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Modified Binder (PG+) Specifications and Quality Control Criteria

Draft Final Report

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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. Differences exist between the PG+ test methods, test conditions, and performance limits being specified among regions, and among states in one region. As a result, these tests are requiring more equipment and significantly more time to quality binders. At the same time, the producers are facing difficulty to satisfy variable criteria when producing and supplying modified binders that can consistently and uniformly meet agency expectations.

The main objectives of this study include: 1) Perform detailed assessment of current PG+ and modified binder quality control procedures in partnering states in terms of reliability, applicability, and relevance to performance and quality of modified asphalt binders. 2) Use a range of modified binders that are representative of the products currently specified by partner states to develop unified test procedures and specification criteria based on products placed in the field. 3) Improve product quality and reliability through ruggedness studies and development of precision and bias statements for selected tests. 4) Introduce consistency to current products supplied by elimination or reduction of differences in modified binder acceptance tests and criteria throughout member states. 5) Validate and establish relevance of suggested PG+ and quality control procedures in terms of mixture performance.

The study results indicate that at this stage there is an interest in changing the PG+ methods to better and more effective tests, but there is also significant interest in keeping the formulation of binders as they are now to reduce the risk of inferior materials. The results are also used to recommend replacing the current PG+ with DSR- based tests that are more technically sound, and that are better related to binders' engineering properties known to impact pavement performance. For high temperature rutting resistance the MSCR-Jnr and % R at 3.2 kPa (AASHTP T350) are recommended, while for intermediate and low temperature cracking performance the DSR-ER and DSR-BYET (AASHTO TP 123) are recommended. Preliminary specification limits and framework are proposed, and continuation of the study to evaluate the blended binders with RAP and RAS is proposed.

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Introduction and Objectives

A. Background

There is no current 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 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 expectations. The intent of this project 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.

From a practical perspective, formal ruggedness testing and statements of bias and repeatability do not exist for many procedure variants and PG+ specifications. A study of test method variability and reliability for promising PG+ tests identified in this project will help reduce binder testing disputes and associated costs during construction. Furthermore, it will help identify purchase specification test procedures that are unacceptable due to high variability and result in greater confidence in quality assurance testing and material compliance.

As a subtask to this project, implementation considerations for the Multiple Stress Creep and Recovery (MSCR) test are offered. The MSCR test is used to characterize the rutting resistance of both unmodified and modified binders. Recently, specification limits were adopted by AASHTO as method M332 as an eventual replacement for current SuperPave guidelines (M320). Conceptually, as a result of implementing the MSCR test State Agencies will be able to select binders based on properties better related to rutting resistance, and with the desired level of elastic response. However, rutting distress may not represent the only critical mode of failure as many pavements fail due to cracking at intermediate and low temperatures. This concern is well recognized in the current SuperPave grading system "PG+" specifications as numerous additional tests in both temperature regimes are required.

Recently, a number of test methods to improve evaluation of materials at intermediate and low temperatures were submitted to the AASHTO Subcommittee on Materials for consideration. Using these tests there is an opportunity to extend the concepts behind the MSCR, namely: (1) a better performance related test, and a test that is (2) capable of evaluating all binder types at the intermediate and low temperature regimes. However, to realize this objective significant efforts are needed in regards to implementation of the MSCR grading criteria and to assess the suitability of newly proposed test methods as agency specification tests for intermediate and low temperature binder properties.

Participation in this pooled fund presents an opportunity for specifying agencies and users to support research on development of specifications and acceptance criteria for modified binders with a focus on test methods that are most related to performance and meet specific needs. The product of this research is a unified modified binder specification developed in cooperation with partner states and User-Producer Groups, delivered in a format that will allow for rapid implementation and deployment.

B. Objectives

Based on the stated needs and goals, the main objectives of this pooled fund research include:

- Perform detailed assessment of current PG+ and modified binder quality control procedures in partnering states in terms of reliability, applicability, and relevance to performance and quality of modified asphalt binders.
- Use a range of modified binders that are representative of the products currently specified by partner states to develop unified test procedures and specification criteria based on products placed in the field.
- Improve product quality and reliability through ruggedness studies and development of precision and bias statements for selected tests.
- Introduce consistency to current products supplied by elimination or reduction of differences in modified binder acceptance tests and criteria throughout member states.
- Validate and establish relevance of suggested PG+ and quality control procedures in terms of mixture performance.

C. Organization of this Report

This report includes a summary of findings for each of the four work areas originally included in the research plan for this pooled fund study:

- Work Area 1: Summary of Current Modified Binder "PG+" Specification and Identification of Promising Characterization Procedures
- Work Area 2: Determination and Validation of Reliability and Applicability of the Selected PG+ Tests
- Work Area 3: Validation of the Specification Using Laboratory Mix and Field Survey Performance Data
- Work Area 4: Identify Opportunities to Integrate Performance Based Acceptance into Current PG+ Procedures

The results collected and analysis for each work area listed above is covered in a separate section of this report. In all work areas supporting documents have been previously completed and submitted to the partner States. These supporting documents are attached as appendices to this report.

Summary of Findings

A. Work Area 1: Summary of Current Modified Binder "PG+" Specification and Identification of Promising Characterization Procedures

Work Area 1 consists of an extensive literature review to identify the PG+ methods currently used throughout the US. In addition, commentary related to the implementation of the MSCR test is included in the scope of Work Area 1. Two deliverables were produced as a result of work completed for Work Area 1: Task Report 1 which covers the literature review and the survey of the partner state agencies, and a white paper summarizing MSCR implementation efforts. The following sections provide a summary of the main findings.

i. Summary of Findings Related to Task Report 1

Task Report 1 presents a review of the literature applicable to the PG+ tests currently specified by the partner states. Table 1 presents a summary of the PG+ methods and limits currently specified by the partner stares (denoted with an 'X' if the particular test is run in the respective state); the test methods listed in bold are those that were extensively evaluated in this project.

Table 1. Summary of PG+ Methods and Limits Used by Partner States

Property		**Test Method**	**Colorado**	**Idaho**	**Kansas**	**Ohio**	**Wisconsin**
Original							
Phase angle	@ Grade Temp.	T315	-	-	-	X (76-80 max)	X (73-79 max)
Specific Gravity	15.6°C	D70	-	-	-	-	X (Report)
Ductility, cm	4°C	D113 T51	X (50 min)	-	-	X (28 min)	-
Toughness and Tenacity	25°C	D5801	X	-	-	X	-
Separation of Polymer, °F		D5976	-	-	X (2 max)	X (10 max)	-
Solubility, %		D5546	-	-	-	X (99 min)	-
Homogeneity (Screen Test)			-	-	-	X	-
Acid or Base Modification		CP-L	X (Pass)	-	-	-	-
RTFO Residue							
Elastic Recovery, %	25°C	T301	X (50 min)	X (50 min)	X (45 min)	X (65 min)	X (60 min)
Ductility	4°C	T51	X (20 min)	-	-	-	-
MSCR		TP70	-	-	-	-	-

A survey of the partner states was conducted to determine the reasoning behind specification of a given test or type of test. Each PG+ test method specified by the partner states was summarized and discussion of the advantages and disadvantages of running said test was presented. Task Report 1, which is attached as Appendix 1, included the following conclusions:

- Phase Angle and Elastic Recovery (T301):
    - Both tests are used as indicators of elastomeric polymers in modified asphalts and while both measures may detect the presence of such modifiers, they have critical shortcomings due to false rejection of some elastomeric additives and lack of correlation to actual performance properties.
    - There is an increasing number of additives that can be used to address different levels of pavement performance that, when used to modify asphalt binders, fail elasticity specifications as measured by these tests.
    - There is no consensus on to the details of the procedure or the limits that should be used in specifications.
    - A DSR-based elastic recovery test described in AASHTO TP123 has shown promise in directly replacing the ductility bath-based elasticity tests.
- Ductility (T51):
    - The ductility test can be misleading due to the extreme change in geometry during the test. Although the test was used as quality indicator in the past for neat asphalts, it cannot provide technically sound engineering properties to compare the quality of different polymer modified asphalts [1].
    - A DSR-based test designed to directly replace the ductility test is part of the AASHTO TP123 standard, called the Binder Yield Energy Test (BYET). The BYET has been shown in the literature to be a more representative method for characterizing true ductility of elastomeric modified binders. The test requires a much smaller sample and keeps the geometry of the sample relatively stable during the test.
- Toughness and Tenacity (D5801):
    - The Toughness and Tenacity test has many limitations including non-representative deformation level, changing specimen geometry, and significant repeatability challenges.
    - Test results are highly sensitive to the addition of certain modifiers [2]. Unfortunately, there are limited correlations relating the change in toughness or tenacity to mixture performance which ultimately limits the overall applicability of this test procedure as a performance indicator.
    - The BYET procedure described in AASHTO TP123 is proposed as a suitable replacement to the Toughness and Tenacity test.

ii. Commentary on Implementation of the Multiple Stress Creep and Recovery

As part of the Work Area 1 effort, commentary on the implementation of the MSCR test and its impact on current binder formulations was planned. Data in support of achieving this objective was provided by the Western States Cooperative Testing Group (WCTG), representing the Rocky Mountains User Producer group; the Combined State Binder Group (CSBG), representing the upper Midwest; the State of Kansas

DOT; and the State of Ohio DOT. Correlations were made between existing methods to measure elastic response in binders produced in these regions to the MSCR Percent Recovery (%R) parameter at 3.2 kPa. In addition, the relationships between %R and Jnr at 3.2 kPa, and performance of mixtures was presented for 13 individual mixtures from different regions in the western part of United States using the Flow Number test. This information is summarized in a white paper distributed to the member states and attached to this report as Appendix 2. A summary of the major findings included in the white paper on the MSCR test can be listed as follows:

- If the objective of the MSCR implementation is to maintain the same modified binder formulations as controlled today by the T301/D6084 Elastic Recovery (ER), the MSCR %R parameter is a good candidate that can be used to detect the presence, and potentially quantity of elastomeric modification. It is shown that %R directly correlates with the results of the current T301/D6084 procedures and the phase angle measured in the DSR on a state by state basis, but not on a universal basis. Using universal limits for the MSCR %R parameter that are dependent on Jnr values, as required in the M332, is not practical nor useful since current binder formulations are controlled differently by the state agencies; more importantly, the %R is not clearly related to rutting or fatigue performance of mixture or pavements.
- If the objective of using the MSCR is to replace the $G^*/\sin(\delta)$ parameter and ensure good binder contribution to rutting resistance, the Jnr parameter measured at 3.2 kPa is a good candidate, irrespective of the %R. The Jnr value at 3.2 kPa is highly correlated with mixture Flow Number results and literature clearly shows it is a better choice than the $G^*/\sin(\delta)$.
- It is important to recognize that the conversion of the grades determined based on the M320 with grade bumping (e.g. PG 58, PG 64, PG 70, and PG 76) to the traffic grades (PG 58 or PG 64 S, H, V and E) is not simple because the $G^*/\sin(\delta)$ used in M320 does not correlate well with the Jnr at 3.2 kPa. Therefore, if states wish to keep the same binder formulations (or minimize change), but wish to implement the MSCR Jnr parameter, the limits for Jnr at 3.2 kPa will likely be different between regions. However, since the Jnr parameter is well related to rutting performance of mixtures, States should not try to maintain formulations and focus on using universal values of Jnr as related to traffic and climate. This is the part of M332 that is ready for implementation. There is more work to be done to verify that the Jnr values of 4.5, 2.0, 1.0 and 0.5 1/kPa correctly correspond to the traffic speed and volume designated in M332.
- The %Jnr Diff. parameter is highly dependent on the binder formulations but lacks a clear relationship to rutting performance. It is claimed in the literature that %Jnr Diff is an indicator of modification quality, unfortunately no clear evidence is found. In addition, since it is measured relative to the Jnr measured at 0.1 kPa, its reliability in terms of variability, and in terms of actual condition in typical asphalt mixtures, is questionable. If a universal value of 75%, as currently listed in M332 is used, changes in formulations of binders to meet this limit are expected as shown in the data collected in this study. These changes might not be in favor of better performance or practice.

The following recommendations are made for each of the MSCR parameters included in AASHTO M332:

- Jnr at 3.2 kPa: The Jnr parameter measured at 3.2 kPa is a good replacement for G*/sin(δ) to control binder contributions to rutting resistance. However the conversion of the current PG grades bumped for traffic to the H, V, E grades should be calibrated locally.
- %R: A strawman specification for %R based on replacing existing PG + methods aimed to keep the same binder formulations, but not necessarily ensure pavement performance, is presented in the white paper for the existing KDOT and ODOT data with commentary provided on the CSBG limits.
- %Jnr Diff.: The limit for this parameter in AASHTO M332 could not be validated, and its implementation could force suppliers to change the formulations with uncertain consequences on performance. The %Jnr Diff parameter should be considered as 'Report Only' until more information is gathered on this parameter.

All of the partner states have indicated that rutting is not a primary distress in their respective regions, and, hence, may not see value in the performance aspect of the MSCR test (e.g. relating Jnr to rutting). However, if the opportunity exists to eliminate T301/D6084 elastic recovery by using the MSCR %R parameter (or the AASHTO TP123 ER-DSR procedure), states may benefit given the simplicity of this DSR-based procedure. In support of this effort, 'strawman' specifications were developed and are presented in the attached white paper (Appendix 2) that directly correlates T301/D6084 elastic recovery to MSCR %R or ER-DSR. This specification is presented again below.

