**RAS Usage (no more than 5% by weight of mix)**	**Total Virgin Asphalt Binder Content, Min.**	**Comments**
442 Polymer Surface Course	10%	None	5.2	Polymerized binder is virgin (for non-polymer virgin binder allow 20% max RAP)
441 Surface Course	20%	Manufacturing waste only	5.0	Polymer or non-polymer virgin
441, 442 Intermediate Course	35%	Manufacturing waste and tear-offs	3.0	Any mix type used as an intermediate course
301 Base Course	50%	Manufacturing waste and tear-offs	2.7	OMM will establish the asphalt binder content
302 Base Course	40% (30%)	Manufacturing waste and tear-offs	2.0	A lower RAP limit of 30 percent will be required if poor production mixing or coating is evident
Method 2 – Extended RAP/RAS Limits				
Asphalt Mix Application	**% RAP by Weight of Mix, Max.**	**RAS Usage (no more than 5% by weight of mix)**	**Total Virgin Asphalt Binder Content, Min.**	**Comments**
442 Polymer Surface Course	15%	None	5.0	Polymerized binder is virgin (for non-polymer virgin binder allow 25% max RAP)
441 Surface Course	25%	Manufacturing waste only	5.0	Polymer or non-polymer virgin
441, 442 Intermediate Course	40%	Manufacturing waste and tear-offs	3.0	Any mix type used as an intermediate course
301 Base Course	55%	Manufacturing waste and tear-offs	2.5	OMM will establish the asphalt binder content
302 Base Course	45% (35%)	Manufacturing waste and tear-offs	1.8	A lower RAP limit of 35 percent will be required if poor production mixing or coating is evident

Virginia. Virginia DOT allows the use of RAP, pre-consumer RAS, and post-consumer RAS in HMA mixes. When RAP is used alone, the maximum allowable RAP by the weight of the mix is 30 percent for surface and intermediate mixes, and 35 percent for base mixes. When RAS in used, no more than 5 percent RAS by the weight of the mix is allowed. In addition, the binder replacement from RAP and RAS (Equation 2) cannot exceed 30 percent. Table 9 presents the recommended virgin binder grade for mixes with different RAP percentages. For mixes with RAS, a PG 64S-22 virgin binder is required to meet a PG 64H-16 requirement of the resultant binder. Virgin DOT recently implemented the balanced mix design approach, which requires mixture performing testing using the Asphalt Pavement Analyzer (APA), Indirect Tensile Asphalt Cracking Test (IDEAL-CT), and Cantabro test. The use of rejuvenators is allowed in recycled asphalt mixes designed with the balanced mix design approach.

Table 9 Recommended Virgin Asphalt Binder for Mixes with Different RAP Percentages in Virginia

Mix Type	% RAP ≤ 25%	25% < % RAP ≤ 30%	% RAP > 35%
SM-4.75A, SM-9.0A, SM-9.5A, SM-12.5A	PG 64S-22	PG 64S-22	
SM-4.75D, SM-9.0D, SM-9.5D, SM-12.5D	PG 64H-22	PG 64S-22	
IM-19.0A	PG 64S-22	PG 64S-22	
IM-19.0D	PG 64H-22	PG 64S-22	
BM-25.0A	PG 64S-22		PG 64S-22
BM-25.0D	PG 64H-22		PG 64S-22

1.3 Practices to Increase Recycled Materials Content

1.3.1 Recycling Agents

1.3.1.1 Types and Properties

Over the last decade, asphalt researchers and practitioners have explored the incorporation of petroleum and bio-based recycling agents (RAs) to help mitigate the stiffening effect of RAP and RAS materials through uniform dispersion within the mix and diffusion into heavily aged recycled binders. RAs have been defined as organic materials with chemical and physical characteristics selected to restore the properties of aged asphalt in order to target specification limits (Asphalt Institute, 1986). For optimal restoration of the aged asphalt binder properties, consideration should be given not only to the viscosity-reducing capacity of the RA, but also to its chemical composition. Furthermore, the degree of diffusion of the RA into the aged binder is of the utmost importance, since it will allow changes in the intermolecular agglomeration and self-assembly of the asphalt polar micelles, affecting the overall performance properties of the recycled asphalt mixes.

Although different types of categorization may be employed for RAs based on the material source or manufacturing process, it is also important to differentiate among RAs based on the asphalt chemical fraction with the most affinity with the RA.

Asphalt binder is a complex mixture of high molecular weight hydrocarbon molecules, naturally occurring heteroatoms (nitrogen, oxygen, and sulfur) and trace metals (e.g., vanadium and nickel) that contribute to the polarity within the asphalt molecules. Therefore, asphalts are a continuum of molecules with a gradual transition in polarity, molecular weight, and functionality. The composition of asphalt binder is usually defined in terms of the relative quantity of its so-called SARA fractions: saturates (S), aromatics (A), resins (R), and asphaltenes (A), which have increasing molecular polarity as listed (saturates have the lowest and asphaltenes the highest) (Corbett, 1969). Often, asphalt is described as a colloid that consists of dispersion of asphaltenes in an oily matrix constituted by saturates, aromatics, and resins. It has been established that asphaltenes are stabilized in crude oils by natural resins that are surfactant-like agents.

RAs that are most compatible with the aromatics (i.e., low-polarity naphthenic aromatic fraction) of the asphalt binder will reduce the viscosity and modulus of the binder through lowering the viscosity of the continuous solvent phase. These RAs have small effect on the intermolecular agglomeration and self-assembly of the asphalt polar micelles. RAs that show affinity for multiple fractions of the asphalt binder and are produced through careful engineering of the source material, whether petroleum or bio-based, will reduce the viscosity of the binder through restoration of the original binder asphaltenes to maltenes ratio (i.e., the asphalt chemical fractions). RAs that exhibit low compatibility with the aromatics, asphaltenes and resins fractions of the asphalt binder, especially at low temperatures, have in their composition paraffinic and saturated material with high crystalline fractions. The dispersion of such lower viscosity additives in the asphalt will reduce the modulus of the binder. However, the effectiveness of these RAs was found to diminish with aging since these additives can lead to colloidal instability resulting in the precipitation of the asphaltenes fraction (Johnson and Hesp, 2014).

Table 10 presents examples of recycling agent products that are commercially available in the United States.

Table 10 Example of RA Products Commercially Available in the United States

Category	RAs Commercially Available	Description
Aromatic Oils	Hydrolene® ValAro 130A®	Prepared from aromatic crude oil. Aromatic hydrocarbons are cyclic and derivatives of benzene (rings are characterized by alternating double bonds).
Naphthenic Oils	Cyclogen L® HyPrene BO150® Reclamite®	Prepared from naphthenic crude oil. Naphthene hydrocarbons are ringed molecules and are also called cycloparaffins.
Paraffinic Oils	Valero VP 165® Waste Engine Oil (WEO) Waste Engine Oil Bottoms (WEOB)	Prepared by solvent separation techniques from paraffinic crude oil. Paraffin hydrocarbons are characterized by open or straight chains joined by single bonds.
Either Naphthenic or Paraffinic Oils	Re-refined Engine Oil Bottoms (REOB)/Vacuum Tower Asphalt Extender (VTAE)	Residual distillation product from a vacuum tower in a re-refinery of used lubricating oil. Prepared from either naphthenic or paraffinic crude oil.
Tall Oils	Sylvaroad™	By-product of the Kraft process of wood pulp manufacture when pulping mainly coniferous trees.
Fatty Acids	Anova® Delta S® Modified Vegetable Oils Recycled Vegetable Oils	Derived from bio-based sources.

1.3.1.2 Effect of RAs on Mixes with High Recycled Materials

Concerns exist with respect to the addition of RA to binders as it relates to both high and low temperature performance. For example, the softening effect of these additives can detrimentally affect the high temperature rutting resistance of the resultant asphalt binders and mixes. Furthermore, the effectiveness of rejuvenators at low temperatures was found to diminish with extended aging conditioning (Bahia et al., 2018). This raises the question whether these agents can improve the long-term durability and cracking performance of asphalt mixes with RAP and RAS. Thus, it is crucial to take into consideration the effect of oxidative aging while investigating how RAs affect the aged asphalt binders and what performance characteristics these recycled materials exhibit. Furthermore, it is necessary to develop a method to evaluate these parameters, so they can be controlled to produce asphalt mixes containing RAP/RAS with satisfactory performance.

Over the years, researchers have investigated the effect of various RAs on the performance of asphalt mixes with high RAP and/or RAS contents. Key findings from these studies are presented in Table 11.

Table 11 Effect of RAs on the Performance of Asphalt Mixes with High RAP and/or RAS Content

Research Finding		References
Pros	RAs can soften the aged asphalt binders and reduce the stiffness of asphalt mixes containing RAP/RAS.	Mallick et al., 2010; O'Sullivan, 2011; Hajj et al., 2013; Im and Zhou, 2014; Bonicelli et al., 2017.
	RAs may increase the cracking resistance of asphalt mixes containing RAP/RAS.	Mallick et al., 2010; Tran et al., 2012; Hajj et al., 2013; Im and Zhou, 2014; Zhou et al., 2015.
	RAs may decrease the moisture susceptibility of asphalt mixes containing RAP/RAS.	Hajj et al., 2013; Im and Zhou, 2014.
Cons	RAs may decrease the resistance to permanent deformation of asphalt mixes containing RAP/RAS.	Tran et al., 2012; Zhou et al., 2015.
	RAs can increase the aging susceptibility of asphalt mixes.	Mogawer et al., 2015.

1.3.2 Polymer Modification

1.3.2.1 Modification of Asphalt Binder

Modification is often used to make asphalt grades that are not produced through straight distillation of crude oil. While there are several methods for modifying asphalt binders, polymer modification is the most common. Polymers can be divided into four groups: plastomers (i.e., thermoplastics and thermosets), elastomers (i.e., natural and synthetic rubber), fibers, and additives/coatings. Many polymers can be used to make polymer modified asphalt (PMA) binders, but only a few can provide specified performance at a competitive cost. A brief description of each commonly used asphalt modifier follows.

Thermosetting polymers [e.g., epoxy resin and polyurethane (PU)] are produced by blending two components, one containing a resin and the other a curing agent, that react chemically to form a strong three-dimensional structure. The prefix "thermo" implies that the cross-linking proceeds through the influence of heat energy input, and "setting" indicates that an irreversible reaction occurs on a macro scale (Peng and Riedl, 1995). When thermosetting polymers are fully blended with asphalt binder, the resultant modified binder behaves more like a modified thermosetting polymer rather than a viscoelastic asphalt (Dinnen, 1991). Compared to asphalt binders containing thermoplastic elastomers, asphalt binders containing thermosetting polymers have better thermal stability, rigidity, resistance to deformation, and resistance to oxidative aging and embrittlement. Over the last few years, epoxy asphalt binder has been successfully used in open-graded friction course (OGFC) mixes in New Zealand and the Netherlands (Herrington et al., 2007; Henrrington et al., 2010; Wu et al., 2017; Zegard et al., 2019). Also, a special mixture that uses polyurethane to replace asphalt binder (i.e., porous polyurethane mixture) has been used as a functional surface layer in porous pavements to reduce tire-pavement noise in OGFC (Amundsen and Klaeboe, 2005; Goubert, 2014).

Thermoplastics plastomers [e.g., polyurethane (PU), polyethylene (PE), polypropylene (PP), polystyrene (PS), ethylene-vinyl acetate (EVA), ethylene-butyl acrylate (EBA)] have high early strength under deformation, but they are not as flexible as elastomers and tend to fracture under large strains. In addition, plastomers deform more slowly than elastomers under an equivalent load. When blended with asphalt, plastomers confer a high rigidity to the binder and significantly reduce rutting. Plastomers also increase the viscosity of the asphalt (Read and Whiteoak, 2003).

Elastomers [e.g., natural polyisoprene (NR for natural rubber), synthetic polyisoprene (IR for isoprene rubber), and Styrene-Butadiene Rubber (SBR)] provide increased tensile strength with elongation and have the ability to recover to the initial condition after the applied load is removed. When mixed with asphalt at an appropriate dosage, these polymers can confer their elastic properties to the modified binder, enhancing its elastic recovery capacity and resistance to permanent deformation. Furthermore, elastomeric modification improves the low-temperature cracking resistance of asphalt binders (Lu and Isacsson, 2000; Airey, 2003). When considering a reactive category of elastomers, the DuPont™ Elvaloy® reactive elastomeric terpolymer (RET) is known for creating permanent binder property improvement through chemically interlocking with the asphalt binder at a molecular level.

Thermoplastics elastomers, sometimes referred to as thermoplastic rubbers, are a class of copolymers or a physical mix of polymers (usually a plastic and a rubber) that consist of materials with both thermoplastic and elastomeric properties. Within this group, styrenic block copolymers such as styrene-butadiene-styrene (SBS) have shown the greatest potential when blended with asphalt binder (Airey, 2003).

