(0092-14-20)

TPF-5 (302)

Modified Binder (PG+) Specifications and Quality Control Criteria

Task Report:

Work Area #1

Erik Lyngdal
Cheng Ling
Ryan Sylla
Puya Teymourpour
Hussain U. Bahia
University of Wisconsin-Madison

August 2015

Contents

1. Introduction

The aim of the Pooled fund 0092-14-20 project is to provide essential information to state Department of Transportations (DOT) for five partner state agencies (Wisconsin, Ohio, Kansas, Idaho and Colorado) to support evaluation and standardization of PG plus specifications. Each PG plus test was critically examined for testing variability and correlation to actual mechanical behavior and field performance of asphalt materials. Based on needs and goals of each partner DOT, the main objectives of the proposed pooled fund research 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, 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.

To meet the aforementioned objectives, the project was broken down into the four primary **Work Areas**. After completion of each work area, MARC researchers are expected to produce task reports that document the work performed in the respective work area.

This document is a task report that fulfills objectives in **Area #1** of the work plan. Based on the description of **Area #1**, the report is organized into two sections: (1) Literature Review and (2) MSCR Commentary. The Literature review section includes survey responses provided by Pooled Fund Member states and a review of each PG+ test used by the partner states in an effort to improve each Pooled Fund member's understanding of current PG+ tests and, if needed, identify potential tests or analysis methods to improve the current state of practice. The MSCR commentary section includes a description of the current implementation process according to the AASHTO M 332 standard and information about the advantages and deficiencies of the MSCR procedure with supporting literature and analysis of data collected from the various MARC research projects.

2. Survey and Literature Review

Before recommending changes or alternatives to the current PG + test methods, PG+ tests used by the partnering states were identified and investigated to understand how each test was developed. In addition, literature citing correlations with field performance and apparent short comings for each test method were identified and described. Table 1 provides a summary of the current PG+ tests used by the respective Pooled Fund member's state.

Table 1: summary of current PG+ tests implemented by respective Pooled Fund Members state DOT.

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	-	-	-	-	-

In order to understand why each of the PG+ tests were implemented, a questioner was distributed to Pooled Fund members. The questioner is attached to this report in Appendix A; three main questions were asked for each PG+ test:

- What is the objective for implementing the current PG+ test (i.e. what type of failure is it preventing) and is there clear evidence that the test method can meet the objective?
- Can they agree on one method per specification objective and do we need an AASHTO standard for the selected method?
- Can they agree on a uniform set of specification limits and how do they think limits should be derived (i.e. field performance, mixture data or expert opinion)?

Responses received from different partner state agencies are summarized in Table 2. The results of the survey indicate, in general, that each state primarily uses PG+ test to identify or ensure that certain polymer additives are blended into the asphalt binder. In addition, each Pooled Fund member expressed a willingness to adopt new test procedures that have a higher correlation with actual field performance. Although different states have adopted different PG+ test methods or limits, the objectives are similar in all cases and each member is willing to consider better tests and more uniform specifications.

Table 2: Summary of Questionnaire Responses from Different Partner State DOTs

Test Types	State	Reasons for Selection	Comments
Elastic Recovery	Ohio	Durability, More Polymer is better	• Used it for 20 years • Would like to replace with MSCR • Do not want to stay with current procedure
	Colorado	Presence of Polymer, Distinguished between modified and unmodified	• Test too long • Prefer a better test • Would like to stay at 50%
	Kansas	Ensure Polymer modification rather than PPA & GTR, Good experience with PMB	• Consider DSR only if it is repeatable/reproducible and give the same polymer loading as ER
Phase Angle	Wisconsin	Polymer Loading	• Moving to MSCR in 2016
	Ohio	Polymer Loading	• Willing to consider MSCR but would like to see the test run on original rather than RTFO • Use it in combination with ER
Ductility	Ohio	Specifically to allow using SBR which fails the ER	• DSR or MSCR will be preferred • Minimum 3.5% SBR
	Colorado	Done at 4C to control thermal cracking	• Would consider a new method if performance related
Toughness and Tenacity	Ohio	Same as ductility	• Same as Ductility
	Colorado	Presence of Polymer	• Willing to change it to a new test method
Separation of Polymer	Kansas	Avoiding using GTR and have the polymer stable	• No comment
	Ohio	Prevent cheap formulation	• Could be DSR based but softening point is easy
Acid or Base Modification	Colorado	Avoiding PPA	• No comment
Solubility	Ohio	Avoiding clay and Refined Motor Oils	• FTIR and XRF are too expensive
Homogeneity	Ohio	Avoiding non blended polymers	• FL microscope is pretty simple

Based on the summary of tests currently used (Table 1) and the results of the survey, five PG+ test methods were selected for detailed investigation in order to understand the advantages and possible deficiencies. These include: phase angle, elastic recovery, ductility and toughness and tenacity (T&T). In the subsequent sections, the literature review is summarized for each test method. Each PG+ test section describes the development/intention for implementation, cites any literature correlating the test to field performance, identifies apparent shortcomings of each test and summarizes the most significant findings.

2.1 Elastomer Modifier Indication- Phase Angle and Elastic Recovery

Phase angle and Elastic Recovery (AASHTO T 301) were combined in the literature review process because they have both been implemented to indicate presence of an elastomeric polymer. Asphalt pavements that incorporate binders modified with elastomers tend to have a higher elastic properties, which can increase pavement performance. Although both test methods are used for the same application, Phase angle and Elastic Recovery measurements do not represent identical binder properties. Phase angle is measured at high pavement service temperatures and elastic recovery is measured at 25 °C. Asphalt binders are temperature dependent materials, and the phase angle measured at 25 °C will be widely different than that measured at high in-service temperatures. The following sections only considers each test methods applicability as an elastomer indicator and the implications of modifying binders with elastomers.

2.1.1 Phase Angle

Phase angle (δ) is defined as the lag between the applied shear stress and the resulting shear strain of a dynamically loaded material, as shown in Figure 1. Phase angle is an important parameter describing the viscoelastic nature of a material such as asphalt binder.

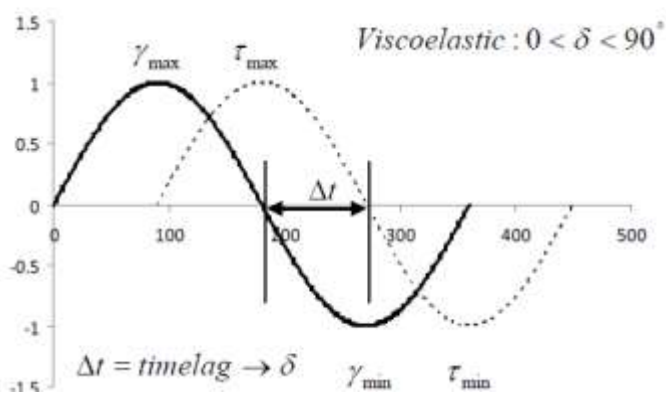


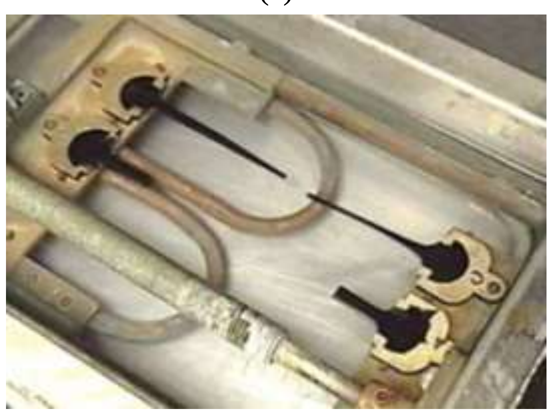
Figure 1: Illustration for how phase is calculated from dynamic shear rheometer (DSR) testing.

The larger the phase angle, the more viscous the material; the lower, the more elastic the material. Phase angle can be obtained from Dynamic Shear Rheometer (DSR) testing using typical PG grading test methods. AASHTO T315 and ASTM D7175 outline the testing procedures for measurement of phase angle of asphalt binder. When elastomers are used as a modifier, the phase angle is expected to decrease. Therefore, agencies specify a maximum phase angle at high temperatures to ensure binder modification with elastomers. Among the five partner states, Ohio and Wisconsin specify the limits for phase angle. In Ohio and Wisconsin a maximum phase angle of 76 to 80 and 73 to 79 depending on the required PG grade is specified, respectively.

2.1.2 Elastic Recovery

Elastic recovery (ER) is the degree to which a material recovers to its original shape after release of stress. The ER is measured with the ductilometer following the procedures specified in AASHTO T301 or ASTM D6084; the apparatus is shown in Figure 2. The test is typically performed at 10°C or 25˚C on RTFO aged material at an elongation rate of 5 cm/min to an elongation length of 10/20 cm. In the ASTM method, the samples are cut immediately after 10 cm elongation while the AASHTO method requires a 5-minute wait period after 20cm elongation before cutting. ER has been used to test for the presence of elastomers by many state agencies across the country. A state agency will allow a modified binder if it produces an elastic recovery greater than an agency specified percentage of recovery. In this study, all five partner states use elastic recovery requirement in testing of modified asphalt. Among the five states, only Kansas adopts testing procedures in ASTM D6084 while the others use AASHTO T301. For the specification limits, various values are specified by each state such as 50% (min) for Colorado, 50% (min) for Idaho, 60% (min) for Kansas, 65% (min) for Ohio and 60% (min) for Wisconsin.

(a)



(b)

Figure 2: Elastic Recovery test apparatus: (a) sample molds and (b) samples being tested

2.1.3 Correlations with Performance

As previously mentioned, the primary objective of both Phase Angle and Elastic Recovery is to indicate the presence of an elastomeric modifier. Elastomers, as implied in the name, are used to increase asphalt binder elasticity, but they also increase viscosity and stiffness at high temperatures. Highly elastic materials can withstand large deformation and recover to their original shape after loading. In pavement applications, high elasticity may contribute to prevention of permanent deformation failure at high temperatures and are claimed to help reduce fatigue cracking at intermediate temperatures. Therefore, there is a general perception that elastomers can increase pavement performance when used to modify asphalt binders.

Despite the perception of elastomers and mixture performance, the relationship between binder elasticity and mixture performance is not clear. Golalipour correlated an increase in asphalt binder elasticity to an increase in high temperature mixture performance, but it was found to be statistically insignificant excluding other material property factors from the analysis [1]. High temperature performance was found to be a function of asphalt binder properties and aggregate structure or gradation factors. Arshadi conducted rutting finite element simulations that indicated the creep compliance of an asphalt binder at high temperatures has a larger effect on rutting resistance relative to high temperature elasticity [2]. The higher an asphalt binder's creep compliance, the higher the susceptibility to rutting. There has been very little research that directly correlates binder elasticity and mixture performance, but different studies have shown that elastomers increase asphalt mixture performance in the laboratory and field [3, 4, 5]. Whether this effect is due to increase in stiffness (reduction in creep compliance), increase in elasticity, or both, is not clear.

Al-Hadidy et al. investigated the performance of Stone Matrix Asphalt (SMA) asphalt mixtures that were modified with tri-block SBS [4]. Wheel tracking, moisture damage, flexural strength, and resilient modulus mixture performance tests were conducted on one SMA mixture with and without SBS. Wheel tracking tests were conducted at high temperatures to measure the potential benefits of SBS on rutting resistance. A 79.8% reduction in rutting rate was observed for the modified mixtures. Moisture damage testing was done by calculating the tensile strength ratio (TSR) after and before saturating asphalt mixtures in water. Lower moisture susceptibility was observed for the SBS modified mixtures. Flexural testing was conducted to measure the low temperature stiffness modulus and modulus of rupture at -10, -20 and -30 ^{o}C. A marginal increase in stiffness modulus and modulus of rupture was observed for the SBS modified mixture. Resilient modulus testing was conducted at 25 ^{o}C. Results showed a 39.4% increase in modulus of rupture with SBS modified binder. Overall, the SBS modified mixture resulted in a higher performing mixture when compared with the unmodified mixture. The study did not elaborate, however, whether this improvement is due to increase in stiffness or due to elasticity.

Although some studies have shown improved performance of asphalt mixtures with SBS modified binders, the amount needed to achieve improvement is not clear; Khodaii et al. conducted dynamic creep tests on SBS modified as mixtures with three different concentrations of polymer: 4, 5 and 6% [6]. Dynamic creep tests were conducted at high temperatures to target the rut resistance of SBS modified mixtures. Results showed that the 5% SBS modified mixtures showed the highest resistance to rutting resistance. In all cases, the SBS modified binder improvement rutting resistance, but there was not a linear relationship between SBS concentration and rutting resistance. Therefore, simply indicating the presence of a polymer does not guarantee the maximum level of mixture performance is achieved.

In addition to the selection of appropriate elastomer concentrations, the morphology of elastomers has been shown to drastically impact the resulting performance of asphalt mixtures. D'Angelo compared the relationship between SBS morphology in terms of ER percent recovery and MSCR percent recovery [7]. Table 3 shows that the MSCR percent recovery is much more sensitive SBS morphology and when compared with ER percent recovery.

Table 3: Data showing differences between SBS morphology as measured by the MSCR and Elastic Recovery.

