TPF-5(302): Modified Binder (PG+) Specifications and Quality Control Criteria

Project Extension Final Report

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Pooled Fund Partner DOTs:

Colorado

Idaho

Kansas

Wisconsin

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16. Abstract:

There is no current consensus among state highway and transportation agencies as to the binder specification test methods required for adequate quality control and acceptance of modified binders. Different supplemental tests have been adopted by these agencies in addition to the conventional Performance Grade (PG) tests and are often referred to as "PG+" procedures. The applicability of the blending charts used to estimate effect of Recycled Asphalt materials (RAM) to the parameters measured in these PG+ tests is not known. In addition, there is a wide variety of rejuvenating oils proposed to mitigate the stiffening effects of RAM on asphalt binders.

The main objectives of this extended study are to study effects of binder replacement using recycled binder and extended aging of binders blended with oils for low temperature grade modification. The study included two tasks: Task 1 evaluated the trends of change in critical binder properties when blended with Recycled Asphalt Materials (RAM) that are artificially produced using the PAV aging procedure and RAM that is extracted and recovered from field RAP and RAS. Task 2 evaluated the effects of using low temperature binder modifiers (rejuvenators or softening oils) on changes due to extended aging in the PAV. In both tasks, testing included MSCR procedure (AASHTO T350) at high pavement temperatures, ER-DSR and BYET procedures (AASHTO TP123) and LAS procedure (AASHTO TP101) at intermediate temperatures, and BBR Procedure (AASHTO T313) at low pavement temperatures.

The study results indicate that there are no simple blending charts that can be used to estimate effects of RAM or the effects of extended aging on critical properties of blended binders. The results showed wide variation in RAM properties and also wide variation of aging effects of oils used in rejuvenation. Therefore, it is recommended that actual testing of blended binders should be required. A concept of Balanced Binder Design is proposed to determine the effects of RAM or extended laboratory aging of blended binders. Further development of this concept and development of criteria for acceptance is proposed as a possible extension of this study.

17. Key Words	18. Distribution Statement
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Contents

Executive Summary of Findings

This report includes a summary of the extended phase of this Pooled-Fund study in which effects of binder replacement using recycled binder and extended aging of binders blended with oils for low temperature grade modification were evaluated. The study included two tasks: Task 1 included binder testing to evaluate the trends of change in critical binder properties when blended with Recycled Asphalt Materials (RAM) that are artificially produced using the PAV aging procedure and RAM that is extracted and recovered from field RAP and RAS. Task 2 focused on evaluating the effects of using low temperature binder modifiers (rejuvenators or softening oils) on changes due to extended aging in the PAV. In both tasks, testing included MSCR procedure (AASHTO T350) at high pavement temperatures, ER-DSR and BYET procedures (AASHTO TP123) and LAS procedure (AASHTO TP101) at intermediate temperatures, and BBR Procedure (AASHTO T313) at low pavement temperatures.

The results of Task 1 indicate that resultant (blended) binder properties are dependent on the constituent binders' properties and percentage of RAM added. Linear relationships between binder replacement and changes in critical parameters cannot be assumed for all the PG+ test methods used in this study, even for relatively low (20%) levels of binder replacement in some instances. It is therefore advised that if properties of the blended binders are desired, actual testing of the blended binders at the intended blend percentages is necessary, particularly for polymer modified or unknown sources of binders. Also, it should be noted that binders' blending charts are based on 100% blending efficiency between the constituent binders; in practice blending is likely less than 100% and is dependent on time and temperature. Therefore, caution should be used in interpretation of blending charts in terms of total effects on performance.

The effect of blending artificially-aged, or extracted and recovered binders from RAM, are shown to significantly change Jnr and increase %R measured using the MSCR test at high pavement temperatures. The effects on Jnr and %R could change rutting performance measured on mixture in the lab, but the effects cannot be estimated using simplistic blending charts as trends are highly dependent on materials being blended and amount of binder replacement. At intermediate temperatures, elastic recovery and strain at maximum stress measured according to AASHTO TP123 are reduced, sometimes very significantly. It is also found that using these aged materials have negative effects on fatigue life as measured by the "B" parameter in the AASHTO TP101. It is recommended that the "B" parameter be used as an indicator of effects of aged binders as this parameter is found to correlate very well with the mixture Flexibility Index (FI) test. The "B" parameter is a very simple measure using the standard 8-mm plate and can be done as a simple extension of the current $G^*\sin(\delta)$ test at intermediate temperatures.

Results of Task 1 show that different RAP sources can have significantly different properties and can either improve or worsen performance of the blended binder for relatively small percentages of RAP. Based on this finding, a "tiered" approach to using RAM (for example allowing 20% binder replacement without requiring any change to the virgin binder grade) is not advisable. For implementation of the results of this study, it is recommended that use of RAM should be controlled by directly testing blended binders at the intended replacement (%RAM) and including any softening/rejuvenating oils used. The testing should include using the MSCR for Jnr and %R, the BYET for strain at maximum stress (DSR-Ductility), and LAS for the "B" parameter. Limits of acceptance should be specified to take into consideration effects of solvents used in the extraction and recovery of the RAM, and the reality that binders may not be 100% blended in production of recycled mixtures. Unless mixture performance testing is conducted to approve the %RAM, a conservative blending efficiency (such as 50% effectiveness) should be assumed.

Findings from Task 2 indicate that characterizing modified asphalt binders using a single level of PAV aging according to M320/M332 may be misleading. Results indicate that the magnitude and rate of changes in binders' properties at all temperature ranges due to extended aging is dependent on the base asphalt and modification technologies used, and that extended aging beyond 20 hours of PAV conditioning show significantly varying performance. It is shown that certain binder blends maintain comparatively favorable levels of performance for lower levels of aging, but quickly deteriorate with extended aging.

PAV aging is found to improve (reduce) Jnr parameter and thus is a positive effect. However, aging reduces elastic recovery at intermediate temperatures, decreases strain at maximum applied stress (ductility), and more importantly negatively affects fatigue resistance related parameters.

Agencies are advised that for modification technologies that do not have a history of performance, or new asphalt materials entering the marketplace, evaluation of binder properties should be conducted at several extended levels of aging and compared to known high-performing binders. This recommendation is particularly relevant for intermediate and low temperature ranges where cracking is expected, and where aging is perceived as determinate.

This project can be extended to develop or refine acceptance criteria for the PG+ procedures including the following:

- Refine the MSCR criteria for acceptance of binders used in high RAM mixes.
- Develop new criteria for Elastic Recovery and Ductility using the DSR for binders used in low and high RAM mixes.
- Develop new criteria for binder fatigue using the LAS test for binders used in low and high RAM mixes.
- Develop criteria for evaluating extended PAV aging effects on binders of the PG xx-28 and PG xx-34. These criteria will include specific parameters that could identify the potential of low durability.

It is envisioned that a framework for these criteria can be developed using a "Balanced Binder Design" approach, in which binder properties controlling critical distresses at different temperature ranges are balanced with one another. Such a process might allow agencies/contractors to select an appropriate amount of RAM and/or binder modification to satisfy multiple testing criteria simultaneously. A similar methodology called "Balanced Mixture Design" is used in the design of asphalt mixtures. An example of this approach using the data generated during this extension is presented in this report.

I. Introduction and Objectives

A. Background of Pooled Fund TPF-5(302) Project

There is no consensus among state highway and transportation agencies as to the appropriate binder specification test methods required for adequate quality control and acceptance of modified binders. Supplemental tests have been adopted in addition to the conventional Performance Grade (PG) tests (AASHTO M320) and are often referred to as "PG+" procedures. Many agencies have implemented these additional testing protocols; however, differences exist between the PG+ test methods, test conditions, and performance limits being specified among regions. As a result, it is difficult to satisfy variable criteria when producing and supplying modified binders that consistently and uniformly meet agency pavement performance expectations.

The principal objective of the TPF-5(302) pooled fund was to provide essential information to state and local agencies to support standardization of PG+ specifications by identifying those PG+ test methods that are reproducible and show promise in simulating actual field performance. The final report in support of this objective was delivered to the partner states in late 2016. As a direct result of the findings outlined in that report, a research extension was agreed upon by the research team and four of the partner states to investigate the use of PG+ procedures to evaluate the effects of the RAP and RAS on binder performance as well as the effects of low temperature modification technologies on binder performance. This report summarizes the findings of research conducted as part of the extension work plan.

B. Objectives of Extension Work Plan

Two work areas are included in the research extension plan for this pooled fund study based on the input from the pooled fund members following presentation of the final report for the original study:

- **Task 1: Evaluate the Effects of RAP/RAS on PG+ and Developmental Test Blending Charts**

Nearly all new asphalt mixtures produced in the United States contain a percentage of recycled asphalt materials (RAM). Implications of adding RAM into asphalt mixtures in pavements is an increase in rutting resistance with a potential reduction in cracking resistance at both intermediate and low temperatures. The decrease in cracking resistance is attributed to the heavily aged binder that coats the recycled aggregates. In response, DOTs often specify softer grades of asphalt binder to be used with high RAM mixtures to offset the negative consequences of the aged recycled binder or require "rejuvenating" additives to be added.

To estimate the performance implications of RAM, designers use simple blending charts to interpolate the effects of recycled materials on blended binder properties (AASHTO M323, Appendix X1). These charts have been proven effective for RAP materials when using standard Superpave PG test methods (G*, S-value, m-value, etc.) during the NCHRP 09-12 study. However, research has shown that the charts may not accurately predict blended binder properties for RAS binders, particularly at low temperatures (Bonaquist, 2011). In addition, the blending charts have not been verified for new binder parameters such as the MSCR Jnr and %R, or the proposed development tests for binder fatigue or cracking resistance recommended in the first part of the study.

The experiment for this Task is designed to investigate the effects of blending between RAM and polymer modified virgin binders on selected PG+ and developmental test methods proposed in earlier phases of this research project. The experiment is divided between two subtasks: Subtask 1.1 is an evaluation of selected PG+ and developmental methods using artificially produced RAM (binders aged for 60 hours in the PAV) in order to limit the amount of binder extraction/recovery required and have control on the variability of aging. Subtask 1.2 incorporates RAM extracted and recovered from RAP and RAS supplied by member states to expand the testing matrix and provide direct information on actual RAM from the field.

- **Task 2: Effects of Low Temperature Modification Technologies on PG+ and Developmental Test Methods**

As an alternative to using a softer base binder grade for mixtures containing RAM in cold climates, using a low temperature (LT) modifier, such as an oil or rejuvenator, is becoming more common. In addition, demand of the PG grades of PG xx-28 and PG xx-34 is increasing as more concerns about cracking are being raised. Although many of the binders using oil modification continue to meet PG specifications, observations from field performance have indicated an increasing number of pavement failures that could be attributed to asphalt binder. Additional testing in this Task will focus on understanding the implications of oil modification on binder properties using selected PG+ and the new damage characterization testing methods.

To accomplish this task, partner states were asked to identify low temperature modifiers (oils/rejuvenators) that are being widely used in their region. Modifiers identified by member states were collected and blended with selected aged asphalt binders. Testing these binders was compared against unmodified soft binders produced by refineries to make recommendations to partner states regarding what test methods/properties of oil modified binders can indicate better or worse pavement performance.

Since a the substantially large amount of data generated for this project prohibits complete presentation in this report, a master testing database has been generated by the research team and is available to the partner states as a deliverable for this project.

C. Organization of this Report

Following this introduction section, a description of the materials and methods used to conduct the testing for each task is presented. Each task listed above is included as a section in this report in which the analysis is discussed separately. Finally, concluding remarks and recommendations are offered based on the findings from both research tasks.

II. Materials and Methods

A. *Task #1: Evaluating the Effects of RAP/RAS on PG+ and Developmental Test Blending Charts*

To investigate the effects of blending polymer modified asphalt binder with heavily aged or recycled binder, this task is divided into two subtasks. To investigate the blending relationship between the two binders, it is necessary to know the original and aged properties of both constituent materials without the potentially effects of interaction with aggregates, and the effects of solvents used in the extraction and recovery process. If the true binder properties of both constituents are known, the observed testing results of the blends of these materials can be better explained.

In Subtask 1.1, "artificial" RAM materials, called "A-RAP (Artificial-Recycled Asphalt Pavement)", were produced from two of the original partner state binders by exposing each to multiple (2 or 3) PAV cycles. These binders were then blended with polymer modified asphalts to investigate the properties of the intermediate blends.

In Subtask 1.2, binder from actual RAP and RAS materials supplied by the partner states was extracted, recovered, and blended in a similar format to Subtask 1.1. Based on the observed trends for this subtask, conclusions can be drawn with regard to the relationship between RAM percentage and blended binder properties, and the ability to predict such behavior in the laboratory if the constituent binders' properties are known. The experimental design and test methods used for both subtasks are described in the following sections.

i. Subtask 1.1: Proof of Concept using Artificial RAP

Two base asphalts from separate crude sources, with one refinery grade and one polymer modified were used to produce 'artificial' RAP materials (A-RAP) by exposing the asphalts to extended PAV aging. The number of PAV cycles was chosen to produce an extensively aged asphalt binder that still was workable enough to blend and cast specimens for further testing. The composition and aging protocol for each A-RAP material is shown below. The aging cycles were changed because the aging the polymer modified binder for 60 hours proved to be too extreme; therefore only 2 cycles (40 hours) were used.

Table 1. A-RAP Materials used for Proof of Concept.

Identification for this Study	Base Asphalt	Aging Level
A-RAP_1	PG 64-22, neat	60 hrs. (3 cycles) PAV
A-RAP_2	PG 70-28, Polymer Modified*	40 hrs. (2 cycles) PAV

*"Wisconsin PG 70-28" source from the original TPF5-302 work plan.

Two polymer-modified base asphalts (PMA) from the original work plan were sampled for blending with the A-RAP material. Each combination of A-RAP and PMA was tested at four ratios (unaged PMA/RAM): 100%/0%, 80%/20%, 60%/40%, and 0%/100%. These ratios are expected to encompass typical usage rates of RAM (~20% Percent Binder Replacement) as well as include higher ratios to establish/confirm linearity or non-linearity in the blending charts. The following testing matrix of materials was used for this experiment.

Table 2. Experimental Design for Subtask 1.1.

Factor	Level	Description
A-RAP	2	A-RAP_1 = PG64-22 neat, 60 hours PAV A-RAP_2 = PG70-28 PMA, 40 hours PAV
Polymer Modified Asphalt	2	PMA_1 = Wisconsin PG 70-28* PMA_2 = Kansas PG 64-28
Blending Ratios	4	PMA/RAM 100%/0% 80%/20% 60%/40% 0%/100%.

*This is the same base asphalt used to produce A-RAP_2

To produce each blend, component materials were first heated until molten, then blended in a low-shear blender for 90 minutes. Each blend was then subjected to the RTFO and/or PAV aging process to simulate short-term and long-term aging, respectively. In this way, any interactive effects between the component materials and aging would be captured. Following the prescribed aging protocol for each blend, the tests listed in Table 3 were conducted as the selected tests based on the findings and recommendations from the first phase of this Pooled Fund project. At least two replicate samples were tested for each test method and averaged to generate the data presented in this report. Detailed descriptions of each test method and responses are available in earlier reports from this project.

Table 3. Testing Procedures for Blends.

Temperature Range	Selected Test Method	Aging Condition	Response
High Temperature	Multiple Stress Creep and Recovery (MSCR)	RTFO Residue	$Jnr_{3.2}$ $\%R_{3.2}$ %Jnr Diff.
Intermediate Temperature	Elastic Recovery – DSR (ER-DSR)	RTFO Residue	%R
	Binder Yield Energy Test (BYET)	PAV Residue	Strain at Peak Stress $BYE_{2500\%}$
	Linear Amplitude Sweep (LAS)	PAV Residue	Cycles to Failure, N_f Fatigue Law "B" Parameter
Low Temperature	Single-Edge Notched Bending (BBR-SENB)	PAV Residue	Failure Energy

During the initial stage of testing for Subtask 1.1 and 1.2, mechanical problems with the BBR-SENB device were discovered that directly influenced the integrity of the data being generated. The complete testing factorial for the BBR-SENB was completed for Subtask 1.1 and a portion of Subtask 1.2 was completed before discovering the problems with the device and repeatability. It was determined by the research team further testing using the SENB would be discontinued for Subtask 1.2; the full dataset is available to the partner States upon request. A portion of the data is presented in this report to demonstrate the apparent erroneous results. Due to the complex nature of the issues and the need to maintain the project schedule, a more in-depth analysis using the BBR (ΔT_c) was conducted as a replacement in for the BBR-SENB in Task 2.

ii. Subtask 1.2: Validation using Field Recycled Materials from Partner States

During this phase RAM from Partner States were collected for extraction and recovery of field aged binders. Three RAP materials were collected in total and one RAS material was obtained from a company specializing in the recovery of recycled asphalt shingle binder for reuse in new asphalt mixtures. RAP materials were selected to include a range in geographic locations and source properties. Brief descriptions of the RAP and RAS materials are given in Table 4 below.

Table 4. Description of RAP and RAS Materials

RAM	Description
RAP - Wisconsin	Millings from central Wisconsin, unknown age. Base asphalt used in existing pavement most likely PG 58-28 unmodified.
RAP - Colorado	Internal CDOT project; Region 2, Project “NH 1604-013”; unknown source and grade of binder.
RAP - Kansas	Millings from Novachip® project placed in 2007 utilizing PG70-28 polymer modified binder.
RAS - RTS	Commercially available product produced by extraction and recovery of recycled asphalt shingles.

Binder from each RAP/RAS source was extracted and recovered following AASHTO T164 and ASTM D5404, respectively, using n-propyl bromide as the extraction solvent. Several extractions were conducted for each source and blended together to ensure enough material was available for all testing. It should be noted that the type of solvent and residue recovery procedure used has been shown to effect recovered binder properties. As part of the ongoing Wisconsin Highway Research Program (WHRP) 17-06 project, solvent type was clearly shown to produce a bias in the MSCR %R parameter for a polymer modified base binder as shown in Figure 1. Unless such a bias is known and accounted for, recovered binder results should be interpreted with care, particularly when comparing results from multiple labs that may use different solvents/procedures. In this study, one solvent and recovery procedure was used for all testing and relative trends between binder blends are the response.

One PMA was selected to be blended with the recovered binders: PG 70-28 from Wisconsin. Blends were again produced before being subjected to aging. At least two replicate samples were taken for each test method and averaged to generate the data presented in this report. The experimental plan for Subtask 1.2 is shown in Table 5 below.

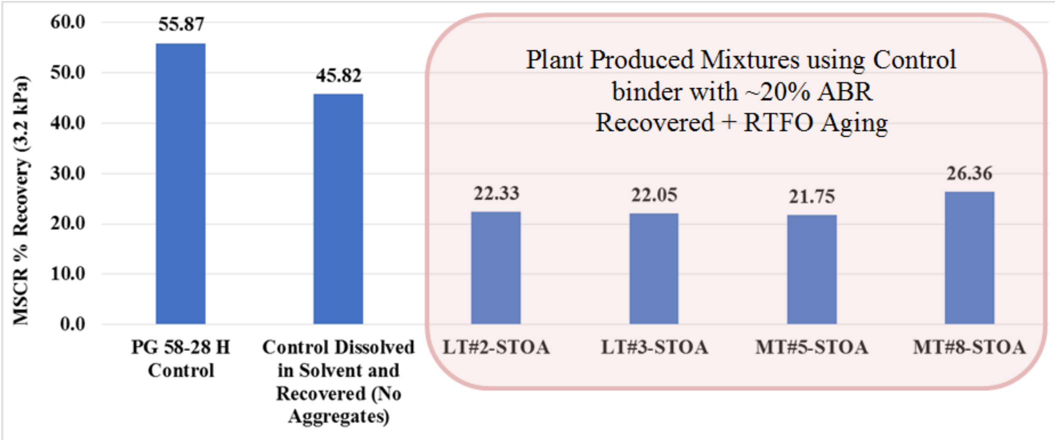


Figure 1. Effect of solvent on MSCR %R and blending with RAP material from WHRP 17-06 Study.

Table 5. Subtask 1.2 Work Plan

Factor	Level	Description
RAM	4	RAP-Wisconsin RAP-Colorado RAP-Kansas RAS-RTS
Modified Asphalt (PMA)	1	Wisconsin PG 70-28
Blending Ratios	4	PMA/RAM 100%/0%, 80%/20% 80%/15%RAP/5%RAS 60%/40%. (RAP Only)
Test Methods	5	Same as Table 3

B. Task #2: Effects of Low Temperature Modification Technologies on PG+ and Developmental Test Methods

The purpose of this task is to evaluate the effects of aging on materials or additives commonly used as low and high temperature modification technologies. The overarching objective is to evaluate the aging susceptibility of these modification technologies and identify test methods that can discriminate between these materials.

To accomplish this objective, a target asphalt binder grade of PG 58-34 H was selected and two commercially available and commonly used low temperature modification technologies that are expected to show different aging susceptibilities were chosen; as a control, a refinery asphalt with the target low temperature grade (-34) was selected. The same base asphalt was used for the two low-temperature modification technologies, and dosage rates for the additives were selected to achieve an approximately equal low temperature continuous grade.

High temperature modification rates were selected to achieve a “Heavy Traffic” designation using the 2017 Combined State Binder Group (CSBG) guidelines. The resulting grade for all four binders used in this study is therefore PG 58-34 H. The binder blends were then exposed to RTFO, followed by one, two, and three PAV cycles before testing. A summary of the work plan is shown in Table 6 below.

Table 6. Low Temperature Modification Work Plan Partial Factorial

Factor	Levels	Description
LT Modification Technology	2	Bio-Oil (Vegetable Based) Recycled/Reclaimed Oil (REOB) Targeting -34 C
Base Asphalt	2	PG 52-34 S (no LT Modification) PG 58-28 S
High Temperature Modification	2	SBS (Kraton D0243) + Sulfur catalyst Elvaloy + PPA
Long Term Aging Level	3	One PAV, double PAV (40 hr.), and Triple PAV (60 hr.)
Test Methods	5	Same as Table 3, without SENB (SENB replaced with BBR and ΔTc analysis)

SBS is Styrene-Butadiene-Styrene elastomeric polymer.
Elvaloy is the trade name for an elastomeric terpolymer modification system trademarked by DuPont.
PPA is Poly-Phosphoric Acid, a high temperature modifier.