Poly-Phosphoric Acid (PPA) is a binder modifier used for improving both high and low temperature performance. It has been used in the U.S. since the early 1970s, and can act as a deflocculant of the asphaltenes fraction (prevent asphaltene association) due to neutralization of polar groups, either by acid/base neutralization or by esterification (Edwards et al., 2006). PPA has been used as a modifier alone or in combination with polymers. The intention of adding PPA to PMA is to reduce the polymer content leading to improved processing condition, high-temperature viscosity, and storage stability.

Although modification of asphalt has been improved over the years, there are still concerns that can limit its future applications, such as high costs, low aging resistance, and poor storage stability. For a modifier to be effective, it must: (1) blend homogeneously with asphalt using conventional equipment; (2) maintain its properties during storage, production at a high temperature (168-180ºC), and in service; and (3) improve resistance to flow at high pavement temperatures without making the asphalt too viscous at mixing and placement temperatures or too stiff or brittle at low pavement temperatures (Bahia, 1995; Read and Whiteoak, 2003).

1.3.2.2 Effect of Polymers on Mixes with High Recycled Materials

For many years, polymers have been incorporated into asphalt binders as a way to mitigate asphalt pavement distress such as rutting, fatigue cracking, and thermal cracking (Bahia et al., 2001; Von Quintus et al., 2001). Several researchers have reported the improvements in performance of mixtures produced with polymer modified binders. Bahia et al. (2001) evaluated the effect of modified asphalts on the rutting and cracking behavior of mixtures using the Simple Shear Test (SST) device and the Bending Beam Fatigue device. For the PMA mixtures, the authors reported an increase in the resistance to permanent deformation. Furthermore, the authors found that the fatigue life of mixtures produced with elastomeric modified binder was significantly longer than other types of binders used in this study. The WHRP project 14-06 evaluated three levels of polymer modification and found a consistent improvement in mixture cracking resistance in the I-FIT test with increasing percent recovery as measured in the MSCR test (Bonaquist, 2016). A similar finding was also reported for the indirect tensile asphalt cracking test (IDEAL-CT) results by Zhou et al. (2017).

When considering the combination of polymers and RAs, it has been established that the addition of polymers can contribute to balance the softening effect of RAs, therefore improving the durability of asphalt mixes with high RAP/RAS content. Bonicelli et al. (2017) showed that the rutting potential of asphalt mixes containing plastomeric polymer, with and without the addition of RAs, was dramatically reduced in comparison with the control mix produced without additives (i.e., polymer and RA). In addition, the authors observed that mixes that did not contain polymer showed the lowest resistance to permanent deformations; in particular, the mix containing only RA showed the highest susceptibility to rutting.

Over the years, many field test sections were constructed with mixtures produced with polymer modified asphalt binders and their performance has been evaluated. These studies are summarized in Table 12.

Table 12 Field performance evaluation of PMA mixtures (West et al., 2018)

Location	Polymer Used	In-Service Age	Findings
USA (32 sites)	LDPE, SBR and SB block copolymers	> 5 years	The test sections with PMA mixtures evaluated in this study were found to have lower amounts of fatigue cracking, transverse cracking, and rutting.
Canada (7 sites)	SBS, SB and RET	8 years	Asphalt modified with RET and PPA performed as desired, without cracking after 8 years of service. One of the two SBS sections cracked at a moderate amount, with intermittent full width transverse cracks of moderate severity. The remaining sections all experienced severe and excessive distress, with numerous longitudinal and transverse cracks.
USA (1 site)	LDPE, SBR and SB block copolymers	11 years	Use of PMA improved the field cracking resistance over the unmodified asphalt. However, LDPE increased the brittleness of the asphalt and mixture, leading to extensive cracking.

1.3.3 Use of Softer Binders

The typical approach to incorporate RAP and RAS into asphalt mixes has been to use a normal PG grade virgin binder in conjunction with the recycled binder. This has proven effective in instances where a relatively low amount of binder replacement (less than 25%) has been the target (Newcomb, 2016). However, at higher amounts of RAP and especially with RAS, several state highway agencies have recommended the use of softer virgin binders to mitigate the stiffening effect of aged binders in RAM. AASHTO M 323 also recommends grade bumping by reducing 6°C and the use of blending charts to adjust the binder grade for mixes with a RAP content between 15 and 25 percent and over 25 percent, respectively. However, conflicting results have been reported regarding the effectiveness of this practice (Behnia et al., 2010; Mogawer et al., 2012; Epps Martin et al., 2018).

McDaniel et al. (2012) evaluated several recycled asphalt mixes from a number of Midwestern contractors and found that mixture produced with 40% RAP, and without having a change in the virgin binder grade, showed an increase of 6°C in the critical cracking temperature in comparison with the control mixture. The authors concluded that there is a need for a binder grade change for RAP contents greater than 25%. Similar results are reported by Hajj et al. (2012), since the authors observed that the low critical temperatures of the binders recovered from 50% RAP mixtures were 7°C to 8°C warmer than those recovered from a virgin mixture (i.e., 0% RAP).

Daniel et al. (2010) evaluated asphalt binders extracted and recovered from 28 field produced mixes containing up to 25% RAP. The results of this study are based on testing the fully blended extracted binders, and are listed as follows: high-temperature PG remained the same or increased only one grade for the various RAP percentages; and the low-temperature PGs remained the same or increased only one grade from the virgin mixture. Willis et al. (2012) examined binders in RAP mixes with up to 50% RAP content and tested the blends using the DSR. The authors concluded that the use of a softer base binder was the best approach to improve the fatigue behavior of the recycled binder blend. On the other hand, Hajj at al. (2012) reported different a different trend. The authors evaluated two types of mixtures: one with no grade change in asphalt binder (PG 58-28) from mixtures with lower RAP content and one with a grade change in asphalt binder (PG 52-34). The authors observed that the recovered binders from the mixtures containing 0% and 15% RAP met the target grade of PG 58-28 for the project location. However, the recovered binders from the mixtures with 50% RAP met or exceeded the target high performance grade of 58°C but failed to meet the target low performance grade of -28°C. This observation was true for both mixtures with and without grade change. Furthermore, the authors concluded that the use of softer asphalt binder (i.e., PG 52-34) with the 50% RAP mixture did not improve the low performance temperature of the blended asphalt binder in the mixture enough to meet the target low performance grade.

In addition to binder grade, binder source also plays a significant role in the performance of recycled binders and mixes. NCHRP project 09-58 evaluated two PG 64-28 virgin binders from different sources in a field project in Texas; one binder was S-controlled and had a positive delta T_c, while the other binder was m-controlled with a negative delta T_c (Epps Martin et al., 2018). The recycled binder blends with the S-controlled binder exhibited significantly better rheological properties and aging resistance than those with the m-controlled binder. Thus, the binder chemistry plays an important role when producing asphalt mixes with high RAM contents.

1.3.4 Increasing Effective Asphalt Binder Content

It is widely accepted by the asphalt pavement industry that an increase in the effective asphalt binder content improves the durability and cracking resistance of a mix. This practice is also valid for asphalt mixes with RAP and RAS materials. There are two ways to achieve a higher effective asphalt binder content during mix design: (1) increasing voids in the mineral aggregate (VMA) and (2) decreasing design air voids. VMA refers to the volume of intergranular space between aggregate particles in a compacted mix. For a given design air void content, a higher VMA will yield a higher asphalt binder content. As shown in Table 13, a survey of state highway agencies that was conducted as part of the NCHRP project 20-07/Task 412 identified 19 state highway agencies that have increased minimum VMA to obtain higher asphalt contents (Tran et al., 2018). For a given design gyration level, VMA is influenced by changing the aggregate blend. As a rule of thumb, a one percent increase in VMA will generally increase design asphalt content by 0.44 percent. The key to achieving this increase in asphalt content is to ensure the correct aggregate specific gravity (G_{sb}) is used in the design. Any increase in asphalt binder content from increased VMA can be reduced or eliminated if G_{sb} of the aggregate is inaccurately increased. The Federal Highway Administration (FHWA) recommends increasing the minimum VMA limits by 0.5% for each nominal maximum aggregate size (NMAS) level to increase the binder content assuming the aggregate structure is sufficient for the traffic conditions (FHWA, 2010). The mix design manual developed in NCHRP Project 9-33 recommends increasing the design VMA by 1.0 percent to produce mixes with improved durability (AAT, 2011). Increasing the design VMA by 1.0% while keeping the design air voids at 4.0% percent increases the volume of effective asphalt binder by 1.0% (approximately 0.4% by weight).

Lowering design air voids can also increase the asphalt binder content in the mix. This approach typically reduces the design air void target to 3.0% or 3.5% rather than 4.0% as required in AASHTO M 323 (Nicholls et al, 2008). As shown in

Table 14, eight state highway agencies were identified in the NCHRP project 20-07/Task 412 survey that have lowered design air voids to obtain higher asphalt contents (Tran et al., 2018).

However, some of the agencies reported that after the change was made, asphalt contents initially increased but after one or two years, generally decreased and returned to earlier levels. For these cases, VMA, or more specifically, the aggregate bulk specific gravity, was not being tightly controlled, and the aggregate bulk specific gravity values reported would slowly increase over time. Using inaccurately higher G_{sb} values will result in higher calculated VMA values and allow a reduction in asphalt content. Thus, the accuracy of G_{sb} is crucial to maintaining asphalt content.

Table 13 List of State Highway Agencies that Have Increased Minimum VMA Requirements (Tran et al., 2018)

NMAS	Minimum VMA			
	19 mm	12.5 mm	9.5 mm	4.75 mm
AASHTO M 323	13	14	15	16
AL	13.5	14.5	15.5	16.5
CA	13.5	14.5	15.5	16.5
DE	13.5	14.5	15.5	16.5
GA	14	15	16	N/A
IL	13.5	N/A	15	18.5
MA	14	15	16	17
MD	13	14	15	16
ME	14	15	16	16
MT	13	14.5	15.5	N/A
NC	13.5	N/A	15.5	16
PA	13.5	14.5	15.5	16
RI	14.5	15.5	16.5	17.5
SC	13.5	14.5	15.5	17.5
SD	N/A	14.5	N/A	N/A
UT	13	14	15	N/A
VA	13	15	16	16.5
VT	14.5	15.5	16.5	17.5
WI	13	14/14.5	15/15.5	16
WV	13.5	14.5	15.5	16.5

Table 14 List of State Highway Agencies that Have Lowered Design Air Voids (Tran et al., 2018)

State	Target Design Air Voids
KS	3.0%
MO	3.5% to 4.0%
NE	3.5%
NY	3.5%
PA	3.5 to 4.0%
SC	3.0 to 4.0%
UT	3.5%
VA	2.5% (binder mix), 3.5% (polymer mix), 4.0% (surface mix and intermediate mix)

2 CHARACTERIZING BLENDED BINDERS FOR RECYCLED MIXTURES

2.1 Extraction Issues

Testing the asphalt binder in the recycled mix requires that the binder be recovered, tested, and compared with specification requirements. There are two ways that the total blended asphalt binder can be tested in the laboratory: (1) The asphalt can be recovered from the RAP/RAS and blended with the new asphalt to be added to the binder; or (2) the RAP/RAS can be blended with the new aggregate and asphalt, and then extracted and recovered for testing. The main issue with testing binders that have been extracted and recovered is the assumption that the binder properties reflect the behavior of a completely blended binder rather than the virgin and replacement binders acting in different phases within the mix (Newcomb, 2016).

For the performance evaluation, the asphaltic materials can be extracted according to AASHTO T 164 or T 176 and recovered by means of AASHTO T 170 or ASTM D5404 (Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator), or by using the combined extraction and recovery process described in AASHTO TP 2. The choice of procedure and solvent can have an impact on the resulting physical properties of the recovered asphalt binder.

Several solvents have been used to extract asphalt binder from the asphalt mix. One of the first solvents that was widely used was carbon disulfide, until it was replaced by benzene due to its high volatility and flammability. Trichloroethylene (TCE), 1,1,1-tricloroethane, and methylene chloride were also found to be as effective as benzene in extracting asphalts from mixes. At a later time, the use of benzene was suspended when it was proven to be carcinogenic, and TCE was adopted as a replacement (Burr et al., 1990). In more recent years, toluene and n-propyl bromide (nPB) have been used for asphalt binder extraction.

Some of the existing problems related to the binder extraction process are related to the type of solvent used. For example, if the extraction is not properly performed, a significant amount of solvent can remain in the recovered binder and will affect the measured properties of the extracted asphaltic material. Also, a reaction between the asphalt binder and the solvent selected for the extraction could happen, altering the properties of the binder.

Studies have shown that binders recovered from asphalt mixes produced with binders containing PPA exhibited a decrease in binder stiffness relative to the PG grade of the binder originally selected for the project (Asphalt Magazine, 2009). Commercial suppliers of TCE and nPB usually add an acid scavenger (typically 1,2 epoxy butane) to stabilize their solvents. This acid scavenger can impact the recovered properties of asphalt binders modified with PPA by artificially softening the binder during the recovery process. Thus, for the extraction and recovery of binder from mixes where PPA may be present, it is imperative that a solvent which does not contain an acid scavenger be used.

