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FINAL REPORT

Long-Term Performance of Asphalt Concrete Mixed with RAP and RAS

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16. Abstract

The objective of this project is to evaluate the short- and long-term aging performance of high RAP and RAS asphalt mixtures utilizing various recycling additives ("rejuvenators") in the context of balanced mixture design. Mixtures were evaluated for workability using gyratory compactor derived parameters, rutting and moisture susceptibility using the Hamburg Wheel-Track Test (HWTT), intermediate temperature cracking using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT), and low temperature cracking using a modified IDEAL-CT test. It is concluded that the recycling additives used in this study can be used to produce an asphalt mixture containing high amounts of RAP with similar performance to a virgin mixture utilizing the same components using concepts of balanced mixture design. However, the use of 5% RAS in conjunction with RAP is shown to cause difficulties in restoring cracking resistance relative to the virgin mixtures. The effect of aging on mixture performance is significant and measuring mixture performance using at least two levels of aging is recommended to evaluate the efficacy of the various recycling additives in terms of long-term performance.

17. Key Words Reclaimed Asphalt Pavement, Recycled Asphalt Shingles, Recycling Agents (RAs), Bio-Oils, REOB, Rutting, Cracking, IDEAL, CTindex, Recycled Mixture, Aging of Mixtures, Long-Term Aging, Binder Properties, BBR, DSR, Blended Binders	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service. 5285 Port Royal Road, Springfield, VA 22161

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Contents

Common Acronyms and Abbreviations

BBR = Bending Beam Rheometer
DOT = Department of Transportation
DSR = Dynamic Shear Rheometer
FTIR = Fourier Transform Infrared Spectroscopy
Gmm = Theoretical Maximum Specific Gravity
HMA = Hot Mix Asphalt
HWTT = Hamburg Wheel-Track Test
IDEAL-CT = Indirect Tensile Asphalt Cracking Test
JMF = Job Mix Formula: The ratio of aggregate stockpiles used when producing a mix, totaling 100%
LAS = Linear Amplitude Sweep
LTOA: Long Term Oven Aging
MSCR = Multiple Stress Creep and Recovery
N92 = Number of gyrations required to achieve 92% of the mixture Theoretical Maximum Specific Gravity (Gmm)
Ndes = Number of gyrations used to design an asphalt mixture
PAV = Pressure Aging Vessel
PBR = Percent Binder Replacement, the ratio of the total recycled binder to the total mixture binder; also called ABR for Asphalt Binder Replacement.
PG = Performance Grade
RA = Recycling Additive (Agent); commonly referred to as "Rejuvenators"
RAP = Reclaimed (Recycled) Asphalt Pavement
RAS = Reclaimed (Recycled) Asphalt Shingles
REOB = Re-Refined Engine Oil Bottoms; sometimes referred to as Vacuum Tower Asphalt Extender (VTAE)
RTFO = Rolling Thin-Film Oven
SCB = Semicircular Bend Geometry Test
SGC = Superpave Gyratory Compactor
STOA: Short Term Oven Aging
WMA = Warm Mix Asphalt
WHRP = Wisconsin Highway Research Program

I. Introduction and Objectives

The 2018 National Asphalt Pavement Association (NAPA) survey of asphalt producers reported that the average nationwide percentage of RAP used in asphalt mixtures has increased from 15.6% in 2009 to 21.1% in 2018; RAS usage increased 11.6% between 2017 and 2018. Interestingly, 77% of responding State Asphalt Paving Associations felt "there was room to increase the use of these materials" (Williams, Willis, & Carter Ross, 2019). Proper engineering in terms of material selection, mixture design, and testing is critical to achieving reliable performance as the recycled materials content in new asphalt mixtures continues to increase.

The main challenge with increasing the amount of RAP/RAS is the increased stiffness and brittleness of the aged binder in these recycled materials. One technology that may allow for responsible usage of higher RAP and RAS percentages is the use of the so called "asphalt rejuvenators". Rejuvenators are used to offset the effects of oxidative aging of the recycled binder, thereby allowing higher percentages of RAP and RAS to be used without sacrificing performance. Since these products do not "reverse" or "undo" aging effects in the asphalt binder, an umbrella term of "Recycling Additive (or Agent)" (RA) is becoming more widespread (Reinke, Baumgardner, Hanz, & King, 2017; Epps Martin et al., 2019). There has been a proliferation of RA products entering the marketplace in recent years, yet much of the technical information and usage guidelines for RAs remains proprietary or lacking scientific justification.

The main goal of this research project is to evaluate the long-term performance of asphalt concrete mixed with relatively high contents of rejuvenated RAP and RAS. The information generated from this research provides engineers and practitioners guidance for increasing RAP and RAS amounts for the design and specification of recycled asphalt concrete for more sustainable pavement construction with proper use of RAs. The project focuses on effects of long-term aging on performance of rejuvenated high recycled content mixtures.

A. *Research Objectives*

The objectives of this study are:

- Perform a literature search to synthesize findings of published studies on the subject of high RAP and RAS mixtures and the use of RAs;
- Develop a testing matrix to assess the performance of representative mixtures containing varying levels of RAP and RAS with and without the use of RAs;
- Execute the testing matrix utilizing up to three levels of laboratory aging conditions and including different modes of mixture failure (e.g. deformation, cracking, etc.) as well as assess the changes in chemistry and composition of the blended binders in the AC-RAS/RAP mix that might associate with aging of the mix.
- Prepare a final report that includes all the data, analyses, and recommendations and present the findings to an assigned Oversight Committee.

B. *Organization of this Report*

Following this section, a description of the research approach, including selection of mixtures and mixture performance tests, is presented in Section II. Subsequent sections (III, IV, and V) present the results of the mixtures tested in accordance with the balanced mix design concept including workability of mixtures in Section III, Rutting Resistance in Section IV, and Cracking Resistance in Section V. To relate the performance of mixtures to binder performance, Section VI includes the properties of the blended binders and presents the changes in chemical properties as measured by the FTIR test. Finally, Section VII presents the concluding remarks and recommendations offered.

II. Research Approach

A. Mixture Selection and Design

The Wisconsin DOT (WisDOT) allows contractors to use up to 25% RAP and RAS used in any combination for upper (surface) mixture layers. When RAS is used in combination with RAP, the RAS component cannot exceed 5% of the aggregate blend Job Mix Formula (JMF). The recycled material percentage is quantified and specified using the Percent Binder Replacement (PBR) parameter (sometimes called Asphalt Binder Replacement – ABR), which is the amount of recycled asphalt binder relative to the total mixture (recycled binder plus virgin binder) asphalt binder, all by weight of the total mixture. Using this methodology for reporting RAP and RAS, the PBR percentage may differ slightly from the percentage listed on the aggregate JMF since the aggregate JMF is expressed as a percentage of the aggregate blend only; for example, a mixture containing "30% RAP" usually has a PBR in the range of 25-28% for surface mixtures in Wisconsin. It is the PBR percentage that is limited to 25% by WisDOT, although designers usually are referring to JMF percentage for ease of communication. In this report, percent JMF or percent PBR will be specified.

According to WisDOT specification, contractors wishing to exceed the 25% PBR limit must furnish test results indicating that the blended binder (AASHTO M323, X1) meets the binder grade specified on the contract; no performance testing of the mixture is currently required.

For this project, a representative surface layer mix design for a "Medium Traffic – MT" project was sourced from a local contractor in Southeast Wisconsin (WisDOT Mix Designation: 4 MT 58-28 S). The mixture design contained 24% JMF RAP resulting in 18.5% PBR, which is a typical PBR for Wisconsin surface mixtures. By sourcing a single design any differences in aggregate physical properties and recycled binder rheology are minimized when designing different levels of PBR. The virgin binder used for this project was PG58-28 S selected from a single local source. The baseline mix design was adjusted to create four distinct levels of RAP/RAS while attempting to maintain the same composite gradation and relative ratios of sand types: 0% JMF (Virgin), 30% JMF (RAP Only), 50% JMF (RAP only) and 30%/5% JMF (RAP/RAS).

It was decided early in the project that design total asphalt content for each mixture should ideally be held constant assuming the volumetric properties of the respective mixtures at the design number of gyrations (75 for this design) were within reasonable agreement with the current WisDOT Standard Specification. Since the performance tests run during this project require samples to be compacted to a predetermined air void content rather than a number of gyrations and the objective is to investigate the effects of PBR, it is more important to maintain the same ratio of binder to aggregate (i.e., total asphalt binder content) while varying PBR than it is to verify each mix exhibits the same volumetrics at the mix design gyration level.

The mix designs used during this project are summarized in the table below. All volumetric properties listed are measured after two hours of Short-Term Oven Aging (STOA) following the protocol listed in subsequent sections.

Table 1. Mix Design Information

Mix Design	Virgin	30% JMF RAP (27.0% PBR)	50% JMF RAP (45.0% PBR)	30%/5% JMF RAP/RAS (47.5% PBR)
Composite JMF				
19.0 mm (3/4")	100.0	100.0	100.0	100.0
12.5 mm (1/2")	97.3	97.3	97.5	97.3
9.5 mm (3/8"	88.6	88.8	88.9	88.1
4.75 mm (No. 4)	70.1	69.5	70.2	69.6
2.36 mm (No. 8)	55.0	55.1	55.3	56.0
1.16 mm (No. 16)	42.0	42.2	42.3	43.0
0.600 mm (No. 30)	33.0	32.8	33.1	33.3
0.300 mm (No. 50)	17.2	17.1	18.8	18.6
0.150 mm (No. 100)	6.9	6.7	8.6	8.7
0.075 mm (No. 200)	5.36	5.16	5.42	5.49
Recycled Materials Content				
RAP JMF (PBR)	--	30% (27.0%)	50% (45.0%)	30% (27.0%)
RAS JMF (PBR)	--	--	--	5% (20.5%)
Mixture Volumetrics				
Total Binder, Pb, %	5.50	5.50	5.50	5.50
Design Gsb	2.618	2.617	2.619	2.619
Design Gse	2.699	2.695	2.702	2.691
Added Binder, %	5.50	4.01	3.02	2.89
Effective Binder, Pbe, %	4.39	4.44	4.37	4.52
Gmm @ Pb	2.474	2.471	2.476	2.468
Total Voids, Va @ Ndes, %	4.41	4.05	2.87	4.01
VMA @ Ndes, %	14.6	14.4	13.2	14.5

B. Mixture Aging Conditions

Two levels of mixture aging were selected during the study. Aging levels were not selected to approximate any level of field aging, but rather to produce a significant effect on mixture properties. Prior Wisconsin Highway Research Program (WHRP) projects (WHRP 15-04 and WHRP 17-04) as well as current AASHTO mixture preparation guidelines were used as the basis for selecting the aging protocols used in this study. Mixtures were otherwise prepared and compacted following AASHTO and WisDOT standard practice. Aging conditions used in this study are summarized in Table 2.

A unique Gmm sample was tested for each mixture at each aging condition in order to compact aged samples to the appropriate air void level for performance testing samples. In general, the Gmm increased with increased levels of aging for each mixture, as expected, although the differences were not significant in terms of test method variability.

Table 2. Aging Conditions used in this Study

Aging Condition	Loose or Compacted Mix	Total Duration	Oven Temperature, °F	Condition of Sample
Volumetric Mix Design Verification	Loose, Uncovered	2 hours	275	Sample in pan at thickness of around 1.5 inch; Stir sample at 1 hr.
Short-Term Oven Aging (STOA)	Loose, Uncovered	4 hours	275	Sample in pan at thickness of around 1.5 inch; Stir sample every 1hr.
Long-Term Oven Aging (LTOA)	Loose, Uncovered	8 hours	275	Sample in pan at thickness of around 1.5 inch; Stir sample at 1 hr. and 2 hr.

C. Selection of Recycling Additives and Dosage

Six generic types of RAs are identified in the most recent National study on recycling - NCHRP 09-58: Aromatic Extracts, Paraffinic Oils, Tall Oils, Vegetable Oils, Modified Vegetable Oils, and Reacted Vegetable Oils. In practice, Tall Oils and all the types of vegetable oils listed can be considered “Bio-Based”. The principal difference between Aromatic and Paraffinic Oils and Bio-Based Oils is their origin and subsequent processing: Bio-Oils are derived from plant life while Aromatic and Paraffinic oils are derived from petroleum or petroleum derivatives. Processing of the various oils by the manufacturer to manipulate desirable properties further differentiates the oils.

Not all RA types are used in all regions of the U.S. as a result of availability or specification. For this study two criteria were used in selecting RAs for inclusion in the work plan: availability and usage in the Upper Midwest region and selecting at least one Bio-Based oil and one non-Bio-Based oil that would be expected to show significant differences in performance. Work conducted by the authors as part of WHRP 17-04 and Pooled Fund TPF 5-302 was also referenced for guidance.

For this study two bio-based oils and one recycled petroleum-based oil were ultimately selected. The Bio-oils selected are referred to in this study simply as Bio-Oil 1 and Bio-Oil 2, both used in practice in various regions of the USA and abroad. The exact differences between the products is a trade secret but the manufacturer claims differing values of solvency and chemistry between the products. The Recycled Oil ("REOB") used in this study was sourced from a prominent supplier of recycled oils in the Midwest.

A reliable method to estimate RA dosage was a major objective of the NCHRP 09-58 study. Ultimately that study recommended selecting the RA dosage that restored the high temperature PG of the blended binder (the recycled binder and virgin binder) to the design level (usually the high temperature PG of the region the pavement will be constructed in). The researchers discovered that by correcting the high temperature PG, the low temperature PG and ΔT_C resulting values were also generally acceptable (Epps Martin et al., 2019). For this study both blended binder rheology and practical considerations were balanced based on the authors' experience using similar materials in practice. The dosages listed in Table 3 were selected for use in this study; evaluation of the resulting binder properties is included in a later section of this report, although this evaluation was not a primary objective of this project. It should be mentioned that the maximum dosage of 10% is derived from the practical limitations of in-line blending practiced by many contractors.

Table 3. RA Dosage Levels for Recycled Mixtures

Mixture	Bio-Oil Dosage* (Both Bio-Oil 1 and Bio-Oil 2)	REOB Dosage*
30% JMF RAP	3%	5%
50% JMF RAP	5%	10%
30% JMF RAP / 5% JMF RAS	5%	10%

*Dosage is weight percentage of total mixture asphalt, e.g. 3% is 3% RA + 97% Blended Binder

Two general methods exist for introducing RAs into the mixture in field operations. The first is by pre-blending (either tank blending or in-line) the RA into the hot asphalt during mixture production. In this approach the recycled binder content is accounted for by overdosing the virgin binder to net the desired level of RA by weight total asphalt (virgin plus recycled asphalt) in the mixture. The second approach is directly applying the RA to the RAP/RAS material before incorporating the recycled material into the mixing drum; this is typically accomplished using a spray bar attached above the RAP/RAS conveyor. Logistically the second approach is more difficult to implement. However, if the RA is significantly more effective using this approach, the added difficulty and expense may be justified.

Prior research has shown that the method of RA addition – either sprayed directly onto the RAP/RAS or blended into the virgin asphalt – does not have a significant impact on the residual asphalt properties in the mixture, meaning there is no inherent advantage to pre-dosing the RAP/RAS with an RA in terms of rheological modification (Epps Martin et al., 2019; Zaumanis, Cavalli, & Poulikakos, 2018). A brief sub-study was conducted in this project to confirm these prior findings and is summarized in a later section. Although differences in mixture performance were noted, it is concluded that for this project the method of RA incorporation does not significantly and reliably improve mixture performance; as a result, unless otherwise stated all RA additions in this study were made by blending in the virgin binder before mixing with aggregates and RAP/RAS.

D. Selection of Mixture Performance Tests and Final Work Plan

The incorporation of RAP and RAS materials into asphalt mixtures is generally expected to improve rutting resistance but worsen cracking resistance. RAs, by contrast, are expected to provide a general "softening" response in mixtures, which is intended to improve cracking resistance at the expense of rutting resistance. Therefore, several studies investigating the performance of RAs, such as NCHRP 09-58, utilize concepts of balanced mixture design to “balance” rutting performance with cracking performance. For this project specific testing methods were selected based on the author’s experience, the literature review conducted as part of this project, and adjusted based on findings during the study. A summary of the testing framework follows.

In this study, volumetric design with performance verification is used. First, a traditional Superpave volumetric mix design method was used to select gradation, binder content, and design volumetric properties. This information is presented in Table 1. Workability of the design mixtures was evaluated using the Superpave Gyratory Compactor (SGC). After the workability testing, rutting and moisture damage performance is assessed using the Hamburg Wheel Tracking Test, HWTT (AASHTO T324). Cracking is measured at intermediate temperature and at low temperature using the Indirect Tensile Asphalt Cracking (IDEA-CT – ASTM D8225) test and Semi-circular Bending (SCB) following a modified version of AASHTO TP105. A summary of mixture combinations and testing methods is shown in Tables 3 and 4, respectively. In addition, an investigation of internal structure of asphalt mixtures was also intended to be performed using the image processing software IPAS. Due to unexpected and unprecedented circumstances surrounding the 2020 Covid-19 pandemic, this testing was postponed indefinitely. If this testing is completed an amendment to this report will be issued.

Table 3. Mixture Combinations Tested

Factor	Level	Explanation
Mixture type	4	See Table 1
Binder added	1	PG 58-28 S
Recycling agent type	3	Bio-Oil 1, Bio-Oil 2, REOB
Adding method for recycling agent	1	Blended into virgin asphalt Based on “Application Study”
Aging Condition	3	See Table 4

Table 4. Mixture Tests and Associated Aging Conditions

Measured Property	Test Method	Temperature	Mixture Aging Condition
Workability	SGC Compaction Curve Analysis	Production (275 °F)	For volumetric design, STOA, LTOA
Rutting Resistance	Hamburg Wheel Tracking (AASHTO T324) + Modified Dry Analysis (Lu and Bahia, 2019)	High Temperature (122 °F)	STOA
Moisture Damage			
Fatigue Cracking	IDEAL-CT (ASTM D8225)	Intermediate (77 °F)	STOA, LTOA, Extended LTOA*
Thermal Cracking	IDEAL-CT (ASTM D8225, Modified) SCB (AASHTO TP105, Modified)	Low (32 °F)	STOA, LTOA, Extended LTOA*

*For a subset of samples, a LTOA period of 16 hours was also evaluated.

III. Workability of High RAP and RAS Mixtures

A. Workability of STOA Mixtures

A practical concern with using higher percentages of RAP and RAS is the expected decrease in mixture workability as a result of the stiffening effect of the recycled binder. Although there is not a widely accepted mixture workability test used in practice, researchers have recommended using the compaction curve generated by the SGC as a surrogate for workability. One commonly cited workability measurement that is easily extracted from the compaction curve is the "N_{92}" parameter, which is the number of gyrations required to achieve 92% mixture density relative to the mixture Gmm (Bonaquist, 2011). The "N92" parameter is also used in the AASHTO R35 mixture design procedure to evaluate workability of Warm Mix Asphalt. A higher N_{92} parameter is indicative a less workable mixture since more compaction energy is required to densify the mixture to 92% mixture density (8% total air voids).

Figure 1 shows typical compaction curves for the four project mixtures in the volumetric mix design condition without the use of RAs; note the curves shown in Figure 1 highlight the region of % Gmm centering around 92% for clarity. It is observed that the four mixtures exhibit different values for N_{92}, indicating a potential difference in workability; interestingly, three of the four mixtures exhibited an average N_{92} of 15 gyrations with a range of 13-17 gyrations, while the 50% RAP mix exhibited an average N_{92} of 11 gyrations and a range of 10-11 gyrations. This finding suggests the 50% RAP mixture is more workable than the other three mixtures, including the virgin mix.   This will be discussed further in this section.

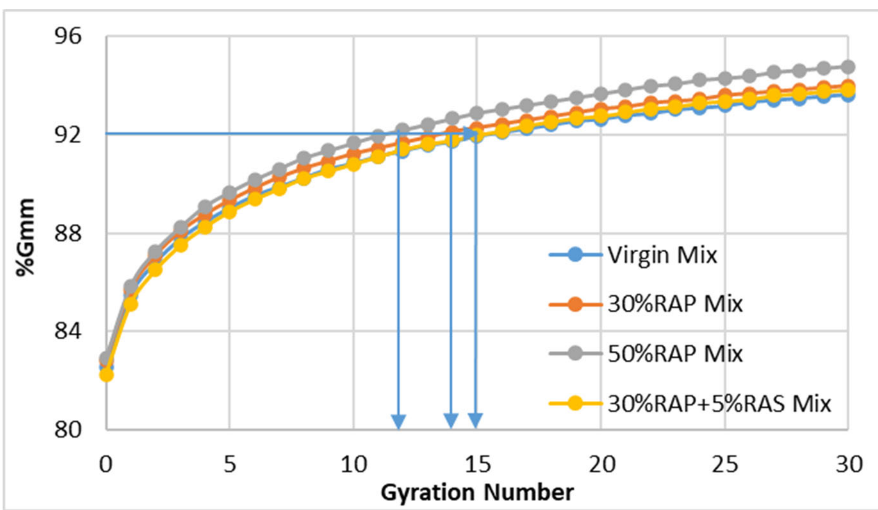


Figure 1. Examples of partial compaction curves measured for the four project mixtures without RAs in the volumetric mix design condition.

Upon closer inspection, it is observed that the initial "Zero Gyration" density (the %Gmm measured at zero gyrations) is different for each mixture, likely as a result of aggregate orientation and minor differences in placing the sample during charging the mold, operator variation, or other sample preparation factors. Within the range of N_{92} values observed, this makes it difficult to directly compare these mixtures. Therefore, a normalization calculation was made to remove the initial density bias. First, the slope of the compaction curve using a logarithmic scale was calculated. This parameter is relatively simple to interpret (a higher slope is indicative of a more workable mixture), but includes the entire compaction curve, not just the initial portion. A parameter unique to this study called the Workability Index Value (WIV) was also calculated by considering the portion of the compaction curve between two gyrations and the N_{92} value. The WIV is the inverse of the slope of the compaction curve between these two points; therefore, a lower WIV is indicative of a more workable mixture. The calculation for WIV is defined below:

$$Workability\ Index\ Value\ (WIV) = \frac{N_{92} - 2}{92\%\ Gmm - \%Gmm_{N=2}}$$

Where: N_{92} = *Number of gyrations to achieve 92% Gmm*
$\%Gmm_{N=2}$ = *%Gmm at two gyrations*

The slope of the compaction curve and the WIV parameter are summarized in Table 5. The color coding in Table 5 is meant to convey the comparison between the two parameters ranked from most workable (Green) to least workable (Dark Orange). The two parameters do not provide equal ranking of mixture workability overall but do provide equivalent ranking for the two least workable mixtures. Based on these two parameters it is again determined that the highest binder replacement mixtures (50% RAP and the RAP and RAS mixture) are more workable than even the virgin mixture. The authors believe that a cause of this observation could be differences in binder absorption between the mixtures as a result of changes in binder availability and blended aggregate properties. Accordingly, calculated binder absorption (Pba) and resulting effective asphalt content (Pbe) are also included in Table 5 (note all mixtures had a total asphalt content of 5.50%).

Table 5. Workability of Project Mixtures in STOA Condition Without RAs

Mix ID	Pba	Pbe	N_{92}				Workability Index Value (WIV)				Slope of Entire Compaction Curve			
			Rep. 1	Rep. 2	Rep. 3	Average	Rep. 1	Rep. 2	Rep. 3	Average	Rep. 1	Rep. 2	Rep. 3	Average
Virgin	1.17	4.39	16	13	--	15	2.69	2.56	--	2.63	0.0231	0.0266	--	0.0249
30% RAP	1.12	4.44	14	14	17	15	2.45	2.46	2.82	2.57	0.0267	0.0262	0.0262	0.0264
50% RAP	1.19	4.37	11	10	--	11	1.90	1.96	--	1.93	0.0292	0.0275	--	0.0284
30% RAP + 5% RAS	1.04	4.52	15	--	--	15	2.36	--	--	2.36	0.0286	--	--	0.0286

During the process of verifying volumetric properties (Table 1), it was observed that the virgin mix had slightly higher voids than the design target (4.0%) at N_{des}, while the 50% RAP mx had slightly lower voids than the design target at N_{des}, indicating the 50% RAP mix may contain slightly more total asphalt than is required to achieve design voids. Although these mixtures have practically equivalent Pbe, the volumetric analysis suggests another property (differences in aggregate JMF, angularity, etc.) is resulting in differences in measured workability. Conversely, the 30% RAP and RAP and RAS mixture exhibit greater differences in Pbe despite having nearly equivalent design air voids at N_{des}; for these mixtures, a trend of increasing workability with increasing Pbe is observed. This trend is logical.

As a result of the analysis presented above, it is concluded that the workability of asphalt mixtures can be quantified using gyratory compaction curve-derived parameters (N_{92}, slope, WIV, etc.), but caution must be exercised when evaluating mixtures without prior knowledge of volumetric properties of the mixtures, namely effective asphalt content at the design level of air voids. In addition, aggregate angularity, total dust or mineral filler, and asphalt rheological properties also contribute to workability. For the data generated during this study, it can be concluded that use of higher percentages of RAP and RAS did not reduce mixture workability as measured in the lab after short term aging.

B. Effect of RAs on Workability

A desirable secondary benefit of using RAs may be increased mixture workability for higher RAP and RAS mixtures as a result of the softening (viscosity reducing) effects of the additives on the recycled asphalt. To evaluate this potential, the N_{92} and WIV was calculated for the four mixtures utilizing each of the three RAs. For this evaluation four-hour STOA samples were used since these samples were already being prepared for performance testing. The data for all mixtures is summarized in Figure 2.

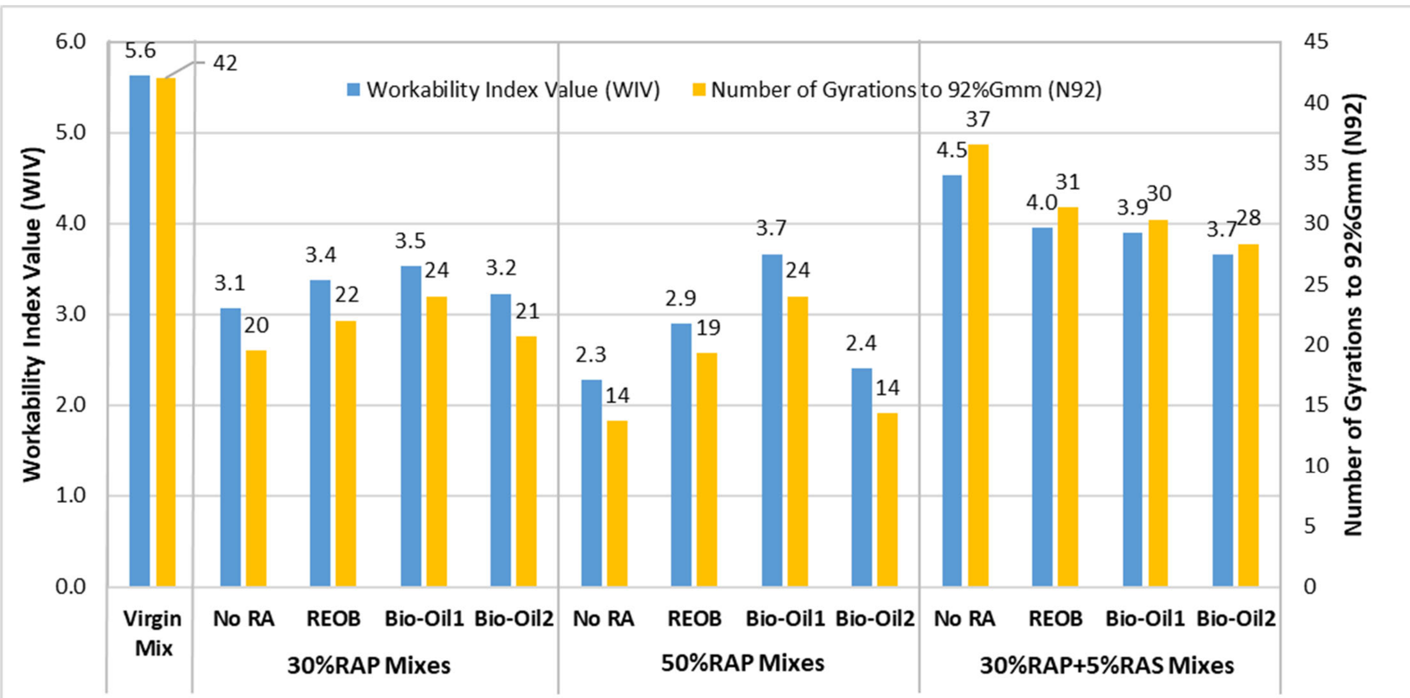


Figure 2. Effect of RAs on Workability Index Value and N92 for mixtures aged four hours.

Comparing the results of the "No Additive" mixtures, it is observed that the mixtures change workability ranking relative to the two-hour STOA samples presented in Table 5. However, the 50% RAP and Virgin mixture still represent highest and lowest workability observed, respectively. Using the N_{92} parameter, the overall differences in workability between the mixtures increased significantly relative to the two-hour STOA condition; for example, the N_{92} of the Virgin mixture increased from 15 gyrations to 42 gyrations, a change of 27 gyrations. By contrast, an observed difference of one gyration between the four mixtures was observed for the two-hour STOA condition. This finding suggests the ramifications of laboratory aging: increased binder viscosity and increased binder absorption (lower effective binder content) can have a significant effect on mixture workability.

For the 30% and 50% RAP mixtures the addition of RAs did not improve workability, but rather reduced mixture workability relative to the respective "No Additive" mixture. Interestingly the relative increase in N_{92} appears to be dependent on the additive type (Bio-Oil vs. REOB), but also the Bio-Oil product itself. Since the two Bio-Oil products were used at the same dosage rate, this finding suggests that the chemical composition of a given additive type impacts workability. The REOB was added at a higher dosage rate relative to the Bio-oil, so although chemical composition may similarly have an effect, dosage rate is also likely to affect results.

In contrast, the RAs increased workability for the RAP and RAS mixture. This could be attributed to a combination of factors. RAS residue is significantly stiffer than RAP residue, to the relative difference in viscosity between the treated virgin binder and recycled binder portion is greater for the RAP and RAS mixture relative to the RAP only mixtures. In addition, the RA may be providing more binder utilization from the RAS, which in turn would increase mixture workability. Given that these findings would be considered advantageous for field operations, mixture performance is considered more important than workability.

Another noteworthy observation is that the relative differences in workability between the additives is different for each mixture: for example, the difference in N_{92} between the two Bio-Oils is only three gyrations for the 30% RAP mixture, whereas the difference increases to 10 gyrations for the 50% RAP mixture. One hypothesis to explain this behavior is that the dosage of Bio-Oil is higher for the 50% RAP mixture, meaning a larger percentage of the total binder is Bio-Oil rather than asphalt binder. Since Bio-Oil and asphalt have very different rheological and aging properties, the effect of additive type might be more pronounced when larger percentages are used.

Based on the findings presented above, it is concluded that RAs do influence mixture workability, although the relative trends compared to untreated mixtures can be counterintuitive. There are likely several interrelated factors affecting this result – effective binder content/binder utilization, relative oil percentages, etc. The practical significance of the observed changes in workability is unknown but should be at least considered during the mix design process.

C. Effect of Laboratory Aging on Workability and Laboratory Implications

The workability parameters presented above are intended to provide insight into compaction during field operations. However, as the use of performance tests and laboratory aging protocols become more widespread, these sane parameters can be used to assess whether production of long-term aged specimens in the laboratory presents practical challenges. For this analysis, four-hour STOA samples were compared to eight-hour LTOA samples. The results of the comparison are shown in Figure 3.

For the RAP-only mixtures the aging conditions used in this study do not appear to practically affect the ability to produce test specimens to 8% air void. The N_{92} parameter is always within six gyrations between the two aging conditions for the RAP mixtures and is reduced for one combination. Conversely, for the RAS mixture the N_{92} increases by as much as 28 gyrations for the more advanced level of aging and appears to be more dependent on the RA type. Although this observed change is significant, the difference in laboratory procedure is not greatly impacted and results to an approximate maximum increase in compaction time of one minute (at the specified gyration rate of 30 gyration/minute). Overall, it is concluded that although more compaction effort is required to densify aged mixtures, the increase is not excessive and does not preclude the efficient production of specimens for performance testing.

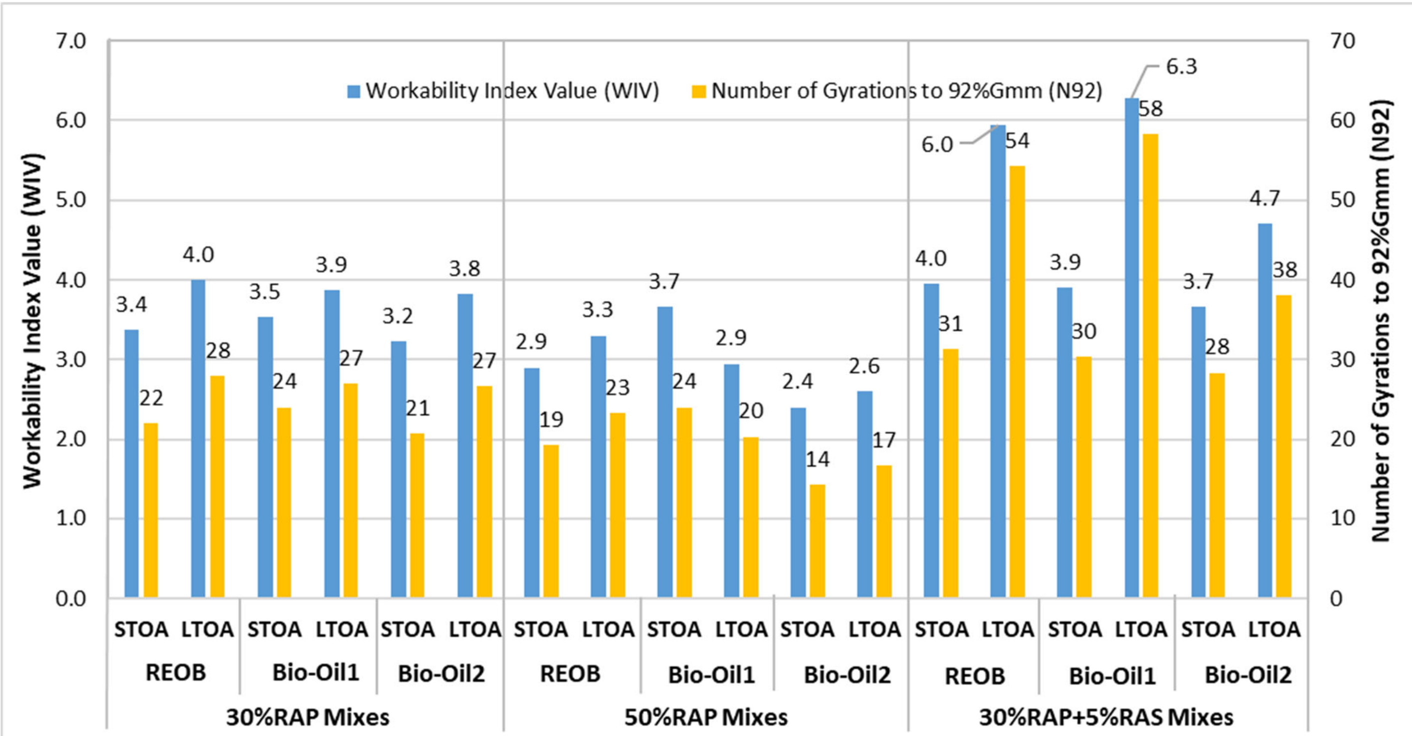


Figure 3. Effect of RAs on WIV and N92 for mixtures aged four hours.