Table 2. Example Specification for MSCR %R at 64 °C for Partner States Wishing to Replace T301/D6084 and keep formulation unchanged

Kansas		Ohio	
Binder	**Min. %R at 64 °C**	**Binder**	**Min. %R at 64 °C**
Base	-	Base	-
64-28	25%	64-28*	25%
70-22	25%	64-22	25%
64-34	50%	70-22	50%
70-28	50%	76-22	75%
76-22	50%	88-22	75%
76-28	75%		

*Tested at 58 °C if intended for PG 58 region

Table 3. Example Specification for ER-DSR for Partner States Wishing to Replace T301/D6084

Elastic Recovery, % (T301/D6084)	ER DSR, % (AASHTO TP123)
45	32
50	38
60	51
65	57
75	70

Based on the review of the draft final report, the Ohio DOT team requested that a ranking of the DSR-ER procedure with the MSCR %R is formulated to reflect the analysis of data collected by the Ohio DOT. A memorandum was written to cover this topic and is included as Appendix A in this report.

B. Work Area 2: Determination and Validation of Reliability and Applicability of the Selected PG+ Tests

In this work area potential tests to replace the current PG+ conventional tests, such as the ductility and the T301 Elastic Recovery tests, were selected based on recent research published and the analysis of information gathered in Work Area 1. Table 4 includes the "Candidate Replacement Tests" that were selected and a brief statement to justify their selection. Testing of a large number of binders from the partner state agencies and from WCTG was completed, and correlations between the results of the PG+ tests and the proposed replacement tests were plotted. In addition, ruggedness testing was conducted for the replacement tests that did not have precision and bias statement already to facilitate the implementation.

Table 4. Current PG Plus Tests Used by Partner States and Candidate Replacement Tests Selected Based on Work Area 1 effort

Current PG Plus Test	Partner States Using Test	Candidate Replacement Tests	Current Research Needs
Phase Angle	WI	MSCR Percent Recovery MSCR (MP-19) Elastic Recovery - DSR	**MSCR:** Establishing correct test temperatures, assessing need for adjusting %R and Jnr limits to reflect regional materials. **ER-DSR:** Adjusting limit for DSR-based test as it will be ~15% lower than AASHTO T301 results (see supporting information).
Elastic Recovery	ID, KS, OH, WI		
Ductility	OH	Binder Yield Energy Test (BYET) @ 25°C	**BYET:** Reclassification of regional materials as shear vs. extensional tests give significantly different rankings (see supporting information).
Toughness and Tenacity	OH	Binder Yield Energy Test (BYET) @ 4°C	

The results of the effort for this work area were summarized in three reports: Task Report 2 (attached in Appendix 3), White Paper 2 on Intermediate Temperature Cracking (attached in Appendix 4), and White paper 3 on Low Temperature Thermal Cracking (attached in Appendix 5). The following sections summarize the findings of these three reports which have been already delivered to the partner States.

i. Task Report 2 Findings on the Candidate Replacement Tests

The objectives of the partner state agencies was used to define the engineering property of the distress targeted by the PG+ test used, and the recommendation for the replacement as shown in Table 5. The table also includes the justification for the replacement recommendation.

Table 5. Summary of Preliminary Replacement and Implementation Test Methods

Engineering Property or Distress	Partner State Objective	Recommendation	Justification
High temperature elasticity (recovery of strain)/permanent deformation	Replace Phase Angle	ER DSR	Correlates well; apparent better differentiation between modified binders
	Replace ER T301	ER DSR	DSR-based; less material intensive; provides logical ranking
	Presence of Elastomer	MSCR %R	High temperature test; established standard; obtain more information from one test
	Address high temperature pavement deformation (rutting)	MSCR %R or MSCR Jnr	Damage characterization test; DSR-based; significant literature correlating test to field performance
Intermediate temperature elasticity (fatigue cracking)	Replace T51 ductility	BYET Strain at Max. Stress 5 °C	Logical ranking of modification types; good correlation between tests; no change in sample geometry; less material intensive; easier to run
	Replace toughness and tenacity	BYET yield energy at 25 °C.	No change in sample geometry; easier to run; widely available
	Address intermediate temperature (fatigue) cracking potential	*Linear Amplitude Sweep (LAS) Cycles to Failure	Damage characterization test; DSR-based; evidence of correlation to field performance in Wisconsin
		BYET yield energy at intermediate PG	Easy to run; same geometry as current G*sinδ; widely available; correlates well to full scale testing in ALF
Low temperature cracking potential	Address thermal cracking potential	*BBR-SENB	Damage characterization test; evidence of correlation to field performance in Wisconsin

*Denotes a supplementary test method for consideration

The following comments pertain to each of the PG+ tests being replaced:

- Phase Angle: Findings suggest that the ER DSR procedure is a more robust method for quantifying the degree of elasticity (in terms of elastic recovery) for the modified binders used in this study. Although the ER DSR procedure is run at 25 °C and the phase angle at the high temperature PG, a strong linear correlation exits between the two methods. Based on the analysis, the ER DSR procedure can be used as a direct replacement for phase angle.
- Elastic Recovery (AASHTO T301): The ER DSR procedure was found to correlate reasonably well with the AASHTO T301 elastic recovery results. All binders tested in this study that passed the phase angle requirement also passed the elastic recovery requirements. The ER DSR procedure can directly replace the T301 recovery procedure with appropriate modification to the elastic recovery limits.
- Elastic Recovery and MSCR: The results in this report suggest that if performance at high temperature (i.e. reduction of permanent deformation) is desired, a high temperature test

method that measures that performance should be used. The findings contained in Task Report 2 related to the MSCR procedure are outlined in Section II of this report and attached as Appendices 2 and 3.

- Ductility at 4 °C (AASHTO T51): The DSR-based BYET test strain at maximum stress parameter appears to be a viable alternative to ductility at 4 °C. A strong linear correlation was found between T51 ductility and BYET strain at maximum stress consistent with the exiting literature, suggesting direct replacement of the T51 ductility test is possible with the BYET test. The BYET test also has several methodological advantages that make it an attractive replacement to T51, including consistent sample geometry during testing, lower sample quantity requirements, more accurate temperature control (and ability to run at any test temperature easily), and logical ranking of modified binders. It should be noted that this analysis does not necessarily directly address pavement performance at intermediate temperature.
- Toughness and Tenacity (ASTM D 5801): The BYET test yield energy parameter shows a logical trend with binder toughness; as the yield energy of the binder increases, so too does the toughness. For the binder set tested in this study, the toughness and tenacity parameters were strongly linearly correlated, and as a result the tenacity parameter was also correlated with the BYET yield energy. Although the correlations are relatively poor, given the differences in strain rates between the two tests, unknown modification types and polymer loadings, and somewhat arbitrary means for defining the toughness and tenacity, the results are promising. Overall, the data suggests the toughness parameter can reasonably be estimated using the BYET yield energy at 25 °C. If the tenacity parameter remains of interest to the partner states, results from representative materials should be collected and analyzed to determine if the yield energy parameter from the BYET run at 25 °C can be used to estimate minimum specification limits. If the toughness and tenacity are linearly related, specifying one (i.e. toughness) parameter should satisfy the other.
- Fatigue Cracking Resistance: The Linear Amplitude Sweep (LAS) test (AASHTO TP101) is suggested for evaluation of fatigue cracking resistance of asphalt binders on the basis of recently published findings which show a high correlation between the LAS cycles to failure and actual fatigue cracking reported for field sections. A suggested preliminary specification is offered and will be evaluated after Phase 3 mixture testing and field evaluation of the present binders. In addition, BYET can be used as it showed very good correlation with fatigue cracking measured at the Accelerated Loading Facility ALF at FHWA. The limits for acceptance can be derived from correlations of that study.
- Thermal Cracking Resistance: The BBR-SENB test is suggested for evaluation of thermal cracking potential of asphalt binders based on the same study referenced for the LAS test. The SENB test is a more practical a repeatable alternative to the original DTT test from the original Superpave specification and more accurately characterizes modified binder thermal cracking potential relative to using stiffness and stress relaxation rate (m-value) alone. The two parameters of interest in the SENB test are the deformation at maximum load and the fracture energy. A preliminary specification is offered and will be evaluated again after Phase 3 testing is complete.

The challenge in using this test is the availability of equipment. Partner states should consider setting up of SENB in their laboratories if there is sufficient interest.

After sending the Work Area 2 report for review and comments, the interest of summarizing the results in white papers similar to the MSCR white paper was expressed. The research team submitted two white papers: one focused on the contribution of asphalt binders to resistance of Intermediate Temperature Cracking, and the other for the contribution of binders of Asphalt Binders to Low Temperature Thermal Cracking. The papers are attached as Appendix 4 and Appendix 5, respectively, and a summary of findings are listed in the following sections.

ii. White Paper 2: Intermediate Temperature Cracking of Asphalt Binders

Based on the results of Work Area 2 the LAS binder testing procedure was recommended for evaluating the binder contribution to fatigue cracking resistance. However, the test was considered to be too complicated due to the relatively complex mathematical procedure involved in determining the number of cycles to failure (Nf) at specific strain levels. Therefore this white paper was written to achieve the following objectives:

- Compare LAS testing results with other simpler testing methods such as the Binder Yield Energy Test (BYET), ductility or Elastic Recovery (ER) to determine if these simpler tests can be used as surrogates to indicate binders' cracking resistance,
- Propose an implementation strategy for the LAS and the simplest alternative that can represent field cracking and recommend preliminary specification limitations based on the data collected, and Use mixture testing using a well-accepted intermediate cracking test for mixtures and derive reasonable limits of binder properties for acceptance.

The analysis of the results indicated that there is potential for using simpler alternatives to the LAS Nf which includes the following parameters:

- LAS strain at peak stress measured at IT of PG grade using the TP101 procedure.
- Energy to 2500% strain measured using the BYET procedure at 25 °C following TP123-Method B.

In order to determine proper limits for using these parameters in standard, limits based on simple ranking of the binders in each state were proposed in this white paper, as shown in Table 6.

Table 6. Proposed AASHTO TP101 and AASHTO TP123 Limits

Traffic Level	AASHTO TP 101		AASHTO TP 123 Energy to 2500%, kPa
	LAS N_f at 2.5% strain in 1000s	LAS Strain at peak stress, %	
Standard	≥ 80	≥ 12	≥ 750
Heavy	≥ 300	≥ 16	≥1500
Very Heavy	≥ 700	≥ 18	≥ 2500
Extreme	≥ 1100	≥ 22	≥ 3200

The white paper also included a critical analysis with regard to the changes to the limits for the G*sinδ from 5000 kPa to 6000 kPa proposed in the AASHTO M332 for the H, V, and E grades. The results collected in the pooled-fund indicate that this change could result in more risk of fatigue cracking. The results of testing a large number of binders from the WCTG group show that fatigue life as measured in the LAS at PG-IT decrease significantly with higher G*sinδ values. It is thus recommended that States re-consider this change, and instead use lower G*sinδ limits as the traffic level increases. In other words, the limits for H, V, and E grades should decrease sequentially similar to the Jnr value limits. The trends shown in Figure 1, taken from the white paper explain the need to reconsider the increase in limit specified in the AASHTO M332.

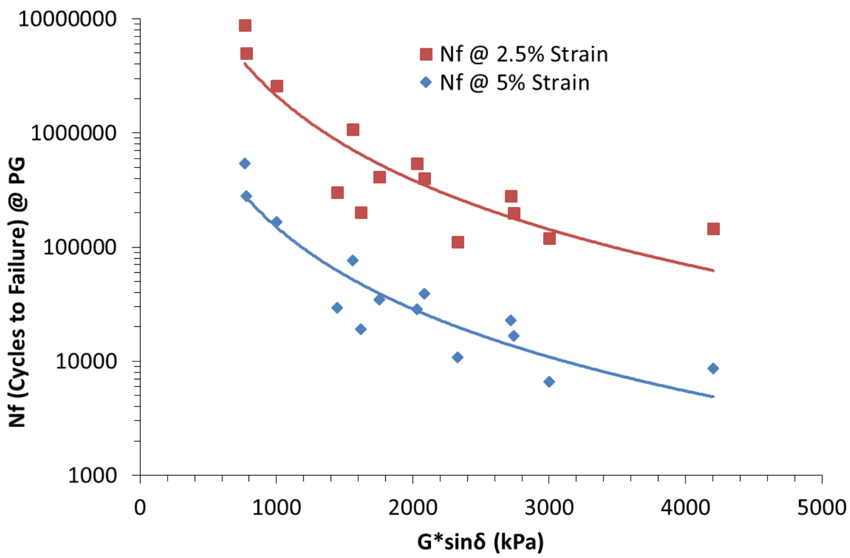


Figure 1. Relationship between LAS Nf at IT-PG and G*sinδ for numerous modified and un-modified binders.

iii. White Paper 3: Low Temperature Cracking Properties of Asphalt Binders

In the current PG system (AASHTO M320) the Bending Beam Rheometer (BBR) is used to determine the low temperature grade limits based on the stiffness (S) and logarithmic creep rate (m). Both these parameters are measured at relatively low levels of load and deformation; thus there is a concern that resistance to fracture (cracking or breaking) is not really measured. For modified asphalts this concern is important as some modifiers could create a network of long-chain molecules reinforcing the binder and increasing its resistance to fracture [3]. In the original PG grading system an attempt to measure cracking was proposed by using the Direct Tension Test (DTT), but only a few State Agencies use the test today because the test implementation proved to be not feasible due to variability, sample preparation issues and amount of material and replicates needed.