Regarding the effect of the extraction and recovery process on asphalt binders modified with polymers, it is necessary to consider the fact that polymers may adhere strongly to the aggregates. Thus, it may not be true that extracting the asphalt binder from RAM will allow the full extraction of the polymer utilized for modification. Furthermore, dissolving and then re-precipitating the PMA can cause morphological rearrangement of the polymer network, affecting the rheological behavior of the extracted modified asphalt binder. The ongoing Wisconsin Highway Research Program (WHRP) 17-06 project indicated that the solvent type can affect the percentage recovery (%R) parameter of a polymer modified asphalt binder recovered from mixes containing RAP material (Figure 1).

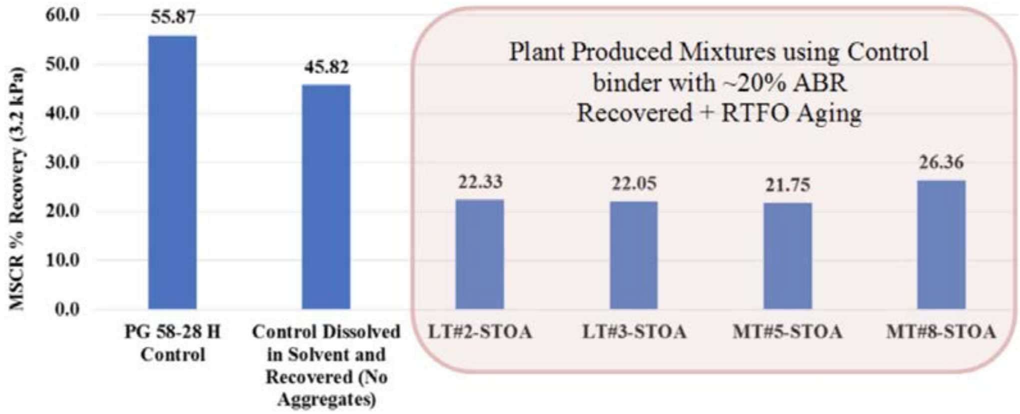


Figure 10 Effect of Solvent on MSCR %R Parameter (Bahia et al., 2018)

Physical property test results of recovered binders have much higher variability compared to unrecovered binders. Therefore, the properties of recovered asphalt binders should be analyzed with caution, particularly when comparing results from multiple labs that may use different solvents and procedures.

2.2 Rheological Testing

RAM are useful alternatives to virgin materials because they reduce the use of virgin aggregates and the amount of virgin binder required in the production of asphalt mixes. However, the hard, oxidized nature of reclaimed binder is a major concern when incorporating recycled materials into asphalt mixes since the stiff binder in the RAM can cause premature fatigue and low temperature cracking failures in asphalt pavements (McDaniel and Anderson, 2001). Therefore, the performance of asphalt mixes containing RAP and/or RAS is dependent on the properties of its constitutive components, and the level of blending between the aged and unaged binder is influenced by the chemical composition of the individual binders.

In general, the proportion of any induced strain in asphalt that is attributable to viscous flow, i.e. non-recoverable, increases with both loading time and temperature. Non-load related cracking of asphalt pavements (i.e. transverse and block cracks) is related to oxidation and hardening of the asphalt binder, which is the main concern when incorporating RAP and/or RAS material in the production of HMA.

To estimate the performance implications of RAP and/or RAS, mix designers have been using blending charts to interpolate the effects of recycled materials on blended binder properties. These charts have been proven effective for RAP materials and using standard Superpave PG test methods during the NCHRP 09-12 study. However, research performed during WHRP project 11-13 showed that the blending charts may not accurately predict blended binder properties for RAS binders, particularly at low temperature (Bonaquist, 2011). Therefore, researchers have made significant efforts to classify cracking resistance of asphalt binders using an index parameter. Table 15 presents rheological tests that have been used to identify the cracking potential of asphalt binders. The description of each test is included as follows.

Table 15 Rheological Tests Used to Identify the Cracking Potential of Asphalt Binders

Test Type	Standard	Research Parameter
Dynamic Shear Rheometer (DSR) Mastercurve	AASHTO T315	Glover-Rowe (G-R)
Linear Amplitude Sweep (LAS)	AASHTO TP101	Cycles to Failure (N_f)
Bending Beam Rheometer (BBR)	AASHTO T313	Stiffness, m-value and ΔT_c
	AASHTO TP122	Physical hardening behaviour

Kandhal et al. (1977) evaluated many Pennsylvania pavements and noted that the decrease in low-temperature ductility is an important factor as asphalt binder ages (i.e., age-induced surface damage is related to a tensile failure strain in the brittle region). Following this work and by using a mechanical-empirical relationship with observed cracking, Glover et al. (2005) suggested a parameter [G′/(η′/G′)], relating storage modulus (G') and dynamic viscosity (η′) to ductility at 15 °C and 0.005 rad/s, which serves as a surrogate for tensile strain at failure.

The AASHTO TP 101 test method "Estimating Damage Tolerance of Asphalt Binders Using the Linear Amplitude Sweep" was proposed and used in various studies to estimate fatigue cracking resistance (Hintz et al., 2011). The LAS test considers pavement structure (i.e., strain) and traffic (i.e., number of cycles to failure). In this test, the use of viscoelastic continuum damage mechanics allows for prediction of fatigue life at any strain amplitude from a single 30-minute test. The test consists of two steps: a frequency sweep and an amplitude sweep. In the first part of the LAS procedure, an initial 100 cycles is applied at small strain (0.1 %) to determine undamaged linear viscoelastic properties. The second part of the procedure consists of ramping strain amplitude, beginning at 0.1 % and ending at 30 % applied strain, over 3100 cycles of loading at 10 Hz. Once the strain sweep is applied to the sample, damage accumulation can be then determined through Viscoelastic Continuum Damage (VECD) analysis, resulting in the fatigue power law damage model (Equation 3), and the corresponding coefficients, *A* and *B*.

$$N_f = A\,(\gamma_{max})^{-B} \qquad \text{(Equation 3)}$$

N_f is the traffic volume failure criteria and defines the number of cycles to fatigue failure at a user-defined damage level. γ_{max} is the maximum tensile strain expected in the binder phase under traffic loading, which will be a function of pavement structure. *A* is the LAS power-law parameter representing the intercept at 1 % strain. *B* is the LAS power-law parameter representing the slope of the N_f-strain curve. The logarithmic slope of the storage modulus (G'(ω)) as a function of angular frequency is used to calculate the damage accumulation and the parameter *B*.

As shown in Figure 11, the LAS fatigue test procedure was validated through comparison with performance of Long-Term Pavement Performance (LTPP) test sections showing good correlation with field measurements (Hintz et al., 2011).

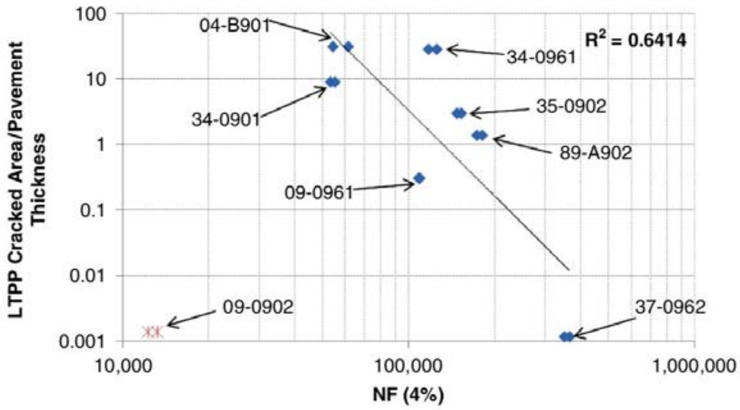


Figure 11 LTPP Measurements vs. LAS Number of Cycles to Failure (N_f) (Hintz et al., 2011)

Anderson et al. (2011) investigated the relation between ductility and binder properties to non-load associated cracking potential for airport pavements. The findings of the study identified the Glover parameter [G′/(η′/G′)], the fatigue parameter *B*, and ΔT_c as parameters to identify changes in cracking susceptibility with aging. ΔT_c is the difference between the continuous low temperature binder grade measured via the BBR creep stiffness (related to thermal stresses in an asphalt pavement due to shrinking) and m-value (related to the ability of an asphalt pavement to relieve these stresses). Reinke (2017) showed that binders with a highly negative ΔT_c have been implicated in projects with high rates of cracking. Regarding the importance of the ΔT_c parameter for RAP binders modified with polymers and recycling agents, a Pooled Fund study performed among Colorado, Idaho, Kansas, and Wisconsin (Bahia et al., 2018) showed that ΔT_c is an applicable parameter to differentiate between stiffness and relaxation properties of different modification technologies and base asphalts (Figure 12).

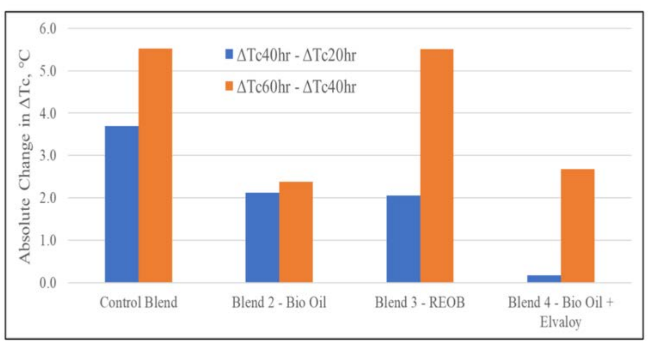


Figure 12 Absolute Change in ΔT_c for RAP Binders Modified with Polymers and RAs (Bahia et al., 2018)

Rowe (2011) proposed modifications of the Glover parameter by introducing the Glover-Rowe (G-R) parameter (Equation 4), which focuses attention on complex modulus (|G*|) and phase angle (δ) of asphalt binders at 15 °C and a frequency of 0.005 rad/s. On his proposal, Rowe ignored the frequency term and expressed the G-R parameter purely in terms of |G*| and δ, allowing users to plot the ductility-based failure planes in a Black Space diagram. It is known that asphalt binders with higher values of *G-R* experienced a higher level of oxidative aging than those with lower values of *G-R* parameter.

$$G-R\,Parameter=\left\{\frac{G^*\left[\cos(\delta)^2\right]}{\sin(\delta)}\right\}_{T=15^\circ C,\,f=0.005\,rad/s}$$ (Equation 4)

Asphalt binders that are excessively aged, due to susceptibility to oxidation and/or the presence of higher percentage of RAM materials in a mix, are more prone to low temperature cracking. Time-dependent hardening was observed near the glass transition (T_g) temperature of asphalt binders during the Strategic Highway Research Program (SHRP) contract A002-A and was referred to as physical hardening (Anderson et al., 1994; Bahia, 1991). Physical hardening causes time-dependent isothermal changes in the rheological behavior and specific volume of asphalt binders (Andreson and Marasteanu, 1999). The process is reversible: when the asphalt binder is heated to room temperature or above, the effect of physical hardening is completely removed. Physical hardening for asphaltic materials is generally observed both above and below T_g. The study performed during the SHRP program resulted in a requirement in the AASTHO M320 specification of testing in the BBR after 1 and 24 hours of conditioning at low temperature. Although this requirement was not implemented, recent work by Hesp and Subramani (2009) observed better correlations between BBR results and the low temperature field when physical hardening was considered. Tabatabaee et al. (2012) have shown that the rate of physical hardening peaks at the glass transition temperature (T_g) and becomes relatively insignificant beyond the limits of the glass transition region. Andreson and Marasteanu (1999) showed that asphalt binders with higher wax content have stronger physical hardening effects both above and below their T_g.

2.3 Chemical Testing

The principal cause of asphalt aging and embrittlement in service is the atmospheric oxidation of molecules with the formation of highly polar and strongly interacting functional groups containing oxygen (Petersen, 2009). Therefore, binder oxidation has a significant impact on age-related pavement failure, since through oxidation the binder becomes stiffer and more brittle, reducing the performance life of the pavement (Petersen et al., 1993). As asphalts age, they harden; this results in a progressive increase in the stiffness modulus of the asphalt, together with a reduction in its stress relaxation capability (Read and Whiteoak, 2003). Since the aging behavior of asphalt mixes containing recycled material (i.e., RAP/RAS) is influenced by the chemical composition of the individual binders, chemical analyses are important to investigate the impact of RAM on the molecular distribution, thermal response and chemical composition of the resulting blends.

