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FINAL REPORT ~ FHWA-OK-14-19

CREEP COMPLIANCE AND PERCENT RECOVERY OF OKLAHOMA CERTIFIED BINDER USING THE MULTIPLE STRESS RECOVERY (MSCR) METHOD

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April 2015

Oklahoma Department
of Transportation

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ODOT SP&R ITEM NUMBER 2248

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A laboratory study was conducted to develop guidelines for the Multiple Stress Creep Recovery (MSCR) test method for local conditions prevailing in Oklahoma. The study consisted of commonly used binders in Oklahoma, namely PG 64-22, PG 70-28, and PG 76-28. The testing program also included binders recovered from four reclaimed asphalt pavement (RAP) samples and Sasobit®-modified virgin binders. Non-Recoverable Creep Compliance (J_{nr}) and MSCR %Recovery, obtained from the MSCR test data, were analyzed for the MSCR grading. In addition, the Asphalt Institute (AI) recommended Polymer and Quadrant methods were followed in interpreting the test data. Analyses of test results showed that the AASHTO T 350 and AASHTO T 332 recommended J_{nr} criteria could be followed in the MSCR-based grading for conditions prevailing in Oklahoma. It was observed that 97% of the tested polymer-modified binders met the Asphalt Institute (AI) recommended minimum %Recovery and stress sensitivity. Acceptable %Recovery limits are proposed for both PG 70-28 and PG 76-28 binders without penalizing a significant number of suppliers or users. It was also found that an addition of 3% Sasobit® would reduce the rut depth by half compared to other binders. It is expected that these guidelines will assist ODOT in a successful transition to the latest MSCR specifications for binders.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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ABSTRACT

Unlike neat (unmodified) binders, polymer-modified binders are sensitive to the applied stress levels, and they exhibit nonlinear response with respect to rutting factor and phase angle. The Superpave® test protocols work well for neat binders, but they are inadequate for characterizing viscoelastic properties of polymer-modified binders. Consequently, many state agencies have introduced additional tests to characterize polymer-modified binders, which, along with their specifications, are called the Superpave® “PG Plus” specifications.

A major drawback of the “PG Plus” tests is that they may not be reflective of performance in the field in some cases, but rather an indicator of the presence of a particular modifier in the binder. These tests are generally expensive and time consuming. The absence of common test standards and specifications across states and variations in performing these tests pose additional challenges. The Federal Highway Administration (FHWA) has introduced a new test method for measuring the high temperature properties of binders, called “Multiple Stress Creep Recovery” (MSCR) test that can provide information on both performance and formulation of the binder. A major benefit of the new MSCR test is that it can eliminate the need for the “PG Plus” tests. The MSCR test can also capture the actual field conditions experienced by a pavement through repeated creep-recovery cycles.

The present study was intended to examine the feasibility of using the MSCR test method by the Oklahoma Department of Transportation (ODOT) to characterize polymer-modified binders. To this end, a laboratory study was conducted with commonly used binders in Oklahoma. The experimental plan comprised of Superpave®

and MSCR testing of three selected performance grade (PG) binders, namely PG 64-22, PG 70-28, and PG 76-28. Binders recovered from three simulated RAP (SRAP) and one field-RAP (FRAP) samples were evaluated. Also, selected viscoelastic properties of additional binders modified with a Warm Mix Asphalt (WMA) additive, namely Sasobit®, were evaluated. Two selected parameters, Non-Recoverable Creep Compliance (J_{nr}) and MSCR %Recovery (%Recovery) at 3.2 kPa, obtained from the MSCR test data, were analyzed for MSCR grading. In addition, the Asphalt Institute (AI) recommended Polymer and Quadrant methods were used in the interpretation of the test data.

Analyses of MSCR test results showed that the AASHTO T 350 and AASHTO M 332 recommended J_{nr} criteria could be followed in the MSCR-based grading for conditions prevailing in Oklahoma. From the test data 97% of the tested polymer-modified binders were found to meet the minimum %Recovery and stress sensitivity criteria recommended by the AI. Acceptable %Recovery limits were proposed for both PG 70-28 and PG 76-28 binders without penalizing a significant number of suppliers or users. From the MSCR test results for Sasobit®-modified binders, it was found that an addition of 3% Sasobit® would reduce the rut depth by half compared to other binders. Based on the results from this study, guidelines were developed for possible adoption of the MSCR test method by ODOT for quality assurance purposes. It is expected that these guidelines will assist ODOT in a successful transition to the latest AASHTO specifications for binders.

1 INTRODUCTION

1.1 Background

About 95% of paved roads in the United States are surfaced with asphalt [1]. There is a widespread recognition that binder plays a key role in the behavior of asphalt mix and performance of asphalt pavements. Binder, as one of the load carrying components of the asphalt mix, is a viscoelastic and thermoplastic material, characterized by a certain level of rigidity of an elastic solid body. However, it flows and dissipates energy through frictional losses as a viscous fluid [2]. As the binder is responsible for the viscoelastic behavior of asphalt mixes, it plays a dominant role in overall pavement performance such as resistance to permanent deformation, or rutting [3-6]. The accumulated strain in the binder, a consequence of traffic, is mainly responsible for the rutting of asphalt pavements. Attempts have been made previously to develop specifications and to identify parameters that can describe the contribution of a binder to pavement rutting.