IV. Permanent Deformation and Moisture Susceptibility of High RAP and RAS Mixtures

A. Evaluation of Mixtures using the Hamburg Wheel Tracking Test

The Hamburg Wheel Tracking Test, HWTT, was conducted on four-hour STOA samples at 50 °C following AASHTO T324. Three test parameters that are most commonly specified are number of testing cycles or passes to produce a 12.5 mm (1/2”) rut depth (“Cycles or Passes to 12.5 mm”), Number of Passes to Stripping Inflection Point (SIP), and the maximum rut depth (AASHTO T324 specifies the similar Number of Cycles to Failure, N_f, parameter). The SIP and N_f are formally defined in AASHTO T324, while the Passes to 12.5 mm is self-explanatory. The maximum rut depth is simply the rut depth measured at the termination of the test, which occurs when either the passes limit of the machine (20,000 passes) or maximum rutting limit of the machine is reached. The advantage to reporting maximum rut depth is when the machine cycles limit is reached for some mixtures, a unique number is still determined for that mixture to allow comparison to other mixtures.

Data analysis for this portion of the study followed the 6th-order polynomial-fitting method developed in part by the Iowa DOT and described in prior studies (WHRP 15-04); an Excel spreadsheet was developed to standardize this procedure for this study. Results for the project mixtures without the use of RAs are shown in Figure 4.

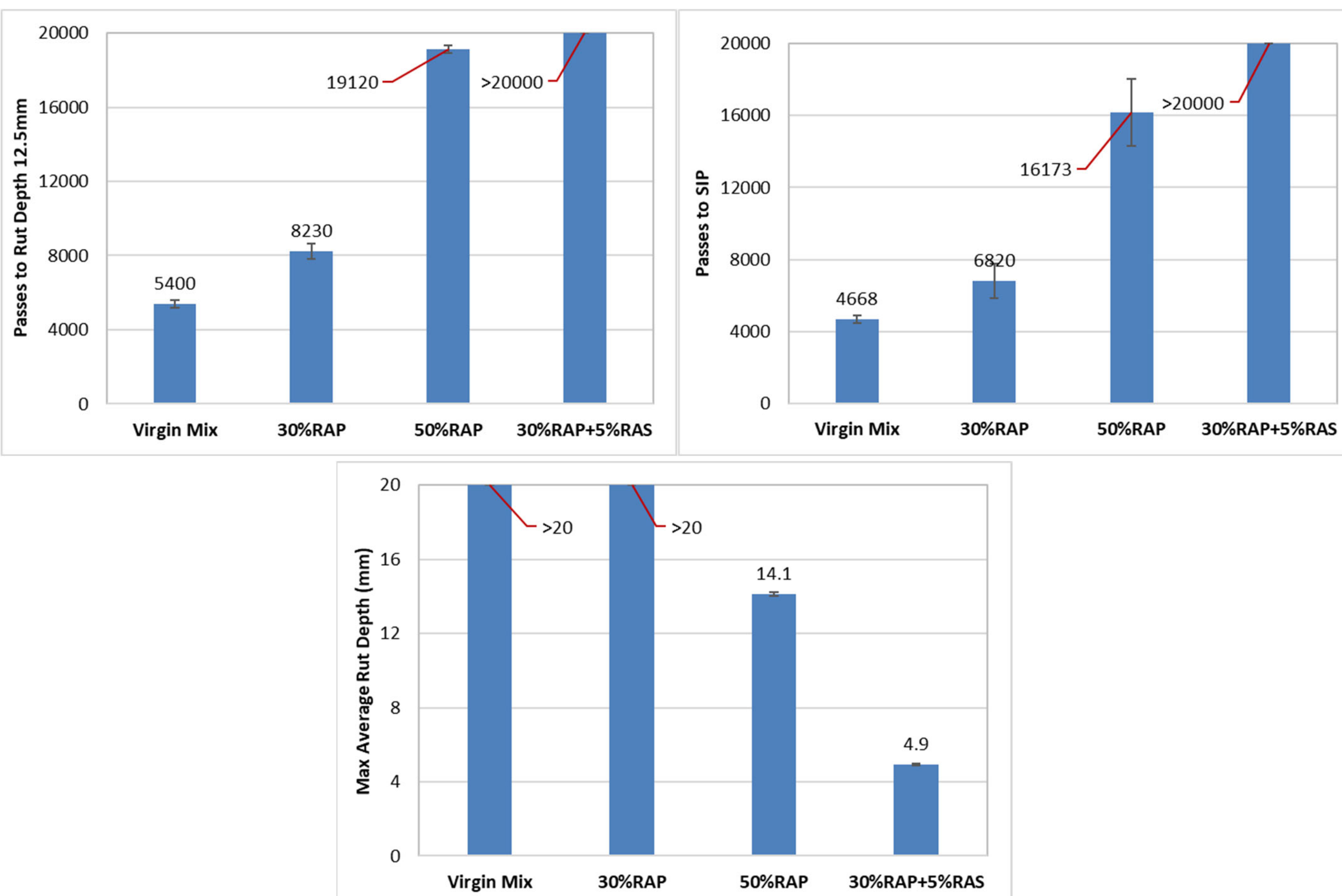


Figure 4. HWTT Results for mixtures without RAs.

The results presented in Figure 4 indicate that as RAP and/or RAS percentage increases, the resistance to rutting also increases, as expected. This is most likely a result of increased binder stiffness at higher levels of RAP and RAS. The effect is most pronounced in the 50% and RAP and RAS mixture, with both mixtures nearly reaching or reaching the machine maximum cycles limit of 20,000 cycles. The passes to SIP appear to follow a similar trend as the Passes to 12.5 mm, with increasing SIP for progressively stiffer binder; no defined SIP was detected for the RAS mixture. The dependence of the HWTT parameters on residual binder stiffness is well documented, and the results presented in Figure 4 are expected given the virgin binder grade of PG 58-28.

The addition of RAs is expected to reduce rutting resistance as an artifact of reduced binder stiffness. Therefore, an objective of the balanced mixture design procedure for higher RAP and RAS mixtures that utilize RAs is to ensure a baseline level of rutting resistance is not compromised. To evaluate this effect, the three RAP and RAS mixtures utilizing RAs were compared against the virgin and RAP/RAS mixtures without the use of RAs. The results of this comparison for the HWTT are shown in Figure 5. Note that for clarity only the Passes to 12.5 mm and Passes to SIP are shown. The SIP could not be calculated for the RAS mixture for two of the RAs and is omitted from the chart.

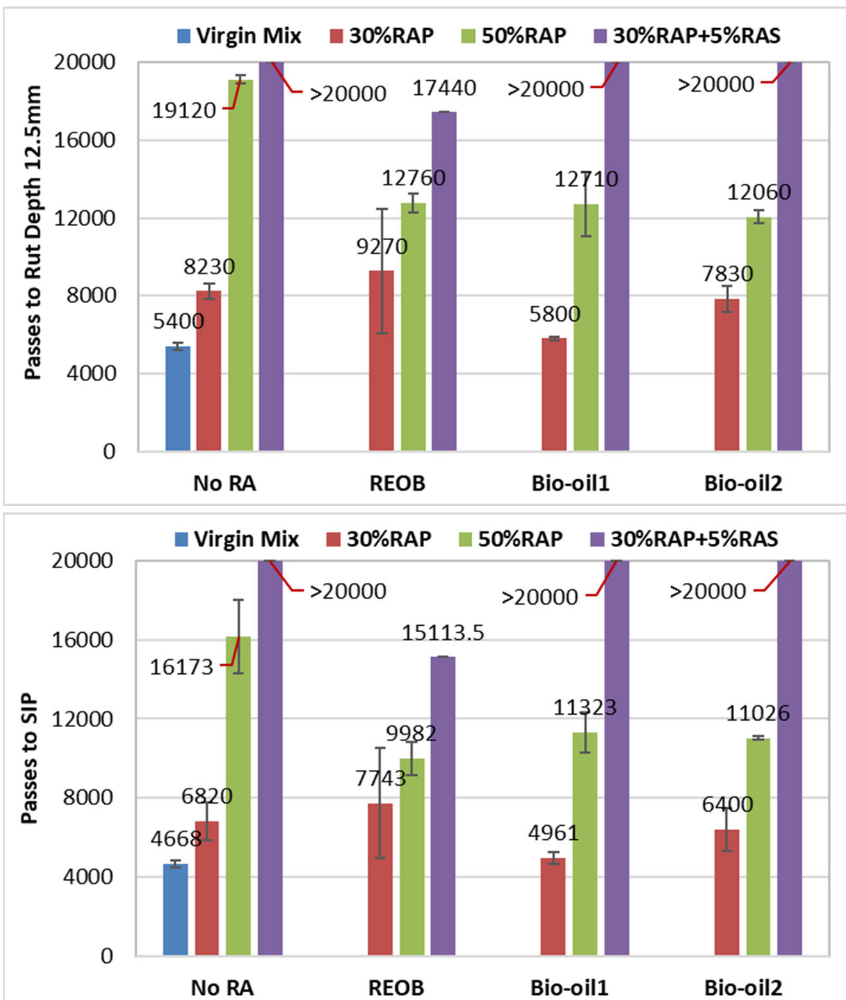


Figure 5. Effect of RAs on HWTT results.

The results in Figure 5 show that for the 30% RAP mix the choice of RA affects Passes to 12.5 mm to a greater extent than for the other two recycled mixtures. This could be a combined result of changes in dosage between the 30% RAP mixture and the other two mixtures and differences in dosage among the RA types (REOB vs. Bio-oil) for the same mixture (REOB is dosed higher than Bio-oil for all mixtures in this study). The effect of RA chemistry is evident: Bio-Oil 1 reduced Passes to 12.5 mm for the 30% RAP mixture by about 30%, whereas Bio-Oil 2 reduced the same parameter by only about 5%. The difference between the two Bio-Oils is much less pronounced for the 50% RAP mixture. At 50% RAP, each of the three RAs produced a similar drop in Passes to 12.5 mm of about 1/3. Interestingly, the Bio-Oils did not produce a measurable difference in Passes to 12.5 mm for the RAS mixture, and the average maximum rut depth remained below 5 mm. The REOB produced a measurable reduction in Passes to 12.5 mm for the RAS mixture, although the mixture still exhibited about 35% more passes than the next highest RA-containing mixture. This is an indication of the pronounced stiffening caused by RAS and the apparent lack of effectiveness of conventional RAs at reducing RAS stiffness under normal production temperatures.

The addition of RAs reduced the Passes to SIP relative to the "No RA" mix in all but one combination, an indication of increased moisture susceptibility potential. It is difficult to determine whether the reduction is SIP is indeed related to moisture susceptibility or whether this result is an artifact of the apparent correlation of Passes to 12.5 mm and Passes to SIP demonstrated by these mixtures. To better understand this relationship, the Passes to 12.5 mm for all mixtures that produced a measurable result (less than 20,000 passes) was plotted against the Passes to SIP for the same mixture. The result is shown in Figure 6.

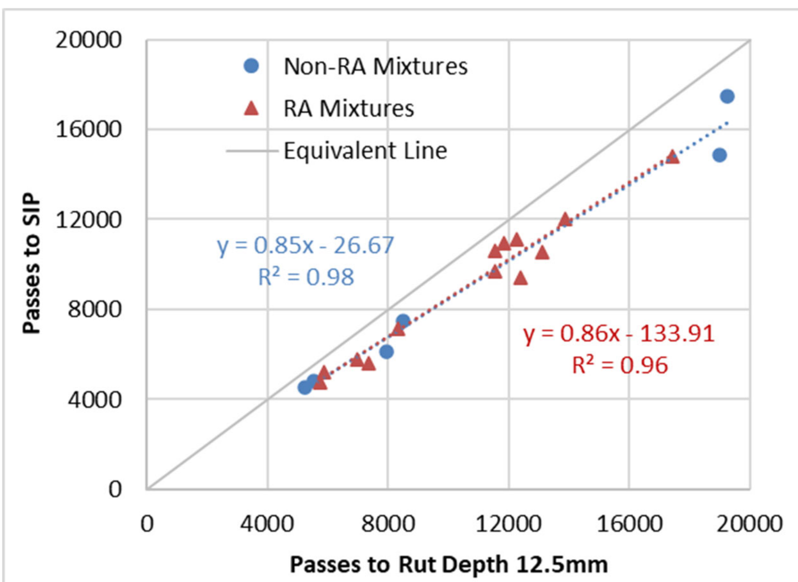


Figure 6. Passes to 12.5 mm vs. Passes to SIP for all project mixtures.

It is clear the Passes to 12.5 mm is highly correlated to the Passes to SIP for this set of mixtures. This finding suggests that the Passes to SIP as it is currently measured is perhaps not uniquely related to moisture susceptibility for this set of mixtures and that moisture damage susceptible mixtures may "Pass" a SIP specification by way of mixture stiffness as opposed to moisture damage resistance. In other words, if a mixture were to fail the Passes to SIP parameter, a simple adjustment would be to stiffen the mixture with the use of more/different recycle materials. This notion highlights the need to better understand the effects of moisture during the HWTT, as is expanded upon in the next section.

Based on the testing using the standard HWTT protocol, it is concluded that the addition of RAs produces a generally expected effect of reducing the Passes to 12.5 mm (increasing total rut depth), but that the relative effect is RA type dependent. The effect of RA type appears to be less pronounced with increased levels of RAP, and for the RAS mix only the REOB was shown to produce a measurable, albeit relatively small, change in rut performance. Although the RAs are all shown to reduce the Passes to SIP (in all but one combination), it is difficult to determine whether this finding is a result of increased moisture susceptibility or an artifact of the apparent trend between Passes to 12.5 mm and Passes to SIP for these mixtures. This confounding effect of rutting and moisture in the HWTT has been described previously (Lu & Bahia, 2019). None of the mixture-RA combinations produced a mixture with less rut resistance than an approximately equivalent virgin mixture; in other words, the concept of RAs producing detrimentally "soft" or rut-prone mixtures was not observed for the mixtures in this study for the dosage levels of RA investigated.

B. Effect of RAs on Rutting in Dry Conditions

The confounding effects of moisture during the HWTT has been widely reported (Lu & Bahia, 2019). One method to separate the effects of moisture from rutting proposed by Lu and Bahia (2019) is an advancement on the methodology proposed as a result of NCHRP 09-49. As a result of the novel analysis method a parameter called the Moisture Ratio (MR) is calculated, which conceptually is the proportion of the final rut depth that is determined to be caused by moisture effects. Therefore, a higher MR is indicative of a mixture with less resistance to moisture induced damage; the MR concept is depicted in Figure 7, with complete calculation details found in Lu and Bahia (2019).

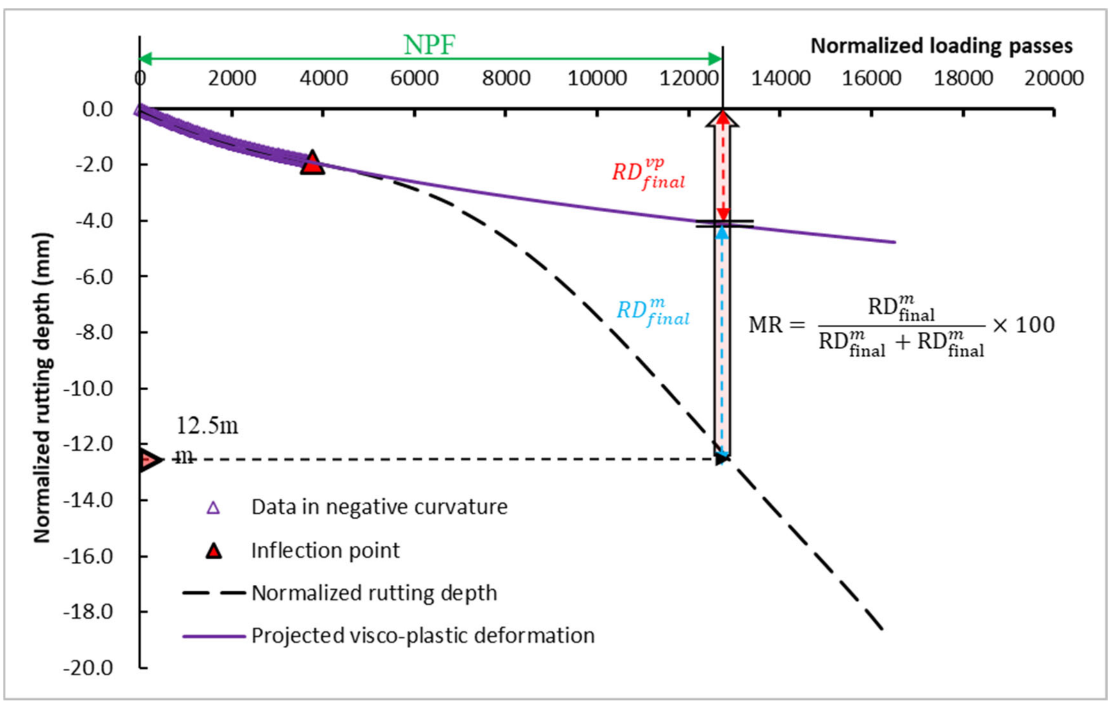


Figure 7. Calculation of the MR parameter from fitted HWTT trace, from Lu and Bahia, 2019.

The mixture HWTT data was reanalyzed using this approach of separating loading effects. The NPF factor defined in Figure 7 is the number of passes to achieve 12.5 mm rut depth. Since some of the mixtures in the present study never achieved a 12.5 mm rut depth, the NPF was selected to be 10,000 passes for this study. This allows for interpolation of the HWTT trace for all mixtures and for the comparative purposes of this study is sufficient to differentiate mixtures. The parameter "Dry Rut Depth at 10,000 Passes" was calculated to represent the dry, or visco-plastic portion of rut depth (RD^{m}_{final} in Figure 7). Figure 8 shows the results of this analysis for the mixtures without the use of RAs.

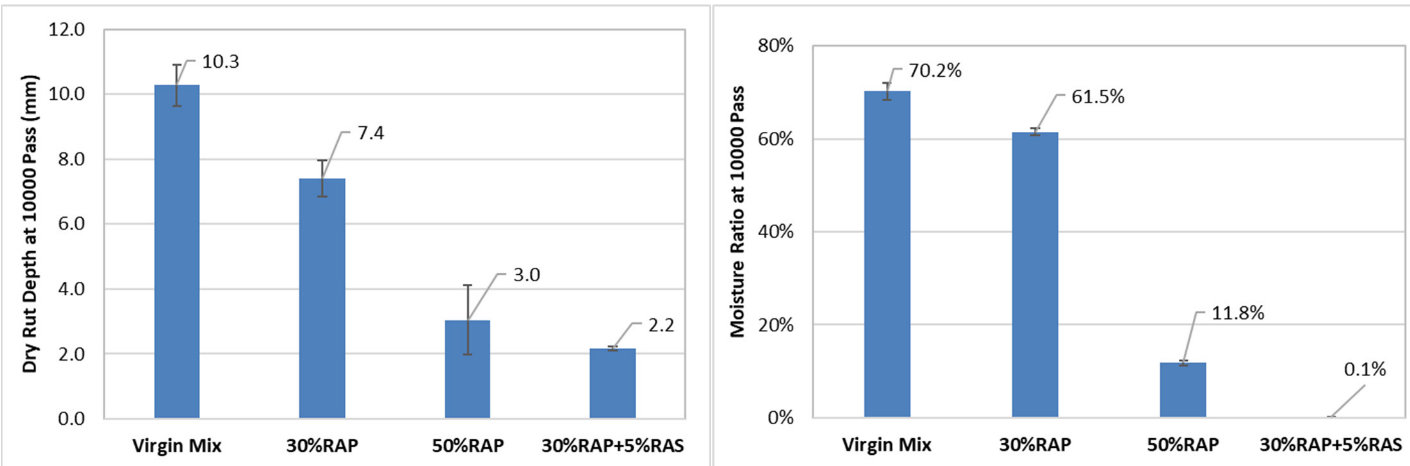


Figure 8. Separation of moisture effects for mixtures without RAs.

Using the modified analysis method, a very clear trend is observed with regard to dry rut depth and expected binder stiffness, with higher RAP and RAS percentages resulting in greatly reduced rut depth at 10,000 cycles. This finding agrees with the traditional HWTT analysis method findings for Passes to 12.5 mm and confirms the proposed analysis method can effectively differentiate between these mixtures. The MR at 10,000 passes is also in agreement with the Passes to SIP: as the rut resistance for these mixtures increases, the moisture resistance also increases. Interestingly, the MR for the virgin mixture is fairly high at 70%, which is among the highest MR values reported by Lu and Bahia (2019), indicating this mixture could be moisture susceptible. Mixtures containing the RAs were analyzed using the same procedure with the results shown in Figure 9.

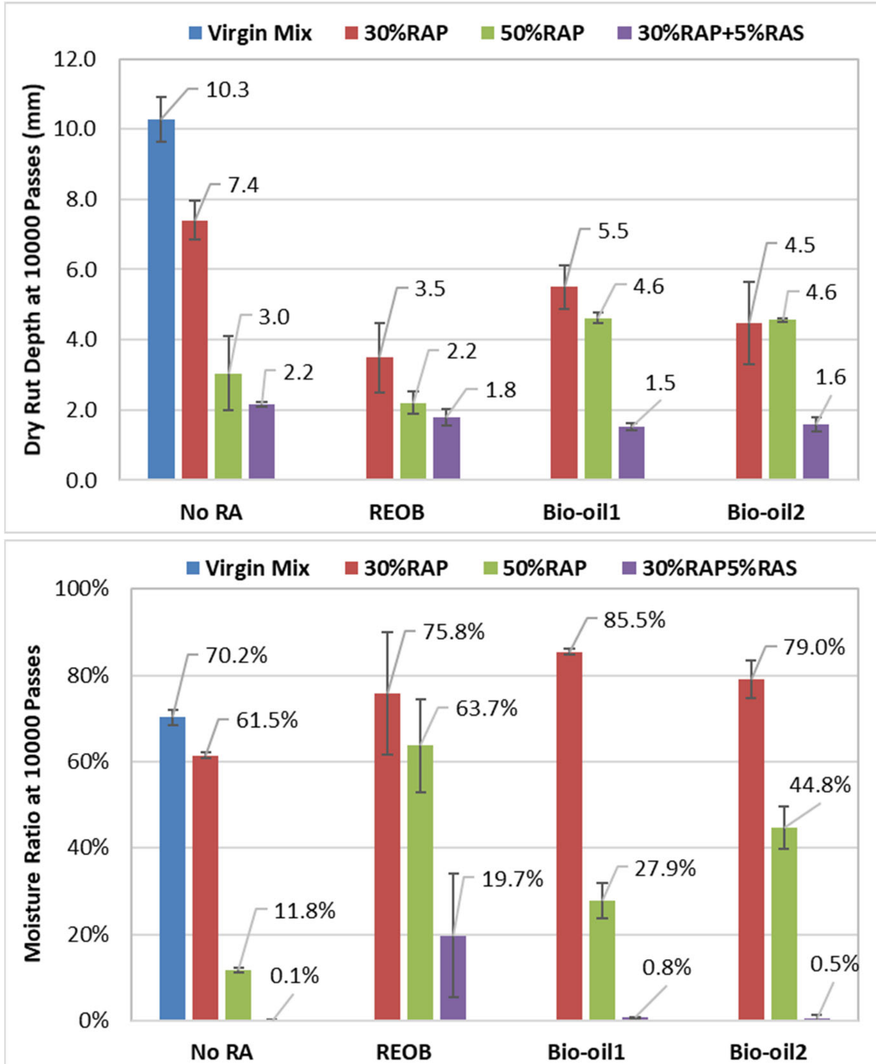


Figure 9. Effect of RAs on Dry Rut Depth and MR

The highest relative changes to rut depth occurs in the 30% RAP mixture, although more differentiation is also noted for the 50% RAP mix using this analysis method relative to the traditional method. The RAS mixture again shows very little sensitivity to RA in terms of rut depth. Noteworthy, however, is that the dry rut depth noticeably decreases with the addition of RAs for the 30% RAP mixture. A decrease is also measured for some combinations for the 50% and RAS mix, although the differences are not as significant as measured with the 30% RAP mixture. Note that this finding contrasts the Passes to 12.5 mm parameter results in which the RAs reduced rut resistance.

Based on the MR data for the 30% and 50% RAP mixtures, it is observed that the addition of RAs (both REOB and Bio-Oil) increase the moisture damage portion of the rutting curve, sometimes significantly. For the 30% RAP mixture the REOB and Bio-oils produced a statistically similar increase in MR, whereas for the 50% RAP mixture the REOB produced an MR significantly higher than the Bio-oils. This may be a result of increased dosage for the REOB magnifying the moisture effects. In the RAP and RAS mixture, the addition of REOB significantly increased the moisture damage in the mixture, whereas the Bio-oils produced a negligible effect. Observations made by the laboratory technician running these tests confirmed this measurement: significant stripping was noted in the REOB mixture at the conclusion of the test. Since the MR increases for the RA mixtures, the dry potion of the rut depth is shown to decrease, not as a result of rutting resistance but moisture damage in the mixture.

This data highlights the importance of understanding the confounding effects of moisture in the current version of the HWTT. For all combinations of additives used in this study the moisture damage effect on rutting was found to be on average higher than the corresponding mixture without the additive, sometimes significantly so. Using the traditional analysis method did not provide the same conclusion. With regard to the present study, the data suggests that the addition of RAs may significantly increase moisture damage potential in the mixture, and the relative effect is specific to the type and composition of the RA.

V. Cracking Resistance of High RAP and RAS Mixtures

Premature cracking remains one of the most cited pavement distresses attributed to high RAP and RAS usage (Epps Martin et al., 2019). Accordingly, an intermediate and/or low temperature cracking test is usually included in Balanced Mix Deign Framework. Several mixture cracking tests have been developed that simulate the various modes of failure encountered in the field, although no consensus exists on which test, or tests, best simulate field conditions. One test that has gained popularity as a relatively quick and simple cracking indicator is the IDEAL-CT proposed by Zhou (2019) and standardized as ASTM D8225. In this study, the IDEAL-CT, a modified version of the IDEAL-CT and a modified version of the AASHTO TP105 SCB test were used to evaluate cracking resistance of the project mixtures.

A. Evaluation of RA Dosage Method using the IDEAL-CT

A limited study was designed to evaluate whether the RA addition method influenced cracking results. The design of this experiment is summarized in Table 6. The rationale for using the IDEAL-CT at 0 °C is explained in subsequent sections. Note that the dosage of Bio-Oil was the same between methods: 3% for the 30% RAP mixture and 5% for the 50% RAP mixture. To apply the Bio-Oil directly on the RAP, a hand-held sprayer was used; a known mass of lab-temperature RAP material was placed into a pan, the pan was placed on a balance and the balance was tared. The calculated quantity of Bio-Oil was sprayed onto the RAP and the RAP was placed into the oven to preheat before mixing. All other mixture production variables were the same otherwise.

Table 6. Dosage Method Experiment

Mixture	Level	Recycling Agent	Comment
Mixture type	2	30% RAP	--
		50% RAP	--
Recycling agent	1	Bio-Oil 1	--
Dosage Method	2	Pre-Blending with Virgin Binder	Control Method
		Direct Application on RAP Material	RAP materials dosed immediately prior to mixing
Aging condition	2	STOA	4 hours at 275 °F
		LTOA	8 hours at 275 °F
Test	2	IDEAL at 25 °C	LLD rate of 50 mm/min
		IDEAL at 0 °C	LLD rate of 0.5 mm/min

Results of the experiment are shown in Figure 10 with the CT Index measured at 25 °C on the top row and the CT Index measured at 0 °C on the bottom row.

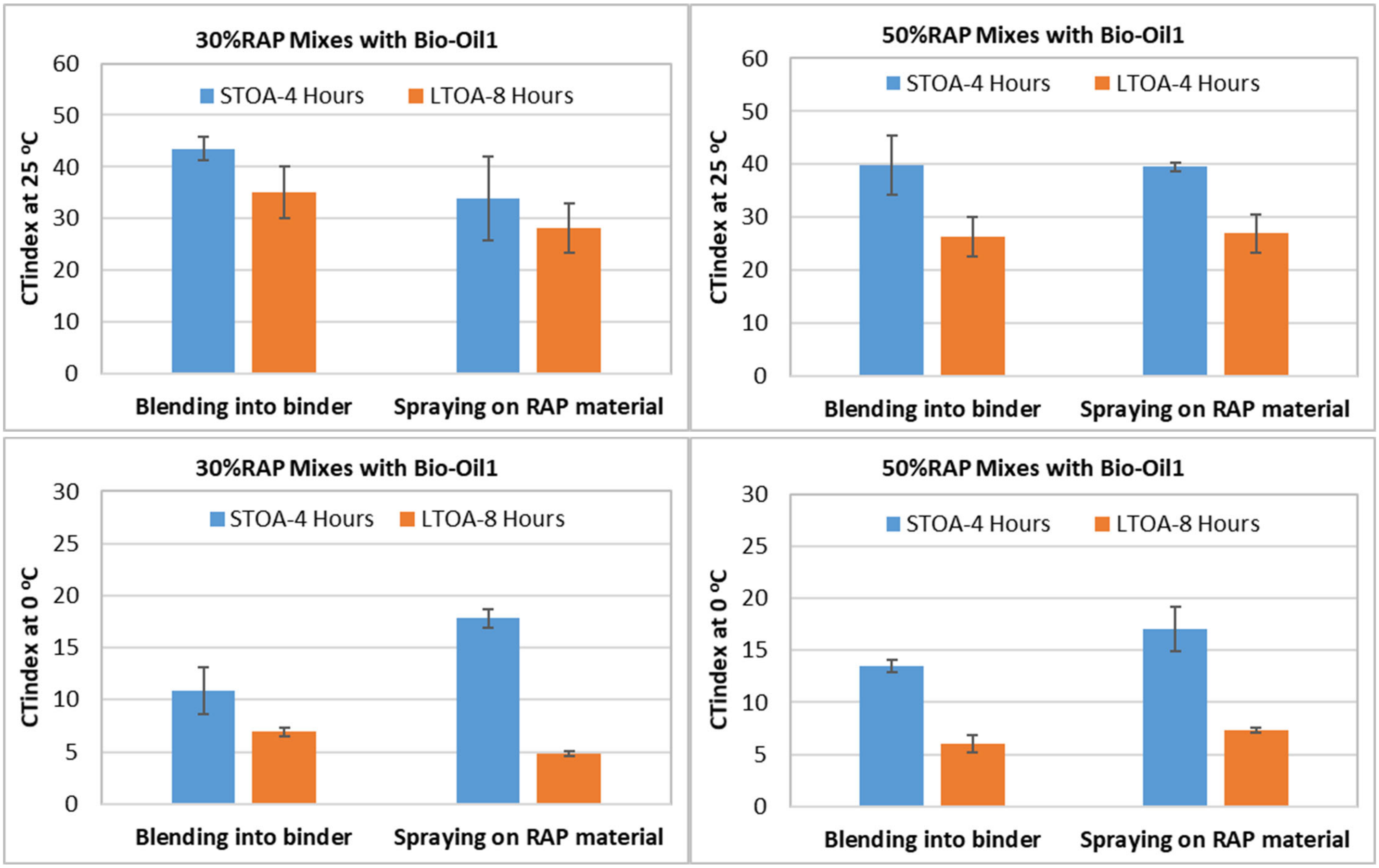


Figure 10. Dosage method results for mixtures tested at 25 °C (top row) and 0 °C (bottom row).

Although differences in average CT Index are noted between the two dosage methods the differences are generally within one standard deviation of each other for both aging levels and both RAP levels at 25 °C. Testing results at 0 °C show the differences in CT Index are greater for the STOA-4 hour condition, with the direct application method producing higher CT Index values. The difference in CT Index is more pronounced for the 30% RAP mixture (48% difference in values) and appears to reduce somewhat with aging (37% difference in values). For the 50% RAP mixture the percent difference in CT Index is 2% for the STOA-4-hour condition and 19% for the LTOA-8-hour condition. It is also noted that the average CT Index for the STOA-4-hour condition is lower for the direct application method at 25 °C but higher for the direct application method at 0 °C. The LTOA-8-hour samples do not show consistent trends for a given temperature.

Based on the findings, it is noted that application method marginally affects the CT Index at both temperatures and aging levels, particularly for the 0 °C samples. However, the practical significance of the observed differences in CT Index is questionable. It is concluded that for this project the method of RA incorporation does not significantly and reliably improve mixture performance. As such, and accounting for the findings of the literature review, the research team decided to use the method of incorporating the RA into the virgin liquid as this is the method most practical for producers using less than 100% RAP.

B. Evaluation of Cracking Resistance using the IDEAL-CT at 25 °C

In this section the project mixtures were tested at 25 °C according to ASTM D8225 at two levels of aging: STOA-4 hours and LTOA-8 hours. The primary output of the IDEAL-CT is the "CT Index" which is a calculated parameter involving the mixture Fracture Energy and the slope of the loading trace following the peak load at the point where the load is 75% of the peak value (referred to as PPP_{75} or "Post-Peak Slope" in this study). In addition, the peak load measured during the test is also a useful parameter to note since it is a basic indicator of mixture stability. The details of these parameters can be found in the associated testing standard. For the purposes of this report, the CT Index is presented along with the Peak Load, Fracture Energy, and Post-Peak Slope. Post-Peak Slope is inherently a negative value, with lower values (i.e., more negative) being viewed as detrimental to cracking resistance; for the purposes of this report the absolute value of Post-Peak Slope is reported, i.e., the higher the reported value, the more negative the Post-Peak Slope, and the lower resistance to cracking that is expected. Note that there are several proposed limits for CT Index presented in the literature but note that the limits may be at different aging conditions than those used in this report. The CT Index is used in this report primarily as a comparative tool between mixtures. Findings for the mixtures without RAs are shown in Figure 11.

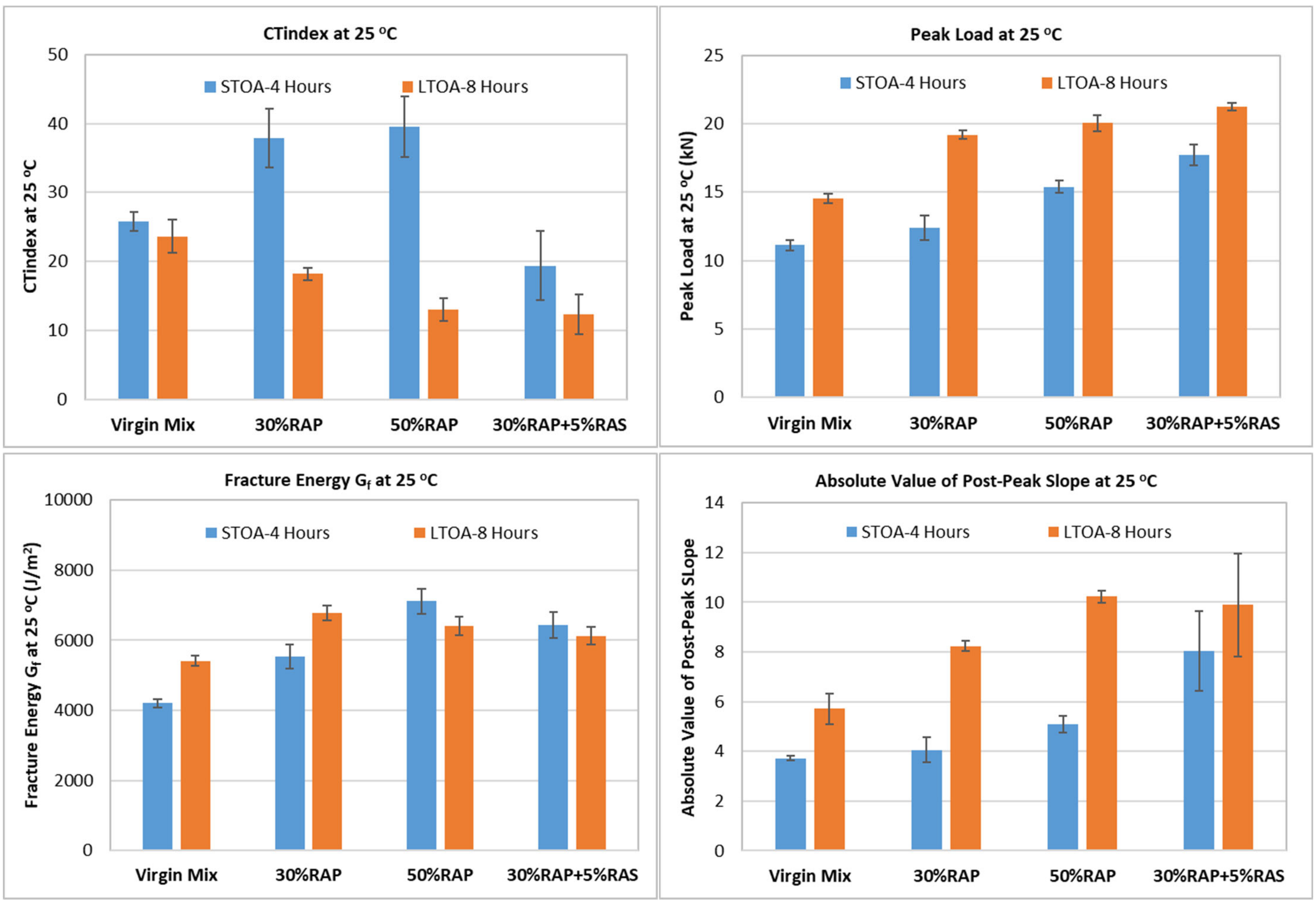


Figure 11. IDEAL-CT results for mixtures without RAs.