A summary of the binder blend formulations with critical AASHTO M332 grading properties is shown in Table 7. The controlling grade properties are bolded for reference based on the 2017 CSBG asphalt binder specification. For all four blends, the MSCR %R parameter controlled at high temperature; the CSBG lower limit for %R is 30%. The range in %R observed for the binder blends in this study is 4.3%. The resulting Jnr for all blends is considerably lower than the maximum H grade limit of 2.0 kPa^{-1} as specified by the CSBG and all four blends would grade as a “very Heavy” or V grade based on Jnr; this observation is in agreement with experience producing commercially viable H graded binders in the CSBG region in that the %R is usually the controlling MSCR parameter. Three of the four binders were stiffness (S(60)) controlled at low temperature and the resulting spread in low temperature continuous grade is 1.6 °C. The difference between the stiffness continuous grade and m-value continuous grade (known as the ΔT_c) varies between 2.3 °C and -5.0 °C, indicating that there is a significant difference between the binder blends with regard to the low temperature viscoelastic nature of these binders, despite exhibiting a similar low temperature continuous grade.

Table 7. Binder Formulations for Low Temperature Modification Work Plan

		Blend I.D.			
		Blend 1 (Control)	Blend 2	Blend 3	Blend 4
Binder Formulation, % Total Binder Weight	PG 58-28		93.75%	89.5%	94.8%
	PG 52-34	97.0%			
	SBS (Kraton D0243)	3.0%	3.0%	2.5%	
	Elvaloy (4170)				1.0%
	PPA				0.2%
	Bio-oil (Veg. Base)		3.25%		4.0%
	Recycled Oil (REOB)			8.0%	
Original Binder	O.B. C.G., °C	66.4	67.6	68.7	65.8
RTFO Residue	Jnr, 3.2 kPa, 58 °C	0.610	0.760	0.670	0.750
	%R, 3.2 kPa, 58 °C	**35.9%**	**33.6%**	**36.9%**	**32.6%**
	Jnr, % Diff.	32.1%	47.4%	50.6%	22.7%
PAV Residue	S(60) C.G., °C	**-35.3**	**-34.6**	-38.7	**-33.7**
	m(60) C.G., °C	-35.8	-35.6	**-33.7**	-36.0
	L.T. C.G., °C	-35.3	-34.6	-33.7	-33.7
	ΔT_c (S(60)-m(60))	0.5	1.0	-5.0	2.3
Resultant M332 PG (CSBG Modified)		PG58-34 H	PG58-34 H	PG58-34 H	PG58-34 H

SBS is Styrene-Butadiene-Styrene elastomeric polymer.
PPA is Poly-Phosphoric Acid, a high temperature modifier.
Elvaloy is the trade name for an elastomeric terpolymer system trademarked by DuPont.
O.B. is Original (unaged) Binder.
C.G. is Continuous (true) Binder Grade.
L.T. is Low Temperature.

III. Analysis of Results and Summary of Findings

This section presents the testing results associated with the two subtasks. Interpretation of the individual test method parameters can be found in more detail in the Phase I report for this Pooled Fund Project. For some test methods, such as the Linear Amplitude Sweep (AASHTO TP101), several additional binder parameters not shown in this report are available for analysis. For that reason, complete databases for both subtasks are available to the partner States.

A. Task #1: Effects of RAP/RAS on PG+ and Developmental Test Blending Charts

i. Subtask 1.1: Proof of Concept using Artificial RAP

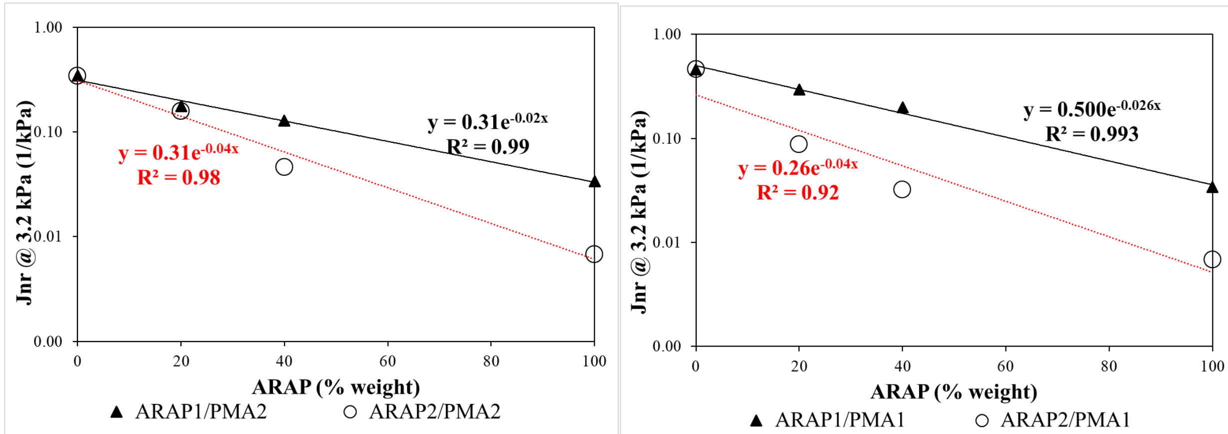
In this subtask, two asphalt binder sources (one unmodified and one modified) were exposed to extended PAV aging protocols to generate "artificial RAP", or A-RAP materials (Table 2). These A-RAP materials were blended with two polymer modified base asphalts and tested according to the schedule shown in Table 3. All binder blends were produced by first blending the component binders together, then subjecting the blended materials to the specified aging protocols.

Multiple Stress Creep and Recovery Test

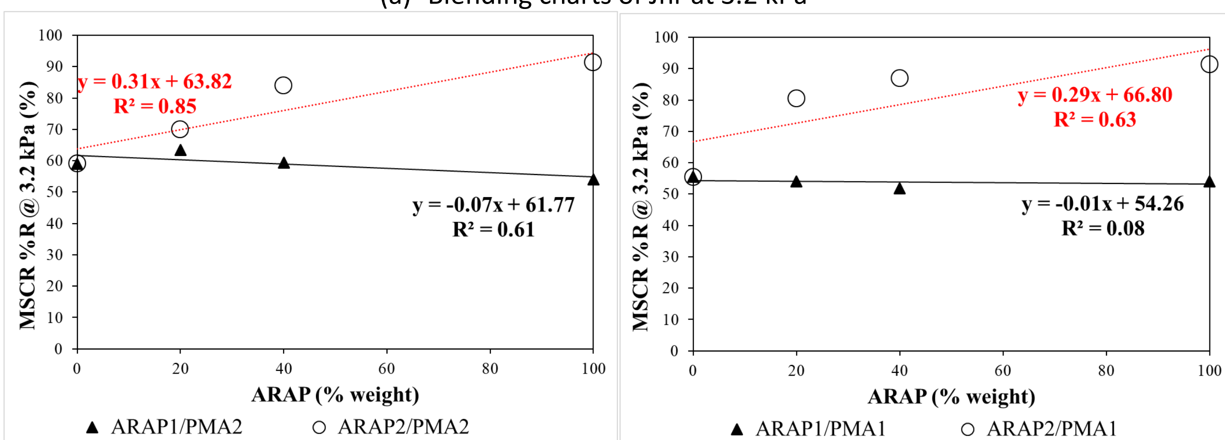
Binder blends using the A-RAP materials were tested using the MSCR procedure at 64°C. Three parameters of interest were extracted from the data: the non-recoverable creep compliance (Jnr) at the 3.2 kPa stress level, the percentage of elastic strain (MSCR %R), and the percent difference in Jnr between the two stress levels (Jnr % Difference). All binder blends were tested after RTFO aging the blended material and results are shown in Figure 2.

The Jnr parameter is plotted on a log-linear scale since the data spans three orders of magnitude, even though the magnitude of the Jnr values themselves is very small. The resulting trend exhibits a linear relationship on the log-linear scale, indicating an exponential relationship between the amount of aged material in the blend and the Jnr, with a logically decreasing Jnr with increasing A-RAP percentage. This finding is logical since it has been established in various literature sources that the relationship between binder stiffness and percentage of RAP material is near linear at high pavement temperatures. Since a lower Jnr is perceived as 'better' in terms of rutting resistance and in terms of being conservative for agencies, there would not be a need to adjust the limits for Jnr if the trend between recycled binder percentage and Jnr remains negative as shown.

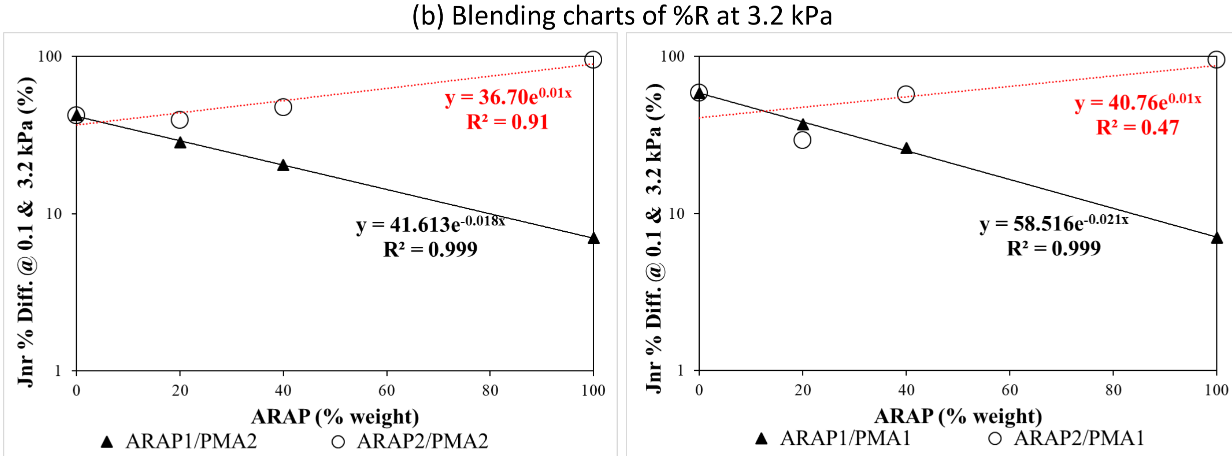
Figure 2 shows that the trend for all three MSCR parameters is highly dependent on the combination of aged binder and virgin binder tested; that is, the rate and magnitude of change of the test parameters is dependent on the properties of RAP and binder source, as expected.



(a) Blending charts of Jnr at 3.2 kPa



(b) Blending charts of %R at 3.2 kPa



(c) Blending charts for Jnr % Diff

Figure 2. A-RAP blending charts for the MSCR test conducted at 64 °C, showing Jnr at 3.2 kPa (top), MSCR %R (middle) and Jnr % Difference (bottom).

The MSCR %R parameter blending charts show more varying trends (part b of Figure 2). For A-RAP$_1$ and with both PMA binders (PMA$_1$ and PMA$_2$), the %R remains nearly unchanged between 0% and 100% A-RAP$_1$ binders. However, the A-RAP$_2$ material shows an increase in %R with increasing A-RAP material. These trends are logical since A-RAP$_1$ is produced from an unmodified base asphalt, so one might expect a decrease in %R with increased A-RAP percentage. However, in earlier phases of this project it was shown that MSCR %R is dependent on Jnr at high temperature; %R usually increases with decreasing Jnr for a given binder system. Therefore, although A-RAP_1 has no modifier, its %R is high (about 50%) because the aging reduced the Jnr. This finding may help to highlight that it is not necessarily polymer content/quality that drives the MSCR %R parameter at high temperature, but rather binder compliance (Jnr). That is to say the MSCR %R parameter could be highly influenced by compliance as measured in the MSCR test rather than solely material elastic modifier content.

For the A-RAP_2 system, which is produced from polymer modified base asphalt, a more complex effect is observed since Jnr is reduced while %R in increased as more of the polymer modified A-RAP_2 in increased. The results for MSCR %R in Figure 2 indicates that although the Jnr blending charts can be linearized, the relationship between %R and A-RAP's percentage could be non-linear and could vary in the direction, rate, and magnitude of change depend on the blended binder system being evaluated.

The Jnr %Difference parameter was found to provide limited information in earlier phases of this study. Nevertheless, it appears from Figure 2 that the parameter is essentially linear on a log-linear scale (exponential relationship). Since this parameter does not appear to be related to performance, this information should not be used to adjust limits on recycled binder percentage allowed.

ER-DSR (AASHTO TP123)

The ER-DSR (AASHTO TP123) test was found in earlier phases of this study to be a good candidate test for replacing the Elastic Recovery (AASHTO T301) procedure and demonstrated sufficient ruggedness and repeatability for a quality control indicator to detect elastomeric polymers in binders. Because the ER-DSR test is nominally run at 25°C, the information from this test is expected to be different than if the test was conducted at high pavement temperature, such as the information generated using the MSCR %R parameter. Figure 3 shows the ER-DSR blending charts for the two A-RAP materials.

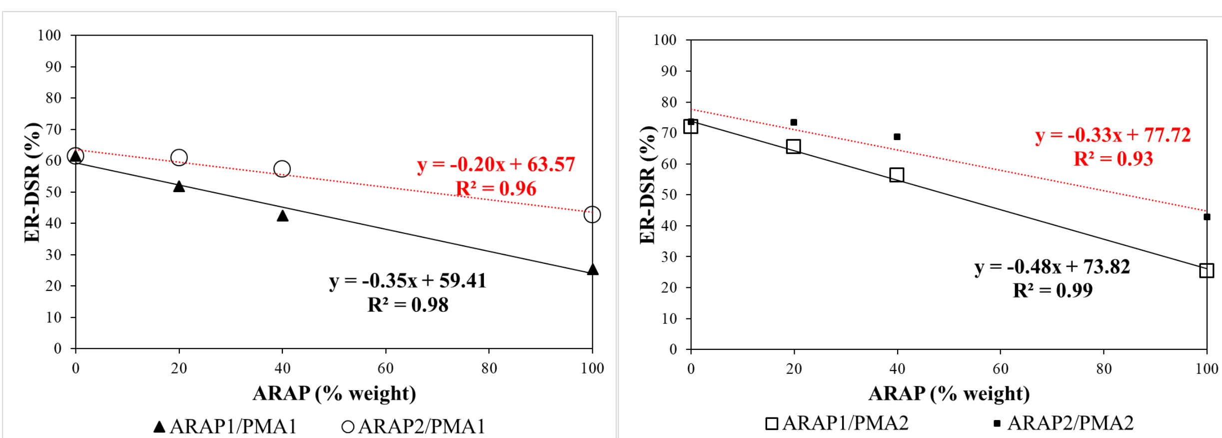


Figure 3. A-RAP blending charts for the ER-DSR (AASHTO TP123) test conducted at 25°C.

Based on the data shown in Figure 3, the assumption of linearity for blending charts is valid and the rate of change in ER is dependent on the A-RAP source. For all combinations, the percent recovery decreases with increasing A-RAP percentage; the relative magnitude of the decrease is greater for the A-RAP_1 system, which is logical given A-RAP_1 was produced with unmodified base asphalt binder. However, the greatest total change in ER ranged from 72.0% to 25.3% in the most extreme case; a rate of change of only 0.47% ER/%binder replaced; for a typical 20% PBR, this amounts to an ER change of only 9.3%. This change could be considered insignificant for practical applications.

Interestingly, the ER-DSR recovery for the 100% A-RAP_1 case is not zero; this matches the observations for MSCR %R from Figure 2 although it is hypothesized that the cause of this behavior is a result of a different phenomenon at intermediate temperature. The cause of this behavior is the increase in elastic behavior of asphalt binders as the temperature is reduced and/or as aging changes the microstructure of the binder. This elasticity is commonly seen when testing at Intermediate temperatures for the G*sin(δ) parameter. It is well recognized that the phase angle (delta) decreases with decrease in temperature of testing and with aging. It also confirms that the high binder stiffness at the test temperature is related to increase in asphalt binder elasticity response. It should be noted that the mode of loading for the ER-DSR test is different than that of the MSCR test; whereas the ER-DSR test utilizes a fixed peak strain, the MSCR test is a true creep test in which the stress and time are controlled. Since the strain in the ER-DSR test is therefore much higher, the strain recovery might be expected to be lower for A-RAP_1, which is confirmed with this data.

In the case of A-RAP_2, the recovery increases slightly with an increase in binder replacement through about 20% replacement. A-RAP_2 was produced with a polymer modified base asphalt, so the cause of this increase may be the combined effect of stiffening (reinforcing) effect of the base binder as well as the polymer response; note that the 100% A-RAP_2 case exhibited an approximately 45% elastic recovery. When this base asphalt was tested in the earlier phases of this study, the measured ER-DSR value for RTFO residue was approximately 63%. Apparently, the effect of extended aging time in the PAV either degraded the polymer network to some degree and/or the test method response is stress sensitive; this is not necessarily unexpected, as extended aging is known to degrade some polymer systems.

Binder Yield Energy Test (AASTHTO TP 123)

The Binder Yield Energy Test (BYET) was shown in earlier phases of this project to be a suitable direct replacement for the AASHTO T51 ductility test by utilizing the strain at maximum stress parameter. The test may also show promise as a predictor for intermediate temperature cracking resistance. Three parameters of interest are generated from the BYET: Yield Energy, Maximum Stress, and Strain at Maximum (Peak) Stress. This data is shown in Figure 4 for the two A-RAP sources.

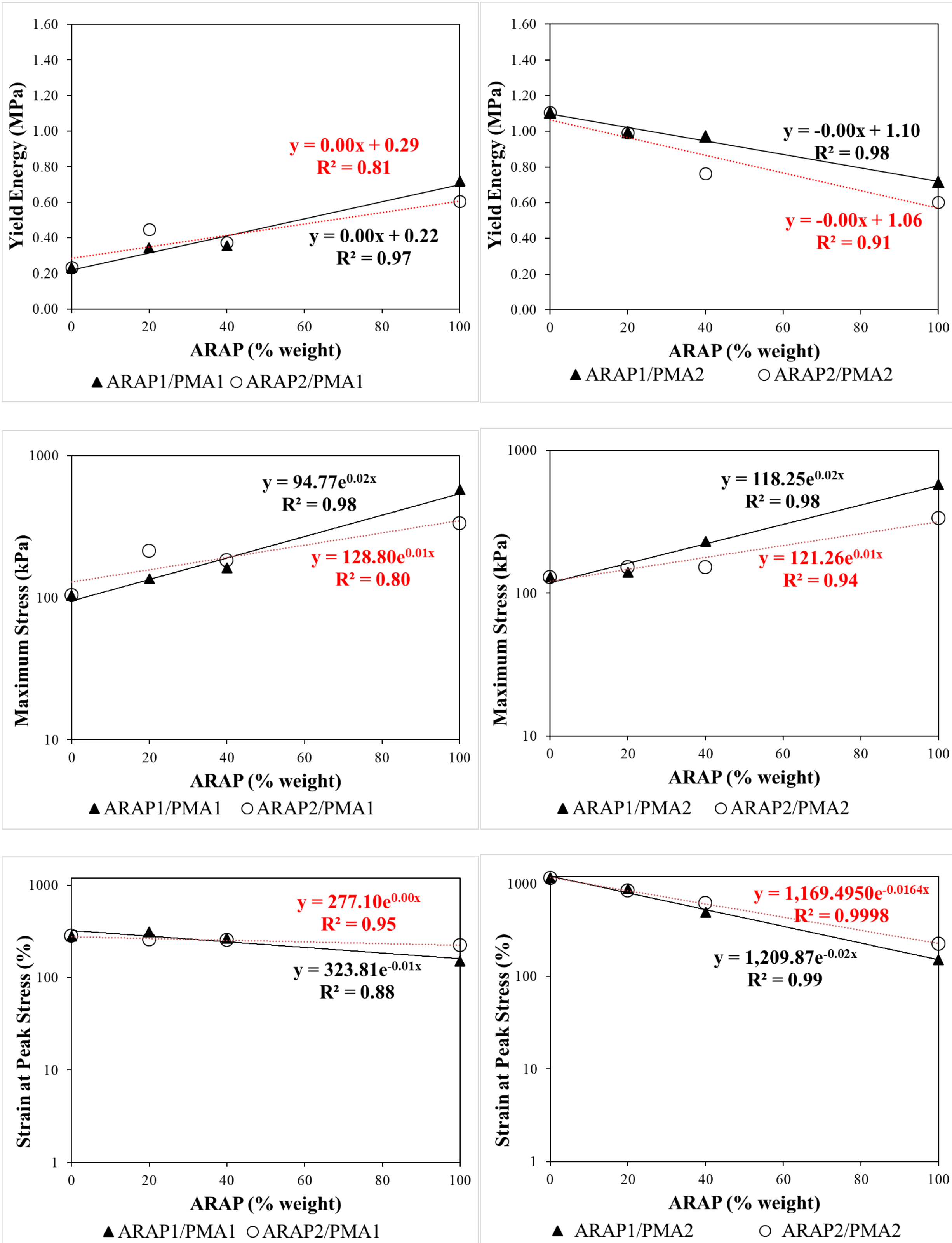


Figure 4. A-RAP blending charts for the BYET (AASHTO TP123) test conducted at 25°C showing Yield Energy (top), Maximum Stress (middle), and Strain at Peak Stress (bottom).

Based on the data in Figure 4, the relationships for binder "Yield Energy" with %ARAP appears to be linear, and the magnitude and direction of change is dependent on the A-RAP and PMA yield energy. For example, PMA_1 has a lower yield energy relative to the two A-RAP materials, so the trend between binder replacement and yield energy increases with increasing binder replacement. Just the opposite is true for PMA_2, which has a higher yield energy relative to the two A-RAP materials. Since a higher yield energy is viewed as beneficial, the implication of this finding is that unless the yield energy of the recycled material is known, the relationship between binder replacement and yield energy cannot be predicted.