In order to improve the performance and durability of roads in the United States, the Strategic Highway Research Program (SHRP) was established in 1987 [2, 3]. From 1987 through 1992, the SHRP carried out a major research program to develop the Superpave® specifications and test methods for binders and asphalt mixes [2, 3]. These specifications were collectively called the Superpave® pavement design system. The Superpave® pavement design system addresses asphalt pavement performance by offering the American Association of State Highway and Transportation Officials (AASHTO) testing protocols and specifications for minimizing distresses in roadway pavements such as rutting, low temperature cracking, and fatigue cracking [2-5]. In 1993, after the completion of the 1987 SHRP program, the Performance Grade (PG) binder specifications were adopted by the AASHTO and were introduced as AASHTO M320 (formerly designated as AASHTO MP1) and AASHTO MP1a [2]. One of the objectives in the development of the Superpave® binder specifications was to use performance-related criteria specific to distress, climate, and traffic loading. The introduction of Superpave® provided a useful method for evaluating and understanding the mechanism of rutting. The Dynamic Shear Rheometer (DSR)-based test (AASHTO T 315) was introduced to measure the contribution of the binder to rutting under high service temperatures. Although the Superpave®-specified PG grading system was a significant improvement to the earlier grading systems (e.g., penetration, or viscosity grading), there were concerns because the pertinent test methods were based on unmodified binders [4, 5, 6].

The Superpave®-specified rutting parameter ($G^*/\sin\delta$) is generally obtained from a DSR test (AASHTO T 315). This parameter is used in the high temperature performance grading of a binder, particularly in rating the binder for rutting resistance. Although used for many years, the DSR-based rutting parameter ($G^*/\sin\delta$) was found to have poor correlations with field rutting [4-10]. The rutting parameter was found to be inadequate in describing the rutting performance of certain binders, particularly polymer-modified binders. As a consequence, the applicability of the existing AASHTO M 320 and AASHTO T 315 specifications to polymer-modified binders has been questioned by some private sectors (e.g., Asphalt Institute (AI)) and many state highway agencies and Departments of Transportation (DOTs) [10-12]. Many DOTs then added additional tests to the AASHTO M 320 specifications to ensure that a desired modifier is included in the binder [10, 11]. These additional tests, some of which are empirical, were referred to as the Superpave® Plus tests, "PG Plus" tests, PG+, or SHRP+ specifications. The "PG Plus" tests raised difficulty for the manufacturers and suppliers because of their variation in standards across the states [7, 8, 12]. Some PG+ tests only indicate the presence of a particular modifier in the binder, but do not necessarily relate to performance. Consequently, a DOT needs to consider the implications of the "PG Plus" specifications carefully before using them.

Many studies have been carried out in the development of a new PG binder test that is both performance-based and blind to modification type [12-19]. Multiple binders, both neat and polymer-modified, have been evaluated previously. In a project under the National Cooperative Highway Research Program (NCHRP), Bahia et al. [4, 5] proposed the Repeated Creep Recovery Test (RCRT) method as a possible way to estimate the rate of accumulation of permanent strain in the binder. The Federal Highway Administration (FHWA) modified the RCRT method by increasing stress levels and renamed it as the Multiple Stress Creep Recovery (MSCR) test [20]. D'Angelo et al. [15] improved this MSCR test by running creep and recovery testing on one sample at multiple stress levels and introduced a new parameter called non-recoverable compliance (J_{nr}) [15]. The J_{nr} parameter shows the differences between stress-related deformation properties of different polymer-modified binders. Subsequently, this MSCR test method was proposed as a replacement of the “PG Plus” tests [15-22]. The present study, supported by the Oklahoma Department of Transportation (ODOT), aims to establish guidelines for implementing the MSCR test method for commonly used binders in Oklahoma. This aim is achieved by performing the Superpave® and MSCR tests on selected neat, polymer-modified and Sasobit®-modified binders from different sources along with recovered binders from two laboratory simulated reclaimed asphalt pavement (SRAP) samples.

1.2 Need of the Study

Several state DOTs have raised some issues concerning the implementation of the MSCR test method as a quality control tool. The AI researchers have taken a leadership role in establishing the need for the MSCR test method through various regional meetings and presentations [24-30]. The current study is expected to address the following issues:

- Unlike neat (unmodified) binders, polymer-modified binders are sensitive to the applied stress levels and show nonlinear response pertaining to rutting parameter and phase angle. The widely used DSR-based test method (AASHTO T 315) does not sufficiently capture the viscoelastic properties of polymer-modified binders [4, 10-15]. This is because the polymer chains can be rearranged substantially with an increase in stress. As a consequence, many DOTs routinely perform additional tests that are referred to as “PG Plus” tests. Major drawbacks of the “PG Plus” tests include: (i) they are not reflective of performance in the field in most cases, but rather serve as an indicator of the presence of a particular modifier in the binder; and (ii) specific test standards are not common across the states, like Elastic Recovery (ER) [12-15].

- Unlike the MSCR test specifications (AASHTO T 332), the current AASHTO M 320 test method does not have a high correlation to rut performance in the field. Under AASHTO M 320, improving performance based on traffic conditions is accomplished by “bumping” up the high temperature grade of the binder. In the “bumped” grading system, a binder is tested at 6-18˚C above the actual highest temperature of the pavement. Consequently, the agencies may be over estimating the need for higher grade binders. The MSCR test specifications use a more realistic high temperature in the testing process than the AASHTO M 320 test method with no arbitrary grade bumping [17-21].
- A weak polymer structure in binder that either breaks down or undergoes substantial re-orientation under high stress leads to poor pavement performance. The AASHTO M 320 test method, which is currently used by transportation agencies, fails to identify weak polymer structure in a binder. The proposed MSCR specifications, with their stress sensitivity criterion, help identify a binder that has a high likelihood to perform poorly in the pavement when exposed to high stresses [17-21].

1.3 Significance of the Study

The present study generated useful test data based on the MSCR testing of commonly used binders in Oklahoma. These test data are expected to have a significant impact on ODOT's binder testing specifications. Specifically, these test data are expected to help ODOT in developing guidelines and test protocols for the MSCR test method by setting desirable limits for the MSCR %Recovery and J_{nr} values. The potential elimination of the need for conducting time-consuming and expensive "PG Plus" tests is another expected benefit of this study. Moreover, this study uses the Long Term Pavement Performance (LTPP) Bind software, which allows for applying local temperatures and traffic conditions in grading binders.