2.3.1 Gel Permeation Chromatography

The Gel Permeation Chromatography (GPC) technique is used to determine the molecular size distribution (MSD) of asphalt binders (aged, unaged, modified and unmodified), providing a distinct and reproducible molecular-size distribution curve (chromatogram) of the asphalt sample in solution (Jennings et al., 1980; Churchill et al., 1995). In this method, the asphalt binder is dissolved in a solvent and then injected into the GPC system. The injected sample travels through a series of columns that separate the sample based on molecular size (Figure 4). The larger molecular size particles exit the columns first and are detected by the system's detectors. The smaller molecular size particles travel into the pores of the columns, and therefore, have longer retention times. As a result, the chromatogram of molecular size distribution (which can be thought of as analogous to a type of sieve analysis of the sample) is obtained.

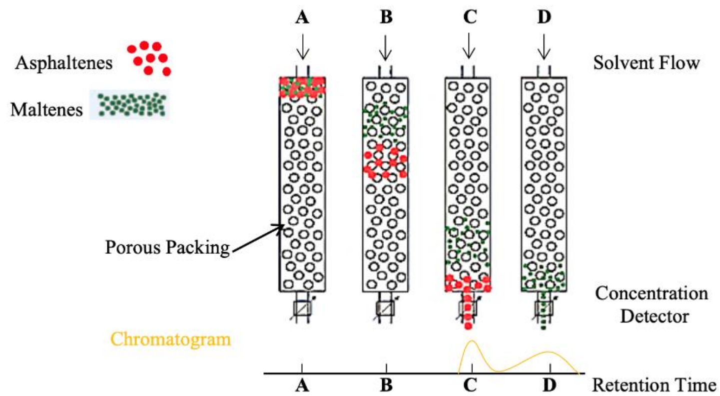
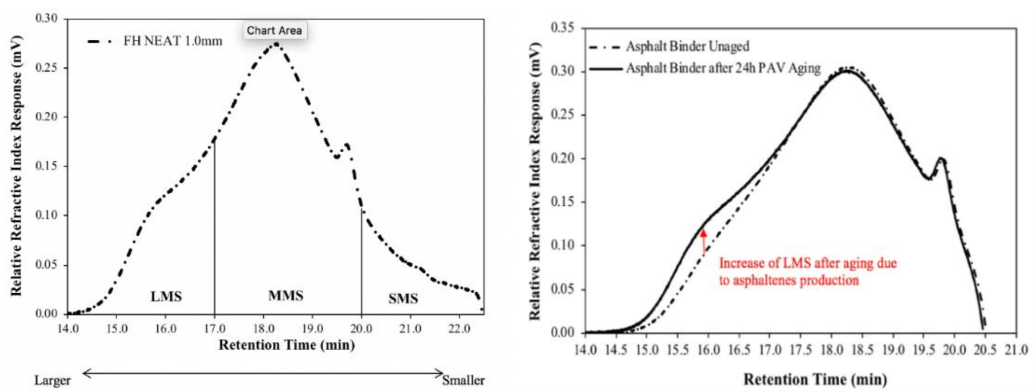


Figure 13 Schematic of Gel Permeation Chromatography (Moraes and Bahia, 2015a)

The chromatogram allows the classification of the chemical composition of binders into three groups based on molecular size. These groups are: large molecular size molecules (LMS), medium molecular size molecules (MMS), and small molecular size (SMS) molecules. Thus, the GPC chromatograms can provide insights about what fractions of the asphalt binder are affected after oxidative aging. It has been reported that a strong correlation exists between LMS and asphaltenes content (Moraes and Bahia, 2015) (Figure 14).



(a) (b)

Figure 14 (a) GPC Chromatogram of an Asphalt Binder. (b) GPC Chromatogram of an Asphalt Binder Before and After 24 Hours of PAV Aging (Moraes and Bahia, 2015)

One of the great advantages of GPC is its ability to separate by molecular size rather than by solubility or adsorptivity. The GPC is a simple separation technique available that responds to molecular weight alone and not to chemical structure. This feature makes GPC especially suited for fractionating complex mixtures, like asphalt binders. Table 16 presents an overview of the literature involving the application of GPC to asphalt binders.

Table 16 Examples of Application of GPC to Asphalt Binders (Moraes, 2014)

Gel Permeation Chromatography Application	Literature
Determine asphalt molecular weight distributions.	Snyder, 1969; Ying et al., 2013.
Use of GPC to characterize asphalt properties and the relationship of GPC parameters to pavement performance.	Jennings et al., 1980; Jennings et al., 1993; Yapp et al., 1991.
Evaluate the effects of oxidative aging on asphalt binders and mixes using the gel permeation chromatography procedure.	Kim and Burati, 1993; Churchill et al., 1995; Siddiqui and Ali, 1999; Lu and Isacsson, 2002; Doh et al., 2008; Lee et al., 2009.
Estimate absolute viscosity of aged binder in Reclaimed Asphalt Pavement (RAP) by using gel permeation chromatograph technique.	Kim et al., 2006.
Characterize blends of laboratory-aged crumb rubber modified binders (CRM) and rejuvenating agents by using GPC.	Shen et al., 2007.
Demonstrate that GPC can be used as a simple screening test to identify when asphalt binder has been modified with a polymer.	McCann et al., 2011.
Evaluate Reclaimed Asphalt Pavement (RAP) blending efficiency by using gel permeation chromatograph technique.	Bowers, 2013.
Investigate the oxidative aging levels of polymer-modified asphalt produced with Warm Mix Asphalt (WMA) technologies.	Kim et al., 2013.
Correlated an increase in large molecular sizes to the complex modulus (|G*|) of asphalt binder.	Zhao et al., 2013.
Evaluate changes caused by oxidative aging in the colloidal structure of the asphalt due to changes in the degree of association of the different asphalt fractions (i.e. asphaltenes and maltenes).	Moraes and Bahia, 2015a.

2.3.2 Glass Transition Temperature

The glass-transition temperature (T_g) has been considered as a characterization parameter that helps to determine the process and aging level of asphalts (Moraes and Bahia, 2015b). The T_g depends on the asphalt source and the degree of aging, since complex arrangements of molecules are formed (Turner et al., 1997). Conducting glass-transition measurements on asphalts with different amount of asphaltenes, Wada (1960) showed that the glass-transition temperature increases with an increase of the asphaltenes content. The transition to glassy behavior is known to increase the brittleness of the binder extensively, reducing the potential for stress relaxation, increasing stiffness, and therefore result in higher cracking susceptibility. There are speculations in the asphalt community that the glass-transition temperature of asphalt is responsible for low-temperature cracking of the mix (Marasteanu et al., 2007).

By using a dilatometric system to measure the glass transition temperature of asphalt binder, Moraes and Bahia (2015b) showed that oxidative aging and increase in asphaltenes content shift the T_g towards higher temperatures, thus increasing the susceptibility of the binder to cracking and durability issues due to the ductile-to-brittle transition behavior. The behavior presented in

Figure 15 is explained by the authors as the result of the effect of the aging process on the asphaltenes and resins asphalt fractions. During the beginning of the oxidative aging process, the glass-transition behavior of the evaluated neat binder is dominated by the increase in the lower T_g resins fraction, which leads to an overall decrease in the glass-transition temperature (i.e., becomes more negative). After six hours of PAV aging, the asphaltenes content starts to increase which results in an increase of the T_g.

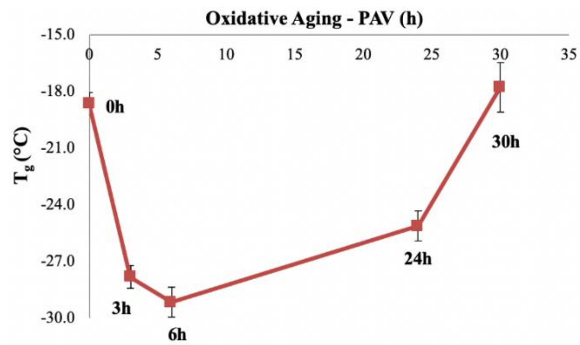


Figure 15 T_g of Neat Asphalt Binder after Different Aging Conditioning in PAV (Moraes and Bahia, 2015b)

The T_g of asphalt binders can also be determined by using Differential Scanning Calorimetry (DSC). In this technique, the difference in the amount of heat required to increase the temperature of a sample and a reference material are measured as a function of temperature.

2.3.3 Fourier Transform Infrared Spectroscopy

Fourier Transform Infrared Spectroscopy by Attenuated Total Reflectance (FTIR-ATR) exploits the attenuation of light reflected internally in a non-absorbing prism, due to energy absorption of an analyte in contact with the reflecting surface (Figure 16). It has been applied to asphalt binder for characterization of chemical composition and aging, for detection of impurities, and for studying polymer modification. Two of the major advantages of FTIR-ATR applied to asphalts, compared to transmittance FTIR, are: (a) the spectrum is obtained without solvent, and (b) the chemical influence of solvents can be avoided (Kelli-Anne et al., 2014).

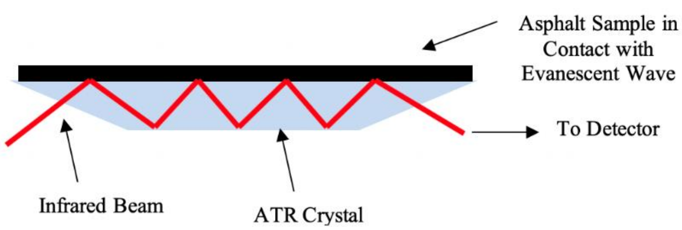


Figure 16 A Multiple Reflection FTIR-ATR System

According to the literature, the change in chemical structure of asphalt binders can be obtained with the calculation of functional and structural indices of some groups from FTIR-ATR spectra, since with oxidative aging the absorbance bands representing oxygen-containing functionalities of asphalt increase (Jennings et al., 1980). Thus, to quantify oxidation-related changes collected by means of infrared absorption, band areas values can be used to calculate chemical changes in carbonyl (C=O) and sulfoxide (S=O) groups. As can be seen in Figure 17, the content of carbonyl compounds increases during aging, and the degree of the changes is dependent on the asphalt binder source.

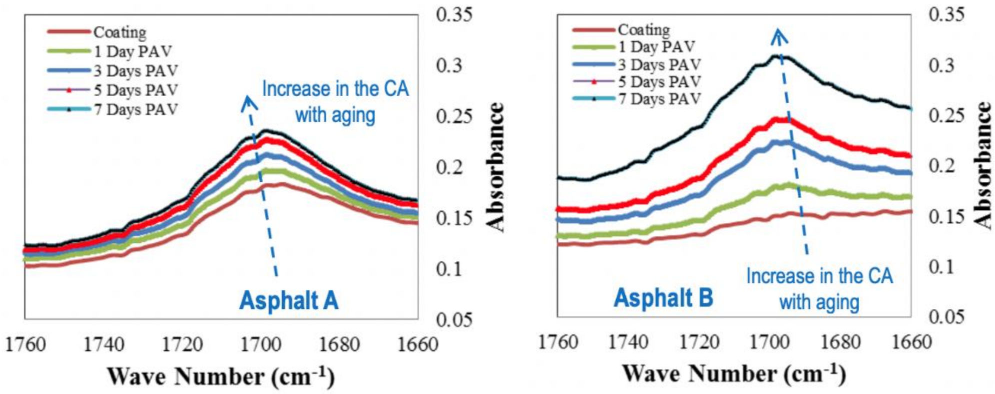


Figure 17 Increase in C=O Area with PAV Aging Time for Asphalt Binders from Different Sources

The absorption spectrum of carbonyl functions (such as ketones, dicarboxylic anhydrides, and carboxylic acids) is calculated by integrating the area of the spectrum between the wavelengths of 1660 and 1753 cm^{-1} and using the magnitude of the absorption at 1753 cm^{-1} as the baseline. For asphaltic materials, because of overlapping between the peaks at ~1700 cm^{-1} (carbonyl functions) and at ~1600 cm^{-1} (aromatic function), it is preferred to consider the surface area between these two limits (RILEM, 2012). Sulfoxide area is calculated by integrating the area of the spectrum between the wavelengths of 995 and 1047 cm^{-1} and using the magnitude of the absorption at 1047 cm^{-1} as the baseline. Table 17 presents studies involving the application of FTIR to asphalt binders.

Table 17 Examples of Application of FTIR to Asphalt Binders

FTIR Application	Literature
Investigate the diffusion of recycling agents within the asphalt binder.	Karlsson and Isacsson, 2003.
Investigate the effect of antioxidants in the aging susceptibility of SBS polymer modified asphalt binder.	Ouyang et al., 2006.
Evaluate changes in C=O and S=O groups with the addition of RAS to asphalt binder.	Abbas et al., 2013.
Validate rheological results which indicated that aging susceptibility of asphalt binders modified with polymers and recycling agents is dependent on modification chemistry.	Li et al., 2016.

2.3.4 Gas Chromatograph/Mass Spectrometry

Gas chromatography-mass spectrometry (GC-MS) is a method that combines the features of gas-liquid chromatography and mass spectrometry to identify different substances within a test sample. The GC/MS technique is comprised of a gas chromatograph (GC) coupled to a mass spectrometer (MS), by which complex mixtures of chemicals may be separated, identified and quantified.