During the last five years a bending test has been introduced and became a standard in European Norms. The same bending concept was used in the US to propose a modification of the BBR to allow measuring fracture of a notched BBR specimen. The modified BBR that allows measuring fracture is called the Single Edge Notched Beam (SENB) [3]. As part of this project the binders collected were tested for the cracking properties using the SENB device and the results were correlated with low temperature testing results of mixtures produced in the lab. The results of analysis of binders and mixtures are summarized in a white paper on low temperature cracking properties and are attached to this report in Appendix 5.

The findings of the paper can be summarized as follows:

- The Single Edge Notched Bending (SENB) test can be used to measure binder stress and energy at failure, which have superior correlations with asphalt mixture low temperature cracking indicators.
- Since the SENB device is not readily available at this time, a combination of BYET binder properties and the ΔTc parameter measured by the BBR can provide an estimated value of the SENB Failure Energy. This estimated value can be used as a fair surrogate to the SENB test.
- More effort is needed to find a manufacturer willing to produce the SENB device. The shop drawings are attached to this report as Appendix 6, and the software is ready to be shared with potential manufacturers. It will remain the partner state's choice whether the benefits from the SENB test method in more precise prediction of mixture cracking is worth the effort needed for duplicating the SENB apparatus.
- Further analysis specifically on extended aging BBR and ΔTc evaluation can help partner states better understand whether or not the practice ready procedures (BYET and ΔTc) can be further considered for specification implementation.
- It is clear in this study that RAS and RAP could significantly change the relationship between binder fracture properties and mixture fracture properties. This issue is very important and deserves further study.
- Based on data collected to date, a minimum value of Failure Energy of binders measured in the SENB or estimated from the BYET and BBR of 40 J/m^2 could be proposed for specifications. This value is very preliminary and was selected because about 70% of the binder testing could achieve this value. Field verification and local calibration will be needed to validate this limit.

iv. Ruggedness Testing for AASHTO TP123

Ruggedness testing is used to determine what factors, if any, influence measurements of candidate testing methods, and estimate how closely those factors need to be regulated. The factors chosen are typically features of the test method that may vary between laboratories and are believed to have the potential to affect the results. In order to successfully conduct a ruggedness experiment, factors that may affect the outcome of the testing procedure are intentionally varied to quantify the effects of altering the selected factors. In this project two experiments were conducted, one for the ruggedness of the BYET procedure and the other for the ER-DSR. The complete report is attached to this document as Appendix 7. The findings of the testing are summarized in the following section. It should be mentioned that the LAS ruggedness was already conducted in a previous recent study and thus it was not included in this project.

For the BYET ruggedness a 2^3 factorial design (3 factors at 2 levels each), with each factor level selected to be at the +/- 5% range of the target value specified in AASHTO TP123, was completed. Variables included in this experiment were (1) the loading rate, (2) sampling frequency, and (3) sample placement temperature. The testing responses statistically analyzed include: binder yield energy and binder strain at max stress. Binders used for the study included RTFO-aged CO 64-28 and KA 64-34. The experimental setup is shown in Table 7.

Table 7. AASHTO TP123 Method A Ruggedness Experimental Design

Factor Label	Designation	Level	
		-	+
Loading Rate (1/s)	1	0.02199	0.02431
Sampling Frequency	2	855	945
Sample Placement Temperature deg C	3	60	70

The Elastic Recovery ruggedness was a 2^{4-1} factorial design (interactive effects confounded), with each factor selected within +/- 5% range of the specified value. The factors selected in this study include: (1) loading rate, (2) loading time, (3) recovery time, and (4) loading temperature. The response recorded in this study was the elastic recovery. Binders used in this study were the RTFO aged CO 64-28 and KA 64-34. The experimental setup is shown in Table 8.

Table 8. AASHTO TP123 Method B Ruggedness Experimental Design

Variable	Designation	Level	
		-	+
Loading Rate (1/s)	1	0.02199	0.02431
Loading Time (s)	2	114	126
Recovery Time (min)	3	28.5	31.5
Sample Placement Temperature C	4	60	70

Based on the statistical analysis conducted following ASTM standard E1169, the following findings can be listed for the AASHTO TP123 testing procedures (ER-DSR and BYET):

- All factors included in the study were found to be rugged with the exception of loading time for the ER-DSR procedure. The loading time or maximum strain prior to failure should be kept within 1 second or 2.3% of the target value, respectively.
- Half normal plots for the binder yield energy test showed factors indicated to be significant at a p-value level 0.05 can be attributed to sampling or random error that occurs during the test.
- Analysis of the stress-strain plots for the CO binder showed that some binders will not show a clear peak in the BYET and thus make the interpretation of the results very difficult. In case the strain at peak stress is used in the specification, proper conditions that will ensure ability to define a peak stress is very important.
- Analysis of the ER-DSR recovery time indicated that 30 minutes is sufficient to ensure repeatable binder measurements.

C. *Work Area 3: Validation of the Proposed Binder Specification Using Laboratory Mix and Field Survey Performance Data*

The primary objective of Work Area 3 is to validate any findings and recommendations of the previous work areas with mixture testing. Representative mixtures were supplied by the partner states to the University of Wisconsin laboratory for evaluation (plant mixed, lab compacted). Member states were consulted as to which primary pavement distresses each was most interested in validating. In general, states selected intermediate and low temperature cracking as the two distresses most prevalent in their respective regions. As such, primary consideration for the mixture testing conducted during this study is given to an intermediate temperature cracking test (Illinois I-FIT SCB procedure, AASHTO TP124) and low temperature cracking (Asphalt Thermal Cracking Analyzer – ATCA). A limited data set of high temperature Flow Number for WCTG mixtures is also used to validate the MSCR parameters that best predict permanent deformation of mixtures.

In support of the objectives in Work Area 3, a literature review of existing performance test methods was conducted and primary test methods were selected. In addition, three white papers were produced and distributed to the member states detailing efforts at high, intermediate, and low temperature to predict pavement distress using selected PG+ test methods. These white papers are attached in their entirety as appendices to this document and summarized in subsequent sections.

Mixtures submitted by member states to the research team were tested using the SCB-Illinois (I-FIT) procedure at intermediate temperature and the Asphalt Thermal Cracking Analyzer (ATCA) procedure at low temperature. Although this Pooled Fund study does not include high temperature performance testing, a limited data set of WCTG mixtures was used to validate the properties of the MSCR test most related to permanent deformation resistance of mixtures. Findings at high, intermediate, and low temperature testing are summarized in the following sections.

i. *High Temperature Performance of Mixtures*

The primary pavement distress at high temperature is permanent deformation. AASHTO M332, which includes the Multiple Stress Creep and Recovery (MSCR) test has been proposed to replace AASHTO M320 for the PG grading of binders. In general, there is a consensus in the literature that the Jnr parameter does a better job of predicting deformation resistance of polymer modified asphalt [4]. Two other parameters are also calculated from the MSCR procedure, the percent recovery (%R) and percent difference in Jnr measured at 0.1 kPa and 3.2 kPa (%Jnr Diff.). During this study, an attempt was made to correlate the three MSCR parameters to high temperature mixture performance using the Flow Number test. Findings in support of this effort are included in the white paper related to the analysis of the MSCR test attached as Appendix 1.

Results comparing MSCR Jnr and %R parameters and mixture flow number at equivalent temperatures to isolate binder stiffness are shown in Figure 2 below. The findings indicate that a logical trend exists between Flow Number and Jnr at 3.2 kPa. A power law was used since Jnr cannot fall below zero, yet flow number can continue to increase unbounded; this presents an important observation: there is a diminishing return on very low Jnr values (i.e. agencies are paying more for a limited and unpredictable amount of improvement to performance). Note that in terms of similar levels of performance, binders can show large changes in the Jnr value (Jnr is on a logarithmic scale). Clearly this indicates that while a general trend exists, and it appears a lower Jnr improves rut resistance, the other components/design factors in the mixture have a large impact on performance.

In terms of the %R parameter, although the power fit is similar, the general scatter in the data suggests that the %R is much less important for high temperature performance. For changes in recovery of less than 5%, nearly two orders of magnitude difference in flow number exists for the data. %R is not normalized to the load as is Jnr, so it is a parameter derived from the deformation that takes place during each cycle. Therefore, if a binder had a very large %R and a relatively high Jnr, the %R parameter might impact performance more. This is the converse of how the M332 spec is written, however, in that high Jnr values require lower minimum %R values.

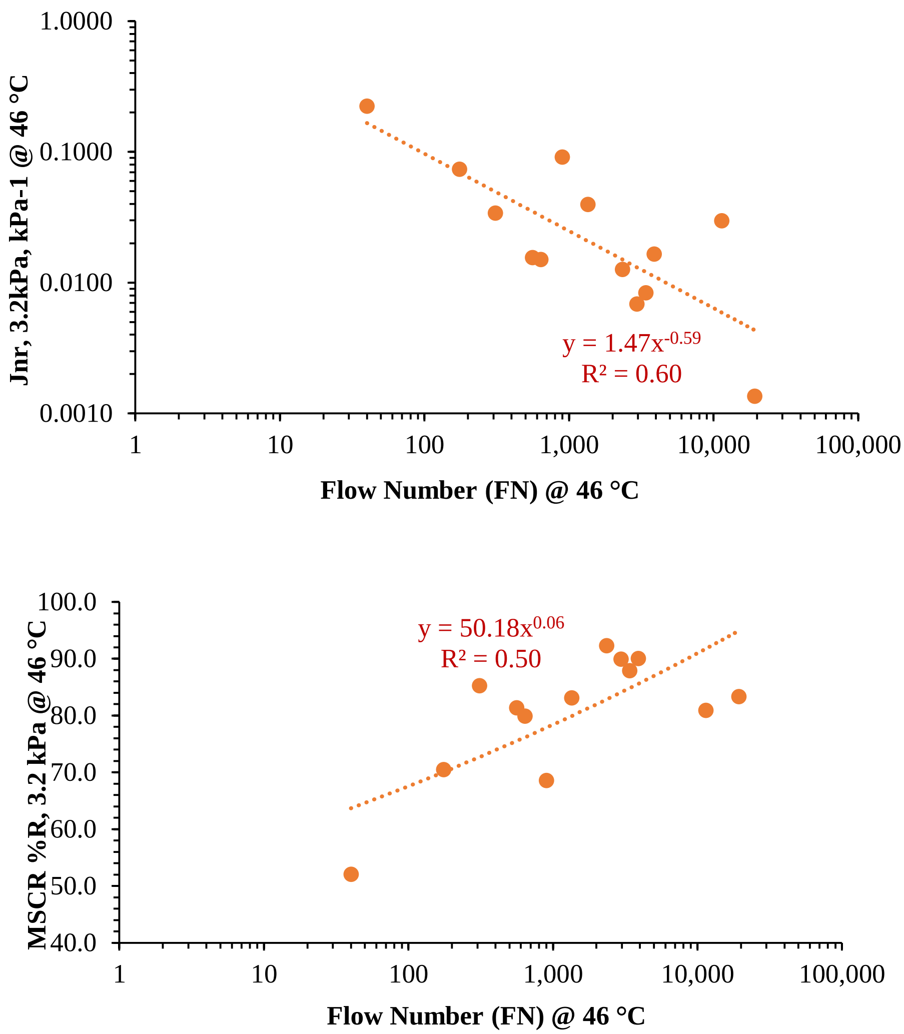


Figure 2. Flow Number testing comparing Jnr at 3.2 kPa and %R.

From the data presented above, it can be concluded that the Jnr shows merit in predicting high temperature performance of mixtures, but the binder properties alone cannot be used to fully predict mixture performance. For lower Jnr values, the %R value does not appear to easily discriminate mixture performance. Since the M332 spec is written to allow lower %R limits for higher Jnr values, the impact of

%R on performance is not expected to be strong for any level of Jnr. Therefore, if states wish to implement a performance based specification, it appears the Jnr value is the most important, and the %R is included to force the use of elastomeric modification (which may or may not directly benefit performance).

The attached white paper also provides extensive commentary on the implementation considerations for the MSCR test in light of these findings. Several partner states have expressed concern that implementing the MSCR might significantly change binder formulations. To better understand the relationship between PG grade bumping and Jnr decrease, the continuous PG grade and Jnr values for the pooled fund and WCTG binder are plotted as shown in Figure 3. There are two significant takeaways from plotting the data in this way: (1) for a given continuous grade, there can be a wide range of Jnr values and (2) Jnr values are relatively low for all binders that were PG bumped. This suggests that the Jnr and PG bumping systems are providing different information with respect to a binder's resistance to rutting. If DOT agencies would like to ensure, with a high level of reliability, that asphalt binders graded with the MSCR are identical or improved in performance to binders graded with PG bumping system, a target Jnr of 0.1 kPa-1 is recommended. Justification for this recommendation based on the data provided for this study is included in the white paper.