1.4 Objectives

The major objectives of the proposed study are:

1. Evaluation of the non-recoverable creep compliance (J_{nr}) and MSCR %Recovery relationships of the following binders, for conditions prevailing in Oklahoma:
    - (i) Unmodified binders,
    - (ii) Polymer-modified binders,
    - (iii) Binders recovered from Reclaimed Asphalt Pavements (RAP) materials.
2. Determination of J_{nr} and MSCR %Recovery limits for commonly used binders in Oklahoma.

3. Assessment of the presence of polymer through MSCR %Recovery of polymer-modified binders and binders recovered from RAPs.

1.5 Organization of the Report

This report is organized into six chapters, including this “Introduction” Chapter. Chapter 2 presents a literature review focused on the development of the MSCR test method, its implementation, and its advantages. Chapter 3 focuses on the material selection, methodologies, and executions of the Superpave® and MSCR tests on selected binders. In Chapter 4, analyses of MSCR test data from various sources, statistical analyses, comparisons of MSCR test results, and the feasibility of using the MSCR test method are described in detail. This chapter also includes analysis of data using the Long Term Pavement Performance (LTPP) Bind software. Chapter 5 contains the MSCR test results and analysis of Sasobit®-modified binders and recovered binders from RAP. Summary, conclusions, and recommendations for future work are presented in Chapter 6. There are four appendices in this report, namely A, B, C and D. Appendix A contains MSCR databases. The detection of outliers for all types of binders is presented in Appendix B. Appendix C contains the detailed analysis of LTPPBind software. Lastly, Appendix D elaborates on the MSCR test method.

2 LITERATURE REVIEW

2.1 Introduction

The MSCR test method incorporates the well-established creep and recovery test concepts in order to evaluate the binder's susceptibility to permanent deformation. Creep is generally defined as deformation under sustained loading. In the context of binder, it refers to slow changes in material characteristics and properties under loading over a given period of time. Recovery means relaxation after removing the load completely for a given period of time. The MSCR tests are conducted at two stress levels, namely 0.1 kPa and 3.2 kPa. A total of 30 cycles (20 cycles at 0.1 kPa, followed 10 cycles at 3.2 kPa) of load is applied on the binder samples. A cycle is when the load is applied for one second, it is removed completely and the sample is allowed to recover for nine seconds (Figure 2.1) [15, 20]. Twently cycles are ran at 0.1 kPa. The first ten (10) cycles' results are used for conditioning. The last ten (10) cycles are ran at 3.2 kPa. The original version of AASHTO TP 70 did not include the conditioning cycle. Two important parameters, namely Non-Recoverable Creep Compliance (J_{nr}) and MSCR Percent Recovery (MSCR %Recovery), both obtained from the MSCR test, are used for analyzing properties of a binder at high temperatures. Physically, J_{nr} is a measure of the amount of residual strain left in the binder specimen after repeated creep and recovery, relative to the applied stress magnitude. The MSCR %Recovery at 3.2 kPa or $R_{3.2}$, also called %Recovery in this report, is a measure of how much the sample returns to its previous shape after being repeatedly stretched and relaxed.

In this chapter, pertinent literature related to the development and implementation of the MSCR test method, along with the interpretation of MSCR test data, is reviewed. The reasons behind using the MSCR test method as an alternative to “PG Plus” tests are explained herein based on the findings of ongoing and previous studies available in the public domain. It should be understood that ultimately, agencies use AASHTO M 320 and AASHTO M 332 as purchase specifications.

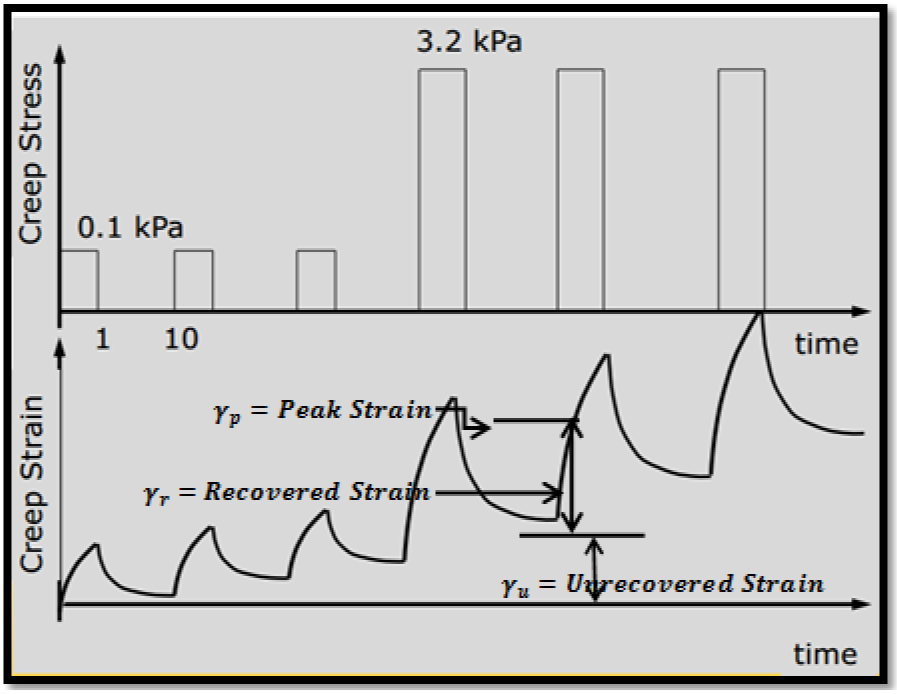


Figure 2.0-1 Examples of Modified Binder Response to Repeated Loading [20].