Although it is shown that the CT Index can effectively discriminate between mixtures, the results presented in Figure 12 also demonstrate the advantage of reporting all parameters as opposed to the CT Index alone when comparing mixtures. The CT Index of the STOA samples increases for the 30% and 50% RAP mixtures relative to the virgin mix, an indicator of better overall cracking resistance. The post peak slope becomes more negative for these mixtures, suggesting decreased crack propagation resistance. However, it is shown that the peak load and fracture energy of these mixtures is higher than the virgin mix. Since CT Index is a calculated parameter involving both measurements, the net effect of the changes for these mixtures is a higher CT Index. For the RAP and RAS mixtures and the LTOA mixtures this effect is reduced, and the CT Index for those mixtures is lower than the corresponding virgin mix.

The effect of loose mixture aging on CTindex is logical. As aging was increased from four to eight hours, cracking resistance decreased, primarily as a result of the corresponding reduction in Post-Peak Slope. Fracture Energy is not shown to change as drastically as Post-Peak Slope between aging conditions, or between mixtures for that matter. It appears that based on this data CT Index is strongly controlled by Post-Peak Slope. Peak load follows a logical trend that aligns with the HWTT findings presented earlier; As the mixture effective binder becomes stiffer by way of increased RAP and/or RAS or aging, the peak load increases. In other words, the mixture deformation resistance (stiffness) increases with RAP/RAS and/or aging. Indirect tension peak load has been used by researchers as a simple surrogate for deformation resistance (Bennert, Haas, & Wass, 2018).

The addition of RAs is expected to restore cracking resistance to the mixture, resulting in an expected increase in CT Index, reduction in Peak Load, and increase in Post-Peak Slope (less negative). The effect on Fracture Energy is likely a function of the Peak Load and Post-Peak Slope changes. CT Index results for the three RAs are shown in Figure 12. To further differentiate between mixtures and to evaluate the extended aging susceptibility, a third aging condition “LTOA-16 hours” was added to this data set of the results measured at 25 °C.

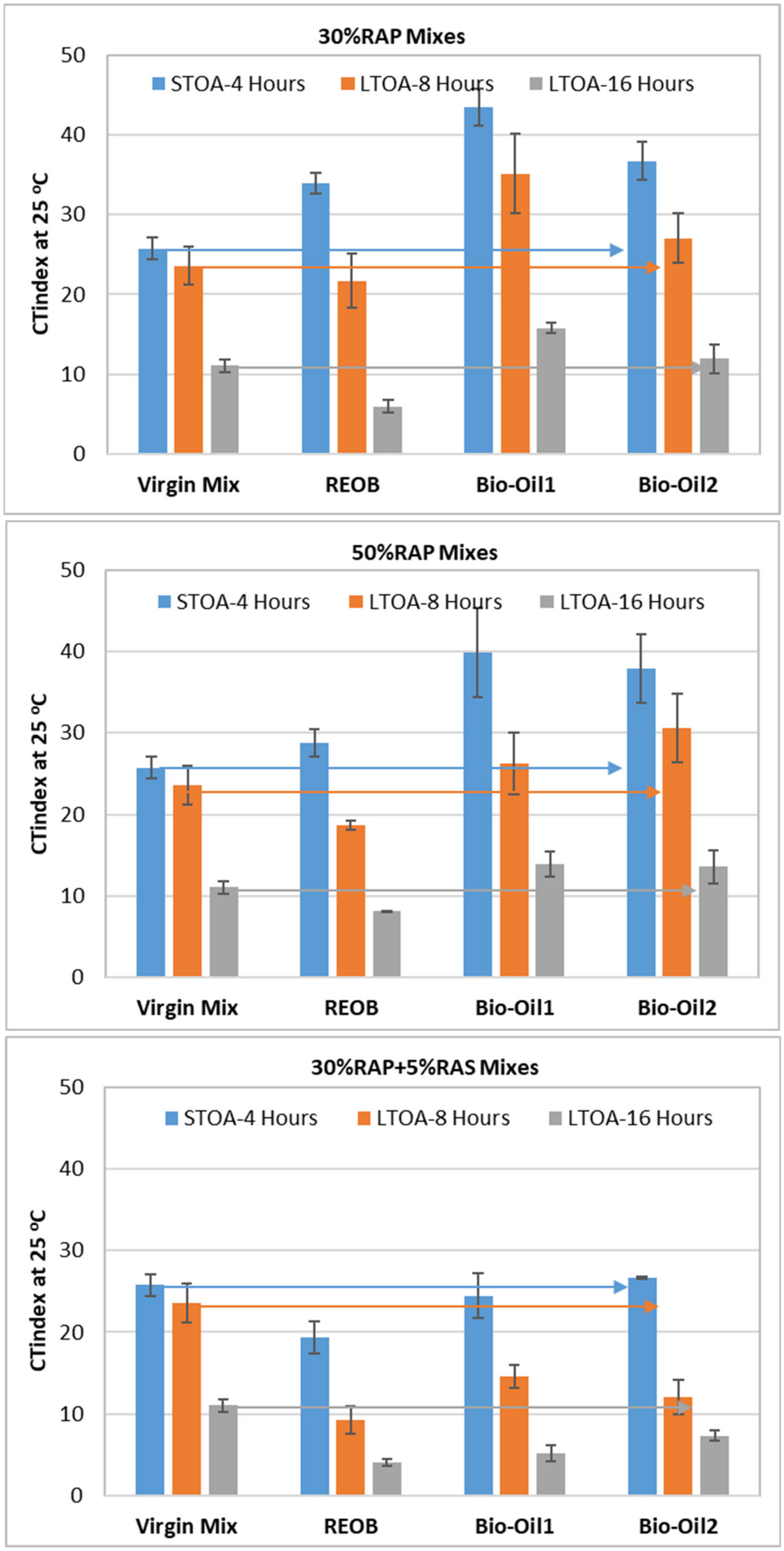


Figure 12. CT Index values for mixtures with RAs at three levels of aging.

Confirming trends seen in Figure 11, all mixtures exhibited a decrease in CT Index with more aging for all RA types, and the magnitude decrease due to aging is dependent on the mixture composition and the RA type. The ability of RAs to restore cracking resistance to the Virgin Mix is also found to be dependent on the RA type and composition of mix. The 30% and 50% RAP mixtures show similar trends in their reaction to addition of RA. For example, REOB could not restore the CT Index values for the 8-hour and 16-hour aging conditions relative to the corresponding Virgin mix, and for the RAP and RAS mixture this was also the case for the 4-hour aging. In addition, for the 30% and 50% RAP mixtures, the Bio-Oils resulted in a higher CT Index value relative to the corresponding Virgin mix at all levels of aging, suggesting the addition of Bio-Oil can effectively offset some or all of the effects of adding high percentages of RAP on cracking resistance parameters, even after extend aging (16 hours). However the effect of RAs are not as successful with the 30%RAP +5 % RAS mixture; results show that adding the 5% RAS could not be rejuvenated to the virgin condition with 10% REOB for all aging conditions and adding the 5% Bio Oils could only restore the CTindex for 4-hours aging. The 8-hour and 16-hour results show the Virgin mix continued to have a higher CT Index by a significant margin. This finding regarding the RAS mixtures suggests that the additives are not as effective at restoring and maintaining cracking resistance for very stiff asphalt materials such as RAS.

One practical application of this research is troubleshooting a mixture that exhibits a lower than specified CT Index value (i.e., how can a mix designer most efficiently address non-conforming mixtures?). Since it was demonstrated for the control (No Additive) recycle mixtures that there are confounding effects of changing Peak Load, Fracture Energy, and Post-Peak Slope on the CT Index, these parameters were calculated separately for each mix. The results for the 30% RAP + 5% RAS mix are shown in Figure 13 but the findings are representative of the other mixtures in this study. The CT Index is presented again for completeness.

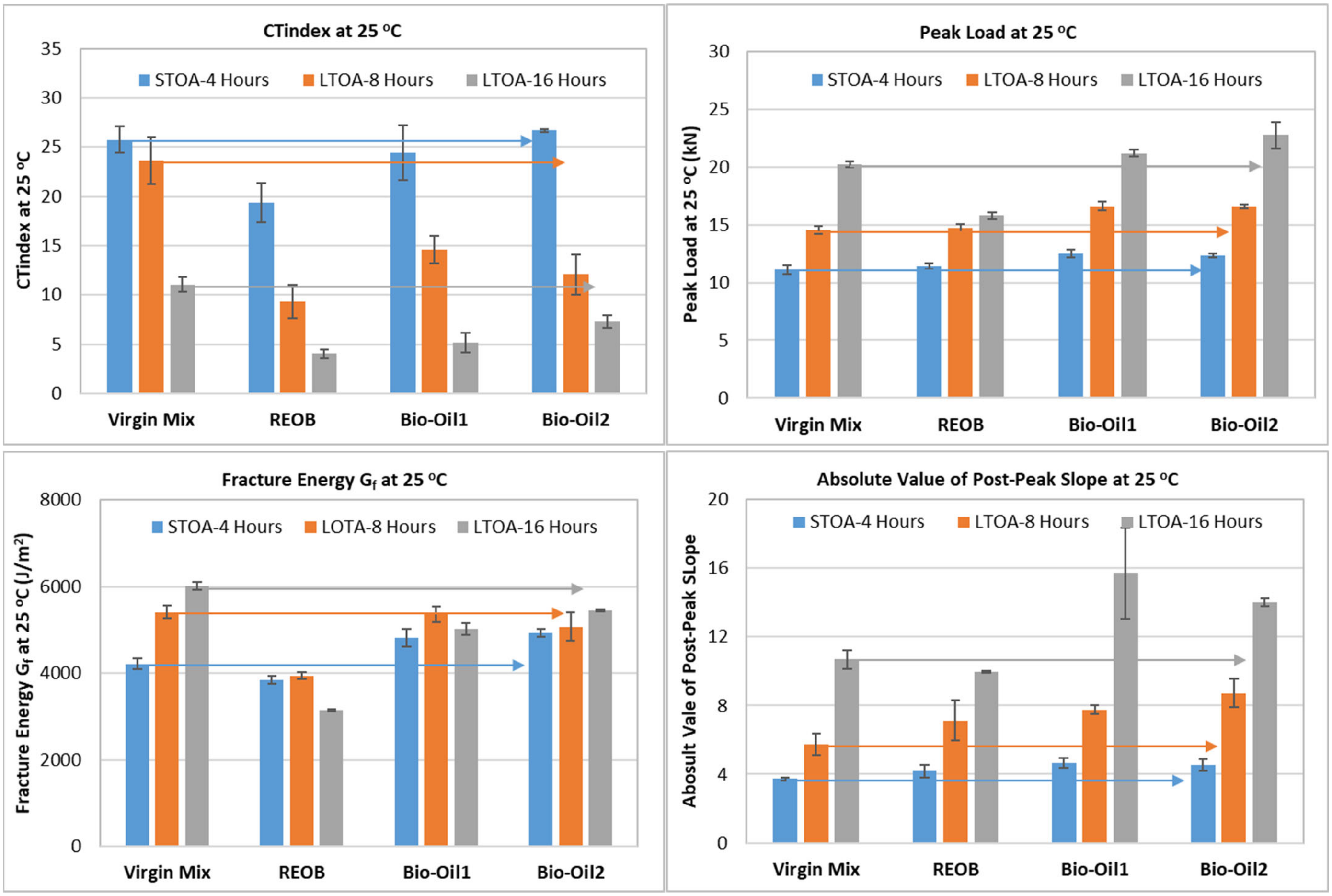


Figure 13. IDEAL CT parameters for 30% RAP+5% RAS mixture with RAs.

The results presented in Figure 13 confirm the findings presented in Figure 11 that the confounding effect of increasing Fracture Energy while decreasing Post-Peak Slope as a result of aging can make interpreting the CT Index difficult when comparing mixtures. In Figure 13 the incorporation of RAs is further shown to complicate this analysis since RAs characteristically reduce fracture energy but have less predictable effects on Post-Peak Slope. Figure 13 also provides further confirmation that CT Index is highly correlated to the inverse of the Post-Peak Slope.

To further illustrate this finding, Figure 14 includes all mixture combinations and aging levels; an exponential fit provided the highest coefficient of determination of 80%. Note that the aging levels are color-coded and that some overlap exists between the colored groupings.

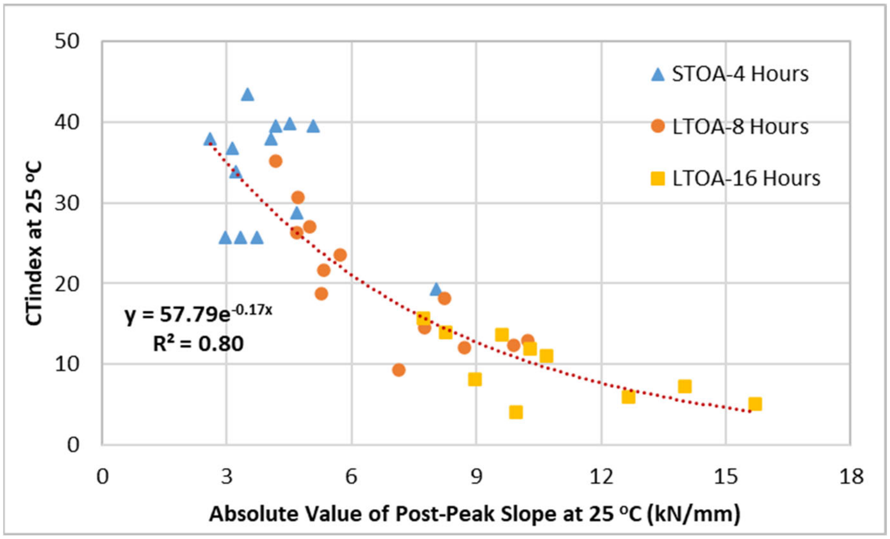


Figure 14. Relationship between CT Index and Post-Peak Slope for all mixtures.

Attempting similar correlations between the other individual parameters and CT Index resulted in significantly lower coefficient of determination values; for example, the best fit correlation between Fracture Energy and CT Index is less than approximately 0.005 for the available regression models. This finding suggests that Post-Peak Slope and Fracture Energy are providing different information about the sample, and that by separating both parameters, more information can be gained relative to using CT Index alone. This concept can help during the design and/or troubleshooting process for mixtures that fail specification.

An example of such an approach to specification is shown in Figure 15; data labels in Figure 15 represent the corresponding CT Index value for that mixture combination. Two key examples are offered: incorporating a vertical line at a Post Peak Slope of 10.0, one can observe that CT Index values of 4.0 and 13.0 can be achieved as a result of increasing Fracture Energy. Conversely, incorporating a horizontal line at approximately 5,000 J/m^2 on the Fracture Energy axis one can observe differences in CT Index values from 5.2 to approximately 37.9 as a result of changes in Post-Peak Slope. Since there is at least some overlap between the data points for each aging condition, mixture factors other than aging are causing the changes in parameters.

It is important to mention that Fracture Energy represents the total energy under the load vs deformation curve which means that some of the energy is spent in visco-plastic deformation before the crack initiates. On the other hand, recognizing that the peak load occurs just before a crack is initiated, the post peak slope can be considered as the indicator for cracking propagation rate. Ideally good performance should include high resistance to crack initiation (high Fracture Energy) and high resistance to crack propagation (low post peak slope). Therefore, it is logical to have a minimum limit on Fracture Energy and a maximum limit of the Post Peak Slope, as hypothetically shown in the green shaded area in Figure 15. Such an approach will reduce or eliminate the risk of using very soft mixtures that will have a very low value of Fracture Energy with a very low Post Peak Slope. This is a similar approach to using the S(60) and m(60) in the BBR test of the Superpave binder specifications.

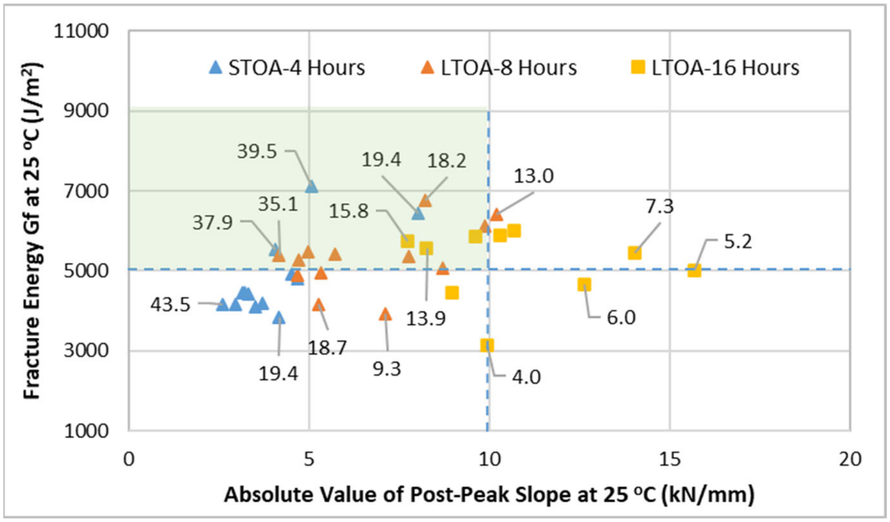


Figure 15. Fracture Energy and Post Peak Slope for all mixture combinations at 25 °C.

Based on the data presented in this section it is concluded that the IDEAL-CT Test at 25 °C can effectively differentiate between mixtures, but using the CT Index value alone can be misleading as the contribution of the factors used to calculate the CT Index can somewhat offset each other when changes to aging or additive level are considered. It is demonstrated that CT Index is primarily (~80% in this study) controlled by the Post-Peak Slope, and by considering Fracture Energy and Post-Peak Slope behavior independently, more information regarding mixture performance can be gained. An example of such an approach using "CT Index Envelopes" is given.

C. Low Temperature Cracking Resistance

Two procedures were used to evaluate low temperature cracking resistance during this project. A low temperature version of the SCB test (AASHTO TP105, modified) was first selected based on the authors' prior experience using the test and existing literature using the test to characterize mixtures from the upper Midwest region. The procedure was modified to accommodate the capabilities of the laboratory, namely the use of LLD strain rate control versus the specified CMOD control during the test. Based on the findings using the SCB test described below, the authors opted to use a modified version of the IDEAL-CT test at low temperature.

i. Evaluation of Cracking using Modified AASHTO TP105 – SCB

The research team selected the 30% RAP mixture as the first mixture to be tested since it represents a "middle ground" for the mixtures included in this study. A test temperature of -12 °C was first selected based on the anticipated effective low temperature PG of this mixture. Four replicates were tested, and results exhibited very high variability. Example test traces from this mixture are shown in Figure 17.

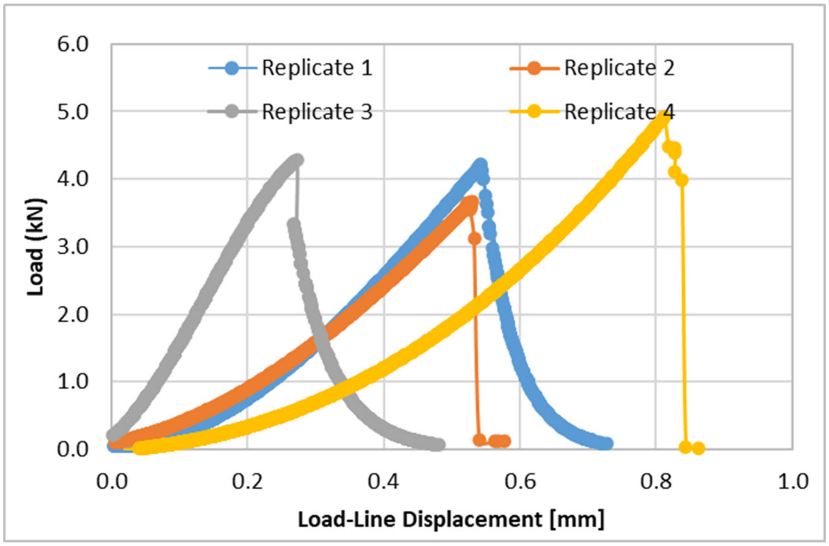


Figure 17. Example test output for 30% RAP mixture using the Modified TP105 procedure at -12 °C.

In addition to the high variability, the initial testing showed that some of the aggregate at the cracking interface fracture during the test, although the pattern of aggregate fracture appeared inconsistent between samples. An example photograph of this behavior is included in Figure 18. Prior studies have identified a similar observation for the Disc-Compact Tension (DCT) test, which is similarly run at low temperature (Bahia et al., 2016). It is hypothesized that the semi-random nature of the aggregate fractures is causing the significant variability during the test. The research team does not believe that such aggregate fracturing is caused by the fast loading rate and it is not representative of field conditions. To resolve this problem two means to reduce or eliminate this phenomenon the temperature and cooling rate needed to be adjusted.

Figure 18. Fracture of aggregate at cracking interface using the modified TP105 SCB procedure.

First, the research team attempted to raise the testing temperature initially to -6 °C then to 0 °C to determine if testing temperature alone could eliminate the aggregate fracture. For this analysis it was decided to use the mixture with the expected highest stiffness, the 30% RAP + 5% RAS mixture, to represent "worst case scenario". A similar observation of aggregates fracture that was made for the 30% RAP mixture was noted at both -6 °C and 0 °C for the mixture containing RAS. Similarly, high variability was also noted in the testing results. Based on this observation, a decision was made to adjust the loading rate as it appeared to be necessary to obtain repeatable results with no fracture of aggregates.

Following the findings using the SCB test the research team decided to explore using a modified IDEAL-CT test at low temperature since samples are easier to produce and less variability is induced by cutting and notching the sample required for the SCB. To screen variables and define the best temperature and loading rate for the IDEAL test, a representative Wisconsin mixture was selected. Testing was conducted first at -10 °C using strain rates of 1 mm/min, 0.5 mm/min, and 0.1 mm/min. At this temperature aggregate fracture was observed at all three strain rate levels, although the prevalence of fracture appeared to be lower when lower strain rates are used.

Next, the temperature was increased to 0 °C. Using a strain rate of 1 mm/min, the sample exhibited very little aggregate fracture at 0 °C compared to -10 °C, as shown in Figure 19. Fixing the test temperature at 0 °C, the research team then reduced the strain rate to 0.5 mm/min and again to 0.1 mm/min. The 1 mm/min samples exhibited relatively brittle failure (highly negative Post-Peak Slope), making differentiation between mixtures difficult (Figure 19). The samples tested at 0.1 mm/min and 0.5 mm/min exhibited clear post-peak behavior and very little aggregate fracture. Ultimately the time savings associated with conducting the test at 0.5 mm/min was factored in and the final conditions for the low temperature cracking tests conducted for this study were fixed at 0 °C using a strain rate of 0.5 mm/min. The sample preparation and analysis method followed ASTM D8225.

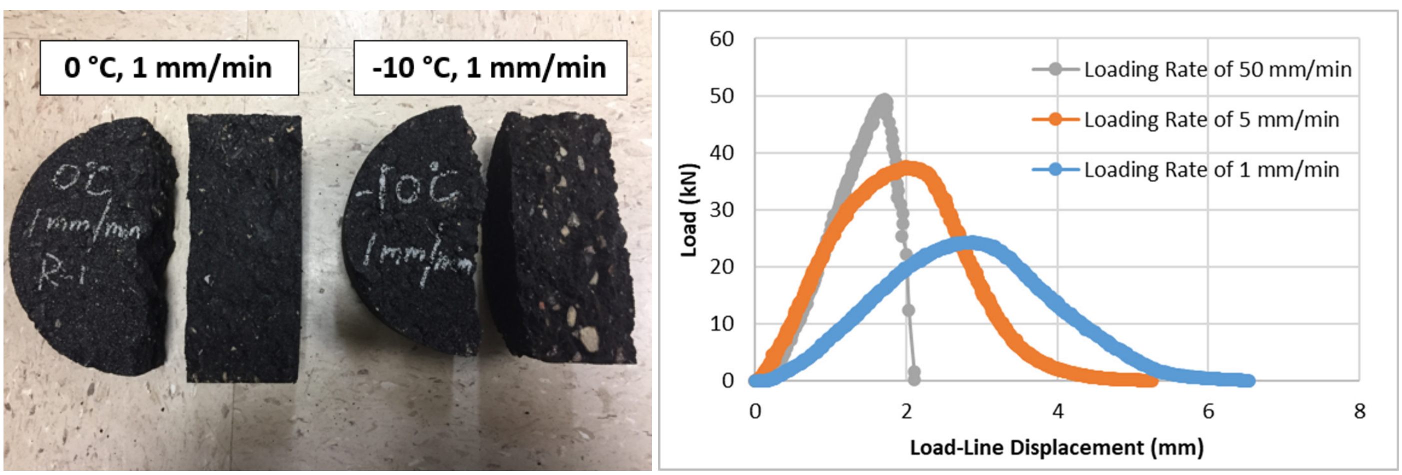


Figure 19. Left: aggregate fracture at -10 °C; Right: effect of loading rate on testing trace at -10 °C.

ii. Evaluation of Low Temperature Cracking Resistance using the Modified IDEAL-CT Method

The four mixtures without RAs were first tested using the prescribed conditions of 0 °C and 0.5 mm/min. Similar to the 25 °C testing, the CT Index and three consitutent parmaters were calcualted for all mixtures from data collected at 0 °C as shown in Figure 20.

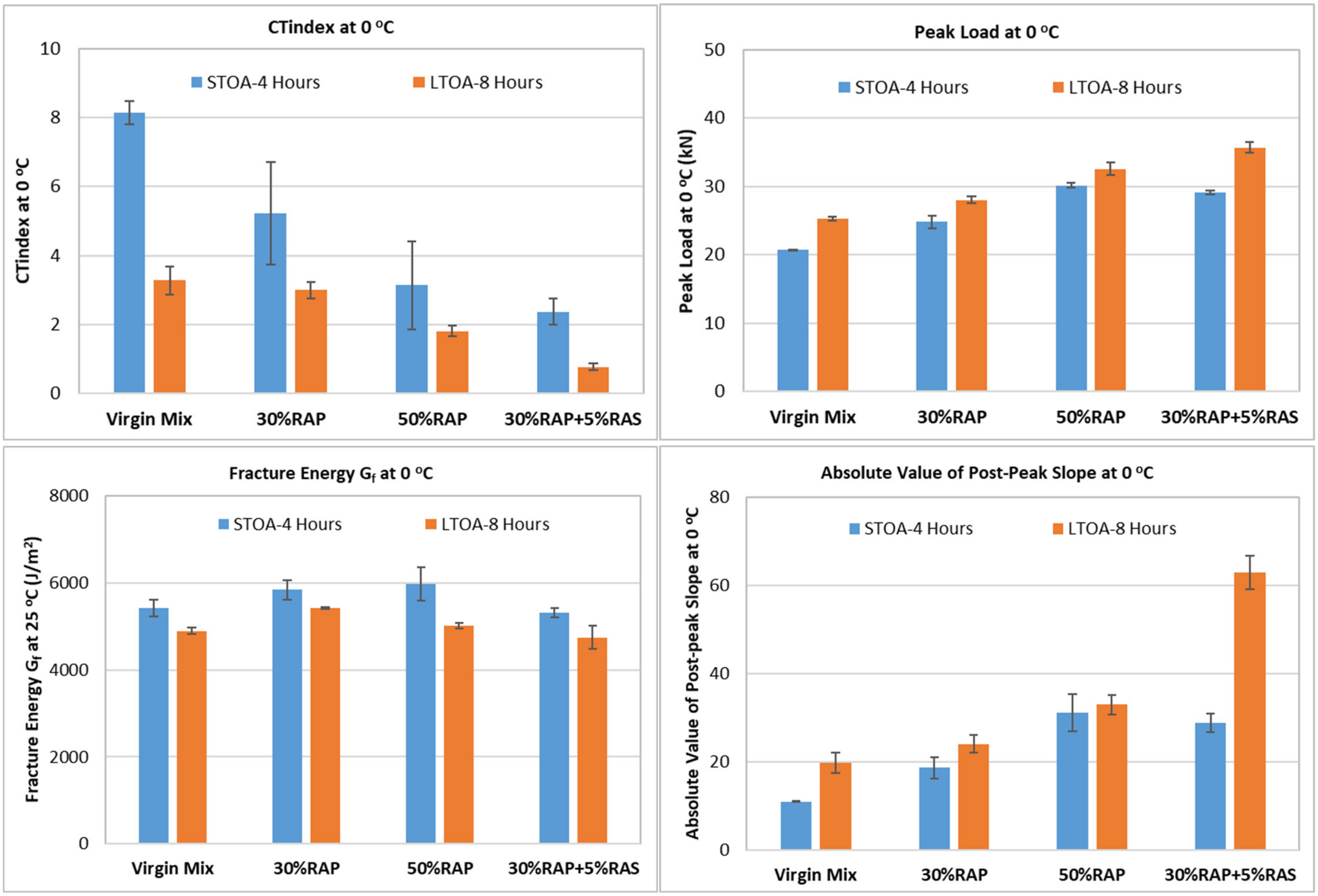


Figure 20. CT Index results for mixtures without RAs at 0 °C and 0.5 mm/min and two levels of aging.

A logical trend is observed for the CT Index changes; with increasing RAP and/or RAS resulting in a lower cracking index. The effect of aging on the CT Index is also pronounced and logical. Recall that this was not the observation made at 25 °C. It is also observed that the mixtures exhibit less differentiation in Fracture Energy at 0 °C than at 25 °C, whereas Post-Peak Slop differentiation is still very high, which justifies the trends in CT Index values. Note that the Fracture Energy measured at 0 °C is within the range of Fracture Energy measured at 25 °C (albeit on the high end), whereas the Post-Peak Slope is significantly lower (more negative) at 0 °C relative to 25 °C. Peak load is higher at 0 °C than at 25 °C, but the differences between the two temperatures are not as pronounced as compared to Post-Peak Slope. For example, the 50% RAP mix at the STOA (4-hour) condition exhibited a 0 °C Peak Load of 30 kN and 16 kN at 25 °C, an increase of about 90%. The Post-Peak Slope of the same mix was measured at approximately 30 at 0 °C and approximately 5 at 25 °C, an increase of approximately 500%. The results show that the Post Peak slope is the most sensitive parameter to changing the temperature and the loading rate. It is also the most sensitive to the RAP/RAS addition in the mixture.

The mixtures with the addition of RAs were similarly tested with the results shown in Figure 21. Although not shown, the three individual parameters of Peak Load, Fracture Energy, and Post-Peak Slope exhibited similar behavior to what was demonstrated at 25 °C for each mixture, suggesting the same mechanisms control CT Index at 0 °C and 0.5 mm/min.

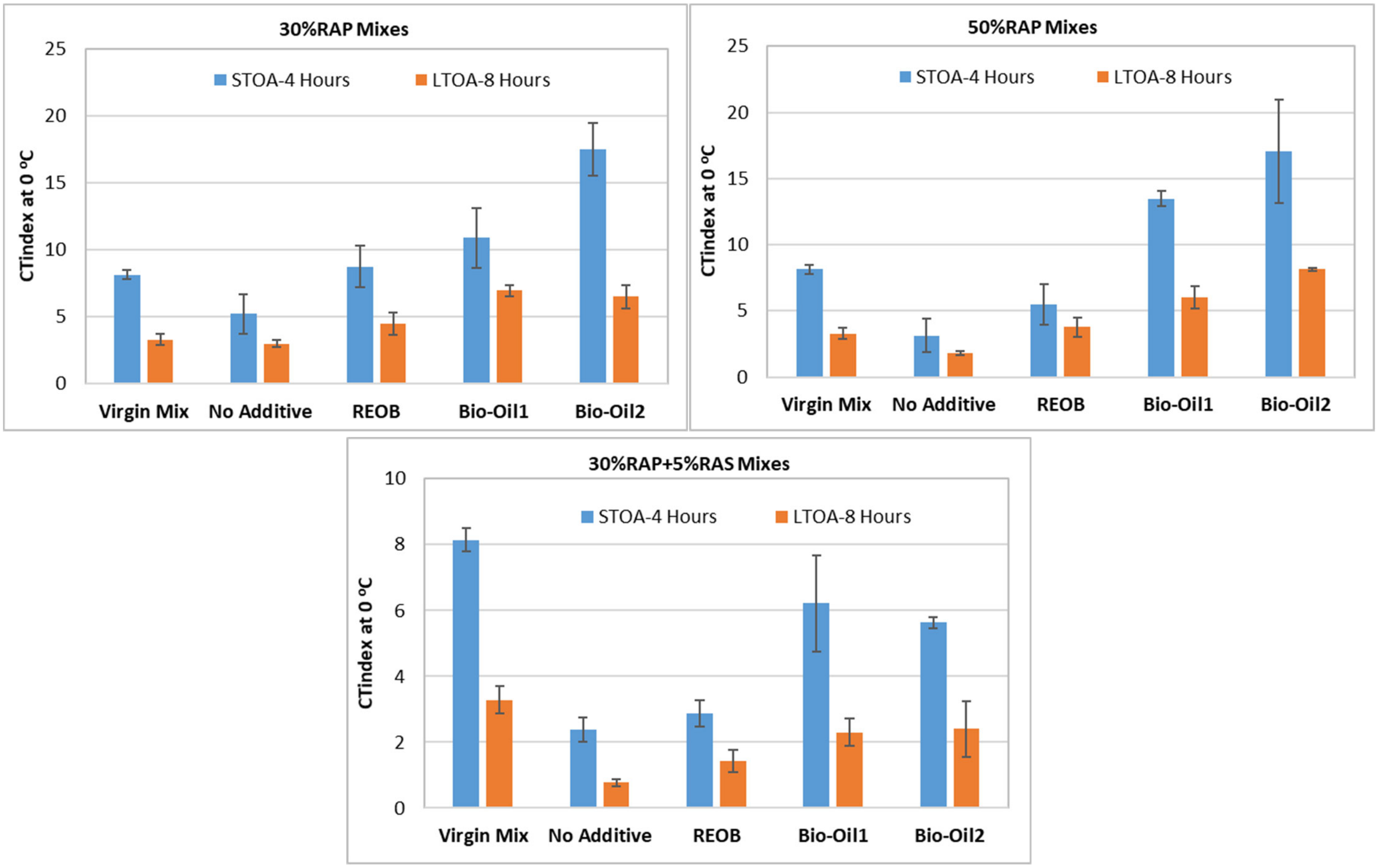


Figure 21. CT Index results for mixtures with RAs at 0 °C and 0.5 mm/min and two levels of aging.