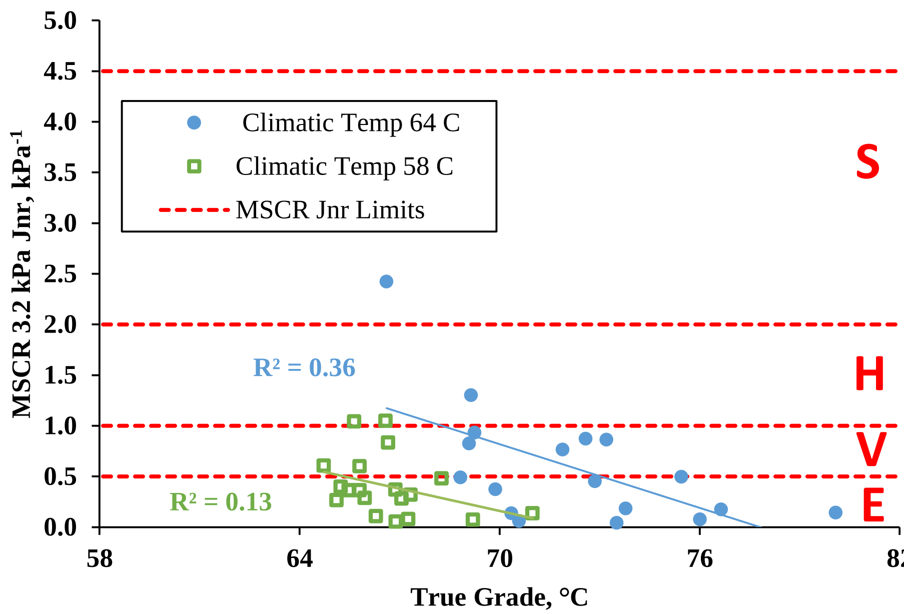


Figure 3. Relationship between asphalt binder continuous grade and Jnr at 3.2 kPa.

ii. Intermediate Temperature Performance of Mixtures

After discussion with the Pooled Fund member states, the Illinois Flexibility Index Test (AASHTO TP124) semi-circular beam testing method was selected to measure intermediate temperature cracking resistance of plant produced Hot Mix Asphalt (HMA) samples provided to University of Wisconsin Researchers. In order to complete an I-FIT testing sample, one gyratory compacted specimen is cut with a diamond saw into the dimensions shown in Figure 4.

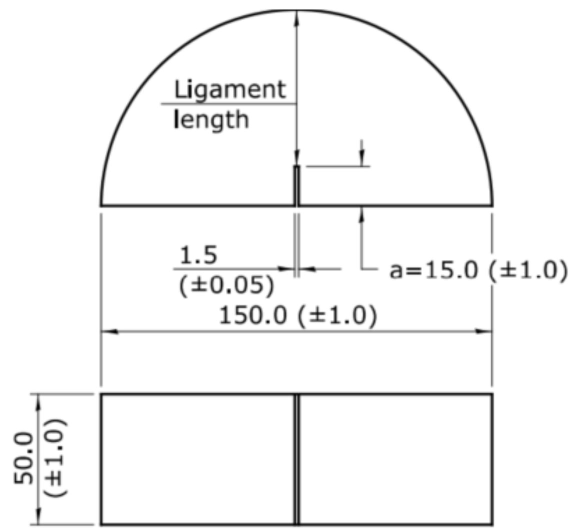


Figure 4. I-FIT specimen dimensions; all in millimeters [5].

From each gyratory specimen, four specimens can be prepared for testing. The test is conducted at 25 °C and at a deformation rate of 50 mm/min. The rate is intentionally selected to reduce the effects of dissipating energy in plastic or viscous deformation. There are two primary outputs that are calculated from the I-FIT testing procedure: fracture energy, (G_f) and Flexibility index (FI). Fracture energy is calculated as the area under the load-displacement curve (W_f). Flexibility index is calculated as the fracture energy divided by the post-peak slope of the load–displacement curve. Flexibility index is best described visually using Figure 5 and Equation 1.

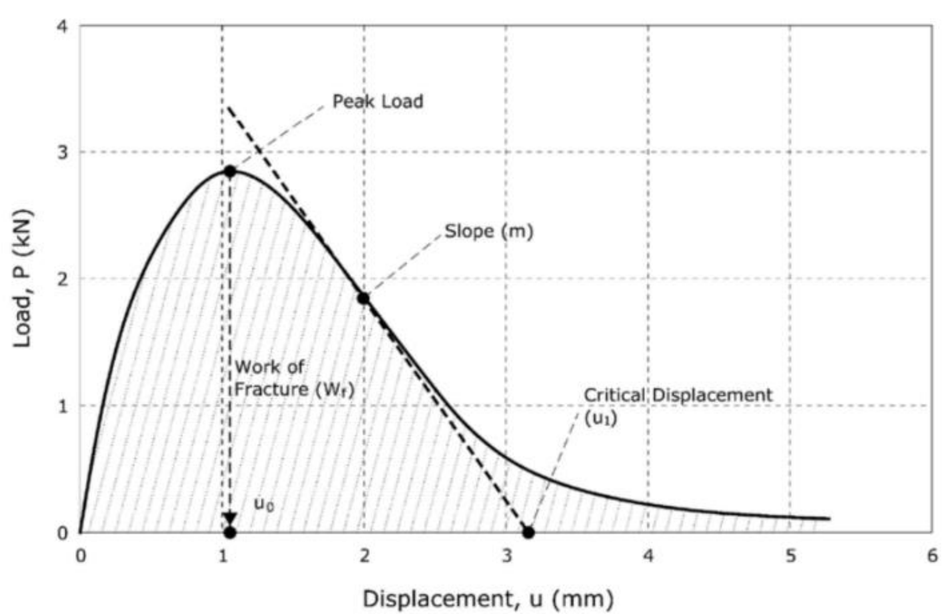
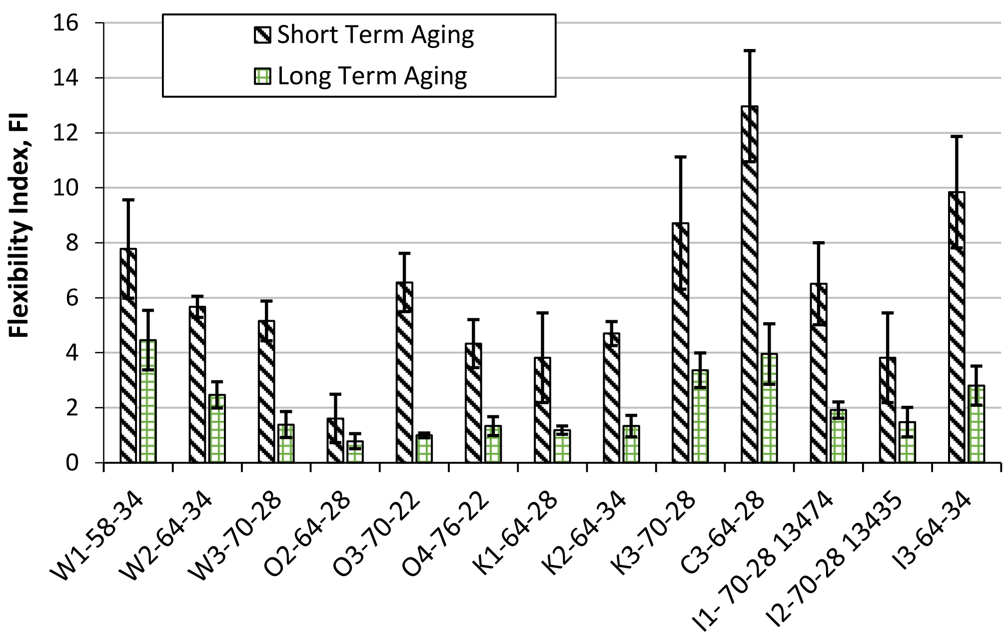


Figure 5. I-FIT-load displacement schematic from Illinois standard procedure 405 [5].

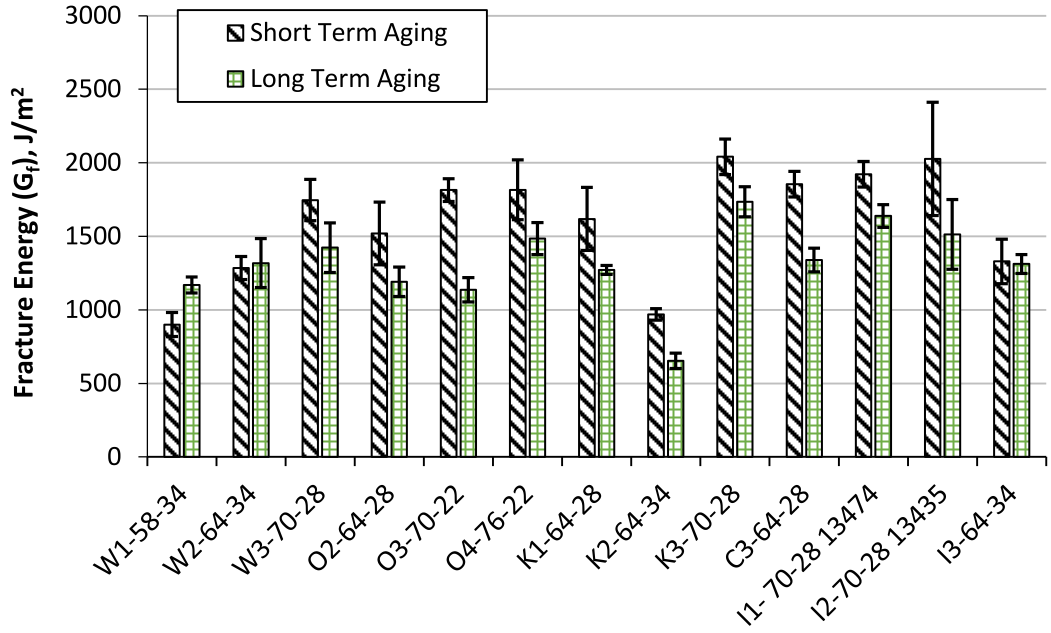
$$Flexibility\ Index\ (FI) = \frac{Fracture\ Energy\ (Wf)}{Slope\ (m)} * 0.01 \quad (1)$$

As can be seen from Figure 5, the post-peat slope is calculated at the load-displacement inflection point while the crack is propagating though the specimen. The I-FIT procedure is used to measure an asphalt mixture's resistance to fracture at intermediate temperatures. Fracture Energy, G_f, indicates an asphalt mixture's capacity to resist cracking resistance and FI is used take into account the post-peak behavior of mixtures and to rank cracking resistance of alternative mixtures for a given layer in a structural design. Both parameters are used to help researchers understand the extent to which binder and aggregates properties affect mixture performance properties and determine which candidate test method included in this study is the best indicator of cracking resistance.

To meet these objectives, all thirteen Pooled Fund mixtures provided to the University of Wisconsin were included in two rounds of testing; short term and long term aging. Short term aging consisted of two hours of oven conditioning at the mixture design specified compaction temperature. Long term aging was consisted of the short term aging procedure plus an additional twelve hours conditioning at 135 °C. Graphs showing both the FI and G_f values for all the mixtures included in this study are shown in Figure 6.



(a)



(b)

Figure 6. SCB-IFIT results after short and long term aging for all Pooled Fund mixtures included in this study. (a) Flexibility index (FI), and (b) fracture energy (Gf)

From Figure 6, there are clear trends that can be inferred based on the spread of data measured:

- The FI can distinguish between mixtures much more than the Gf values. The FI values vary between 1.0 and 13.0 while the Gf value varies between 700 and 2000 J/m^2 .
- Aging has a significant effect on both the FI and Gf. With aging, both the FI and fracture energy tend to decrease. The reduction in FI values is for all mixture and is more significant than the reduction of the Gf. For the Gf not all mixtures show reduction in the values with aging.
- There is no clear trend between the PG grade and the resulting FI or Gf for mixtures coming from the same state, and of the same grade. For example, PG 64-28 binders had a wide range of possible FIs; the Colorado 64-28 binder shows the highest FI of the entire data set and the Ohio 64-28 binder shows the lowest FI for the entire data set.
- This finding regarding lack of clear trends with PG grades indicates that a) the current PG grading system cannot capture binder contribution to fracture resistance of mixtures, and 2) the FI and fracture energy are heavily influenced by mixture design properties such as recycled material concentration, aggregate structure, aggregate quality, etc.

Trends observed after short and long term aging suggest that binder properties significantly affect the outcome of the test, as the binder is the only component affected by aging. However, the lack of a correlation between FI and PG grade suggest that other properties, such as mixture design properties, can influence a mixture's resistance to cracking to the same extent as binder properties. The following sections will investigate the relationship between I-FIT testing, binder properties, and mixture design factors. This analysis is aimed to help provide guidance with respect to selection of new binder testing methods to be considered for specification development and comment on the extent to which binder properties affect mixture performance.

iii. I-FIT SCB Correlations with Candidate Binder Testing Methods

In the previous section of the white paper, two binder testing procedures were identified as potential candidates to provide more information regarding an asphalt pavement's resistance to intermediate temperature distress: LAS N_f, LAS strain at peak stress, and BYET energy to 2500% strain. Initially, each of these parameters were correlated with FI and fracture energy identify any trends; R^2 correlation values are shown in Table 9.