2.2 MSCR Test Method and Concept

2.2.1 Historical Development of Superpave® and Performance Grade

A binder needs to be stiff for high-temperature performance, but the same material also needs to be soft for low-temperature performance. When selecting an appropriate binder, sometimes asphalt producers focus on the high-temperature performance while sacrificing the low-temperature performance or vice versa [23]. Recognizing the limitation of the long-established binder characterization procedures (e.g., viscosity or penetration grading) in 1987, the Federal Highway Administration (FHWA) initiated a nationwide research program called the Strategic Highway Research Program, usually referred to as SHRP [3]. One of the final products of the SHRP project was the creation of Superpave® (Superior Performing Asphalt Pavements) specifications. The Superpave® protocols work well for neat binders, but they are inadequate for characterizing viscoelastic properties of polymer-modified binders. For instance, AASHTO T 315 is not appropriate for measuring mechanical and viscoelastic properties of polymer-modified binders beyond their linear viscoelastic ranges. The National Cooperative Highway Research Program (NCHRP) Project 9-10, “Superpave® Protocols for Modified Binders,” was initiated to determine if the current Superpave® binder test protocols are suitable for modified binders [5]. The NCHRP Project 9-10 report concluded that the Superpave® performance grade (PG) specifications could not be used for full characterization of binders modified with different types of polymers. The underlying reason is that the Superpave® specifications are based on simplifying assumptions that cannot be reliably extended to modified binders. Consequently, many state agencies have introduced additional tests to characterize polymer-modified binders, such as elastic recovery (ER), tenacity, and forced ductility (FD). These tests, along with their specifications, are called the Superpave® “PG Plus” specifications [15, 37]. However, the “PG Plus” test results may not be reliable indicators of field performance. Moreover, they are costly as they require special equipment and time. In 2006, a federally funded study by the Virginia Department of Transportation (VDOT) employed some alternative test methods (chemical and mechanical) to identify the presence of polymer modifiers in binders as part of the agency's quality assurance practices [38]. The VDOT study used AASTHO T 302 "*Polymer Content of Polymer-Modified Emulsions and Binders using Fourier transform infrared (FTIR) Spectroscopy,"* and AASTHO T 301 "*Elastic Recovery Test of Bituminous Materials by Means of a Ductilometer."* It concluded that neither the FTIR spectroscopy nor the elastic recovery technique is sensitive to the neat binder grade, and neither of them is suitable for identifying polymers in modified binders [38]. Another group of researchers recommended the zero shear viscosity (ZSV) concept to characterize polymer-modified binders [39-44]. However, the coherency and reliability of the ZSV test protocols are not always ensured in the case of polymer-modified binders [45, 46].

2.2.2 Drawbacks of Various Concepts

2.2.2.1 Drawbacks of DSR (AASTHO T315)

In 1993, the Dynamic Shear Rheometer (DSR) test method (AASHTO T 315) was introduced as a test protocol to measure the mechanical and rheological properties of binders. In particular, a DSR device helps to evaluate a binder's rutting and fatigue resistances. However, some studies have shown that AASHTO T 315 does not give an acceptable correlation with the rutting potential of asphalt mixes. Also, this test method does not correlate well with the rutting potential of actual pavements [9, 15, 20]. In the PG grading system, the high-temperature parameter, G*/sinδ (called the rutting factor), is measured by applying an oscillating stress to the binder at a very low strain level. Under a very low stress and strain level, it is unlikely that the polymer network in the binder would be activated. The polymer chains, however, can be rearranged substantially with increasing stresses levels [20]. In the existing Superpave® PG specifications, the polymer is only viewed as a filler material that stiffens the binder [20].

In the MSCR test method (AASHTO T 350), higher levels of stress and strain are applied to the binder, which reflect the actual field conditions experienced by a pavement. By using higher levels of stresses and strains in the MSCR test, the response of the binder displays not only the stiffening effects of the polymer, but also the delayed elastic effects.

2.2.2.2 Drawbacks of "PG Plus" Tests

The "PG Plus" tests do not relate directly to performance, rather, they only relate to the presence of a particular modifier in the binder. Some state agencies including ODOT use ASTM D6084 or AASHTO T 301 "*Elastic Recovery test of Binder by Means of a Ductilometer*," to determine the presence of polymer by evaluating the elasticity of a binder. The elastic recovery (ER) test (ASTM D6084 or AASHTO T 301) is typically performed at 25˚C on an RTFO-aged binder at an elongation rate of 5 cm/min until the elongation reaches 20 cm. A state agency will allow a modified binder for construction projects if its elastic recovery (ER) meets the agency-specified requirement. The ER test is time consuming as a single ER test requires about 4 hours (around 3 hours for sample preparation and 1 hour for testing). On the other hand, the MSCR test can be performed within 40 to 50 minutes (about 25 minutes for instrument initialization, setting target temperature, and sample preparation, and about 15 to 20 minutes for conducting the test). The time required for sample preparation and Rolling Thin Film Oven (RTFO), AASHTO T 240, aging is not detailed. The ER tests are generally performed on RTFO residue as well. The MSCR test is conducted using a DSR, which is a commonly used piece of equipment for the determination of the Superpave® PG grading. The ER test requires a ductilometer, which is a fairly expensive piece of equipment and imposes additional cost to the agency. Moreover, in many cases not only is there little agreement among experts on the reliability of some of the “PG Plus” test results, but there are also contradictory findings from the forced ductility test results. For instance, a study conducted by researchers at the University of Wisconsin revealed no correlation between ductility and fatigue or rutting resistance of asphalt pavements [39]. The aforementioned issues with the “PG Plus” tests have encouraged many asphalt researchers, engineers, and industry professionals to use the MSCR test as a suitable tool to examine high temperature performance of binders. It can potentially replace many “PG Plus” tests as a reliable indicator of performance.