Sample ID	Continuous PG Grade	Polymer Content	PPA(%)	Temp(°C)	J_{nr} at 3.2 kPa	% Recovery at 3.2 kPa	ER (%)
LC	66.7-24.1		0	64	3.1	0	5
LC 4	75.7-22.3	4% linear SBS	0	70 76	1.9 4.6	19.2 6.0	73.8
LC 4P	81.2-22.2	4% linear SBS	0.50	70 76	1.1 2.4	28.4 20.6	93.8
LOP 4	76.6-25.2	4% radial SBS from concentrate	0	70 76	1.2 2.4	40.3 37.0	86
LOP 4P	81.6-24.5	4% radial SBS from concentrate	0.50	70 76	0.7 1.4	52.1 42.5	91.6

For binders used in this study, all of the SBS modifiers would pass their respective state elastic recovery requirements while the MSCR percent recovery varies widely based on modification type. A different study conducted by Hanyu et al. furthered this concept by comparing the effects of SBS morphology and concentration on mixture performance [8]. Figure 3 shows mixture bending beam fatigue results for two different types of SBS morphology and concentration.

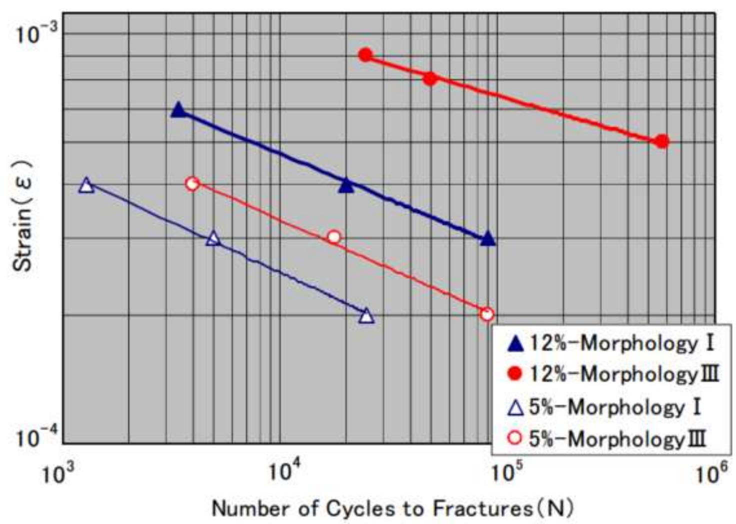


Figure 3: Relationship between SBS morphology and concentration and asphalt mixture bending beam fatigue performance.

Results show that as the concentration of SBS increases so does the bending beam fatigue life, but SBS morphology III shows significant improvement in fatigue performance when compared with SBS morphology I. Results of both studies by D'Angello and Hanyu suggest that the extent to which elastic recovery is increased with elastomers does not necessarily indicate the potential improvement in mixture performance.

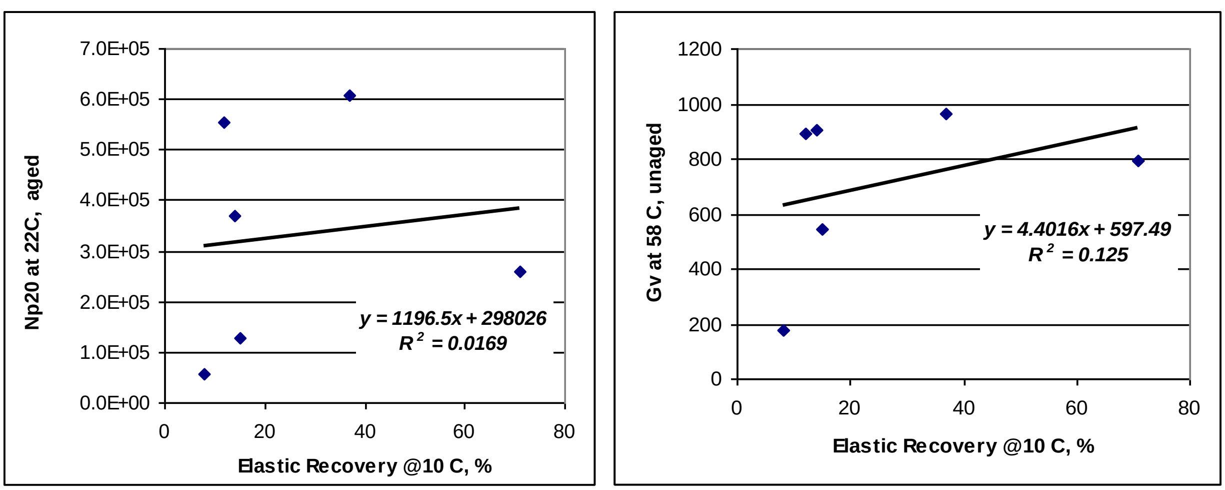
Aforementioned studies have all shown the potential benefits of elastomeric modification, but there is no clear relationship between elastic recovery and mixture performance. In fact, no literature could be found to directly correlate mixture performance to elastic recovery measured using the ductilometer. If an alternative elastomer indication test is desired by the Pooled Fund member DOTs, elastomer morphology and concentration should be considered to help understand to what extent performance is improved with modification.

2.2 ER and Phase Angle Tests' Shortcomings

There are three general shortcomings associated with elastomer indicating tests: 1) elastomer binder modification does not ensure that performance is equal to or better than binders using other types of modifiers/additives, 2) the test does not directly address a specific mode of failure since it is not clear how elasticity contributes to rutting or fatigue resistance, and 3) more time and money are required to use additional testing apparatus.

There are several different types of additives in the asphalt industry that can be used to increase pavement performance. For example, there are plastomeric polymers, recycled tire rubber, oil modifiers, warm mix additives, and acids. With the exception of tire rubber, all of the other additives will not increase the Elastic Recovery of asphalt binders while providing performance related benefits. If a phase angle is specified, plastomeric polymers can be used to reduce the phase angle of an asphalt binder; which is a false indication of an elastomer. Therefore, two binders can be modified to achieve the same phase angle, but may result in different pavement performance.

Common types of failure in pavements include: rutting, fatigue cracking, thermal cracking and moisture damage. Each mode of failure has a unique mechanism and thus one type of polymer or additive is unlikely to help prevent all modes of failure. Elastic Recovery and Phase Angle cannot quantify the extent to which each additive improves performance. For example, fatigue cracking in the asphalt pavement layer is the result of repetitive loading due to traffic and/or temperature changes [9]. There are a few studies that have attempted to study the relationship between ER and performance. Kamel et al studied a number of binders and compared to results of fundamental binder tests for fatigue and rutting. The results are duplicated in Figure 4, which shows lack of any relationship with the ER. In addition, a more recent study by Daranga and Clopotel conducted fatigue simulating binder tests in the DSR and observed a relatively low correlation between binder fatigue and elastic recovery measurements [10].



(a) Fatigue Performance Np20 (Np20= Number of cycles to 20 % damage)

(b) Rutting Parameter (Gv) (Gv = Viscous Component of Creep Stiffness)

Figure 4: ***Lack of Correlation between Elastic Recovery and Binder Performance Characteristics (a) Binder Fatigue (b) Binder Rutting (After Kamel et al, 2004)***

The third shortcoming is related to the Elastic Recovery Apparatus and the agreement among agencies on the method of measurement. As shown in Figure 2, the ductilometer requires large water bath that must be maintained at a constant temperature for approximately 2 to 3 hours to complete the testing. In addition, there is no agreement on the best test method and limits to be followed in the specifications. Table 4 is a list of the various procedures, conditions and limits used by the North East Asphalt User Producer Group (NEAUPG) as reported by C. Mooney in 2005.

Table 4- ER Procedures, Conditions, and limits as reported the NEAUPG (Mooney 2005).

Specs	AASHTO T301	ASTM D6084	LC25-005 Quebec	ASTM D6084 PADOT	ASTM D6084 NJDOT	ASTM D6084 Mod. AASHTO T301 - NY
Sample Elongation	200 mm	100 mm +/- 25mm	200 mm	100 mm +/- 25mm	2 in/min	100 mm
Sample Hold Time	5 min	Immediate Cut	5 min	Immediate Cut	90 min	None
Relaxation Time	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour
Min. ER			40% & 60%	60%	50%	60%
Test Temp.	25 °C Standard	25 °C Standard	10 °C	25 °C Standard	25 °C	25 °C
Cutting Clips	Straight	Straight	Straight	Straight	As per ASTM	T301-95 or 99 (as noted)

Given recent advancements in mechanical testing technology, new test methods can be considered in the Dynamic Shear Rheometer (DSR). By comparison, a DSR PG test requires significantly less material and each test requires 20 minutes per temperature. An Elastic Recovery Procedure has been developed in the DSR, called ER-DSR, which can be directly correlated with AASHTO Elastic Recovery test procedure. The ER-DSR procedure requires the same amount of time as a performance grading test and can be used for the same application as the AASHTO T 301 Elastic Recovery procedure.

2.3 Summary of ER and Phase Angle

Elastic Recovery and Phase Angle measurements have been successfully used to indicate the presence of an elastomeric polymer and elastomer modified asphalt binders have been shown to improve asphalt mixture performance. However, the extent to which elastomers increase performance cannot be captured by Elastic Recovery or Phase Angle parameters. It is not known whether this improvement is due to elasticity or increase in stiffness. In addition, there is an increasing amount of additives that can be used to address different levels of pavement performance that, when modified with asphalt binder, fail Elastic Recovery and Phase Angle specifications. Depending on the objectives of each respective state agency, there are alternative DSR testing procedures that are well developed and can directly address typical modes of pavement distress or replace the need for a large ductilometer.

3. Ductility Test

Asphalt ductility testing is currently conducted under two different standardized testing procedures. The first, referred to as the standard ductility test, is conducted per ASTM D113 or AASHTO T51, and measures the amount of elongation an asphalt binder sample can withstand before fracture at a specified elongation rate (5cm/min) and temperature (25°C) [11, 12]. The parameter reported through this procedure is the overall length of elongation of the sample before fracture occurs. The second ductility test is known as the "Force Ductility Test" and is conducted according to the AASHTO T300 procedure. The test measures the force during elongation at a specified elongation rate (5cm/min) and temperature (4°C) [13]. The test normally yields two stress peaks, one near the initial elongation area and one prior to rupture. The primary parameter reported is the force ratio which is the force at the second peak (f_2) divided by the force of the initial peak (f_1). Specimens for each test are very similar and are shown in Figure 5. The difference between the two tests are the sides of the molds, as the standard ductility mold has angled sides and the force ductility test has straight sides. Molten binder is placed in these "dog-bone" shaped molds, trimmed, then the side plates are demolded, and specimens are ready for conditioning and testing. Figure 6 shows a test in process and displays binder specimens pre and post rupture.

Both of these testing procedures are typically used identify the use of certain modifiers within the asphalt binder. These results can also be used to characterize the ductile nature of asphalt binder material; higher elongation assumes higher ductility characteristics of the binder in the asphalt mixture phase. Although advanced binder rheology characterizations are used by many agencies, these ductility tests are still regarded as a performance indicator for modified asphalt in some specifications within the USA and a few countries [14].

Figure 5- Testing molds for ductility specimens. Right Mold is for ASTM D113/AASHTO T51. Left mold is for AASHTO T300.

Figure 6- Image showing a ductility test in progress. Photo courtesy of Anton-Paar.

According to the Asphalt Institute, only 6 of the 52 states' agencies have included either of these tests within their specifications, and only 1 (Michigan) of these 6 states requires all binders to be tested. The 5 other states specify these tests only for binders that are modified to meet a certain PG grade. For the states using these tests, the required thresholds used to indicate a pass/fail test are different from state to state and also within binder PG.

3.1 Correlations with performance

Ductility testing through these two methods are based off an empirical approach and no known engineering properties are obtainable through this procedure. The significance of the results from the tests have also been contested as there is an unclear relationship between the measured results and any fundamental material properties [15]. Although this procedure doesn't yield these properties it has been used effectively to determine the level of aging in asphalt binders of both laboratory and field aged samples [16, 17, 18, 19, 20].

Field experiments have shown that asphalt binder ductility can correlate well with pavement cracking but the results are highly sensitive to the laboratory testing conditions. Doyle (1958) attempted to correlate ductility to durability performance with Ohio test sections. He noted rather poor correlations with the test sections and ductility at 25°C, but found significantly better correlations when the ductility was performed at lower temperatures and elongation rates such as 12.8°C at a rate of 1cm/min [21]. He showed that higher ductilities correlated to less cracking in the field after five years of pavement service. He also provided results of other roadway sections and showed that a pavement with no cracking after five years had a recovered binder ductility of 29cm while two other poor performing test sections have significantly lower ductilities. Kandhal also analyzed test sections and attempted to correlate conventional binder tests with field cracking using Pennsylvania test sections [21]. This study showed that among penetration at 77°F, viscosity at 140°F, and ductility at 60°F, only ductility was able to give the correct ranking in cracking of the roadways after 10 years of in-service conditions.

Table 5 shows the measured properties of six test sections while

Table 6 shows the resulting performance of these materials in the field. Performance was quantified in Table 6 by creating a rating system which indicates higher performance by higher rating values. This rating system is further described by Kandhal and Wegner [22]. It is clearly seen that only ductility gives the correct ranking when compared to the overall rating number. Better pavement condition was also noted when ductility remained above 10cm, but poor condition was shown when the ductility decreases below 5cm. It was also noted that the test results as 60°F were much more reproducible than that of higher temperatures which was also shown by Doyle. Second and third sets of test sections were laid and ductility at 60°F was able to generate the correct ranking with respect to pavement cracking. This same relationship was also shown in multiple other studies as well [18, 23, 24].