Table 9. Linear correlation R2 values between corresponding I-FIT and binder testing methods.

I-FIT Parameter	Aging Level	LAS, N_f at 2.5% strain	LAS, strain at peak stress, %	BYET Energy to 2500% Strain, Pa
Fracture Energy	Short Term	0.01	0.03	0.25
	Long Term	0.00	0.00	0.07*
Flexibility Index	Short Term	0.13*	0.19*	0.2*
	Long Term	0.06	0.20*	0.28*

*indicates that there was a negative correlation between I-FIT and candidate test method.

From Table 9, it is clear that there is no correlation between the recommended testing procedures and I-FIT fracture parameters. The most promising correlation is the relationship between BYET energy to 2500% strain and short term fracture energy, but an R^2 value of 0.25 is considered to be poor. Testing temperature and aging condition may be able to explain the incongruence between the poor binder mixture correlations. For the LAS testing procedure, the intermediate grade was recommended as the testing temperature while 25 °C was used to test all of the I-FIT specimens per the standard procedure. In addition, I-FIT testing was conducted on the short and long term aging condition of the mixtures. LAS testing was only completed on the PAV binder; BYET testing was completed on both the RTFO and PAV aging conditions. To better understand the relationship between the binder and mixture tests, the effects due to temperature and aging condition (for the BYET procedure) were blocked. Revised correlation values are shown in Table 10**.**

Table 10. Correlation R2 values between I-FIT and binder testing parameters at 25 °C.

I-FIT Parameter	**Aging Level**	**LAS, N_f at 2.5% strain**	**LAS, strain at peak stress, %**	**BYET Energy to 2500% Strain, Pa**
Fracture Energy	Short Term	0.18*	0.10*	0.25
	Long Term	0.13*	0.00	0.07*
Flexibility Index	Short Term	0.21*	0.04*	0.01
	Long Term	0.07	0.03	0.01

*indicates that there was a negative correlation between I-FIT and candidate test method.

Table 10 still shows that there are illogical/poor correlations between the I-FIT parameters and the candidate testing methods. Given that all of the mixtures provided to the University of Wisconsin include different types of gradations and design traffic levels, a direct correlation between binder and mixture properties was not expected. However, given the I-FIT procedure's sensitivity to aging, binder properties were expected to show logical correlations in terms expected performance. To understand the illogical correlations further, literature concerning the development of the I-FIT procedure and recent research utilizing this test method was investigated and summarized in the following section.

iv. Investigation of Binder-Mixture Correlations

Based on the information collected from the Pooled Fund, SCB testing, and the development of the FI it is clear that binder properties do affect the outcome of the testing procedure. However, mixture design properties can have an equal or larger impact on the resulting I-FIT SCB FI. This consideration was validated by researchers after observing how each mixture failed after testing. Figure 7 shows two mixtures tested in this study: one where the mixture failed in the asphalt binder and the other where the mixture fractured through the aggregate.

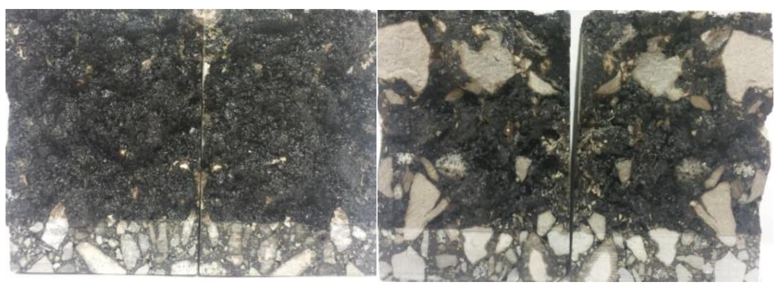


Figure 7. Example of two mixtures tested using the I-FIT procedure. Where, the left mixture failed in the binder and the right mixture failed in the aggregate.

From the above picture, binder properties may influence the outcome of the mixture on the left hand side of Figure 7 more significantly relative to the mixture pictured on the right hand side. To better understand how and to what extent binder properties affect the FI, researchers included mixture design factors into the regression analysis of the SCB-binder correlations. Initially, Minitab® 17 statistical analysis software used to conduct a best-subsets regression for selected mixture design properties. Best subsets regression ranks single and combined linear predictors of a given response; FI wasthe response in this study. In other words, best-subsets regression can indicate which mixture designs factors most significantly influence the FI. Mixture design factors included in the best subsets regression include:

- Asphalt binder film thickness
- Aggregates passing the #8 sieve.
- Nominal maximum aggregate size
- Dust to binder ratio
- Fine aggregate angularity
- Volume of effective binder
- Percent binder replacement (recycled binder content).

Of the mixture design factors included in the best subsets regression, the two most significant factors included aggregates passing the #8 sieve and nominal maximum aggregate size; mixtures with smaller aggregates and finer gradations tend to have a higher flexibility index. Aggregates passing the #8 sieve has a particularly compelling correlation with flexibility index as shown in Figure 8.

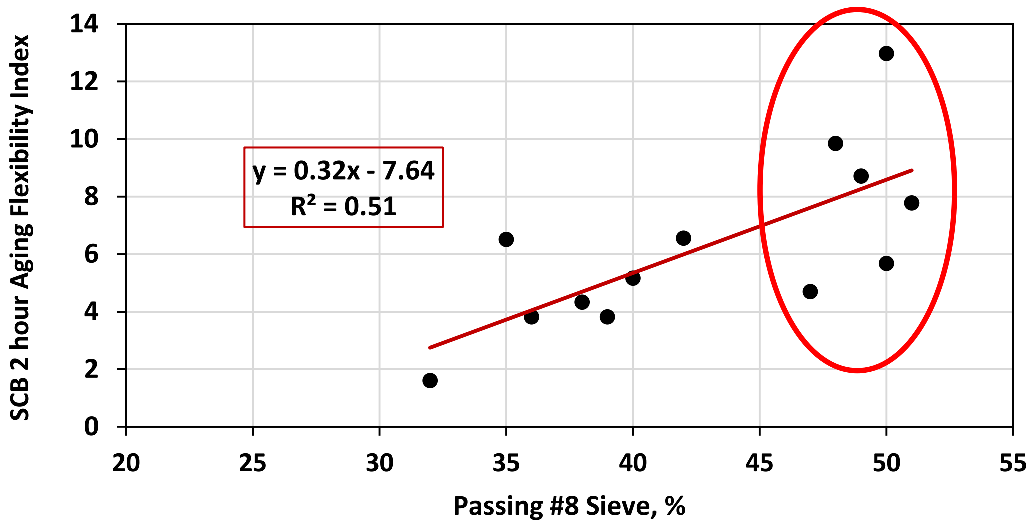


Figure 8. SCB FI correlated with aggregates passing the #8 sieve.

It is clear that increasing the aggregates passing the #8 sieve increases the FI. However, for multiple mixture designs at a similar passing the #8 sieve, circled in red, there is a wide spread in the data. The wide spread at a given passing #8 sieve indicates that other factors, mixture design or binder, also significantly affect the FI. To investigate this relationship further, the fine mixture designs (i.e. mixture designs with passing #8 around 50) were statistically analyzed independent of other mixtures.

After only considering the mixtures that have identical passing #8 aggregate sizes around 50%, binder and mixture design properties were correlated with FI. Results of the statistical analysis showed that there were no factors, binder or mixture design that correlated well with FI. Instead of correlating binder and mixture design properties directly with FI, researchers separated the two components of FI, fracture energy (G_f) and post peak slope (m). For the post-peak slope, there appears to be a direct correlation with asphalt binder content, shown in Figure 9.

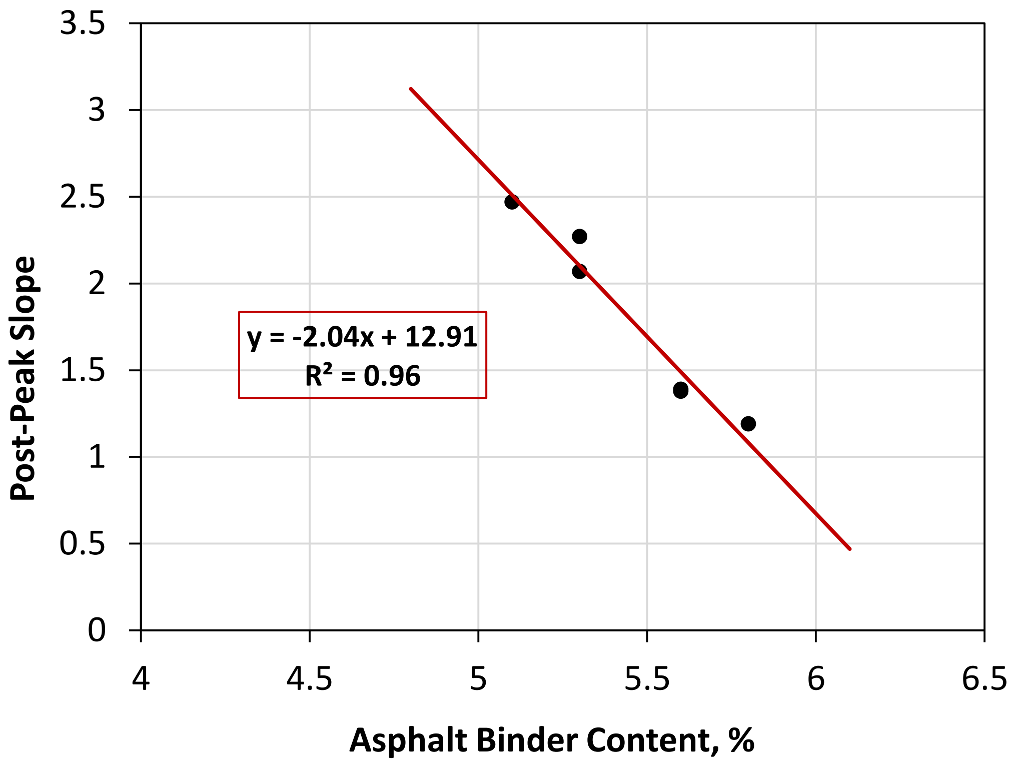


Figure 9. Correlation between post-peak slope and asphalt binder content.

Logically, as the asphalt content increases the post peak slope decreases, which would cause the FI to increase. The correlation suggests that, for a given gradation, the asphalt binder content controls the post-peak slope as measured by the I-FIT testing procedure. These results are not surprising given that the asphalt binder is the component of an asphalt pavement that provides “flexibility” (i.e. flexible vs. rigid pavements).

The same exercise was used to identify which mixture or binder properties most heavily influence fracture energy; the second component of the FI calculation. Results of the analysis showed that two binder properties were most significantly affect fracture energy: intermediate temperature grade and binder yield energy. Figure 10 shows the intermediate PG temperature and intermediate continuous grade correlated with fracture energy.

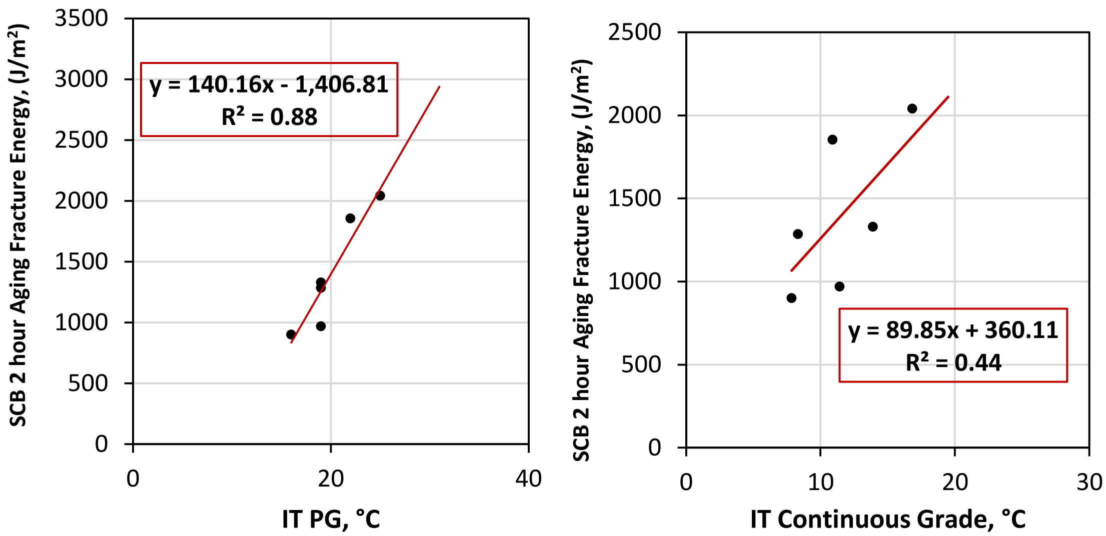


Figure 10. Correlation between ITPG (right) and continuous grade (left) with fracture energy.

As the intermediate temperature grade increases, so does the fracture energy. This result is surprising given that Figure 10 shows that as mixture aging increases, the fracture energy decreases. The binder grading and aging results contradict each other. In the PG grading system, a maximum limit is placed on the G*sinδ to ensure that the binder is not susceptible to cracking. Despite the confounding data sets, both figures clearly indicate that asphalt binder modulus/stiffness can significantly affect the fracture energy of a mixture. To what extent and how binder modulus and mixture fracture energy relate cannot be interpreted from the data collected. A more logical trend was observed when correlating binder yield energy at 25 °C, as shown in Figure 11.