The trends between %ARAP and maximum stress, and strain at peak stress, are found to be linear on a log-linear scale (exponential trend). The trends in this case are consistent between A-RAP and PMA sources. The maximum stress increases exponentially with increasing binder replacement, whereas strain at peak stress decreases exponentially with increasing binder replacement. These trends are logical, given the mode of loading during the BYET. As asphalt binder ages, it becomes stiffer and less ductile; since the BYET is a strain-controlled test, it would be expected that the strain at peak stress is reduced due to the increase in binder stiffness. The rate of change in these parameters is strongly dependent on the fresh binder and ARAP values, as expected.

Notably, despite the stark differences between the base binders used to produce the A-RAP materials, they both ended up very similar in terms of yield energy and strain at peak stress. This may be evidence of damaging the beneficial effects of polymer with long term aging in terms of strain tolerance.

The strain at peak stress parameter measured with the BYET has been shown to be a good replacement for the ductility test. Based on the results shown in Figure 4, the addition of highly aged material is detrimental to this parameter. In the most extreme case for this testing, the reduction in strain at peak stress (ductility) between 0% and 20% replacement is about 27% of the original value.

Agencies wishing to implement this parameter measured in the AASHTO TP123 in place of ductility would therefore need to determine a minimum strain limit at peak stress based on the binders currently in use in their region as compared to the ductility test on those same binders. The minimum limit should be increased by a factor of safety as determined based on the desired reliability of the BYET strain criteria.

Linear Amplitude Sweep Test

The Linear Amplitude Sweep (LAS) test (AASHTO TP101) has shown promise as a predictor of fatigue cracking resistance of asphalt binder in earlier phases of this study, and in literature (Hintz, et al., 2011) Binder blends for this study were tested at 25°C using the LAS procedure. Several useful testing parameters are derived from this test but for the purposes of this report, three parameters are reported: the calculated Cycles to Failure at 2.5% Strain, Strain at Peak Stress, and the Fatigue Law "B" parameter. Other LAS parameters are available to the partner states in the master testing database generated as part of this study. Results of blending for LAS are shown below in Figure 5.

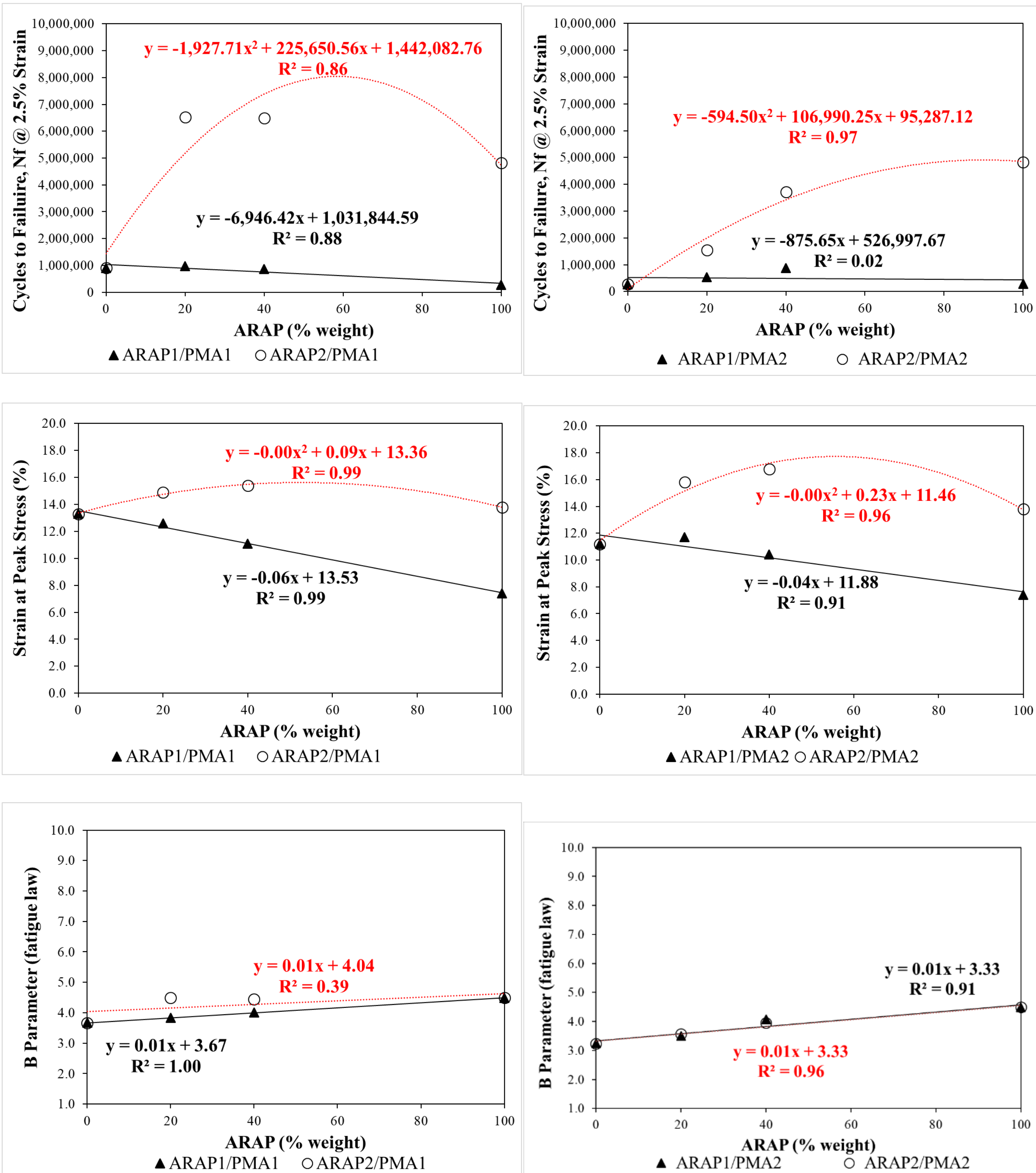


Figure 5. A-RAP blending charts for the LAS test conducted at 25°C showing Cycles to Failure at 2.5% Strain (top), Strain at Peak Stress (middle), and Fatigue Law "B" Paramter (bottom).

Cycles to Failure at 2.5% Strain is shown to be nearly linear for %ARAP binder replacement levels to 100%, when $ARAP_1$ (Unmodified RAP) is used. However, the trends for A-RAP_2 (Modified RAP) shows somewhat non-linear trends. For the PMA_1, blends show a marked increase in cycles to failure for the 40% binder replacement blend and a subsequent decrease in cycles to failure to 100% replacement. A-RAP_2

does not exhibit the same behavior when blended with PMA_2, which indicates 'compatibility' between constituent binders appears to influence this test parameter. Notably, A-RAP_2 shows the greatest deviation from linear behavior for all three parameters reported and with both A-RAP materials. An increase in cycles to failure is viewed as beneficial to fatigue life, and since a uniform trend is not observed for all cases, it is concluded that only by testing the actual blended binder can an accurate assessment of the blended property properties be achieved when using the LAS test.

A similar observation is made with the strain at peak stress parameter, in which the blends containing the A-RAP_1 material are highly linear, whereas the A-RAP_2 blends shown almost perfectly parabolic behavior. Since A-RAP_2 is made with highly polymer modified base asphalt and A-RAP_1 is made with neat base asphalt, it might be expected that the trends of these two materials would differ significantly when independently blended with a second asphalt source, particularly when subjected to a damage characterization test like the LAS.

The fatigue law "B" parameter is calculated as the slope of linear relationship between the Log of the cycles to failure versus log applied strain results; it is characteristically a negative number (a reduction in fatigue life with increased strain) and is reported above in Figure 5 as the absolute value. A higher absolute B parameter 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 data presented in Figure 5, which shows a linear increase in the B parameter with increasing binder replacement, therefore matches the expectation that increased recycled materials content reduces the fatigue life of the blended binder. Since the cycles to failure data depends not only on the B parameter, but also the fatigue law "A" parameter, these findings are not contradicting, but rather a matter of interpretation of the data.

Prior research regarding the effects of oxidative aging on the LAS parameters is in general agreement with these findings. Hintz et al. (2011) found that laboratory oxidative aging using the RTFO and PAV changes the relationship between fatigue life and applied strain. Such changes actually appear to increase fatigue life with aging at lower strain levels, contrary to the common ideology that aging universally reduces fatigue life. Findings from that study also indicated the changes are "highly" asphalt specific. Figure 6 shows the effect of aging on the fatigue law for a single asphalt binder; it is observed that the fatigue law relationship very clearly rotates in a clockwise fashion around a single strain level, in this case about 7%. The result is an absolute increase in the slope parameter (B) and increase in the intercept A.

It is clear from Figure 6 that for low levels of strain (2%, for example), the fatigue life (N_f) is actually shown to "increase" with increased aging from the Unaged condition up to 80 hours of PAV aging (4 cycles); in this case the increase in N_f is approximately two orders of magnitude between the Unaged and 60-hour PAV condition.

It is hypothesized that this phenomenon causing the non-linear behavior in Figure 5 since by increasing the A-RAP percentage is equivalent to artificially increasing the aging level of the PMA. Since the PMA and A-RAP materials do not necessarily contain the same base asphalt, the effect of aging and asphalt source are confounded, and a combination of the behavior shown in Figure 6 and source dependency is observed.

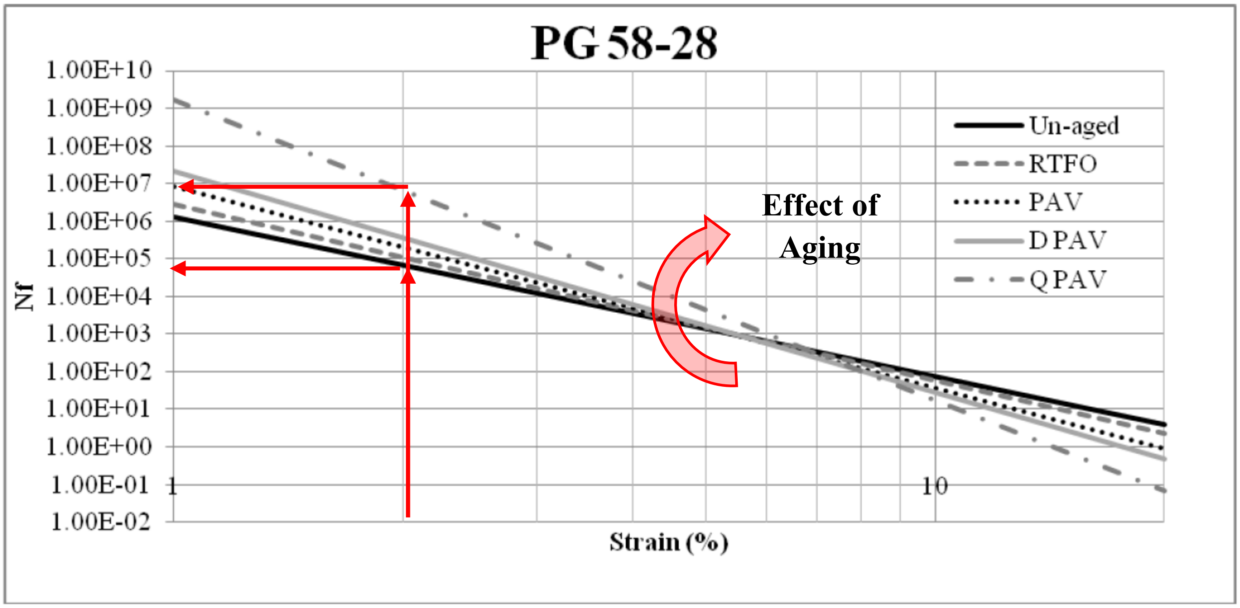


Figure 6. Effect of oxidative aging on Fatigue Law parameters and resultant N_f. "D PAV" and "Q PAV" is 40-hour PAV and 60-hour PAV aging, respectively.

Overall, it is concluded that the LAS test is sensitive to constituent binder properties and blending ratios, but that the trend observed between blend percentage and the property in question cannot be assumed linear in all instances. The non-linear behavior is most likely caused by the complex relationship between binder aging and strain sensitivity. This finding is in agreement with the literature and implies that a linear model for prediction cannot be used and direct testing of the blended materials at the desired ratios is necessary to accurately characterize the LAS parameters for the blend.

Single-Edge Notched Bending (SENB) Test

As described in an earlier section, repeatability problems with the BBR-SENB device were discovered during the course of testing that were determined to directly influence the integrity of the data being generated. An example of BBR-SENB data is shown below in Figure 7. Two properties, Displacement at Failure and Total Failure Energy, are shown in Figure 7 for one of the binder blends for clarity. As observed in the figure, the trend between increasing A-RAP percentage and each of the report properties appears to be erratic, with an inconsistent pattern of first decreasing, then increasing and remaining unchanged with increasing A-RAP percentage. Error bars are shown for ± 1 standard deviation from the respective data point in each plot; variability between data points for the same report property is very inconsistent, potentially indicating problems with the procedure or device. In the case of Total Failure Energy, the standard deviation for the 40% A-RAP data point is about 58% of the data point itself, which could result in one order of magnitude of uncertainty for this data.

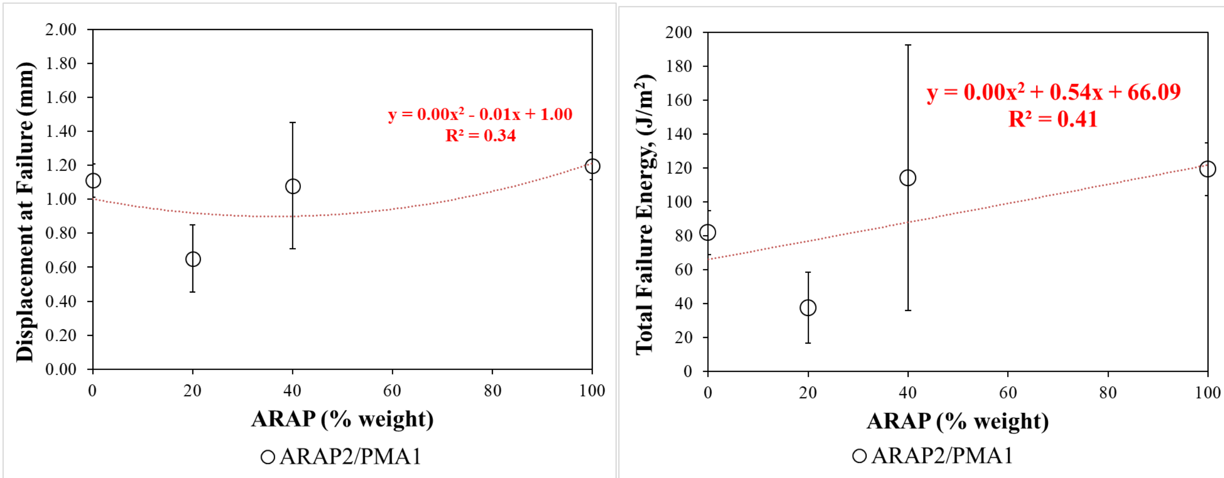


Figure 7. Example blending chart for the SENB test showing variability of Displacement at Failure (left) and Total Failure Energy (right) for one binder blend. Error bars are ± 1 SD.

The testing factorial for Subtask 1.1 was completed for the BBR-SENB, and one field RAP material was completed for Subtask 1.2. This data can be provided to the partner states upon request but will not be presented further in this report. To replace the forgone testing, extended BBR testing was completed for Task 2.

ii. Subtask 1.2: Validation using Recycled Materials from Partner States

In this subtask, asphalt binders recovered from recycled materials supplied by three partner states were blended with a single polymer modified asphalt material and tested for the properties listed in Table 3. In addition to three levels of RAP binder replacement, an additional blend at 15% RAP binder replacement + 5% RAS binder replacement was included for each RAP source; this 20% effective binder replacement blend was included to simulate commonly used blend percentages in practice when using RAP and RAS together. RAS binder for this study was procured from a commercial source specializing in the recovery and resale of recycled asphalt shingle binder. All binder blends were produced by first blending the component binders together, then subjecting the blended materials to the specified aging protocols.

Multiple Stress Creep and Recovery Test

Binder blends were tested in the RTFO condition at 64°C using the MSCR procedure, with the results shown in Figures 8 and 9. Figure 8 includes the RAP-only binder blends, and Figure 9 includes a comparison of the 20% RAP-only blend with the 15% RAP + 5% RAS blend for the same three MSCR parameters.

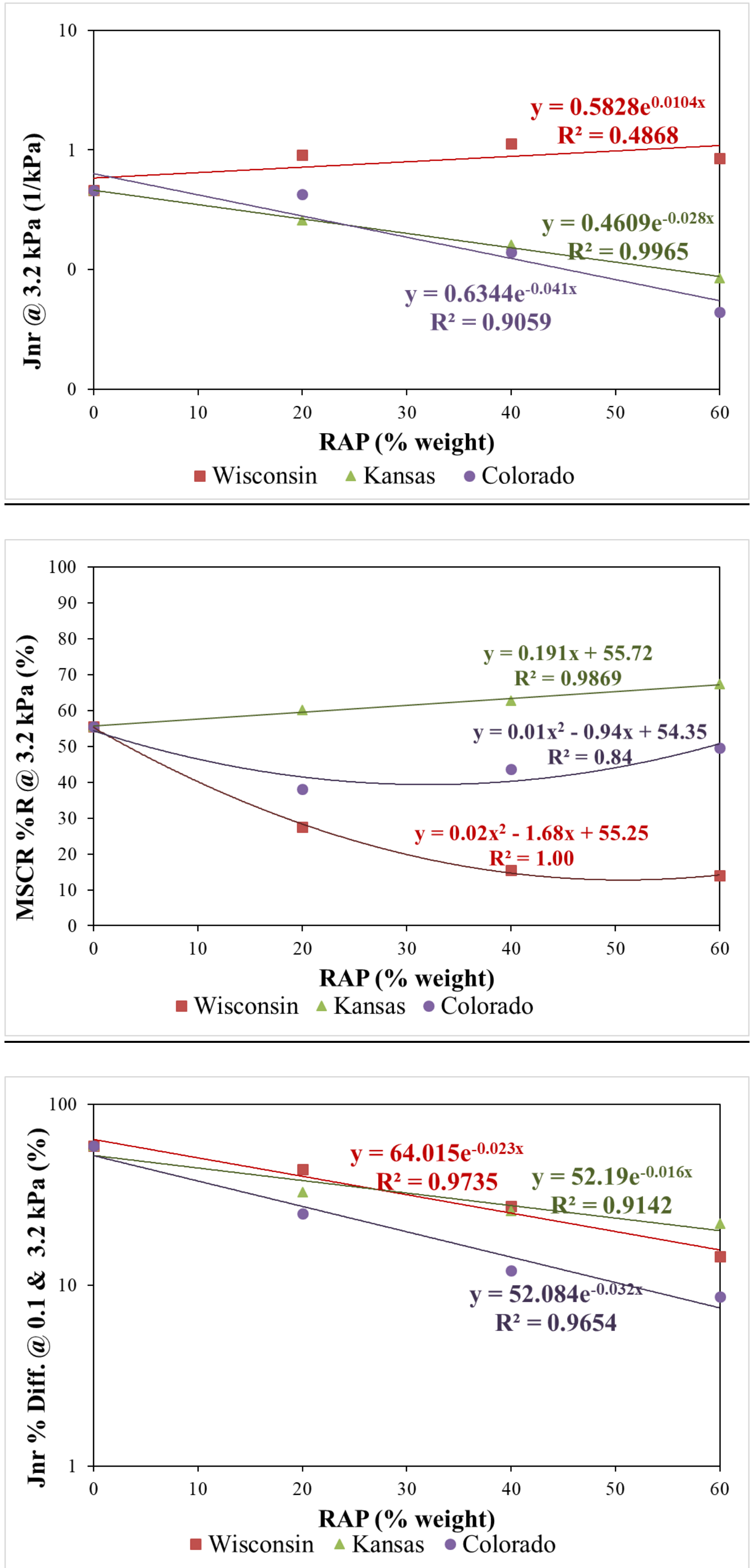


Figure 8. RAP blending charts for the MSCR test conducted at 64°C, showing Jnr at 3.2 kPa (top), MSCR %R (middle) and Jnr % Difference (bottom).

For the Kansas and Colorado RAP sources, the trend between binder replacement and Jnr is linear on a log-linear scale, indicating an exponential relationship between Jnr (decreasing) with increased binder replacement. This agrees with the data presented for the A-RAP materials in which the recycled material has a lower Jnr relative to the base asphalt. For the Wisconsin RAP source, there is very little change between the Jnr and percent binder replacement, and in fact the Jnr increases slightly with higher replacement levels, indicating that the recovered RAP binder has a higher Jnr at 64°C relative to the PG 70-28 (PMA) base binder. Since the Wisconsin RAP source is assumed to contain an unmodified asphalt (most likely a PG 58-28), this behavior is expected, particularly if the RAP millings came from a relatively newer pavement section. The findings serve to illustrate the importance of the RAP source in determining blended binder properties.

For example, the base asphalt used in this study would technically grade as a "V" grade in terms of Jnr ($0.5 < Jnr < 1.0$ kPa^{-1}). If the Wisconsin RAP source was used in a new pavement construction, the grade of the blended binder at 20% binder replacement (well within the usage percentages common in the State of Wisconsin) would drop to "H". Although in this case the change in Jnr between the base asphalt and the blended asphalt at 20% is relatively small and the performance implications are unlikely to be significant, the change is great enough to result in a grade change for the blended binder.

The MSCR %R parameter has been shown in Subtask 1.1 to be influenced by the modification of the binders used in the blends and the combined blend Jnr. Indeed, the trends shown in the MSCR %R appear to confirm this; for the Kansas RAP source, which is known to come from a highly modified pavement section with a substantially lower Jnr relative to the PMA used in this study, the expected trend would be an overall increase in %R with increasing binder replacement. On the other end of the spectrum is the Wisconsin source, which likely contains no modification and has a higher Jnr than the PMA used in this study and exhibits an initial decrease in %R as expected. However, the trend in %R very clearly levels off just as Jnr remained nearly constant for the higher RAP levels for this source. The Colorado source may show the combined effect, where the %R begins to increase at higher levels of binder replacement due to the possible offsetting effects of a low Jnr.