Table 5-Measured properties of six types of Pennsylvania test sections [22].

Test	Asphalt Type T-1	T-2	T-3	T-4	T-5	T-6
Penetration at 77°F, 100 g, 5 sec	15	26	35	25	22	35
Viscosity at 140°F, poises	13,339	20,556	7,422	14,418	6,495	11,263
Viscosity at 275°F, centistokes	815	858	721	781	583	815
Ductility at 60°F, 5 cm/min, cm	1.2	4.5	14.0	5.0	4.0	11.2

Table 6- In field performance of six different asphalt types with Pennsylvania test sections [22].

Observations	Asphalt Type T-1	T-2	T-3	T-4	T-5	T-6
Loss of fines (matrix)	Slight to moderate	Slight	Slight	Slight	Slight	None to slight
Raveling (loss of particle .25-inch or larger)	Moderate	Slight	None to slight	Slight	Slight to moderate	Slight
Transverse cracking	Very severe	Slight	None	Slight to moderate	Very severe	Slight to moderate
Longitudinal cracking	Very severe*	Moderate	None to slight	Slight to moderate	Severe*	Slight
Overall rating number	18.4	29.4	36.2	30.5	20.8	31.7

Goodrich studied the correlation between conventional asphalt binder testing to the properties of asphalt concrete mixes. He showed that temperature susceptibility, forced ductility, toughness-tenacity, and low temperature ductility did not always correlate well to performances of asphalt mixes [25]. Forced ductility was able to correlate relatively well with beam fatigue at 25°C, but the standard ductility procedure had a poor correlation. This study also showed that polymer modification didn't significantly alter the fatigue mixture performance so it may be suggested that certain conventional binder tests are susceptible to certain polymer modifiers as they show drastic changes in ductility but limited correlations to mixture performance.

From a durability study conducted by the Federal Highway Administration (FHWA), it was shown that multiple binder rheological parameters including the storage modulus (G'), the ratio of dynamic viscosity to the storage modulus (η'/G'), and the ratio of these two (G'/(η'/G')) have high correlations with the ductility test when considering unmodified binder [21]. Correlations were especially high when the ductility values were below 10cm, which has been shown to be a highly critical range regarding asphalt mixture performance [26]. Although the correlations were strong between these parameters, the correlation was diminished when highly modified binders were used.

3.2 Test Shortcomings

The primary disadvantages of using these test procedures is the inability to relate the results to any fundamental material properties and the inconsistent specimen geometry during the testing [14]. Due to test procedure, which allows very large deformation reaching more than 10000% strain (100 cm), the sample geometry changes so much that the strain rate varies due to the necking and change in cross-section [12]. Since the change in geometry is material dependent, the results cannot be compared since they represent inconsistent strain rate conditions. In simple terms, this geometry effect is equivalent to testing materials at different temperatures. With the introduction of various effective binder modification, this test has resulted in rejecting materials that are known to perform very well and contribute to better performance. This false rejection is a real problem since it restricts the use to binders that can pass the test but are not necessarily better than others in terms of pavement performance.

The recent increase in interest of binder modifiers is a cause for concern with respect to specimen geometry as many of today's commonly used modifiers change the elastomeric three dimensional networks which potentially change the material's Poisson ratio and the rate of stress relaxation as the sample elongates [14]. Vonk and Korenstra conducted a study regarding the different structures of polymer modified binders and concluded that the ductility test will measure different material properties depending on the level or presence of modification, and is not a suitable performance indicator or binder selection tool [27]. The results from these two ductility testing procedures are also rather erratic and inconsistent especially when testing modified asphalt binders [14]. This causes issues when optimizing formulations as the test will not be able to distinguish minor changes in performance.

A study conducted by Tabatabaee and co-workers suggested replacing these procedures with dynamic shear rheometer (DSR) based procedure. It was shown that not only were the results very repeatable, but the geometry of the test specimen is much more consistent for all binder types when the DSR is used in comparison to conventional ductility testing.

3.3 Summary

Although ductility has shown promising results in certain instances when used as a durability indicator for unmodified binders, there are multiple limiting drawbacks of this procedure. Firstly, the variable specimen geometry is a key shortcoming as this limits the ability for any engineering properties to be derived from the procedure. As previously mentioned, this issue has been studied by multiple research efforts and a dynamic shear rheometer has been used in place of the traditional ductility setup [14, 21]. Another limitation of the ductility tests are the poor mixture performance-ductility correlations when modifiers are introduced into the binder [27, 21, 14]. Also very few state agencies have implemented these test procedures into their specifications, which indicates that the results are not widely accepted as the best method to characterize binder performance or modifier presence indicator.

4. Toughness and Tenacity

The asphalt toughness and tenacity test, currently conducted under ASTM D5801-12 specification, characterizes an asphalt binder's ability to with stand a tension force under constant deformation rate both pre and post ultimate (maximum) load [28]. The test is typically conducted on asphalt binder specimens to describe the elastomeric properties, which is useful when elastomer modifiers are used.

The toughness and tenacity test was first introduced by Benson [29] in an attempt to better characterize rubberized asphalts. This procedure was primarily used as a marketing tool during the early years and was not created as a performance indicator. The toughness and tenacity test was initially used in the 1960's by rubber manufacturers to promote their products effect on the asphalt binder as a modifying agent [30]. The toughness and tenacity procedure measures the force required to withdraw a steel probe embedded in an asphalt binder sample at a constant rate at a specified temperature [31]. The testing apparatus is shown in Figure 7.

Figure 7- Toughness and Tenacity testing apparatus displaying a test in progress.

During the 1970's this test was also promoted by polymer modifier manufacturers as a method to distinguish polymer-modified from unmodified asphalt [32]. Although this test displays great differences between unmodified and modified asphalts, these differences in behavior have had limited correlations to actual field performance.

The primary output of the test is a load vs displacement relationship. The toughness component provides a measure of the energy or strength of the asphalt binder which is driven by cohesive and elastomeric properties of the asphalt binder [31]. This parameter is typically used to serve as an indicator of how a polymer-modifier effects the base asphalt [33]. The tenacity parameter is a measure of the binder's elastomeric properties and its capacity for delaying failure after the peak load has been reached [31]. Tenacity is typically used to indicate the amount and type of polymer used with the base asphalt [33]. Wang and Tsai have suggested that the toughness parameter can also be used as an indicator of the amount and type of polymer added to the base asphalt [34, 35]. Figure 8 shows a schematic of how the toughness and tenacity are calculated based on the load-displacement plot.

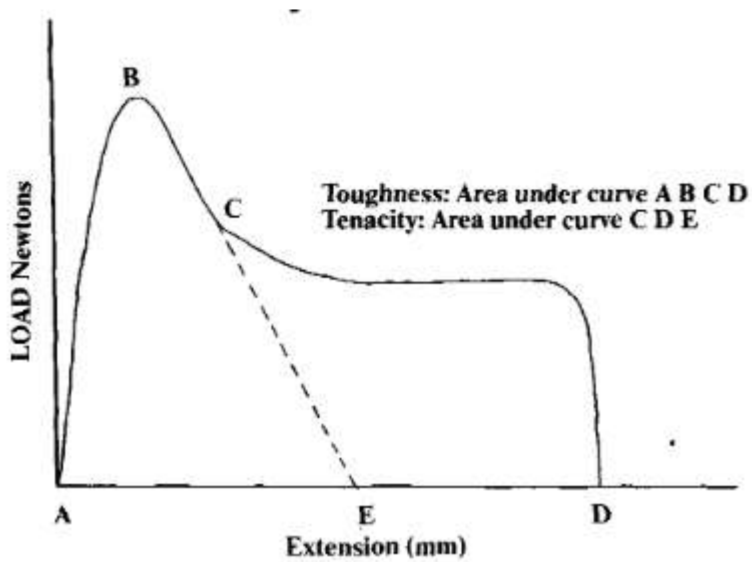


Figure 8- Plot displaying how the toughness and tenacity parameters are calculated from the load-displacement curve.

According to the Asphalt Institute, only 5 of the 50 state agencies have adopted the toughness and tenacity parameter into their specification. These 5 agencies require the test to be conducted only on modified binders, especially styrene-butadiene-rubber (SBR) modified binders. This test appears to be used primarily as an indicator for binder modification and its effectiveness. The threshold for a pass/fail test for most of these specifications are the same including a minimum of 75 in-lbs for the toughness parameter and 110 in-lbs for the tenacity parameter.

4.1 Correlations with Performance

Goodrich studied the correlations between multiple conventional binder tests including toughness and tenacity and attempted to correlate these results to asphalt mixture performance [25]. Although significant increases in performance were noted with respect to the conventional asphalt tests, this increase in performance could not always be directly correlated to increases in mixture performance. It was noted by this author that neither the toughness nor tenacity parameter correlated to the limiting stiffness temperature (LST), which is a parameter of monitoring the susceptibility to thermal cracking or the creep properties of the mixture which is a characteristic of permanent deformation [25].

Isacsson also showed limited correlations existing between toughness and tenacity and field performance [36]. He also suggested that when introducing polymer into the bitumen, the testing conditions of nearly all the conventional binder testing methods are modified in one way or another and are no longer measuring the exact same parameter. This statement indicates the need for the binder tests to measure engineering properties of the material rather than empirical based characteristics related to type of material.

4.2 Test Shortcomings

One of the primary concerns regarding the toughness and tenacity test is the large deformations experienced by the binder in the test, which are not representative of the deformations that asphalt binders could experience in the field [33]. The Toughness and Tenacity procedure is purely empirical as no engineering material properties are obtained through the testing process, unlike the more advanced rheological characterization methods. Empirical testing is the best testing option when engineering properties are difficult to obtain. But when substituting empirical behavior for engineering properties it is essential to characterize the material of interest within conditions similar to what the material experiences in the field. With regards to the toughness and tenacity test procedure, the tested asphalt binder experiences significantly higher deformation than what would be experienced in the field [33]. Jyh-Dong suggested the increase in resisting deformation due to modification should only be accounted for when the deformation is relatively small, as the increase in performance at high deformation is not significant as the binder in the field will not reach these deformations [33]. With this in mind the calculated increase in performance calculated from ASTM 5801 may overestimate the change in performance [33].

Another primary concern with this testing procedure is the variable cross-sectional geometry as the testing deflection occurs. As the steel stub is being pulled from the asphalt binder, the overall cross-section is continuously changing as the further the stub is displaced, the smaller the cross-sectional area exists is to resist deformation. This attribute makes this test nearly impossible to relate its results to any engineering material property as the stress of the sample is changing with time and space with unknown relations. The behavior of this changing cross-section may also be highly variable with the presence of the modifiers. Binder modification, especially with polymers, can affect the elastomeric three dimensional networks which may inherently change the rate of relaxation and Poisson's ratio [14]. The changes of the networks will result in a different geometries of the asphalt binder specimen at the same deformation level depending upon the modification which doesn't allow for completely equal comparisons between test specimens, especially between unmodified and highly modified specimens.

Repeatability is also a large concern for toughness and tenacity testing as the results are subject to large changes by minor alterations to the testing specimen and data interpretation. Robinson showed the results are highly sensitive to the depth of immersion into the binder of the testing probe [31]. This causes minor unintended changes in specimens resulting in variable results. With regards to the amount of tests required for suitable characterization, Robinson suggested in order to get within +/- 10% of the true mean five tests should be conducted and 24 tests to get within +/- 5% of the true mean [31]. Test data interpretation is also another critical source of variability; certain specimens have different overall curve types from what is seen in the schematic in Figure 8. Figure 9 shows another load-displacement case that is seen with the testing results and shows multiple peaks of the specimen.

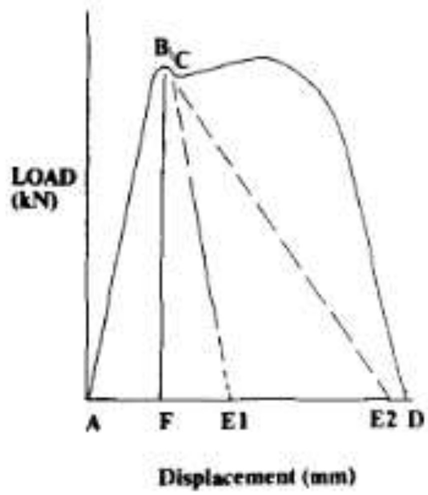


Figure 9- Toughness and Tenacity load-deformation curve displaying the complexities possible with analysis.

4.3 Summary

The review of the toughness and tenacity procedure has shown that there are many limitations including non-representative deformation level, changing specimen geometry, and significant repeatability challenges. This procedure also has limited correlations to field or mixture performance. Even with these shortcomings, this test has the potential to be an indicator of presence of the modifier in comparison to neat binder as the results are highly sensitive to the addition of certain modifiers. Unfortunately, there have been 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.

It should be mentioned that recent development of the DSR testing procedures indicates that there is a possibility to use the DSR and apply a monotonically increasing deformation (similar to the T&T test), but keeping the geometry constant between the DSR plates. The new test in the DSR is called the Binder Yield Energy Test (BYET). As shown in Figure 8, the test applies a constant rate of rotation and measures torque required. The test can be used to calculate the energy to yielding of binder and can clearly distinguish polymer modified binders [14].