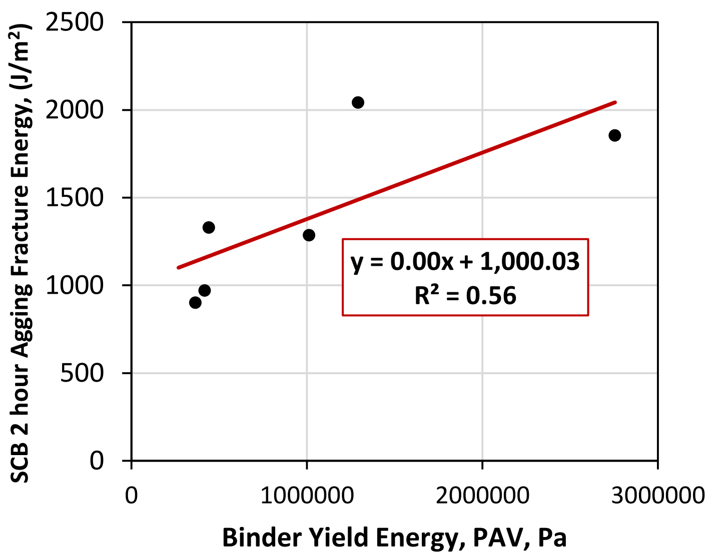


Figure 11. Correlation between binder yield energy and SCB fracture energy.

As the binder yield energy increases, the SCB fracture energy increases. This trend was expected because both are measurements of resistance to load and deformation under a constant displacement rate. Despite the logical correlation, this is a limited sub-set of data that merits further investigation to validate the trends observed in this study. Currently, UW researchers have been conducting SCB tests using the I-FIT procedure on several controlled mixtures through the Wisconsin Highway Research Program. This data was leveraged to determine if results collected from a separate data base can detect binder and mixture design properties similar or identical those to the factors that correlated well with I-FIT testing collected as part of the Pooled Fund.

Sensitivity Analysis for Cracking Resistance of Mixtures to Mix and Binder Variables

To estimate which of the factors have the most influence on critical response variables of Flexibility Index, Fracture Energy, and Post-Peak Slope, a sensitivity analysis can be used. Table 11 shows such an analysis for the mixtures in this study. The three responses are listed in columns, with the mix design and aging factors determined to significantly affect a particular response listed in rows. The range of each predictor observed in this study is shown and the resulting change in the response when moving from the minimum to maximum predictor value is included. For example, increasing the P8 from 32% to 51% while holding all other factors constant, one can expect an increase in the Flexibility Index of 5.3. Finally, the descriptive statistics for each response is shown at the bottom of the table to give an indication of scale.

Table 11. Sensitivity Analysis for Pooled Fund Mixtures

Response			Flexibility Index	Fracture Energy, J/m^2	Slope
Predictors	**Range of predictors**		**Change**	**Change**	**Change**
%Passing #8 Sieve	Min	32	5.3		-4
	Max	51			
Binder Yield Energy to 2500% strain, kPa	Min	217	2.5	1121	
	Max	2426			
LAS Fatigue Law "A" in 10,000s	Min	146	-4.64		
	Max	9933			
LAS Fatigue Law "B"	Min	-4.40		780.6	-2.1
	Max	-3.03			
Aging, hours	Min	2	-4.2	-281	6
	Max	14			
Film Thickness, µm	Min	6.5		-468.9	-1.9
	Max	11.4			
Average Response			4.2	1463	5.3
Min Response			0.5	654	0.5
Max Response			15.5	2251	23.5
Standard Deviation Response			3.2	363	4.6

v. Low Temperature Performance of Mixtures

Thermal cracking is the primary distress in asphalt pavement at low temperature. In AASHTO M320 the Bending Beam Rheometer (BBR) is used to determine the low temperature grade limits based on the stiffness (S) and logarithmic creep rate (m). Both of these parameters are measured at relatively low levels of load and deformation; thus there is a concern that resistance to fracture (cracking or breaking) is not really measured [3]. In the original PG grading system an attempt to measure cracking was proposed by using the Direct Tension Test (DTT), but only a few State Agencies use the test today because the test implementation proved to be not feasible due to variability, sample preparation issues and amount of material and replicates needed.

During the last five years a bending test has been introduced and became a standard in Europe. The same bending concept was used in the US to propose a modification of the BBR to allow measuring fracture of a notched BBR specimen. The modified BBR that allows measuring fracture is called the Single Edge Notched Beam (SENB). Research work reported in the literature including a recent Wisconsin Highway Research Program (WHRP) project show that SENB can successfully discriminate between different materials and correlate well with pavement cracking behavior observed in the field [6]. The SENB procedure is proposed in this study as a candidate PG+ method to predict thermal cracking.

Currently there is only one SENB machine at the national scale that can run the test; mechanical drawings and manufacturing directions for the SENB are provided in Appendix 6 for reference. Due to the existing challenges in manufacturing the device in large scales there is a need to explore simpler alternatives for testing and evaluating binders at low temperatures. An attempt was made during this study to correlate simpler to run test methods with mixture results from the Asphalt Thermal Cracking Analyzer (ATCA). These efforts are summarized in a white paper attached as Appendix 5.

Based on the findings presented in the white paper, the following general conclusions are offered:

- The SENB test can be used to measure binder stress and energy at failure, which have superior correlations with asphalt mixture low temperature cracking indicators, as shown in Figure 12.

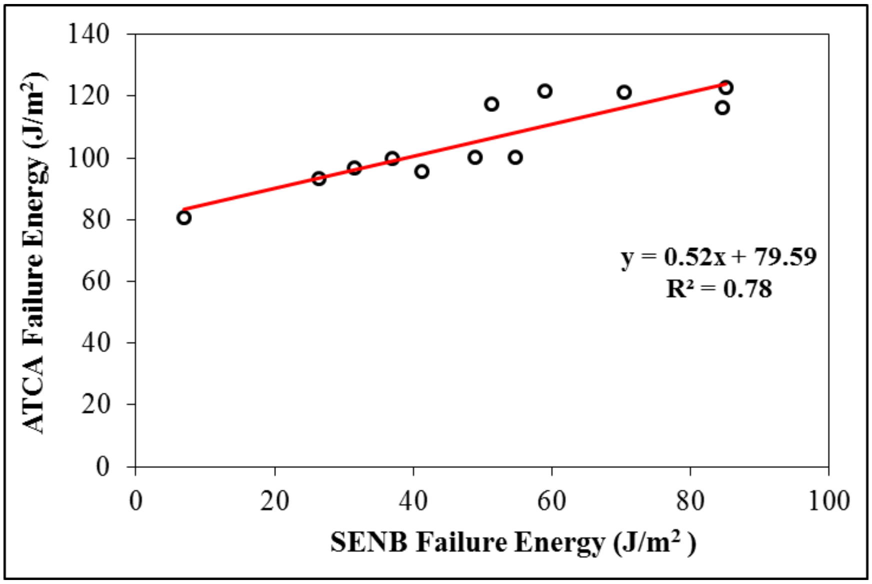


Figure 12. Correlation between mixture and binder failure energy for mixtures prepared with RAP only (no RAS).

- Since the SENB device is not readily available at this time, a combination of BYET binder properties and the ΔTc parameter measured by the BBR can provide an estimated value of the SENB Failure Energy. This estimated value can be used as a fair surrogate to the SENB test. A regression model to predict SENB failure energy is provided below:

$$SENB\ Failure\ Energy = 0.083 \times Strain\ at\ Peak + 0.911 \times Yield\ Enrgy - 5.122 \times LT\ Grade - 4.562\Delta T_c - 108.301$$

- It is apparent that binder properties alone cannot wholly predict the performance of mixtures at low temperature, and a combination of binder and mixtures properties is needed to better predict performance.
- Further analysis specifically on extended aging BBR and ΔTc evaluation can help partner states better understand whether or not the practice ready procedures (BYET and ΔTc) can be further considered for specification implementation.
- It is clear in this study that RAS and RAP could significantly change the relationship between binder fracture properties and mixture fracture properties. This issue is very important and deserves further study.
- Based on data collected to date, a minimum value of Failure Energy of binders measured in the SENB or estimated from the BYET and BBR of 40 J/m^2 could be proposed for specifications.

D. *Work Area 4: Identify Opportunities to Integrate Performance Based Acceptance into Current PG+ Procedures*

i. Pooled Fund Database

Throughout the duration of the Pooled Fund project, test results were tabulated into a database that will be provided to all member states as a separate attachment. The database is in a Microsoft Excel workbook that includes all testing results collected to date. There are two tabs in the workbook, one is labeled "Binder Database" and the other is labeled "Mixture Database." The Binder Database tab, containing all binder testing results, is organized by state supplier, PG grade, aging condition and testing method. Each binder and state is listed in the first two columns "A" and "B." All other binder testing methods included in this study can be found in the corresponding columns listed below:

- PG grading: C-AE
    - Standard PG grading is provided for binder types including: high temperature G*/sinδ, intermediate temperature G*sinδ, and BBR S and m values. Each testing method includes the experimental response and corresponding temperature for the measurement.
- Multiple Stress Creep and Recovery: AF-BA
    - Samples were tested in accordance with the AASHTO T350 with one additional stress level (10 kPa). This additional stress level does not affect the results of tests and was included to provide more information regarding the stress sensitivity of each binder. In addition, results were reported for binders tested in both the unaged and RTFO aged condition.
- Elastic Recovery DSR (AASHTO TP 123): BB-BK
    - All results reported were done so in accordance with AAHSTO TP123 and tested at a temperature of 25 °C. Binders were tested in both the RTFO and PAV aging condition.
- Binder Yield Energy Test measured at 4 °C (AASHTO TP 123): BL-CO
    - Binder Yield Energy Testing was conducted in accordance with AASHTO TP123. Three responses were reported in the database: Yield Energy, Energy to 2500% strain and the strain at peak stress. Only the yield energy and strain at peak stress are required to be reported in AASHTO TP123. Energy to 2500% strain was reported due to the positive results collected in this study. Results were reported in the RTFO and PAV aging conditions.
- Binder Yield Energy Test measured at 25 °C (AASHTO TP 123): CP-DS
- Linear Amplitude Sweep Test measured at 25 °C: DT-EM
    - LAS testing was completed after PAV aging and four parameters are reported in the database: N_f at 2.5% strain, N_f at 5% strain, fatigue law "A" parameter and fatigue law "B" parameter. N_f values are an indication of a binders damage resistance at the corresponding strain level. Fatigue law parameters can be used to estimate a binder's damage resistance at different strain levels varying from 1 to 10% strain.
- Linear Amplitude Sweep Test measured at IT PG: EN-FL
- Single Edge Notched Beam (SENB) Test measured at LT PG: FM-GD

- SENB testing was done using the porotype equipment available at the University of Wisconsin. More information regarding how the test is run and how to build the testing equipment can be found in the Appendix 6 and White Paper 3.

For each binder testing method, replicates were included to provide an indication of the variability. However, most of these procedures do not yet have specification limits or precision and bias statements. Results should be interpreted with these considerations in mind. Perceived high standard deviation values may be within acceptable precision and bias limits set based on future testing.

In the mixture performance data tab, there were two types of testing completed: Semi-circular bending Illinois-Flexibility Index Test (SCB I-FIT) and Asphalt Thermal Cracking Analyzer. As shown in the previous sections of the report, SCB I-FIT testing was completed after two aging conditions: short and long term aging. Therefore, the mixture database tab includes information for three different types of testing that each correspond to the state and binder in the same fashion as in the binder database tab. For each testing method, the experimental outputs and replicates are provided. The following lists the columns corresponding to each mixture performance parameter that can be found in the Mixture Database tab:

- Short term aging SCB results including fracture energy, flexibility index and post-peak slope: B-V
- Long term aging SCB results including fracture energy, flexibility index and post-peak slope: W-AQ
- Asphalt Thermal Cracking Analyzer results including: fracture temperature, fracture stress, glass transition temperature, liquid coefficient of contraction, glassy coefficient of contraction and fracture energy: AR-BQ.

Only the final results were reported for each test method included in both databases. However, more information can be interpreted from stress-strain curves, LAS fatigue law charts etc. Any additional information can be provided to member states upon request.

ii. Field Performance Trends

One objective of the Pooled Fund study is to validate selection of mixture and binder performance testing methods using field survey data. Binder-field survey correlations can provide evidence to support implementation of a candidate test method into state specifications. To date, two states of provided survey data for one mixture and field pavements for each state. Within in each survey, the following modes of distress were tabulated to compare with field binder testing results:

- High temperature rutting-total rut depth per mile
- Intermediate temperature fatigue cracking-square feet per mile
- Low temperature thermal cracking-transverse cracks per mile

For each of the distress type, binder tests were plotted versus the survey data based on each test methods targeted mode of distress. High temperature rutting, intermediate temperature fatigue cracking, and low temperature thermal cracking were correlated with MSCR Jnr, LAS N_f and SENB fracture energy in Figure 13, Figure 14, and Figure 15, respectively.