Overall, the trends for %R confirm the findings of Subtask 1.1. The resulting %R appears to be not only a function of the modification used in the constituent materials, but also the Jnr of the blended materials. These effects are not mutually exclusive, but rather interdependent. In some instances (Colorado source), the effects can be cancelling or additive depending on the replacement level, whereas for other cases (Kansas), the effects can be additive throughout the range of replacement levels. In other words, without directly testing the input materials at the desired blend percentage, it cannot be assumed that %R always increases, decreases, or stays the same at a given replacement level. For the Wisconsin RAP, the drop in %R between 0% and 20% binder replacement would be great enough to technically drop from a "V" grade to an "H" grade based on the %R parameter alone.

The Jnr %Difference parameter, although of limited significance to this study, is again found to be linear on a log-linear scale, indicating an exponential relationship exists. In this subtask, the base asphalt used to produce the blends has a relatively high Jnr %Difference, and all trends are negative: Jnr %Difference decreases with increasing binder replacement. However, in Subtask 1.1, it was shown that if the recycled material has a higher Jnr %Difference relative to the base asphalt, this trend can be reversed, although still linear.

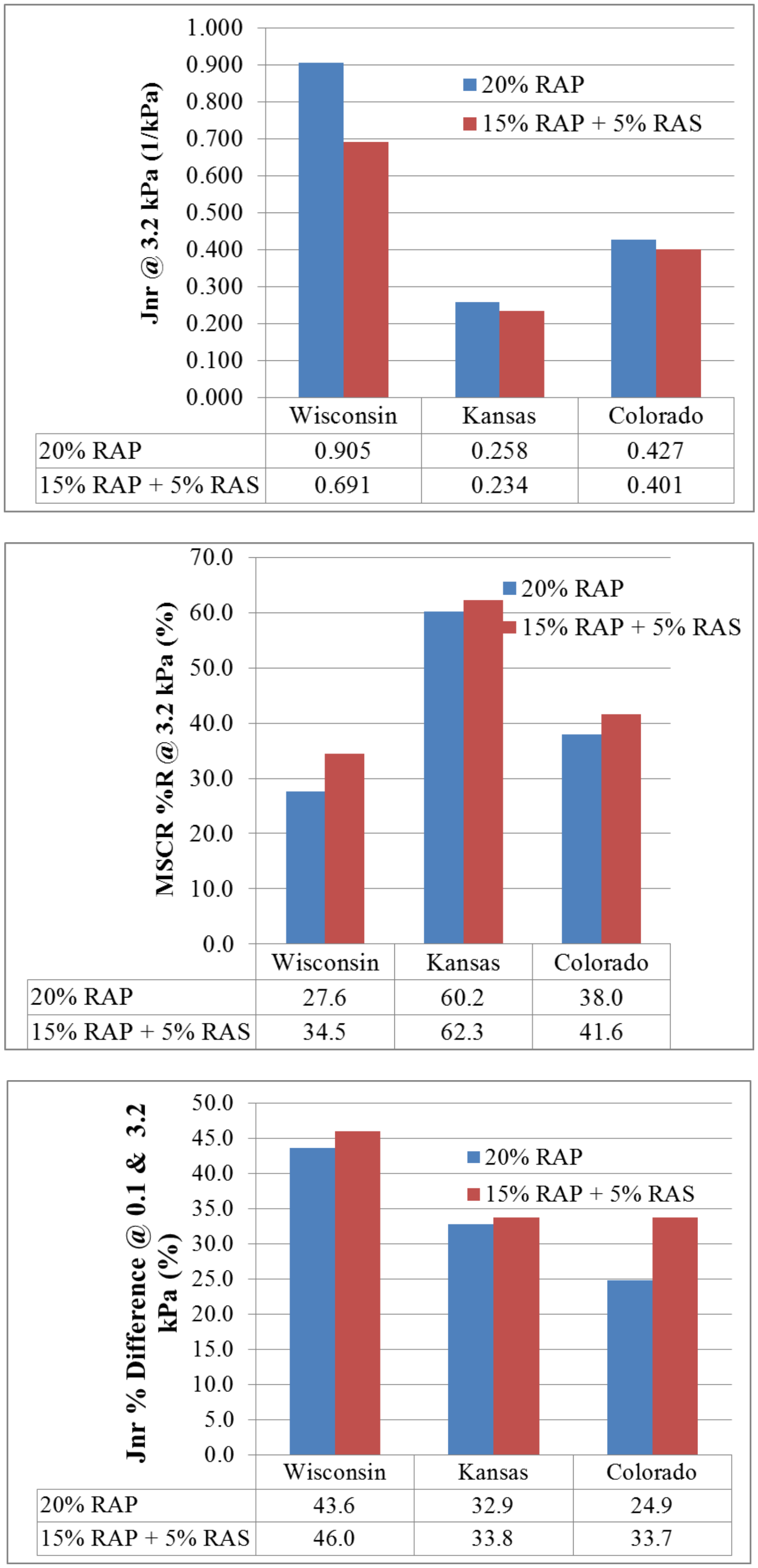


Figure 9. Difference in MSCR parameters for 20% RAP and 15% RAP + 5% RAS blends.

Figure 9 shows the effect of adding a relatively small percentage (5%) of RAS binder to the blend for the three MSCR parameters of interest. For all three RAP sources, the effect is a decrease in the Jnr value relative to the 20% RAP-alone blend; this is expected since it is known RAS binder is typically much stiffer on average than paving grade asphalt, even after field aging in this case. For the Wisconsin source, which has been determined to have the highest Jnr of the three sources, the effect of adding the RAS is more pronounced, as expected. In no case would the addition of the RAS alone cause the traffic grade of the base binder to change based on Jnr alone, with the maximum change in Jnr of just over 0.2 kPa^{-1}.

The MSCR %R data is particularly interesting because the inclusion of RAS binder changes only the blended binder stiffness, not polymer loading. Yet for each RAP source, an increase in MSCR %R is noted. Although the increase observed for each case is relatively small (a maximum increase of 6.9% for the Wisconsin source), the data again serves to illustrate the influence of the Jnr parameter on the MSCR %R. Data for the Jnr %Difference parameter is also shown, with the effects of including the RAS binder being minimal and of no practical significance for this study.

Overall, it is concluded that effect of adding a small portion of RAS binder in the recycled blend for this PMA has a measurable effect on the MSCR results of the blended binder, but in general does not produce a significant change in the MSCR results. Regarding the Jnr and %R parameters specifically, the changes observed would be viewed as conservative, since the Jnr was lowered and the %R increased. It should be noted, however, that the increase in %R is not due to increased polymer loading, but rather a reduction in Jnr through stiffening.

ER-DSR (AASHTO TP123)

Binder blends for the ER-DSR procedure were tested using the 8 mm plate at 25°C on the RTFO aged residue. Results are again presented with RAP-only blends in Figure 10 and the inclusion of RAS in Figure 11.

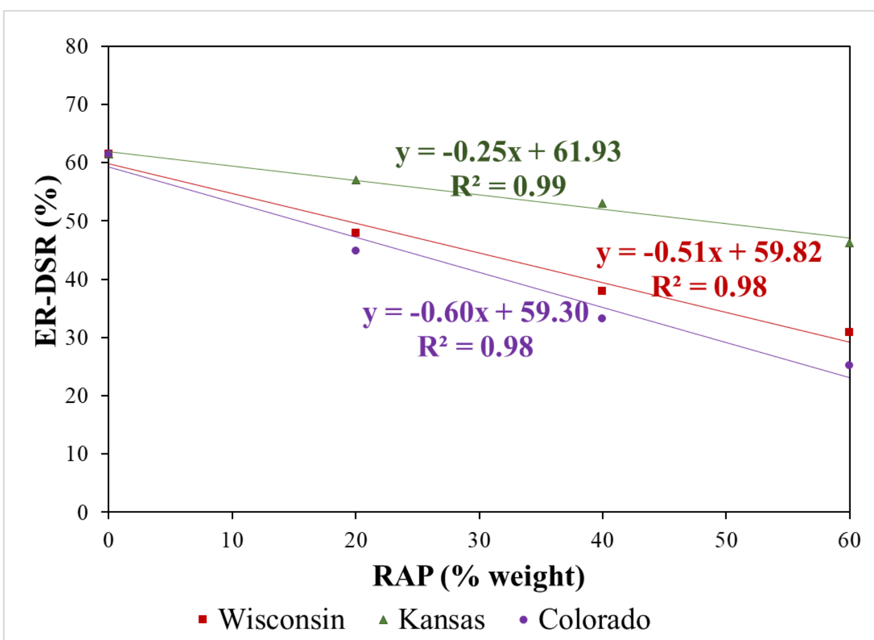
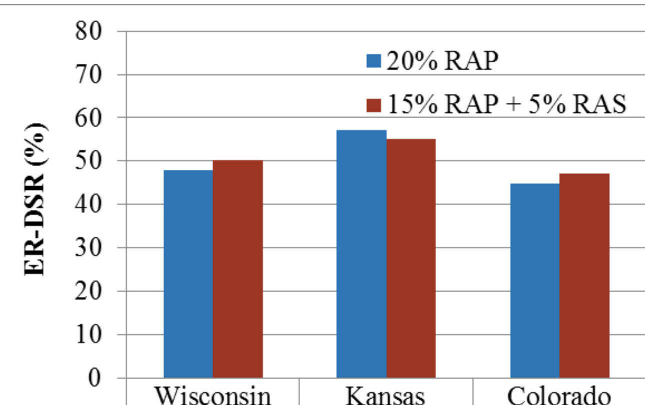


Figure 10. RAP blending charts for the ER-DSR (AASHTO TP123) test conducted at 25 °C.

The data shown in Figure 10 shows a linear decrease (on a linear scale) with increasing binder replacement, which agrees with the findings for ER-DSR in Subtask 1.1. Interestingly, the results for the ER-DSR procedure for the Kansas source shows a steady decrease in recovery with increasing binder replacement, whereas the same blends tested using the MSCR procedure exhibited a linear increase in recovery at 64°C. Further, the data for the other two sources also shows a steady decrease for the ER-DSR procedure at 25°C, but a decrease and then increase in recovery when tested using the MSCR procedure at 64°C. Since these blends were both tested in the RTFO aged condition, it is concluded that the two test methods, although both measuring strain recovery, are giving different information.

In addition to being conducted at different temperatures, it should be noted that maximum strain in the ER-DSR procedure is fixed as part of the test, whereas maximum strain in the MSCR is dependent on the compliance of the binder since the stress is fixed. The strain level used in the ER-DSR procedure is much higher than the strain levels obtained in the MSCR procedure. It is theorized that this critical difference in test methods, and the difference in temperature, may be causing the differences in the strain recovery data observed between the test methods. As was discussed in Subtask 1.1, it is well established that asphalt binder shows increased elastic response with aging and/or reducing test temperature, particularly at intermediate and lower temperatures. This behavior is likely contributing to the differences in trends shown.

Figure 11 compares the 20% RAP-only blend for each source with a blend of 15% RAP and 5% RAS. The data in Figure 11 shows minimal differences between the binder blends with and without RAS, with a maximum difference of 2.2%, which is expected to be within the normal deviations observed in the test. It is therefore concluded that addition of small amounts of RAS material should not be expected to significantly alter the relationship between ER-DSR and binder replacement through at least 20% total binder replacement.



	Wisconsin	Kansas	Colorado
20% RAP	47.9	57.1	44.9
15% RAP + 5% RAS	50.1	55.1	47.1

Figure 11. Difference in ER-DSR for 20% RAP and 15% RAP + 5% RAS blends.

Binder Yield Energy Test (AASTHTO TP 123)

Figures 12 and 13 show the results of the blended binder testing using the BYET test. All BYET testing was conducted on PAV residue at 25°C.

Based on the data in Figure 12, the relationships for binder Yield Energy and Maximum Stress are confirmed to be linear up to at least 60% binder replacement. For all three RAP sources, the direction of change is the same, with increasing binder replacement resulting in an increase in both the yield energy and maximum stress. This agrees with results of Subtask 1.1, in which PMA_1 is the same PMA used in Subtask 1.2; this PMA has a lower yield energy and maximum stress relative to the recycled materials. Since a higher yield energy is viewed as beneficial, the implications of this finding confirm that if the yield energy of the recycled material is known, the relationship between binder replacement and yield energy can be predicted.

The trends between maximum stress and binder replacement shown in Figure 12 indicates that the maximum stress value for any blend is dependent on the stiffness of the recycled binder, as would be expected. For example, the data for Jnr shown in Figure 8 shows that the Colorado source has the lowest Jnr (the stiffest of the three sources); as shown in Figure 12, this source also accumulates the most stress before yielding.

The data for Strain at Peak Stress also appears to be linear, but for this Subtask it is more variable than what was observed in Subtask 1.1. It is theorized that this behavior is due to the extreme stiffness of the recovered binders causing difficulties in testing rather than true material variability; for example, delamination of the test sample from the DSR plate is often observed when testing very stiff binder at intermediate temperatures. Despite efforts to ensure valid tests, it cannot be determined with 100% confidence that such errors in testing are or are not occurring to some degree. However, in general, it is observed that the strain at peak stress is lowered with increasing binder replacement levels, as would be expected based on the common mentality that as binder ages, the ability to elongate is reduced. Moreover, the data in Figure 12 confirms that the BYET method is sensitive to source and appears to show logical trends in the data.

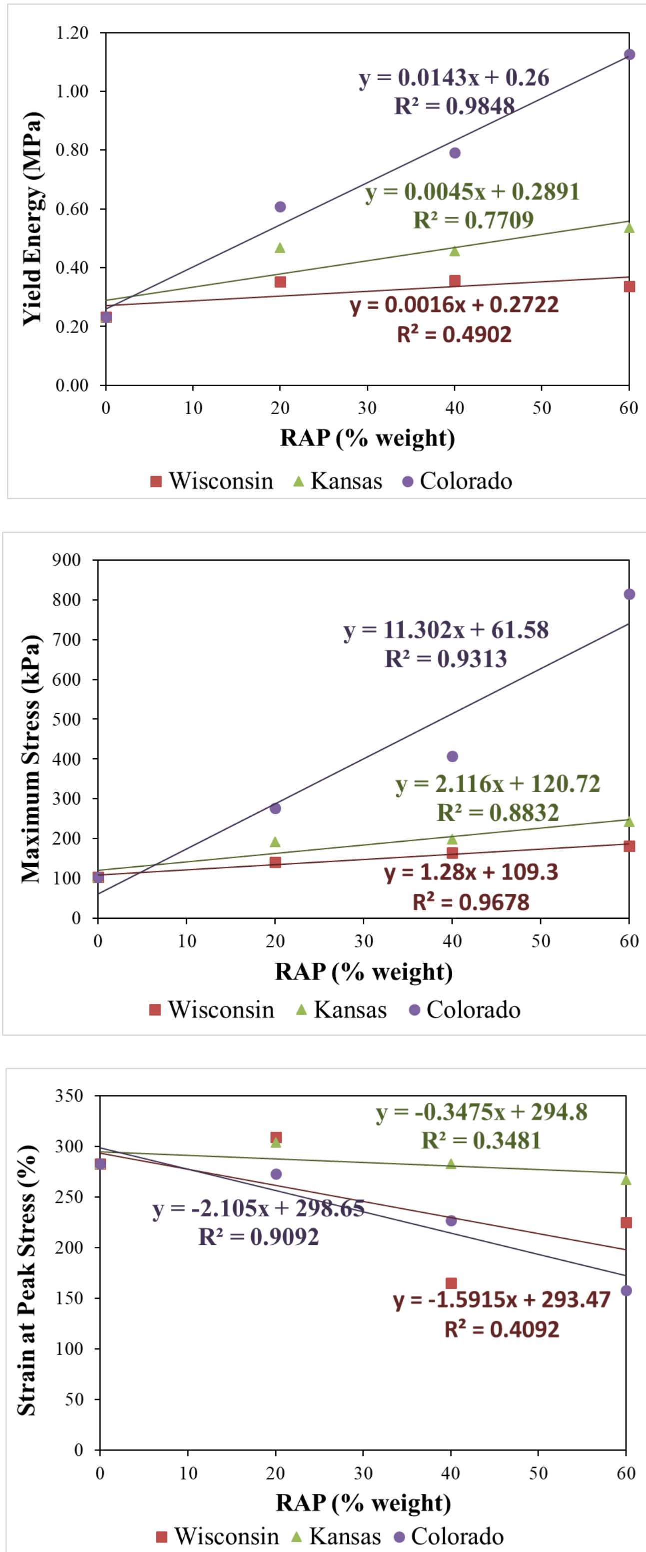
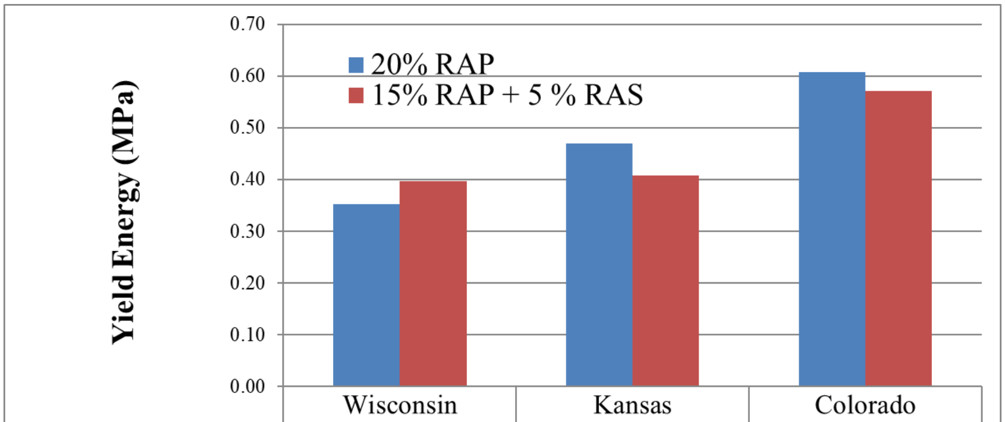


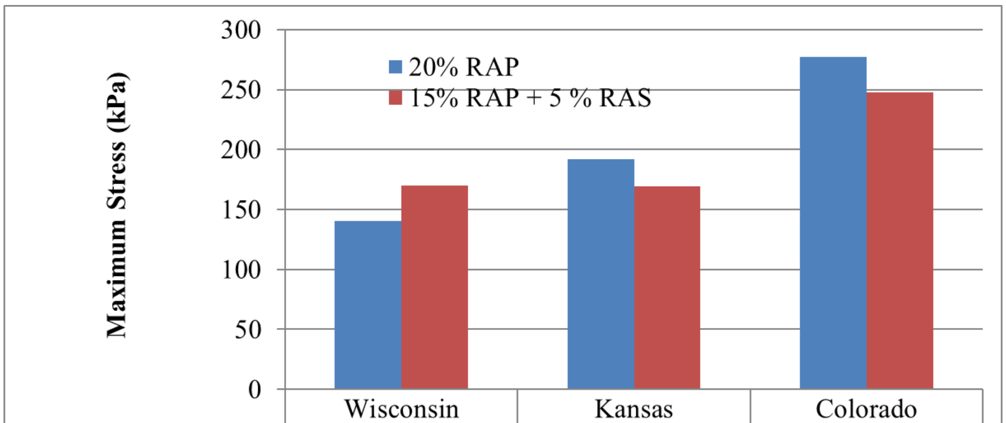
Figure 12. RAP blending charts for the BYET (AASHTO TP123) test conducted at 25°C showing Yield Energy (top), Maximum Stress (middle), and Strain at Peak Stress (bottom).

As was noted in Subtask 1.1, the strain at peak stress parameter has been shown to be a direct replacement for the ductility test. Based on the results shown in Figure 12, the addition of highly aged material is detrimental to this parameter. Consequently, agencies wishing to implement this parameter in place of ductility need to determine a minimum strain at peak stress based on the binders currently in use in their region, as compared to the ductility test on those same binders. Also, they should increase this minimum by a factor of safety as determined based on the desired reliability of the criteria.

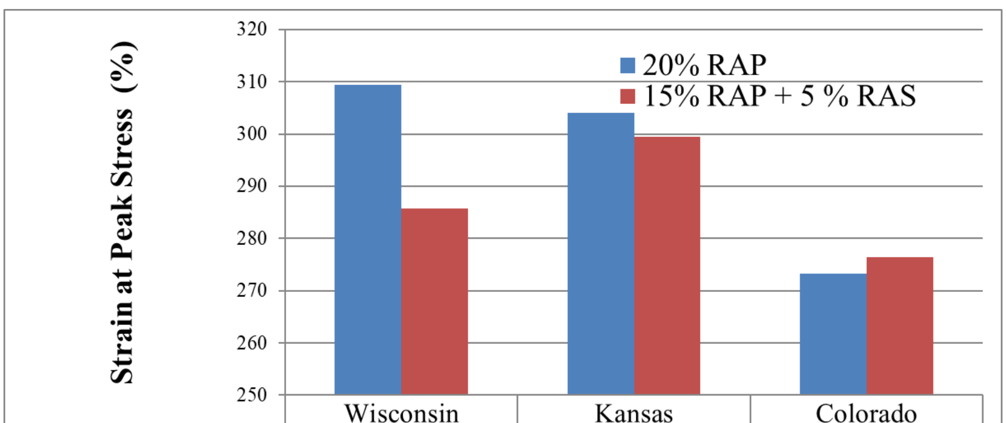
Data shown in Figure 13 compare the difference between 20 % RAP and 15% RAP + 5% RAS. The results indicate that the combination of RAS with RAP could change properties of the blend significantly different than using RAP only. Taking the Wisconsin source as an example, the inclusion of 5% RAS material in the 20% total binder replacement blend increased the maximum stress by approximately 20% but reduced the strain at maximum stress by just over 7% relative to the 20% RAP-only blend. This data may be further influenced by the difficulty in testing extremely stiff asphalt at intermediate temperature, but nevertheless shows that the inclusion of RAS material may significantly affect the results of the BYET, sometimes in a perceived negative way.