2.2.2.3 Drawbacks of Other Viscosity-Based Test Methods

Zero shear viscosity (ZSV), or the viscosity at zero shear rate, of a binder can be measured by means of different laboratory test methods (creep, frequency sweep, shear rate sweep, and multi-creep tests). It has been documented that ZSV test results show better correlations with the rutting performance of a corresponding asphalt mix than the conventional rutting factor, G*/sinδ [40-44]. For example, Philips and Robertus [41] used ZSV to characterize the contribution of a binder to the rut depth of asphalt mixes by plotting the rut rate versus viscosity. Morea *et al.* [45] found that in the case of a Styrene-Butadiene-Styrene (SBS)-modified binder, the ZSV values derived from frequency sweep and creep tests were not in agreement. Desmazes *et al.* [46] also reported that highly polymer-modified binders never reached steady state flow conditions because they are cross-linked; rather, they behave as viscoelastic solid. Therefore, the ZSV concept may not be applicable to highly polymer-modified binders. To address this issue, the concept of low shear viscosity (LSV) was introduced while evaluating the effects of modified binder on laboratory mixing and compaction [6, 47, 48]. In these studies, the viscosity level was selected to avoid excessive heating and to consider the shear-rate dependency of modified binders [6, 47, 48]. Morea *et al.* [49] evaluated the LSV of original and RTFO-aged binder in order to relate this rheological property to rutting. It was found that the LSV values of 500 Pa.s and 2,000 Pa.s represent reasonable limits for the partial contribution of binder to the rutting resistance of asphalt mixes for the original and RTFO-aged conditions, respectively [49]. Zoorob *et al*. [50] reported that ZSV and LSV test protocols were not sufficient for characterizing high-temperature creep behavior of polymer-modified binders (SBS-modified binders). These researchers suggested that the MSCR test method would be a more satisfactory performance evaluation tool for polymer-modified binders than the ZSV or LSV test method [50].

2.2.3 Advantages of Multiple Stress Creep Recovery Method

Several studies have been conducted previously to address the aforementioned drawbacks of the AASHTO T 315 test method along with other relevant rheological tests. Among these studies, the NCHRP Project 9-10, "*Superpave® Protocols for Modified Binders*," recommended modifications to the Superpave® binder tests for modified binders [5]. The NCHRP 9-10 study hypothesized that repeated loading is a factor to which a modified binder responds differently than a neat binder. This hypothesis is important because traffic loading is cyclic in nature. The morphology of a modified binder can indeed play an important role in showing stable, non-thixotropic responses to the traffic loading. The accumulated strain in binders, a consequence of traffic, is primarily responsible for the rutting in asphalt pavements [40, 41]. The Repeated Creep Recovery Test (RCRT) method was proposed by Bahia *et al*. [5, 6] as a possible means to estimate the rate of accumulation of permanent strain in the binder. Each cycle in the RCRT test consists of applying a creep load of 0.3 kPa for 1 second (loading time), followed by a recovery or rest period of 9 seconds. The total number of cycles in the RCRT test is 100 cycles. Bouldin *et al.* [51] developed a semi-empirical approach to predict the viscoelastic response of a binder in the RCRT test framework. The RCRT test method applies low stress levels that may not fully depict the actual field condition. D'Angelo *et al*. [15] improved the RCRT test procedure by conducting creep and recovery testing on binder samples at multiple stress levels (0.1 kPa and 3.2 kPa). These researchers introduced a parameter called non-recoverable compliance (J_{nr}) that is capable of differentiating a polymer-modified binder from a neat binder.

In recent years, several studies have been conducted to evaluate the relationship between the MSCR test parameter "J_{nr}" and actual field rutting. Rutting is a nonlinear, high stress and strain phenomenon. Previous studies show that J_{nr} is highly correlated with rutting [20]. Among related studies, the relationship between J_{nr} and rutting was addressed well in the following studies: I-55 in Mississippi, FHWA ALF polymer study, and the MnRoad Hamburg mix study. These studies reported that reducing J_{nr} by half typically reduces rutting by half. Full scale testing was conducted on the test sections constructed with multiple neat and modified binders at the Federal Highway Administration's (FHWA) Accelerated Loading Facility (ALF) [20]. The test results (Figure 2.2) clearly showed the improved performance of the MSCR test results over the Superpave® G*/sinδ criteria at high PG temperatures (Figure 2.3). In related studies by D'Angelo [18, 19], MSCR tests were performed on multiple neat and polymer-modified binders to determine if there was a relationship between the existing SHRP grading and the J_{nr} at 3.2 kPa. For neat binders, properties obtained from the MSCR specifications were found to be similar to those obtained for the original SHRP binder, i.e., linear behavior up to the stress level of 3.2 kPa. Polymer-modified binders, however, are likely to have different properties (i.e., nonlinear behavior at a much lower stress level), as illustrated in Figure 2.4. In a few other studies [12, 14, 20], the MSCR test has been found to be able to distinguish the difference in rutting potentials of various binders, both modified and neat. Thus, grading a binder based on the J_{nr} values that correlate well with field rutting is expected to lead to a more realistic choice of appropriate binder based on the traffic condition [18].

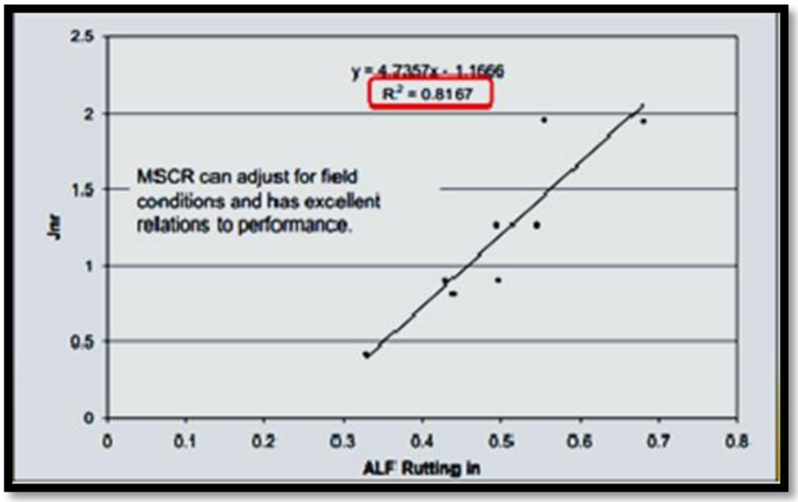


Figure 2.0-2 J_{nr} vs. ALF (Accelerated Loading Facility) Rutting [20].