The GC utilizes a capillary column that depends on the column's dimensions (length, diameter, film thickness) as well as the phase properties of the sample being analyzed. The difference in the chemical properties between different molecules in a mixture will separate the molecules as the sample travels the length of the column. Since the molecules take different amounts of time (i.e., retention time) to travel through the GC, the MS downstream can capture, ionize, accelerate, deflect, and detect the ionized molecules separately. This MS performs this process by breaking each molecule into ionized fragments and detecting these fragments using their mass to charge ratio.

The GC/MS technique can be used for investigation of the chemical composition (i.e., fatty acid content) of some anti-aging additives (i.e., bio-oils) in order to correlate the ratio of the components to the effectiveness of each additive. Since the effectiveness of bio-rejuvenators in changing asphalt binder properties could be related to its composition, the fatty acid and non-fat acid content of oils can be a useful parameter when choosing among different bio-rejuvenators.

A fatty acid is a carboxylic acid with a long aliphatic chain, which is either saturated (no carbon-carbon double bond) or unsaturated (with carbon-carbon double bond). If saturated, the chain of carbon atoms holds as many hydrogen atoms as possible. If unsaturated, the fatty acid can be further classified as monounsaturated (with one carbon-carbon double bond) or polyunsaturated (with >1 carbon-carbon double bond). It is important to mention that the stability of these fatty acids is related to the degree of unsaturation. An example of the GC/MS results for characterization of different bio-based RAs is presented in Figure 18.

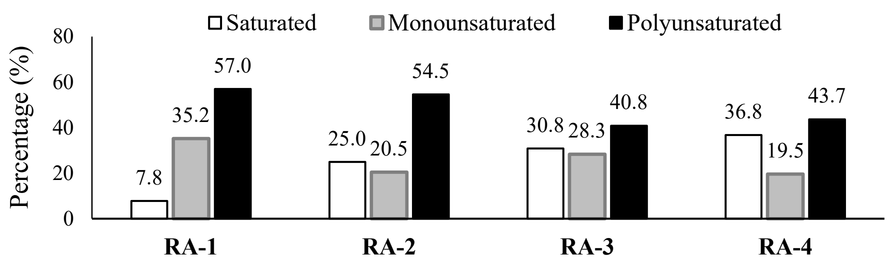


Figure 18. Fatty Acid Content of Bio-based Recycling Agents

By using GC/MS, Zhou et al. (2018) evaluated the chemical composition of eight bio-based recycling agents (Figure 19). The rheological performance of RAP asphalt binders modified with the RAs was also investigated in the study. After analysis, the authors suggested that the total fatty acid content measured by GC/MS is a good performance indicator for bio-based RAs due to two factors: (1) the low temperature PG grade of recycled asphalt binders is controlled primarily by its relaxation property (or m-value); and (2) the total fatty acid content has higher correlation with the m-based low temperature PG in comparison with dynamic viscosity.

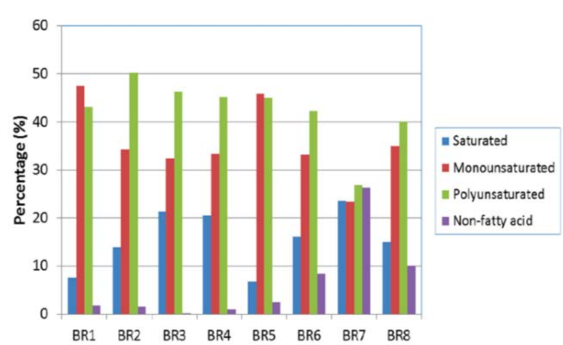


Figure 19. Fatty Acid and Non-fatty Acid Contents (Zhou et al., 2018)

3 PERFORMANCE EVALUATION OF RECYCLED MIXTURES

The characterization of RAP aged binder and blended binders with and without RAs is crucial to understand the behavior of asphalt mixes with RAM, but to better understand the properties and performance of these mixes, performance testing is needed. There is a general agreement that the stiffness and rutting resistance of asphalt mixes containing RAM increase with increasing RAM percentage, but the mixes may have reduced cracking resistance and durability due to the heavily aged asphalt binders in RAM that are stiffer and more brittle than virgin binders. Contrarily, the use of RAs could potentially improve mixture cracking resistance but decrease their rutting resistance. Therefore, it is of high priority to design recycled asphalt mixes with balance performance.

The following sections discuss some of the key studies that have assessed the performance of recycled asphalt mixes with regards to their resistance to rutting, cracking and moisture damage as well as field performance.

3.1 Rutting and Moisture Susceptibility

A study conducted by Al-Qadi et al. (2012) evaluated the laboratory performance of high RAP mixes with percentages of RAP ranging from 30 to 50%. The mixes were designed with a PG 64-22 virgin binder. For laboratory testing, specimens were produced using a single and double bumped binder PG 58-22 and PG-58-28, respectively. Moisture susceptibility and rutting potential were assessed using the Illinois modified AASHTO T283 and Flow Number (FN) tests, respectively. The study found that in general, the tensile strength ratio of the mixes increased with an increased RAP content. FN test results showed less rutting potential as the RAP content increased when the base binder PG 64-22 was used; when a softer binder was used, the rutting potential of the mixes increased.

Maupin et al. (2007) conducted a study in Virginia to evaluate the laboratory performance of ten asphalt pavement sections that used mixes with RAP content ranging from 21% to 30%. Control mixes were also placed and evaluated when possible. Laboratory test results using the Asphalt Pavement Analyzer (APA) were conducted to evaluate rutting susceptibility, and TSR testing was conducted to evaluate moisture susceptibility. The researchers found that there was no significant difference between the APA and TSR test results for high RAP and control mixes, and therefore, their predicted performance was equivalent.

A study by Zhao et al. (2012) used laboratory performance tests to evaluate the effect of high percentages of RAP on warm-mix asphalt (WMA). Mixture rutting resistance and moisture susceptibility were studied. Four WMA mixes were designed using the Marshall mix design procedure with 0, 30, 40, and 50% RAP and a PG 64-22 virgin binder. In addition, two control HMA mixes were designed with 0 and 30% RAP. Performance testing on plant mix samples included APA at 50°C for rutting resistance evaluation and HWTT and TSR for moisture susceptibility evaluation. It was found that rutting and moisture resistance was improved by adding RAP to the mixes and that the improvement for WMA was more pronounced than that of HMA mixes.

Tran et al. (2012) conducted a study to evaluate the effect RAs on performance properties of asphalt mixes with high RAM contents. A total of five mixes, including a control virgin mix, a 50% RAP mix, a 20% RAP plus 5% RAS mix, a 50% RAP mix with RA, and a 20% RAP plus 5% RAS mix with RA, were evaluated in this study. A RA dosage of 12% by the total weight of recycled binders was selected to restore the properties of the recycled binders to meet the PG 67-22 requirements of the virgin binder. TSR and APA tests were conducted to assess the mixture moisture and rutting susceptibility, respectively. The TSR values for all the mixes tested were equal or greater than the commonly accepted threshold of 0.8. The use of rejuvenator at the determined content in the two RAP/RAS mixes did not negatively affect the TSR values. The addition of RAs to the recycled mixes increased their susceptibly to rutting, but all the mixes exhibited APA rut depths of less than 5.5 mm, which indicates adequate rutting resistance based on past research at the NCAT Test Track.

A study conducted by Mogawer et al. (2013) evaluated if RAs could be used with high RAP and RAS mixes to offset the increase in stiffness without negatively impacting the mixture rutting performance. A total of four mixes were evaluated: a control virgin mix, a 40% RAP mix, a 5% RAS mix, and a 35% RAP plus 5% RAS mix. For each mix, three different RAs were added to the virgin asphalt binder with dosages ranging from 0.5 to 1.6% by weight of the recycled material. Rutting performance and moisture damage were assessed using the HWTT at a temperature of 45°C. The researchers found that the control mix performed poorly in terms of rutting and moisture damage. The addition of 40% RAP, 35% RAP plus 5% RAS, and 5% RAS mixes improved the performance of the mixes. The incorporation of RAs to the 35% RAP plus 5% RAS mix slightly reduced the mixture resistance to rutting and moisture damage, while this reduction was more evident when RAs was added to the 40% RAP and 5% RAS mixes.

3.2 Fatigue and Reflective Cracking Resistance

Mogawer et al. (2012) evaluated the characteristics of plant-produced mixes containing up to 40% RAP (0, 20, 30 and 40%). Eighteen mixes were obtained from three contractors located in the Northeastern United States. One contractor used a PG 64-22 virgin binder for four of the mixes and then adjusted the virgin binder to a PG 58-28 for the two highest RAP content mixes (for a total of six mixes) to evaluate the effect of using a softer virgin binder. Another contractor used a PG 64-28 virgin binder for four mixes and adjusted to a PG 52-34 for all RAP contents for a total of eight mixes. The third contractor only used a PG 64-28 virgin binder for its mixes. Mixture cracking resistance was measured using the Overlay Test (OT) at 15°C. The OT results showed decreased cracking resistance with increasing RAP content. For one of the contractors, the use of a softer virgin binder did not improve the OT results. However, mixes produced by the other contractor did show improved cracking resistance using a softer virgin binder.

The study conducted by Mogawer et al. (2013) previously described in Section 3.1 also evaluated the fatigue and reflective cracking potential of the mixes using the OT. The RAP, RAS, and RAP plus RAS mixes without RAs exhibited a significant reduction in the number of cycles to failure relative to the control virgin mix. This behavior can be attributed to the hardened binder in the RAP and RAS. The incorporation of RAs improved the cracking performance of all the RAP, RAS, and RAP plus RAS mixes, but the degree of performance improvement was dependent on the type of RAs used.

Xie et al. (2017) conducted a study to evaluate the effect of RAs on the laboratory test results and field performance of mixes with high recycled contents. The field study consisted of three mixes: a control mix containing 20% RAP and no RA, and two experimental mixes containing 25% RAP and 5% RAS and two recycling agents. OT and Illinois flexibility index tests (I-FIT) were performed to determine mixture resistance to cracking. Based on the OT and I-FIT results, the control 20% RAP mix had significantly better resistance to cracking than the two experimental mixes with 25% RAP plus 5% RAS with RAs. The control section with 20% RAP and no RA showed less amount of field cracking than the two rejuvenated mixes with 25% RAP plus 5% RAS, which indicated the RAs used in these experimental mixes were not effective.

3.3 Low-Temperature Cracking Resistance

Behnia et al. (2010*)* conducted a study to assess the effect of RAP on the low-temperature fracture properties of asphalt mixes. One of their goals was to evaluate the practice of reducing the virgin binder grade to compensate for the increased stiffness of mixes with high RAP contents. The disk-shaped compact tension test (DCT) as described in ASTM D7313 was used. Four RAP sources from the state of Illinois were used. A 19-mm NMAS mix was used for each RAP source using 30% RAP. The mix designs used a PG 64-22 and a PG 58-28. In addition to the RAP mixes, virgin mix designs using PG 58-28 and PG 64-22 binders were also tested. Fracture energy at -12°C was measured for each of the mixes. The researchers found that there was a significant decrease in fracture energy when 30% RAP was added to the virgin PG 58-28 mix. The virgin PG 58-28 mix test specimens had fracture energy values of approximately 2,000 J/mm^2 while the 30% RAP test specimens had fracture energy values ranging from 540 to 680 J/mm^2. When compared to the PG 64-22 virgin mix, the 30% RAP mixes with PG 58-28 were found to have an approximately 50% improvement in DCT fracture energy values. These findings showed that the RAP mixes with a softer virgin binder had acceptable low-temperature fracture properties compared to the PG 64-22 mix without RAP and that the practice of adjusting the virgin binder grade one grade softer was adequate for high RAP mixes.

The previously mentioned study by Tran et al. (2012) also evaluated the low-temperature cracking potential using the Indirect Tensile (IDT) Creep and Compliance test. The study found that the addition of RAs reduced the critical low temperature of recycled asphalt mixes. As presented in Figure 20, the control mix exhibits the lowest critical failure temperature (-27.7°C), followed by the 50% RAP mix with RA, then the 20% RAP plus 5% RAS mix with RA, and the 20% RAP plus 5% RAS mix without RA. In addition, the study found that the critical low temperatures determined using the IDT test correlated well with those determined using the binder BBR test.