For all mixtures the addition of RAs increased the CT Index at both levels of aging, sometimes by almost a factor of four relative to the corresponding No Additive mix, but could not restore the CT Index to the values of the Virgin Mix in in all cases. The increase of the RAs is generally greater for the RAP only mixtures. The Bio-Oils produced a more pronounced effect on CT Index relative to the REOB, and differences between the Bio-Oils are also observed, suggesting there the composition off the Bio-oil has some effect in particular for the 30 % RAP mix. The differences between the two Bio-Oils is muted after the LTOA-8-hour conditioning, although the effect remains greater than that of the REOB for each mixture. The CT Index for the LTOA-8-hour samples remained higher than the corresponding No-Additive mixture all combinations as well, suggesting that the cracking resistance gained through the use of RAs is at least somewhat maintained after aging. The gain for the mixture with the RAS, however, is not sufficient to match the Virgin Mix cracking resistance at both aging levels.

Given the dependence of CT Index on Post-Peak Slope, a chart of the Fracture Energy and Post-Peak Slope at 0 °C can be produced similar to what was presented at 25 °C. CT Index values for the various combinations are included as the data labels in Figure 22 for select combinations. Again, overlap between the aging conditions is noted, suggesting that there are several mix designs factors that influence CT Index. Figure 22 confirms that Fracture Energy and Post-Peak Slope are measuring different mixture properties independent of temperature, suggesting there may be utility in specifying limits or ranges for both parameters to control CT Index.

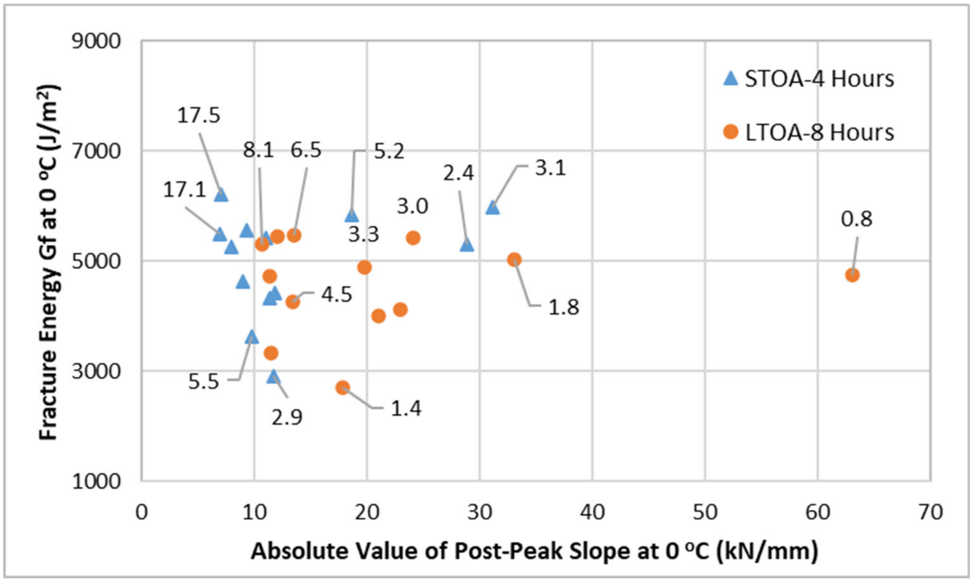


Figure 22. Fracture Energy and Post Peak Slope for all mixture combinations at 0 °C and 0.5 mm/min

The findings summarized above are in general agreement with the findings at 25 °C. The implication of this is that the mechanism by which the RAs increase cracking resistance is not necessarily dependent on temperature, although the relative magnitude of the effects of a given RA on cracking resistance is. In other words, a given additive may be more effective within a certain temperature range than another, but this ranking could flip if the temperature range is changed. The selection of additives should therefore be based on the intended climate as well as performance and cost-related factors.

VI. Effect of RAs on Asphalt Binder Properties

NCHRP 09-58 determined that the most realistic assumption of whether the binders in RAP and RAS are contributing to performance of the mixture is that they are partially activated and have a certain contribution that is less than fully blended. The researchers of the NCHRP study also determined that the binder availability factor is dependent on mixing temperature, RAP source (effective binder grade), and virgin binder grade. RAP from Texas used in that study, for example, was determined to have an availability factor of approximately 68% (Epps Martin et al., 2019).

The most widely used approach to estimate the RAP and RAS binder properties is with the use of linear blending charts, as specified in AASHTO M323, Appendix X1. The blending chart approach has been shown to produce reasonably accurate estimations of blended binder properties for lower levels of RAP and RAS (Bonaquist, Effect of Recovered Binders from Recycled Shingles and Increased RAP Percentages on Resultant Binder PG , 2011; McDaniel, Soleymani, Anderson, Turner, & Peterson, 2011). Blending charts assume 100% availability (blending), which as determined in NCHRP 09-58 is not an accurate assumption. Furthermore, the use of linear blending charts for some PG+ tests and/or RAP/RAS sources has been shown to be invalid in recent studies (Bahia, Swiertz, & Kilger, TPF-5(302): Modified Binder (PG+) Specifications and Quality Control Criteria , 2018), and the use of blending charts to estimate mixture performance for high RAP/RAS mixtures and mixtures containing RAs needs to be validated.

A. Rheological Characterization of Blended Binders

The RA dosages used in this study were selected based on the rheological characterization of the virgin binder, RAP/RAS binder, and blends of the RAs with the virgin and RAP/RAS binders, but subject to practical limitations that may be experienced by contractors blending RAs at dosages higher than about 10%. Blends of the virgin binder with the three RAs were first tested to determine an “Oil Modification Index” or OMI, which is the change in blended binder continuous grade per one percent added RA (called a “Slope Rate” in NCHRP 09-58). Two levels of each RA (in addition to the virgin binder) were used to determine the OMI for this study. For each RA, OMI values for each of the binder PG parameter can be estimated but for this study the OMIs for G*/sinδ after RTFO, the S(60) after PAV and the m(60) after PAV were calculated. The average OMI for each RA is summarized in Table 7.

Table 7. OMI Values for RAs used in this Study.

	Average OMI (^oC reduction in C.G./%RA)		
	REOB	**Bio-Oil1**	**Bio-Oil2**
RTFO-G*/sin(δ) (=2.2 kPa)	-0.56	-1.73	-1.54
PAV-Cr. Stiffness, MPa (=300 MPa)	-1.02	-1.54	-1.79
PAV-m-value (=0.300)	-0.42	-1.47	-1.25

The calculated OMI for the three RAs is lowest for the low temperature m-value, meaning each of the RAs has the least effect on changing blended binder m-value. The OMI values for the high temperature Continuous (true) Grade (CG) is similar although slightly lower for the Bio-Oils to what was proposed as the average slope rate in NCHRP 09-58 for Bio-Oils (1.82). Although NCHRP 09-58 did not include REOB, the slope rate recommended for aromatic extract was 1.38, which is considerably lower than Bio-Oil. In this study the OMI of REOB is approximately three times lower at high temperature relative to Bio-Oil.

The data in Table 7 suggests that the use of REOB as an RA is not only less efficient on a pound for pound basis, the amount of REOB required to correct PG for higher levels of RAP/RAS may not be practical.

RAP and RAS binders were extracted and recovered for characterization using AASHTO T164 and ASTM D5404, respectively, with n-Propyl Bromide as the extraction solvent. Based on the OMI and the RAP and RAS properties, an estimation of the required RA dosage to restore the blended binder to a target PG is calculated using blending charts. In this project, the target PG value was selected as the low temperature PG of the virgin binder. The required amount of Bio-Oil using this target and the measured respective OMI ranged from approximately 2.2% for the 30% RAP mixture to 6.8% for the 30% RAP + 5% RAS mixture (slight differences between the Bio-Oils exist as well). Ultimately 3% Bio-oil was selected for the 30% RAP mixture and 5% Bio-Oil was selected for the 50% RAP and 30% RAP + 5% RAS mixture. The required amount of REOB using this target ranged from approximately 2.8% for the 30% RAP mixture to 20.2% for the 30% RAP + 5% RAS mixture. It was determined that using dosages above approximately 10% is difficult in practice (generally requires a separate blending tank) and may not be cost-effective, 5% REOB was selected for the 30% RAP mixture and 10% REOB was selected for the 50% RAP and 30% RAP + 5% RAS mixture.

The measured PG properties of the virgin binders blended with the RAP/RAS binders and RAs are shown in Table 7. The calculated blended binder PG properties using liner blending charts is shown in Table 8. Also included in Table 8 are the measured continuous grades (along with ΔTc) of the blended binders at the target dosage level for each RA. The data in Table 8 for the No Additive mixtures confirms that the error when using blending charts at low temperature increases with increasing recycled binder content and is nearly 6 °C (a full PG) for the 30% RAP + 5% RAS mixture. Interestingly, low temperature stiffness estimation remains within 0.5 °C for all mixtures, matching findings from Bonaquist (2011) also using Wisconsin RAP and RAS (Bonaquist, Effect of Recovered Binders from Recycled Shingles and Increased RAP Percentages on Resultant Binder PG , 2011). It is also noted that ΔTc decreases with increasing recycled binder content, particularly with the inclusion of RAS.

The Bio-Oils are effective at restoring the low temperature CG of the blended binder to within 1 °C of the virgin binder, and for the 30% RAP and 50% RAP mixtures they actually produce low temperature CG lower than the virgin binder at the specified dosage. Given that the dosage of Bio-Oil selected for the 50% RAP and the 30% RAP+ 5% RAS mixtures is lower than what was calculated as required, this finding confirms that less than 100% blending is occurring. The high temperature CG is always higher for the Bio-Oil blends relative to the virgin binder, and for the 30% RAP + 5% RAS mixture is over 13 °C higher. Since the low temperature CG is satisfactory, this result is not problematic as a higher high temperature CG is viewed as advantageous to rutting performance, as long as workability is not adversely impacted. The addition of Bio-Oil also increases ΔTc for all mixture combinations, which is expected to improve cracking resistance.

The REOB at the selected dosages was effective at restoring low temperature CG for the 30% RAP mixture but did not restore low temperature CG for the 50% RAP and 30% RAP + 5% RAS mixture, likely a result of using much lower than the calculated amount required. Similarly, the high temperature CG of the REOB mixtures was always higher than the Bio-Oil. Notably, the REOB significantly reduced the ΔTc relative to the corresponding No Additive mixture by as much as 13.9 °C. This finding is in agreement with recent studies and suggests the REOB mixtures will be more prone to age-induced cracking (Kilger, Swiertz, & Bahia, 2019).

Table 7. Measured PG Properties for Blended Binders

Binder sample		Recycling Additive Composition			PG high true grade	PG low true grade	ΔTc	RTFO Residue	PAV Residue	
		REOB	Bio-oil1	Bio-oil2				G*/sinδ at 58C	Stiffness at -28C	m-value at -28C
Base Binder	PG 58-28				59.7	-30.6	0.56	3.3	232	0.308
Blends for 30%RAP Mixes	30%RAP blend				67.9	**-27.9**	-0.44	8.1	289	**0.299**
	30%RAP+5%REOB	5.0%			64.4	-31.1	-2.18	5.0	168	0.330
	30%RAP+3%Bio-oil1		3.0%		62.3	-32.8	-0.07	3.8	161	0.354
	30%RAP+3%Bio-oil2			3.0%	62.2	-32.9	0.99	3.8	161	0.367
Blends for 50%RAP Mixes	50%RAP blend				72.6	**-24.8**	-1.73	13.6	289	**0.299**
	50%RAP+10%REOB	10.0%			66.9	**-27.0**	**-9.16**	6.7	128	**0.295**
	50%RAP+5%Bio-oil1		5.0%		63.3	-34.6	-0.31	4.4	124	0.360
	50%RAP+5%Bio-oil2			5.0%	62.2	-33.9	-0.16	3.8	132	0.359
Blends for 30%RAP&5%RAS Mixes	RAP & RAS blend				81.0	**-22.7**	-5.01	37.2	310	**0.263**
	RAP&RAS+10%REOB	10.0%			78.8	**-16.4**	**-18.86**	27.6	157	**0.259**
	RAP&RAS+5%Bio-oil1		5.0%		73.6	-30.0	-3.64	14.2	153	0.313
	RAP&RAS+5%Bio-oil2			5.0%	73.7	-29.7	-3.94	14.0	156	0.312

Table 8. Predicted and Measured Continuous Grades for Blended Binders in this Study.

	Virgin Binder	30% RAP Mixture (27% ABR)				50% RAP Mixture (45.1% ABR)			
		No Additive	REOB	Bio-Oil 1	Bio-Oil 2	No Additive	REOB	Bio-Oil 1	Bio-Oil 2
Measured High Temperature RTFO CG	61.1	67.9	64.4	62.2	62.2	72.6	66.7	63.3	62.2
Measured Low Temperature $S(60)_{cr}$	-30.6	-28.3	-33.3	-32.9	-32.9	-26.6	-36.1	-34.9	-34.1
Predicted Low Temperature $S(60)_{cr}$	--	-28.4	--	--	--	-26.1	--	--	--
Difference (Measured - Predicted)	--	0.1	--	--	--	-0.5	--	--	--
Measured Low Temperature m_{cr}	-31.1	-27.9	-31.1	-32.8	-33.9	-24.8	-27.0	-34.6	-33.9
Predicted Low Temperature m_{cr}	--	-26.5	--	--	--	-21.8	--	--	--
Difference (Measured - Predicted)	--	-1.3	--	--	--	-3.1	--	--	--
Measured ΔTc	0.56	-0.44	-2.18	-0.07	0.99	-1.73	-9.16	-0.31	-0.16
Resulting Blended CG (Measured)	59.7-30.6	67.9-27.9	64.4-31.1	62.2-32.8	62.2-32.9	72.6-24.8	66.7-27.0	63.3-34.6	62.2-33.9

	Virgin Binder	30% RAP + 5% RAS Mixture (47.5% ABR)			
		No Additive	REOB	Bio-Oil 1	Bio-Oil 2
Measured High Temperature RTFO CG	61.1	81.0	78.8	73.6	73.7
Measured Low Temperature $S(60)_{cr}$	-30.6	-27.7	-35.3	-33.6	-33.7
Predicted Low Temperature $S(60)_{cr}$	--	-27.7	--	--	--
Difference (Measured - Predicted)	--	0.0	--	--	--
Measured Low Temperature m_{cr}	-31.1	-22.7	-16.4	-30.0	-29.7
Predicted Low Temperature m_{cr}	--	-17.5	--	--	--
Difference (Measured - Predicted)	--	-5.2	--	--	--
Measured ΔTc	0.56	-5.01	-18.86	-3.64	-3.94
Resulting Blended CG (Measured)	59.7-30.6	81.0-22.7	78.8-16.4	73.6-30.0	73.7-29.7

It is concluded from the characterization of the blended binders that the use of linear blending charts may produce significant error relative to the actual blended binder properties, and the error is likely to increase with increasing binder replacement levels (increasing RAP and RAS). This is likely a result of incomplete blending of the recycled and virgin binders and inherent non-linearity in the properties being measured caused by chemical incompatibility between the RAs and the aged binders. The use of REOB to restore blended binder properties can be effective at lower binder replacement levels but may not be practical for higher levels of RAP and RAS. In addition, the REOB is shown to reduce ΔTc for all mixtures. The following sections compare the measured properties of the blended binders with the mixture properties from earlier sections to further evaluate the efficacy of using blending charts to predict performance.

B. Use of Blended Binder Properties to Predict Rutting

The High Temperature Continuous Grade is a relative representation of the blended binder stiffness and should therefore correlate with rutting resistance in the HWT. Figure 23 presents the comparison between the measured high temperature CG and the respective Passes to 12.5 mm for that mixture (STOA-4-hour condition). Although in general a higher CG appears to result in a higher Passes to 12.5 mm, there are several data points that do not follow this trend. In particular, the high temperature CG for the 30% RAP + 5% RAS mixture with Bio-Oil is found to be similar to the 50% RAP No-Additive mixture, yet the Passes to 12.5 mm is higher. Conversely, the CG for the 30% RAP + 5% RAS REOB mixture is higher than the Bio-Oil mixtures, yet the Passes to 12.5 mm is lower. Since passes to 12.5 mm was shown to be confounded by moisture effects, a better rutting parameter selected from the HWT is the Creep Slope rate ,which will be used in further analysis in this section.

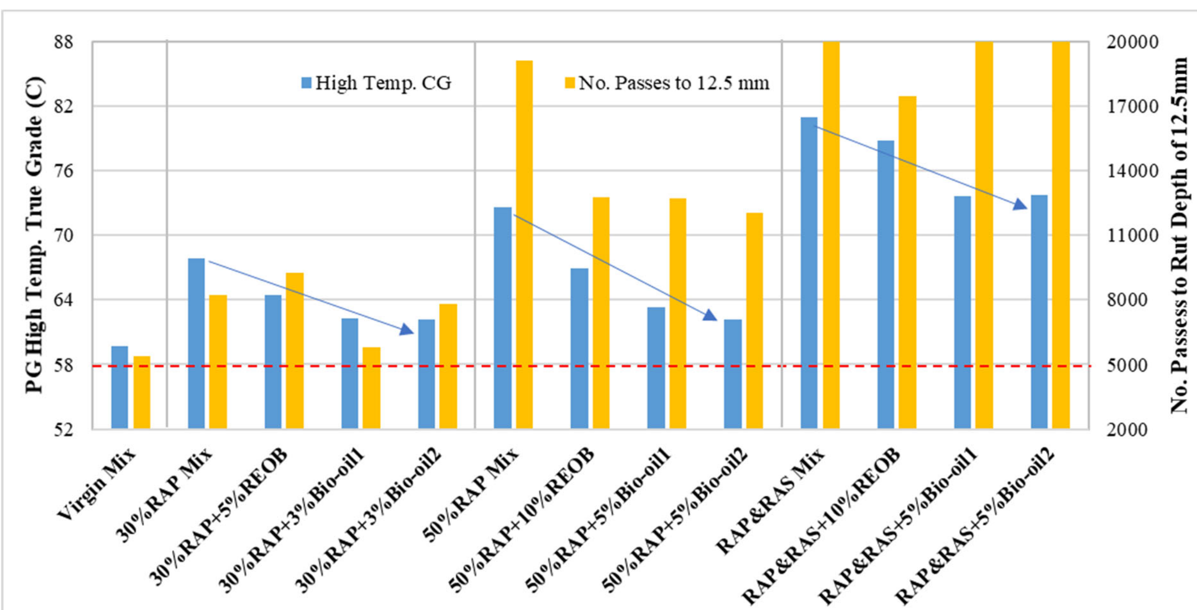


Figure 23. Relationship between High Temperature Continuous Grade and Passes to 12.5 mm

The G*/sin(δ) parameter is intended to measure rutting resistance in the AASHTO M320 Performance Grading system. This parameter should therefore correlate to HWTT rutting resistance for these mixtures. Relatively recent advancements in binder testing have suggested the non-recoverable creep compliance parameter, Jnr, measured from the Multiple Stress Creep and Recovery (MSCR) test as a better alternative to measure rutting resistance. Figure 24 shows the correlation between G*/sin(δ) and Jnr and HWT Creep Slope (STOA-4 hour). The correlation between G*/sin(δ) and Creep Slope is relatively strong at 72% explained variance, but the use of an exponential relationship (which provided the highest R^2) demonstrates that a wide range of Creep Slope values were measured for a relatively narrow range of G*/sin(δ) values. Conversely, the same correlation drawn for Jnr shows a more logical linear trend with decreasing Jnr related to better rutting resistance. In addition, the explained variance is slightly higher at 80%. It is therefore concluded that for this data set the Jnr parameter is a better predictor of rutting resistance than the high temperature CG or G*/sin(δ) measured at one temperature.

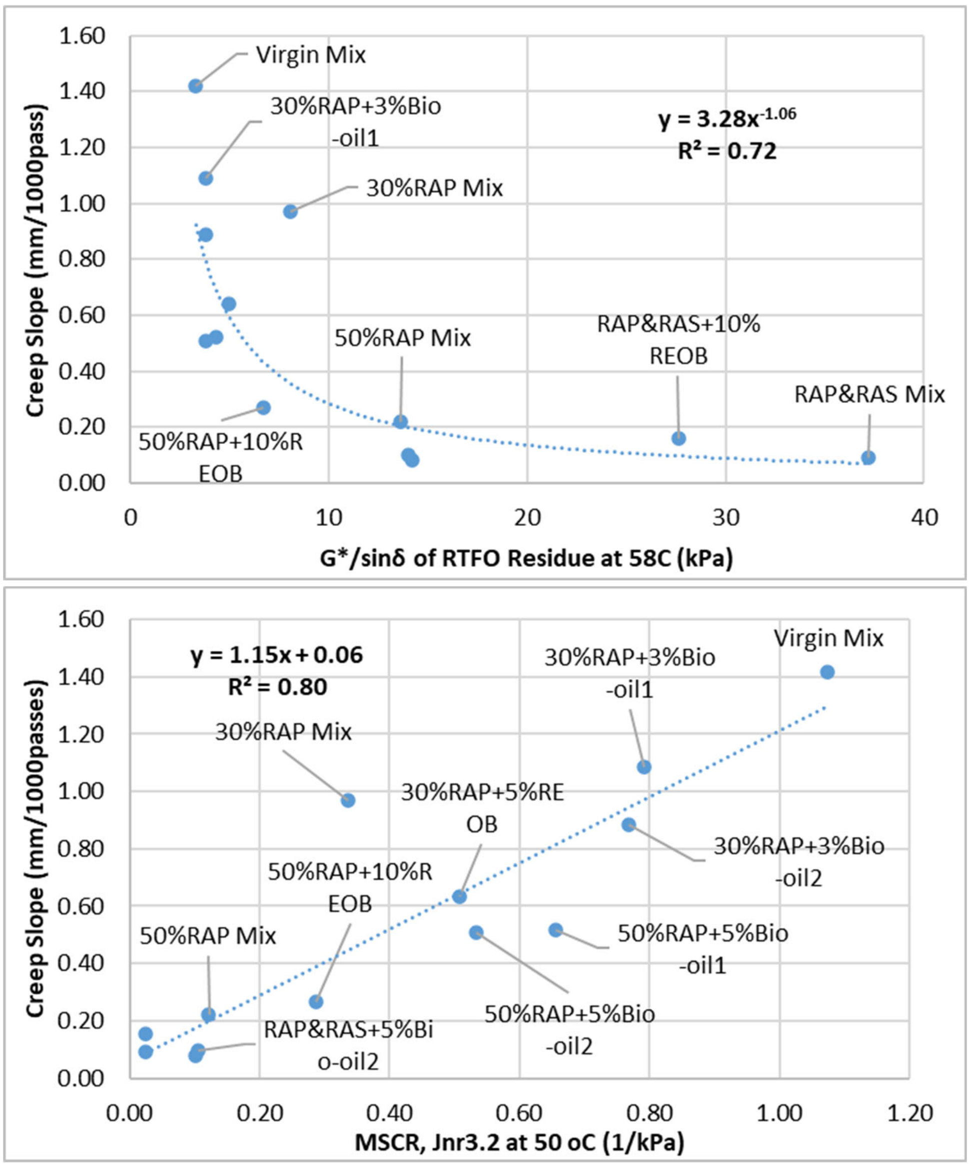


Figure 24. Correlation between G*/sin(δ) or Jnr and Creep Slope for Project Mixtures (STOA)

AASHTO M323, Appendix X1 directs users to create blending charts using high temperature continuous grade as the rutting control. Figure 23 clearly demonstrates that high temperature CG may not accurately represent rutting performance. Recent work conducted by the authors has shown that Jnr is linearly related to binder replacement percentages (Bahia, Swiertz, & Kilger, TPF-5(302): Modified Binder (PG+) Specifications and Quality Control Criteria , 2018); as such, if an estimate of binder availability is made based on experience or testing, a blending chart to predict blended binder Jnr can be constructed and may provide a more reasonable representative of rutting resistance in terms of HWT performance. This could be a useful tool for mix designers troubleshooting mixtures exhibiting inadequate HWT rutting performance.

C. Use of Blended Binder Properties to Predict Cracking at 25 °C

Similar evaluations of correlation between blended binders' properties and mixtures performance were made at intermediate temperature (25°C) to compare blended binder properties and IDEAL-CT parameters. Although the AASHTO M320 system includes the G*sin(δ) fatigue cracking parameter, some researchers have developed many alternative ("PG+") procedures to predict cracking resistance. Ultimately if the IDEAL-CT is the method chosen to represent cracking resistance at intermediate temperature, practitioners must foremost understand which binder properties affect this test. In this study the Linear Amplitude Sweep (AASHTO TP101) was used to estimate the G*sin(δ) at 25 C as well as provide the fatigue resistance parameters unique to that test. The research team found the best correlation between the IDEAL-CT at 25 °C and the G*sin(δ) parameter calculated at 25 °C. This correlation is shown in Figure 25 for the blended binders after PAV and the IDEAL-CT results of mixtures after the LTOA-8-hour conditioning.

The Post-Peak slope is shown to be highly (R^2 = 83%) and logically correlated with G*sin(δ) at the same temperature; since Post-Peak Slope was shown earlier to be highly correlated with CT Index, the G*sin(δ) value is similarly corelated to CT Index. There is no apparent trend between G*sin(δ) and Fracture Energy. The concept of the need to split Post Peak Slope from Fracture Energy is therefore further strengthened by this finding since it implies Post-Peak Slope can be effectively controlled by binder properties, whereas Fracture Energy is perhaps better controlled by mix design related factors.

Comparisons between the other LAS parameters (Cycles to Failure and "B" Value) and CT Index parameters are shown in Figure 25, which shows less compelling correlations. However, when the data set included both STOA and LTOA mixtures with RTFO and PAV residues, respectively, the correlation between LAS-B Value and the CT Index became clear (Figure 26). The LAS B-Value is calculated as the slope of linear relationship between the Log of the cycles to failure versus log applied strain results from the LAS Test; it is characteristically a negative number (a reduction in fatigue life with increased strain) and is reported above in Figure 26 as the absolute value. A higher absolute B-Value indicates a greater reduction in cycles to failure per unit increase in strain, which is perceived as detrimental since the asphalt binder is more strain sensitive. The trend shown in Figure 26 is logical and agrees with findings in the literature regarding the LAS B-Value as a controlling Fatigue-related parameter (Bahia et al., 2016; Bahia, et al., 2018). Since the G*sin(δ) is already measured as part of the standard grading method, produced a similar correlation to mixture results, and is generally understood by practitioners, it is concluded that this parameter is a good binder indictor that practitioners can use to adjust CT Index of mixtures from a binder formulation perspective. The trend shown in Figure 25 indicates lowering the value of G*sinδ almost always reduces the Post Peak slope which increases the CTindex value.

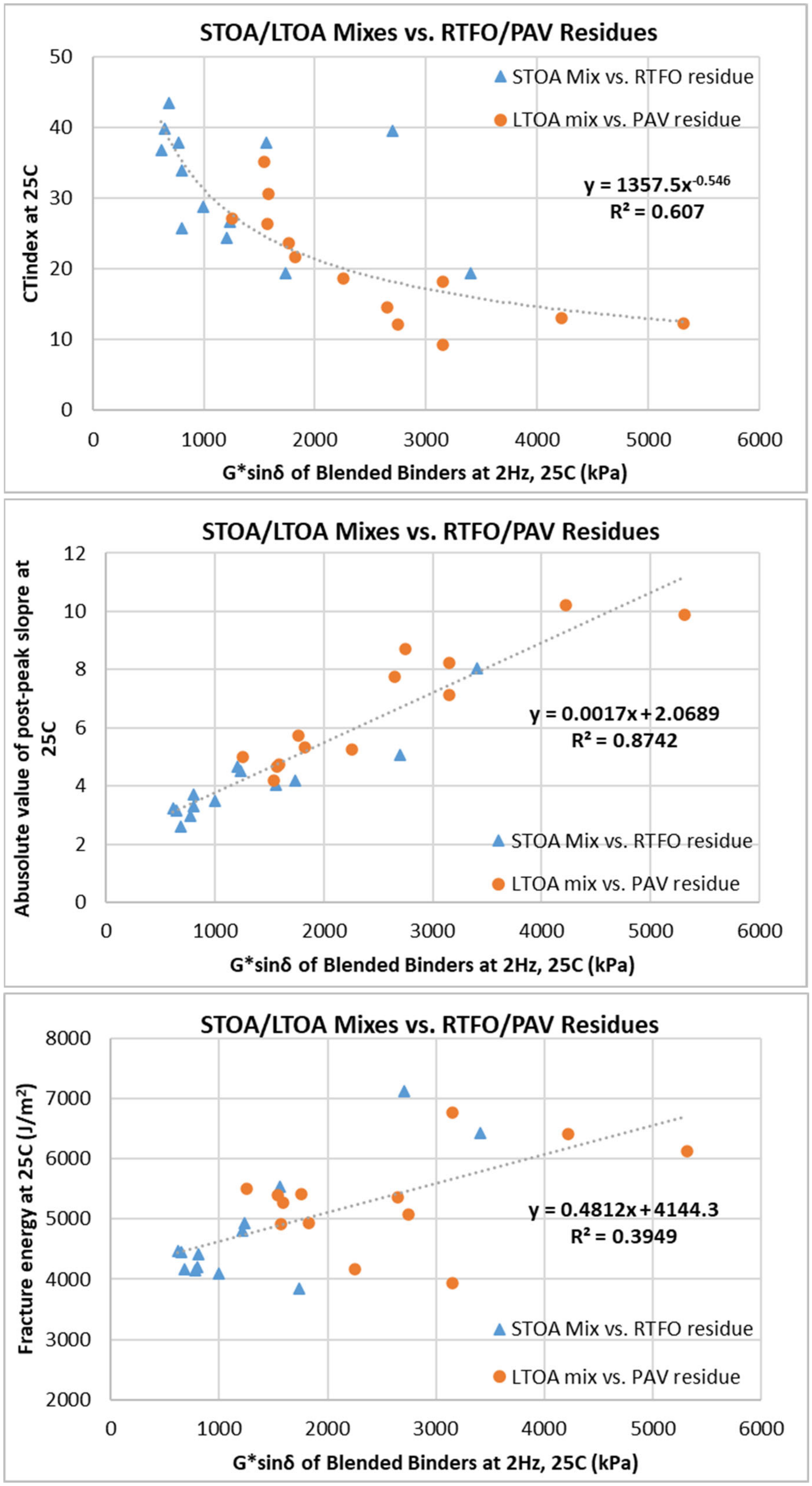


Figure 25. Correlation between G*sin(δ) and IDEAL CT at 25 °C.

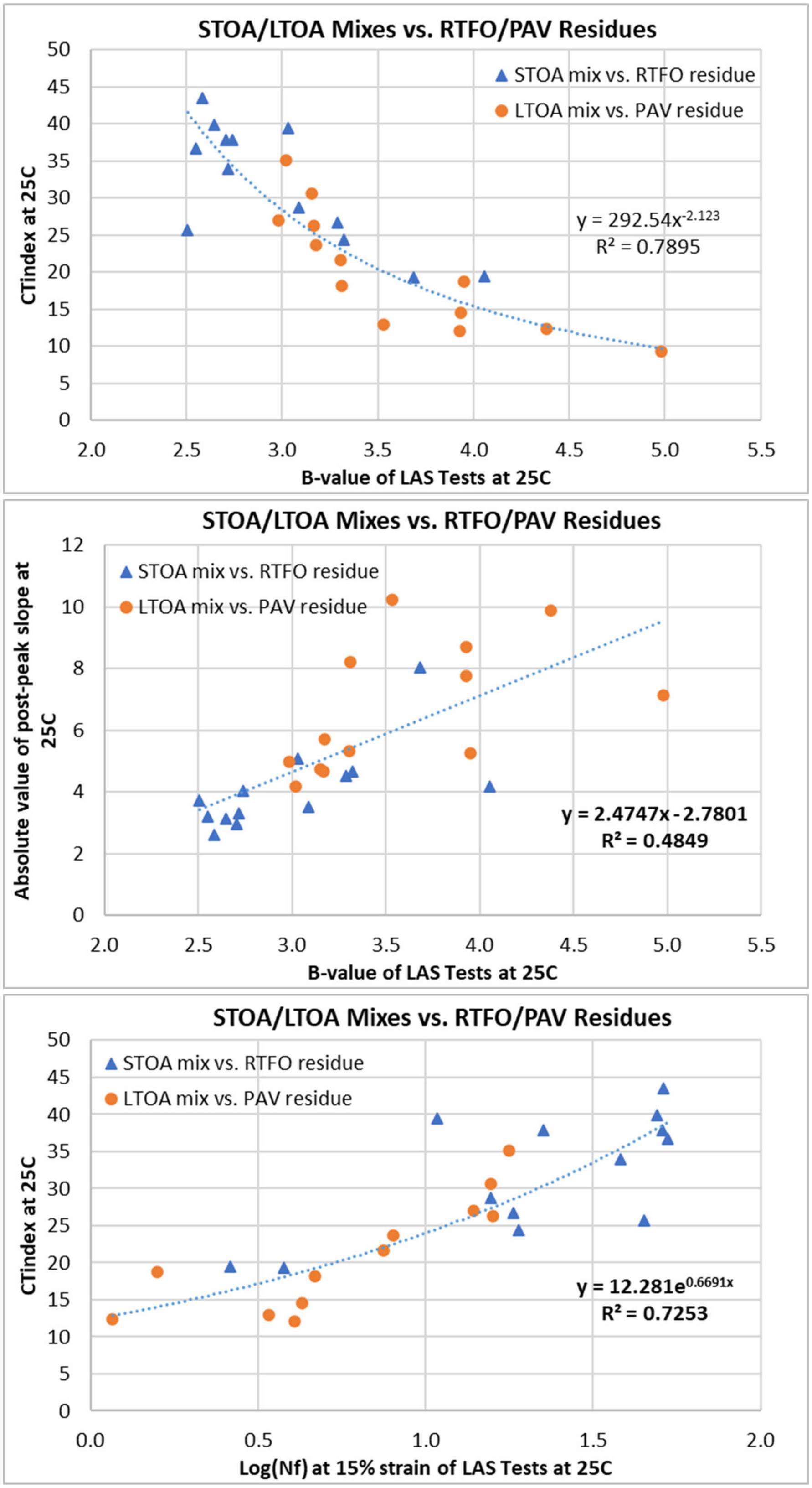


Figure 26. Correlation between LAS B-Value and IDEAL CT at 25 °C at two aging conditions.

D. Use of Blended Binder Properties to Predict Cracking at 0 °C

Asphalt binder low temperature properties are typically measured using the BBR at sub-zero temperatures. Since the low temperature cracking resistance of the project mixtures was measured at 0 °C for this study, no direct comparison between binder and mixture properties can be made at the same temperature. However, if a reasonable correlation between BBR-measured properties and 0 °C IDEAL-CT, practitioners may still be able to predict and adjust mixture cracking resistance measured in the IDEAL test at low temperatures via binder properties measured using the BBR.

Initial correlations between blended binder low temperature continuous grade (CG) based on limits of the m(60) and S(60) parameters and CT Index parameters at 0 °C provided poor or inconsistent results. However, when the respective low temperature BBR parameters (S and m) were directly correlated with CT Index independently at one temperature (similar to what was done at high temperature), the correlation between m-value measured at -18 ^{o}C and CT Index measured at 0 ^{o}C became compelling. Figure 27 shows the correlation between m-value and CT Index for mixtures in the LTOA-8-hour condition.

As the m-value increases, the CT Index also is shown to increase, which is logical; m-value is a measurement of stress-relaxation, which at least conceptually may relate to post-peak behavior using the IDEAL CT test. Interestingly, however, the correlation between m-value and Post-Peak Slope was not found to be strong (39%), suggesting that perhaps m-value may capture both Post-Peak Slope and Fracture Energy behavior. A similar observation was made for Stiffness at -18 °C.

From a practical perspective, Bio-Oils were shown to be much more effective at adjusting m-value relative to REOB for the blended binders, so if m-value indeed controls cracking at low temperature, it appears the use of Bio-Oils may provide an advantage over REOB or similar RAs when attempting to adjust CT Index. Similarly, since the blended binder for these mixtures is “m-controlled”, there is always an advantage to increasing ΔTc (less negative) by way of increasing m-value for these mixtures (ΔTc is correlated with m-value for these mixtures with increasing m-value at -18 °C correlating to increasing ΔTc).