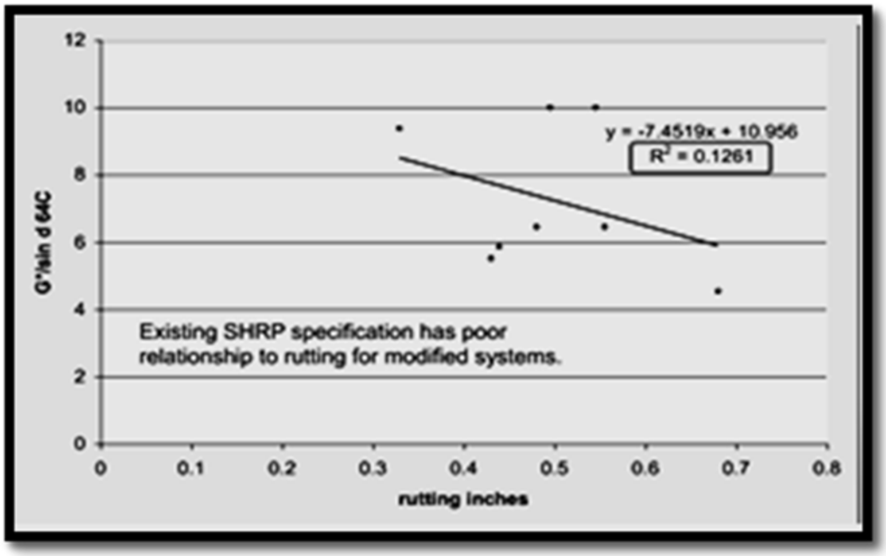


Figure 2.0-3 G*/sinδ Vs ALF (Accelerated Loading Facility) Rutting [20].

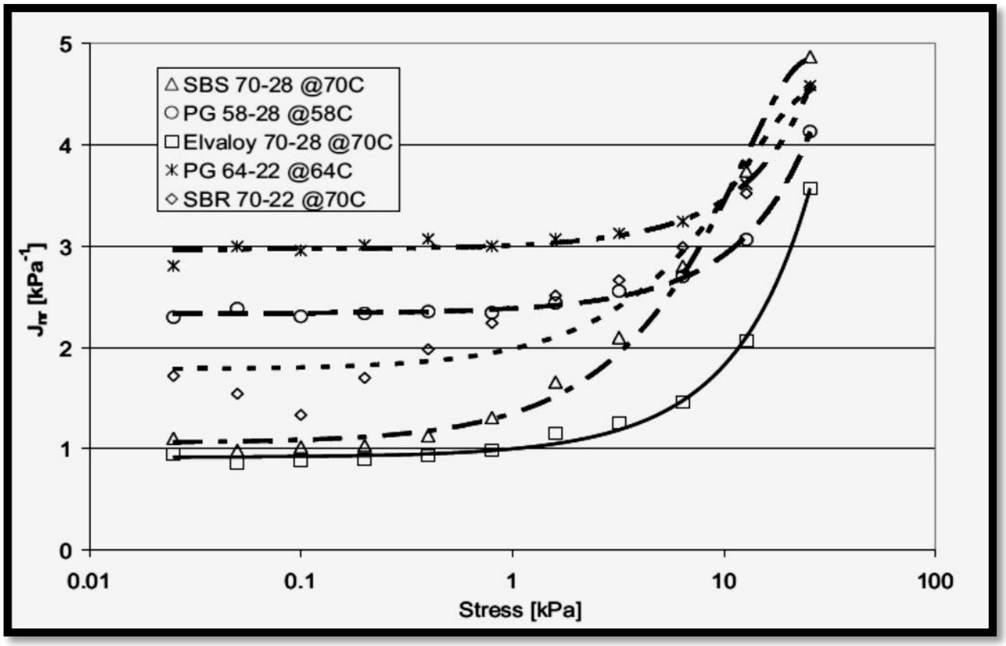


Figure 2.0-4 Plot of Neat and Modified Asphalt Binder Showing the Relationship Between Stress and Non-Recoverable Creep Compliance [18].

2.3 MSCR Curve

It is important to understand the creep-recovery curve obtained from the MSCR test data, which can provide an indication of the presence of polymer and the nonlinear viscoelastic performance of a binder. A Dynamic Mechanical Analyzer (DMA) can provide basic understanding of the MSCR curve. As shown in Figure 2.5, there are four distinct parts of the curve: initial deformation, transition zone, equilibrium zone, and the recovery zone [52]. As illustrated by Menard [52], three types of creep tests can be conducted to simulate the performance of a polymer-modified binder, and these are: (a) multiple creep cycles applied to the sample which help measure the degree of degradation as a function of the number of cycles; (b) application of variable temperatures with each cycle to predict the properties related to degradation with the increase in temperature; and (c) variation of temperature within one cycle. The MSCR test for polymer-modified binder is essentially a combination of the first two types of creep tests wherein load is applied in 10 cycles, where each cycle has a duration of 10 seconds. The loading and relaxation times are fixed at 1 second and 9 seconds, respectively. In this test a binder is subjected to creep loading at different stress levels with recovery (unloading) periods between stresses.

The current method to analyze MSCR test data uses the total strain accumulation at the end of the test to derive the parameter J_{nr}, which describes the resistance of binder to permanent deformation. The accumulated strain is not solely due to permanent strain; some of this accumulated strain is viscoelastic strain that might not fully recover throughout the duration of the unloading period. Huang [53] explained that in order to ensure that binders are characterized based on the actual permanent strain at the end of the test, a method to separate the actual permanent strain (irrecoverable) from the viscoelastic strain (recoverable with time) is needed. This researcher described the viscoelastic responses of a binder by three components. The first component is the instantaneous elastic component. The second component is the viscoelastic component (or delayed elastic) that is fully recovered provided that sufficient unloading time is allowed. The third component is the permanent or viscous component. This researcher also introduced additional nonlinear viscoelastic parameters based on the strains (ε) shown in Figure 2.6 and developed an analytical method that was able to separate recoverable (nonlinear viscoelastic) strain from irrecoverable (or permanent) strain developed in the binder [53]. Performance data obtained from the aforementioned study [53] showed a good correlation between the field test data and the ALF study [20]. With a little modification to the Huang's model [53], Shirodkar *et al*. [54] also characterized the creep and recovery curve of polymer-modified binders using three components: linear-viscoelastic, nonlinear viscoelastic, and permanent strain (PS) (Figure 2.7). This study verified that linear and nonlinear viscoelastic binder properties can be determined from the analysis of the MSCR curve, which provides valuable insight into how the polymer modification influences different types of mechanical responses [54, 61].