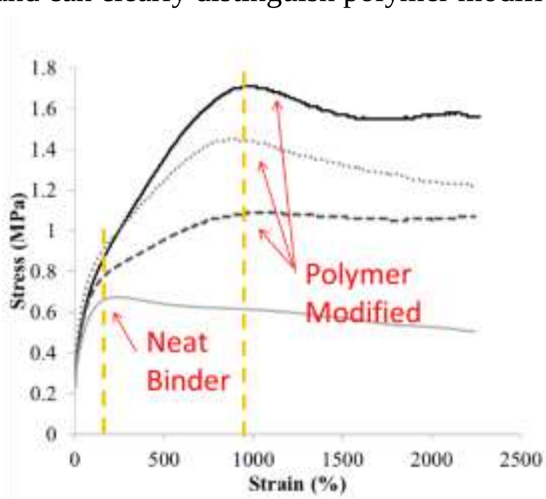


Figure 10: Binder Yield Energy Test in the DSR.

5. Overall Summary of PG + Tests

This report was completed to meet the objectives outlined in **Area #1** of the pooled fund project work plan, which included a detailed evaluation of the PG+ tests currently used by the project partners and a detailed commentary on the MSCR test procedure and protocol. From the literature review of current PG+ test methods, the following points summarize the main findings:

- The phase angle and Elastic Recovery measured in the ductility bath are used as indicators of elastomeric polymers in modified asphalts. While both measures may detect the presence of such modifiers, they have critical shortcomings due to false rejection of some elastomeric additives and lack 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 Elastic Recovery and Phase Angle specifications.
- The Elastic Recovery in the ductility bath is used by various states differently and there is no consensus with respect to the details of the procedure or the limits that should be used in specifications. In addition, an elastic recovery test can be conducted in the DSR. There is clear evidence that the DSR-ER test is a more practical and easier to conduct in the presently used DSR devices.
- The Ductility test is highly 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. Similar to the ER, the ductility test can be replaced by a more effective test in the DSR called the Binder Yield Energy Test (BYET), which requires much less material, can solve the geometry problem, and is expected to clearly show the benefits of polymeric additives.
- The Toughness and Tenacity test has many limitations including non-representative deformation level, changing specimen geometry, and significant repeatability challenges. Even with these shortcomings, this test has the potential to indicate the presence binder modification; test results are highly sensitive to the addition of certain modifiers. 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.
- It should be mentioned that recent development of DSR testing procedures has resulted in a monotonically increasing deformation test, similar to the T&T test, which can maintain a constant geometry in the DSR parallel plate system. The new test in the DSR is called the Binder Yield Energy Test (BYET) and it addresses many of the shortcomings identified with the T&T procedure.

6. Commentary on MSCR

One of the objectives of **Work Area #1** is to provide a detailed commentary for the Multiple Stress Creep and Recovery (MSCR) test procedure based on a comprehensive literature review. The following sections provide a discussion of the current MSCR implantation process and procedural details. The implantation section covers how state agencies can implement the MSCR procedure in accordance with AASHTO standards T350 and M332. The procedural considerations section cites literature to address concerns associated with different aspects of the MSCR procedure.

6.1 Current Implementation Process

There are two AASHTO standards that are currently being used to implement the MSCR testing procedure: AASHTO T350 and M332. AASHTO T350 describes how to conduct the MSCR procedure in a Dynamic Shear Rheometer (DSR). AASHTO M332 describes how the MSCR results can be incorporated into specifications to replace the current M320 Superpave asphalt binder grading system.

Two parameters are calculated form the MSCR testing procedure: (1) average non-recoverable creep compliance (Jnr) and (2) average percent recovery (%R). Jnr and %R values are reported for two different applied stress levels, 0.1 and 3.2 kPa, using a standard 25 mm DSR geometry. The procedure applies a total of 30 loading and unloading steps in two sequential stages for 20 and 10 cycles each. For the first 20 cycles, a 0.1 kPa stress is applied for 1 second and then released for 9 seconds and repeated 20 times (each application and release of load represents one cycle). The process is then repeated at a stress level of 3.2 kPa for 10 cycles instead of 20. To calculate Jnr, the strain accumulated after each cycle is subtracted from the recovery strain from the previous cycle and divided by the applied stress. To calculate %R, the maximum accumulated strain in each cycle is subtracted from the recovery strain and divided by the maximum accumulated strain. This is best understood visually in Figure 11 and Equations 1 and 2.

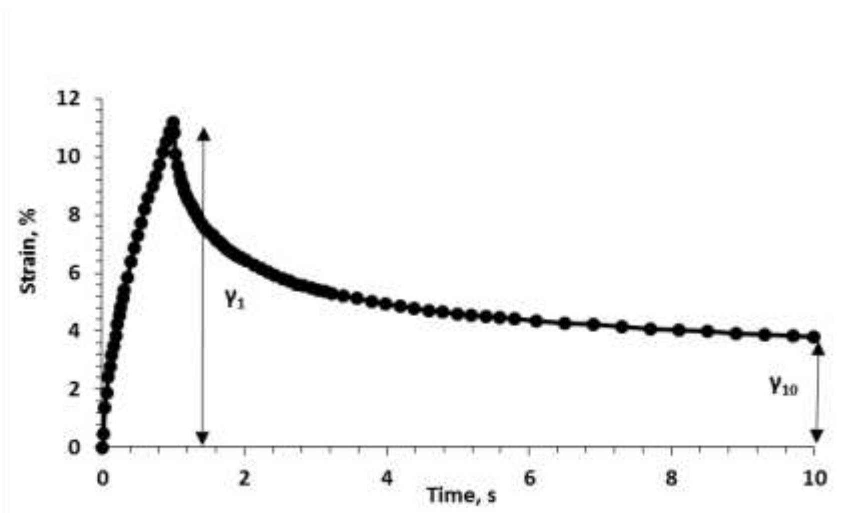


Figure 11- Visual description of the data output from the MSCR testing procedure. Where, γ_1 is the maximum strain after 1 second of creep loading and γ_{10} is the accumulated strain after 9 seconds of recovery.

$$Jnr = {}^{\gamma_{10}}/_{\sigma_{step}} \quad (1)$$

Where, γ_{10} is the recovery strain for each cycle and σ_{step} is the applied stress; either 0.1 or 3.2 kPa.

$$Percent\ Recovery\ (\%R) = {}^{(\gamma_1 - \gamma_{10})}/_{\gamma_1} \quad (2)$$

Where, γ_1 is the maximum accumulated strain during each cycle.

Figure 11 represents one of 10 cycles that occur for each stress level of the MSCR procedure (only the last 10 cycles of the 0.1 kPa stress level are used for data analysis). After calculating the Jnr and %R for each cycle, the average values are reported. A typical data output for all cycles and stress levels is shown in Figure 12.

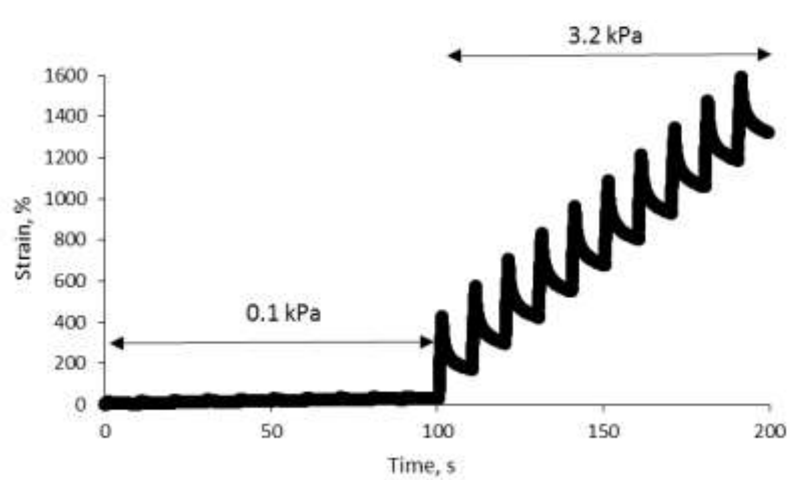


Figure 12- Typical data output for MSCR procedure. 10 creep and recovery cycles are conducted at each stress level.

AASHTO M332 specifies that the MSCR test should be run at the climatic pavement temperature as an alternative to the current traffic PG grade "bumping." PG grade "bumping" specifies that the high temperature grade be increased to account for an increase in traffic volume or reduced traffic speed. Grade "bumping" requires producers to modify the base asphalt binder to meet typical G*/sinδ specifications at higher temperatures. Two concerns exist for the "bumping" system: 1) an asphalt binder will never experience temperatures associated with "bumped" temperatures, and 2) polymer systems may behave differently at "bumped" temperatures compared with the actual climatic grade temperature.

Instead of increasing the high temperature PG grade, M332 specifies 3.2 kPa Jnr limits for different traffic levels at the same climactic pavement temperature. In this way, asphalt binder producers are required to modify binders to decrease the Jnr value at the actual climatic grades. Table 7 shows a summary of the specification limits provided in AASHTO M332.

Table 7-MSCR specification limits at the climatic temperature for different levels of traffic.

Traffic Rating	Maximum Jnr at 3.2kPa (kPa^{-1})	Traffic Guidelines (ESALs and Traffic)
S Standard	4.5	<10 million ESALs and standard traffic loading
H Heavy	2.0	10-30 million ESALs or slow moving traffic
V Very Heavy	1.0	>30 million ESALs or standing traffic
E Extreme	0.5	>30 million ESALs and standing traffic

In M332 system, a binder will be graded with the traffic level labeled in the grade. For example, a PG 64-22 binder modified to meet the Very Heavy traffic level would be designated as a 64V-22 instead of a 76-22 in the grade "bumping" system.

In addition to the Jnr limits, there are two additional specification limits that are outlined in M332: Jnr difference and %R. Jnr difference is the calculated percent difference between the Jnr at 0.1 and 3.2 kPa stress levels. Jnr difference was intended to ensure that small changes in stress do not result large changes in rutting susceptibility of the asphalt binder. %R is an optional specification that can be used to indicate the presence of an elastomer. To indicate the presence of an elastomer the relationship between Jnr and %R is compared against a curve in the APPENDIX of the M332 specification. If the Jnr-%R relationship is above the curve, the binder contains an elastomer. Figure 13 shows the Jnr-%R relationship to indicate a polymer.

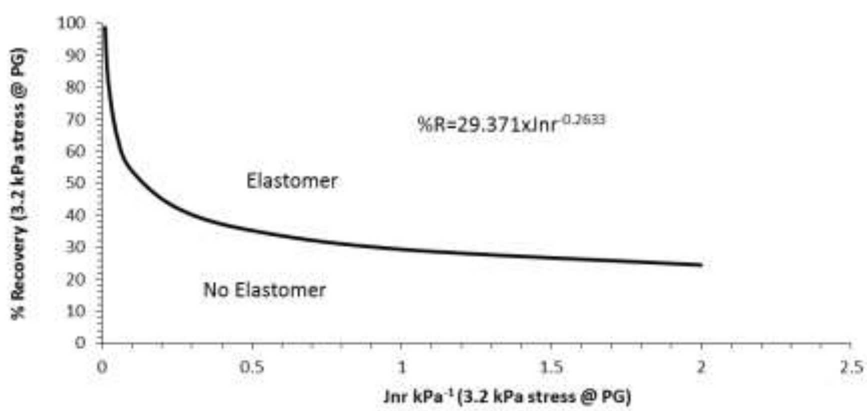


Figure 13- Elastomer indication curve. Where, binders that are above the curve indicate presence of an elastomer.

6.2 Procedure Considerations

After introduction of the MSCR procedure to the asphalt industry, several researchers have investigated the potential for Jnr and %R as a state agency specified test. The primary research that has supported development of the current MSCR standards has been summarized in the Transportation Research Board's 2010 Transportation Research Circular. In the circular, as well as other publications, justifications for selecting the current Jnr and %R were explained [37]. The following sections summarize the justification for the AASHTO M332 specification limits and provide insight on different aspects of the MSCR procedure.

6.2.1 AASHTO M 332 Standard Jnr and %R limits

First, an initial limit was set for unmodified binders based on the relationship between the MSCR Jnr and the RTFO G*/sinδ parameter. A G*/sinδ of 2.2 kPa was found to be equivalent to a MSCR Jnr of 4 kPa^{-1}. Table 8 shows the Superpave grade and MSCR Jnr data used to derive this relationship.

Table 8: Data used to generated Jnr measurement equivalent to a G*/sinδ of 2.2 kPa. All of the binders used for this testing were unmodified [37].