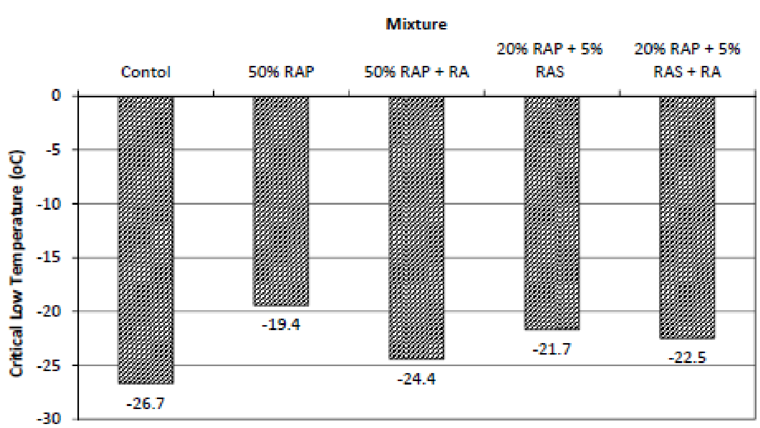


Figure 20. Critical Low Temperature of Recycled Mixes (Tran et al, 2012)

A study by Zaumanis et al. (2013) investigated the effect of using different RAs to restore the properties of an aged RAP asphalt binder and determining the low temperature performance properties of 100% RAP mixes. Nine different RAs were tested, including plant oils, waste derived oils, engineered products, as well as traditional and non-traditional refinery base oils. Ten different 100% RAP mix samples were prepared, including a control virgin mix and nine rejuvenated mixes. Mixture low-temperature cracking resistance was evaluated by determining the IDT strength and creep compliance at -10°C. The study showed that an improvement in the mixture low temperature performance depended on the type of RA used. Adding five RAs was found to be effective in maintaining or increasing the low temperature creep compliance and at the same time increasing the indirect tensile strength and fracture energy, therefore improving mixture resistance to low-temperature cracking. The mixes that compared with the control mix were able to maintain or increase the creep compliance without reducing the tensile strength and fracture energy were those with the following RAs: organic blend, refined tallow, aromatic extract, naphthenic flux oil, and distilled tall oil.

3.4 Field Performance of Recycled Mixes

Paul (1996) conducted a study in Louisiana that examined pavement condition, structure, and serviceability of asphalt mixes containing 20% to 50% RAP after six to nine years of service life. This study found that the pavements containing RAP mixes had statistically equivalent performance as those containing virgin mixes, although the recycled pavements exhibited slightly more distress related to longitudinal cracking.

The performance of the Texas SPS-5 experimental sections from the LTPP program were analyzed by Hong et al. (2010) based on approximately 16 years of field data. Test sections containing 35% RAP were compared to the virgin sections with regard to ride quality, transverse cracking, and rutting. The test sections with RAP had a higher amount of cracking, less rutting, and similar roughness change over time. The overall evaluation showed that a well-designed mix with 35% RAP could perform as satisfactorily as that produced with virgin materials.

In a study by West et al. (2011), 18 projects across the U.S. were included to compare the performance of overlays with virgin asphalt mixes to overlays containing 30% RAP. The database covered projects ranging from 6 to 17 years old. Statistical analyses were conducted to compare the rutting, fatigue cracking, longitudinal cracking, transverse cracking, block cracking, and raveling of these test sections. Overlays using mixes with 30% RAP were found to perform equivalent to virgin mixes in terms of IRI, rutting, block cracking, and raveling. The virgin mix overlays had statistically better performance with regard to fatigue cracking and longitudinal cracking, but the RAP mixes still performed well in general.

NCAT has evaluated the construction and performance of several high RAP content sections since 2006 (Willis et al., 2009). In the 2006 to 2009 Test Track cycle, four sections with mixes containing 45% RAP were constructed and compared to a control section of virgin mix. The sections used different grades of virgin binder ranging from a PG 52-28 to a PG 76-22 polymer-modified binder with 1.5% Sasobit. The mixes were placed 2 inches thick as surface layers. These sections were left in place for two cycles for a total of 20 million ESALs. All of the test sections had less than 5 mm of rutting and small amounts of low-severity cracking. The amount of cracking was also consistent with the virgin binder grade in the RAP sections, with the RAP section containing the softest virgin binder having the least amount of cracking. The findings of this experiment led to NCAT's recommendation to use a softer virgin binder grade for high RAP content (over 25%) mixes with no change to the binder grade for low to moderate RAP content mixes (equal or less than 25%).

In the 2009 to 2012 NCAT Test Track cycle, three additional high RAP test sections were constructed (West et al., 2012). The first section was a 45% RAP content section with a PG 67-22 virgin binder. After 10 million ESALs, the section had only 3 mm of rutting and only 61 feet of low severity cracking. The other two sections contained 50% RAP in each of the three layers of the 7-inch asphalt pavement structure. One of the 50% RAP mix sections was produced as Warm Mix Additives (WMA) using foaming technology for volume expansion and better coating of aggregates. These two sections were compared to a virgin mix control section built to the same thickness with a polymer-modified PG 76-22 binder in the top two layers. After 10 million ESALs, the 50% RAP mix sections had less rutting and fatigue cracking than the control section.

Anderson et al. (2010) examined the long-term performance data of 19 high RAP content pavement sections from eight states and one Canadian province. These pavements had been in service for more than 10 years. In each of the case studies, the sections containing RAP were compared to similar pavements built with virgin materials using data obtained by the state highway agency. The study found that most of the high RAP mix sections had similar or even better performance compared to the virgin mix section. Although rutting and fatigue cracking were observed on the high RAP mixes in some cases, the differences were generally not great enough to substantially affect the long-term performance.

3.5 State of Practice on Mixture Performance Tests

In 2018, NCAT conducted NCHRP project 20-07/Task 406 to develop a framework for balanced mix design and investigate the implementation status of mixture performance tests (West et al., 2018). A survey conducted as part of this project identified 26 state highway agencies that require at least one mixture performance test in their current mix design specifications. Among these agencies, most focus on the evaluation of rutting resistance while only a few assess cracking resistance. However, for mixes with RAM, cracking is a more critical mode of distress than rutting due to reduced flexibility and relaxation properties. Based on different mechanisms in crack initiation and propagation, cracking can be further categorized into bottom-up fatigue, top-down fatigue, reflection, and thermal cracking. In the survey, state highway agencies were asked to select performance tests with the most potential based on their experience and knowledge, and the top two selections for each mode of distress are summarized in Table 18.

Table 18 Selection of Mixture Performance Tests by State Highway Agencies (West et al., 2018)

Pavement Distress	Top Two Selections
Rutting	Hamburg Wheel Tracking Test (HWTT), Asphalt Pavement Analyzer
Thermal Cracking	Disc-shaped Compact Tension (DCT) Test, Semi-circular Bend Test
Reflection Cracking	Overlay Test, Illinois Flexibility Index Test (I-FIT)
Bottom-up Fatigue Cracking	I-FIT, Bending Beam Fatigue Test
Top-Down Fatigue Cracking	I-FIT, Direct Tension Cyclic Fatigue Test
Moisture Damage	HWTT, Tensile Strength Ratio

The NCHRP project identified the following nine critical steps for implementation of a test method into routine practice. The study then identified candidate tests to address the major forms of asphalt pavement distresses. A comprehensive literature review was conducted related to each test to determine the status of each of the nine critical steps.

1. Develop draft test method and prototype equipment;

2. Evaluate sensitivity to materials and relationship to other lab properties;
3. Establish preliminary field performance relationship;
4. Conduct ruggedness experiment to refine its critical aspects;
5. Develop commercial equipment specification and pooled fund purchasing;
6. Conduct round-robin testing to establish precision and bias information;
7. Conduct robust validation of the test to set criteria for specifications;
8. Conduct training and certification; and
9. Implement into engineering practice.

As part of this current research project (WHRP 19-04), the research team will assess mixture performance in terms of resistance to common distresses as follows: HWTT for rutting evaluation, I-FIT test for intermediate-temperature cracking evaluation, and DCT for thermal cracking evaluation. The status of the critical steps identified by West et al. (2018) for each of these tests is as follows.

HWTT

- All of the critical steps have been completed for the HWTT test as reflected by the number of highway agencies currently using it as part of their mix design specifications.
- Analysis of the HWTT results should be further refined to distinguish rutting from moisture damage. A research study should be commissioned to explore the advantages and disadvantages of different analysis methods, propose revisions to AASHTO T 324, and prepare training materials to facilitate implementation.

I-FIT

- [Step 2] The test was found sensitive to binder grade, RAP and RAS contents, and mix aging. Conflicting results have been reported regarding its sensitivity to binder content. Also, the effect of specimen air voids has been shown to be counterintuitive when specimen air voids are outside of the range of 7.0 ± 1.0 percent; for any given mix, as air voids decrease, the FI decreases. [Step 3] The Illinois DOT has established preliminary criteria for FI based on field performance and the 2012 FHWA ALF experiment; however, the mode of cracking for many of the field projects was not well documented as top-down cracking.
- [Step 4] The I-FIT is one of the seven tests selected for ruggedness testing in NCHRP 09-57A. The project started in June 2018 and will completely address Step 4 upon its completion.
- [Step 6] The Illinois DOT is leading a round-robin experiment that includes 30 I-FIT machines from three state agency labs, 15 private labs, and the Illinois Center for Transportation (Pfeifer, 2018). The study will completely address Step 6 upon its completion.
- [Step 7] I-FIT is one of the tests being evaluated for top-down cracking as part of the ongoing NCAT cracking group study (Van Deusen, 2017). This study will partially address Step 7 upon its completion. Further validation may be needed in other climates.

DCT

- [Step 2] The test was found sensitive to key mix design variables of binder grade, aggregate type, RAP and RAS contents, and WMA technology, but conflicting results were reported regarding its sensitivity to binder content and air voids.
- [Step 4] DCT is one of the seven tests selected for ruggedness testing in NCHRP 09-57A. The project started in June 2018 and will completely address Step 4 upon its completion.
- [Step 7] The fracture energy parameter had a good correlation with field transverse cracking data for field projects in three states (i.e., IL, MN, and NY). In addition, MnROAD and NCAT are conducting a national cracking study to validate laboratory tests for thermal cracking and top-down cracking. DCT is being evaluated as one candidate test for thermal cracking. The study will partially address Step 7 upon its completion.

4 SUMMARY OF LITERATURE REVIEW FINDINGS

The objective of this report is to perform a comprehensive literature review based on current practices on a national level and develop an initial understanding of how quantity and quality of RAM material can affect the performance of the resultant asphalt binders and mixtures for use in Wisconsin. Based on the findings of this literature review, the following conclusions are drawn with respect to full blending *vs.* black rock debate, cold weather state specifications for use of RAM, practices to increase RAM content, characterization of asphalt binders containing RAM, and performance testing of recycled asphalt mixtures as they apply to the current project work plan.

- *Full Blending vs. Black Rock Debate*
  - There are three approaches for determining the amount of "active" asphalt binders in RAM: the "full blending" approach, the "black rock" approach, and the "partial blending" approach. Among the three approaches, the "partial blending" approach has been found the most appropriate in designing recycled asphalt mixes containing RAM.
  - The degree of blending between recycled and virgin binders has a significant effect on the volumetric and performance properties of recycled asphalt mixes. Underestimating the degree of blending will yield "dry" mixes with increased susceptibility to cracking and durability issues, while overestimating the degree of blending will yield mixes with excessive asphalt binders and increased susceptibility to deformation and bleeding issues.
  - The laboratory test methods for determining the degree of blending between recycled and virgin binders can be grouped into eight categories: preparation of coarse-aggregate, fine RAP mix; preparation of gap-graded mixes; volumetric analysis; comparing measured and predicted asphalt mixture dynamic modulus; use of titanium dioxide in virgin binder as a tracer; use of artificial glass beads in virgin aggregate as a tracer; staged solvent extraction; and other methods.
- *Cold Weather State Specifications for Use of RAM*
  - Currently, four state highway agencies require the use of a discount factor to account for the "non-active" recycled binders in RAM. The discount factor varies between 0.60 and 0.85 among these agencies.
- *Practices to Increase RAM Content*
  - Currently, there are four practices in use to allow the production of asphalt mixtures with higher RAP/RAS content. These practices are: incorporation of recycling agents, polymer modification of asphalt binders, utilization of softer asphalt binders, and the approach of increasing the effective asphalt binder content.
- *Characterization of Asphalt Binders Containing RAM*
  - It was observed that the performance of asphalt mixtures containing RAP/RAS is dependent on the properties of its constitutive components, and the level of blending between the aged and unaged binder is also influenced by the chemical composition of the individual binders.
  - Non-load related cracking of asphalt pavements (i.e. transverse and block cracks) are related to oxidation and hardening of the asphalt binder, which is the main concern when

incorporating RAP /RAS material in the production of HMA. Therefore, researchers have spent significant efforts to classify cracking resistance of asphalt binders using an index parameter. From the literature review, the key parameters used for evaluation of cracking potential of asphalt binders are:

  - From DSR master curves, the G-R parameter;
  - From the LAS test, the N_f (number of cycles to fatigue failure); and
  - From BBR measurements, the creep stiffness (S), m-value, ΔT_c and physical hardening.

- Since the asphalt binder oxidation has a significant impact on age-related pavement failure, chemical testing was found important to understand and capture asphalt aging. From the literature review, four techniques have been to investigate the aging characteristics of asphalt binders.
  - GPC, for evaluation of the molecular size distribution (MSD);
  - DSC, for determination of the glass transition temperature (T_g);
  - FTIR-ATR, for calculation of both carbonyl and sulfoxide groups; and
  - GC-MS, for evaluation of the fatty acid content of recycling agents.