	Wisconsin	Kansas	Colorado
20% RAP	0.35	0.47	0.61
15% RAP + 5 % RAS	0.40	0.41	0.57



	Wisconsin	Kansas	Colorado
20% RAP	141	192	278
15% RAP + 5 % RAS	170	169	248



	Wisconsin	Kansas	Colorado
20% RAP	309	304	273
15% RAP + 5 % RAS	286	300	276

Figure 13. Difference in BYET paramters for 20% RAP and 15% RAP + 5% RAS blends.

Linear Amplitude Sweep Test

Figures 14 and 15 show the results of the blended binder testing using the LAS test, with Figure 14 showing the RAP-only blends and Figure 15 showing the results of using 5% RAS binder to replace the RAP binder. All LAS testing was conducted on PAV residue at 25°C.

Cycles to Failure at 2.5% Strain is shown to be nearly linear for binder replacement levels to 60% for the Wisconsin and Colorado source, while the Kansas source shows erratic results. The trends in general agree with the findings from Subtask 1.1 in which it is shown that Cycles to Failure generally decrease with increased binder replacement. The difference in slopes between the trend lines indicates the net effect of adding recycled binder is dependent on the source of the recycled binder, as would be expected.

Strain at peak stress parameter is also shown to be nearly linear up to 60% binder replacement for these three sources, which again agrees with the findings of Subtask 1.1. The trends are again dependent on the RAP source; interestingly, the Wisconsin and Kansas sources, which are known to have drastically different properties, show nearly the same effect on Strain at Peak Stress. This would seem to indicate the importance of testing the actual materials used in practice rather than assuming polymer modification will always significantly improve binder properties.

As stated earlier, a higher absolute B parameter 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 data presented in Figure 14 shows a strongly linear trend between increasing binder replacement and increasing B parameter, which again matches the expectation that increased recycled materials content reduces the fatigue life of the blended binder. Since the cycles to failure data depends not only on the B parameter, but also the fatigue law “A” parameter, these findings are not contradicting, but rather a matter of interpretation of the data.

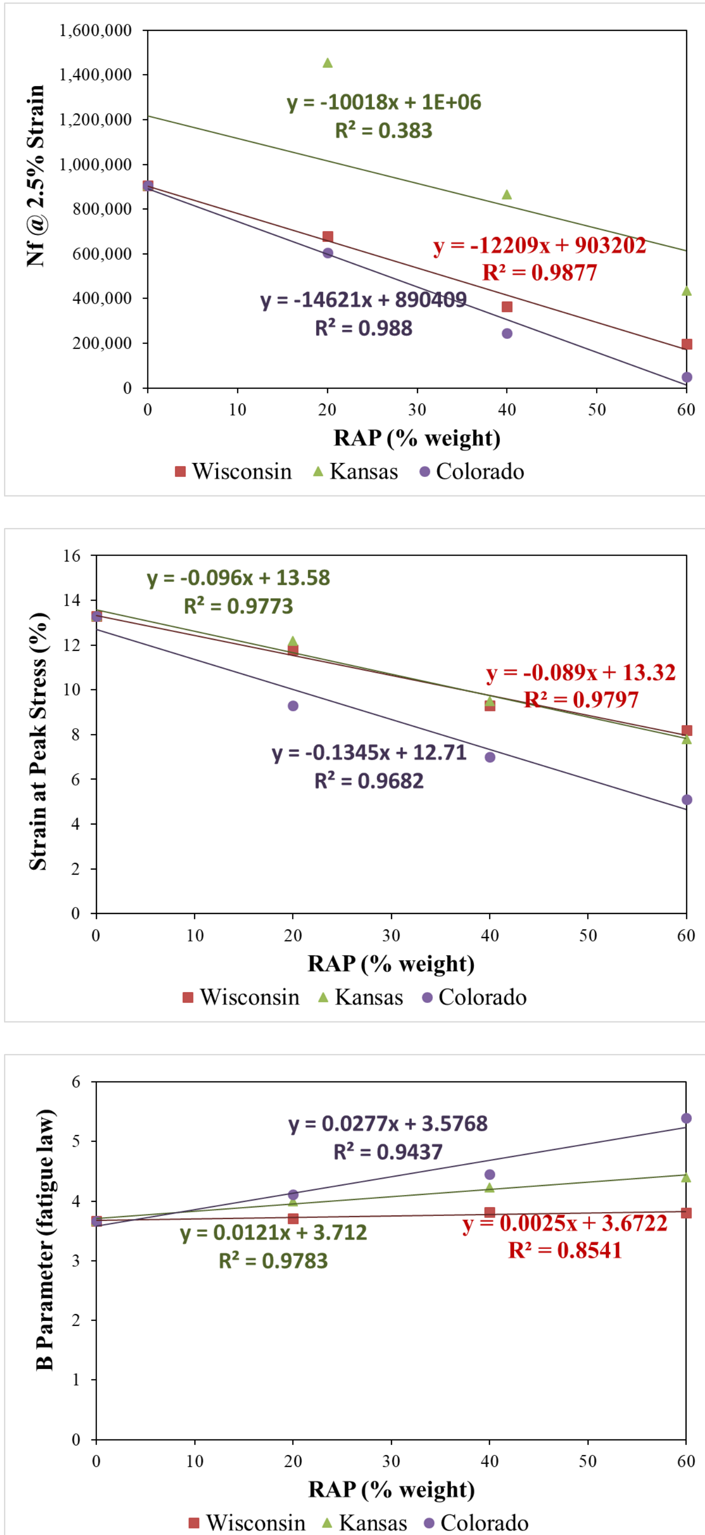


Figure 14. RAP blending charts for the LAS test conducted at 25°C showing Cycles to Failure at 2.5% Strain (top), Strain at Peak Stress (middle), and Fatigue Law "B" Paramter (bottom).

The addition of RAS binder is expected to reduce the overall fatigue performance of the binder blends. As shown in Figure 15, this hypothesis is difficult to validate with certainty for the three sources of RAP tested when mixed with the RAS source used. Cycles to Failure would be expected to decrease with the addition of RAS binder, but is shown to increase for two of the RAP sources. Strain at peak stress would be expected to decrease with the addition of RAS, and this is true for two of the three sources. The magnitude of change in the strain at peak stress parameter between the 20% RAP-only blends and the RAS blends is very small, however, so the practical significance of the change observed is questionable.

The B parameter would be expected to increase with the addition of RAS, and this is confirmed to be true for all three sources of RAP. In the context of the magnitude of difference between the RAP-only and RAS blends, the practical significance of the observed changes should be considered. For example, the Wisconsin RAP source which is known to be the softest of the three RAP sources exhibited a change in the B parameter of 0.13 units between 0% and 60% RAP binder replacement (0.0025 units/% binder replaced), whereas the change between the 20% RAP-only and RAS blends exhibited a change of 0.25 units. A change of 0.25 units in this parameter for this RAP source would be equivalent to more than 100% RAP binder replacement, which is a very significant effect. Therefore, the addition of RAS binder, for this combination, would be approximately 20 times more detrimental to the B parameter than RAP binder alone. This ratio comes to approximately 1.6 times for the Kansas source and 0.71 for the Colorado source, indicating an extreme dependence of the RAS effects on the RAP source.

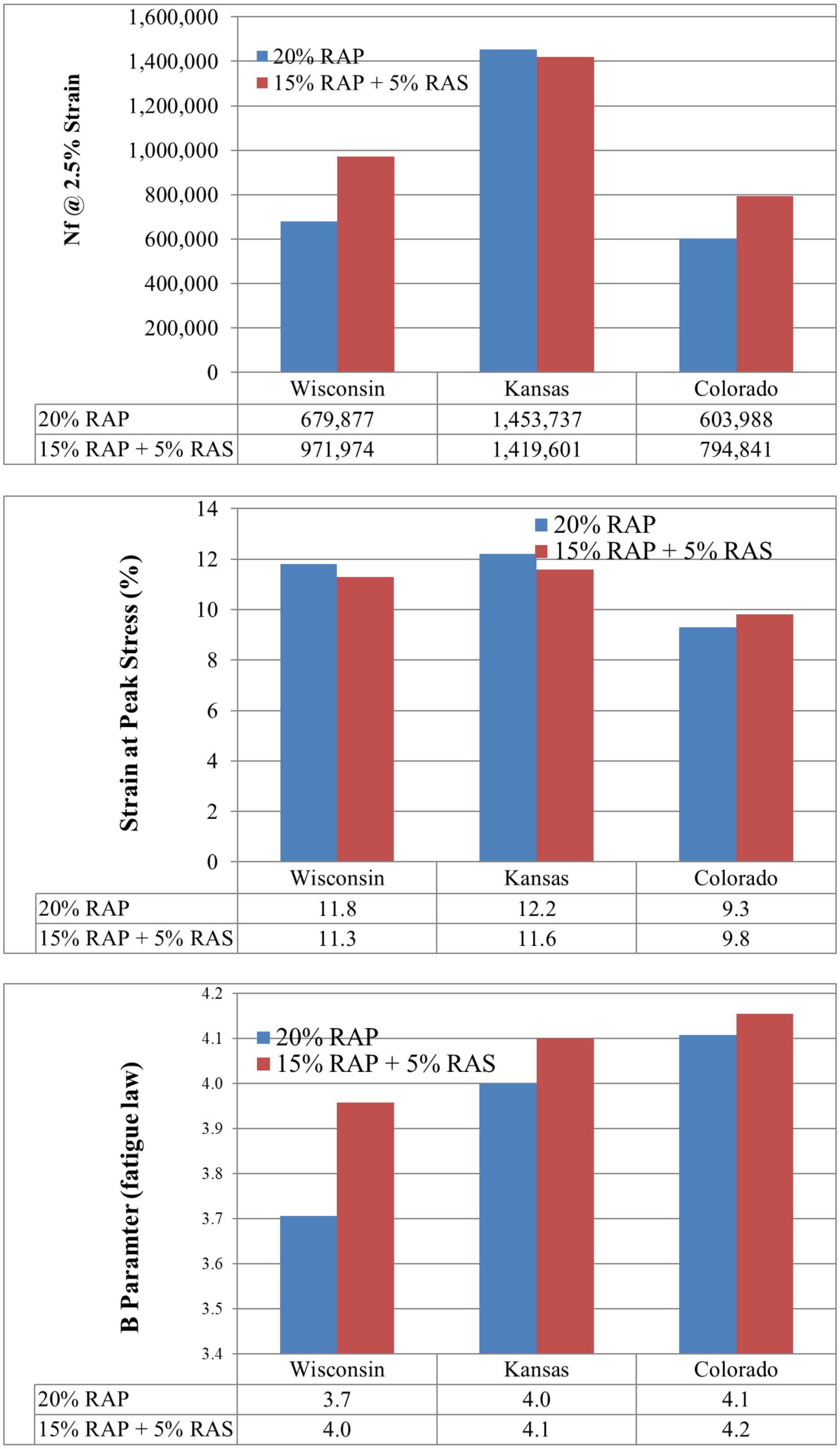


Figure 15. Difference in LAS paramters for 20% RAP and 15% RAP + 5% RAS blends.

B. *Task #2: Effects of Low Temperature Modification Technologies on PG+ and Developmental Test Methods*

The specification and usage of extended low temperature PG binders has increased in many regions to increase reliability of pavement designs against low temperature thermal cracking. In the upper Midwest, for example, a transition away from PG xx-22 to PG xx-28 and PG xx-34 binders has been observed in recent years. WisDOT, as an example, has made the use of PG 58-34 asphalt binders mandatory for new asphalt construction (wearing course) in the northern zone of the State (the approximately northern half of the State).

To produce these binders, asphalt binder suppliers have essentially two options. The first option is to use a softer refinery grade (typically PG 52-34) and either blend with a stiffer asphalt source or more typically modify the soft grade with high temperature modifiers to increase the high temperature grade to the desired level. The second option is to start with a harder asphalt such as PG 58-28 and modify with a low temperature additive to reduce the low temperature grade to -34; in doing so the high temperature grade usually must be adjusted higher to remain in the desired high temperature grade. For example, modifying a PG 58-28 to meet the demands of a PG 58-34, the high temperature grade usually falls to PG 52; a high temperature modifier is then used in a small amount to 'bump' the grade back to PG 58 to achieve the desired PG 58-34, in this example.

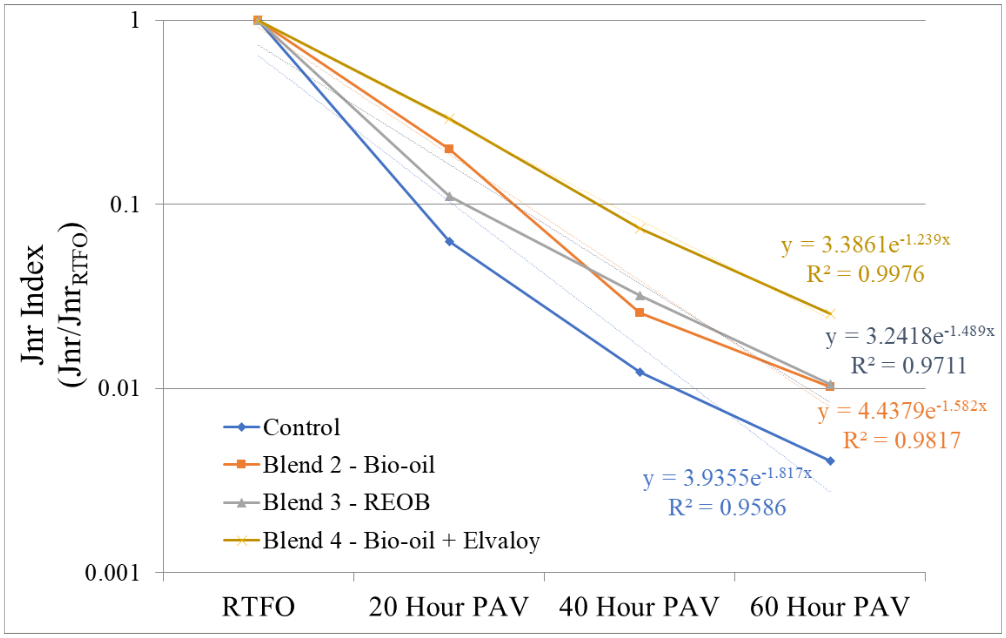
The use of low temperature modifiers has increased to a point where several technologies are readily available in the market; however, there is speculation in industry that some of these additives lack the extended aging performance relative to unmodified asphalt. This task evaluates several low temperature modification practices in the context of extended aging performance of the asphalt using the same testing methods as used throughout this report but including three long term aging intervals: PAV (1 cycle), 2PAV (40 hours), 3PAV (60 hours). In addition, an extended analysis using the BBR test (and ΔT_c) parameter is included.

Multiple Stress Creep and Recovery Test

Rutting resistance of asphalt binders is expected to increase with increased levels of aging, which is the reasoning behind MSCR testing on the RTFO residue only. Nevertheless, information regarding the relationship between Jnr and %R as well as aging susceptibility of different asphalt binder blends can be gained from testing several levels of binder aging. The four binder blends in this study were therefore tested in the RTFO aging condition as well as the PAV aged conditions.

Figure 16 shows the relationship between Jnr and MSCR %R and aging condition for the four blends. A "Jnr Index" is used to normalize the changes among the binders due to aging; the Jnr Index is defined as the ratio of the Jnr at 3.2 kPa for any aging level to the Jnr at 3.2 kPa of the RTFO residue. All testing was conducted at 58°C. Since Jnr spans several orders of magnitude for the blends, data is plotted on a log-linear scale as was done in earlier sections of this report for Jnr. As expected, Jnr decreases with increased aging in an exponential fashion. The difference in aging susceptibility (slope of fit line) is readily apparent from the plots, with the control blend showing the greatest reduction in Jnr and Blend 4 exhibiting the least aging susceptibility.

MSCR %R is shown to increase at a decreasing rate with aging for all the blends using a %R Index. An increase in %R of 220% to 250% relative to the %R of the RTFO residue is observed for the blends. Note that the composition of the blends does not change between aging conditions, indicating that oxidative aging is the only cause of the increased %R. Interestingly, the Control Blend shows the greatest increase in %R for all aging conditions while Blend 4 shows the least increase except for the 60-hour PAV condition, where the %R Index for Blend 4 is very similar to Blend 3. This finding coupled with the observations made for the Jnr Index indicates a strong relationship between changes in Jnr and %R exists.



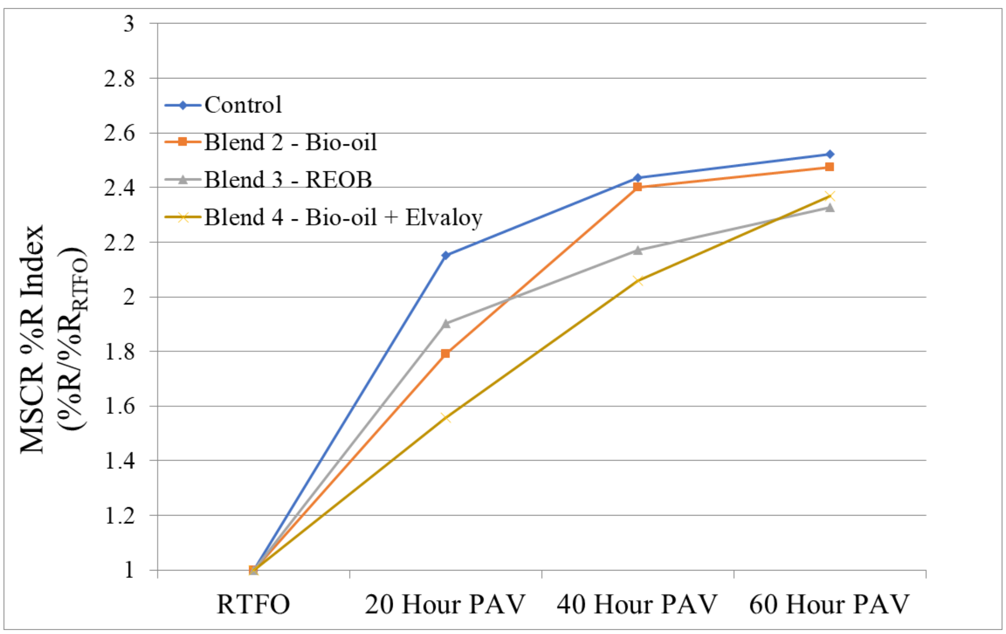


Figure 16. Jnr Index (top) and MSCR %R Index (bottom) for the four binder blends at four levels of aging at 58°C.

Figure 17 shows the same data plotted on a Jnr vs. %R plot, as is found in AASHTO M332 with all aging conditions are represented on the same plot; note that the power function line drawn in the figure is a best fit line for the data in this study and not the %R limit in M332. When a trend line is drawn for all of the data combined, an explained variance (R^2) of 95% is obtained, indicating changes in %R for a given asphalt binder blend is highly related to the Jnr of the binder. Since aging changes the Jnr, the %R must also change. The spread in the data indicates that this phenomenon is blend dependent, so changes in the polymer, additive, base asphalt, etc. may change where individual data points fall, but will not change the overall trend. This data is in good agreement with the MSCR analysis presented in earlier phases of this pooled fund project.

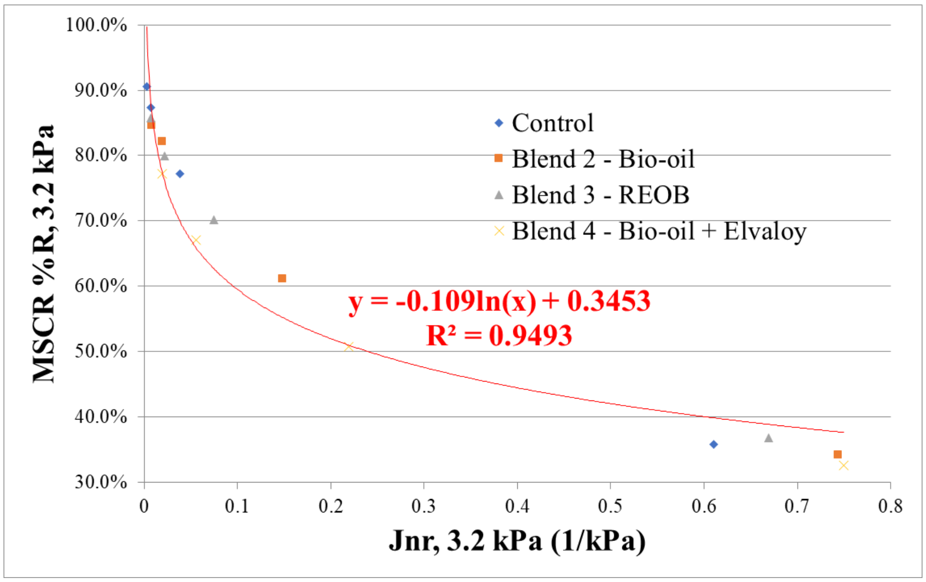


Figure 17. MSCR Jnr vs. MSCR %R plot at 58 °C for all blends and all aging conditions. Red trend line is drawn for all data points combined.

For agencies' applications, these findings demonstrate the importance of thermal history when testing binders for qualifications and acceptance. Binder aging alone could result in lower Jnr and high %R values. Similarly, testing of mixtures sampled from the field should take into account the effects field aging may have on Jnr and resulting %R. Note that the controlling MSCR parameter for these blends was %R (30%, minimum for achieving 'H' grade), these findings show that for all blends except Blend 4, the change in %R between the RTFO and 20-hour PAV condition is enough to effectively make these binders change from 'H' grade to 'V', despite not changing composition.

The Jnr %Diff parameter shows more curious behavior. The blend data in Table 7 shows that there is a relatively large spread (from about 22.7% to 50.6%) in the stress sensitivity (Jnr % Diff. parameter) of the binder blends. However, for all blends the parameter decreases at the 20-hour condition then increases again for the 40- and 60-hour conditions as shown in Figure 18, with the magnitude of change dependent on the blend. The reasoning for this trend is unclear. Although this parameter was not found to be related to performance in earlier work for this project, and its utility as an acceptance criterion was called into question, it is hypothesized that the stress state within the sample may affect the response of the binder. This will manifest itself in tests that are primarily strain controlled, such as the ER-DSR (discussed next section).