Sample ID	Name	Grade	True Grade	Temp [ºC]	J_{nr} [3.2 kPa^{-1}]
ALF 6727	Control	70-22	72.7-74.2	72.7	4.4
BBRS3	Straight	64-22	66.1-27.3	66.1	4.2
MN county rd 112	Neat Valero	58-28	60.8-33.4	60.8	3.7
MN county rd 112	AshlandM	58-28	60.7-31.4	60.7	4.3
Minn Road	Straight	58-28	61.8-30.8	61.8	3.0
Shandong	Straight	64-22	64.4-23.5	64.4	4.4
BBRS3	Straight	70-22	71.4-24.8	71.4	4.8
BBRS3	Straight	58-28	61.3-30	61.3	4.0
MD project	Straight	64-28	64.8-29.6	64.8	4.6
Citgo	Straight	70-22	71.6-26.9	71.6	4.6
Lion	Straight	64-22	66.7-24.1	66.7	4.5
Average					4.2
Coefficient of variation (%)					12

Data shows that a Jnr of 4.0 is not exactly equivalent to a G*/sinδ of 2.2 kPa. Jnr values, in this study, ranged from 3.0 to 4.6 kPa^{-1}. In order to pass the MSCR standard traffic level, a Jnr maximum limit of 4.5 kPa^{-1} is specified. Table 8 suggests that the standard traffic limitation may reduce the high temperature grade of current unmodified binder even though the G*/sinδ meets the 2.2 kPa limitation at climatic temperatures.

Next, traffic level Jnr limitations, in the AASHTO M332 specification, were derived from three different studies: MnRoad research center, Accelerated Loading Facility (ALF) and a Mississippi test site. Each of the aforementioned studies were conducted to set limits for increased traffic volumes and slower speeds. Three binders were used for each study to achieve Jnr values of 4, 2, and 1 kPa^{-1}. In the ALF study, each binder incorporated into one mixture design and was loaded with an 80 kN wheel load traveling at 19 km/h at 64 ℃. MnRoad conducted a similar study using the dry condition of the Hamburg Wheel Tracking Device test procedure. In Mississippi, a test section was paved into sections with the three binders and rutting was monitored with live traffic for 6 years. Results of each study were summarized and are shown in Table 9.

Table 9- Results of three MSCR studies to develop Jnr specification limits [37].

MS test site			ALF study			MnRoad		
J_{nr} at [3.2 kPa^{-1}]	Rut [mm]	% Change in Rut with Change in J_{nr}	J_{nr} at [3.2 kPa^{-1}]	Rut [mm]	% Change in Rut with Change in J_{nr}	J_{nr} at [3.2 kPa^{-1}]	Rut [mm]	% Change in Rut with Change in J_{nr}
4	13.3		4	27.7		4	10.2	
2	6.4	51.7	2	17.0	38.7	2	5.7	44.2
1	3.0	53.5	1	11.6	31.6	1	3.4	39.7

Results of the three studies show that a 50% reduction in Jnr is approximately equivalent to a 30-50% reduction in rut depth. Thus, it is assumed that for each traffic level increase the Jnr is specified to be reduced by half. This assumption is not well justified since the traffic levels used in the M332 specification is spaced at 0.3, 1.0, 3.0, 10.0 and 30 million ESALs. So the logical in using 50% reduction in Jnr to change limits for the traffic limits is not clear and in fact contradictory to the known trend that rut depth is not a linear function of the traffic volume. This known trend is part of the MEPDG and is evident in many studies done in the lab and in the field [1].

The %R specification limits were investigated by Anderson et al. using twenty-two different Canadian asphalt binders [38]. Based on the correlation between Jnr and %R for each binder, the use of the curve for indicating the presence of a polymer was derived. The equation derived from binders used in this study is shown in Figure 13. Results also showed that the MSCR %R-Jnr relationship was more sensitive to blending times and concentrations of elastomer modified binder when compared with the AASHTO T301 elastic recovery. The Majority of the binders that fell above the %R-Jnr curve had T301 elastic recovery values greater than 70%. Anderson concluded that the MSCR procedure can be used not only to ensure that an elastomer be used, but also that proper blending and concentrations of elastomers are utilized.

6.2.2 Stress Dependence and History

In the AASHTO M332 specification, Jnr and %R are measured at 0.1 kPa and 3.2 kPa. The following section cites literature that lead to selection of these stress levels and studies that have investigated how stress affects MSCR results. Modified asphalt binders, polymer modified asphalts in particular, are stress dependent materials. The stress levels selected in the MSCR to indicate rutting resistance should be related to the stress experienced by the binder within a pavement system. Selection of 0.1 and 3.2 kPa were recommended by D'Angelo et al. to represent low and high traffic stress levels, respectively [39]. No clear justification for selection of 0.1 kPa was identified. The 3.2 kPa was selected based on a comparison between a highly networked Elvaloy (elastomer) and non-cross linked SBS modified binders. Jnr was measured for each modified binder at several stress levels. Results showed that Jnr values were similar until reaching a stress level of 3.2 kPa. At 3.2 kPa, the highly networked modified binder maintained a much lower Jnr in comparison with the non-cross linked binder. Therefore, 3.2 kPa was selected as the high stress level to differentiate between good and poor elastomer modification structures within asphalt binder.

Laukkanen et al. evaluated the effect of stress levels on Jnr and %R for both unmodified and modified asphalt, as shown in Figure 14 [40]. Where B1 is unmodified, binders designated with an E are elastomer modified, W7 is wax modified and EW8 is wax/elastomer modified.

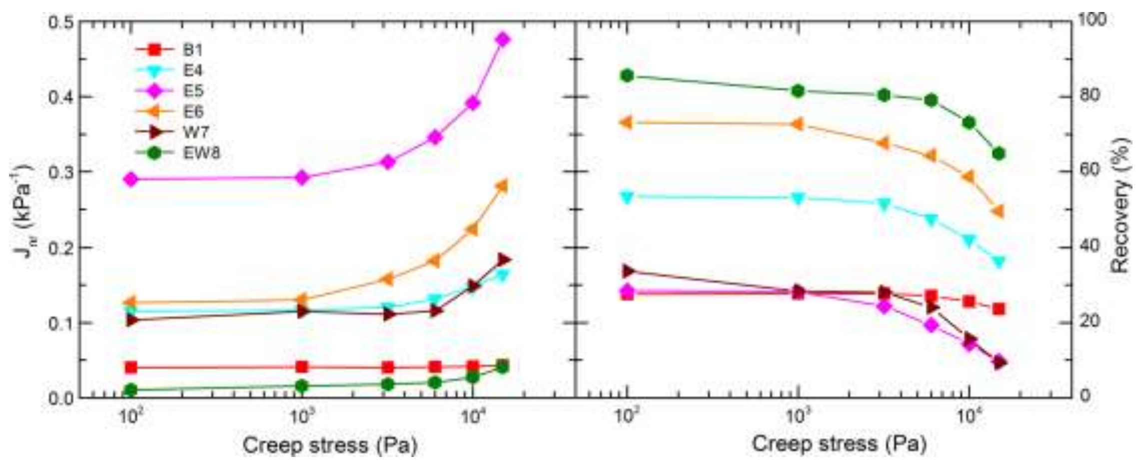


Figure 14- Jnr and %R modification and stress dependence comparison with polymer modification.

As can be seen in Figure 14, Jnr and %R stress dependence change based on the type of polymer modification. But the results show that at 0.1 kPa and 3.2 kPa there is only a small change and it may not give the necessary differentiation of the stress sensitivity of the various binders. Selection of one stress level may not be appropriate to accurately characterize the rutting resistance of asphalt binders with larger volumes of traffic and slower speeds. Results from a studies conducted by both Wasage et al. and D'Angelo both show that the non-linearity of Jnr and %R measurements approaching 10 kPa are different for different types of asphalt binder modification types [41, 37].

A Jnr difference parameter (Jnr diff) was proposed by Anderson et al. to measure stress dependence and was incorporated into the AASHTO M332 specification [38]. Jnr difference is calculated as the percent difference between the 0.1 kPa and the 3.2 kPa Jnr. The proposed maximum limit of 75% Jnr difference was intended to ensure that small changes in applied stress did not result in a pavement that was susceptible to rutting. When binders are modified to obtain Jnr values less than 0.1 kPa^{-1}, the Jnr difference has a tendency to be uncharacteristically large. Both Mandal and Anderson have reported Jnr difference values greater than 500% when the 0.1 kPa Jnr is below 0.1 kPa^{-1} [42]. Table 10 shows Jnr measurements for heavily modified binders at three different stress levels.

Table 10- Jnr data at three different stress levels for heavily polymer modified asphalt binders [42].

Binder	%Recovery			J_{nr}		
	0.1 kPa	3.2 kPa	10 kPa	0.1 kPa	3.2 kPa	10 kPa
Neat binder	12.81	13.04	18.81	30.61	31.99	38.61
4% LE + 1.5% FPE	89.85	3.17	20.74	0.20	5.85	18.24
4% LE + 1.5% FPE + 0.1% Sulphur	99.05	45.21	2.25	0.02	1.60	6.27
4% LE + 1.5% FPE + 0.225% Sulphur	99.10	91.72	14.47	0.02	0.18	3.76
4% LE + 1.5% FPE + 0.1% CL2	98.58	15.60	5.92	0.02	3.02	7.51
4% LE + 1.5% FPE + 0.1% CL3	98.53	10.99	6.79	0.02	3.48	8.25
4% LE + 1.5% FPE + 0.25% CL4	97.52	20.58	5.58	0.04	3.10	8.02
4% LE + 1.5% FPE + 0.1% CL5	97.90	30.56	3.39	0.03	2.34	6.66
4% LE + 1.5% FPE + 0.1% CL5 (extended curing)	98.22	49.94	5.58	0.03	1.41	5.70
4% LE + 1.5% FPE + 0.225% CL5 (extended curing)	99.49	91.34	10.01	0.01	0.17	4.19
4% LE + 1.5% FPE + 0.3% CL6	98.34	77.96	2.42	0.03	0.58	5.68
4% LE + 1.5% FPE + 0.3% CL7	98.47	24.63	4.60	0.02	2.80	7.48
4% RE + 1.5% FPE	92.11	35.30	3.23	0.09	2.35	5.52
4% RE + 1.5% FPE + 0.1% Sulphur	101.91	78.31	25.18	−0.01	0.37	2.47
4% RE + 1.5% FPE + 0.225% Sulphur	102.56	98.04	87.67	−0.02	0.02	0.19

Note: LE, Linear Elastomer; FPE, Polyethylene; RE, Radial Elastomer.

Several binders in Table 10 have 3.2 kPa Jnr values that are two orders of magnitude larger than the 0.1 kPa Jnr value. However, when the stress is further increased to 10 kPa the % difference between the 3.2 kPa and 10 kPa Jnr is much lower. The Jnr difference should always increase with increasing stress level comparisons, as shown in Figure 14. This may indicate that current analysis methods and testing equipment may be inadequate to measure the true Jnr of highly modified asphalt binders.

In addition to stress dependence, stress history also can affect the non-recoverable creep compliance. Sheony et al. conducted a stress history study that measured the Jnr after three loading steps: 25 Pa, 3200 Pa and another 25 Pa step [43]. This procedure was conducted on several different types of asphalt binders and the %difference was calculated between the Jnr measured after the first and second 25 Pa step. Results from the study are shown in Table 11. Each measurement was conducted at the same stress level, but the % difference ranged from 1 to 4500% between the different 25 Pa steps. As it stands, the MSCR procedure applies an identical stress history, but it is not possible to know the state of stress within the asphalt binder after sample preparation (i.e. loading and trimming the sample). Differences in pre-test stress states could result in drastically different Jnr measurements as shown in Table 11.

Table 11-Results showing the effect of stress history on the Jnr of asphalt binders [43].

Binder code	Binder type/modifier	Testing temperature (°C)	% Absolute difference in J_{NR} between first 25 Pa run and the second 25 Pa rerun after completion of multi-stress
AC-5	Unmodified	58	7
AC-10	Unmodified	58	3
		52	25
AC-20	Unmodified	64	8
		58	23
		52	126
Styrelf	SB modifed	70	2504
		58	4450
Novophalt	PE modifed	70	1955
B6224	Flux	52	3
B6225	Base	64	4
B6226	High	70	4
B6227	Air-blown	70	1
B6228	Terpolymer	70	512
B6229	SBS LG	70	78
B6230	SBS L	70	25
B6231	SBS RG	70	865
B6232	EVA	70	73
B6233	EVA G	70	188
B6243	ESI	70	19
B6251	CMCRA	70	79
B6267	Control	64	9
B6272	Control	64	1
B6298	Control	64	1
B6281	Air-blown	64	23
B6289	Terpolymer	64	771
B6295	SBS LG	64	4229
B6280	SBS 64-40	64	4044
B6286	CR–TB	64	1526
B6310	Terpolymer	59	2
B6311	Terpolymer	68	28
B6312	Terpolymer	72	20
B6313	CR–TB	70	0
B6314	CR–TB	76	211
B6315	CR–TB	82	977
B6316	Terpolymer	82	24
B6324	SBS LG	68	2
B6325	SBS LG	77	60
B6226	SBS LG	84	32

6.2.3 Loading Cycles and Loading Times

In the AASHTO TP 70 procedure, 10 loading cycles are specified per stress level and each cycle consists of a 1 second creep time and 9 second recovery time. Researchers have conducted studies to understand the implications of increasing the number loading cycles, creep times and recovery times. Golalipour measured the Jnr and %R for different binders in intervals of ten from 10 cycles up to 900 cycles [44]. Results showed that the Jnr tends to increase with increasing number of cycles. The opposite is true for % R. However, Jnr values converge to a constant Jnr as they approach 100 cycles of loading. To account for this issue, Golalipour recommended increasing the number of cycles to reduce the variability of the procedure. Laukkanen also found that taking the average Jnr for 10 cycles may not be representative of actual material properties [40]. Even within the 10 cycles used in the standard MSCR procedure, the calculated Jnr for the first 2 cycles tended to be less than the all subsequent Jnr values.