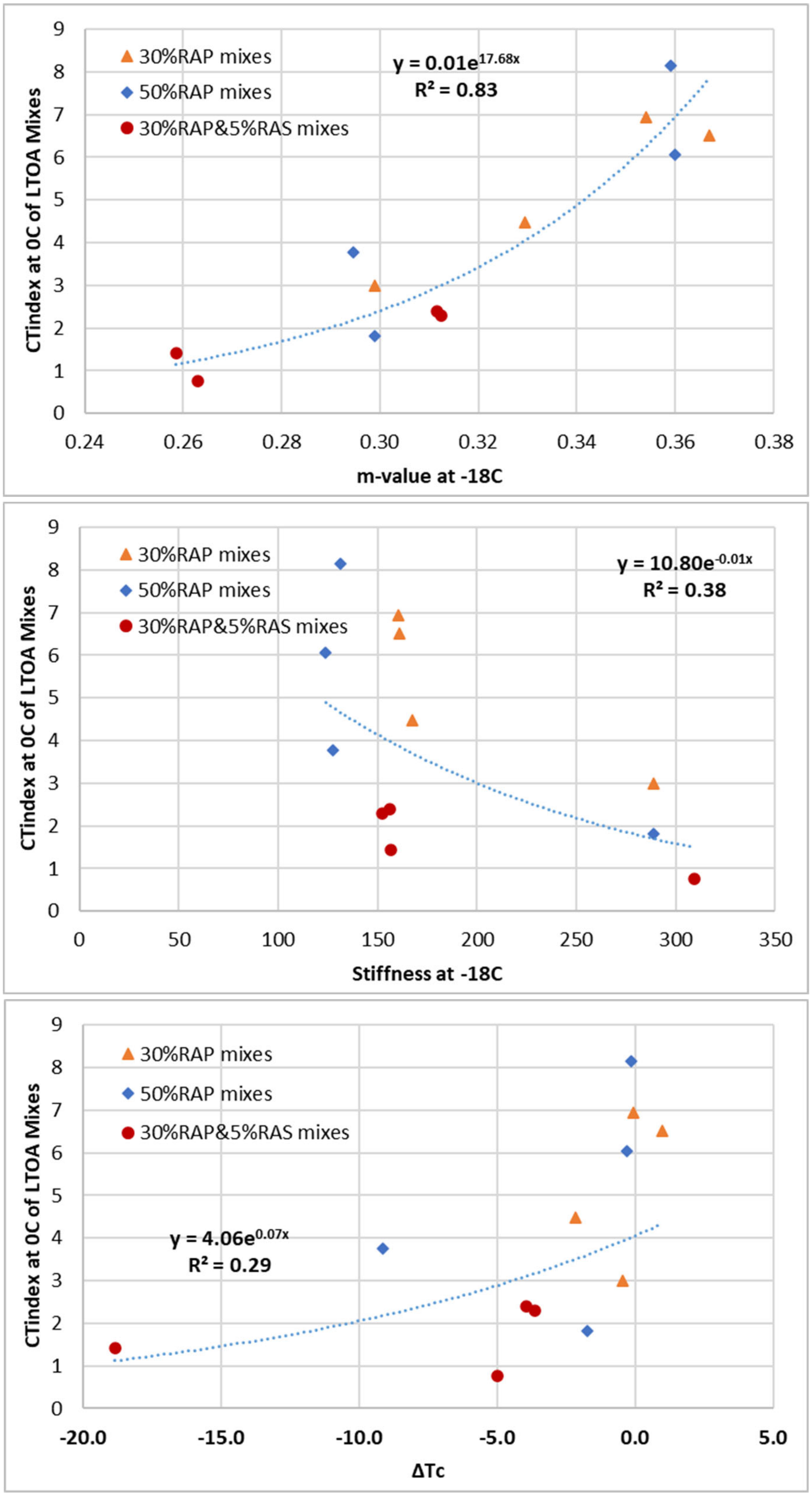


Figure 27. Correlation between CT Index at 0 °C and m-value measured at 18 °C.

E. Chemical Characterization of Blended Binders

Fourier transform infrared (FTIR) spectroscopy is a promising technology to characterize chemical changes in asphalt binder associated with oxidative aging. The carbonyl (C=O) and Sulfoxide (S=O) are the two major chemical functional groups that are produced upon oxidation of an asphalt binder (Peterson 2009). The carbonyl functional group has long been used to indicate the level of oxidation within asphalt binder and is directly related to changes in asphalt binder viscosity (Peterson, 2009). In the recently published report for NCHRP Project 09-54 (Kim et al., 2018), chemical aging index properties measured by using the FTIR spectroscopy were used as one of two main categories for quantifying the extend of aging of asphalt binder. It is confirmed that the chemical aging index properties (i.e. carbonyl and sulfoxide peaks and areas) showed good sensitivity to aging duration.

In this study, the attenuated total reflectance (ATR) FTIR measurements were employed to measure the infrared spectrum of blended binders. The technique of ATR-FTIR has been applied to asphalt binder for characterization of chemical composition, polymer modification, and aging in the recent decade. The major advantage of ATR-FTIR, compared to traditional transmittance FTIR technology, is that the test can be conducted directly on binder sample without involving any solvent. Thus, the measured infrared spectra have a relatively high reproducibility. The infrared spectra of blended binders were collected using 32 scans within the wavenumber range of 400-4000 cm^{-1} at a resolution of 2 cm^{-1} using a minimum of two replicates. The absorbance peaks at wavenumbers of 1700 cm^{-1} and 1030 cm^{-1} represent carbonyl and sulfoxide groups, respectively. Figure 28 shows the representative infrared spectra of based binder at three aging conditions: original binder, RTFO residue, and PAV residue. As aging extent of base binder increases, the carbonyl and sulfoxide peaks increase. The changes in carbonyl and sulfoxide functional groups are more obvious for the PAV aged residue.

To quantify the changes in the carbonyl and sulfoxide functional groups, their peak areas are calculated by determining the area under the infrared spectrum that lies between specific wavenumbers. The wavenumber ranges for carbonyl and sulfoxide functional groups are 1660-1753 cm^{-1} and 995-1047 cm^{-1}, respectively. In order to minimize the influence of penetration depth of infrared beam into testing sample, the general principle is to normalize the peak area obtained for the specific wavenumber by calculating a ratio of peak area at a reference wavenumber which is supposed not to be significantly affected by oxidative aging. The absorbance peaks at wavenumbers of 1460 cm^{-1} and 1376 cm^{-1} are attributed to the ethylene functional group (CH_2) and methyl functional group (CH_3), respectively. It is known that the ethylene and methyl groups are generally not subject to obvious change during the oxidative aging of an asphalt binder. Therefore, they are usually taken as reference peaks (Van den Bergh, 2011). Thus, the semi-quantitative formulae for the carbonyl index and sulfoxide index can be written as follows:

$$Carbonyl\ index = \frac{A_{1700}}{A_{1460} + A_{1376}}$$

$$Sulfoxide\ index = \frac{A_{1030}}{A_{1460} + A_{1376}}$$

Where A1700 is peak area of the carbonyl group at a wavenumber range of 1660-1753 cm^{-1}, A1460 is peak area of the ethylene group at a wavenumber range of 1525-1399 cm-1, A1376 is peak area of methyl group at a wavenumber range of 1399-1350 cm-1, and A1030 is peak area of the sulfoxide group at a wavenumber range of 995-1047 cm^{-1}.

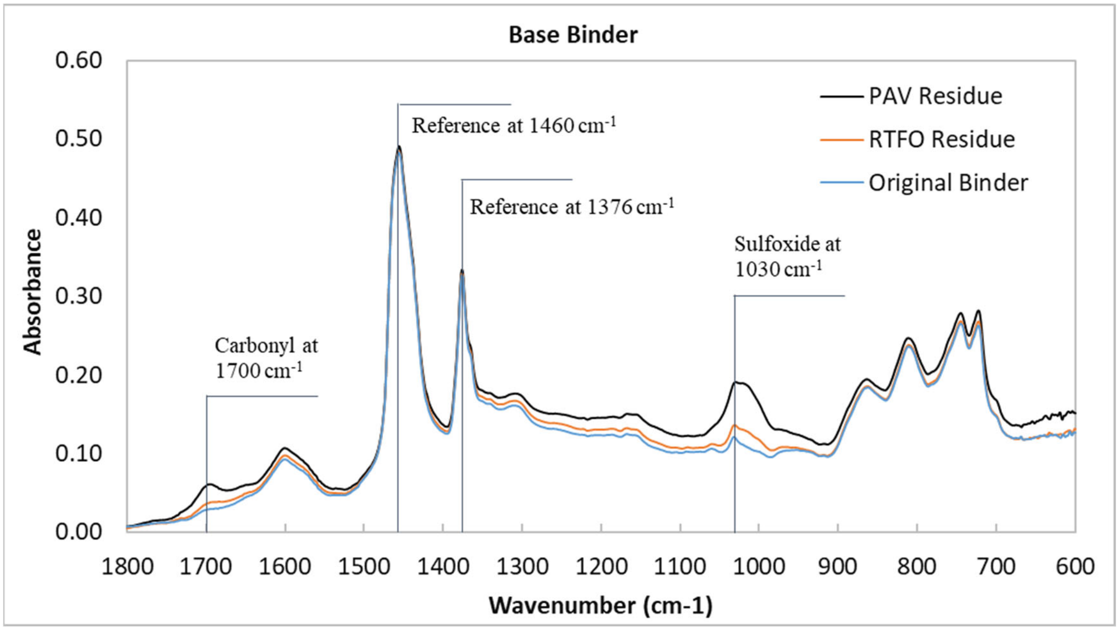
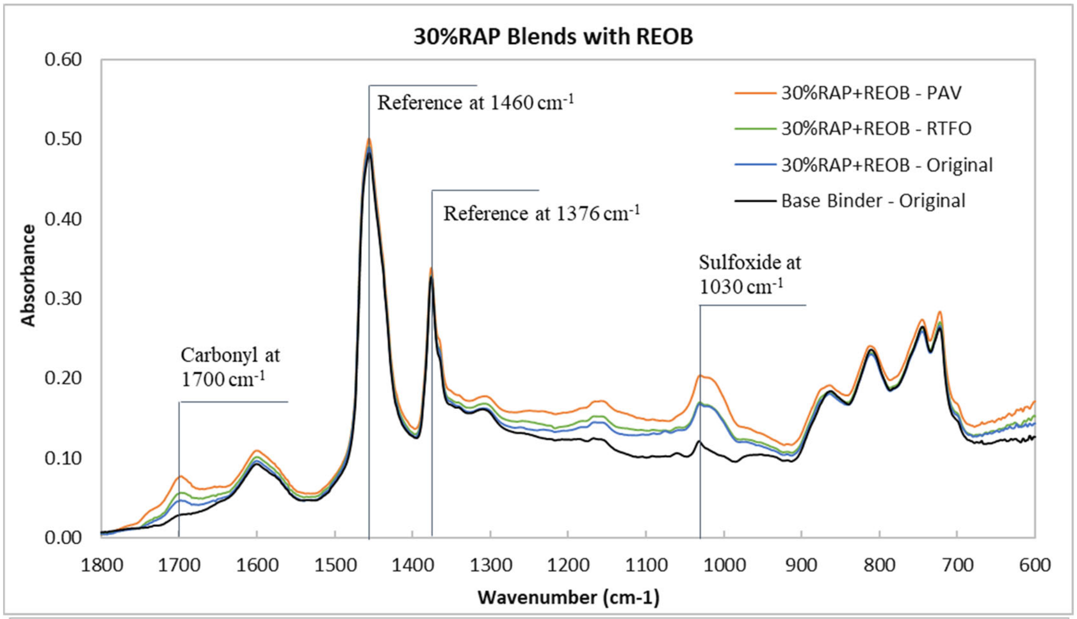


Figure 28. Representative infrared spectra of base binder at various aging levels in the wavenumber range of 1800 to 600 cm^{-1}.

Before comparing the results of carbonyl index and sulfoxide index from the base binder and blends for rejuvenated RAP/RAS mixes, it is important to understand the changes of infrared spectrum due to the addition of the RAs. Figure 29 shows examples of representative infrared spectra of the 30% RAP + REOB and 30% RAP + Bio-Oil 1 blends. The infrared spectrum of 30% RAP + REOB original blend shows increased peaks of the carbonyl and sulfoxide groups as compared to original base binder, which is due to the addition of RAP binder. No other distinct absorbance peak that might be induced by the REOB is observed in the measured infrared spectra. In the infrared spectrum of 30% RAP + Bio-Oil 1 original blend another two absorbance peaks at wavenumbers of 1740 cm^{-1} and 1160 cm^{-1} are found, which are attributed to the aliphatic ester and tertiary alcohol groups from the Bio-oil1. Similar infrared spectra are found for the 30% RAP + Bio-Oil 2 blends. Even though the bio-oils introduced specific absorbance peaks into the binder's infrared spectrum, the oxygenated functional groups (carbonyl and sulfoxide) in the infrared spectra of 30% RAP + Bio-Oil blends still provide an opportunity of illustrating their chemical changes associated to the aging. The increased peaks at wavenumber of 1700 cm^{-1} and 1030 cm^{-1} clearly indicate the chemical changes due to the addition of RAP binder.



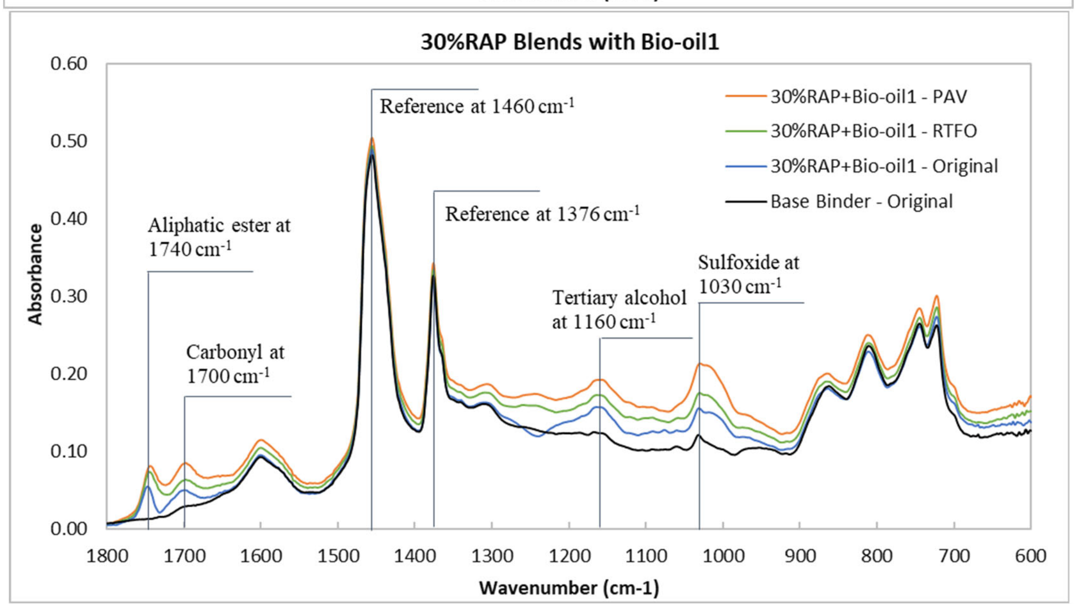


Figure 29. Representative infrared spectra of blend binders for 30%RAP+REOB (top) and 30%RAP+Bio-oil1 as compared to base binder.

The carbonyl index and sulfoxide index for original blends and their RTFO and PAV aged residues were calculated from their infrared spectra. The results of average values for 50% RAP blends with and without RAs are shown in Figure 30 as examples. The carbonyl index of 50% RAP original blend without RA shows a higher average value than the original base binder, while after PAV aging the 50% RAP blend without RA has a similar carbonyl index as the base binder. This clearly indicates that the base binder is more sensitive to aging than the 50% RAP blend without RA, which is logical because of RAP binder's is already aged. The original blend of 50% RAP + REOB does not show obvious difference in the carbonyl index comparing to the 50% RAP original blend without RA. The addition of REOB did not decrease the carbonyl functional group of aged binder. This is also observed for the bio-oils. The average values of carbonyl index for the 50% RAP + Bio-Oil 1 and 50% RAP + Bio-Oil 2 original blends are even higher than the PAV aged base binder and 50% RAP blend without RA. The high carbonyl index values are not due to oxidative aging of these two bio-oil blends. Instead, it is because of the influence of the aliphatic ester group at the wavenumber of 1740 cm^{-1}. This absorbance peak observed in the infrared spectrum of the bio-oils rises the nearby spectrum, resulting in a larger peak area for the carbonyl functional group at the wavenumber of 1700 cm^{-1}. This causes a challenge of using the carbonyl index for characterizing aging of the blends with bio-oils.

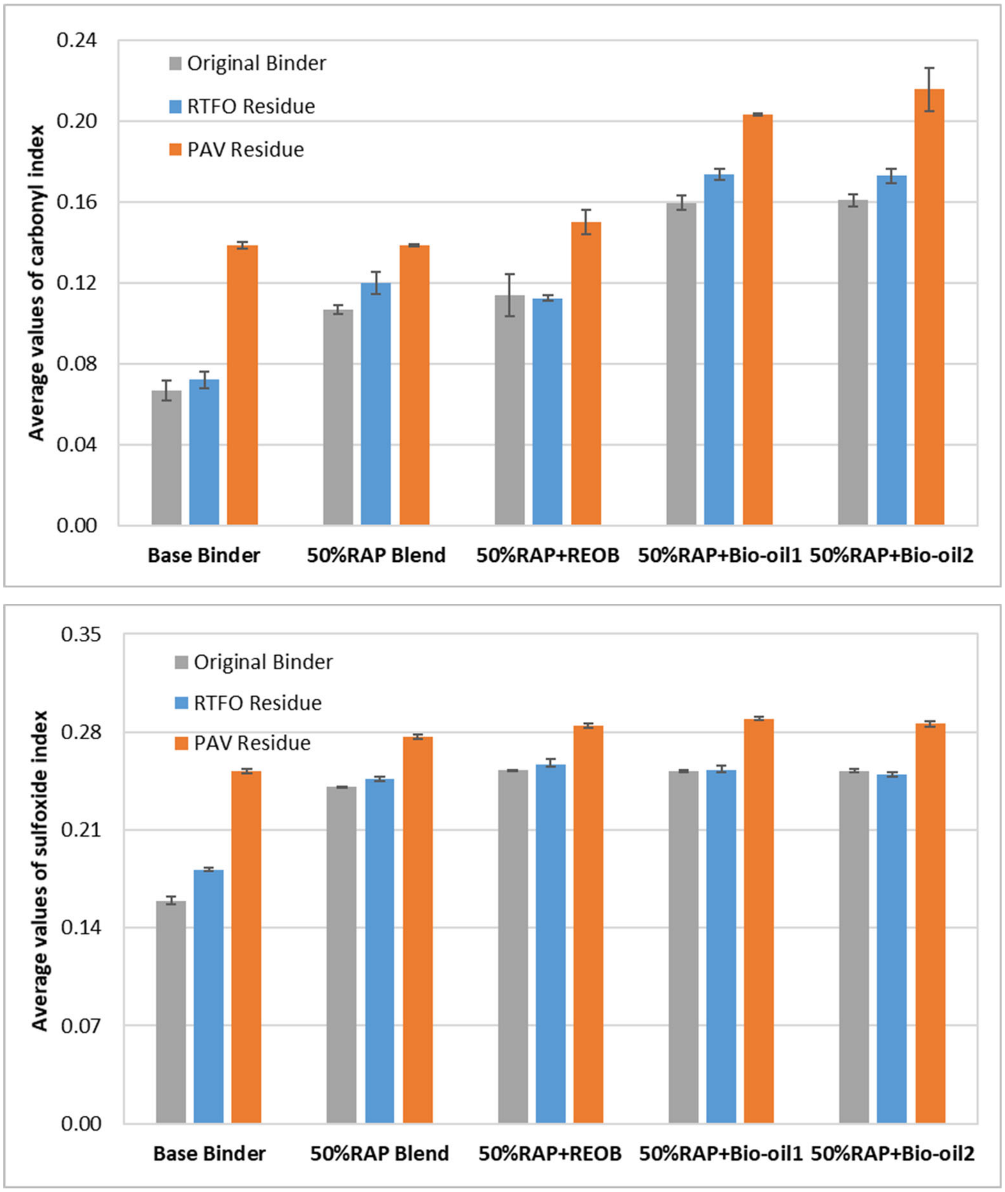


Figure 30. Results of Carbonyl index (top) and Sulfoxide index (bottom) of base binder and 50%RAP blends w/ and w/o RAs at various aging levels

In terms of the sulfoxide index, the 50% RAP original blend without RA exhibits a higher aging level than the original base binder because of addition of RAP binder. After the RTFO and PAV aging conditioning, the base binder shows significant increase of the sulfoxide index. A relatively lower increase of the sulfoxide index is found for the 50% RAP without RA. The 50% RAP blends with REOB and Bio-Oils show similar values of sulfoxide index as the 50% RAP without RA at all three aging levels. This indicates that the addition of RAs does not change aging resistance of 50% RA blend when measured by the sulfoxide index.

The same trends for carbonyl index and sulfoxide index of the 30% RAP blends and 30% RAP + 5% RAS blends are found. The RAP/RAS blends seem to exhibit better aging resistance than the base binder, in terms of the carbonyl index and sulfoxide index of infrared spectra.

For comparing the sensitivity to oxidative aging of all tested blends, the aging rates of carbonyl index and sulfoxide index are determined by dividing their average value of RTFO/PAV residue by the value of the original blend. The parameter of aging rate can also help to address the confounding effects of carbonyl group due to the bio-oil's aliphatic ester group. The results of aging rate for base binder and RAP/RAS blends after RTFO and PAV aging conditioning are shown in Figure 31.

$$Aging\ rate = \frac{Carbonyl/Sulfoxide\ index\ of\ RTFO/PAV\ residue}{Carbonyl/Sulfoxide\ index\ of\ original\ blend}$$

For the PAV residues, all the RAP/RAS blends with and without RAs exhibit lower aging rate in terms of both carbonyl and sulfoxide index than the base binder. The 50% RAP and 30% RAP + 5% RAS blends without RA show lower values of aging rate than the 30% RAP blend without RA since the former have higher percent binder replacement than the latter. In terms of the aging rate of carbonyl index, the addition of RAs shows relatively lower aging rates than the 30% RAP without RA, particularly for the REOB blends. While the 50% RAP blends with RAs have similar values as its blend without RA. A similar trend is found for the 30% RAP + 5% RAS blends with the REOB showing a marginally higher aging rate. These results indicate that the RAP/RAS binders have dominant effect in the aging resistance of RAP/RAS blends with RAs. In terms of sulfoxide index, trends for effect of aging are very similar to those of the carbonyl index. From all the information mentioned above, it is concluded that the RAs will not cause significant change to long-term aging behavior of the blends with high contents of RAP/RAS binders.

For the RTFO residues, all RAP/RAS blends show similar aging rates in terms of carbonyl index as the base binder, except for the 30% RAP blends. The aging rates of sulfoxide index of RAP/RAS blends are slightly lower than the base binder. Thurs, in general the chemical properties of RAP/RAS blends with RAs do not change significantly during the short-term aging conditioning. This provides a better understanding of how the RAs are subjected to the short-term aging during the mixing and compaction of RAP/RAS mixtures.

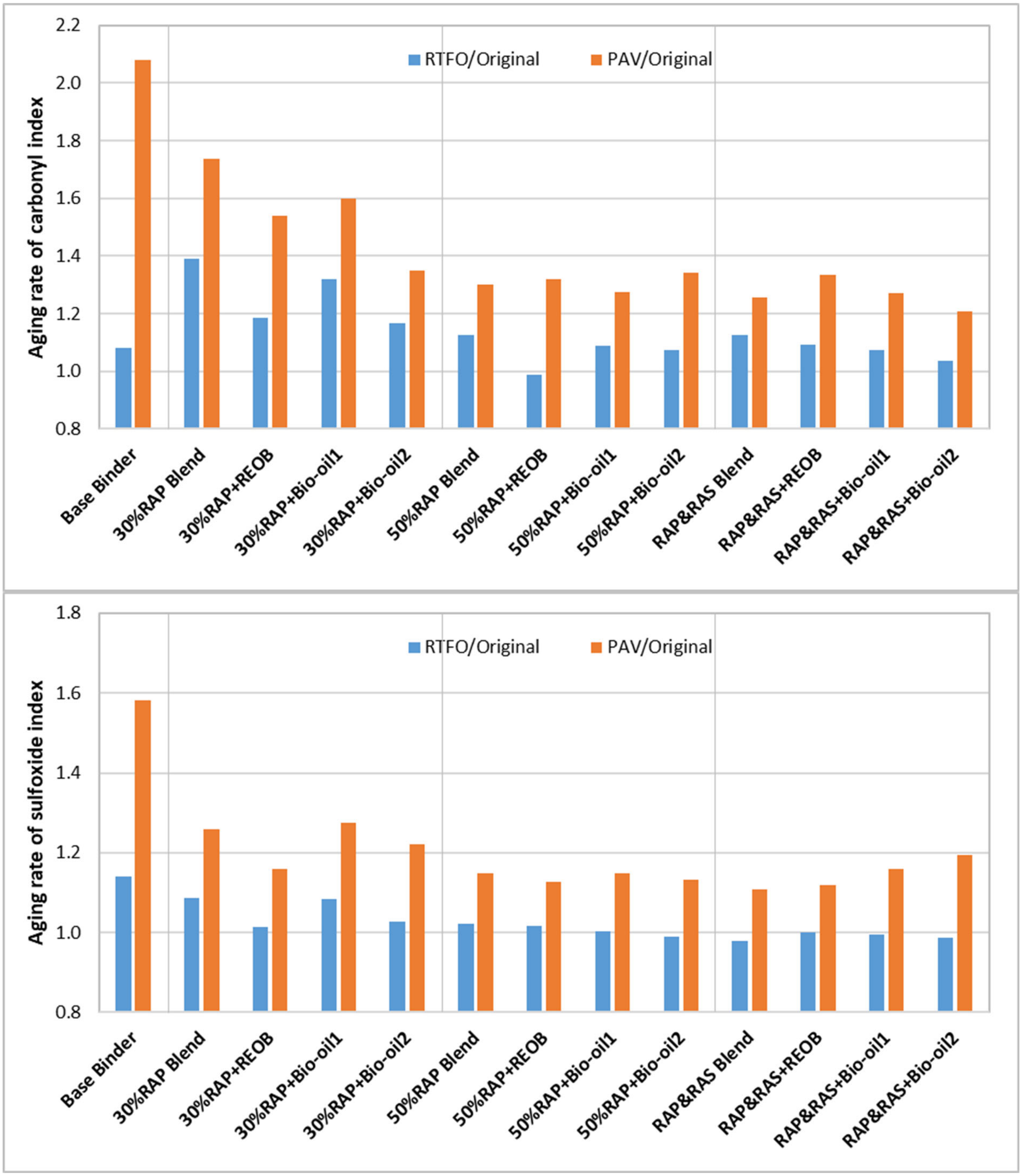


Figure 31. Results of aging rate in terms of carbonyl index (top) and sulfoxide index (bottom) of the RAP/RAS blends w/ and w/o RAs after RTFO and PAV aging conditioning

F. Characterization of RAs for Specification and Quality Verification Purposes

One major challenge associated with the rapidly expanding RA marketplace is ensuring quality and consistency of individual RA products since manufacturing and specification information is usually proprietary. Efforts to characterize RA materials generally fall into two categories: measuring physical properties of the RA materials (such as viscosity) or measuring chemical properties of the RA material. In a limited sub-study for this project the research team measured the viscosity of six commercially available RA products as well as a chemical marker of the same six RAs, in this case Acid Value (also called Acid Number). Note that the Bio-Oils and REOB materials listed have been alphabetically coded separately from the RAs used in prior portions of this project. Results of the characterization are shown in Figure 32.

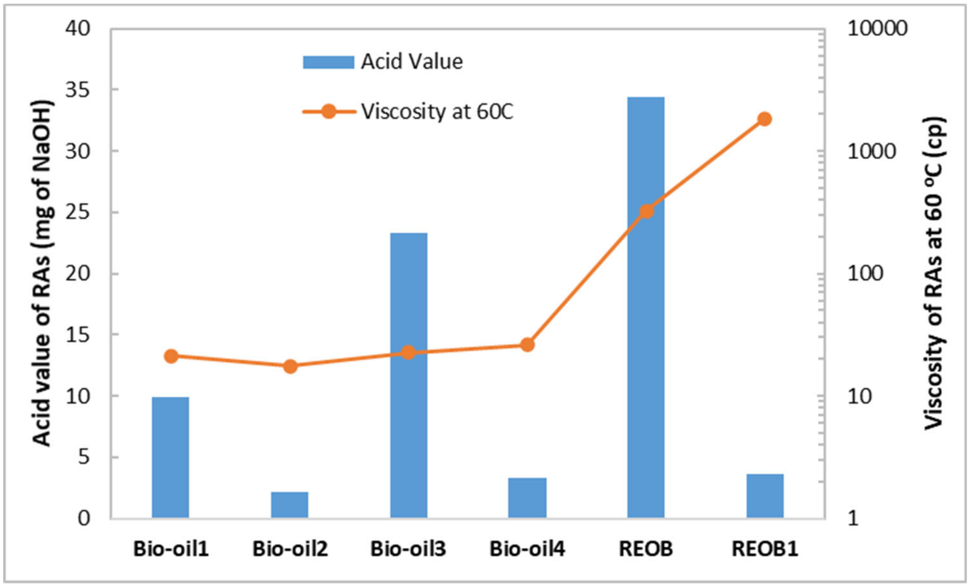


Figure 32. Characterization of RA materials using Acid Value and Viscosity

Figure 32 clearly indicates that Viscosity is not correlated with Acid Value for the RAs tested. The viscosity of the four Bio-Oil products is approximately equal, yet the Acid Value differs by as much as 60% of the average. Conversely, both the Acid Number and Viscosity are widely different for the two REOB materials. Since differences in efficiency and performance were noted between Bio-Oils in this study it is reasonable to consider a chemical marker such as Acid Number could be used to "fingerprint" individual additives. As such, Acid Value may be a useful tool for quality verification purposes. In addition, viscosity could be used to differentiate between bio oils and REOB oils.

VII. Summary of Findings

The objective of this RMRC Project is to evaluate the short- and long-term aging performance of high RAP and RAS asphalt mixtures utilizing various recycling additives ("rejuvenators") in the context of balanced mixture design. Three mixtures with different levels of RAP and RAS but sharing the same aggregate and asphalt binder sources were evaluated with three recycling additives (RAs): two bio-based additives and one recycled oil-based additive. A virgin mixture was also included in the comparison. Mixtures were evaluated for workability using gyratory compactor derived parameters, rutting and moisture resistance using the Hamburg Wheel Tracking Test, intermediate temperature cracking using the IDEAL-CT test, and low temperature cracking using a modified IDEAL-CT test. In addition, chemical and rheological characterization of the blended binders with and without the RAs was conducted and compared against the mixture testing results to determine the role of RAs and RAP/RAS binders in mixture behavior before and after extended oven aging. The main findings of the study are summarized below:

Workability Evaluation

- Workability of high RAP and RAS asphalt mixtures can be quantified using gyratory compaction curve-derived parameters after accounting for volumetric properties (e.g., effective binder content) and the physical characteristics of the aggregate (e.g., angularity). For the data generated during this study, the use of higher percentages of RAP and RAS did not significantly reduce mixture workability and thus cannot be considered as a challenge in increasing RAP or RAS content.
- RAs show marginal influence on mixture workability, although in most cases the workability stayed the same. The practical significance of the observed changes in workability due to the RAs is unknown but should be at least considered during the mix design process for potential forensic evaluation during production.
- Higher gyration effort is required to densify long-term aged samples in the laboratory relative to short-term aged samples, but the increase does not preclude the efficient production of test specimens in the laboratory in the long-term aged condition.

Rutting and Moisture Damage Resistance

- The addition of RAs reduces the number of Passes to 12.5 mm Rut Depth, but none of the RA-mixture combinations produced a mixture with less rut resistance than the virgin mixture.
- Passes to SIP for these mixtures also reduce, which indicates a possibility that some RAs increase potential of moisture damage. It should be notes, however, that it is difficult to determine whether this finding is a result of increased moisture susceptibility or an artifact of the correlation to Passes to 12.5 mm rut depth. This confounding effect of rutting and moisture in the HWTT has been described previously in the literature (Lu & Bahia, 2019).
- Using a modified analysis method to isolate the effects of moisture damage, the addition of RAs (both REOB and Bio-Oil) is shown to increase the moisture damage portion of the rutting curve independent of changes to dry rutting resistance. Based on the detailed analysis in this study, it is concluded that addition of RAs may significantly increase moisture damage potential in mixture, and the relative effect is specific to the type and composition of the RA.

Intermediate Temperature Cracking

- The IDEAL-CT Test at 25 °C can effectively distinguish between high RAP and RAS mixtures utilizing RAs but using the CT Index value alone for specification can be misleading. It is demonstrated that CT Index is primarily (~80% in this study) controlled by the Post-Peak Slope of the test trace; the research team proposes an evaluation method considering Fracture Energy and Post-Peak Slope behavior independently since valuable information regarding mixture performance can be gained using a dual-parameter approach than the CT Index. A minimum value of fracture energy and a maximum value of the post peak slope could be more effective as performance criteria for cracking and aging resistance.
- The RA application method (blending RA into virgin binder vs. direct application of RA on RAP and RAS) influences the CT Index measured for the mixture; however, the practical significance of the observed differences in CT Index are considered marginal.
- The addition of RAs produced CT Index values similar and at times higher than an equivalent virgin mixture at three levels of mixture aging for the RAP only mixtures. Differences in effectiveness at restoring CT Index among the RAs was noted, and each RA appeared to exhibit differing levels of aging susceptibility. The Bio-Oil additives produced, on average, the highest CT Index values for each aging condition.
- RAs were less effective at restoring CT Index values for the mixture containing the RAS after long term aging and produced lower CT Index values relative to the virgin mixture after long term aging. Like the RAP mixtures, Bio-Oils produced the highest average CT Index values among the RA types for each aging condition.

Low Temperature Cracking

- Using a modified AASHTO TP105 SCB test the research team observed significant aggregate fracture at the cracking interface that was not mitigated by increasing test temperature. High variability in test results using this test method were noted. The research team does not believe that such aggregate fracture is representative of field conditions and therefore investigated the use of a modified version of the IDEAL CT test at low temperature.
- The IDEAL CT test conducted at 0 °C and a strain rate of 0.5 mm/min was selected based on observation of the fractured samples, test repeatability, and differentiation between mixtures. The three individual parameters of Peak Load, Fracture Energy, and Post-Peak Slope exhibited similar behavior to what was demonstrated at 25 °C for each mixture, suggesting the same mechanisms control CT Index at 0 °C and 0.5 mm/min.
- For all mixtures, the addition of RAs increased the CT Index at both levels of aging (4 and 8 hours), sometimes by almost a factor of four relative to the corresponding control mix. The effect is generally greater for the RAP only mixtures. The Bio-Oils produced a more pronounced effect on CT Index relative to the REOB, and differences between the Bio-Oils are also observed, suggesting there is a chemical component contributing the increase in CT Index.
- The CT Index for the LTOA-8-hour samples remained higher than the corresponding control mixture for all combinations as well, suggesting that the cracking resistance gained through the

use of RAs is at least somewhat maintained after aging. The differences between the two Bio-Oils is muted after the LTOA-8-hour conditioning, although the effect remains greater than that of the REOB for each mixture.