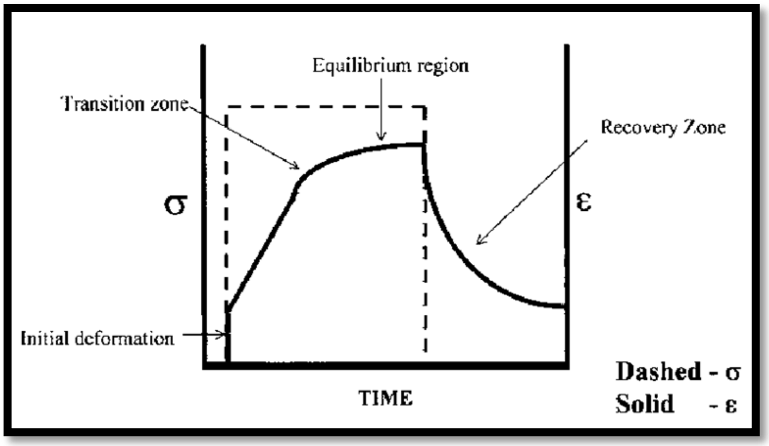


Figure 2.0-5 Analysis of a Creep Recovery Curve from a Modern DMA [52].

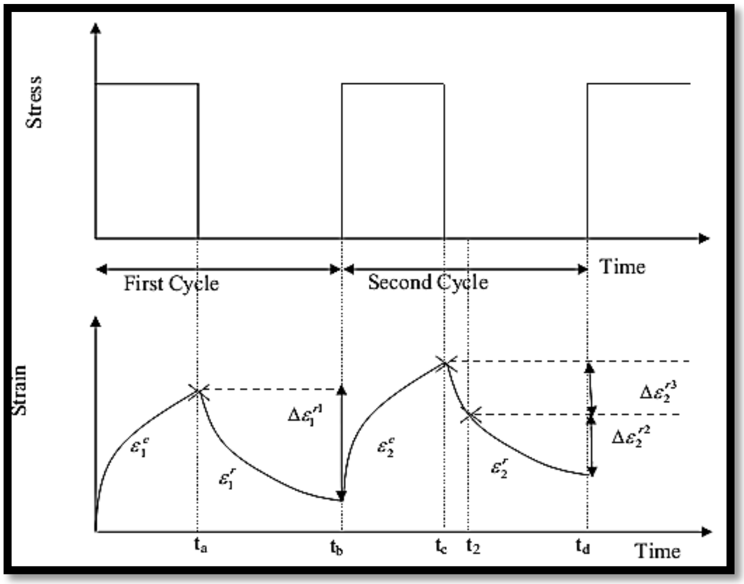
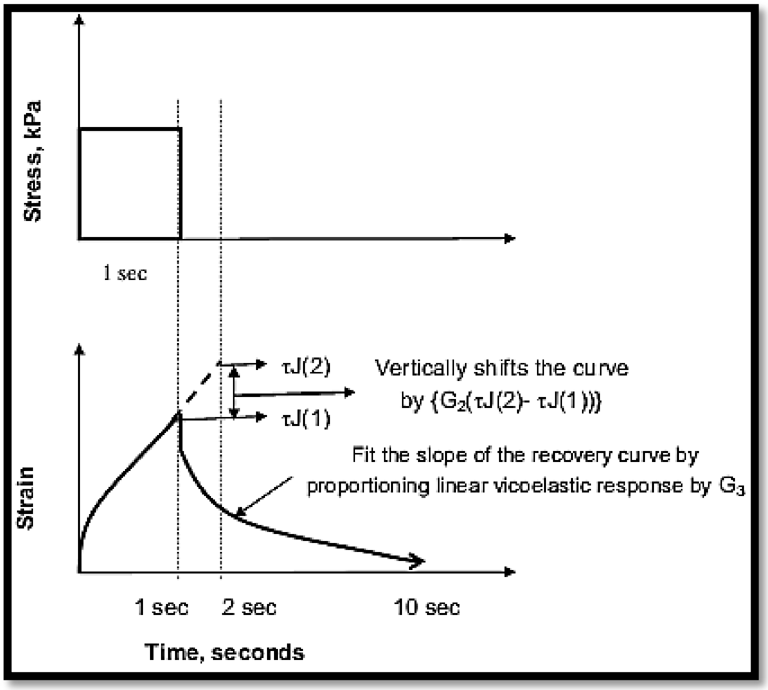
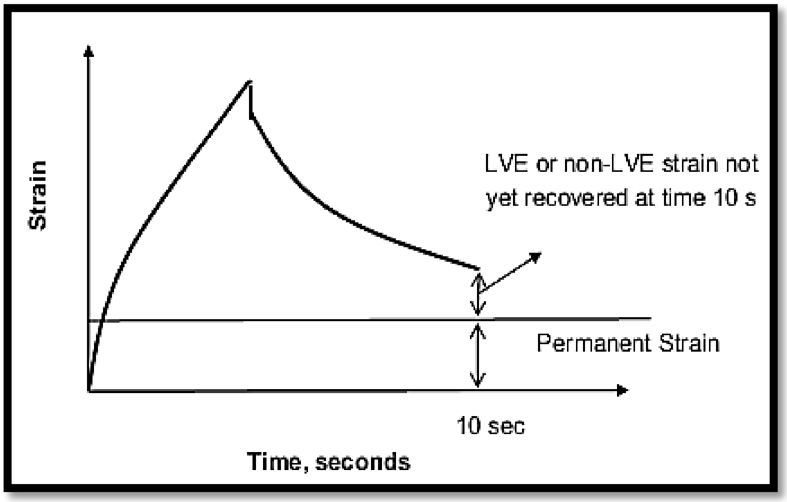


Figure 2.0-6 A Schematic Diagram of Creep and Recovery Loading and Strain Response [53].