Domingos et al. compared the current 1 second creep and 9 second recovery loading with 2 second creep and 18 seconds loading [45]. It was expected that the Jnr and %R values would be similar because the extended amount of creep and recovery times were proportional. However, results in Table 12 show that Jnr and %R were dependent on the temperature and binder modification type. Studies conducted by Diab and Dellgadillo also concluded that binder modification directly impacts how the Jnr changes for different loading times [46, 47].

Table 12- Jnr and %R comparison ratios for 1 and 9s creep and recovery with 2 and 18s creep and recovery times.

Temperature/ stress level (kPa)	Percent recovery ratio R_P (R_{1-9}[a]/R_{2-18}[b])				Nonrecoverable compliance ratio R_C (Jnr_{2-18}[c]/Jnr_{1-9}[d])			
	Base binder (AC)	AC+PPA	AC+EVA	AC+EVA+PPA	Base binder (AC)	AC+PPA	AC+EVA	AC+EVA+PPA
52°C/0.1	1.57	1.07	0.88	1.05	1.91	1.73	0.52	1.86
58°C/0.1	1.99	1.10	0.89	1.07	1.91	1.81	0.66	1.90
64°C/0.1	—	1.15	0.94	1.02	1.93	1.80	1.23	1.91
70°C/0.1	—	1.26	1.09	1.08	1.97	1.88	1.79	2.07
76°C/0.1	—	1.35	1.05	1.09	1.96	1.89	1.66	2.13
52°C/3.2	2.62	1.10	0.91	1.14	1.94	1.82	0.80	2.22
58°C/3.2	—	1.24	0.86	1.39	1.97	1.93	0.67	2.73
64°C/3.2	—	1.65	0.97	1.86	1.96	1.99	1.57	2.98
70°C/3.2	—	3.67	3.86	4.22	1.96	2.04	2.13	2.56
76°C/3.2	—	—	—	—	1.98	2.00	1.91	2.38

[a] R_{1-9} = percent recovery at 1-s creep time and 9-s recovery time.
[b] R_{2-18} = percent recovery at 2-s creep time and 18-s recovery time.
[c] Jnr_{2-18} = nonrecoverable compliance at 2-s creep time and 18-s recovery time.
[d] Jnr_{1-9} = nonrecoverable compliance at 1-s creep time and 9-s recovery time.

6.2.4 Variability of Results

Repeatability and reproducibility are two important aspects leading to the variability of the test results. Soenen et al. (2013) studied the repeatability and reproducibility of MSCR test using 9 binders (binders 1-3 were unmodified while binder 4-9 were modified) [48]. The results in Table 13 show that for unmodified binders, the test results were approximately within ASTM limits for CV single operator variation (repeatability). For multi laboratory variation (reproducibility), only the J_{nr} values were close to ASTM specification. For %R (1 kPa and 3.2 kPa), the reproducibility was out of ASTM limits. For modified binders, the repeatability of %R (1 kPa and 3.2 kPa) are almost within the boundary of ASTM specification limits. But in case of reproducibility, the calculated CV's are not within the limits specified by ASTM. Reasons for testing variation exceeding the ASTM D7405 limits were identified to be variation in sample preparation procedures, DSR manufacturer differences and problems dealing with inherent material variation.

Table 13: Overview of multi-laboratory and single-operator CVs for all binders [48]. Where "r" represents repeatability and "R" represents reproducibility.

	Repeatability and Reproducibility CV(%)									
	R100%		R3200%		J_{nr} 100 (1/kPa)			J_{nr}3200 (1/kPa)		
Binder	CV-r	CV-R	CV-r	CV-R	J_{nr}	CV-r	CV-R	J_{nr}	CV-r	CV-R
1	2	6	2	7	0.053	3	6	0.054	3	8
2	4	26	10	65	0.722	3	6	0.764	3	7
3	16	46	4*	9*	1262	4	8	1.354	4	8
4	1	2	1	4	0.144	3	7	0.157	3	10
5	11	34	11	36	0.336	7	13	0.371	6	13
6	10	36	10	44	0.192	23	67	0.244	19	58
7	2	2	2	3	0.012	51	82	0.017	50	94
8	4	19	5	33	0.019	29	121	0.053	13	93
9	1	3	1	4	0.006	11	61	0.010	10	63
Avg. 1-3	7.0	26.0	5.1	26.8		3.4	6.7		3.4	8.0
Avg. 4-9	4.5	15.9	4.9	20.7		20.5	58.7		17.0	55.3
ASTM	2.4	5.4	3.0	6.5						
					J_{nr}>1	4.6	9.1		5.7	7.9
					1-0.26	5.4	12.7		5.5	13.9
					0.25-1	13.7	16.7		9.5	15.2
					J_{nr}<0.1	n/a	n/a		n/a	n/a

For the past five years, MARC researchers have analyzed the variability of various tests for the Western Cooperative Testing Group (WCTG). Approximately 40 labs have conducted the MSCR procedure on 44 binders in the past 5 years. Table 14 shows a coefficient of variation summary for all binders tested for the MSCR as part of the WCTG. Where the coefficient of variation is equal to the standard deviation divided by the average value measurement for each binder.

Table 14- Variability analysis conducted on 44 binders from 40 different laboratories as part of the WCTG

COV Comparison of Superpave PG Plus Tests, 2010-2015 samples				
Test	Maximum	Minimum	Average	Median
Jnr, 0.1 kPa @ PG Temp.	98.8%	4.2%	19.1%	12.3%
Jnr, 3.2 kPa @ PG Temp.	198.4%	4.6%	22.6%	15.1%
% Rec, 0.1 kPa @ PG Temp.	26.6%	1.1%	5.0%	4.2%
% Rec, 3.2 kPa @ PG Temp.	58.4%	1.4%	11.6%	8.2%

From this analysis, the median and average coefficient of variation are around 10-20%. Given that the data was reported for random operators and DSR manufacturers the results show that the test can be run with relatively low variability. There are, however, outliers in the data that resulted in very high COVs for some binders. For the statistical analysis conducted on the PG grading parameters, the maximum coefficient of variation is around 20%; much lower than the 198% calculated for the MSCR. To understand if the outliers were due to lack of familiarity with the procedure, the statistical analysis was broken down by durations of time to track the sample variability. For each time duration, the COV values were categorized as follows: COV less than 10%, COV greater than 10% but less than 20% and so on up to 60%. The number of binders that fall into each COV category were tabulated and summarized in Table 15.

Table 15- Number of binders within each COV category for the respective time frame.

	2010-2015	2014-2015	2010-2011
COV<10%	4	1	3
10%<COV<20%	18	6	7
20%<COV<40%	14	4	2
40%<COV<60%	3	0	1
COV>60%	5	2	0
Total Binders	44	13	13

Regardless of when the binder was tested, approximately half of the binders gave inter-lab COV values greater than 20%. Typical PG tests had COV values lower than 10% for all binders and none of the PG tests exceeded a COV of 25%. Form the WCTG data, there are some concerns regarding the MSCR repeatability since there are many binders with COV higher than 20%. However, analysis shown in Table 15 suggests that state agencies should consider alterations to current MSCR procedure to ensure that the inter-lab COV values primarily occur at or below 10% and high variability outliers are avoided.

6.3 Correlation with performance

MSCR Jnr was developed to provide an indication of high temperature rutting resistance. There have been a wide range of experimental studies aimed at understanding the correlation between MSCR Jnr and accelerated performance testing. Overall, there appears to be a correlation between MSCR Jnr and high temperature rutting resistance. However, each publication reviewed by MARC researchers arrives at a unique solution with respect to how the MSCR procedure should be implemented to indicate rutting resistance, if at all. The following section will summarize results of various studies that correlated MSCR test results with accelerated performance testing methods and provide supporting data from previous/current research being carried out by MARC researchers.

Wasage et al. conducted wheel tracking and MSCR tests at 40, 50 and 60 ℃ with two different asphalt binders. MSCR Jnr was compared with the wheel tracking rut depth at 10,000 cycles of loading. Results showed that the MSCR Jnr below 12.8 kPa correlated poorly with the wheel tracking results while the MSCR Jnr at 12.8 kPa gave a linear correlation R^2 value of 0.98. Figure 15 shows the correlation between wheel tracking rut depth and Jnr at 12.8 kPa. These results were expected because the strains experienced by the binder in the wheel tracker are much larger than the 3.2 kPa standard stress level. The high correlation at elevated stress levels implies that use of stress levels within the linear viscoelastic region may not be applicable to indicate the rutting susceptibility of an asphalt binder when comparing with wheel tracking device testing.

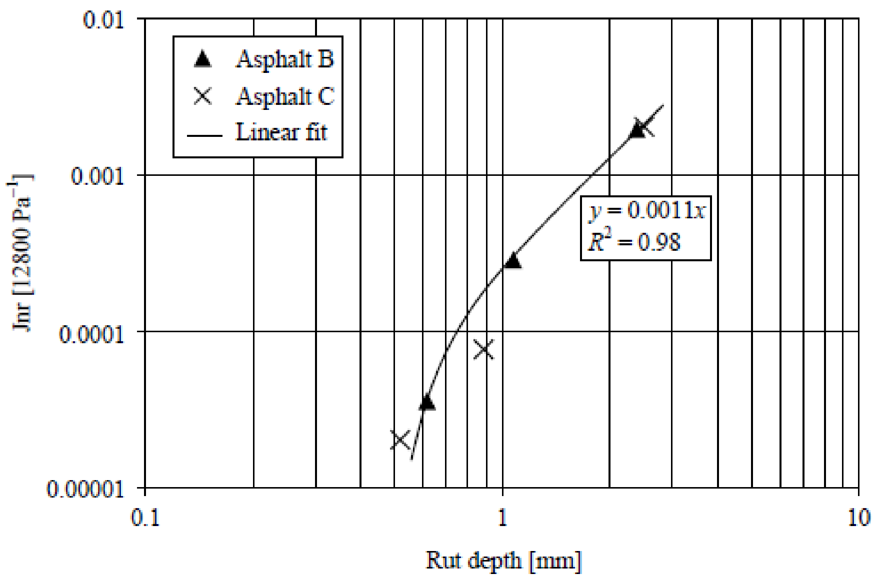


Figure 15: Wheel tracking rut depth correlation with MSCR Jnr at 12.8 kPa.

Shenoy et al. conducted MSCR testing at stress levels of 0.05, 0.4, 3.2 and 25.6 kPa for binders used on two Accelerated Loading Facility (ALF) test tracks. MSCR data was correlated to rut depth and strain accumulation for each test track that were constructed in 2002 and 1993. Results of the study are shown in Table 16 and Table 17. Correlations varied widely depending on when the pavement was constructed, MSCR stress level, and the rutting parameters used for comparison. Results from the test track paved in 1993 showed the highest correlation with MSCR Jnr values, but the binders used in this study were primarily unmodified. When modified binders were incorporated into the 2002 study, very low correlations were observed for all stress levels and correlation fitting equations.

Table 16: Comparison of MSCR Jnr and asphalt mixture rut depth/accumulated strain from 2002 ALF test track.

Table 6a. Using binders from Set 1, data at 64°C and correlation coefficients for $(1-(1/\tan\delta\sin\delta))/|G^*|$ from the dynamic oscillatory test and for J_{NR} from MSCR test at different stress levels.

Binder (continuous PG) lane number section number	AC rut depth in mm at 40,000 wheel passes	$(1-(1/\tan\delta\sin\delta))/\|G^*\|$	J_{NR} @ 50 Pa	J_{NR} @ 400 Pa	J_{NR} @ 3200 Pa	J_{NR} @ 25,600 Pa
CR–TB (79-28) L5S1	8.8	0.00049	0.099	0.116	0.123	0.250
Terpolymer (74-31) L12S1	11.8	0.00128	0.376	0.458	0.528	0.933
SBS LG (74-28) L4S1	12.1	0.00165	0.165	0.194	0.192	0.547
SBS LG (74-28) L11S1	13.4	0.00165	0.165	0.194	0.192	0.547
Air-blown (74-28) L10S1	15.7	0.00218	0.557	0.712	0.786	1.683
Unmodified (72-23) L8S1	15.7	0.00450	1.236	1.595	1.736	3.084
Terpolymer (74-31) L6S1	18.0	0.00128	0.376	0.458	0.528	0.933
SBS64-40 (71-38) L9S1/S2	19.5	0.00058	0.037	0.042	0.039	0.073
Considering all the above eight	Linear fit $R^2 =$	0.027	0.038	0.039	0.042	0.035
Considering only the first six	Linear fit $R^2 =$	0.66	0.53	0.53	0.53	0.63

Table 6b. Using binders from Set 1, data at 64°C and correlation coefficients for $(1-(1/\tan\delta\sin\delta))/|G^*|$ from the dynamic oscillatory test and for J_{NR} from MSCR test at different stress levels.