— *Performance Evaluation of Recycled Asphalt Mixtures*

- The performance of recycled mixtures with or without RAs in regards to rutting, fatigue cracking, and thermal cracking resistance is dependent of the amount of recycled materials used, and the type and amount of RA used. In general, the literature review shows that for recycled mixes:
  - Rutting resistance increases with an increase in the RAP/RAS content, but tends to decrease with the addition of RAs.
  - Intermediate temperature cracking resistance decreases with an increase in the RAP/RAS content, but may improve with the incorporation of RAs.
  - Low temperature cracking resistance improves when the virgin binder grade is reduced to compensate for the increased stiffness of mixes with high recycled content. In addition, the use of RAs also tends to improve the low temperature properties of recycled mixtures.

5 REFERENCES

Abbas, A.R., Mannan, U.A., and Dessouky, S. (2013). Effect of Recycled Asphalt Shingles on Physical and Chemical Properties of Virgin Asphalt Binders. Construction and Building Materials, Vol. 45, pp.162-172.

Airey, G. D. (2003). Rheological Properties of Styrene Butadiene Styrene Polymer Modified Road Bitumens. *Fuel*, Vol. 82, pp. 1709-1719.

Al-Qadi, I., Q. Aurangzeb, S. Carpenter, W. Pine, and J. Trepanier. (2012). Impact of High RAP Contents on Structural and Performance Properties of Asphalt Mixtures. Report FHWA-ICT-12-002. Illinois Center for Transportation, Urbana, Ill.

Amundsen, A., and Klaeboe, R. (2005). A Nordic Perspective on Noise Reduction at the Source. Institute of Transport Economics.

Anderson, A. and Marasteanu. M. (1999). Physical Hardening of Asphalt Binders Relative to Their Glass Transition Temperatures. *Transportation Research Record: Journal of the Transportation Research Board,* N. 166, pp. 27-34.

Anderson, M., G. N. King, D. I. Hanson, and P. B. Blankenship. (2011). Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking. *Journal of the Association of Asphalt Paving Technologists*, Vol. 80, pp. 615-664.

Anderson, D., Christensen, D., Bahia, H., Dongre, R., Sharma, M., Antle, C., and Button, J. (1994). Binder Characterization and Evaluation, Volume 3: Physical characterization, SHRP A-369. Washington DC: National Research Council.

Anderson, E. Long-Term Performance of High RAP Sections: Case Studies. MS thesis. University of New Hampshire, Durham, May 2010.

Asphalt Institute. (1996). Asphalt Hot-Mix Recycling, The Asphalt Institute Manual Series No. 20 (MS-20), Second Edition.

Asphalt Magazine. (2009). http://asphaltmagazine.com/lab-corner-spring-2009-extraction-solvents

Bahia, H. (1991). Low-Temperature Isothermal Physical Hardening of Asphalt Cements. Ph.D. Thesis. Pennsylvania State University.

Bahia. H. (1995). Critical Evaluation of Asphalt Modification Using Strategic Highway Research Program Concepts. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1488, 1995, pp. 82-88.

Bahia, H., Hanson, D. I., Zeng, M., Zhai, H., Khatri, M. A. and Anderson, R. M. (2001). Characterization of Modified Asphalt Binders in Superpave Mix Design. NCHRP Report 459, Transportation Research Board, Washington, DC.

Bahia, H., Swiertz, D., Kilger, A. (2018). Modified Binder (PG+) Specifications and Quality Control Criteria. Project WHRP (0092-14-20) TPF-5(302) Extension Final Report.

Behnia, B., Ahmed, S., Dave, E., Buttlar, W. (2010). Fracture Characterization of Asphalt Mixtures with Reclaimed Asphalt Pavement. *International Journal of Pavement Research and Technology*, Vol. 3. No. 2, Chinese Society of Pavement Engineering, Jhongli City, Taiwan.

Bonaquist, R. (2011). Effect of Recovered Binders from Recycled Shingles and Increased RAP Percentages on Resultant Binder PG. Wisconsin Highway Research Program, Report No. WHRP 11-13.

Bonaquist, R. (2011). NCHRP Report 673: A Manual for Design of Hot Mix Asphalt with Commentary. Transportation Research Board of the National Academies, Washington, D.C.

Bonaquist, R. (2005). Laboratory evaluation of hot mix asphalt (HMA) mixtures containing recycled or waste product materials using performance testing. Publication FHWA-PA-2005-006-98-32 (19), Pennsylvania Department of Transportation, Office of Planning and Research.

Bonicelli, A., Calvi, P., Martinez-Arguelles, G., Fuentes, L., Giustozzi, F. (2017). Experimental Study on the Use of Rejuvenators and Plastomeric Polymersfor Improving Durability of High RAP Content Asphalt Mixtures. *Construction and Building Materials*, Vol. 155, pp. 37-44.

Booshehrian, A., Mogawer, W. S., & Bonaquist, R. (2012). How to construct an asphalt binder master curve and assess the degree of blending between RAP and virgin binders. *Journal of Materials in Civil Engineering*, 25(12), 1813-1821.

Bowers, B. F., Huang, B., He, Q., Shu, X., Jia, X., & Miller, B. C. (2014). Investigation of sequential dissolution of asphalt binder in common solvents by FTIR and binder fractionation. *Journal of Materials in Civil Engineering*, 27(8), 04014233.

Burr, B. L., Davison, R. R., Glover, C. J., and Bullin, J. A. (1990). Solvent Removal from Asphalt. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1269, pp. 1-8.

Carpenter, S. H., & Wolosick, J. R. (1980). Modifier Influence in the Characterization of Hot Mix Recycled Material. *Transportation Research Record: Journal of the Transportation Research Board*, No. 777, pp. 15-22.

Castorena, C., Pape, S., & Mooney, C. (2016). Blending Measurements in Mixtures with Reclaimed Asphalt: Use of Scanning Electron Microscopy with X-Ray Analysis. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2574, 57-63.

Chen, C., Moore, N., West, R., Yin, F., and Taylor, A. (2018) Evaluation and Comparison of Cracking Tests for Top-Down Cracking Resistance of Asphalt Mixtures. Submitted for presentation and publication at the 94th Association of Asphalt Paving Technologists Annual Meeting.

Churchill, E. V., S. N. Amirkhanian, J. L. Burati Jr. HP-GPC Characterization of Asphalt Aging and Selected Properties. *Journal of Materials in Civil Engineering*, Vol. 7, pp. 41-49, 1995.

Coffey, S., DuBois, E., Mehta, Y., Nolan, A., & Purdy, C. (2013). Determine the Impact of Degree of Blending and Quality of Reclaimed Asphalt Pavement on Predicted Pavement Performance using Mechanistic-Empirical Design Guide (MEPDG). Proceedings of the international conferences on the bearing capacity of roads, railways and airfields, pp. 445-454.

Copeland, A. (2011). Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice (No. FHWA-HRT-11-021).

Corbett, L. W. (1969). Composition of Asphalt Based on Generic Fractionation Using Solvent Deasphalteneing, Elution-Adsorption Chromatography and Densiometric Characterization. *Analytical Chemistry*, Vol. 41, pp. 576-579.

Daniel, J. S., Pochily, J.L., and Boisvert, D.M. (2010). Can More Reclaimed Asphalt Pavement Be Added? Study of Extracted Binder Properties from Plant-Produced Mixtures with up to 25% Reclaimed Asphalt Pavement. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2180, pp. 19-29.

Dinnen, A. (1991). Epoxy Bitumen Binders for Critical Road Constructions. Proceedings of the 2nd Eurobitume Symposium, pp. 294-296.

Edwards, Y., Tasdemir, Y., and Isacsson, U. (2006). Rheological Effects of Commercial Waxes and Polyphosphoric Acid in Bitumen 160/220 - Low Temperature Performance. *Fuel*, Vol. 85, pp. 989-997.

Epps Martin et al. (2018). The Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios. NCHRP Project 09-58 Draft Final Report.

FHWA Tech Brief. Superpave Mix Design and Gyratory Compaction Levels. FHWA-HIF-11 031. Office of Pavement Technology, December, 2010.

Glover, C., R. R. Davison, C. H. Domke, Y. Ruan, P. Juristyarini, D. B. Knorr, and S. H. Jung. (2005). Development of a New Method for Assessing Asphalt Binder Durability with Field Validation. Publication FHWA/TX-05/1872-2, Report 0-1872-2, U.S. Department of Transportation.

Gottumukkala, B., Kusam, S. R., Tandon, V., & Muppireddy, A. R. (2018). Estimation of Blending of Rap Binder in a Recycled Asphalt Pavement Mix. *Journal of Materials in Civil Engineering*, Vol. 30(8), 04018181.

Goubert, L. (2014). Developing a Durable and Ultra-Low Noise Poroelastic Pavement. Inter Noise Conference 2014, Melbourne, Australia.

Hajj, E.Y., Salazar, L., Guillermo, L., and Sebaaly, P.E. (2012). Methodologies for Estimating Effective Performance Grade of Asphalt Binders in Mixtures with High Recycled Asphalt Pavement Content: Case Study. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2294, pp. 53-63.

Hajj, E., Souliman, M., Alavi, M., and Salazar, L. (2013). Influence of Hydrogreen Bio-Asphalt on Viscoelastic Properties of Reclaimed Asphalt Mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, 2371, 13-22.

Herrington, P. R., Alabaster, D., Arnold, G., Cook, S., Fussell, A., and Reilly, S. (2007). Epoxy Modified Open-Graded Porous Asphalt. Land Transport New Zealand Research Report 321.

Herrington, P. (2010). Epoxy-Modified Porous Asphalt. NZ Transport Agency Research Report 410.

Hesp, S., and Subramani, S. (2009). Another Look at the Bending Beam Rheometer for Specification Grading of Asphalt Cements. Proceedings of 6th MAIREPAV Conference, Torino, Italy.

Hintz, C., R. Velasquez, Z. Li, and Bahia, H. (2011). Effect of Oxidative Aging on Binder Fatigue Performance. *Journal of Association of Asphalt Paving Technologists*, Vol. 80, pp. 527-548.

Hong, F., D-H Chen, and M Mikhail (2010). Long-Term Performance Evaluation of Recycled Asphalt Pavement Results from Texas Pavement Studies Category 5 Sections from the

Long-Term Pavement Performance Program. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2180, pp.58-66.

Huang, B., Li, G., Vukosavljevic, D., Shu, X., & Egan, B. K. (2005). Laboratory investigation of mixing hot-mix asphalt with reclaimed asphalt pavement. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1929, pp. 37-45.

Im, S., and Zhou, F. (2014). Field performance of RAS test sections and laboratory investigation of impact of rejuvenators on engineering properties of RAP/RAS mixes. Rep. No. FHWA/TX-14/0-6614-3, Texas Transportation Institute, College Station, TX.

Jennings, P. W., Pribanic, P. W., Campbell, W., Dawson, K., Shane, S., and Taylor, R. (1980). High Pressure Liquid Chromatography as a Method of Measuring Asphalt Composition. FHWA-MT-79-30 Final Report, Bozeman, Montana.

Johnson, K.-A. N., & Hesp, S. A. M. (2014). Effect of Waste Engine Oil Residue on Quality and Durability of SHRP Materials Reference Library Binders. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2444, pp. 102-109.

Jiang, Y., Gu, X., Zhou, Z., Ni, F., & Dong, Q. (2018). Laboratory Observation and Evaluation of Asphalt Blends of Reclaimed Asphalt Pavement Binder with Virgin Binder using SEM/EDS. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2672(28), pp. 69-78.

Kandhal, P. S. (1977). Low-Temperature Ductility in Relation to Pavement Performance. Low-Temperature Properties of Bituminous Materials and Compacted Bituminous Paving Mixtures, ASTM STP 628. C. R. Marek, Ed. American Society for Testing and Materials, pp. 95-106.

Karlsson, R. and Isacsson, U. (2003). Application of FTIR-ATR to Characterization of Bitumen Rejuvenator Diffusion. *Journal of Materials in Civil Engineering*, Vol. 15, pp.157-165.

Kaseer, F., Arámbula-Mercado, E., & Martin, A. E. (2019). A Method to Quantify Reclaimed Asphalt Pavement Binder Availability (Effective RAP Binder) in Recycled Asphalt Mixes. *Transportation Research Record: Journal of the Transportation Research Board*, 0361198118821366.

Kelli-Anne, N. J., and Hesp, S. A. M. (2014). Effect of Waste Engine Oil Residue on the Quality and Durability of SHRP MRL Binders. 93rd Annual Meeting Transportation Research Board.

Li, Y., Moraes, R., Lyngdal, E., and Bahia, H. (2016). Effect of Polymers and Oils Modification on the Aging Susceptibility of Asphalt Binders. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2574, Vol. 1, pp. 28-37.