- The findings at 0°C are in general agreement with the findings at 25 °C suggesting that the mechanism by which the RAs increase cracking resistance is not necessarily dependent on temperature, although the relative magnitude of the effects of a given RA on cracking resistance is. In other words, a given additive may be more effective within a certain temperature range than another, but this ranking could flip if the temperature range is changed. The selection of additives should therefore be based on the intended climate as well as performance and cost-related factors.

Asphalt Binder Rheological and Chemical Characterization

- Bio-Oil is more efficient relative to REOB in terms of the Oil Modification Index; the calculated dosage of REOB using the traditional linear blending charts to restore low temperature PG properties for very high (~50%) RAP and/or RAP and RAS mixtures was as high as approximately 20% for this study. Dosages this high are generally impractical and may not be cost-effective.
- The use of linear blending charts may produce significant error relative to the actual blended binder properties, and the error is likely to increase with increasing binder replacement levels. Directly testing binder blends with RAs or utilizing mixture performance testing is a more reliable way to predict performance.
- Blended binder Jnr at 3.2 kPa is highly correlated (R^2 = 80%) with mixture rutting performance and appears to be a better predictor of rutting behavior relative to high temperature continuous grade or G*/sin(δ).
- A strong (R^2 = ~70%) correlation between the CT Index at 25 °C and the G*sin(δ) parameter calculated at 25 °C was found. Although the Post-Peak slope is shown to be highly (R^2 = 83%) and logically correlated with G*sin(δ) at the same temperature there is no apparent trend between G*sin(δ) and Fracture Energy. The concept of splitting Post Peak Slope from Fracture Energy is therefore further strengthened by this finding. Since the G*sin(δ) is already measured as part of the standard grading method it is concluded that controlling this parameter is the most logical means for practitioners to adjust CT Index results from a binder formulation perspective.
- The correlation between BBR m-value measured at -18 °C and CT Index measured at 0 °C is strong (R^2 = 83%). The correlation between m-value and Post-Peak Slope was not found to be strong (R^2 = 39%), suggesting that perhaps m-value may capture both Post-Peak Slope and Fracture Energy behavior.
- The blended binders for these mixtures are all "m-controlled", thus increasing ΔTc (less negative) by way of increasing m-value for these mixtures (ΔTc is correlated with m-value for these mixtures with increasing m-value at -18 °C correlating to increasing ΔTc). It was observed that Bio-Oil is more effective at increasing m-value relative to REOB.
- Using chemical characterization methods (e.g., FTIR) to evaluate the blended binders, it is concluded that the use of RAs will not cause significant change to long-term aging behavior of the blends with high contents of RAP/RAS binders. All of the RAP/RAS blends show similar aging rates in terms of carbonyl index relative to the base binder, except for the 30% RAP blend. The aging

rates of sulfoxide index of RAP/RAS blends are slightly lower than the base binder. Thus, the chemical properties of RAP/RAS blends with RAs do not change significantly during the short-term aging process.

- The Acid Value (Acid Number) of RAs may be a useful “fingerprinting” tool for managing quality and consistency of RA products. It is shown that Acid Value may not correlate with a physical RA property (such as viscosity) and may therefore be a more robust practical tool for assessing RA consistency and quality.

VIII. Conclusions and Recommendations for Future Work

It is concluded that the RAs in this study can be used to produce an asphalt mixture containing high amounts of RAP with similar performance to a virgin mixture utilizing the same components using concepts of balanced mixture design. However, the use of 5% RAS in conjunction with RAP is shown to cause some difficulties in restoring cracking resistance relative to the virgin mixtures. Thus, extra caution is warranted with the use of RAS at similar levels, particularly for wearing or surface mixture courses where temperature fluctuations and aging is greatest.

Making decisions to compare, qualify, or otherwise accept mixture performance using short-term aging data alone can be misleading. It is clearly shown in this project that aging rate and relative ranking of mixture performance can change based on the level of aging. Agencies should consider implementation of a maximum aging rate parameter during the mixture design phase to account for these findings. Any major change to mixture composition during production (particularly a change to RA source/quality and/or RAP/RAS source/quality) may justify the need to reevaluate long-term aging performance for verification against the design mixture.

Use of direct testing of recovered binders with RAs is an effective means to estimate initial RA dosage and testing actual blends project binders is recommended over the use of linear blending charts, particularly for higher levels of RAP/RAS. A relatively simple parameter to evaluate ("fingerprint") RA quality is proposed in this study; contractors and Agency should be aware that RA composition can change significantly within the same RA "type" (E.g., Bio-Oil), and these changes could manifest in different mixture performance.

Recommendations for Future Work

The effect of aging on mixture performance in this study is pronounced. A recommendation for future is to evaluate the concept of using aging rate in terms of performance to evaluate mixtures. Such an approach somewhat side-steps the uncertainty of simulating field aging in the laboratory. Since this study included only one mixture design source, a logical testing matrix would include different aggregate sources, base asphalt sources, and RA types/sources.

According to contractor feedback received during Balanced Mixture Design (BMD) workshops held throughout the Country in 2019, contractors generally believed that any BMD approach should allow more flexibility during mixture design in terms of mixture composition (Yin, 2020). Since the type of RA was shown in this study to exhibited differing aging susceptibilities, a tool for Agency or contractors to better understand how basic changes in mix composition results in performance changes is needed. As States such as Wisconsin continue to benchmark their high-performing mixtures against performance test methods to develop reasonable limits, such a tool will have utility in both design and quality control.

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X. Appendix I: Literature Review Report

LONG-TERM PERFORMANCE OF ASPHALT CONCRETE MIXED WITH RAP AND RAS

LITERATURE REVIEW REPORT

Transportation Pooled Fund Program Project TPF-5(352)

Modified Asphalt Research Center

Department of Civil and Environmental Engineering

UNIVERSITY OF WISCONSIN – MADISON

May 2020

TABLE OF CONTENTS

1. Introduction

1.1 *Background*

The United States has more than 2.7 million miles of paved roads and highways, and 94 percent of those are surfaced with asphalt concrete (AC). These asphalt pavements require regular maintenance and periodic rehabilitation/reconstruction to perform effectively under repetitive traffic loads and environmental conditioning. The maintenance and rehabilitation/reconstruction in turn requires a continuous supply of asphalt binder and mineral aggregate, both of which are from nonrenewable resources. Consequently, there is growing interest in the use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) materials in the production of new AC mixes to reduce material costs and to preserve nonrenewable resources. The FHWA's asphalt pavement industry survey reported that the average percentage of RAP used in asphalt mixtures has increased from 15.6 percent in 2009 to 20.4 percent in 2014. From the first survey in 2009 to 2014, RAS use in asphalt mixtures has increased nearly 180 percent (Hansen & Copeland, 2014). The most recent survey conducted by NAPA and FHWA reported that the average percent RAP used increased to 21.1 percent in 2018, and in 2018, more than 97 percent of companies responding to the survey reported using RAP

Today AC pavement is America's most recycled material. In addition to conserving energy and protecting the environment, the use of recycled materials can significantly reduce the asphalt paving cost. Significant use of RAP in hot-mix asphalt (HMA) started in the mid-1970s due to high asphalt binder prices as a result of the oil embargo. Due to the increasing use in pavement construction/maintenance and lack of proper performance related knowledge, research projects have been completed to assess performance of asphalt concrete (AC) mixed with RAP and RAS (McDaniel & Anderson, 2001; Copeland, 2011; West, Willis, & Marasteanu, 2013). Since performance of binders and AC blended with recycled materials after long-term aging has not been clearly understood, limits were generally determined based on engineering judgment or plant production capacity rather than through a thorough scientific investigation. The recently published NCHRP Synthesis 495 reports that only two agencies in the survey use long-term aging tests, whereas several agencies commented they do not use long-term aging procedure for performance evaluation (Stroup-Gardiner, 2016). Therefore, it appears there is a significant gap in the effect of RAP/RAS on long-term aging of asphalt mixture.

In addition, there is the potential to use high RAP and RAS contents in AC without compromising the performance of the mix. The amount of binder replacement realized by using RAP and RAS in AC mix can be quite significant. An average asphalt binder in RAP may be approximately 4% and in RAS between 18-32% depending on the source. The amount of virgin binder conserved by increasing RAP content from 15% to 40% in AC mix increases from 10% to 30%. There is the same increase in virgin asphalt binder conservation when RAS content in AC mix increases from 2% to 5% (Robinette & Epps, 2010). Although researchers have shown that increasing RAP and RAS contents in AC mix increases the stiffness and potential cracking (Stroup-Gardiner & Wagner, 1999; Li, Marasteanu, Williams, & Clyne, 2008; McDaniel, Kowalski, & Shah, 2012; Hajj, Salazar, Guillermo, & Sebaaly, 2012), some recent research showed that recycling agents (RA) such as rejuvenators or softening agents blended with the AC mix can offset the effect of stiff binders from RAP and RAS and improve performance of recycled AC mix (Tran, Taylor, & Willis, 2012; Reinke, Baumgardner, Hanz, & King, 2017; Epps Martin, Kaseer, Arambula-Mercado, & Akash, 2020).

RAs can reduce the stiffness, improve workability and cracking resistance of recycled AC mix and contribute to significant cost savings. While softening agents such as asphalt flux oil, lube stock, and slurry oil can lower the viscosity of the aged binder, rejuvenators can restore the physical and chemical properties of aged binders. Rejuvenators often consist of lubricating oil extracts and extender oils, which contain a high proportion of maltene constituents that help re-balance the composition of the aged binder that lost its maltenes during construction and service. However, there is lack of information on the optimum dosage of RAs with different percentages of RAP and RAS, effect of type of RAs, appropriate type of laboratory tests to represent performance of recycled AC mix blended with RAs, and evolution of effectiveness (aging) of RAs on performance of recycled AC mix with high RAP and RAS contents.

Most pavement damage occurs only after a considerable service life, from 10 to 20 years for surface layers to considerably longer times for binder and base layers, depending on the structural design approach used. The material properties change during this time due to aging, especially for the surface layers which are exposed to moisture, large temperature changes, oxygen and UV light. As a result, it is the aged material properties that determine its sensitivity to damage. This means that to assess the suitability of asphalt binder/mix for a given application, not only its original properties, but also some indication of how these properties change over time or an indication of a minimum performance that will be retained over time is needed (Bahia & Anderson, 1995; Qin, Schabron, Boysen, & Farrar, 2014). Most rheological characterizations of blended binders and AC with recycled materials have been based on the small strain tests and limited aging treatments. Characterizations at larger strain levels and different extended aging conditions as well as changes in chemistry and composition of the blended binders in the AC-RAS/RAP mix that associate with aging of the mix are very important to assess brittleness, cracking problems, and service life of AC with various levels of RAP and RAS contents (Cavalli, Zaumanis, Mazza, Partl, & Poulikakos, 2018; Kilger, Swiertz, & Bahia, 2019).

To confidently use higher percentages of RAP and RAS in new AC mixtures, further investigations are needed to fill the knowledge gap regarding long-term performance of the recycled AC mix, particularly with the use of RAs.

1.2 *Research Objectives of Project TPF-5(352)*

The overall objective of this research is to understand long-term performance of asphalt concrete mixed with high contents of rejuvenated RAP and RAS. The information from the results of this research is needed so that the engineers have the confidence in increasing RAP and RAS for the design and specification of recycled asphalt concrete for sustainable pavement construction. The research will include the following steps to achieve the overall objective:

- Perform a thorough literature search to document and synthesize similar studies on the subject including performance of recycled AC, effects of aging on performance of virgin binders, AC mixes, recycled AC mixes, chemical composition and properties of RAs, investigation of different laboratory tests for proper assessment or performance of aged recycled asphalt concrete, and any field data on performance of recycled asphalt concrete, and similar studies conducted by other DOTs that would have applicability to this research.
- Develop a testing matrix and conduct short-term and long-term laboratory tests on representative recycled AC mix samples rejuvenated with different RAs.
- Characterize recycled AC mixes at larger strain levels and different extended aging conditions including brittleness, cracking resistance, fatigue resistance, and service life of AC with various levels of RAS and RAP contents and RAs as well as assess the changes in chemistry and composition of the blended binders in the AC-RAS/RAP mix that associate with aging of the mix.
- Prepare a final report that includes all the data, analyses, and recommendations and presentation to an assigned Oversight Committee.

This document is intended to satisfy the first research objective listed above.

1.3 *Report Organization*

The purpose of this report is to provide a summary of the existing literature in support of the listed objectives and the methodology proposed for investigating the long-term performance of AC containing RAP and RAS as submitted with the work plan. The findings of this review are used to determine the recycling agents and laboratory test methods for rejuvenated AC mixes in this study. This report will be organized in the following sections:

- Effects of aging on performance of asphalt materials;
- Performance of recycled AC;
- Laboratory test methods for recycled AC;
- Chemical composition and properties of recycling agents;
- Method of applying recycling agents; and
- Field data on performance of recycled AC.

2. Effects of Aging on Performance of Asphalt Materials

2.1 *Aging of asphalt binder in mixture*

The physical and chemical properties of the asphalt binder are changed due to exposure to oxygen and temperature extremes in the field (Bishara & McReynolds, 1996; Marasteanu & Arindam, 2004; Lu & Ulf, 2002). Oxidation in asphalt binder makes the binder harder and more brittle (Zupanick, 1994). Different researchers reported that molecular size distribution (LMS) of the binder increased because of aging which is caused by increasing the viscosity and stiffness of the binder (Asi, Wahhab, Al-Dubabi, & Ali, 1997; Jennings, et al., 1980). RAP and RAS are extremely aged materials which can lead to accelerated fatigue and thermal cracking of the pavement within the design life (Boriack, Katicha, & Flintsch, 2014; West, Kvasnak, Tran, Powell, & Turner, 2009; Hajj, Sebaaly, & Raghubar, 2009). Therefore, rheological properties of the RAP modified binder should be evaluated before using in the asphalt mixtures.

The rate of aging is affected by asphalt binders' composition and interactions with mix design components (e.g., aggregates gradation, surface area, and voids content or connectivity). Literature also suggests that changes in performance-based properties of asphalt mixtures are dependent on climatic conditions and aggregates source or mineralogy (Moraes, 2014). Binder changes are due primarily to two phases of aging: loss of volatile components and oxidation during high temperature production and construction stage, called short-term aging (STA); and progressive, in-place oxidation at ambient pavement temperatures, called long-term aging (LTA) (Bell, AbWahab, Cristi, & Sosnovske, 1994). In addition, recent research has shown that interactive effects between aggregate (particularly the P200 material) and asphalt binder significantly changes the rate of asphalt aging (Moraes, 2014). It is generally accepted that aging process of asphalt binder results in performance improvements to pavement within high temperature service range, while aging detrimentally affects pavement performance at intermediate and low temperature service ranges. As such, particularly in cold climates like Wisconsin, the accurate estimation of aging effects on performance is critical to achieving cost-effective pavements.

Due to the increase in the use of very stiff recycled asphalt such as RAP and RAS, there is more interest in using rejuvenators in the asphalt mixtures to improve the fatigue and thermal cracking performance. Very limited studies have been done to investigate the effect of rejuvenators on the performance of the mixtures when it undergoes to long term aging. Researchers are still not clearly understood about true restoration and softening mechanism of rejuvenators with mixtures during aging as RAP modified asphalt mixture is complex matrix of virgin binder, RAP binder, aggregates, and dust. Tran et. al (Tran, Taylor, & Willis, 2012) reported that softening mechanism mainly depends on the dispersion and diffusion technique of rejuvenators with in the mixtures. However, rate of diffusion depends on types and dosages of rejuvenators as well as a time and temperature dependent mechanism. Therefore, it is very necessary to investigate the effect of the aging on the rejuvenated asphalt mixtures.

2.2 *Summary of WHRP project 17-04 related to laboratory aging*

Laboratory protocols for estimating effects of rate and extent of aging on performance of asphalt mixtures in field is an ongoing research topic on a national scale. The recently completed NCHRP 09-52 (Newcomb, et al., 2015) project "Short-Term Laboratory Conditioning of Asphalt Mixtures" identified predictive methods to simulate short-term aging of asphalt mixtures, whereas the objective of recently completed NCHRP 09-54 (Kim, et al., 2018) project "Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction" identified methods to better predict long-term aging of asphalt mixtures. The recently completed WHRP Project 17-04 (Bahia, et al., 2018) aims to select the method that best represents aging of mixtures produced in the field. The specific objectives are: (1) plan and oversee the construction of a field test strip which will be used to supply plant produced mixtures for measuring field aging effects (short and long term) on changes in performance related properties of mixtures and extracted binders; (2) develop laboratory short and long term aging protocols that will simulate field aging effects measured on plant produced mixtures from the field strip by comparing mixture and extracted binder properties to those of laboratory produced mixtures; (3) determine the effects of changing binder grade, binder content, filler content and mixture traffic designation on mixture aging as measured by rutting and cracking resistance, as well as on moisture resistance potential; (4) verify the effects of softening oils and polymers used to adjust binder grades on results of short- and long-term aging protocols developed in that study.

Three types of aging conditions were used in WHRP 17-04 project to investigate the rutting and fatigue performance. For short term oven aging (STOA), all mixtures were heated in the oven at 135C for 2 hours. For long term oven aging (LTOA), mixtures heated at 135C for 6 hours (LTOA 6), and 14 hours (LTOA 14). In this study, effect of low-temperature modifiers on asphalt mixture aging and performance was also investigated. The six oil modified mixtures were compared to two mixtures that were prepared binders of PG52S-34 grade with no oils. The key findings related to effect of aging on the mixtures are shown below.

- A better distinction between mixtures can be found for STOA and LTOA-6 data, however FI values of mixtures after 14 hours of oven aging are found to vary in a very narrow range. Therefore, it was recommended to evaluate fatigue performance of mixtures at short-term and 6-hour long-term aging.
- Flexibility Index (FI) parameter is highly sensitive to mixture aging and magnitude of FI is controlled by post-peak slope during test.
- DCT Fracture Energy (FE) results were not found to be significantly affected by aging.
- SCB-IFIT results showed that mixtures with REOB oil have the lowest FI values at all aging levels, but also the lowest aging rates when compared to the mixture with no oils or with bio-oils.
- Long-term oven aging of 14 hours (LTOA-14) is too severe for asphalt mixtures and not suitable to distinguish between mixtures. The use of 6 hours was therefore recommended as the standard long-term aging procedure for asphalt mixtures.

3. Performance of Recycled AC

Many states allow to use recycled AC materials with low contents of RAP/RAS materials (RAP at a limit of 20%-25%, RAS at a limit of around 5%) in surface course since the promising mixture performance from scientific evidence and long-term experience of using recycled AC in field projects. AASHTO M323 recommends no change in binder selection when RAP content is less than 15%, and to select virgin binder one grade softer than normal when the RAP content at 15%-25%. Furthermore, an investigation on the state-of-the-practice of RAP in asphalt mixtures published in 2011 (Copeland, 2011) has compared the virgin mixes and recycled AC containing up to 30%RAP from 18 projects across North America. Those projects ranged from 6 to 17 years, and their pavement distresses including the rutting, fatigue cracking, longitudinal cracking, transverse cracking, block cracking, and raveling, were collected and statistically analyzed. It was found that the RAP mixes performed better than or equal to virgin mixes for the majority of the locations for each distress parameter.

NCAT has summarized several states' successful experience on the use of RAP and RAS (West & Willis, 2014). It was highlighted that in Florida, over 75% of all mixes produced for DOT projects contain RAP, with an average RAP content of 22%. The FDOT has found RAP mixes to perform very well. The MnDOT initially began incorporating RAP into plant mixed asphalt nearly 40 years ago and has maintained RAP usage within the standard MnDOT specifications for more than 30 years (Kuehl, Korzilius, & Marti, 2016). The most common maximum percent of RAP agencies are comfortable adding without decreasing the durability and long-term performance of their pavements is 30%. These lead to more attention on recycled AC materials containing the RAP at contents of higher than 30% and the use of RAP/RAS together. In the following sections, the workability, rutting performance, resistance to fatigue and thermal cracking of the recycled AC with higher RAP/RAS contents from literatures will be introduced.

3.1 Workability of recycled AC

Due to the stiffer binder in RAP/RAS materials, reduced mixture workability could be a problem when asphalt mixtures with higher RAP and RAS contents are used. Very limited literature reports the study of workability on recycled asphalt mixture are available. The NCHRP Project 09-46 (West, Willis, & Marasteanu, 2013) has drawn attention about the workability of RAP mixes. In that study, workability of mixes was measured using a device developed by the Massachusetts Dartmouth Highway Sustainability Research Center. The device measures the workability of an HMA mix suing torque measurement principles. The results showed that the addition of RAP decreased mixture workability and that the use of a softer virgin binder could improve workability to levels comparable to the control mixes. It is also noticed that studies of the changes in workability of RAP mixes due to the addition of the recycling agents have researcher's attentions.

Zaumanis et al. (Zaumanis, Mallick, Poulikakos, & Frank, 2014) used the Superpave gyratory compactor (SGC) samples prepared for performance tests for evaluating the mixture workability through calculating the number of gyrations to 8% air voids from densification curves. The mixture workability was compared with rotational viscosity of the binder (see Figure 3.1). All the rejuvenated mixtures/binders aligned between the virgin and RAP data points both based on mixture workability and binder viscosity. The 100%RAP mix with no recycling agent required more compaction energy than virgin mix. It was assumed that the 100%RAP have the least activated binder content. The results also indicated that caution should be used when evaluating the workability of rejuvenated binder since the results might not be reflected in compatibility of the mixture.

Jia et al. (Jia, Huang, Moore, & Zhao, 2015) investigated the rejuvenated mixture's workability through analyzing volumetric properties of compacted samples. The 40%RAP mix showed lower bulk specific gravity than the control mix (containing 25%RAP) when the same gradation and asphalt content were employed. The inclusion of waste engine oil seemed to improve the compactability resulting in an increase of bulk specific gravity and decrease in air voids of specimens.

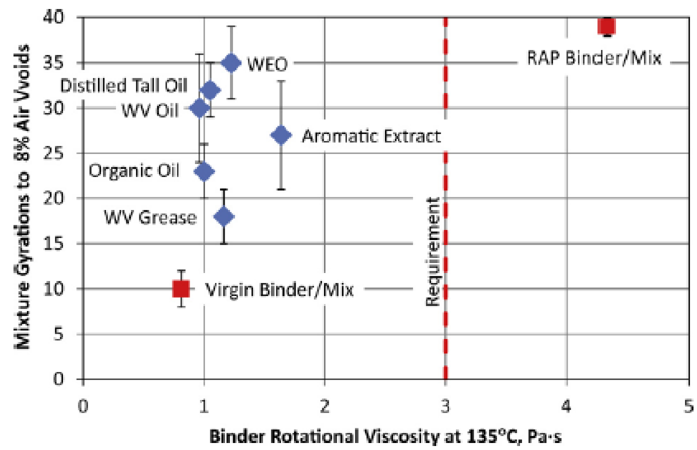


Figure 3.1 Mixture gyrations to 8% air voids vs. binder rotational viscosity (Zaumanis, Mallick, Poulikakos, & Frank, 2014).

The SGC densification curve has also been used to evaluate workability of asphalt mixtures (Bahia, Friemel, Peterson, & Russell, 1997). The concept of compaction energy indices was introduced to use the change in the volume of a sample as a function of the number of gyrations (response measured by the SGC), as an indicator of densification characteristics. The work applied by the paver and/or the rollers to compact the mix to the required density during construction was illustrated by the compaction energy index, which is defined as the area of SGC densification curve between 8 gyrations and the gyration that meets the 92% of Gmm specification. Mixes that require lower compaction energy in this range are more desirable (workable).

3.2 Rutting of recycled AC

It can be expected that the addition of RAP/RAS can increase the rutting resistance of recycled AC due to increased binder stiffness. The NCHRP Project 9-46 (West, Willis, & Marasteanu, 2013) was conducted to develop a mix and evaluation procedure that provides satisfactory long-term performance for asphalt mixtures containing high RAP contents-in the range of 25% to 50% or greater. A series of mix designs was then prepared with materials from four different parts of the United States with different RAP contents and different virgin binders. As expected, high RAP contents substantially increased the dynamic modulus of the asphalt mixtures as well as their rutting resistance as measured by the confined flow number test. It recommended a rutting test for high RAP mixes seems unnecessary unless a softer grade of virgin binder or rejuvenator is used.

For high RAP mixes to be used in climates prone to thermal cracking, agencies should consider for assessing low-temperature properties. This is also confirmed by an Iowa's study (Lee, Mokhtari, & Williams, 2015) on three test sections with target amounts of RAP materials of 30%, 35%, and 40%. Field mixtures were compacted in the laboratory to evaluate their performance. The Hamburg Wheel Tracking test results showed all three mixtures' rut depths after 20,000 passes were less than 3mm. Many other researchers (Williams R. , Cascione, Yu, Haugen, & Marasteanu, 2013; Al-Qadi, Aurangzeb, Carpenter, Pine, & Trepanier, 2012) have also reported that higher amounts or recycled RAP/RAS content would potentially decreasing rutting. The newly completed NCHRP Project 9-58 (Epps Martin, Kaseer, Arambula-Mercado, & Akash, 2020) focused on using recycling agents to facilitate recycled AC with high RAP and RAS binder ratios. The survey results indicated that rutting resistance mixtures with high RAP/RAS mixes is not a concern unless higher recycling agent doses are used. Of greater concern in recycled AC is fatigue, reflective, and thermal cracking since cracking resistance decreases with aging, and mixes with high RAP/RAS are expected to have lower cracking resistance due to their aged, stiff, and brittle binders.

3.3 *Fatigue cracking of recycled AC*

It is believed that the fatigue properties of asphalt mixtures at intermediate temperature relate to pavement resistance to alligator cracking. Under the traffic loads, aged asphalt pavements are prone to fatigue cracking due to increased stain sensitivity of aged binders. Generally, it is expected that the use of RAP/RAS materials has a potential of decreasing resistance to fatigue cracking of recycled AC. However, the results from several state research projects seem do not conform to expectations. McDaniel et al. (McDaniel, Shah, & Huber, 2011) investigated the fatigue properties of plant-produced PG 58-58 mixes and PG 64-22 mixes with 15%, 25%, and 40% RAP using the direct tension cyclic fatigue tests at two intermediate temperatures. The results showed that the mixes with 40% RAP had the greatest fatigue life, and the PG 64-22 mix with 40% RAP had an even higher fatigue life than the PG 58-28 mix with the same RAP content. While, the PG 58-28 mix with 25% RAP had improved fatigue performance compared to the PG 64-22 mix with the same RAP content, which is in line with conventional expectation that as softer binder may have improved fatigue performance. The mixes with 25% and 40% RAP showed superior fatigue life compared to the control regardless of the virgin binder grade.

Another study on fatigue performance of asphalt pavements containing RAS and RAP from Oklahoma DOT showed similar findings (Ghabchi, Zaman, Barman, Singh, & Boeck, 2015). In that study, the changes in fatigue resistance and cycles to fatigue failure with changes in the amount of RAS and RAP were examined using both flexural fatigue (four-point beam) and axial fatigue (cyclic direct tension) tests on laboratory compacted specimens. Eight fine surface course mixes with different types of asphalt binders (i.e., PG 64-22 and PG 70-28) containing different amounts of RAP and RAS were investigated. It was concluded that the fatigue life of asphalt mixes with a PG 64-22 binder increased with use of RAP (30%) or a blend of RAP and RAS. Using a blend of 5% RAP and 5% RAS in a mix led to the maximum increase in fatigue life. However, it was observed that the fatigue life of the mix decreased when 6% RAS was used compared to that of virgin mix with the same type of asphalt binder (PG 64-22). Also, it was found that when a PG 70-28 asphalt binder was used, use of RAP and/or RAS in a mix resulted in a decrease in fatigue life. Using 6% RAS resulted in the maximum decrease in fatigue life, compared to that of virgin mix with the same type of asphalt binder (PG 70-28). Those studies provide an insight of the fact that the fresh binders matter in the change of fatigue performance of recycled AC.

The complexity of RAS materials and less experience led to a Transportation Pooled Fund (TPF) Program TPF-5(213) (Williams R. , et al., 2013). It is a partnership of several state agencies with the goal of researching the effects of RAS on the performance of HMA applications. Agencies participating in the study include Missouri, California, Colorado, Illinois, Indiana, Iowa, Minnesota, Wisconsin, and the Federal Highway Administration. Field mixes from each demonstration project were sampled for conducting the following tests: dynamic modulus, flow number, four-point beam fatigue, semi-circular bending, and binder extraction and recovery with subsequent binder characterization. Pavement condition surveys were then conducted for each project after completion. The RAS mixes have very promising prospects since laboratory test results indicate good rutting and fatigue cracking resistance with low temperature cracking resistance similar to the mixes without RAS. The pavement condition of the mixes in the field after two years corroborated the laboratory test results. The mixes demonstrated good fatigue cracking resistance in the four-point bending beam apparatus.

Meanwhile, many researchers (West, Willis, & Marasteanu, 2013; Al-Qadi, et al., 2015; Bahia, et al., 2016) reported that it is as expected, compared to control mixtures without RAP, the high RAP content mixtures generally had lower fracture energies at intermediate test temperatures used to evaluate susceptibility to fatigue cracking. It was also reported that RAS mix which was stiffer had a poorer fatigue resistance at intermediate temperatures than the RAP mixtures (Foxlow, Daniel, & Swamy, 2011). West et al. investigated the resistance to fatigue cracking of four asphalt mixtures containing 25-50% RAP using the IDT fracture energy property based on a testing temperature of 10°C. The average fracture energy results were higher for the virgin mixes than for the mix designs containing RAP. The mix designs with 55 percent RAP had slightly higher average fracture energy results compared to the mix designs containing 25 percent RAP. It was also suggested that careful attention should be given to the selection of the performance grade of the virgin binder used in high RAP content mixtures to minimize any long-term risk of cracking distress.

Al-Qadi et al. (Al-Qadi, et al., 2015) evaluated protocols, procedures, and specification for testing engineering properties and performance of AC mixtures with high contents (up to 60%) of RAP and RAS. The effects of increasing the RAP and RAS content were shown with a reduction in the flexibility index (FI) demonstrating a more brittle behavior (as shown in Figure 3.2). The FI values varied from 15 to 1 for the best- and poorest-performing laboratory-produced mixtures. The FI proved to have a very good correlation with the performance rankings based on fatigue cracking measurements and structural analysis predictions for the sections with completed accelerated loading facility (ALF) and semi-circular bending (SCB) tests. The ALF tests demonstrated that increasing the recycled content up to 40% asphalt binder replacement levels without adequate binder grade bumping, or introducing excessive amounts of RAS (6%), can have some detrimental effects on fatigue cracking performance.

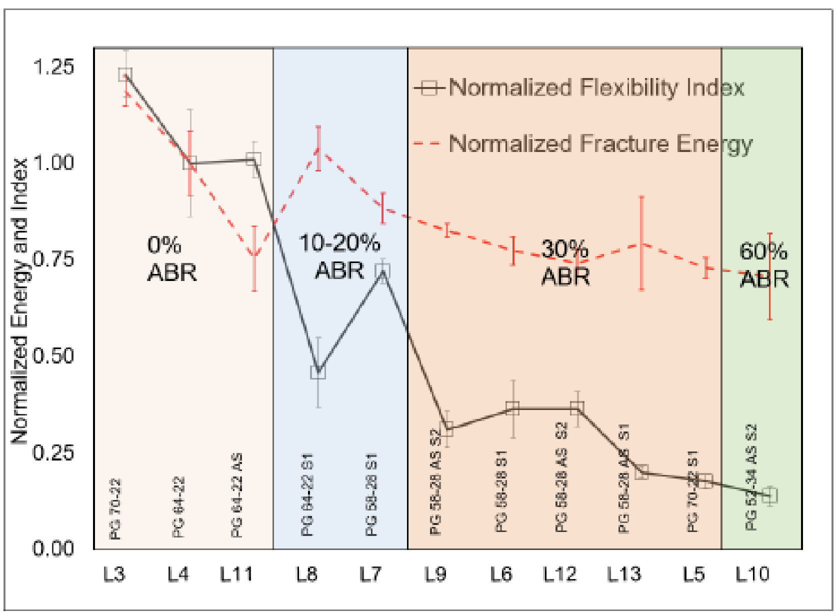


Figure 3.2: Normalized fracture energy and FI for AC laboratory mixes (Al-Qadi, et al., 2015).

In the recently published report for NCHRP Project 9-57 (Zhou, et al., 2016) the performance tests that can be used to eliminate brittle mixes or used to model asphalt pavements to predict cracking were evaluated. The urgent needs to establish and implement reliable such performance tests in a national level are due to the fact of that asphalt mix designs are becoming more and more complex with the increasing uses of recycled materials, recycling agents, binder additives/modifiers (e.g. recycled engine oil bottom), and multiple warm-mix asphalt technologies. Incorporating the conflicting outcomes on fatigue properties of recycled AC with RAP and/or RAS, it calls for more attentions on the study of long-term cracking properties of asphalt mixtures containing high contents of RAP and RAS in this study.

3.4 *Thermal cracking of recycled AC*

The replacement of virgin binder with oxidized or aged recycled binder is believed to increase the thermal cracking potential of AC. The indirect tensile (IDT) test, semi-circular bending beam (SCB) test and the disc-shaped compact tension (DCT) test at PG low temperatures have been commonly used to characterize AC thermal cracking potential. The decrease of fracture energy at low temperatures illustrates a reduced thermal cracking resistance. In a national pooled fund study of low temperature cracking in asphalt pavements accomplished in 2012 (Marasteanu, Buttlar, Bahia, & Williams, 2012), eleven mixtures used in pavement sections construed in Olmsted County (Minnesota) were investigated through the SCB and DCT tests. Both the SCB and DCT results yielded a similar range of values for fracture energy, between approximately 170 J/m^2 and 380 J/m^2. In general, the ranking of the mixtures according to the DCT and SCB fracture energy were in good agreement. The DCT result showed that the fracture energy of the mixtures decreases significantly when RAP is used. The SCB fracture energy showed similar behavior to that observed for DCT. On the contrary, the SCB fracture toughness results of mixtures containing RAP were considerably higher than that of mixtures without RAP, indicating that adding RAP increases the strength and toughness of the material but reduces the energy required for crack propagation.

Johnson et al. (Johnson, Watson, & Clyne, 2012) reported in one of their researches that distinct fracture energy trends emerged for MnROAD field mixtures that were grouped by RAP percentage (0%, 20%, 30%). Higher RAP percentages are prone to fracture. That was also confirmed at another research, in which two asphalt mixtures (PG 58-28 and PG 58-34) containing higher contents of RAP (25%, 40%, and 55%) were compared. The IDT critical temperature results showed that the addition of RAP significantly increased the critical temperature, predicting less crack resistance. The SCB fracture testing (see Figure 3.3) showed that the addition of RAP lowered the fracture energy and increased the fracture toughness of the mixtures, and the highest RAP contents had the most reduced fracture performance, in particular at the lowest temperature.

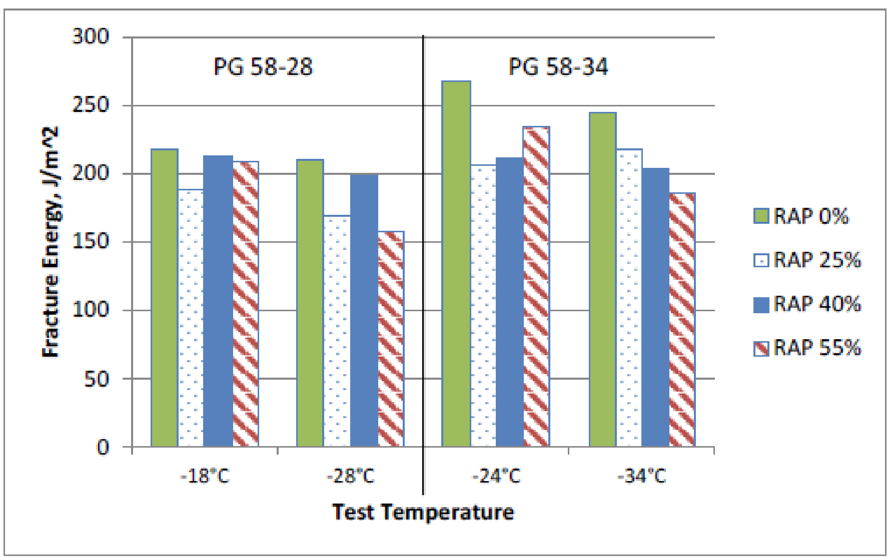


Figure 3.3: SCB fracture energy of asphalt mixtures with high RAPs (Johnson E. , et al., 2013).