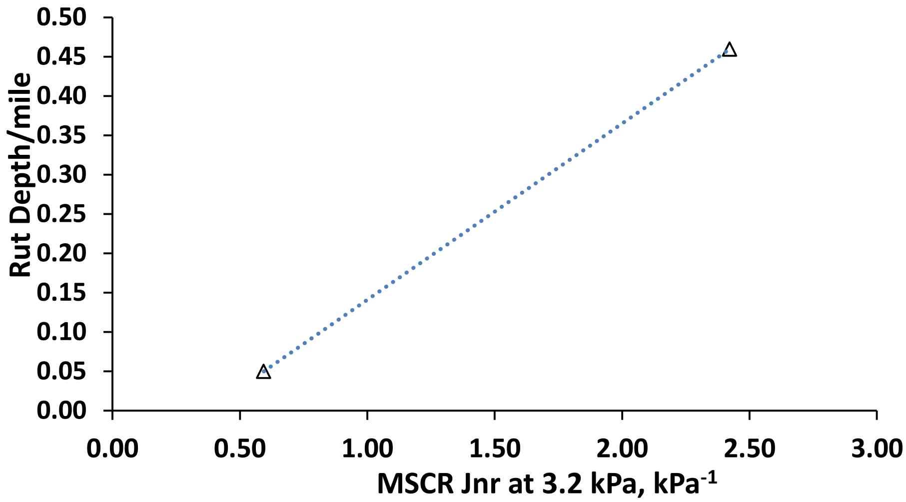


Figure 13. MSCR Jnr correlated with pavement rut depth per mile.

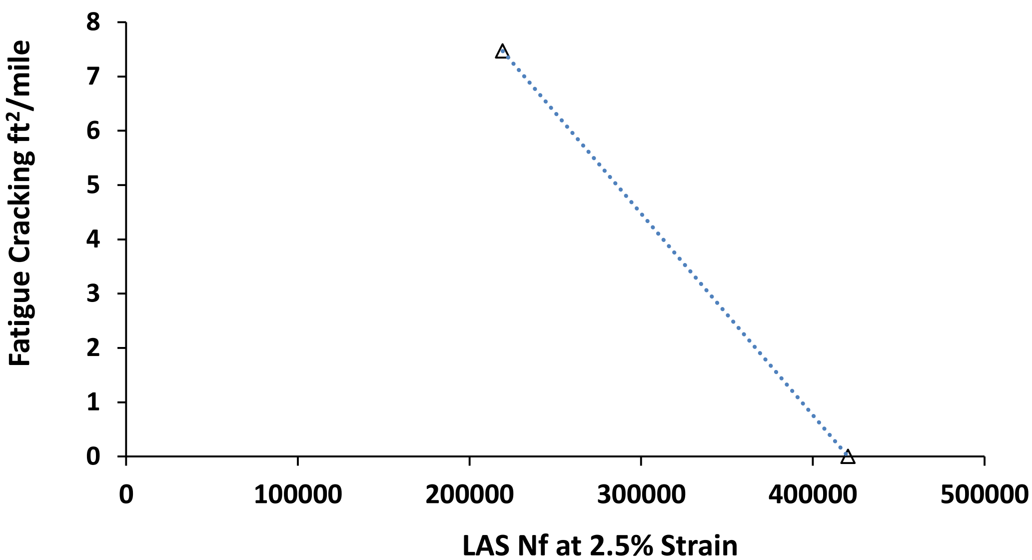


Figure 14. LAS Nf correlated with square footage of fatigue cracking.

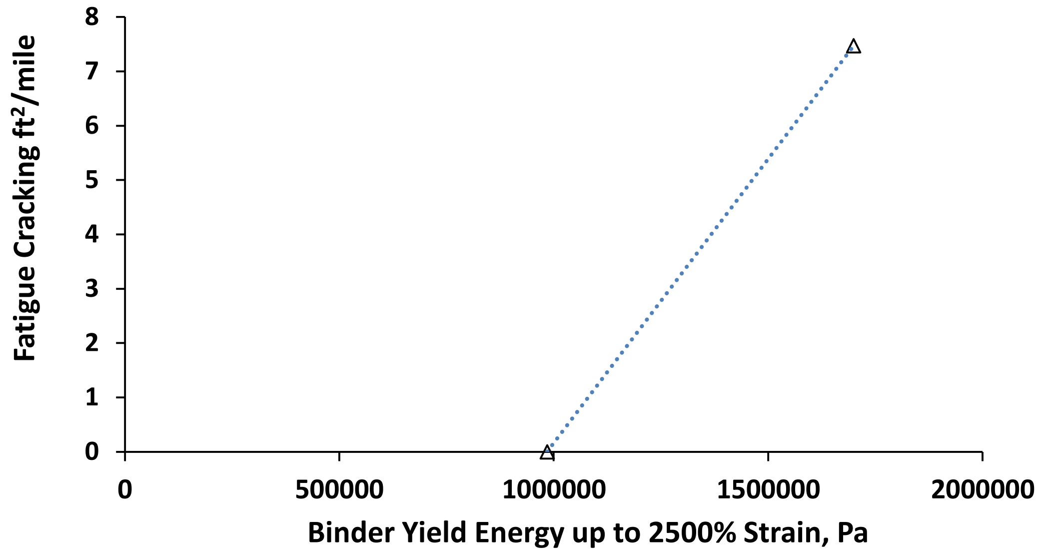


Figure 15. SENB fracture energy correlated with number of thermal cracks per mile of pavement.

Results from the field survey collection data show logical trends for the high and low temperature test results MSCR and SENB results that are in-line with the conclusions summarized in the White Papers. For high temperature MSCR Jnr values correlate with the rutting performance as higher values show more rutting. For the low temperatures, the SENB fracture energy values decrease with more field cracking. However, the intermediate temperature binder properties (LAS Nf at 2.5% strain) and mixture/field fatigue cracking performance do not appear to be related. Despite the agreement in trends for the high and low temperatures, the current field survey data set is too small to draw any meaningful conclusions. In addition, effects due to traffic and pavement age are not considered in this analysis. Researchers recommend additional pavements be surveyed and traffic information be provided before validating the existence of relationships between mixture and binder testing results.

iii. Modified Binder Characterization and Quality Control Specification

Based on the results of this study it is recommended that for Quality Control purposes the current PG+ tests that are used by the Partner State Agencies be replaced with the new DSR based tests as listed in Table 12. The tests are all based on the original binder and the RTFO-aged since the intention is not to test the meeting of the specifications but to ensure consistency of the binder properties. The main changes are replacement of the Ductility standard test with the BYET Strain at Peak stress, replacement of Toughness and Tenacity with the BYET Yield Energy, and replacement of the Elastic Recovery (T301) with the DSR-ER test.

It should be noted that the temperature for testing the BYET is proposed to be at 3 °C lower than the PG-IT since it is observed that some modified binders do not show clear stress peak and thus do not allow clear definition of strain value at peak-stress. In addition, no limits are specified for the BYET test since these limits will have to be determined based on testing binder supplies in each State.

Table 12. Recommendations for Quality Control Tests for Modified Binders

Property		Test Method	Colorado	Idaho	Kansas	Ohio	Wisconsin
Original							
MSCR	**@ Climate Temp.**	**T350**	**X**	**X**	**X**	**X**	**X**
Specific Gravity	15.6°C	D70	-	-	-	-	Report
BYET Strain at [(1)] Peak Stress, %	**IT PG-3 °C**	**TP123**	**__ min**	**-**	**-**	**__ min**	**-**
BYET Yield [(2)] Energy, Pa	**IT PG-3 °C**	**TP123**	**__ min**	**-**	**-**	**__ min**	**-**
Separation of Polymer, °F		D5976	-	-	2 max	10 max	-
Solubility, %		D5546	-	-	-	99 min	-
Homogeneity (Screen Test)			-	-	-	X	-
Acid or Base Modification		CP-L	Pass	-	-	-	-
RTFO Residue							
ER DSR, % [(3)]	**25°C**	**TP123**	**38 min**	**38 min**	**32 min**	**57 min**	**51 min**
BYET Strain at [(1)] Peak Stress, %	**IT PG-3 °C**	**TP123**	**__ min**	**-**	**-**	**-**	**-**

[(1)]: This parameter replaces Ductility test , [(2)]: This parameter replaces Toughness and Tenacity, [(3)]: This parameter replaces Elastic Recovery in the Ductility bath (T-301)

Proposed Research Extension Plan

The intention of the Pooled Fund 0092-14-20 work plan was to meet the following research objectives:

- Perform detailed assessment of current PG+ and modified binder quality control procedures in terms of reliability, applicability, and relevance to performance.
- Use a range of modified binders to develop unified test procedures and specification criteria based on products placed in the field.
- Improve product quality and reliability through ruggedness studies and development of precision and bias statements for selected tests.
- Introduce consistency to current products supplied by elimination or reduction of differences in modified binder acceptance and criteria.
- Validate and establish relevance of suggested PG+ and quality control procedures in terms of mixture performance.

To date, the research team in support of these objectives has generated three reports and three white papers. Presentation of these update reports ("Task Reports") has prompted discussion of refined research topics to address immediate needs of the Pooled Fund member states. In order to address these refined research topics directly, an extension of this research outside of the current scope of work is proposed. The intention of this section is to propose extension research topics that require additional testing past December 31st. This proposal is a working draft and the input of member states is required to refine extension topics and commit funding.

Extension research topics were identified based on significant findings from preliminary data reported as well as key discussion points from previous teleconference calls with member states. The extension research topics can be categorized into four working tasks:

1. Evaluating the effects of RAP and RAS on linear blending charts including PG+ and developmental binder test methods.
2. Evaluating low temperature binder modification (e.g. oils) on PG+ and developmental binder methods.
3. Expansion of the current binder database.
4. Expansion of mixture database to include low and high performing mixtures to validate proposed PG+ specification limits.

After presenting each of the proposed research topics above, it was found that that investigation of RAP and RAS blending and low temperature binder modification were of more interested to the member states. Therefore, these two topics were prioritized in order of interest. A brief description of each topic is shown below.

A. Results of Preliminary Evaluating the Effects of RAP and RAS on PG+ Binder Tests

Based on discussion during a recent conference call, member states indicated the importance of including recycled materials into the development of a binder specification. Nearly all Hot Mix Asphalt materials produced in the United States contain a percentage of recycled asphalt materials (RAM). Accepted implications of adding RAM into asphalt pavements is an increase in rutting resistance with a reduction 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. DOTs often specify that softer grades of asphalt binder be used with high RAM mixtures to offset the negative consequences of heavily aged recycled binder. In practice mixture designers use simple blending charts to interpolate the effects of recycled materials on blended binder properties. These charts are very useful to understand the effects of RAP on unmodified binders. However, blending charts may not be applicable for blending between Polymer Modified Asphalt (PMA) and recycled binder. Furthermore, it is unknown whether linear blending is appropriate for PG+ or other binder test methods.

To accomplish this task, PMA binders collected from member states will be blended with extracted or heavily aged binders at several concentrations and tested using proposed PG+ and/or developmental test methods. This will allow researchers to determine if linear blending applies to selected test methods and provide guidance to member states for incorporating RAM into their binder specification. To understand the importance of this research topic, UW researchers sampled a select subset of mixtures to extract, recover, and test using PG and PG+ methods included in this study. Results collected from the extracted binder were then compared with RTFO binders tested. PG grading and percent binder replacement results for high temperature PG grading are shown in Figure 16**.**

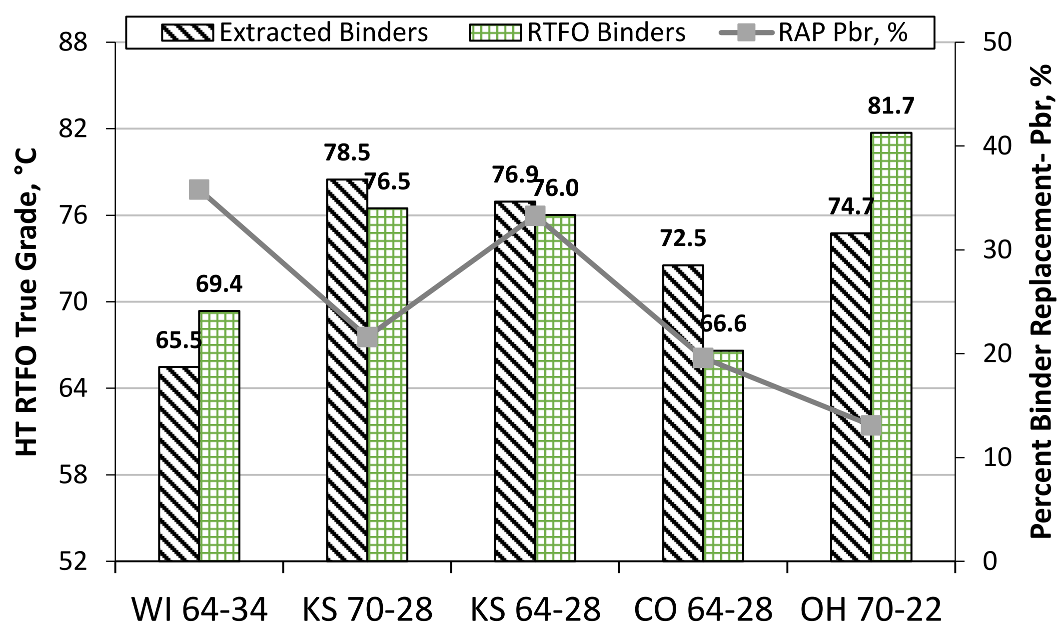
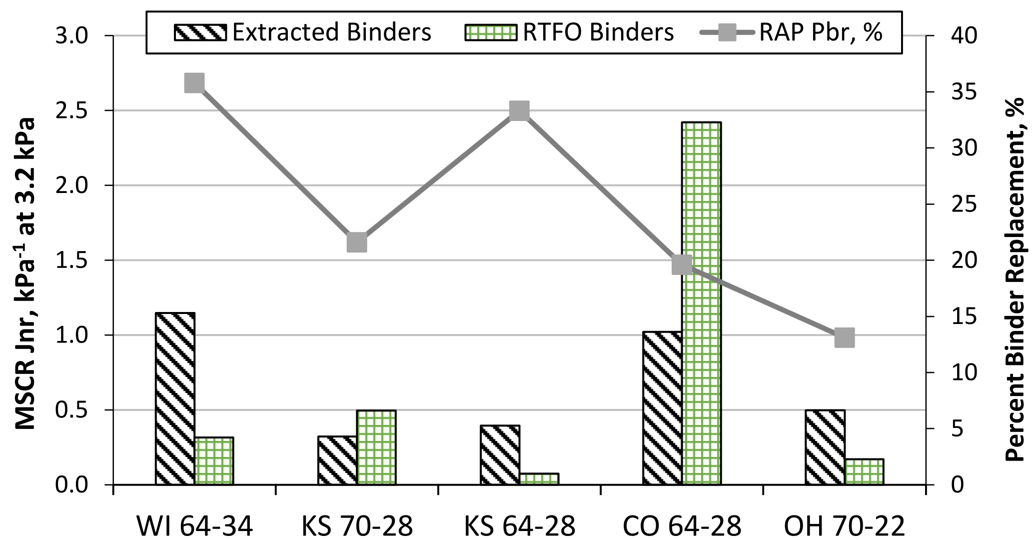