Lu, X., and Isacsson, U. (2000). Modification of Road Bitumens with Thermoplastic Polymers. *Polymer Testing*, Vol. 20, No. 1, pp. 77-86.

Mallick, R., Tao, M., O'sullivan, K., and Frank, R. (2010). Why not (use rejuvenator for) 100% RAP Recycling? Procedings, 89th TRB Annual Meeting, Transportation Research Board, Washington, DC.

Marasteanu, M., Zofka, A., Turos, M., Li, X., Velasquez, R., Buttlar, W., Paulino, G., Braham, A., Dave, E., Ojo, J., Bahia, H., Williams, C., Bausano, J., Gallistel, A., and McGraw, J. (2007). Investigation of Low Temperature Cracking in Asphalt. Pavements National Pooled Fund Study 776: Report N. MN/RC 2007-43, Minnesota Department of Transportation, St. Paul, MN.

Maupin, G. W., S. Diefenderfer, and J. S. Gillespie. Evaluation of Using Higher Percentages of Recycled Asphalt Pavement in Asphalt Mixes in Virginia. Virginia Transportation Research Council, Charlottesville, Va., 2007.

McDaniel, R., and Anderson, M. (2001). Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual. National Cooperative Highway Research Program (NCHRP) Report 452.

McDaniel, R. S., Kowalski, K. J., and Shah, A. (2012). Evaluation of Reclaimed Asphalt Pavement for Surface Mixtures. Report FHWA/IN/JTRP-2012/03. Indiana Department of Transportation and Purdue University, West Lafayette, Indiana.

Mogawer, W., Bennert, T., Austerman, A., and Ericson, C. (2015). Using Binder and Mixture Space Diagrams to Evaluate the Effect of Re-Refined Engine Oil Bottoms on Binders and Mixtures after Ageing. *Road Materials and Pavement Design*, 16(2), in press.

Mogawer, W. S., Booshehrian, A., Vahidi, S., & Austerman, A. J. (2013). Evaluating the effect of rejuvenators on the degree of blending and performance of high RAP, RAS, and RAP/RAS mixtures. *Road Materials and Pavement Design*, 14(sup2), pp. 193-213.

Mogawer, W., Bennert, T., Daniel, J., Bonaquist, R., Austerman, A., Booshehrian, A. (2012). Performance Characteristics of Plant Produced High RAP Mixtures. *Road Materials and Pavement Design,* Vol. 13, pp. 183-208.

M. Mohajeri, A.A.A. Molenaar, M.F.C. Van de Ven (promotor), Hot Mix Asphalt Recycling: Practices and Principles, doi: http://doi.org/10.4233/uuid: 75ea46bc-deab-4259-9a73-0ca420cb94f6 (2015).

Moraes, R. (2014). Investigation of Mineral Filler Effects on the Aging Process of Asphalt Mastics. Ph.D. Thesis, University of Wisconsin-Madison.

Moraes, R., and Bahia, H. (2015a). Effect of Mineral Filler on Changes in Molecular Size Distribution of Asphalts during Oxidative Ageing. *Road Materials and Pavement Design*, Vol. 16, Supplement 2, pp. 55-72.

Moraes, R., and Bahia, H. U. (2015b). Effect of Mineral Fillers on the Oxidative Aging of Asphalt Binders: A Laboratory Study Using Mastics. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2506, pp. 19-31.

Nazzal, M. D., Kim, S. S., Abbas, A., Qtaish, L. A., Holcombe, E., & Hassan, Y. A. (2017). Fundamental Evaluation of the Interaction between RAS/RAP and Virgin Asphalt Binders (No. FHWA/OH-2017-24). Ohio Department of Transportation, Office of Statewide Planning & Research.

Newcomb, D., Epp, J., and Zhou, F. (2016). Use of RAP & RAS in High Binder Replacement Asphalt Mixtures: A Synthesis. Special Report 213, National Asphalt Pavement Association.

Nicholls, J.C., McHale, M.J., and Griffths, R.D., Best Practice Guide for Durability of Asphalt Pavements, Road Note 42, Transport Research Laboratory, Workingham, Berkshire, United Kingdom, 2008.

Noureldin, A. S., & Wood, L. E. (1987). Rejuvenator Diffusion in Binder Film For Hot-Mix Recycled Asphalt Pavement. *Transportation Research Record: Journal of the Transportation Research Board*, N. 1115, pp. 51-61.

O'Sullivan, K. (2011). Rejuvenation of Reclaimed Asphalt Pavement (RAP) in Hot Mix Asphalt Recycling with High RAP Content. Master's thesis, Worcester Polytechnic Institute (WPI), Worcester, MA.

Ouyang, C., Wang, S., Zhang, Y. (2006). Improving the Aging Resistance of Styrene-Butadiene-Styrene Tri-block Copolymer Modified Asphalt by Addition of Antioxidants. *Polymer Degradation and Stability*, Vol. 91, p.795-804.

Paul, H. R (1996). Evaluation of Recycled Projects for Performance. *Journal of the Association of Asphalt Paving Technologists*, Vol. 65, pp. 231-254.

Peng, W., and B. Riedl. (1995). Thermosetting Resins. *Journal of Chemical Education*, Vol. 72, pp. 587-592.

Petersen, J. C. (2009). A Review of the Fundamentals of Asphalt Oxidation: Chemical, physicochemical, Physical Property, and Durability Relationships. Washington, DC, United States: Transportation Research Board.

Petersen, J. C., Branthaver, J. F., Robertson, R. E., Harnsberger, P. M., Duvall, J. J., and Ensley, E. K. (1993). Effects of Physicochemical Factors on Asphalt Oxidation Kinetics. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1391, pp. 1-10.

Pfeifer, B. (2018). Illinois Department of Transportation's Practices for Balanced Mix Design. TRB Workshop 124, Balanced Asphalt Mixture Design: Implementation Efforts and Success Stories.

Read, J.; and Whiteoak, D. (2003). The Shell Bitumen Handbook. 5th Edition, Edited by R. Hunter.

Reinke, Gerald. (2017). The Relationship of Binder Delta Tc to Mixture Fatigue. Southeastern Asphalt User Producer Group, Jacksonville, Florida.

RILEM. (2012). Proposal for a Pre-Normative FTIR Method. International Union of Laboratories and Experts in Construction Materials, Systems and Structures, TC SIB-TG5-Recycling.

Rowe, G. M. (2011). Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking (prepared discussion). *Journal of the Association of Asphalt Paving Technologists*, Vol. 80, pp. 615-664.

Rad, F. Y., Sefidmazgi, N. R., & Bahia, H. (2014). Application of Diffusion Mechanism: Degree of Blending Between Fresh and Recycled Asphalt Pavement Binder in Dynamic Shear Rheometer. *Transportation Research Record: Journal of the Transportation Research Board*, N. 2444(1), pp. 71-77.

Shirodkar, P., Mehta, Y., Nolan, A., Sonpal, K., Norton, A., Tomlinson, C., & Sauber, R. (2011). A Study to Determine the Degree of Partial Blending of Reclaimed Asphalt Pavement (RAP) Binder for High RAP Hot Mix Asphalt. *Construction and Building Materials*, Vol. 25, pp. 150-155.

Sreeram, A., Leng, Z., Zhang, Y., & Padhan, R. K. (2018). Evaluation of RAP Binder Mobilization and Blending Efficiency in Bituminous Mixtures: An Approach Using ATR-FTIR and Artificial Aggregate. *Construction and Building Materials*, 179, 245-253.

Stroup-Gardiner, M. (2016). Use of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Asphalt Mixtures (No. Project 20-05, Topic 46-05).

Tabatabaee, H. A., R. Velasquez, and Bahia, H. (2012). Predicting Low Temperature Physical Hardening in Asphalt Binders. *Journal of Construction and Building Materials*, Vol. 34, 2012, pp. 162-169.

Tran, N., Taylor, A., and Willis, R. (2012). Effect of rejuvenator on performance properties of HMA mixtures with high RAP and RAS contents. Rep. No. 12-05, National Center for Asphalt Technology (NCAT), Auburn, AL, 70 pp, 2012.

Tran et al. Adjustments to the Superpave Volumetric Mixture Design Procedure for Selecting Optimum Asphalt Content. NCHRP project 20-07/Task 412, Interim Report, 2018.

Turner, T. F., and Branthaver, J. F. (1997). DSC Studies of Asphalts and Asphalt Components. Asphalt Science & Technology, Arthur Usmani: Editor, New York, Marcel Dekker.

Van Deusen, D. (2017). NCAT/MnROAD Cracking Group Update. Test Track Sponsor Meeting, St. Paul, MN.

Von Quintus, H. L., Mallela, J. and Buncher, M. (2001). Quantification of Effect of Polymer Modified Asphalt on Flexible Pavement Performance. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2007, pp. 141-154.

Wada, Y., and Hirose, H. (1960). Glass Transition Phenomenon and Rheological Properties of Petroleum Asphalt. *Journal of the Physical Society of Japan*, Vol. 15, No.10, pp. 1885-1894.

West, R., Michael, J., Turochy, R. and Maghsoodloo, S. (2011). Use of Data from Specific Pavement Studies Experiment 5 in the Long-Term Pavement Performance Program to Compare Virgin and Recycled Asphalt Pavements. Transportation Research Record No. 2208, Transportation Research Board of the National Academies, Washington, D.C., pp. 82-89.

West, R., Rodezno, C., Leiva, F., Yin, F. (2018). Development of a Framework for Balanced Mix Design. National Cooperative Highway Research Program (NCHRP) Project 20-07/Task 406.

West, R., Timm, D., Willis, R., Powell, B., Tran, N., Watson, D., Sakhaeifar, M., Brown, R., Robbins, M., Vargas-Nordcbeck, A., Leiva-Villacorta, F., Guo, X., and Nelson, J.. Phase IV NCAT Test Track Findings. NCAT Report 12-10. National Center for Asphalt Technology, Auburn, Ala., 2012.

Williams, B. A., Copeland, A., and Ross, T. C. (2017). Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2017. NAPA Information Series 138.

Willis, J. R., D. H. Timm, R. C. West, R. Powell, M. A. Robbins, A. J. Taylor, A. D. F. Smit, N. H. Tran, M. A. Heitzman, and A. Bianchini. (2009). Phase III NCAT Test Track Findings. NCAT Report 09-08, National Center for Asphalt Technology, Auburn, Al.

Willis, J.R., Turner, P., Julian, G., Taylor, A.J., Tran, N.H., and Padula, F. (2012). Effects of Changing Virgin Binder Grade and Content on RAP Mixture Properties. NCAT Report No. 12-03. National Center for Asphalt Technology, Auburn University, Auburn, Alabama.

Xie, Z., Tran, N. Julian, G., Taylor, A., and Davis Blackburn, L. (2017). Performance of Asphalt Mixtures with Recycled Contents Using Rejuvenators and Warm-Mix Additive: Field and Lab Experiments. *Journal of Materials in Civil Engineering*, Vol. 29, Issue 10, Yu, S., Shen, S., Zhang, C., Zhang, W., & Jia, X. (2017). Evaluation of the blending effectiveness of reclaimed asphalt pavement binder. *Journal of Materials in Civil Engineering*, Vol. 29(12), 04017230.

Wu, J. P., Herrington, P. R., and Alabaster, D. (2017). Long-Term Durability of Epoxy-Modified Open-Graded Porous Asphalt Wearing Course. *International Journal of Pavement Engineering*, DOI: 10.1080/10298436.2017.1366764.

Zaumanis, M., R. Mallick, and R. Frank (2013). Evaluation of Rejuvenator's Effectiveness with Conventional Mix Testing for 100% Reclaimed Asphalt Pavement Mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2370, pp. 17-25.

Zearley, L. J. (1979). Penetration Characteristics of Asphalt in a Recycled Mixture. Iowa Department of Transportation.

Zegard, A., Smal, L., Naus, R., Apostolidis, P., Liu, X., van de Ven, M.F.C., Erkens, S. and Scarpas, A. (2019). Field Trials with Epoxy Asphalt for Surfacing Layers Province of North Holland Case Study. Paper submitted for presentation for the 98th meeting of the Transportation Research Board.

Zhao, S., Huang, B., Shu, X., Jia, X. and Woods, M. (2012). Laboratory Performance Evaluation of Warm Mix Asphalt Containing High Percentages of RAP. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2294, pp. 98-105.

Zhou, F., Im, S., Morton, D., Lee, R., Hu, S., and Scullion, T. (2015). Rejuvenator Characterization, Blend Characteristics, and Proposed Mix Design Method. *Journal of the Association of Asphalt Paving Technologists*, Vol. 84, pp. 675-704.

Zhou, F., Im, S., Sun, L., and Scullion, T. (2017). Development of an IDEAL Cracking Test for Asphalt Mix Design and QC/QA. *Road Materials and Pavement Design*, Vol. 18, pp. 405-427.