The negative impacts of using high amounts of RAP on the thermal cracking of recycled AC have also been reported by other researchers. Mensching et al. (Mensching, et al., 2014) evaluated the plant-produced HMA mixtures containing varying percentages of RAP to investigate low-temperature performance of the mixes. The results highlighted some challenges in using high amounts of RAP. Based on results from the IDT test, tensile strength increased with RAP content. However, due to a faster-building thermal stress, warmer critical cracking temperatures resulted, indicating more sensitive to thermal cracking. It was also determined that degree of blending may impact the effectiveness of using softer binder grades at higher RAP percentages to improve low temperature cracking resistance. Lee's research (Lee, Mokhtari, & Williams, 2015) on filed mixtures with RAP amounts of 30%, 35% and 40% performed the SCB tests at two different temperatures of -18 and -30 ^{o}C. As the RAP amount increased, the stiffness increased, and the fracture energy decreased. In the WHRP Project 0092-15-04 (Bahia, et al., 2016), laboratory-produced Wisconsin mixtures with the RAPs at various binder replacement ratios were evaluated by using the DCT tests. The results showed that the recycled AC with binder replacement ratio of 50% given lower values of fracture energy than those with 15% binder replacement ratio.

However, several researchers have reported fracture energy does not always decrease with an increase in recycled (RAP or RAS) content. The NCHRP Project 09-46 (West, Willis and Marasteanu, Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content 2013) reported that the SCB fracture energy was not significantly affected by RAP content (even up to 55%) when a careful attention is given to the selection of the performance grade of the virgin binder used in high RAP content mixtures. Compared to the corresponding virgin mixes, the high RAP content mixes generally had higher fracture toughness but similar, or lower, fracture energy results. Williams et al. (Williams R. , et al., 2013) reported that the fracture properties of the mixes at low temperatures determined by the SCB fracture energy test showed no statistical change in mixes with RAS compared to the mixes without RAS for the Missouri, Minnesota, Indiana, Wisconsin, Illinois and Colorado projects. Based on the SCB results, the addition of RAS materials to HMA was not detrimental to its fracture resistance, and fibers in the RAS could be contributing to the mix performance. Tang investigated the fracture properties of high-RAP mixtures (with RAP contents of 30%, 40% and 50%) at three different temperatures (-10, -20 and -30 ^{o}C) through the SCB testing. As expected, the fracture energy increased as the test temperature was increased. However, the fracture energy values did not show a good correlation with the amounts of the RAP materials. Al-Qadi et al. (Al-Qadi, et al., 2015) had also found that there was no significant difference in the SCB fracture energy results at low temperature for various AC with RAP contents varying between 30% and 50%.

4. Laboratory Test Methods for Recycled AC

4.1 *Testing methods for blended binder containing RAP/RAS*

National research efforts such as NCHRP 09-12 (McDaniel & Anderson, 2001) validated the concept of linear blending charts in estimating the effects of RAP materials on blended binder properties. As recommended in AASHTO M323 Superpave Volumetric Mix Design, when the RAP content is higher than 25% a blending chart is to be used for selecting the fresh binder grade. However, the applicability of linear blending charts is facing more and more challenge as the increased use of polymer modified asphalts and increased RAP binder replacement level. Bonaquist (Bonaquist, 2011) demonstrated that blending charts for RAS materials becomes non-linear at binder replacement levels of approximately 30% for low temperature m-value. The Transportation Pooled Fund Project TPF-5(302) has the findings of that linearity of blending charts cannot be assumed for all the used PG+ test methods (e.g. Multiple Stress Creep and Recovery) , even for relatively low (20%) levels of binder replacement (Swiertz, Kilger, & Bahia, 2019). It was recommended that testing individual binder materials is the most direct approach to quantify performance of the blends.

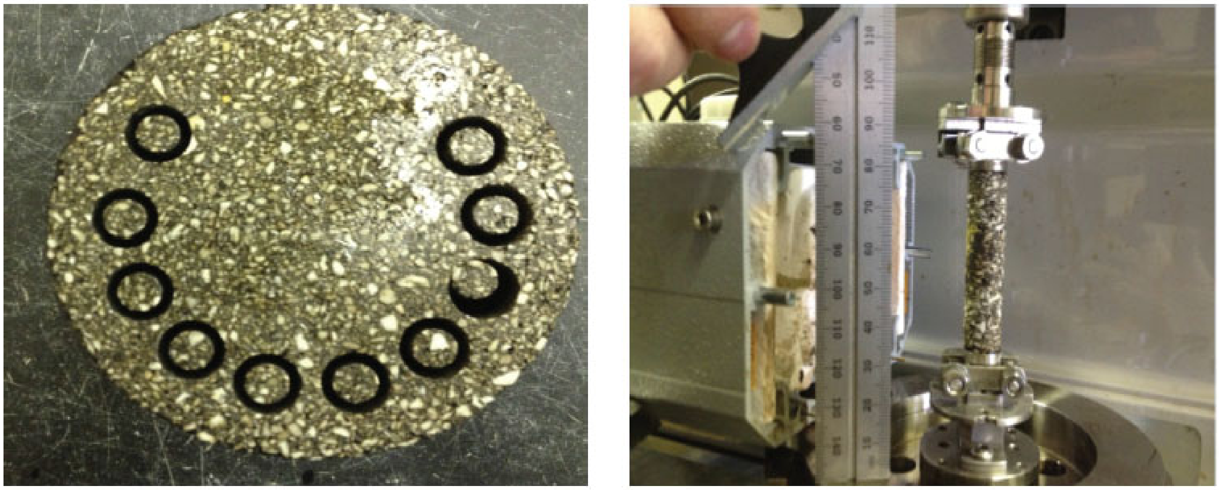
Many researchers have implemented the DSR and BBR tests on recovered binders to study the effects of RAP/RAS on mixture properties. William et al. (Williams R. , et al., 2013) reported that the test results of the extracted binder from field mixes of several states' projects showed that when RAS was used in HMA, the performance grade of the base binder increased on the high and low side. The average results of all the studied mixes showed that for every 1 percent increase in RAS, the low temperature grade of the base binder increased 1.9 ^{o}C; and for every 1 percent increase in RAP, the low temperature grade of the base binder increased 0.3 ^{o}C. Lee et al. (Lee, Mokhtari, & Williams, 2015) tested the binders recovered from field mixes containing 30%, 35%, and 40% RAP and found the addition of RAP stiffened the virgin binder PG 64-28 to PG 76-22, PG 76-16, and PG 82-16, respectively. The corresponding mixtures showed decreased fracture energy through the SCB testing at low temperatures. Even though the binder testing can rise the concern of low temperature cracking of recovered binders and it has certain correlation with the recycled mixture's low temperature performance. The uncertainty of impacts of RAP/RAS binders on mixture performance still exists, especially at low temperature range.

Foxlow et al. (Foxlow, Daniel, & Swamy, 2011) compared the laboratory performance of four HMA containing RAP and/or RAS and the corresponding binders recovered from the mixes. The binder testing results of complex shear modulus and critical cracking temperature indicated that the three RAS mixtures are stiffer than the RAP mix at high temperatures and would perform better with low temperature cracking. While the mixture testing results of dynamic modulus and failure temperature illustrated that the RAP mix was stiffer than the RAS mixtures and all four mixtures had similar low temperature performance.

In 2007 the Virginia DOT piloted a specification allowing up to 30% reclaimed asphalt pavement (RAP) in certain dense-graded asphalt surface mixtures while changing virgin binder grade requirements. Recently a following up study which evaluated the in-service performance of these mixtures after approximately 7 years has been published (Diefenderfer, Nair, & Bowers, 2018). It encompassed field visits and a laboratory investigation of a sample of 23 in-service pavements used in the initial laboratory evaluation. Cores were collected from each site and used to evaluate the binder and mixture properties. These data were compared to data from the original construction to assess the changes in the mixtures over time. Comparison of binder grades determined from mixture collected during construction and from cores at 6 years of service indicated that all mixtures, regardless of RAP content, gained one to two high-temperature performance grades over the 6-year in-service period evaluated. Low-temperature grades were similarly affected. The relationships among ΔTc, RAP content, continuous low temperature grade, and the stiffness and m-value failure temperatures were further examined using correlation analysis. The outcomes of that analysis suggested that although there were concerns about the cracking potential of the binders, these concerns were independent of the RAP content of the mixture.

4.2 Testing methods for fine asphalt mixture containing RAP/RAS

Another concern about the method of testing recovered binder from recycled mixture is that the solvent used to recover asphalt binders influence the properties of old and virgin binders. The potential effects of this need to be considered when testing the performance properties of recovered binders and using them to understand the effects of high contents of RAP/RAS on mixture performance. In recent years, an alternative testing protocol of using fine asphalt mixture (FAM) specimens for characterizing the inherent properties of RAP/RAS materials and the interaction of RAP/RAS with virgin aggregates and asphalt binder. This eliminates the need for chemical solvents by directly testing FAM specimens composed of fine RAP/RAS particles and virgin aggregates and binder. Typically, FAM mixes are a homogenous blend of asphalt binder and fine aggregates (i.e., passing a #4, #8, or #16 [4.75 mm, 2.36 mm, or 1.18 mm] sieve). The asphalt binder content and the gradation of the FAM are representative of the binder content and gradation of the fine portion of a full-graded asphalt mix. The DSR tests are normally performed on the cylinder FAM specimens for measuring the complex shear modulus and fatigue behavior of the mortar (see Figure 4.1).



(a) (b)

Figure 4.1: Preparation process for FAM specimens including (a) coring locations of cut gyratory-compacted specimen and (b) test setup (Kanna, Ozer, & Al-Qadi, 2014).

Kanna et al. (Kanna, Ozer, & Al-Qadi, 2014) prepared the FAM specimens with two types of binder (PG 64-22 and PG 46-34) and at three levels of RAS (0.0%, 2.5%, and 7.1% RAS from two RAS sources). The testing program included complex shear modulus, shear strength, and fatigue (stress and strain control modes) using the DSR with modified testing features. Results from FAM specimens were shown to be consistent and sensitive to varying RAS percentages and sources. It was concluded that the FAM testing can be used effectively to quantify effects of RAS on asphalt mixtures and can be used effectively to address RAS source variability.

Alavi et al. (Alavi, He, Harvey, & Jones, 2015) also investigated the procedures of preparing and testing FAM specimens with RAP and RAS fines passing the #8 (2.36 mm) sieves. Cylindrical specimens 0.5 in. (12.5 mm) in diameter cored from a Superpave gyratory-compacted FAM specimen were tested using a torsion bar fixture in a DSR. Five different asphalt binders covering two performance grades (PG 64-16 and PG 58-22) and sourced from three California refineries were evaluated in that study. The influence of two different percentages of RAP (25 and 40 percent by binder replacement) and one percentage of RAS (15 percent by binder replacement) were evaluated through partial factorial asphalt binder testing and full factorial FAM mix testing. Preliminary testing of FAM mixes indicated that this approach appears to be repeatable and reproducible, and produces representative results for characterizing the performance-related properties of composite binders at binder replacement rates up to 40 percent and possibly higher.

The asphalt binder grade and source, RAP and RAS content, and rejuvenating agent all had an influence on FAM mix stiffness, as expected. RAP and RAS content followed by the use of a rejuvenating agent had the most significant influence. This enhanced mortar approach was used to characterize the effect of RAP on virgin binder true grades by Yan et al. (Yan, Hernando, Lopp, Rilko, & Roque, 2018; Yan, Hernando, & Roque, 2019). The DSR and BBR tests were conducted on FAM specimens of virgin mix and RAP mixes with binder replacement rates of 11-16%. The PG continuous grades measured on blended binders were found to be successfully predicted by the mortar testing approach.

4.3 *Testing methods for AC mixtures containing RAP/RAS*

Based on the literature search in section 3, it is known that the concerns about recycled AC containing high contents of RAP/RAS focus on the moisture damage, and intermediate and low temperature cracking. For those mixture properties, various testes have been developed for characterizing the effects of

RAP/RAS. This section is going to introduce the commonly used testing methods and their effectiveness reported in the literature.

Moisture Damage Tests

The most commonly used moisture damage susceptibility test in the United States is the tensile strength ratio (TSR) test, which is part of the current Superpave mix design method. The AASHTO T283 provides the standard TSR test method for measuring the moisture resistance of HMA mixtures. The conditioned set specimens are saturated to between 70%-80% and then subjected to one freeze-thaw cycle. After conditioning, specimens are loaded diametrically at a rate of 50 mm/min. The ratio of the average tensile strengths of the conditioned specimens to the average tensile strengths of the unconditioned specimens is the tensile strength ratio. The NCHRP Project 09-46 (West, Willis, & Marasteanu, 2013) performed the TSR tests on the mixtures containing high RAP contents and found those mixtures generally had higher conditioned and unconditioned tensile strengths than virgin mixes. The higher tensile strengths are due to the contribution of the stiffer aged RAP binder. In several cases, the TSRs of the high RAP content mixes were lower than those for the virgin mixes and even dropped below the criterion of 0.80 required in AASHTO M 323. Adding anti-stripping additive was usually sufficient to improve the TSRs above 0.80. A few states allow lower TSR criteria if the tensile strengths are maintained above a certain threshold. For example, the Georgia and Florida DOTs will allow TSRs as low as 0.70 as long as conditioned and unconditioned tensile strengths are above 689 kPa (100 psi). States that use a softer PG grade of binder should have lower tensile strength criteria. Johnson et al. (Johnson, et al., 2010) compared the TSRs of recycled AC with the 10%, 15%, and 25% RAP and found that the RAP content is inversely related to the TSR. All tested recycled mixture had TSR values of less than 0.75, while both their conditioned and unconditioned tensile strengths are higher than 100 psi.

Another common moisture damage susceptibility test is the Hamburg Wheel Tracking (HWT) test. It was originally developed in the 1970s in Hamburg, Germany. It was initially intended for measuring rutting behavior, but later it was found also capable of measuring the effects of moisture damage. The HWT test was introduced into the United States to predict moisture damage of HMA because of its simplicity, practicality, and repeatability (Aschenbrener, 1995). The HWT has gained popularity as many state highways DOTs decided to use it in HMA rutting and moisture sensitivity evaluation (Hand, 2013).

The current test standard in accordance with AASHTO T324 was developed in the NCHRP Project 20-07/Task 361, in which testing temperature is not specified. State agencies are specifying test temperatures in several ways. Some agencies are using a single temperature. Some agencies are specifying temperature based on the base PG of the mixture. Lee et al. employed the HWT tests at 50 ^{o}C to evaluate moisture sensitivity of the filed mixtures with 30%-50% RAP (Lee, Mokhtari, & Williams, 2015). All specimens exhibited excellent performance with very little rutting with no stripping inflection point in 20,000 passes. It was concluded than the high-RAP field mixtures were not susceptible to moisture damage. In the WHRP Project 0092-15-04 (Bahia, et al., 2016) it was found that for Wisconsin mixtures the binder properties dominate most of the behavior measured at 50 ^{o}C, while the mixture properties and aggregates showed only minor influence on the main response measured at 50 ^{o}C. The statistical analysis indicated that the HWT tests at 45 ^{o}C is a better testing temperature for successfully characterizing both rutting and moisture susceptibility of Wisconsin mixtures. Therefore, both the binder PG grades and RAP/RAS contents should be taken into consideration when determining the proper testing temperature for HWT test on recycled AC.

Table 4.1 summarizes commonly used testing methods for measuring moisture susceptibility of recycled AC from the literature search. A brief summary of the findings for each method is also given.

Table 4.1 Testing Methods for Moisture Susceptibility of Recycled AC from Literature Search.

Testing Method	Testing Specimens and Settings	Supporting References	Major Findings
Tensile Strength Ratio Test (AASHTO T283)	• Cylinder specimen of Ø100mm and 63.5mm thick or Ø150mm and 95mm • To apply load along the diameter at 50 mm/min and at 25 °C	(Al-Qadi, et al., 2009) (Johnson, et al., 2010) (West, Willis, & Marasteanu, 2013) (Airamgzeb, 2014)	• The tensile strength increased with an increase in RAP content for both conditioned and unconditioned specimens. • It was recommended that a lower TSR limit should be considered for accepting the RAP mixes. • RAP particles might be more resistant to moisture damage than virgin materials due to the selective absorption of binder into the aggregate at initial stage.
Hamburg Wheel Tracking Test (AASHTO T324)	• Slab specimens of 320mm*260mm*(38-100)mm or cylinder specimen of Ø150mm and 62mm with a cut along secant line • To load with a moving wheel at 705 N with speed of 52 passes/min in water bath of 40-50 °C	(Lippert, Sholar, & Williams, 2012) (Lee, Mokhtari, & Williams, 2015) (Mohammad, Elseifi, Raghavendra, & Ye, 2015) (Bahia, et al., 2016)	• Hamburg specifications were discussed in the context of relating mixes to field performance by eliminating mixes that would fail in the field, but not eliminate those that have proven to perform well in the field. • 21 out of 50 states indicated that the HWT are used. • Several researches showed that the field mixtures containing high RAP were not susceptible to moisture damage. • Both the binder PG grades and RAP/RAS contents should be taken into consideration when determining the proper testing temperature for HWT test on recycled AC.

Fatigue Cracking Tests

The four-point bending beam test specified in AASHTO T321 was validated in the SHRP A-003A project (Deacon, Tayebali, Rowe, & Monismith, 1995). It was concluded that this controlled-strain laboratory tests are suitable for pavement predictions. The in-service pavement performance can be predicted for a variety of mixtures, climates, pavement structures, and traffic loadings. Attempts to simulate mixture performance under the accelerated testing of both laboratory wheel tracking and ALF experimentation yielded mixed results. The results showed that the materials that are more flexible (lower stiffness) perform better in constant strain. Williams et al. performed the four-point bending beam tests on field mixes with RAS from several agencies, including Missouri, California, Colorado, Iowa, Illinois, Indiana, Minnesota, Wisconsin and the Federal Highway Administration. All the regression of fatigue curves (i.e. the numbers of cycles to failure vs. strains at log scales) have a coefficient of determination value above 0.9. The results illustrated that mixes containing RAS can possess similar or better fatigue properties to mixes without RAS. Ghabchi et al. (Ghabchi, Zaman, Barman, Singh, & Boeck, 2015) found that the fatigue life of asphalt mixes with PG 64-22 binder increased with use of RAP or a blend of RAP and RAS. Furthermore, it was concluded that high coefficient of variation values of the cycles to failure found for four-point beam fatigue test showed that the repeatability of this method was not very good.

The typical failure criteria used for four-point bending beam tests is defined as when 50% of initial stiffness is achieved. Tang (Tang, 2014) reported that to rely on the reduced stiffness could be misleading for the materials with varying levels of stiffness. It was recommended to use dissipated energy plot to demonstrate the fatigue resistance of the mixes. A stiffer mix has a higher dissipated energy than a softer mix in the initial loading cycles for achieving the same deformation at a constant strain level, and the total cumulative energy integrated with cycle counts can be used to represent the mixture performance. The results showed that the dissipated energy for 40% RAP mixture drops faster than 30% and 50% amounts of RAP for both traditional and fractionated methods. The four-point bending beam test is widely used in research, but is impractical as a routine mix design test because of special equipment needed for sample fabrication and the length of time required to obtain test results.

Several more recently developed fatigue cracking measurements, including the semi-circular bend (SCB) – LTRC test, SCB – Illinois flexibility index test (SCB-IFIT) , and indirect tensile cracking test (IDEAL-CT), are gaining popularity throughout the U.S. The SCB tests of ASTM D8044 was first introduced by Mull et al. (Mull, Stuart, & Yehia, 2002) to characterize the fracture resistance of crumb rubber modified asphalt mixtures. Mohammad et al. (Mohammad, Wu, & Aglan, 2004; Kim, Mohammad, & Elseif, 2012) used the test to derive limits for the critical strain energy release rate Jc. The intermediate temperature fracture resistance of various asphalt mixtures as measured by the SCB-LTRC and IDT test methods and correlated those fracture properties to the cracking performance of Louisiana asphalt pavements. The SCB-Jc values showed good correlation with the IDT measured fracture properties and demonstrated a good correlation with field cracking performance data as well. Bahia et al. (Bahia, et al., 2016) employed this SCB-LTRC tests to determine the Jc of mixes with the RAP at binder replacement ratios of 15%, 30%, and 50%. It was found that no consistent trends between change in Jc values and mixture's binder replacement ratios. In the results, the Jc increases with a decrease of binder replacement ratio for only three out of 16 mixtures, whereas, Jc decreases with a decrease in binder replacement ratio for nine out of 16 mixtures.

The SCB-IFIT testing protocol was developed and reported by Al-Qadi et al. (Al-Qadi, et al., 2015), aiming to ensure performance of high asphalt binder replacement mixes using RAP and RAS. The SCB-IFIT testing protocol introduced the flexibility index to determine cracking resistance which considering the fracture energy and slope of the load-displacement curve after the post-peak representing average crack growth rate. The study of Illinois Center for Transportation was to identify, develop, and evaluate protocols, procedures, and specifications for testing engineering properties of AC mixtures with varying amounts of asphalt binder replacement (up to 60%) using RAP and RAS. As a result, the SCB-IFIT test procedures suggested a testing temperature of 25°C with a loading head displacement rate of 50 mm/min. It was shown that the FI has the ability to capture the effects caused by various changes in the materials and volumetric design of AC mixes. Plant-produced, laboratory-produced, and field core specimens were used in validating the potential of the SCB-IFIT test and the FI to predict cracking resistance among mixes. The FI obtained from the SCB-IFIT tests was in very good agreement with performance rankings developed for the mixes, based on fatigue cracking measurements and structural analysis predictions.

In the WHRP Project 0092-15-04 (Bahia, et al., 2016) the SCB-IFIT tests and SCB-LTRC tests on Wisconsin's recycled mixtures were compared. The FI result range was considered wide and thus could be considered suitable for differentiating between mixture variables. The analyses indicated that the -SCB-LTRC Jc parameter was not able to reliably discriminate between mix design factors known to influence cracking. Instead, using only one notch size and using the analysis described in the SCB-IFIT is the best parameter to be used for controlling intermediate temperature cracking resistance.

Another fatigue cracking test that gains the most interests and discussion in the past few years is the IDEAL-CT. The IDEAL-CT is similar to the traditional indirect tensile strength test, and it can be run at the room temperature with cylindrical specimens at a loading rate of 50mm/min in terms of cross-head displacement. Any size of cylindrical specimens with various diameters (100 or 150mm) and thicknesses (38, 50, 62, 75mm, etc.) can be tested. For mix design and laboratory QC/QA, it is proposed to use the same size specimen as the Hamburg wheel tracking test: 150 mm diameter and 62 mm height with 7±0.5 percent air voids, since agencies are familiar with molding such specimens. This test is becoming popular because it is a simple (no instrumentation, cutting, gluing, drilling, and notching to specimen), practical (minimum training needed for routine operation), and efficient (test completion within 1 minute) cracking test which can be performed with regular indirect tensile strength test equipment (Zhou, Im, Sun, & Scullion, 2017). It was concluded that the IDEAL-CT is sensitive to key asphalt mix components and volumetric properties (RAP and RAS content, asphalt binder type, binder content, aging conditions, and air voids), and the CTindex results correlated well with field performance in terms of fatigue, reflective, and thermal cracking (See Figure 4.2). The detailed comparison between the IDEAL-CT and other cracking testing was reported in the NCHRP Project 9-57 (Zhou, et al., 2016).

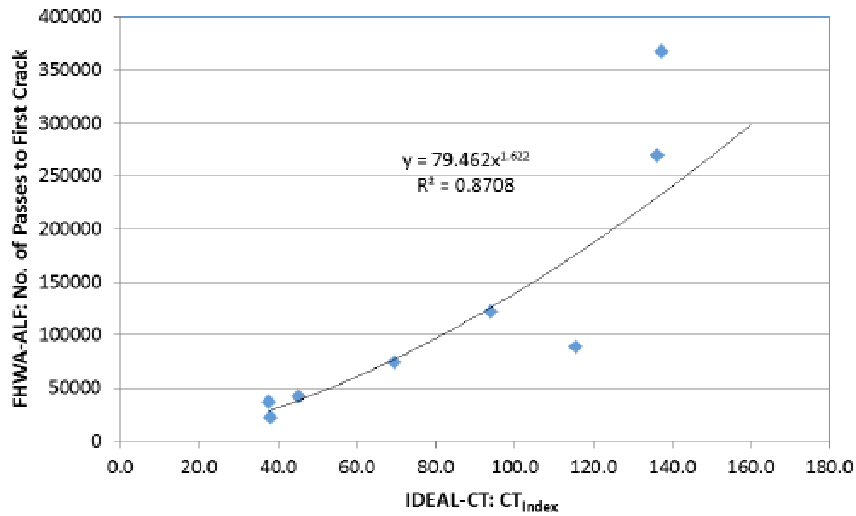


Figure 4.2: Correlation between IDEAL-CT and FHWA Accelerated Loading Facility Full-Scale Testing (Zhou, Im, Sun, & Scullion, 2017).

The NCAT test track findings at Phase VI (2015-2017) (West, et al., 2019) include a study of cracking group experiment, in which the SCB-IFIT and IDEAL-CT were compared. The IFIT yielded a relatively large spread of FI results for the seven mixtures. This kind of statistical spread in results for different mixtures would allow users to better assess how to improve mix designs and adjust field mixtures. Based on a similar calculation method, the IDEAL-CT data showed the same trends as the IFIT data in most respects. The IFIT and IDEAL-CT have the lowest equipment cost and fastest testing time of the six cracking tests in the experiment, but the IDEAL-CT offers faster specimen fabrication than the IFIT since no specimen saw cutting is required.

Table 4.2 summarizes commonly used testing methods for measuring fatigue cracking of recycled AC at intermedium temperature from the literature search. A brief summary of the findings for each method is also given.

Table 4.2: Testing Methods for Fatigue Resistance of Recycled AC from Literature Search.

Testing Method	Testing Specimens and Settings	Supporting References	Major Findings
Four-Point Bending Beam Test (AASHTO T321)	• Beam specimen of 380mm*50mm*63mm • To apply repeated flexural bending at 20C with frequency of 5-10 Hz at a constant strain of 250-750 microstrain	(Deacon, Tayebali, Rowe, & Monismith, 1995) (Williams R. , et al., 2013) (Tang, 2014) (Ghabchi, Zaman, Barman, Singh, & Boeck, 2015)	• The mixes containing RAS possessed similar or better fatigue properties to mixes without RAS and the R^2 of fatigue curves have value above 0.9. • The coefficient of variation of the cycles to failure showed high values illustrating not good repeatability. • Only using cycles to failure criteria is not sufficient to define the fatigue resistance.
Semi-Circular Bend – LTRC Test (ASTM D8044-16)	• Semi-circular specimen of Ø150mm and 57mm thick with three notch depths • To apply constant load-line displacement at 0.5 mm/min at PG intermediate temp.	(Mull, Stuart, & Yehia, 2002) (Mohammad, Wu, & Aglan, 2004) (Kim, Mohammad, & Elseif, 2012) (Bahia, et al., 2016)	• A critical strain energy release rate Jc value ranging from 0.5 to 0.6 kJ/m2 is typically recommended. • The SCB-measured Jc values showed good correlation with the IDT-measured toughness index values and also with field cracking performance data. Incorporating high RAP contents of up to 30% in WMA did not seem to reduce the fracture resistance. • No consistent trends between change in Jc values and mixture's binder replacement ratios were found.
Semi-Circular Bend – Illinois Flexibility Index Test (AASHTO TP124-16)	• Semi-circular specimen of Ø150mm and 50mm thick with a notch depth 15mm • To apply constant load-line displacement at 50 mm/min at 25 °C	(Al-Qadi, et al., 2015) (Ling, Swiertz, Mandal, Teymourpour, & Bahia, 2017) (Bahia, et al., 2018) (Chen, Zhang, & Bahia, 2019)	• The flexibility index was in very good agreement with performance rankings developed for the mixes, based on fatigue cracking measurements and structural analysis predictions. • Compared to SCB-LTRC test, using only one notch size and IFIT analysis is a better approach for controlling intermediate temperature cracking resistance. • Binder fatigue behavior can well explain the range in FI values of asphalt mixtures after varying levels of aging.
Indirect Tensile Cracking Test (ASTM D8225)	• Cylinder specimen of Ø150mm and 62mm without cutting or trimming • To apply constant load-line displacement at 50 mm/min at 25 °C	(Zhou, et al., 2016) (Zhou, Im, Sun, & Scullion, 2017) (West R. , The IDEAL Cracking Test, 2019) (Yan, Zhang, & Bahia, 2020)	• It is designed as a simple (no instrumentation, cutting, gluing, drilling, and notching to specimen), practical (minimum training needed for routine operation), and efficient (test completion within 1 minute) cracking test. • The CTindex values clearly show that the IDEAL-CT test is sensitive to RAP and RAS. • The NCAT test track findings confirmed that the IDEAL-CT data showed the same trends as the SCB-IFIT data in most respects. • The Laboratory tests showed that the IDEAL-CT data have lower variability than SCB-IFIT data.

Thermal cracking tests

The commonly used thermal cracking tests include the indirect tensile (IDT) creep and strength test, disc-shaped compacted tension (DCT) test, and semi-circular bend (SCB) tests at low temperatures, which using the standard methods of AASHTO T322, ASTM D7313, and AASHTO TP105, respectively. In a national pooled fund study on low temperature cracking in asphalt pavements (Marasteanu, Buttlar, Bahia, & Williams, 2012), those three tests were conducted on nine asphalt mixtures used in field studies with respect to their low temperature cracking resistance. The set of mixtures included RAP mixtures, PPA modified mixtures, and SBS and Elvaloy polymer modified mixtures. The results showed that the ranking of the mixtures according to the DCT and SCB fracture energy showed fairly good agreement (as shown in Figure 4.3). The fracture energy results of DCT and SCB tests for conditioned laboratory specimens showed good correlation to field results. While the IDT strength results indicated relatively poor correlations between field and laboratory specimens. The statistical analysis found that the IDT test showed the ability to best distinguish statistical rankings between mixes but the stiffness and strength results were not well correlated.

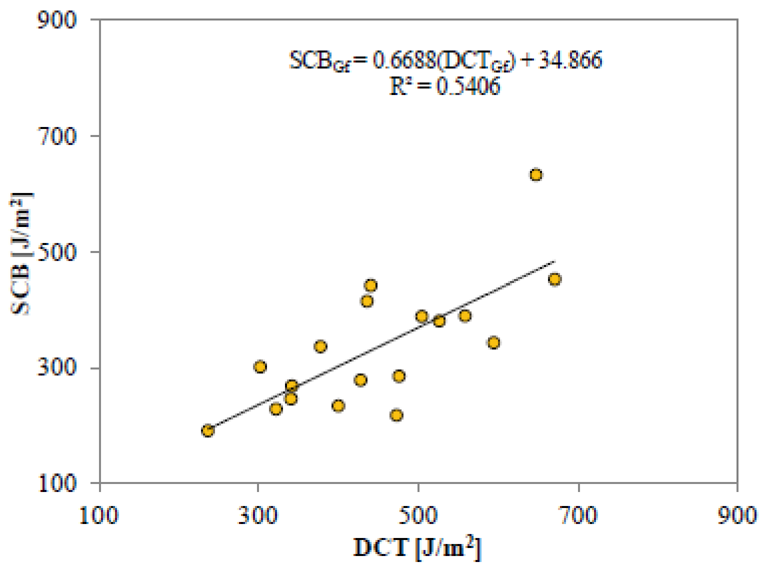


Figure 4.3: DCT vs. SCB correlation plots (Marasteanu, Buttlar, Bahia, & Williams, 2012).

Wagoner et al. (Wagoner, Buttlar, Paulino, & Blankenship, 2005) found that the fracture energy was believed to be a much better indicator for determining the resistance of the mixture to fracture than other indirect measures such as tensile strength. The fracture energy approach clearly distinguished between the materials according to differences in binder properties, whereas the indirect tensile strength was shown to greatly underestimate the tensile strength of highly ductile mixtures. The authors also selected the DCT geometry as the most promising test configuration based on the potential fracture surface being larger than the SCB configuration. Recent research presented at the 2016 AAPT meeting found that for a given aggregate source the DCT test was found sensitive to use of both RAP and RAS as decreasing fracture energy was observed in both cases with increasing recycled contents (Buttlar, Hill, Wang, & Mogawer, 2017). Furthermore, when RAP was held constant at 45% improvements in DCT fracture energy were observed with decreasing binder grade. In that data set use of a PG 46-34 with 45% RAP resulted in equivalent fracture energy to the virgin mix prepared with PG 64-22.

However, many researchers have reported concerns about the DCT test on determining low temperature cracking of recycled AC and instead the SCB test was recommended with respect to this aspect. A study on RAP effect on HMA mixes conducted by Al-Qadi et al. showed that data spread and ability to quantify the impact of RAP on AC diminish as testing temperature decreases for both SCB or DCT (Al-Qadi, et al., 2009). The DCT was found to be incapable of reasonably distinguishing between various mixes at low temperature. The SCB results illustrated that as the RAP content in the HMA increases, the fracture energy of the mix decreases. To compare the fracture energy results between HMA with PG 64-22 binder to that with PG 58-28 binder using 40% RAP in the mix, the effect of double bumping was determined. At testing temperatures, -12 °C and 0 °C, the HMA specimens with PG 58-28 and 40% RAP exhibited lower fracture energy than the HMA specimens with PG 64-22 and 0% RAP. Johnson et al. performed the SCB tests on laboratory mixture designs containing up to 55% RAP and found that the addition of RAP lowered the fracture energy and increased the fracture toughness of mixtures, and the highest RAP contents had the most reduced fracture performance (Johnson E. , et al., 2013).

Table 4.3 summarizes commonly used testing methods for measuring thermal cracking of recycled AC from the literature search. A brief summary of the findings for each method is also given.

Table 4.3 Testing Methods for Thermal Cracking of Recycled AC from Literature Search.

Testing Method	Testing Specimens and Settings	Supporting References	Major Findings
Indirect Tensile Creep and Strength Test (AASHTO T322)	• Cylinder specimen of or Ø150mm and (38-50) mm thick with parallel surfaces • To apply a load to specimen at ram movement rate of 12.5mm/min at the binder PG low temp.	(Marasteanu, Buttlar, Bahia, & Williams, 2012) (McDaniel, Shah, & Huber, 2011) (Ghabchi, Zaman, Barman, Singh, & Boeck, 2015)	• The addition of RAP and/or RAS increased the tensile strength. • The addition of 15%-25% RAP without altering the binder grade changed pavement cracking temperature by about 2 °C. 40% RAP increased by about 4 °C. • Lowering the binder grade for high RAP mix can reduce pavement cracking temperature to the control.
Disc-Shaped Compacted Tension Test (ASTM D7313)	• Cylinder specimen of or Ø150mm and 50mm thick with starter notch, flat surface at crack mouth, and two loading holes • To perform test with a constant crack mouth opening displacement rate of 0.017 mm/s at PG low temp. + 10 °C	(Wagoner, Buttlar, Paulino, & Blankenship, 2005) (Marasteanu, Buttlar, Bahia, & Williams, 2012) (Buttlar, Hill, Wang, & Mogawer, 2017) (Bahia, et al., 2016)	• The fracture energy has been shown to discriminate between the mixtures containing ductile binders more broadly than indirect tensile strength. • Decreasing binder grade can reduce the fracture energy of recycled AC with high content RAP. • It was recognized the insensitivity of DCT to factors affect cracking resistance and the influence of aggregate type on fracture energy.
Semi-Circular Bend Test (AASHTO TP105)	• Semi-circular specimen of Ø150mm and 24.7mm thick with a notch depth 15mm • To apply vertical load for a constant crack mouth opening displacement rate of 0.0005 mm/s at PG low temp. +10 °C or -2 °C	(Li & Marasteanu, 2004) (Li, Marasteanu, Williams, & Clyne, 2008) (Al-Qadi, et al., 2009) (Johnson E. , et al., 2013)	• Measured fracture parameters from this test are used in new low-temperature module of the MEPDG. • As the RAP content in the HMA increases, the fracture energy of the mix decreases. • The amount of transverse cracking in each test section correlated well with the SCB fracture energy measured for RAS mixes with various contents.