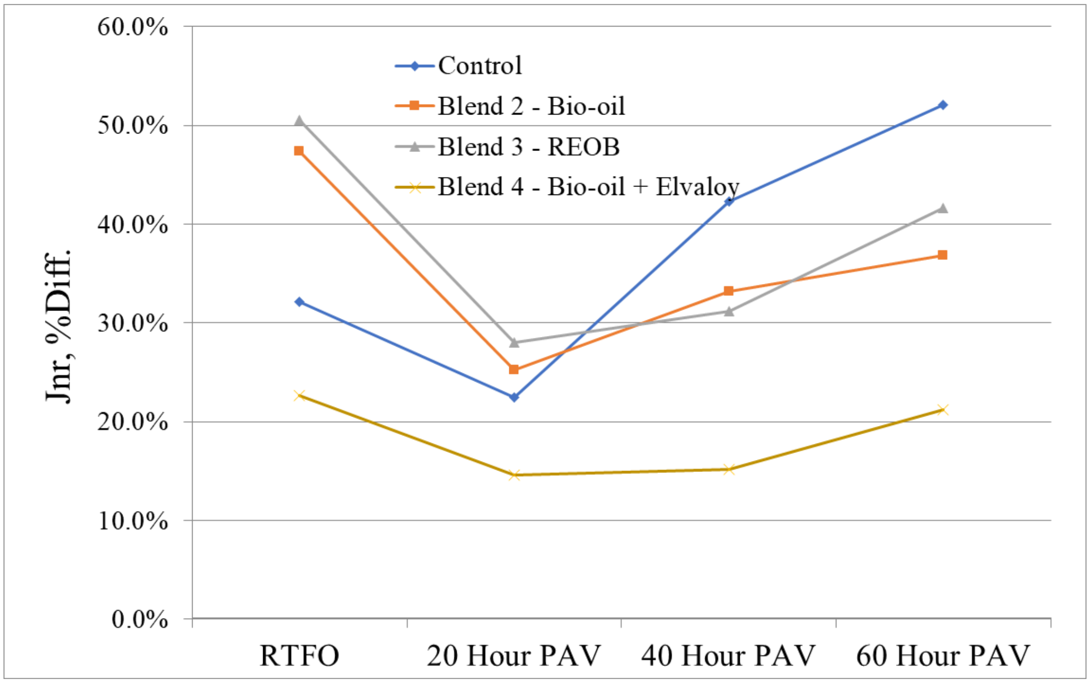


Figure 18. Change in Jnr %Difference parameter with aging at 58 °C.

ER-DSR (AASHTO TP123)

Based on the findings from Task 1, it was expected that the ER-DSR percent recovery would decrease with increased aging level since binder stiffness increases with increased aging; the ER-DSR is a strain-controlled test, and higher binder stiffness results in higher stress and lower strain recovery. Figure 19 presents the ER-DSR results for the four blends tested at 19°C, which is the intermediate PG of the blends. Data is presented as an ER-DSR Index, which is defined as the ratio of the elastic recovery at any level of aging to the elastic recovery of the RTFO residue. A ratio less than one indicates that the elastic recovery for that aging level is less than the elastic recovery for the RTFO condition.

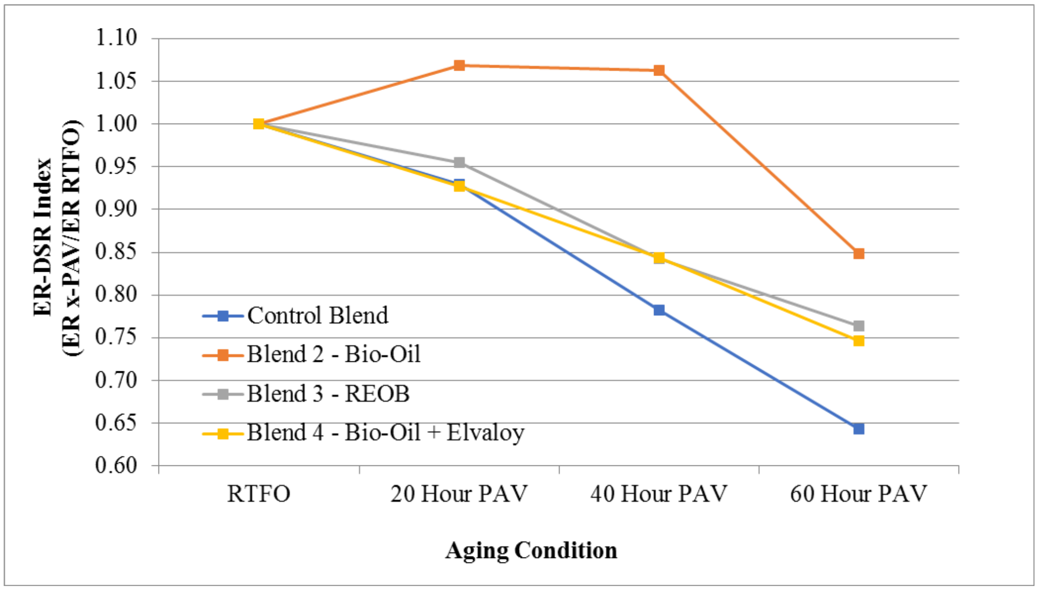


Figure 19. ER-DSR Percent Recovery Index at 19 °C for four aging conditions.

For the control blend and blends 3 and 4, the ER-DSR decreases with aging, as expected. The bio-oil blend interestingly shows a slight increase between the RTFO and 20-hour PAV condition, almost no change between the 20-hour PAV and 40-hour PAV condition, and a decrease between the 40-hour and 60-hour PAV condition. Unlike the results in Task 1, the percentage (and type) of polymer for each blend does not change between aging conditions; that is to say for any single blend the amount and type of polymer is the same for each data point for that blend in Figure 19.

Since the maximum strain in the ER-DSR test is constant, the stress varies based on material properties such as stiffness; this loading condition is just the opposite of the MSCR test, in which the stress is fixed, and the strain is allowed to vary. Figure 20 shows the maximum stress versus the corresponding percent recovery attained during the ER-DSR test for each aging condition and blend and Figure 21 shows the Maximum Stress Index, which is defined as the ratio of the maximum stress at any level of aging to the maximum stress for the RTFO residue. It is clear in the plots that the percent recovery is driven by the maximum stress in a given blend, but not necessarily the relative change in maximum stress between aging levels for the control and blends 3 and 4; it is hypothesized that the stress sensitivity of the polymer network is causing the apparent reduction in elastic response. For example, the greatest drop in elastic recovery occurs in the control blend, which exhibited the highest maximum stress, but the lowest maximum stress index.

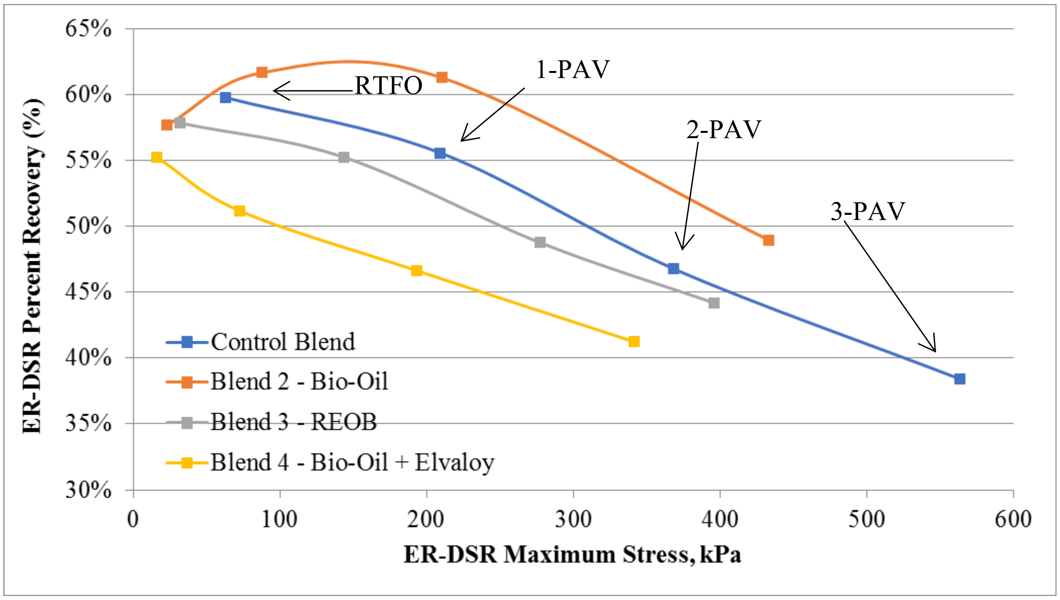


Figure 20. ER-DSR Percent Recovery at 19°C vs. Maximum Stress observed during the test.

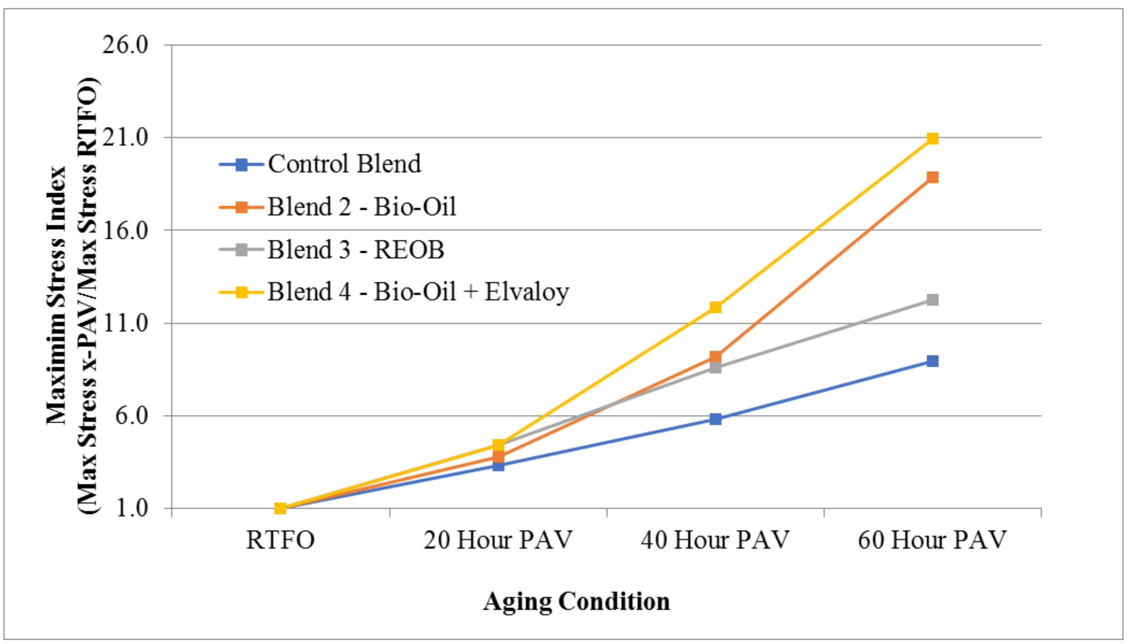


Figure 21. ER-DSR Maximum Stress Index at 19°C.

It should be noted that Blend 2 seems to deviate from this behavior, at least for relatively low stress levels. Blend 2 exhibited a similar increase in maximum stress between aging levels as Blend 4 but exhibited a higher ER-DSR Ratio. Since this blend contains the same base asphalt as Blends 3 and 4, the same oil was used for Blend 2 as in Blend 4, and the same polymer was used in Blend 2 as in Blend 3, it could be concluded that an interaction between the polymer network and oil modification is causing the behavior shown in Figure 20 for Blend 2. Nevertheless, this finding indicates that although general trends can be identified (e.g. elastic recovery generally decreases with increasing stress), actual testing of the blended materials is required to verify material behavior.

In the MSCR test, the %R parameter is observed to decrease with an increase in applied stress, which is the same behavior observed for these blends. In application, if strain recovery is determined to be a critical performance-related or acceptance property, there are two considerations that need to be addressed. The first is the temperature range at which strain recovery is determined to be a performance indicator (low, intermediate, or high pavement temperature ranges, for example). The second is whether pavement distress at that temperature range is stress controlled or strain controlled. At high temperature, for example, permanent deformation (rutting) is the primary distress mode. Rutting is a stress-controlled (creep) phenomenon, so testing strain recovery using creep loading is appropriate.

Binder Yield Energy Test (AASTHTO TP 123)

Based on the findings from Task 1, it was expected that the trends for Yield Energy, Strain at Maximum Stress, and Maximum Stress parameters derived from the BYET with PAV aging level for each blend would be linear or near-linear, but that the relative direction of change with aging could depend on the blend formulation. Figure 22 shows an example output of the BYET for two of the four blends at three aging conditions. The effects of aging are clearly observed in the figure for Strain at Peak Stress and Maximum Stress, demonstrating the efficacy of the BYET test in evaluating changes due to aging.

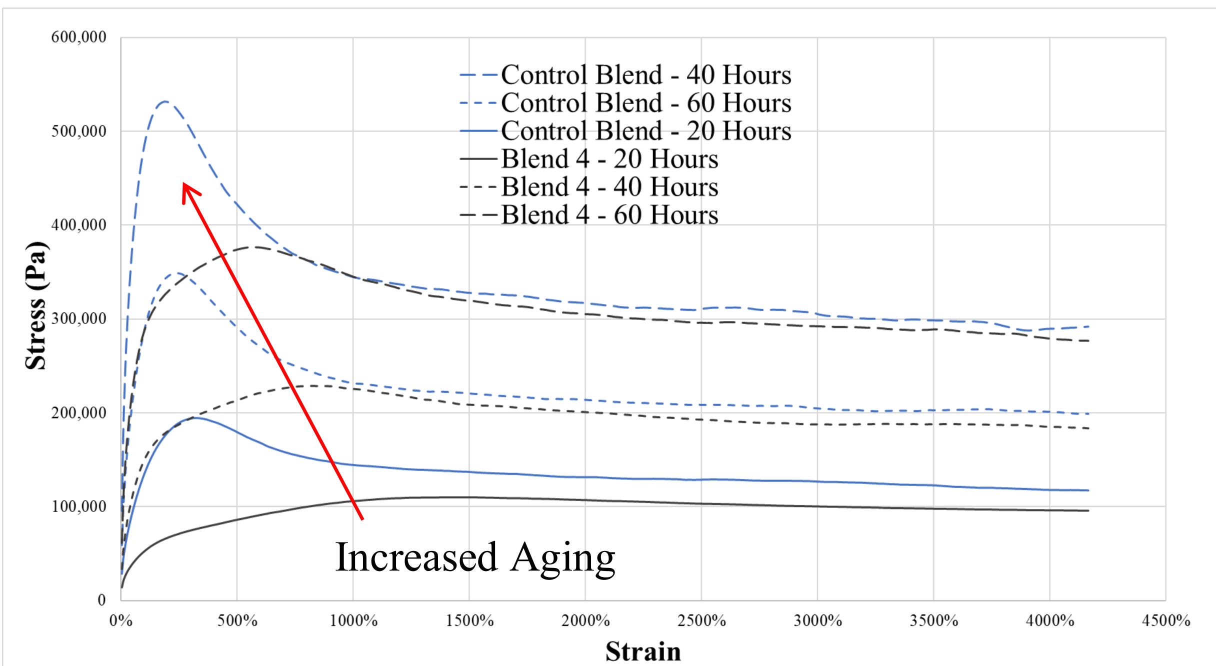


Figure 22. Example BYET data for two blends at three aging conditions.

Figure 23 shows indices derived for the BYET parameters for the four blends; each of the indices is the value of that parameter at any aging condition relative to the 20-hour PAV condition. For all three parameters, the direction of change is the same for all blends and the magnitude of change is dependent on the blend formulation. Interestingly, the ranking of the blends changes between the parameters, with Blend 2 – Bio Oil showing the greatest increase in Yield Energy for all aging conditions, but the second lowest Strain at Maximum Stress among the blends.

The Strain at Maximum Stress parameter has been shown to be a direct replacement to the ductility test. Since it is generally expected that asphalt binders would lose ductility with long term aging (embrittlement), it is expected the Strain at Maximum Stress would also decrease. This is confirmed with all binder blends, and a reduction in this parameter of between 25% and 60% relative to the 20-hour PAV condition is observed, indicating a significant dependency on binder formulation. As will be discussed in later sections of this report, this highlights the importance of testing at more than one level of aging to determine a rate of change due to aging.

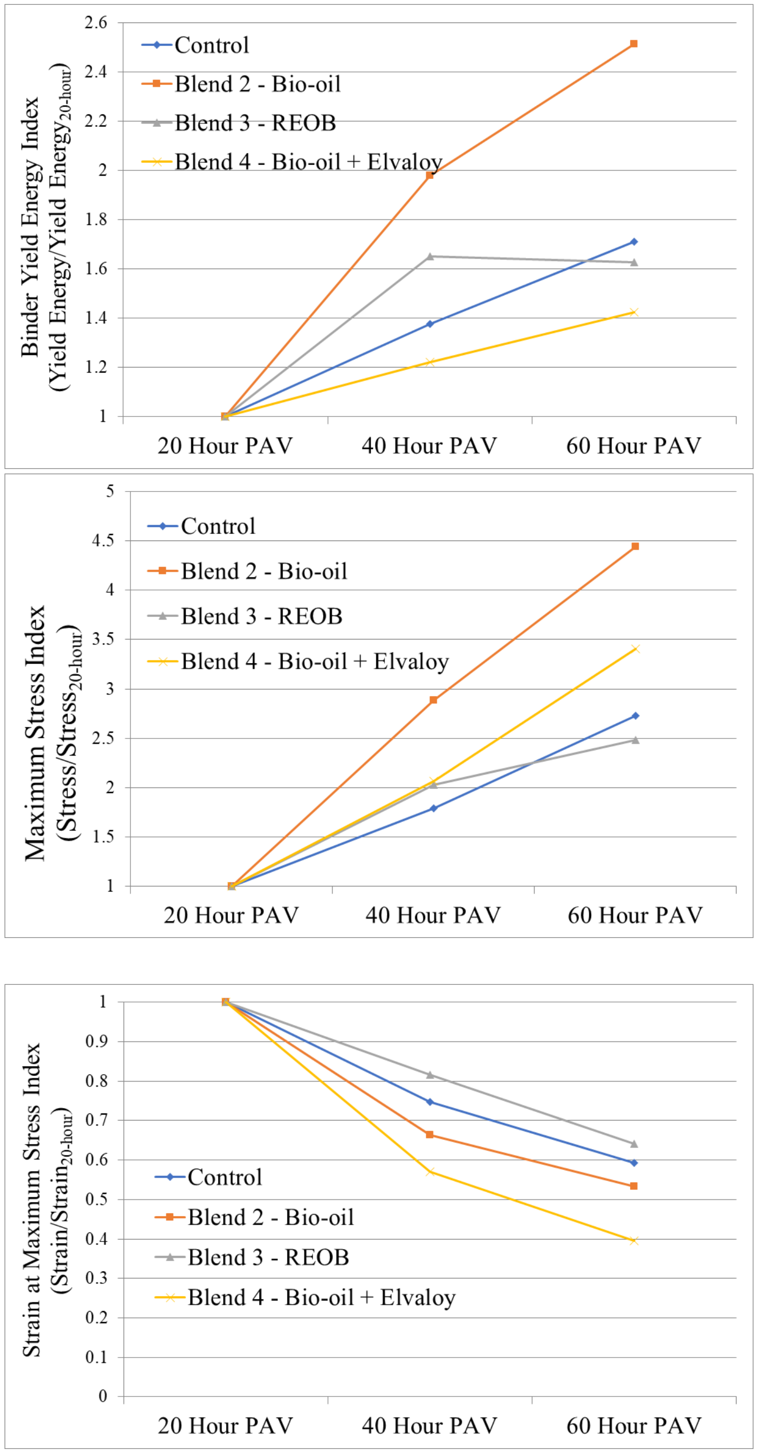


Figure 23. BYET aging indices for the four blends.

The binder Yield Energy parameter increases uniformly for three of the four blends. For Blend 3 – REOB, there appears to be a parabolic shape to the Yield Energy trend. Since higher Yield Energy is considered beneficial, these results are somewhat confusing. As expected, the Maximum Stress increases uniformly with aging since the BYET is strain rate-controlled tests and asphalt binder is known to become stiffer with aging. Again, the relative change and ranking is dependent on the binder formulation.

Linear Amplitude Sweep Test

It was demonstrated in Task 1 that the LAS is sensitive to constituent binder properties for blends of two binders although the direction of change for Cycles to Failure is not always consistent. Nevertheless, the Fatigue Law "B" parameter, which is conceptually the slope of the cycles to failure versus applied strain curve, was shown to logically become more negative with increasing binder replacement levels. Since parameter B is characteristically a negative number, a reduction in fatigue life with increased strain is expected, which confirms the expectation that increased recycled materials content reduces the fatigue life of the blended binder.

The fatigue law B parameter was also shown to correlate very well with the Flexibility Index calculated from the Semi-Circular Bend (SCB) test proposed as an indicator of fatigue resistance of mixtures. In a recent study by the WHRP program of Wisconsin DOT (WHRP 17-04 study), which is still underway, the results of aging two different mixtures produced with binders of the PG 58S-28 and PG 58H-28 have shown the trends in Figure 24. The results shown, although are limited, indicate that increasing negative slope (B) directly correlates with decreasing flexibility index (FI) values. This makes sense since lower FI has been shown to relate to more fatigue cracking in the field and increasingly negative values of "B" is recognized to show less cycles to failure with increasing strain in binders.