Binder (continuous PG) lane number section number	Number of load passes to 10% strain	$(1-(1/\tan\delta\sin\delta))/\|G^*\|$	J_{NR} @ 50 Pa	J_{NR} @ 400 Pa	J_{NR} @ 3200 Pa	J_{NR} @ 25,600 Pa
CR–TB (79-28) L5S1	82,375	0.00049	0.099	0.116	0.123	0.250
Terpolymer (74-31) L12S1	1,69,525	0.00128	0.376	0.458	0.528	0.933
SBS LG (74-28) L4S1	14,450	0.00165	0.165	0.194	0.192	0.547
SBS LG (74-28) L11S1	71,950	0.00165	0.165	0.194	0.192	0.547
Air-blown (74-28) L10S1	33,550	0.00218	0.557	0.712	0.786	1.683
Unmodified (72-23) L8S1	30,350	0.00450	1.236	1.595	1.736	3.084
Terpolymer (74-31) L6S1	2650	0.00128	0.376	0.458	0.528	0.933
SBS64-40 (71-38) L9S1/S2	18,337	0.00058	0.037	0.042	0.039	0.073
Considering all four binders	†Linear fit $R^2 =$	0.04	0.01	0.01	0.01	0.01
Considering first three binders	†Linear fit $R^2 =$	0.21	0.07	0.07	0.06	0.10
Considering all four binders	‡*Power* fit $R^2 =$	0.03	0.003	0.003	0.005	0.002
Considering first three binders	‡*Power* fit $R^2 =$	0.20	0.02	0.02	0.01	0.05

† Linear equation: $y = Ax + B$.
‡ *Power equation*: $y = Ax^B$.

Table 17: Comparison of MSCR Jnr and accumulated strain from 1993 ALF test track.

Binder	Number of load passes to 10% strain	$(1-(1/\tan\delta\sin\delta))/\|G^*\|$	J_{NR} @ 50 Pa	J_{NR} @ 400 Pa	J_{NR} @ 3200 Pa	J_{NR} @ 25,600 Pa
AC-5	560	0.012	0.919	1.178	1.335	7.299
AC-10	1800	0.006	0.870	1.115	1.220	2.471
AC-20	2600	0.003	0.516	0.663	0.705	1.256
Styrelf	4,90,000	6.17246×10^{-5}	0.055	0.064	0.063	0.078
Considering all four binders	†Linear fit $R^2 =$	0.43	0.80	0.80	0.78	0.32
Considering first three binders	†Linear fit $R^2 =$	0.99	0.74	0.74	0.79	0.96
Considering all four binders	‡*Power* fit $R^2 =$	*0.99*	*0.98*	*0.98*	*0.98*	*0.97*
Considering first three binders	‡*Power* fit $R^2 =$	*0.91*	*0.56*	*0.56*	*0.60*	*0.97*

† Linear equation: $y = Ax + B$.
‡ *Power equation*: $y = Ax^B$.

Blazejowski et al. correlated MSCR testing with performance testing on three different types of aggregate mixture designs including: SMA mixtures, standard densely graded asphalt concrete mixtures and high modulus asphalt concrete mixtures [49]. Each aggregate mixture design was combined with five different asphalt binders. A wheel tracking device was used for performance testing of the mixtures at 60 °C following the EN 12697-22 standard. Two different parameters were used from the wheel tracking tests: Proportional Rut Depth (PRD_{AIR}) and Wheel Tracking Slope (WTS_{AIR}). Where a lower PRD_{AIR} and WTS_{AIR} is indicative of higher rutting resistance. Linear R^2 correlations between binder and mixture testing are shown in Table 18 and Table 19. Results show moderate to good correlations between wheel tracking parameters and

MSCR Jnr. However, the R^2 correlations were different for each type of mixture design. Differences in correlation values were attributed to the different degrees of aggregate interlock for each mixture deign type. For SMA mixtures, the rutting resistance is more reliant on the packing, angularity and friction between aggregate particles and thus the binder properties do not contribute as much to the overall rutting resistance of the mixture.

Table 18: Relationship between binder properties and proportional rut depth PRD_{AIR} [49].

Properties:	PRD_{AIR} R^2 determination coefficient		
	AC WMS16	**AC 16W**	**SMA 11**
Penetration @25°C [0,1 mm]	0.7239	0.7109	0.3533
Softening Point R&B [°C]	0.7525	0.9099	0.7872
Brookfield Viscosity @60°C [Pa*s]	0.000008	0.9835	0.7590
Brookfield Viscosity @135°C [Pa*s]	0.4248	0.9794	0.7031
MSCR; Jnr @0.1 kPa, @64°C [kPa^{-1}]	0.9390	0.8270	0.7921
MSCR; Jnr @3.2 kPa, @64°C [kPa^{-1}]	0.8164	0.8140	0.7833
MSCR; Jnr diff, @64°C [%]	0.8340	0.8265	0.6745
MSCR; Jnr @0.1 kPa, @70°C [kPa^{-1}]	0.9422	0.8326	0.8239
MSCR; Jnr @3.2 kPa, @70°C [kPa^{-1}]	0.8541	0.8113	0.7799
MSCR; Jnr diff, @70°C [%]	0.8867	0.9822*	0.5687

* - one outlier value was discarded

Table 19: Relationship between binder properties and wheel tracking slope WTS_{AIR} [49].

Properties:	WTS_{AIR} R^2 determination coefficient		
	AC WMS16	**AC 16W**	**SMA 11**
Penetration @25°C [0,1 mm]	0.7267	0.5757	0.2174
Softening Point R&B [°C]	0.6462	0.9081	0.5710
Brookfield Viscosity @60°C [Pa*s]	0.00001	0.9396	0.5968
Brookfield Viscosity @135°C [Pa*s]	0.3604	0.9791	0.5185
MSCR; Jnr @0.1 kPa, @64°C [kPa^{-1}]	0.8821	0.8159	0.7035
MSCR; Jnr @3.2 kPa, @64°C [kPa^{-1}]	0.7764	0.8031	0.6591
MSCR; Jnr diff, @64°C [%]	0.7229	0.8326	0.6107
MSCR; Jnr @0.1 kPa, @70°C [kPa^{-1}]	0.8874	0.8422	0.6250
MSCR; Jnr @3.2 kPa, @70°C [kPa^{-1}]	0.8141	0.8137	0.5490
MSCR; Jnr diff, @70°C [%]	0.7828	0.9977*	0.3832

* - one outlier value was discarded

A study conducted as part of the Wisconsin Highway Research Program compared MSCR Jnr values with pavement rut depth for six different test sections at the MnRoad research facility [50]. Each of the test section contained the same aggregate gradation, but different asphalt binders. Each binder contained the same asphalt binder source, but was modified with different additives with one control. Rut depth was monitored for each test section and Figure 16 shows the linear correlation between rut depth after 30 months of semi-truck loading with MSCR Jnr and the standard high temperature PG parameter.

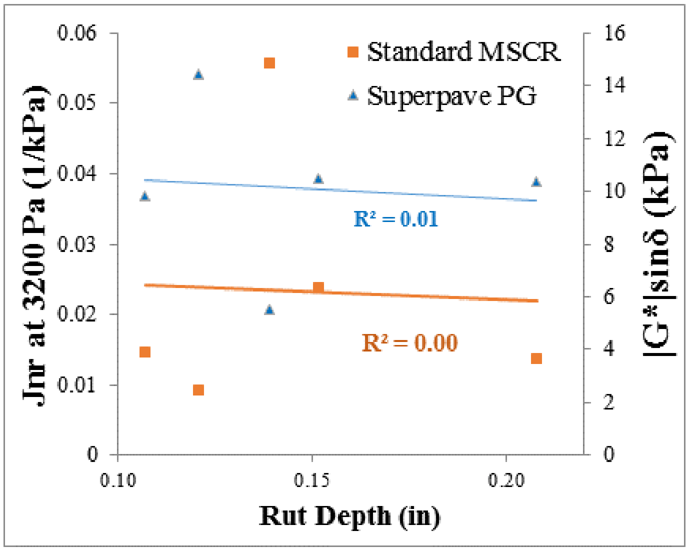


Figure 16- Correlation between MSCR Jnr, PG Parameter and Rut Depth on a MnRoad test track after 3 months.

Neither the MSCR Jnr nor the PG parameters correlated with the MnRoad test section rut depth after 30 months.

As part of the WCTG, 12 different mixture designs were tested for flow number and the corresponding Jnr was measured for comparison at 46 ℃. Correlation between Jnr measurements and Flow Number were best fit using the power law, as shown in Figure 17.

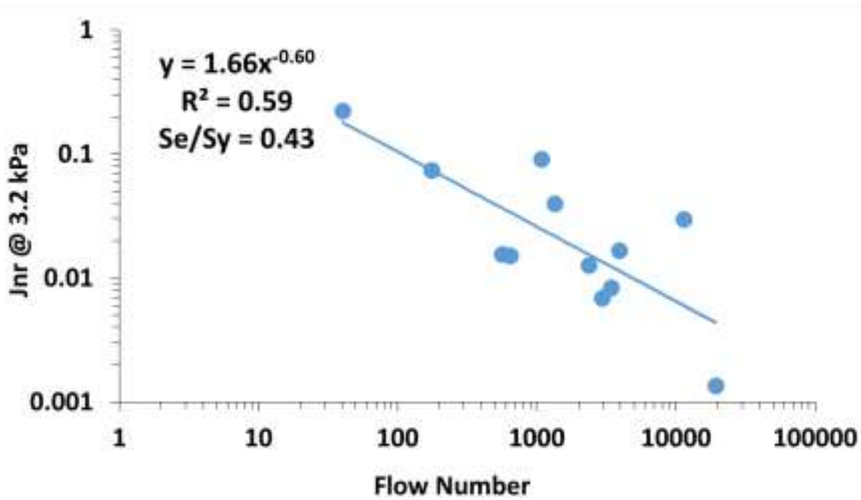


Figure 17- Power law fit between Jnr and Flow Number results for 12 different mixtures and binders from the WCTG.

Results show a moderate correlation between Jnr and Flow Number. When compared with standard limits in AASHTO M332, the results form Figure 17 suggest that specification limits should be set on log scale rather than using a 50% reduction in Jnr for each level of increased traffic.

6.4 MSCR Summary

There are two documents that outline how the MSCR procedure should be conducted and implemented into current state agency specifications (AASHTO T350 and AAHTO 332). The average non-recoverable creep compliance, Jnr, is a primary output of the procedure and can indicate the rutting resistance of an asphalt binder. Average percent recovery, %R, can be used in conjunction with the Jnr parameter to indicate the presence of a polymer. Based on the review of the various studies that have been conducted on the MSCR procedure, the following should be taken into consideration before a state agency can successfully implement the MSCR:

1) A decrease in Jnr has been correlated to an increase in rutting resistance, but studies conducted with multiple mixture designs and pavement test tracks have shown very low correlations with MSCR Jnr. Alterations to the current AASHTO M332 specification limits should be considered based on a comprehensive set of mixture designs and modified binders to avoid an experimental bias.
2) Number of cycles within a given stress step changes the resulting Jnr and %R measurements. The more cycles that are applied to a given stress level (0.1 kPa pr 3.2 kPa), the more repeatable the MSCR measurements. Adding 100 cycles may result in a MSCR procedure that is too long for industrial applications, but using only 10 cycles for the 3.2 kPa stress step could be misleading. A reasonable compromise is needed.
3) Variability analysis conducted on binders as part of the WCTG and an ASTM competence study showed very high inter-lab variability. Therefore, alterations to the procedure should be considered to reduce variability to levels similar to that of current PG tests.
4) Applied stress and stress history change the resulting Jnr and %R differently for different types of polymer modified asphalt. An investigation into what stress level(s) best represent the stress within the asphalt binders of mixtures with traffic loading may validate or

question use of the current MSCR stress levels (0.1 and 3.2 kPa). Also, depending on how the sample is prepared, the stress state of the sample prior to testing can drastically affect the resulting Jnr measurements.

7. Future Work Plan

This report was completed to meet the objectives outlined in **Area #1** of the pooled fund project work plan, which included a detailed literature review of the PG + used by partners of the Pooled Fund Project and commentary regarding the MSCR test procedure and implementation. Findings from the literature review have identified critical shortcomings of current PG+ tests and alternative test methods were proposed at the annual meeting. Currently, testing is underway to meet the objectives outlined for **Area #2** of the pooled fund work plan. Objectives for **Area #2** are as follows:

- Candidate test methods identified to address concerns with current PG+ test methods will be included in a testing program. Table 20 summarizes all newly identified PG+ test methods that may be able to mitigate concerns with the current PG+ test methods.

Table 20-Candidate Test Methods to replace current PG+ test methods.

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	

- Introduce new damage resistance based test methods as a compliment or supplement to current PG plus testing. The goal of damage resistance testing is to provide a binder test the directly correlates with actual mixture performance. Support for implementation of damage tolerance test methods will be provided by the results of mixture testing phase of the pooled fund work plan in **Year 2**.
- Support implementation of select test methods through establishing test precision, test ruggedness, preparation of commentary on existing draft AASHTO standards, and other training materials.

- Prepare a final report that documents results, summarizes findings, draw conclusions and presents: (a) introduction of selected PG+ test from a range of current and suggested alternative test procedures, (b) single lab and multi laboratory precision statements and ruggedness results for each selected tests, and (c) recommendation of the testing procedure's limits and criteria to be applied by partner state DOTs on unified basis.

The aforementioned research objectives for **Area #2** were taken from the work plan written at the beginning of the Pooled Fund Project. Objectives or goals of future work areas, including **Area #2**, can be modified to address concerns highlighted in this report. Specifically, concerns related to MSCR specification may be a desirable research topic for Pooled Fund members.