The SCB test was also employed to determine low temperature fracture properties of the mixtures containing 0%, 4%, 5%, and 6% RAS and correlated with the field evaluations by Williams et al (Williams R. , Cascione, Yu, Haugen, & Marasteanu, 2013). The authors found that the amount of transverse cracking in each test section correlated well with the SCB fracture energy measured for each mixture. The 4% RAS showed the least amount of cracking in the field and had the highest fracture energy, whereas the 0% RAS showed the greatest amount of cracking in the field and had the lowest fracture energy. Both the laboratory fracture energy data and field surveys indicated that adding RAS to the Iowa DOT mix design increased its ability to resist cracking. Furthermore, in the WHRP Project 0092-15-04 (Bahia, et al., 2016) the DCT test was performed on Wisconsin mixtures containing various contents of RAP (with percent binder replacement of 15%, 30%, and 50%) at their PG low temperatures. From the DCT results, it was very difficult to find consistent trends with the variation of any factors controlled in the experiment, especially RAP contents.

5. Recycling Agents for Recycled AC

5.1 *Chemical and Rheological Properties of RAs*

The use of softer binder is one approach to improve fracture resistance of recycled AC containing RAP/RAS. Another popular method to reduce the stiffness of recycled AC is to use recycling agents (RAs), especially for recycled AC with high contents of RAP/RAS. Some researchers have tried to separate recycling agents into two categories—softening and rejuvenating agents. Softening agents, including flux oil, lube stock, lubricating oil, and slurry oil, can lower the viscosity of the aged binder. Rejuvenating agents, which contain a high proportion of maltene constituents such as lube extracts and extender oils, can help restore the balance between maltenes and asphaltenes that were changed during the aging process. As a result, the use of rejuvenating agents can improve the relaxation, ductile, cohesive and adhesive properties of the recycled binder (Willis & Tran, 2015). It is also reported that some proprietary RAs made from biobased oils have been marketed and sold as rejuvenating agents for use with asphalt mixtures containing high RAP and RAS contents. Table 5.1 provides a partial list of currently available rejuvenators arranged by category.

Table 5.1 Recycling agent categories and types (Willis & Tran, 2015).

Category	Examples	Description
Paraffinic Oils	Waste Engine Oil (WEO) Waste Engine Oil Bottoms (WEOB) Valero VP 165® Storbit®	Refined used lubricating oils
Aromatic Extracts	Hydrolene® Reclamite® Cyclogen L® ValAro 130A®	Refined crude oil products with polar aromatic oil components
Nathenic Oils	SonneWarmix RJ™ Ergon HyPrene®	Engineered hydrocarbons for asphalt modification
Triglycerides & Fatty Acids	Waste Vegetable Oil Waste Vegetable Grease Brown Grease Delta S	Derived from vegetable oils *Has other key chemical elements in addition to triglycerides and fatty acids
Tall Oils	Sylvaroad™ RP1000 Hydrogreen®	Paper Industry byproducts Same chemical family as liquid antistrip agents and emulsifiers

The current specifications for RAs (such as AASHTO R14 and ASTM D 4552) mainly classify the viscosity and flash point of RAs. The recycling agent must have a low enough viscosity to mix with the recycled material, but must also have a sufficiently high flash point to be safe and must not evaporate quickly during the production and construction, or from the pavement in its early life. The ratio of the binder viscosity at 60°C is used as an indicator of the agent's durability. A better understanding of the long-term effects of RAs in asphalt mixtures is crucial to achieve more effective recycle practices.

This important understanding of how the blended binders containing RAs will maintain (or degrade) their chemical/rheological characteristics during their long-term service has been limited and requires more tests and observations. King et al. reported in the Emulsion Task Force 2018 meeting about the characteristics of eight recycling agents, including aromatic extract (A1), paraffinic oil (P), tall oil (T1), modified vegetable oils (V2, V3), and reacted bio-oils (B1, B2) (King, Martin, Garcia, & Menopace, 2018). The aging susceptibility of those RAs was characterized by measuring the complex viscosity of their RTFO, PAV 20 and 40 hours aged residues (see Figure 5.1). The tall oil T1 and modified vegetable oil V3 showed an extreme change in viscosity after the laboratory long-term aging. According to the authors, the investigation on oxidation and rheological response of blended binders with RAP and RAs through the FTIR and DSR tests, indicated that the paraffinic oil is only softening agent with poor compatibility; the aromatic extract is sufficient for some combos at higher dosage; the vegetable oils and bio-oils act like emulsifier to stabilize but less rheological effect; the tall oil is not as effective with aging. It was recommended to set specifications for long-term aged binder blends. Haghshenas et al. also declared that the petroleum-based RA improved performance of the binder in long-term service by preserving the chemical composition and maintaining the stability, whereas the agriculture-based RA might increase the aging issues because of its pre-existing high oxygen content, which could negatively affect long-term durability over service period (Haghshenas, et al., 2018).

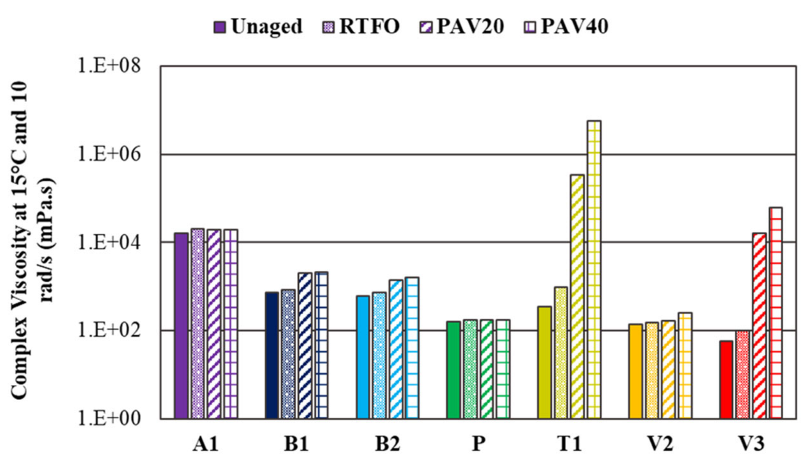


Figure 5.1 Aging susceptibility of rejuvenating oils (King, Martin, Garcia, & Menopace, 2018).

The newly published report for NCHRP Project 09-58 (Epps Martin, Kaseer, Arambula-Mercado, & Akash, 2020) provides tools for estimating RA dosage based on a target climate with minimum laboratory efforts by considering the type, source, and amount of recycled materials, and the source and grade of the base (virgin) binder. Blending charts for recycled binder blends were established and verified, and later used to develop relationships to estimate the optimum dosage of RA. The RA optimum dosages were determined to match the continuous high-temperature performance grade (PGH) of the recycled binder blend to that required by the target climate, as this dosage yielded the best performance for rejuvenated binders and mixtures.

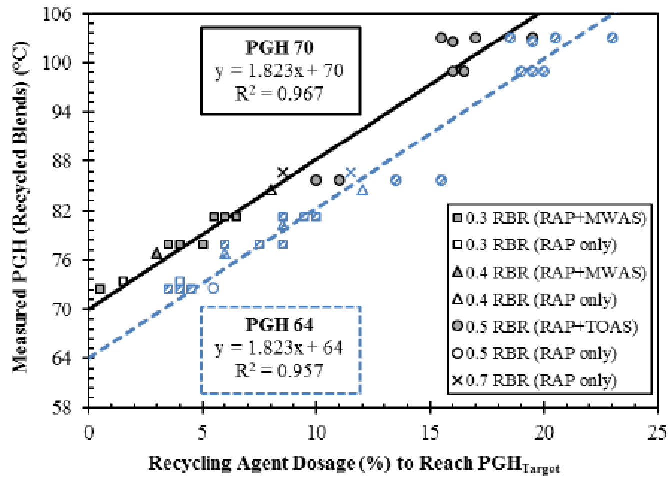


Figure 5.2 Optimum dosages to match the PGH of the recycled blends to PGH_{target} (Epps Martin, Kaseer, Arambula-Mercado, & Akash, 2020).

It is noticed that some researchers (Karki & Zhou, 2016; Kaseer, Cucalon, Arambula-Mercado, Martin, & Epps, 2018; Lee, Mokhtari, & Williams, 2018) recommended the Black space diagram of |G*|-δ and the Glover-Rowe (G-R) parameter to determine the durability of asphalt binders and to evaluate the effectiveness of RAs initially and with aging. The |G*| and δ of blend binders can be plotted in Black space to assess both the effects of adding aged recycled materials and partially restoring the stiffness and flexibility by the inclusion of recycling agents. A new asphalt binder without polymer modification has a relatively lower |G*| and higher δ, therefore it is found toward the lower right corner of the Black space diagram. The inclusion of recycled materials is reflected as an increase in |G*| and reduction in δ, similar to the effect of laboratory and/or field aging. Conversely, considering rejuvenation as the reversal of the impact of aging on asphalt, from a rheological standpoint, the inclusion of recycling agents is expected to reduce |G*| and increase δ. The G-R parameter that calculated from |G*| and δ at 15 °C and 0.005 rad/s were used to tie with inadequate ductility of 5 cm to 3 cm that correlates to G-R parameter values between 180 and 600 kPa, respectively, and relates to cracking onset and significant cracking, respectively, in the field.

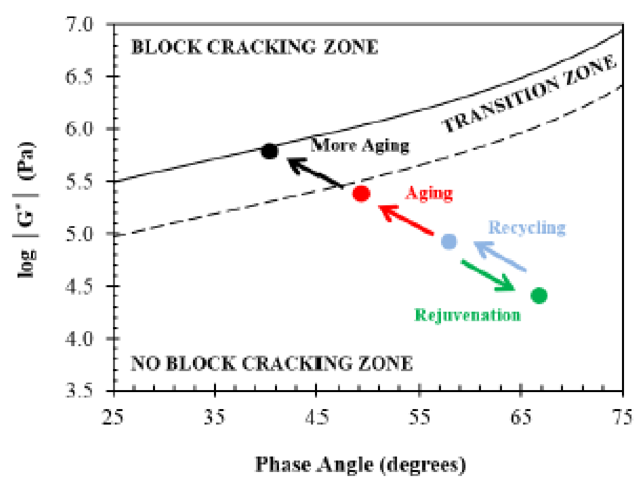


Figure 5.3 Illustration of G* and δ changing with recycling, aging, and rejuvenation in black space (Kaseer, Cucalon, Arambula-Mercado, Martin, & Epps, 2018).

Karki and Zhou characterized the effects of RAs on the rheological, chemical, aging, rutting, and cracking properties of asphalt binders containing recycled binders and then uses the findings to recommend optimum dosages (Karki & Zhou, 2016). According to the analysis using the G-R parameter, the addition of a rejuvenator increased the amount of aging associated with the initiation of damage and the onset of significant cracking. In contrast, blends of moderately aged recycled binders faced durability issues much later than do blends of severely aged recycled binders. Lee et al. evaluated the effects of different rejuvenators through applying each product to aged asphalt binder and high-RAP mixtures (Lee, Mokhtari, & Williams, 2018). Based on DSR test, all rejuvenators lowered both PG high-temperature and low-temperature limits. The G-R parameter was calculated to determine the effect of rejuvenators in lowering the stiffness of the aged asphalt binder. The aged binder showed the higher G-R value indicating a high level of aging whereas rejuvenated asphalt binders exhibited G-R values between the aged asphalt and virgin asphalt. Overall, all rejuvenators lowered the aging level at different extents but did not bring its properties to those of the original virgin binder.

It is worth noting that few researchers report a linkage between the chemical compositions and effectiveness of RAs. Zhou et al. (Zhou, Karki, & Hu, 2019) evaluated many bio-oils to improve cracking resistance through a series of laboratory testing and the construction of 17 field test sections. The bio-oils performed differently in the laboratory and field test sections, and some are more effective than others. Both laboratory and field test results indicated the total fatty acid content is a performance indicator for bio-oils, and the larger fatty acid content, the more effective the bio-oil. To perform well, bio-oils should contain more than 97 percent fatty acid content and less than 50 percent saturate fatty acid. Meanwhile, it is preferred to have the mass loss of less than 5 percent after the rolling thin film oven test. The DSR and BBR test results further confirmed the total fatty acid content as a performance indicator for bio-rejuvenators. Furthermore, it was found that the saturated fatty acid (or wax) content is better within 50 percent, although the higher total fatty acid content is preferred.

5.2 *Effects of RAs on Mixture Properties*

Several research reports focusing on the effects of RA on aged asphalt binders have been published, while limited effort has been given to the study of RA's effects on long-term performance of asphalt mixtures with high contents of RAP/RAS. In recent years, several researchers started to investigate the mixture properties of laboratory-produced recycled AC with RAs, and to extend to evaluation of their pavement performance. Mogawer et al. (Mogawer, Booshehrian, Vahidi, & Austerman, 2013) evaluated the effects of three different RAs on mitigating the increase in stiffness of mixtures having high RAP and RAS contents. The RAs modified asphalt binders (at a dose recommended by the manufactures) were used to fabricate the control mixture with 40% RAP, 5% RAS, and 35%RAP plus 5% RAS. The results showed that the cracking characteristics of the mixture improved by the addition of the RAs, however, the rutting and moisture susceptibility were adversely impacted at the dose and the testing conditions used. It was also noticed that the drop in dynamic modulus for the RAS and RAP/RAS mixtures was not as great as for the 40% RAP mixture. That might be attributed to the RAS binder being stiffer than the RAP binder.

Zaumanis et al. evaluated the effectiveness of RAs for production of 100% RAP content mixtures (Zaumanis, Mallick, Poulikakos, & Frank, 2014). The 100% recycled HMA lab samples were modified with five generic and one proprietary RAs at 12% dose and tested for binder and mixture properties. Waste Vegetable Oil, Waste Vegetable Grease, Organic Oil, Distilled Tall Oil, and Aromatic Extract reduced the PG grades from 94–12 of extracted binder to PG 64-22 while the Waste Engine Oil required higher dose. Workability of RAP mixture was increased by the use of all RAs, but none was able to improve it to the level of the virgin binder or mixture. Fatigue resistance of recycled AC at the used test parameters was higher than that of virgin mixture for all except Waste Engine Oil rejuvenated mixture. Low temperature mixture cracking test results showed that five of the six rejuvenators have decreased cracking susceptibility compared to RAP mixture. Waste Vegetable Oil and Aromatic Extract performed similarly to virgin mixture while others had slightly warmer cracking temperature.

Lee et al. (Lee, Mokhtari, & Williams, 2018) evaluated the low-temperature cracking potential of the laboratory high-RAP mixtures with 27.6% and 70% of RAP materials. Based on the DCT test result, it was concluded that high-RAP mixtures with RAs were more resistant to a low–temperature cracking than the high-RAP mixtures without it. However, based on HWT test results, the RAs did not improve the moisture susceptibility and rutting potential. Overall, the refined tall oil and vegetable oil performed better than petroleum oil at their optimum dosage rates.

Haghshenas et al. (Haghshenas, Nsengiyumva, Kim, Santosh, & Amelian, 2019) investigated the three RAs (triglyceride/fatty acid, aromatic extract, tall oil) by conducting various binder-level and mixture-level tests. Three RAs and an anti-stripping additive were added to the asphalt binder/mixture with 65% RAP/RAS content and 35% virgin materials (i.e., binder and aggregate). The results of various laboratory tests, including two AC performance tests (i.e., flow number and SCB fracture under dry and wet conditions) and several binder tests were carried out. The AC mixtures treated with RAs at the dosage levels selected from the binder PG testing showed improved fracture resistance compared to unrejuvenated mixtures. While a rutting problem was noticed in only one situation where an excessive amount of RAS was utilized, which highlighted the importance of optimizing the RAP/RAS combination (toward more RAP and less RAS), and also highlighted the importance of evaluating rutting susceptibility of rejuvenated asphalt mixtures after the short-term oven aging.

Several studies have demonstrated that the FAM plays a significant role in the performance characteristics of AC mixtures, and it provides an opportunity for investigating the effect of RAP without involving solvent for binder extraction. Nabizadeh et al. (Nabizadeh, Haghshenas, Kim, & Aragao, 2017) investigated the effects of three RAs on mechanical characteristics of asphalt mixtures containing 65% RAP, through both AC and FAM samples. The results of experimental tests on viscoelastic stiffness, cracking behavior, and the permanent deformation of asphaltic materials in both the AC and FAM mixtures were compared. The RAs generally increased the ductility of the high-RAP mixtures, resulting in their improved cracking resistance of asphalt mixtures. The FAM test results generally correlated with the AC test results for all measured properties implying that FAM testing could provide key information for predicting the behavior of the AC mixture and thereby act as an efficient tool for screening materials.

In 2019, Zhou et al. (Zhou, Karki, & Hu, 2019) recommended and demonstrated a four-step balanced mix design process for designing mixes containing RAP/RAS and RAs: 1) selection of RA type, 2) determination of the range of the RA amounts required to meet both the binder specification and aging characteristics, 3) determination of the range of the RA amounts required to meet mixture rutting and cracking requirements, and 4) selection of final RA amount based on engineer judgement.

6. Methods of Applying Recycling Agents in Practice

The efficiency of rejuvenation of RAP binder is mainly affected by the type of rejuvenator, dosage of rejuvenator, and the application method of rejuvenator (Noureldin & Wood, 1987). The current practice of the batch and drum plant is to add the rejuvenator with virgin asphalt binder, and then mix with the RAP or RAS, and fresh aggregate. The main concern of using this approach is that RAP binder is not fully active before adding with fresh aggregate as the some of the rejuvenator is absorbed by the fresh aggregate, and therefore homogeneous film thickness can't be achieved (Al-Qadi, Aurangzeb, Carpenter, Pine, & Trepanier, 2012). This will lead to different types of pavement distress in service life.

Zaumanis et al. (Zaumanis, Cavalli, & Poulikakos, 2020) summarized ten potential rejuvenator addition locations in asphalt mix plant, and compared two most promising addition locations in a full-scale study: spraying of rejuvenator on cold reclaimed asphalt on the feeding belt before heating versus addition of rejuvenator to hot reclaimed asphalt in mixer (as shown in Figure 6.1). RAP samples were collected at various places in the production line to evaluate the effect of rejuvenator addition location on softening point, penetration, rheology and chemical composition of extracted binder. The results revealed that passing through the extreme temperatures in the RAP heating drum does not sacrifice mechanical performance or increase chemical aging of the rejuvenated binder. A benefit of early rejuvenator addition is that it provides a longer residing time of rejuvenator on the binder and thus potentially may allow higher binder activation and better blending of RAP binder with rejuvenator and virgin binder. This has to be evaluated through mixture tests.

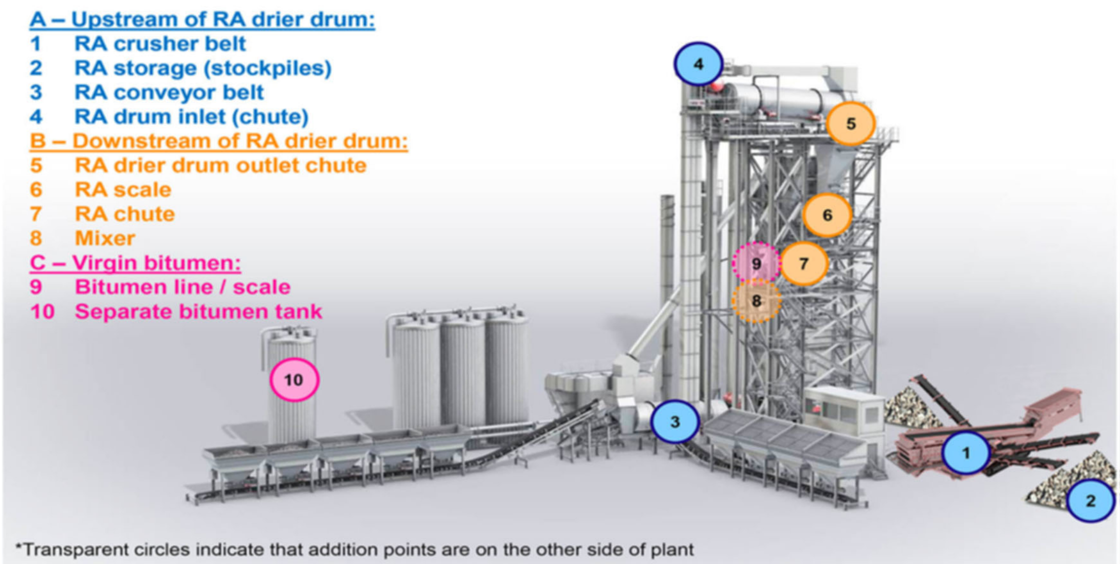


Figure 6.1 Schematic representation of potential rejuvenator dosing locations (Zaumanis, Cavalli, & Poulikakos, 2020).

Haghshenas et al (Haghshenas, Nsengiyumva, Kim, Santosh, & Amelian, 2019) investigated the effect of blending method on the performance of asphalt mixtures and they found that blending method has great influenced on the performance of the mixtures. They used two rejuvenation methods (method1: Directly add the rejuvenators with RAP; method2: use low shear blending method to mix the rejuvenators with base binder before adding into mixtures) to prepare same mixture and conducted SCB and flow test to measure the rutting and fatigue performance. R2-11-UNCURED and R2-11-VBR2 mixtures were prepared by following the methods 1, and 2, respectively and their corresponding flow numbers are shown in Figure 6.2. Based on Figure 6.2, it is revealed that method2 is more efficient than method1 for rejuvenating the RAP as the flow number is increased by 50% (i.e., from 800 to 1235) for R2-11-VBR2 mixture which was prepared by following the method2. It was concluded that rejuvenations method can alter the performance of the mixtures; therefore it should be considered before applying the rejuvenators.

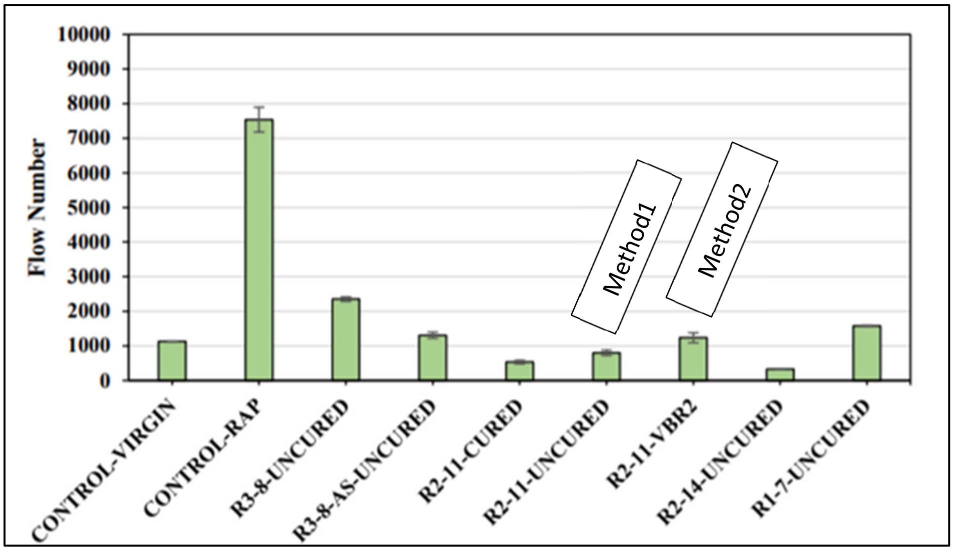


Figure 6.2 Average Flow number with error bars (Haghshenas, Nsengiyumva, Kim, Santosh, & Amelian, 2019).

Researchers also discovered different methods and materials to improve the healing capability of asphalt pavement at service life. Liquid based healing system has been used by researchers to repair the cracks. Liquid based system made from rejuvenators, resin and polymer and then added at different dosages with asphalt mixtures. Liquid based healing system is damaged and releasing the liquid agent into the asphalt pavement to improve the crack when crack is formed in the pavement. It is more efficient than the other methods as it is penetrated and filled the void into asphalt mixtures and decreased the oxidation rate of the mixtures. Researchers have been using the microcapsules containing rejuvenator and fiber containing rejuvenator technique to evaluate the healing rate of the asphalt mixtures for micro crack. The healing rate of these techniques depends on the breakage of the capsule and fiber into the mixtures. When capsule and fiber are broken into the mixtures due to form of micro crack, it's released the rejuvenator resulting in softening the aged mix and recover the crack. To overcome the disadvantages of microcapsules and fiber techniques, researchers try to apply the rejuvenator directly into the mixtures. If rejuvenator can directly penetrate into the aged mixture that could help to reduce the stiffness of the mixtures by diffusion and softening effects. Pan et al (Pan, et al., 2018) applied the different types of rejuvenator (different types of oil) directly in fractured surface of Semi-Circular Bending (SCB) samples and tested them after healing for different days. They found that after 60 days of healing, the strength (Flexibility Index) of the mixtures can be recovered to 40%-55%.

7. Field Data on Performance of Recycled AC

Several laboratory studies have done to determine the effect of the high RAP contains mixtures in the rutting and cracking. However, very few studies have been conducted on thigh recycle content mixtures in the field. This section summarizes the performance of the high RAP contains mixtures in field sections in different States.

Leiva-Villacorta et al. (Leiva-Villacorta & Grant, 2020) evaluated six high RAP pavements that were constructed in Alabama in between 2011 to 2012. They collected the sample from plant and the filed (after 5-6 years in service) and used different test methods to compare the lab vs field performance. They also evaluate the conditions of the existing pavement and discovered that most pavement structures had little to no cracking except for a pavement section on US-29. Table 7.1 shows the details information about this study.

Table 7.1: Summary of filed and lab performance of six projects (Leiva-Villacorta & Grant, 2020).

Mix ID/Location	Mix Variables	Age, Years	Field Performance	FI (SCB-IFIT)-Plant Mixtures	FI (SCB-IFIT)-Filed Core (after 5-6 years)	Comments
AL-50, Lafayette, Chambers County	35% RAP, Fine-graded 12.5-mm NMAS, Water injection (ASTEC)	6	Low-severity transverse cracking	1.92	0.73	%AV of field core sample was higher than the plant sample, so FI was higher for field sample
I-65, Calera, Shelby County	35% RAP, Fine-graded 19.0-mm NMAS, Water injection (Gencor)	6	No cracking or other distresses	0.97	3.07	
AL-137, Wing, Covington County	35% RAP, Fine-graded 12.5-mm NMAS, Water injection	6	No cracking or other distresses	0.09	1.05	
US-29, Troy, Pike County	32% RAP/ 3% RAS, Fine-graded 12.5-mm NMAS, Water injection	6	Low-severity fatigue cracking on both wheelpaths	0.47	1.73	
AL-35, Fort Payne, Chereokee County	35% RAP, Fine-graded 19.0-mm NMAS, Evotherm 3G	6	Low-severity raveling	1.73	3.84	
US-80, Lowndes, Lowndes County	40% RAP, Fine-graded 12.5-mm NMAS, Evotherm 3G	5	Low-severity fatigue cracking	0.73	1.32	

In 2014-2015, NCAT constructed 7 sections with a range of RAP contents under NCAT Test Track Cracking Group Experiment (Phase VI). They applied 10 million equivalent single-axle loads (ESALs) over two years (2015-2017) and evaluated different distress on 7 sections. The rutting, change of international roughness index (IRI), change of texture depth, and cracking (% of lane area) of these sections show in table 7.2.

Table 7.2: Performance of NCAT Cracking Group Test Sections After 10 Million ESALs (West, et al., 2019).

NCAT Test Track Section	Mixture Description	Rutting (mm)	Change in IRI (in./mi)	Change in Mean Texture Depth (mm)	Cracking (% of lane area)
N1	Control	1.7	3	0.4	21.5
N2	Control, Higher Density	2.2	8	0.6	6.2
N5	Control, Low Density, Low AC	1.2	15	0.5	5.0
N8	Control+5%RAS	1.2	17	0.7	16.9
S5	35%RAP, PG 58-28	1.41.5	4	0.5	0
S6	Control, HiMA binder	1.4	11	0.6	0
S13	Gap-graded, asphalt-rubber	2.8	6	0.1	0

In 2006, NCAT constructed 7 test sections under NACT Test Track Cracking Group Experiment (Phase III). The test sections included four with 45% RAP, two with 20% RAP and a control with 0% RAP. West et al. (West, Kvasnak, Tran, Powell, & Turner, 2009) used different binders with 45% RAP mixes included PG 76-22 plus 1% Sasobit, PG 76-22, PG 67-22, and PG 52-28. For 20% RAP mixes, they used PG 67-22 and PG 76-22 binder. To simulate highway traffic, humans drive the five trucks with 18K ESAL for 2 years for applying 10 million ESALs. During applying the load, test sections performance was monitored for measuring the rutting, texture change, roughness, and cracking. All sections were performed good for raveling and rutting. All the sections had no cracking except 45% RAP section with PG 76-22 plus 1.5% Sasobit and 20% RAP section with PG 76-22. The 45% RAP section with PG 76-22 plus 1.5% Sasobit and 20% RAP section with PG 76-22 experienced with moderate (which was the reflection crack) and less (which was the results of the construction defects) severity longitudinal wheel path cracking, respectively.

Furthermore, NCAT also constructed two test sections with 50% RAP to compare the performance of the RAP sections with control and WMA modified sections. Table 7.3 shows the rutting and fatigue performance for all the sections. Based on table 7.3, researchers concluded that 50% RAP sections have considerably less rutting and cracking than two WMA sections. However, cracking was higher for RAP sections than virgin sections. Based on the field performance data, it can be concluded that high percentage of RAP could be used in the field with caution as the performance of the mixes depend on the virgin binder type, and the amount of the activation of RAP binder within the RAP during construction of the pavement.

Table 7.3: Comparison of High RAP and HMA and WMA virgin sections at the NCAT Test Track (West, 2014).

Section	Cracking, %	Rutting, mm
Control HMA	2	2
50% RAP HMA	0	4
50% RAP WMA	3	5
WMA Foam/ No RAP	11	12
WMA Additive/ No RAP	18	18

Virginia DOT recently published an investigation about in-service performance of pavements constructed with high RAP mixture (Diefenderfer, Nair, & Bowers, 2018). It encompassed field visits and a laboratory investigation of a sample of 23 in-service pavements used. Historical performance and maintenance data were collected and evaluated to investigate the long-term performance characteristics of the pavements. Visual survey data from different sites indicated that there were no significant differences between the percentage of sites with mixtures having RAP contents less than 20% and the percentage of sites with mixtures having RAP contents of 21% to 30% exhibiting each distress. Distress data extracted from PMS indicated that most of the pavements were in acceptable ride condition and had low rut depths of less than 0.16 in. Dynamic modulus test results indicated that neither RAP content nor virgin binder grade appeared to have obvious or trending influences on the measured modulus. Repeated load permanent deformation (RLPD) test results on eight mixtures indicated that a correlation between RAP content and increasing of the secondary portion of strain accumulation. However, the results of the Texas overlay test showed no conclusive trends indicating that increased RAP contents positively or negatively affected mixtures.

8. Conclusions and Recommendations for Research

The objective of this report is to prepare a synthesis of current research on the performance of recycled AC and summarize the testing methods being used or in development for characterizing recycled mixture performance for use in the TPF-5(352) project. A secondary objective is to summarize the current state of using recycling agents in asphalt mixtures with high contents RAP/RAS in order to provide recommendations for the current study. Based on these objectives, the following main findings are summarized:

- **Aging of Asphalt Materials**: The aging process of asphalt binder results in performance improvements to pavement within the high temperature service range, while aging detrimentally affects pavement performance at intermediate and low temperature service ranges.

  The findings of WHRP Project 17-04 suggest the use of 6 hours oven aging of loose mixture at 135 ^{o}C as a long-term aging procedure for asphalt mixtures to provide better distinction between mixtures.

- **Performance of Recycled AC**: The rutting resistance of asphalt mixtures with high contents of RAP/RAS is not a concern unless higher recycling agent doses are used.

  Reports of fatigue cracking resistance of laboratory prepared mixtures with high RAP and RAS contents are not conclusive. The fracture energy at low temperatures does not always decrease with an increase in recycled (RAP or RAS) content. The majority of studies reported in the literature provide no consistent conclusion about the performance of recycled materials at intermediate and low temperatures.

  The Hamburg Wheel Tracking test could be a good option for measuring both the rutting and moisture damage susceptibility at one time. The standardized Semi-Circular Bend – Illinois Flexibility Index (SCB-IFIT) and Indirect Tensile Cracking (IDEAL) tests are both comparable methods for characterizing fatigue properties of recycled AC at intermedium temperatures. Many researchers have reported concerns about the Disc-Shaped Compacted Tension (DCT) test on determining low temperature cracking of recycled AC and instead the Semi-Circular Bend test (AASHTO TP105) was recommended with respect to this aspect.

- **Testing Methods for Recycled AC**: To use linear blending charts in estimating the effects of RAP materials on blended binder properties has limitations. It is recommended that testing individual binder materials is the most direct and accurate approach to quantify performance of the blends containing RAP/RAS.

  Testing fine asphalt mixture specimens provides an alternative protocol for characterizing the inherent properties of RAP/RAS materials and the interaction of RAP/RAS with virgin aggregates and asphalt binder, eliminating the possible influence caused by solvent during the binder extraction and recovery.

- **Recycling Agents for Recycled AC**: A better understanding of the long-term effects of recycling agents in asphalt mixtures is crucial to achieve more effective recycling practices. The investigation on both oxidative aging and rheological response of blended binders with RAP/RAS and recycling agents should be conducted for screening recycling agents.

  NCHRP Project 09-58 recommend determining the recycling agent optimum dosage through matching the continuous high-temperature performance grade of the recycled binder blend to that required by the target climate, as this dosage yielded the best performance for rejuvenated binders and mixtures.

  Literature search shows recycling agents can improve the cracking characteristics of the recycled mixtures containing high contents of RAP/RAS. However, the rutting and moisture susceptibility might be adversely impacted. Balanced mix design seems to be an appropriate approach for designing high RAP and RAS mixtures with recycling agents.

- **Pavement Performance of Recycled AC**: Relatively few studies have been done on the field performance of high RAP and RAS mixtures. The performance of NCAT's test sections of recycled AC containing 40-50% RAP illustrated that high percentage of RAP could be used in the field with caution as the performance of the mixes depend on the virgin binder type, and the amount of the activation of RAP binder within the RAP during construction of the pavement.

Based on the main findings of this report, the use of a Balanced Mixture Design framework with additional direct testing of the recycled binder is supported. Since very little peer-reviewed literature on the subject of high RAP and RAS mixture workability was found, it is suggested a workability assessment test be included in the work plan, particularly with respect to ease of production for high RAP and RAS laboratory specimens. The use of the HWT to measure rutting and moisture susceptibility at high temperature is supported. To measure intermediate temperature cracking resistance, the research team will use the IDEAL-CT test at 25 °C as in addition to positive trends in the literature this test appears to have local DOT support. Low temperature cracking will be assessed with the AASHTO TP105 SCB test due to equipment availability and local DOT support. Direct testing of recovered asphalt binder-RA blends will also be conducted to (a) evaluate the effectiveness of linear blending charts, and (b) attempt to provide correlations between binder and mixture performance. To supplement the specification and quality verification of RA materials, chemical characterization testing will also be conducted on the RAs alone and within binder blends.

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