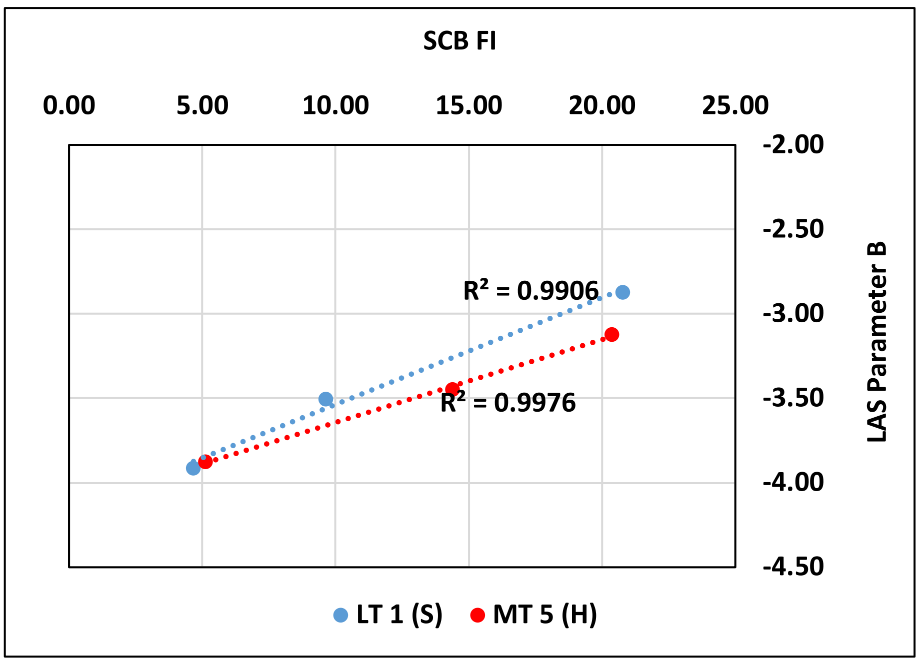


Figure 24. Correlations between mixture Flexibility Index values and LAS "B" parameter for two mix designs.

The fatigue law B parameter for the binder blends with oils in Task 2 at three aging conditions is shown in Figure 25. An index is again used to normalize the data; since "B" is reported as negative, an increasing B parameter index indicates the parameter is becoming more negative with increased aging as expected. Figure 25 indicates that the rate of change in the B parameter is nearly linear with increased aging, but the rate is dependent on the binder blend. For the blends tested, Blend 2 – Bio Oil shows the highest rate and magnitude of change for the B parameter, while the Control Blend and the Blend with REOB show the lowest. The nearly linear relationship suggests evaluating the B parameter at two levels of aging is sufficient for prediction at other aging levels.

The B parameter changes between 127% and 142% for the binder blends relative to the 20-hour PAV sample, which is very similar to the magnitude of change observed for this parameter in Task 1 when blending with the field RAP materials; for example, the B parameter was observed to change 147% between 0% and 60% RAP binder replacement for the Kansas RAP. It is therefore concluded that the B parameter could be used to evaluate the net effect of using RAM and extended aging on blended binder intermediate properties.

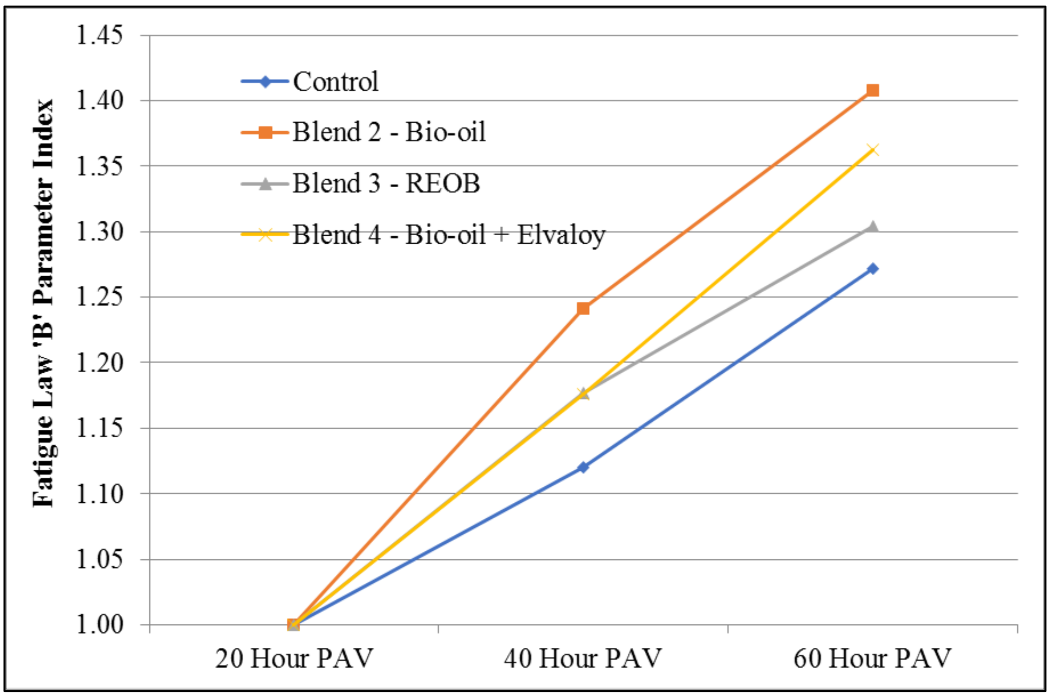


Figure 25. Fatigue Law "B" Parameter Index for four binder blends at 19°C.

Bending Beam Rheometer Test

The effects of low temperature binder modification on pavement performance continues to be a significant topic of ongoing research, with both State and National level research efforts evaluating materials used and methods to characterize these binders. One parameter that has been linked to low temperature cracking resistance of asphalt binders is the ΔT_c parameter (pronounced "delta tee see"); ΔT_c is defined as the difference in degrees Celsius between the BBR Stiffness (S(60)) critical temperature and the BBR m-value critical temperature. The critical temperature is the temperature at which the specification limits (300 MPa for stiffness and 0.300 for m-value) are met by a given binder (also called "continuous" or "true" grade). A more negative ΔT_c is indicative of an asphalt binder that has relatively low stiffness value, thus the S(60) critical temperature is very low as compared to the m(60) critical temperature. Such binder is therefore strongly "m-value controlled". Binders with a highly negative ΔT_c

have been implicated in a few projects with high rates of cracking. Although a universally accepted limit on ΔT_c has not been proposed, a minimum ΔT_c of -5.0 °C has been suggested in literature (Anderson, et al., 2011; Bennert, 2015).

In addition to the ΔT_c parameter, several research studies have called into question the ability of the current 20-hour PAV procedure to capture long term cracking performance of asphalt binders. Several studies have proposed using extended aging times (such as 40 hours or 60 hours) as a more appropriate predictor of performance. Since it is not feasible to directly correlate a given amount of time in the PAV with a set number of years in service, a better approach for research and evaluation of materials could be looking at rates of change between different PAV aging intervals (i.e. testing at several aging levels). In this study the S(60) and m(60) critical temperatures and ΔT_c parameter was measured at three aging intervals (20-hour, 40-hour, and 60-hour in the PAV).

The binder blends in this study were all designed to have approximately equal effective low temperature continuous grades. However, as shown in Figure 26, they exhibit varying critical temperatures for S(60) and m(60). For low temperature stiffness, the control and Blends 2 and 4 exhibit very similar rates of change in S(60) with increased aging. The binder produced with REOB shows a minimum S(60) critical temperature that is significantly lower (3 to 5 degrees) than the three other binder blends, but the highest absolute change in S(60) between the aging levels (3.1°C). The same binder, however, shows the highest m(60) critical temperature that barely meets the PG 58-34 grade. Interestingly, Blends 2 and 4, each containing bio-oil, showed the lowest rate of change in m(60). The control blend exhibited the highest absolute change in m(60) of 11.1°C, which is over double the change in m(60) for Blend 4 (5.0°C).

Based on the results shown in Figure 26, it is clear that effect of modifiers on changing the S(60) and m(60) values, and the aging susceptibility of binder blends could be significantly affected by the types of modifiers used. REOB, for example, appears to have a pronounced effect on lowering the stiffness S(60), but less of an effect on increasing the m-value. In contrast, the bio-oil appears to effect stiffness and m-value at approximately equal rates with respect to lowering the S(60) value or increasing the m(60) values. The control blend, which is a refinery produced -34 base asphalt shows relatively low susceptibility to aging in terms of stiffness critical temperature, but the highest relative change in m-value critical temperature. It is therefore apparent that both the base asphalt properties and the modification technology (if used) influence low temperature aging susceptibility and possibly performance. The variation in the aging rates also provides the basis for recommending that aging rates, rather than aging to a single given level in the PAV is required to estimate effects of oil modifications on binder properties. Higher aging rates such as seen in the control blend and the blend with the REOB used cannot be assumed beneficial.

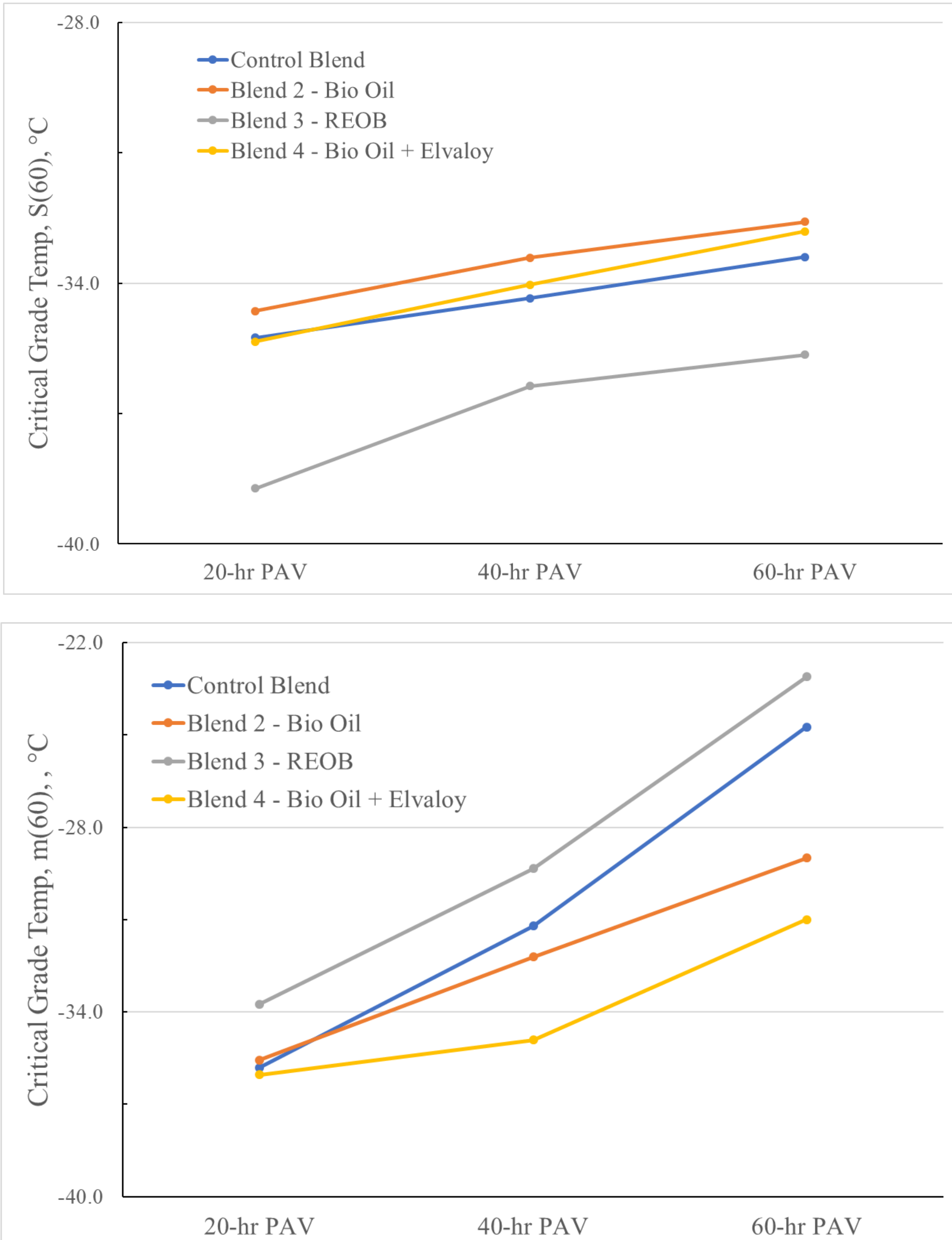


Figure 26. Relative change in low temperature stiffness critical temperature (top) and m-value critical temperature (bottom) at three aging conditions.

Figure 27 is provided to show the relative changes in critical temperatures of S(60) and m(60) with each step of aging (20 to 40 hours in the PAV and 40 to 60 hours in the PAV). The results clearly show that the changes for m(60) values are much greater than the changes for the S(60) values. In addition, the changes between 40 and 60 hours are much more pronounced for the m(60) than those for the 20 and 40 hours of PAV. This is an important finding as it indicates that effects of extended aging are not linear and cannot be captured by limiting the PAV to 40 hours as it is being proposed at the National level. This is certainly a limited dataset that needs further validation.

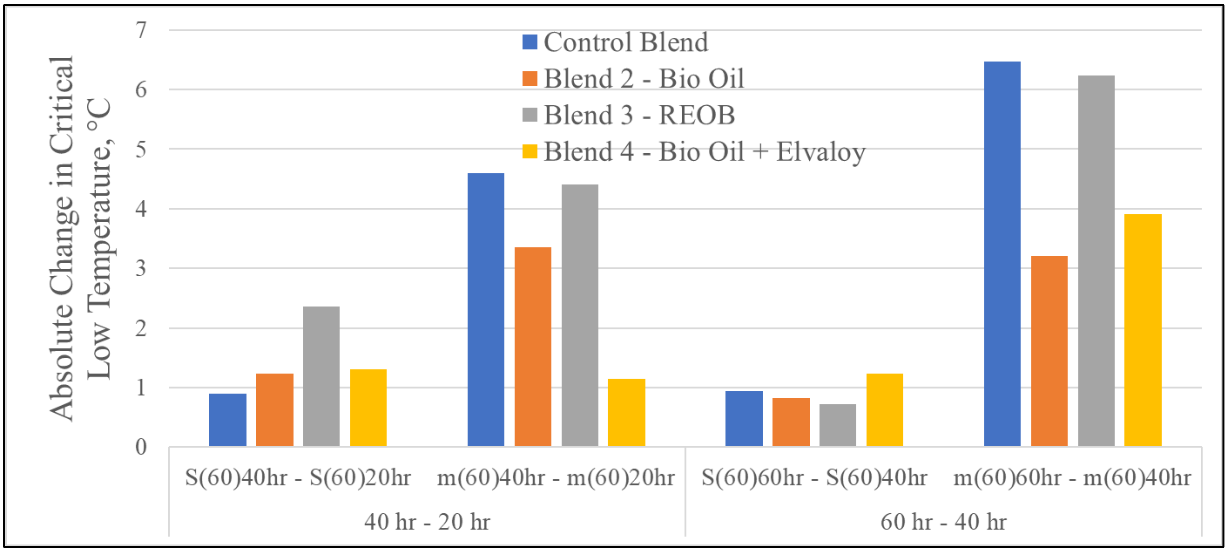


Figure 27. Absolute change in low temperature stiffness critical temperature and m-value critical temperature between 20-hour and 40-hour PAV aging and 40-hour and 60-hour PAV aging.

Figure 28 shows the ΔT_c of the four binder blends at the same three levels of aging. Three of the four binder blends show positive ΔT_c values, which means they are stiffness-controlled at the 20-hour PAV aging condition. They are, however, all m-value controlled at the 60-hour PAV condition (negative ΔT_c values). Blend 3, which contains the recycled/re-refined oil (REOB), shows by far the lowest ΔT_c for all three aging conditions, and even at the 20-hour condition exhibited a ΔT_c of approximately -5°C. Interestingly, if -5°C is accepted as the limit on ΔT_c, the control blend drops below this value between the 40-hour and 60-hour conditions; this raises an important question regarding the aging time required in the PAV to assess performance. Perhaps a more novel way to evaluate ΔT_c rather than specifying a set aging time is to use a rate or magnitude of change.

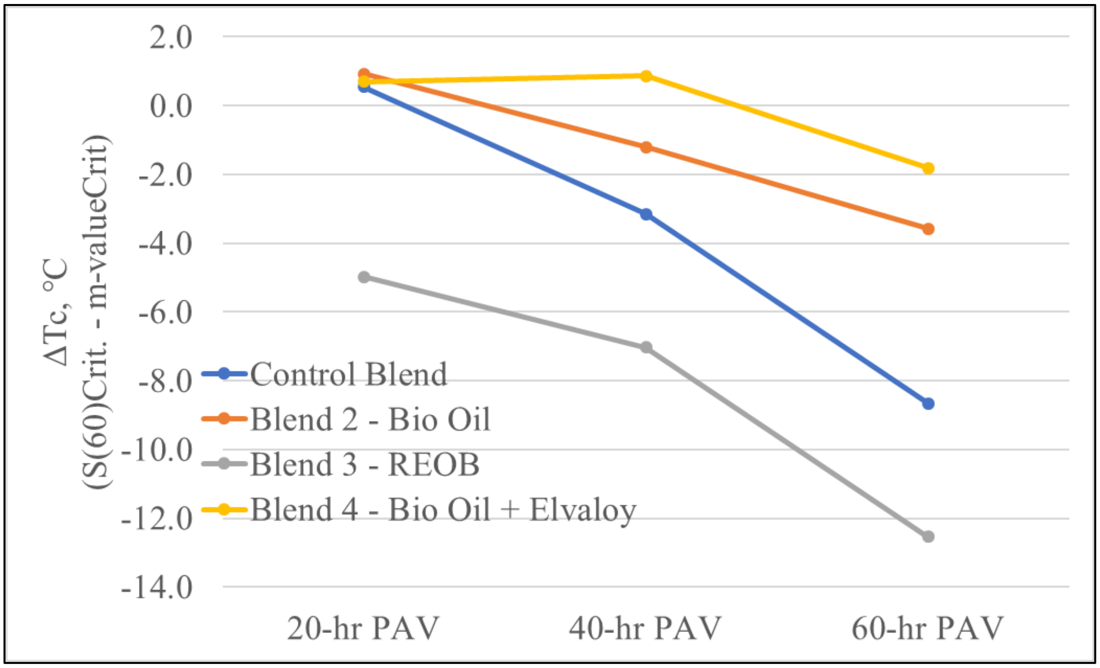


Figure 28. ΔTc for binder blends at three aging conditions.

Figure 29 shows the relative absolute change in ΔT_c between the aging conditions (20 to 40 hours, 40 to 60 hours). Although the value of ΔT_c for Blend 3 is lowest for all three aging conditions, the change in ΔT_c between the 20-hour and 40-hour PAV conditions is greatest for the control blend, and the greatest overall change between 20 hours and 60 hours is also for the control blend, for which the ΔT_c dropped over 9 °C between 20 hours and 60 hours. Blends 2 and 4 show the least reduction in ΔT_c over the aging intervals tested, both of which contain bio-oil as the low temperature modifier.

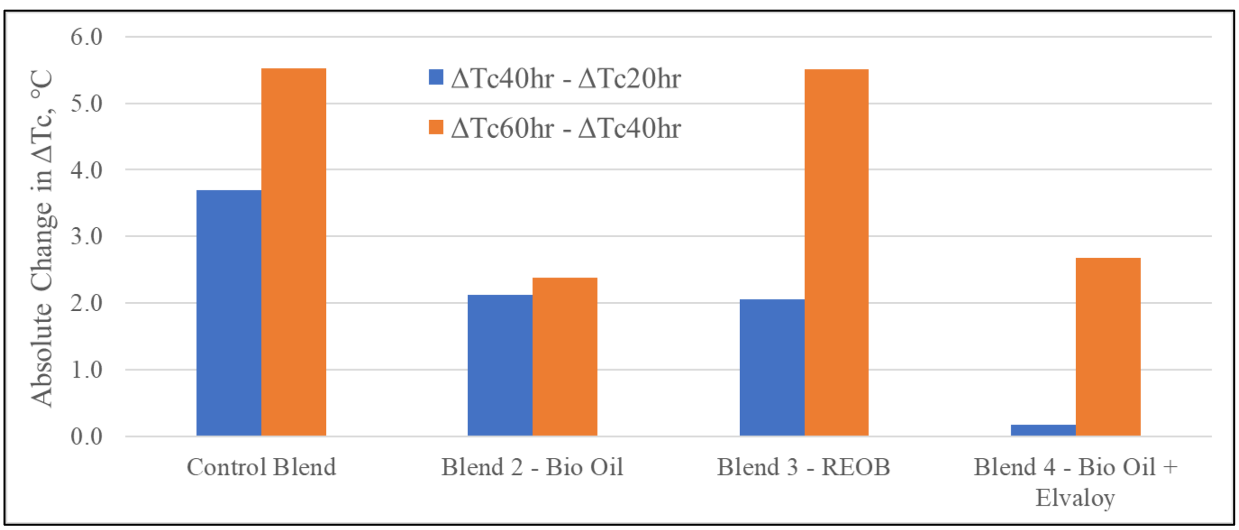


Figure 29. Absolute change in ΔTc for binder blends at three aging conditions.

A noteworthy observation can be made regarding the comparison between the REOB blend and the Control Blend. The REOB blend had the lowest ΔT_c at 20-hour PAV because of the effect of REOB on reducing the low temperature stiffness is much higher than on increasing the m-value; although the ΔT_c is viewed as 'failing' at this aging condition, one would expect that the binder would still perform well at low temperature based on mechanical response since both the S(60) and m(60) critical temperatures are both meeting the required grade temperature. Since the critical stiffness is very low, one would expect very little stress to build in this sample upon cooling, minimizing the importance of a high m-value required for relaxation of stresses built up. The control blend, by contrast, is stiffness controlled at 20-hour PAV but because of the m-value aging susceptibility of this blend, the ΔT_c decreases at a higher rate than the REOB blend, meaning the blend is becoming m-controlled after extended PAV aging. A higher stiffness for this binder would dictate that stresses would build at a faster rate, necessitating a higher m-value to resist cracking. It is therefore recommended that caution be used when interpreting the ΔT_c parameter alone without also referencing the S(60) and m(60) of the binder.

IV. Conclusions and Recommendations

The principal objective of the TPF-5(302) pooled fund study is to provide essential information to state and local agencies to support standardization of PG+ specifications by identifying those PG+ test methods that are reproducible and show promise in simulating actual field performance. The research extension effort reported in this report investigates the use of PG+ procedures to evaluate the effects of the RAP and RAS on binder performance, as well as the effects of low temperature modification technologies (softening oils) on binder performance. The conclusions and recommendations related to this research extension report are summarized below.