8. References

[1] A. Golalipour, "Modification of Multiple Stress Creep and Recovery Test Procedure and Usage in Specification," *University of Wisconsin M.S. Thesis,* 2011.

[2] A. Arshadi, "Importance of Asphalt Binder Properties on Rut Resistance of Asphalt Mixture," *MS Thesis, University of Wisconsin-Madison,* 2011.

[3] G. King, H. King, O. Harders, W. Arand and P. Planche , "Influence of Asphalt Grade and Polymer Concentration on the Low Temperature Performance of Polymer Modified," *Association of Asphalt Paving Technologists,* vol. 62, pp. 1-22, 1993.

[4] A. Al-Hadidy and T. Yi-qiu, "Effect of Styrene-Butadiene-Styrene on the Properties of Asphalt and Stone-Matrix-Asphalt Mixture," *American Society of Civil Engineers,* vol. 23, pp. 504-510, 2011.

[5] F. Olard, "GB5 Mix Design: High Performance and Cost-Effective Asphalt Concretes by Use of Gap-graded curves and SBS Modified Bitumens," *Road Materials and Pavement Design,* pp. 234-259, 2012.

[6] A. Khodaii and A. Mehara, "Evluation of Permanent Deformation of Unmodified and SBS Modified Asphalt Mixtures Using Dynamic Creep Test," *Construction and Building Materials,* vol. 23, pp. 2586-2592, 2009.

[7] J. D'Angelo and R. Dongre, "Practical Use of Multiple Stress Creep and Recovery Test," *Transportation Reserach Record: Journal of Transportation Research Board,* pp. 73-82, 2009.

[8] A. Hanyu, S. Ueno, A. Kasahara and K. Saito, "Effect of the Morphology of SBS Modified Asphalt on Mechanical Properties of Binder and Mixture," *Journal of the Eastern Asia Society for Transportation Studies,* vol. 6, pp. 1153-1167, 2005.

[9] D. Little, A. Bhasin and R. Lytton, "Micromechanics Modeling of Performance of Asphalt Concrete Based on Surface Energy," in *Modeling of Asphalt Concrete*, New York, The McGraw-Hill Companies, 2009, pp. 355-391.

[10] C. Daranga, C. Clopotel and H. Bahia, "Replacing the Elastic Recovery Test of Asphalt Binder with a DSR Test," *Journal of the Transportation Reserach Board,* 2010.

[11] AASHTO, "T51 Standard Method of Test for Ductility of Asphalt Materials," AASHTO, Washington D.C., 2009.

[12] ASTM, "D113-07 Standard Test Method for Ductility of Bituminous Materials," ASTM International, West Conshohocken, PA, 2007.

[13] AASHTO, "T300 Forced Ductility Test of Asphalt Materials," AASHTO, Washington D.C., 2011.

[14] H. A. Tabatabaee, C. Clopotel, A. Arshadi and H. Bahia, "Critical Problems with Using the Asphalt Ductility Test as a Performance Indicator," *Transportation Research Board,* vol. 2370, no. Aspahlt Materials and Mixtures Vol. 1, pp. 84-91, 2013.

[15] F. L. Roberts, P. S. Kandhal, R. E. Brown, D. Y. Lee and T. W. Kennedy, "Hot Mix Asphalt Materials, Mixture Design and Construction," *National Asphalt Pavement Association Research and Education Foundation,* vol. 2, pp. 47-48, 1996.

[16] R. C. Clark , "Practical Results of Asphalt Hardening of Pavement Life," *Proceedings of the Association of Asphalt Paving Technologists,* pp. 196-597, 1958.

[17] P. C. Doyal, "Cracking Characteristic of Asphalt Cement," *Association of Asphalt Paving Technologists,* pp. 581-597, 1957.

[18] W. J. Halstead, "The Relation of Asphalt Ductility to Pavement Performance," *Association of Asphalt Paving Technologists,* pp. 247-270, 1962.

[19] R. H. Lewis and J. Y. Welborn, "Report on the Properties of the REsidues of 50-60 and 85-100 Penetration Asphalts forn Oven Tests and Exposure," *Association of Asphalt Paving Technologists,* pp. 12-68\, 1940.

[20] H. W. Skidmore, "The Effect of Oxidation Upon Ductility of Asphalt Cements," *Association of Aspahlt Paving Technologists,* pp. 69-86, 1940.

[21] C. J. Glover, R. R. Davidson, C. H. Domke, Y. Ruan, P. Juristyarini and D. B. Knorr, "Development of a new method for assessing asphalt binder performance durability," *FHWA/TX-02/1872-1,* 2011.

[22] P. S. Kandhal and M. E. Wenger, "Evaluation of Properties of AC-20 Asphalt Cements," *Transportation Research Record,* vol. 468, pp. 56-64, 1973.

[23] B. A. Vallerga and W. J. Halstead, "The Effect of Field Aging on Fundamental Properties of Paving Asphalts," *Highway Research Record,* pp. 71-92, 1971.

[24] R. C. Clark, "Practical Results of Asphalt Hardening on Pavement Life," *Proceedings Association of Asphalt Paving Technologists,* vol. 27, pp. 196-208, 1958.

[25] J. Goodrich, "Asphalt and Polymer Modified Asphalt Properties Related to the Performance of Asphalt Concrete Mixes," *Journal of the Association of Aspahlt Paving Technologists* , p. 57, 1988.

[26] R. E. Reese and J. L. Goodrich, "California Desert Test Road- A Step Closer to Performance Based Specifications," *Proceedings of Association of Asphalt Paving Technologists,* vol. 62, pp. 247-313, 1993.

[27] W. C. Vonk and J. Korenstra, "The Relevance of Ductility Specifications for Polymer Modified Bitumen," *Eurobitumen Congress,* 2008.

[28] ASTM, "D5801-12 Standard Test Method for Toughness and Tenacity of Bituminous Materials," ASTM International, West Conshohocken, PA, 2012.

[29] J. R. Benson, "New Concepts for Rubberized Asphalts," *Roads and Streets,* April 1955.

[30] D. C. Thomson, "Bituminous Materials: Asphalts, Tars, and Pitches," *Interscience,* vol. 1, pp. 386-388, 1964.

[31] H. L. Robinson, M. B. Taylor and D. J. Tosh, "Toughness/Tenacity Analysis of Bitumen," *Highways,* pp. 14-17, January 1991.

[32] D. J. Tosh and R. Morin, "Building Seals and Sealants," *ASTM STP 606,* pp. 167-169, 1976.

[33] L. Jyu-Dong, C. Shiih-Huang, L. Pei and W. Jian-Neg, "Modified Toughness Used to Evaluate the Effect of Polymer Modified Aspahlt on SMA," *Journal of the Chinese Inistitute of Engineers,* vol. 24, no. 7, pp. 1013-1020, 2004.

[34] J. M. Wang, "The Study of Polymer Modified Asphalt," Taoyuan, Thaiwan, 2000.

[35] P. A. Tsai, W. C. Chen and J. S. Chen, "Final Report on Establishing Relationships between Fundamental Asphalt Properties and Flexible Pavement Distresses," Taiwan, 2000.

[36] U. Isacsson and X. Lu, "Testing and Appraisal of Polymer Modified Road Bitumens- State of the Art," *Materials and Structures,* vol. 25, pp. 139-159, 1995.

[37] J. D'Angelo, "New High Temperature Binder Specification Using Multistress Creep Recovery," *Transportation Research Board,* pp. 1-14, 2010.

[38] R. Anderson, J. D'Angelo and J. Bukowski, "Evaluation of the MSCR Test for Canadian Asphalt Binders," *Proceedsing of the Fifty-Sixth Annual Conference of the Canadian Technical Asphalt Association,* pp. 61-82, 2011.

[39] J. D'Angelo, R. Dongre and G. Reinke, "Evaluation of Repeated Creep and Recovery Test Method as an Alternative to SHRP+ Requirements for Polymer Modified Asphalt Binders," *Canadian Technical Asphalt Association Proceedings,* pp. 143-162, 2006.

[40] O. Laukkanen, H. Soenen, T. Pellinen and G. Lemoine, "Creep Recovery Behavior of Bituminous Binders and Its Relation to Asphalt Mixture Rutting," *Materials & Structures,* 2014.

[41] T. Wasage, J. Stastna and L. Zanzotto, "Rheological Analysis of Multi-stress Creep Recvoery (MSCR) Test," *International Journal of Pavement Engineering,* vol. 12, no. 6, pp. 561-568, 2011.

[42] T. Mandal, R. Sylla, H. Bahia and S. Barmand, "Effect of Cross-Linking Agents on the Rheological Properties of Polymer-Modified Bitumen," *Road Materials and Pavement Design,* vol. 16, no. 1, pp. 349-361, 2015.

[43] A. Shenoy, "Nonrecovered Compliance From Dynamic Oscillatory test vis-a-vis nonrecoverd compliance from multiple stress creep and recovery test in the dynamic shear rheomter," *International Journal of Pavement Engineering,* vol. 9, no. 5, pp. 329-341, 2008.

[44] H. Bahia, H. Tabatabaee, C. Clopotel and A. Golalipour, "Evaluation of the MSCR Test for Modified Aspahlt Binder Specification," *Canadian Technical Asphalt Association (CTAA),* pp. 203-222, 2011.

[45] M. Domingos and A. Faxina, "A Creep-Recovery Behavior of Asphalt Binders Modified with SBS and PPA," *Journal of Materials in Civil Engineering,* vol. 26, no. 4, pp. 781-783, 2014.

[46] A. Diab and Z. You, "Evaluation of Foam-based Warm Mix Asphalt Modified with Nano-sized Hydrated Lime Using Multiple Creep and Recovery Tests," *T&DI Congress,* pp. 230-238, 2014.

[47] R. Delgadillo, H. Bahia and R. Lakes, "A nonlinear constitutive relationship for asphalt binders," *Materails and Structures,* vol. 45, pp. 457-473, 2012.

[48] H. Soenen, T. Blomberg, T. Pellinen and O. Laukkanen, "The Multiple Stress Creep-Recovery Test: A Detailed Analysis of Repeatability and Reproducibilty," *Road Materials and Pavement Design*, vol. 14, no. 1, pp. 2-11, 2013.

[49] K. Blazejowski and B. Dolzycki, "Relationships between Asphalt Mix Rutting Resistance and MSCR Test Results," *Design, Analysis, and Asphalt Material Characterization for Road and Airfield Pavements,* pp. 202-209, 2014.

[50] H. Bahia, H. Tabatabaee, T. Mandal and A. Faheem, "Field Evaluation of Wisconsin Modified Binder Selection Guidelines-Phase II," *Wisconsin Highway Research Program, 0092-13-02,* 2013.

[51] Y. Becker, M. Mendez and Y. Rodgriguez, "Polymer Modified Asphalt," *Vision Tecnologica*, 2001.

[52] J. Greene, B. Choubane and S. Chun, "Evaluation of a Heavily Polymer Modified Binder through Accelerated Pavement Testing," *Presented at the Transportation Reserach Board 92nd Annual Meeting*, 2013.

[53] S. Vahidi, W. Mogawer and A. Booshehrian, "Evaluating the Effects of Ground Tire Rubber (GTR) Modified Asphalt and Dry Added Treated GTR on the Performance Characteristics on RAP Mixtures," *Transportation Research Board Annual Meeting*, 2013.

9. Appendix A

PG+ Survey Questioner

Example for the Phase Angle

Modified Binders (PG+) Specifications Pooled Funds Questionnaire

December 2014

Dear Colleague,

The University of Wisconsin-Madison and the Modified Asphalt Research Center (MARC) as part of the Modified Binders (PG+) Specifications Pooled Funds Project will conduct a survey in order to achieve a better understanding of current PG plus specification and. A segment of our research approach is to overview information obtained through a questionnaire study. The following questionnaire has been prepared with focus on justification of currently used PG plus methods and limits.

We would like to ask each state partner to answer to questions regarding the test they are currently conducting in their agency as part of the PG plus requirement.

We would greatly appreciate your contribution to this study. Please complete and return the questionnaire and also, if possible, any related document to your answers, by January 8th to the email address provided in the following:

teymourpour@wisc.edu
608-890 3321
Pouya Teymourpour

(Property) – Example for Phase Angle

Phase angle (δ) is defined as the lag between the applied shear stress and the resulting shear strain on the tested material as shown in Figure 1. It is an important parameter describing the viscoelastic property of material such as asphalt binder. The larger the phase angle, the more viscous the material. Phase angle can be obtained from Dynamic Shear Rheometer (DSR) testing together with complex shear modulus for asphalt binder. AASHTO T315 and ASTM D7175 specify the testing procedures for complex modulus and phase angle of asphalt binder using DSR. Lower phase angle is preferable indicating higher elasticity and better ability of recovery after deformation. Among the five partner states, only Ohio and Wisconsin specify the limits for phase angle of the modified binder to ensure its elasticity and proper modification.

1. Is the test needed?
   a. If yes what is the specific objective (what failure are we preventing)?

   b. Is there clear evidence the test can do this?

2. Can we agree on one method of test?
   a. If yes should it be in DSR (new methods) or should we stay with current procedures?

   b. Do we need the AASHTO standard for the new method?

3. Can we agree on one set of limits to be used?
    a. What is the reason behind selecting the current limit?

    b. How to go about establishing limits?

    c. Mix data, field performance, or expert opinion?

    d. Do we need a database?