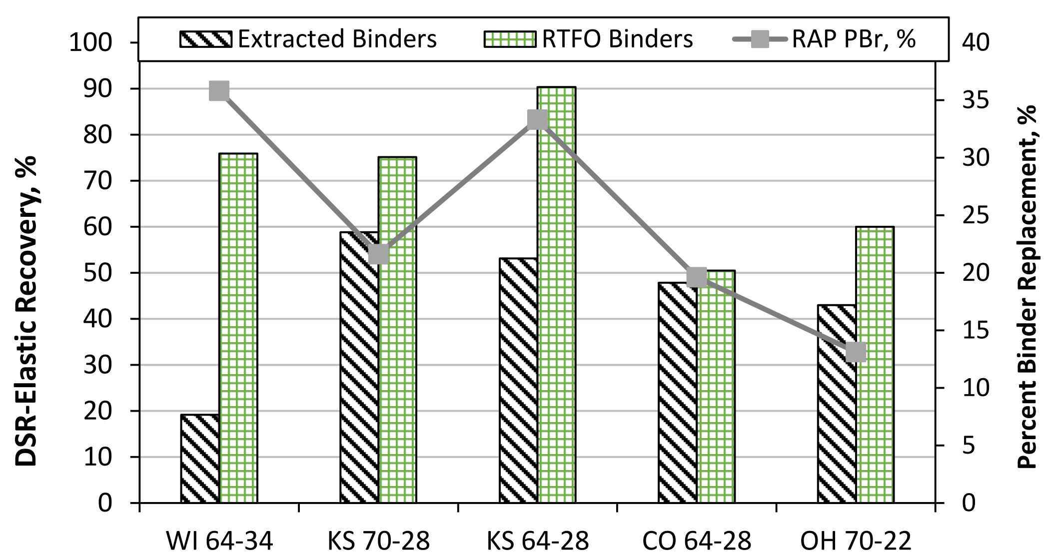
Figure 16. RTFO continuous grade (true grade) of extracted binders compared with RTFO binders.

From Figure 16, it is clear that there is an inconsistent trend with respect to grade of the extracted recycled asphalt binder the grade of fresh binder used in the study. In fact, two of the binders (WI64 and OH 70) had a significantly higher RTFO continuous grade than the extracted binder. These findings highlight the importance of not only the RAP content, but also the RAP quality. For example, the KS 64-28 mixture contains a relatively high recycled asphalt binder replacement of 30%, but shows a comparable PG grade to the RTFO binder. On the other hand, the CO64-28 binder has a percent binder replacement of 20% with a PG grade difference of 6°C between the RTFO and extracted PG binder.

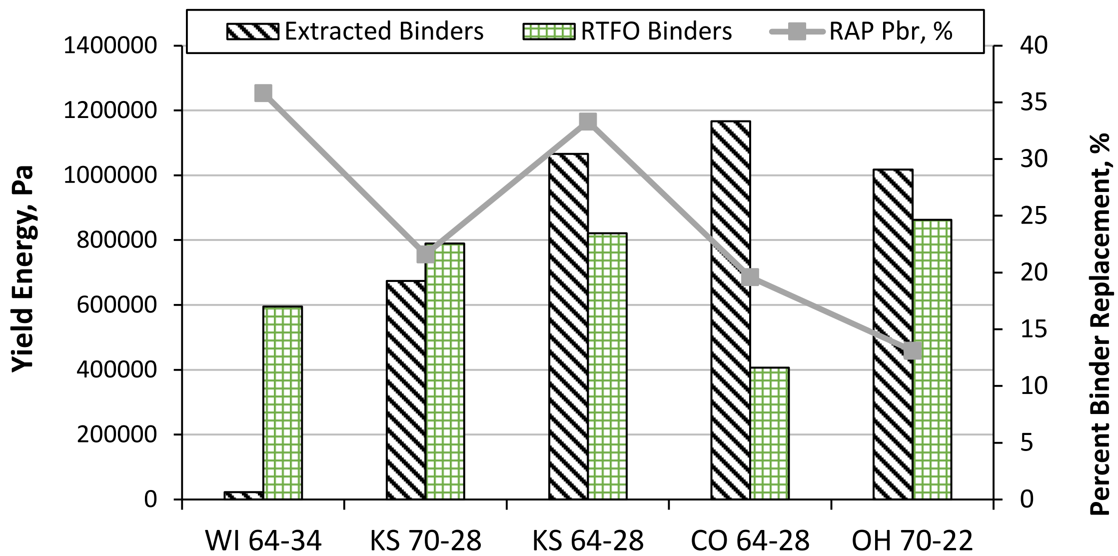
There are several factors that can cause these inconsistencies: production temperature, fresh binder aging sensitivity, RAP binder age, RAP binder aging sensitivity, extent of blending between the RAP and fresh binder, etc. Through an extended work plan, UW researchers can investigate this relationship using not only PG grading techniques, but also incorporate candidate testing methods such as the MSCR, ER DSR and BYET testing methods. The preliminary results for the same binders tested for these methods are shown in Figure 17, which includes the relationship between the extracted and RTFO aged binders using the aforementioned MSCR, ER DSR and BYET procedures, respectively.



(a)



(b)



(c)

Figure 17. Relationship between extracted and RTFO aged binders as measured by MSCR (a), ER DSR (b) and BYET (c) test methods.

The contribution of RAP binder properties for each testing method is not consistent across each binder testing method. Results confirm the importance of understanding the extent to which RAP binder properties affect the performance of the composite (blended) asphalt binder in the pavement. UW researchers can investigate this topic in order to provide guidance regarding specification development of binders used in mixtures containing Recycled Asphalt materials (RAM) and re-evaluate the correlations with mixture performance presented in this report.

B. Effects of Low Temperature Modification Technologies on PG+ and Development of Test Methods

As an alternative to using a softer base binder grade for mixtures containing RAM in cold climates, using a low temperature modifier, such as an oil or rejuvenator, is becoming more popular. Although many of the binders using oil modification continue to meet PG specifications, observation of field performance has indicated an increasing number of pavement failures that can be attributed to asphalt binder. Additional testing will focus on understanding the implications of oil modification using selected PG+ or new damage characterization testing methods. The objective of this task is to capture the unique performance properties of oil modified binders that may relate to pavement performance, such as tackiness or cohesion of asphalt binders. In addition, this topic can be tied to RAP/RAS extension to help understand how oil modification affects the blending of recycled and fresh asphalts.

To accomplish this task, a survey will be sent to partner states to identify low temperature modifiers that are being used in their region. Modifiers identified by member states will be collected and blended with typical asphalt binders at MARC laboratories. MARC has done extensive testing with oils and has identified test methods that may distinguish between the performance of different types of low temperature modifiers. This information will be compared against an unmodified soft binder in order in order to make recommendations to partner states regarding what test methods/properties of oil modified binders can indicate high or low pavement performance.

C. Expansion of the Binder Testing Database

Testing to date has only taken into consideration three PMA asphalts from each partner state. Data collected from testing each binder has shown that current PG+ tests can be replaced by DSR based methods. However, if states are to consider implementing DSR based PG+ or other binder characterization tests, more data will be required from typical binders produced in each partner state. This is important for member states that run different versions of a particular test, such as T301 recovery. To support implementation of different binder characterization tests, it proposed that samples of asphalt binder certified by each respective DOT for the upcoming paving season be sent to the University of Wisconsin to expand the amount of data points for each correlation. UW researchers will then generate an expanded binder database for all partner states. From the databases, more robust specification limits can be set to ensure that future PMA binders are at least equivalent in performance relative to the binders currently used in each respective state.

D. Expansion of the Mixture Performance Database

The purpose of mixture testing is to establish and validate relevance of suggested PG+ and quality control procedures in terms of pavement performance. Based on the results of this task, the research team can propose initial limits for the selected binder test methods. Three mixture performance tests have been selected for the current research to better understand the relationship between binder tests and mixture cracking resistance tests. Incorporation of poor performing as well as high performing mixtures will help determine whether the proposed mixture test methods can predict failure. In addition to the ongoing mixture tests, more mixture testing methods may be included to get a more comprehensive understanding of how each mixture performs.

To accomplish this task, a survey will be sent to partner states to identify mixtures or mixture designs that resulted in premature failure. The findings from phase II will allow for an initial development of specification limits. However, poor performing mixtures are needed to make the specification limits more robust. Researchers will recreate these poor performing mixtures in the laboratory to compare binder and mixture test results. The expected outcome is the identification of binder test methods that best characterize mixture performance and establishment of specification criteria for these test methods.

E. Project Budget Review

The budget for the current Pooled Fund work plan is $195,686. An additional $25,000 per year is required by each member state per year to continue the Pooled Fund project up to Five years; two of which have been completed. In order to continue researching the extension topics outlined in this proposal, annual commitments will be used to budget a work plan. Member state's feedback is requested to prioritize the research objectives to accommodate the future budget. After prioritizing the research objectives, MARC researchers can provide more detailed budgets for completion of each new research topic. Member states are encouraged to commit more funding before the project finish date (December 31st) to ensure all of the objectives can be executed. Table 13 shows the summary of commitments from each state DOT member to date.

Table 13. Summary of commitments taken from Pooled Fund website.

Agency	Year	Commitments
Colorado Department of Transportation	2015	$25,000.00
Colorado Department of Transportation	2016	$25,000.00
Colorado Department of Transportation	2017	$25,000.00
Idaho Department of Transportation	2014	$25,000.00
Idaho Department of Transportation	2015	$25,000.00
Idaho Department of Transportation	2016	$25,000.00
Kansas Department of Transportation	2014	$25,000.00
Kansas Department of Transportation	2015	$25,000.00
Kansas Department of Transportation	2016	$25,000.00
Ohio Department of Transportation	2014	$25,000.00
Ohio Department of Transportation	2016	$25,000.00
Wisconsin Department of Transportation	2014	$25,000.00
Wisconsin Department of Transportation	2015	$25,000.00

F. Summary

Extension research topics identified in this report may be valuable to member states to further the validation of binder testing and limits recommended in this study, and to include important influence of RAM and softening oils. Some of the Pooled Fund Study members have already committed new funding for 2016 and 2017; UW researchers would like to request review of the proposed research topics and current budget by the Pooled Fund members. Proposed research topics can be pursued pending approval from the partner states that would like to commit or release funds for future testing.

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Appendices

A. *Appendix 1: Task Report: Work Area #1- Literature Review and Survey Summary*
B. *Appendix 2: White Paper on Analysis of MSCR Parameters as Related to Specification Development and Performance*
C. *Appendix 3: Task Report: Work Area #2- Candidate Replacement and Supplemental Binder Test Methods*
D. *Appendix 4: White Paper on: Evaluation of Intermediate Temperature PG and PG+ Test Methods for Fatigue and Durability of Asphalt Binders*
E. *Appendix 5: White Paper on: Evaluation of Test Method Alternatives for Thermal Cracking Characterization of Asphalt Binders*
F. *Appendix 6: Single Edge Notch Beam (SENB) Device Auto-Cad Drawings*
G. *Appendix 7: Ruggedness Analysis of AASHTO TP123 Procedures: Binder Yield Energy and Elastic Recovery DSR test methods.*
H. *Memorandum on AASHTO TP123, Method B: Initial Assessment of Repeatability and Reproducibility, Comparison to T301/D6084, and Refinement of Procedure to Reduce Testing Time*