A. Task #1: Evaluating the Effects of RAP/RAS on PG+ and Developmental Test Blending Charts

The purpose of Task 1 is to investigate the effects of blending between Recycled Asphalt Materials (RAM) and polymer modified virgin binders on selected PG+ and developmental test methods proposed in earlier phases of this research project. The work plan for this task was divided into two subtasks: Subtask 1.1: Evaluation of selected PG+ and developmental methods using *artificially produced RAM* materials and Subtask 1.2: Evaluation of the same PG+ and developmental methods using field RAM supplied by member states. The following major findings and conclusions are stated, organized by test method:

- **MSCR Parameters Blending Charts**
    - The relationship between Jnr at 3.2 kPa and binder replacement (% RAM) is nearly linear on a log-linear scale, indicating an exponential relationship between Jnr and % RAM. The trend is shown to generally decrease in Jnr with increasing % RAM, depending on the properties of the recycled asphalt. However, in one instance the Jnr increased with increased % RAM; the increase was not great enough to cause a change in the traffic grade of the resulting binder based on AASHTO M332 limits.
    - The change in MSCR %R with increased % RAM cannot be assumed linear and is affected by the %R and Jnr of the constituent binders, and the ratio at which they are blended. In two of the three field RAP materials, binder replacement levels of 20% resulted in a change of the traffic grade from V to H for the resultant binder based on %R limits used by the Combined State Binder Group (CSBG) specifications.
    - The MSCR %R parameter is related to the Jnr value of a given binder or binder blend as it is observed that binders containing no polymer can still exhibit MSCR %R values as high as 50% when the Jnr is very low (less than 0.10 kPa^{-1} in this study). Therefore, the perception that only polymers can increase %R is not supported by the data collected in this study. Aging will increase stiffness, reduce Jnr and can result in a significant increase in %R for unmodified or modified binders alike.
    - Small amounts (5% binder replacement) of RAS binder reduced the Jnr and increased the %R more than when RAP alone was used. However, in no case was the reduction in Jnr or increase in %R significant enough to change the traffic grade of the resultant binder based on M332 and CSBG limits and tolerances.

- Because of the non-linear relationships for the %R parameter, the effect of binder replacement on resultant binder Jnr and %R should be measured directly on the blends of RAM and fresh binders. Agencies are advised that information about the recycled asphalt binder source and aging history must be known and materials must be directly tested at the project blending ratios.

- **ER-DSR at Intermediate Temperatures Blending Charts**
  - For all binder blends tested in this study, the ER-DSR recovery measured at 25°C or 19°C decreased in a nearly linear fashion with increased binder replacement levels. The relative change (rate and magnitude) is dependent on the ER-DSR properties of the constituent materials.
  - In at least two blends, the polymer content of the sample was zero, yet the ER-DSR recovery was greater than zero; it is well known that unmodified binders can exhibit varying levels of elastic recovery at intermediate temperatures due to the molecular bonding at such temperatures. This is evident by the decreasing phase angle measured in the PG grading system.
  - Small amounts of RAS binder had minimal effect on the resultant ER-DSR of the binder blends relative to RAP only blends.
  - Agencies wishing to implement the ER-DSR recovery parameter as an indicator of polymer presence and/or loading level are advised that both polymer content/type as well as the viscoelastic nature of aged asphalt binder can affect ER-DSR values. Thus, it is erroneous to assume that at intermediate temperatures all recovery comes from polymers. In other words, RAM materials could have high levels of ER even when they have no polymers in them.
  - ER-DSR values for Artificial RAP used in this study were always lower than the fresh binders used, which confirms that aging will decrease the ER-DSR values.

- **BYET Strength and Ductility Blending Charts**
  - The trends of changes in Binder Yield Energy, Strain at Maximum Stress, and Maximum Stress parameters with binder replacement are found to be linear although the coefficient of determination (R^2) for the linear fit is lower for the field materials.
  - The direction of change between Yield Energy and binder replacement is shown to be dependent on the constituent binders. However, Maximum Stress and yield energy increased for all blends while the Strain at Peak Stress decreased for all blends with increasing binder replacement, as expected. The trends therefore indicate that the binders get stronger but less ductile with increase in %RAM.
  - The Strain at Peak Stress parameter, which has been demonstrated to be a good replacement to the ductility test, exhibits a very clear and logical linearly decreasing trend with increased binder replacement levels.
  - Blends containing small amounts of RAS binder showed significant and mostly detrimental differences from RAP only blends, indicating a need to directly test the blended binders when RAS is added.

    - Agencies wishing to implement Strain at Peak Stress from the BYET (AASHTO TP123) to replace place ductility are advised to determine a minimum strain at peak stress based on the binders currently in use in their region and their ductility values. It is also recommended to increase this minimum by a factor of safety based on the desired reliability of the criteria.

- **LAS Fatigue Parameters Blending Charts**
    - Cycles to Failure at 2.5% Strain is shown to be changing mostly linearly with binder replacement levels with mixed trends of increase or decrease with increased binder replacement. The net effect of adding recycled binder is dependent on the source of the recycled binder, as would be expected.
    - Strain at peak stress parameter is also shown to almost always decrease nearly linear with binder replacement. The rates of reduction are again dependent on the RAM source.
    - The Fatigue Law 'B Parameter' exhibits a strongly linear trend between increasing binder replacement and increasing B parameter (more negative), which agrees with the expectation that increased recycled materials content changes the fatigue life of the blended binder and could reduce the fatigue life significantly at high strains.
    - Overall, it is concluded that the LAS test is sensitive to constituent binder properties and blending ratios, and that the "B" parameter shows a clear relationship with increased RAM percentage. However, the trends observed between blend percentage and the fatigue life and strain at maximum stress cannot be assumed linear in all instances. This implies that direct testing of the blended materials at the desired ratios is necessary to accurately characterize the LAS parameters for the blend.
    - The addition of RAS binder produced varying and at times counterintuitive results for the cycles to failure parameter. However, the B parameter increased with the addition of RAS, which is expected. For one RAP source the addition of RAS binder is found to affect the B parameter at a rate approximately 20 times more detrimental than RAP binder alone.

The results of Task 1 indicate that resultant (blended) binder properties are dependent on the constituent binder properties and percentage of RAM added. Linear relationships between binder replacement and changes in critical parameters cannot be assumed for all the PG+ test methods used in this study, even for relatively low (20%) levels of binder replacement in some instances.

It is therefore advised that if properties of the blended binder are desired, actual testing of the blended binder at the intended blend percentages is necessary, particularly for polymer modified or unknown sources of binder. Also note that blending charts shown in this study are based on 100% blending efficiency between the constituent binders; in practice blending is likely less than 100% and is dependent on time and temperature.

The effect of blending aged binders are shown to significantly reduce elastic recovery and strain at maximum stress measured according to AASHTO TP123. They are also shown to reduce fatigue life as measured by the "B" parameter in the AASHTO TP101. It is recommended that the "B" parameter be used as an indicator of effects of aged binders as this parameter is found to correlate very well with the mixture

Flexibility Index (FI) test. The "B" parameter is a very simple measure using the standard 8-mm plate and can be done as a simple extension of the current G*sin(δ) test at intermediate temperatures.

B. Task #2: Effects of Low Temperature Modification Technologies (oils) on PG+ and Developmental Test Methods

The purpose of Task 2 is to evaluate the effects of extended aging on low temperature binder modification technologies as determined by properties measured by select PG+ and developmental test methods. Four binders of the PG 58-34 grade were tested, including binders formulated with the use of softening oils (Bio-oil and REOB oil) and select polymers. Each of the binders were tested after 20-hours, 40-hours, and 60-hours PAV to simulate extended oxidative aging. Based on the analysis of the results, the following major findings and conclusions are stated:

- **MSCR Parameters Change with Extended Aging**
    - Jnr decreases with increased aging in an exponential fashion for all modifiers. The aging rates (slope of fitted line) are highly dependent on modifiers or formulation used. The control blend (which is directly produced in a refinery) shows the greatest reduction in Jnr and Blend 4 – Bio Oil + Elvaloy exhibits the least Jnr reduction with aging.
    - Results of %R show values increase at a decreasing rate with aging for all binders with the magnitude of increase dependent on the binder formulation.
    - Findings indicate that %R for a given binder is related to the Jnr of the binder. The spread in the data indicates that this phenomenon is blend dependent, so changes in the polymer, oil additive, base asphalt, and additive amount may change the effects of, but do not change the overall trend of, increasing %R with aging. The results are in good agreement with the MSCR analysis presented in earlier phases of this pooled fund project.
    - The Jnr %Diff parameter decreases at the 20-hour condition then increases again for the 40- and 60-hour conditions, with the magnitude of change dependent on the blend. The reasoning for this trend is unclear, although the utility of this parameter as an acceptance criterion or performance predictor is called into question in earlier phases of this study.
    - Due to the high sensitivity of Jnr and % R to oxidative aging, agencies should consider the importance of thermal history when testing binders for qualification and acceptance. Similarly, testing of mixtures sampled from the field should take into account the effects field aging may have on Jnr and resulting %R. Note that the controlling MSCR parameter for the blends tested in this study was %R (30%, minimum for 'H'), these findings show that for all blends except Blend 4, the change in %R between the RTFO and 20 hour PAV condition is enough to effectively make these binders change from 'H' grade to 'V', despite not changing composition.
- **ER-DSR at Intermediate Temperature Change with Extended Aging**
    - In general, the ER-DSR recovery decreases with aging while the stress required to achieve the maximum strain increases for all binders. The bio-oil blend interestingly shows a slight increase between the RTFO and 20-hour PAV condition, almost no change between the 20-hour PAV and 40-hour PAV condition, and a decrease between the 40-hour and 60-

hour PAV condition. The results show significant differences in effect of aging on the ER-DSR parameters among the blends tested.

- The ER-DSR recovery is related to the maximum stress in each blend; it is hypothesized that the stress sensitivity of the polymer network is causing the apparent reduction in elastic response with aging. For example, the greatest drop in elastic recovery occurs in the control blend, which exhibited the highest maximum stress, but the lowest maximum stress change with aging.
- Although general trends can be identified, actual testing of the materials is required to verify material behavior.
- Contrasting the results of this test (strain controlled) with the MSCR test (stress controlled), agencies wishing to implement an elastic recovery-type test in their specification should consider not only the temperature range that strain recovery is determined to be a performance indicator (low, intermediate, or high pavement temperature ranges, for example), but also whether pavement distress at that temperature range is stress controlled or strain controlled. For strain-controlled distresses, ER-DSR should be used, while for stress-controlled distresses, MSCR type of test should be used. Stress or strain level used in testing should be related to the level of loading expected and the level of pavement deformation and stiffness in a specific project.

- **BYET Parameters at Intermediate Temperatures and Changes with Extended Aging**
  - The BYET results are highly sensitive to formulation of the blends and to long term aging. Therefore, BYET as described in the AASHTO TP123 is shown to be an effective tool for evaluating the effects of long term aging on the intermediate temperature properties of the binder blends.
  - The trends for Strain at Maximum Stress and Maximum Stress are logical and a near linear trend is observed for all binder blends, indicating testing at two aging levels is sufficient to predict binder behavior.
  - Since Strain at Maximum Stress is a candidate to replace ductility, the ease of running the BYET makes it particularly well suited for Agencies to investigate the aging susceptibility and embrittlement of binder formulations in their respective regions.
- **LAS Fatigue Parameters Changes with Extended Aging**
  - The Fatigue Law B parameter for the binder blends at three aging conditions exhibits a logical and nearly linear relationship with aging for all blends. The B parameter becomes more negative with increased aging.
  - The rate and magnitude of change in B is dependent on the binder blend formulation. For the blends tested, *Blend 2 – Bio Oil shows the highest rate and magnitude of change for the B parameter*, while the Control Blend shows the lowest. The nearly linear relationship suggests evaluating the B parameter at two levels of aging is sufficient for prediction at other aging levels.
  - The B parameter changes between about 127% and 142% for the binder blends relative to the 20-hour PAV sample, which is very similar to the magnitude of change observed for this parameter in Task 1 when blending with the field RAP materials; for example, the

B parameter was observed to change 147% between 0% and 60% RAP binder replacement for the Kansas RAP. It is therefore concluded that the B parameter could be used to evaluate the net effect of using RAM and extended aging on blended binder intermediate properties.

- **BBR Parameters at Low Temperatures and Changes with Extended Aging**
  - Although the binder blends in this study were all designed to have approximately equal effective low temperature continuous grades of PG 58-34, they exhibit widely different extended aging susceptibilities, highlighting the importance of testing at more than one level of aging.
  - For low temperature stiffness, the Control and Blends with Bio-oil exhibit very similar rates of change in S(60) with increased aging. The REOB blend exhibits a considerably lower S(60) critical temperatures and values relative to the other blends but exhibits the highest rate and absolute change in S(60) between the aging levels of 20-hour to 40 -hour, then the rate of change becomes similar to other blends between 40 and 60 hours. For m-value, the REOB blend exhibited the highest m(60) critical temperatures (lowest values of m(60)) for all aging conditions, and along with the control blend a relatively high rate of change. Interestingly, Blends 2 and 4, both containing bio-oil, showed the lowest rate of change in m(60). Based on these findings, it is clear that the mechanism by which low temperature modifiers achieve a target low temperature grade is modifier dependent, and so is the aging susceptibility. Effect of aging on rate of change of S(60) and m(60) critical temperatures are not consistent for a given oil used. Also effect of aging is not proportional for the number of hours in the PAV; change in critical temperatures are much more for the m(60) parameter between 40 and 60 hours of PAV as compared to the changes between 20 and 40 hours. Therefore, extended aging should be thoughtfully considered in relationship to the life of pavement and or age of RAM material used.
  - The data present clearly shows that the change in ΔT_c due to aging can be influenced by the base asphalt used as well as the modifier, indicating that it may not be the modification used that dictates low temperature performance, as the base asphalt susceptibility to extended aging may also be implicated.
  - Although Blend 3 produced with REOB exhibited the lowest absolute ΔTc after aging, the rate of change in ΔTc between the 20hour and 40-hour PAV conditions was greatest for the Control Blend. The rate between the 40-hour and 60-hour PAV conditions was almost equal to the control blend. For the control blend the ΔTc dropped over 9 °C between 20-hour and 60-hour PAV. Blends 2 and 4 show the least reduction in ΔT_c over the aging intervals tested, both of which contain bio-oil as the low temperature modifier.
  - These BBR test findings indicate that using low temperature continuous grade or ΔT_c parameter as the sole design parameter at low temperature may be misleading, as different modification technologies and base asphalts show widely different extended aging susceptibilities. It is recommended that agencies use the ΔTc parameter and absolute (since ΔTc can be positive or negative) change in ΔTc at more than one aging condition, and more extended aging (60 hours or more) to qualify low temperature modification technologies.

Findings from Task 2 indicate that characterizing modified asphalt binders using a single level of aging according to M320/M332 may be misleading. Results indicate that the magnitude and rate of binder aging is dependent on the base asphalt and modification technologies used for all temperature ranges, and that extended aging beyond 20 hours of PAV conditioning show significantly varying performance.

Aging is found to improve (reduce) Jnr parameter and thus is a positive effect. However, aging reduces elastic recovery at intermediate temperatures, decreases strain at maximum applied stress (ductility), and more importantly negatively affects fatigue resistance related parameters.

However, testing at one level of aging may be misleading as it is shown that certain binder blends maintain comparatively favorable levels of performance for lower levels of aging, but quickly deteriorate with extended aging. Agencies are advised that for modification technologies that do not have a history of performance, or new asphalt materials entering the marketplace, evaluation of binder properties be conducted at several extended levels of aging and compared to known high-performing binders. This recommendation is particularly relevant for intermediate and low temperature ranges where cracking is expected, and where aging is perceived as determinate of performance.

C. Proposed Research Extension: "Balanced Binder Design"

Results of this work clearly show that different RAM sources can have significantly different properties that can either improve or worsen performance of the blended binder even for relatively small (~20% binder replacement) amounts of RAM. Based on this finding, the commonly used "tiered" approach to using RAM (for example allowing 20% binder replacement without requiring any change to the virgin binder grade) is not advisable. Furthermore, if Agencies wish to allow higher percentages of RAM without sacrificing reliability, a systematic binder design framework must be used.

It is envisaged that such a framework for these can be developed using a "balanced" design approach, in which binder properties controlling critical distresses at different temperature ranges are balanced with one another. For example, it is shown that RAM improves high temperature rutting resistance but reduces fatigue cracking resistance. Therefore, a balance between these critical properties is desired. Such a process might allow agencies/contractors to select an appropriate amount of RAM and/or binder modification to satisfy multiple testing criteria simultaneously. A similar methodology called "Balanced Mixture Design" is used in the design of asphalt mixtures. An example of this approach is shown below using data generated during this project.

Figure 30 compares the blended binder Jnr and the blended binder LAS B parameter for the three RAP sources tested during this study. From the plot, it is clear that a log-linear relationship exists for the combined data. It is hypothesized that by balancing Jnr and LAS B (in this example) performance, the amount of each RAP source can be determined. For example, if it is desired to have a Jnr value below 0.5 kPa^{-1} to resist extremely ('E') heavy traffic, but a LAS "B" value greater than -4.25 (arbitrarily chosen for this example) to ensure fatigue crack resistance, widely different results are obtained for the different RAP sources. For the Kansas source, up to approximately 40% RAP binder replacement will satisfy both criteria, with the LAS B parameter limiting. By contrast, the Wisconsin source of RAP actually increases the blended binder Jnr, so even 20% will cause the Jnr limit to be surpassed, while the LAS B parameter is not a consideration for this blend.

Figure 30 could also be used to optimize binder modification. Using the Wisconsin RAP example, designing this virgin binder to have a lower initial Jnr may allow increased RAP usage based on the economics of binder modification vs. binder replacement. It is hypothesized that different base binder additives will shift or distort the curve shown in Figure 30 for all three sources of RAM. Finally, the effects of aging can also be included in such a framework. For example, it was shown that increased aging linearly reduced the LAS B parameter while also reducing the Jnr or shifting the trends in Figure 30 down and to the left.

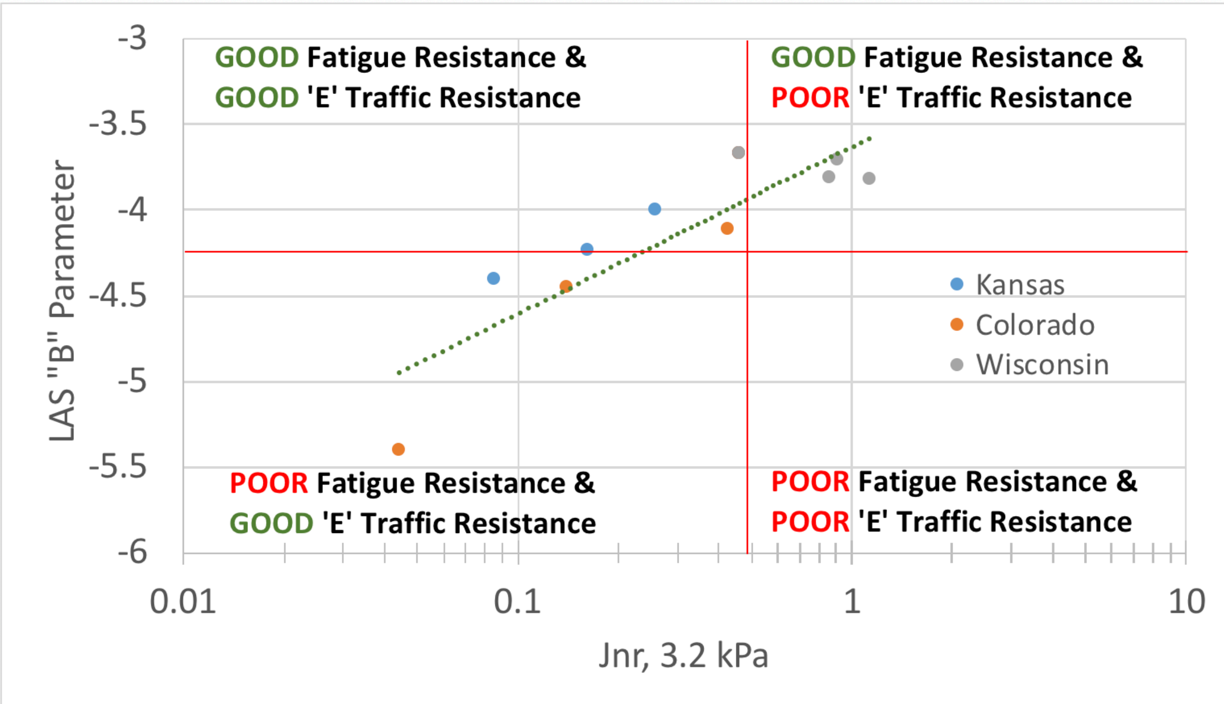


Figure 30. Example "Balanced Binder Design" approach for determining acceptable binder replacement levels and/or modification approaches.

Based on the work conducted during this extension study, this project can be extended using the balanced binder design approach to develop or refine acceptance criteria for the PG+ procedures including the following:

- Refine the MSCR criteria for acceptance of binders used in high RAM mixes.
- Develop new criteria for Elastic Recovery and Ductility using the DSR for binders used in low and high RAM mixes.
- Develop new criteria for binder fatigue using the LAS test for binders used in low and high RAM mixes.
- Develop criteria for evaluating extended PAV aging effects on binders of the PG xx-28 and PG xx-34. These criteria will include specific parameters that could identify the potential of low durability.

V. References

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VI. Appendices

Databases and figures containing the results are available in the folder included with this report named “Databases and Figures”. The files are separated by category, databases or figures, and are named with the corresponding task. The following documents are included:

Task 1:

- Subtask 1.1 Testing Database.xlsx
- Subtask 1.2 Testing Database.xlsx
- Subtask 1.1 Figures.xlsx
- Subtask 1.2 Figures.xlsx

Task 2:

- Task 2 Testing Database.xlsx
- Task 2 Figures.xlsx