(a)



(b)

Figure 2.0-7 (a) Schematic of a 1-Second Creep and 9 -Seconds Recovery Curve at 3.2 kPa for Nonlinear Viscoelastic Curve; (b)Permanent Strain of the Creep and Recovery Curve of Polymer-Modified Binder (Not to Scale) [54, 61].

2.4 Implementation and Adoption of MSCR Method

The Asphalt Institute (AI) researchers have taken a leadership role in establishing the MSCR testing protocol(s) and guidelines so that state Departments of Transportation (DOTs) can begin implementing this improved binder characterization methodology [24-36].

2.4.1 Types of Implementation

According to Horan [25], there are two ways of implementing the MSCR test method: partial implementation (PI), and full implementation (FI). As mentioned in the AI guidelines, the partial implementation technique includes using the MSCR test in conjunction with the AASHTO M 320 specification rather than transitioning to a system that uses different grade names [26]. The full implementation process includes adoption of the revised grading system which includes the new high-temperature binder test – the Multiple Stress Creep Recovery (MSCR) (AASHTO T 350) – and specifications (AASHTO T 332) based strictly on climatic condition and loading [26].

2.4.2 Barriers towards Implementation

Gierhart [28] noted that there is a possibility that some DOTs may not accept the full implementation of the MSCR-based grading. In the case of full implementation, the names of binder types will have to be changed from the Superpave PG naming convention to the MSCR grading techniques. For instance, a “PG 70-22” binder may have to be called “PG 64H-22” because the MSCR tests are typically being performed at 64°C. Sensing possible issues with the new naming convention, the AI recommends that agencies adopt the MSCR-based grading as an interim approach, as outlined in AI [26]. Once both suppliers and users are comfortable with the new naming conventions and are equipped with the new MSCR tool, the agency can move forward with the full implementation. Further, the AI recommends that if the evaluation of the delayed elastic response of binder is the target of MSCR testing, other “PG Plus” tests with a similar purpose should be eliminated. Because “PG Plus” tests provide simplified results with a much higher degree of error than the MSCR test, it will be of no use to establish a strong correlation between them and the MSCR results. Further, results of a survey conducted in 2010 indicate that there are barriers to states regarding implementation of the MSCR test [31]. These barriers include inadequate DSR equipment/software, lack of resources to perform transitional tests, lack of guidance from suppliers and other states, and uncertainty about the effect on binder supply and modification.

2.3.3 Current Status of Implementation

The MSCR test (AASHTO T 350) method has been implemented and is being used in the United States by various user groups. Such initiatives have led a few state agencies to verify the reproducibility of MSCR tests and the specification criteria [15, 55]. Research has been conducted by the AI through an inter-laboratory study to determine the precision of AASHTO T 350 for the Southeastern Asphalt User/Producer Group (SEAUPG) and for the North East Asphalt User/Producer Group (NEAUPG). The SEAUPG in 2011 and the NEAUPG in 2010 have initiated inter-laboratory studies (ILS) through the participation of multiple laboratories to evaluate the repeatability and reproducibility of AASHTO T 350 test results using DSRs [56, 57]. Technical articles and presentations from these studies provide detail statuses of MSCR adoption strategies and plans of various states participating in these inter-laboratory studies. The AI is attempting to make states aware of the benefits of the MSCR test method over non-standard and time consuming “PG Plus” tests [24-36]. The AI engineers are striving to establish awareness by conducting meetings, presentations, and webinars in various states [24-36]. According to the AI MSCR Implementation Database [58], four states (Maine, New Hampshire, Rhode Island, and Florida) have adopted full implementation of the MSCR test method with modified MSCR grades. An overview of the MSCR test method implementation pathways of these state DOTs is provided below:

- Maine Department of Transportation (MaineDOT) has been testing the agency’s binder using MSCR since 2011 and it began specifying the PG 64E-28 grade by replacing the PG 70-28 grade on new projects starting January 2014.
- New Hampshire Department of Transportation (NHDOT) has been testing the agency’s binders using MSCR since 2013 and NHDOT began specifying the PG 64E-28 grade by replacing the PG 76-28 grade on new projects starting January 2014.
- Rhode Island Department of Transportation (RIDOT) has been testing the agency’s binders using MSCR since 2012 and implemented the use of M332 MSCR graded binder of PG 64V-28 and PG 64E-28 grades in 2013, depending upon traffic.
- Florida Department of Transportation (FDOT) has been testing the agency’s binders using MSCR since 2009 and implemented M332 binders as PG 67E-22 and PG 67V-22 grades, replacing the PG 82-22 grade and the PG 76-22 grade, respectively, in 2013.

Recently two other Departments of Transportation (DOTs), namely Louisiana and New Jersey, have decided to adapt the MSCR test method after conducting multi-year projects [60, 61]. Kabir [59, 60] listed the steps necessary for adopting the MSCR test method for conditions prevailing in Louisiana. The Louisiana Transportation Research Centre (LRTC) conducted a two-year project (LRTC Project # 11-1B) to examine the utility of the MSCR test method for the Louisiana Department of Transportation (LADOT). They recommended the adoption of AASHTO MP 19, and now AASHTO M 332, at 67°C with some limitations [60]. New Jersey Department of Transportation (NJDOT) recently conducted a project to demonstrate the use of J_{nr} as a standard measure of performance for modified binders [61]. This study investigated the feasibility of using the MSCR test method by conducting performance testing of asphalt mixes and correlating test results obtained from asphalt mix and binder testing [61]. Both studies concluded that it is possible to replace the currently used elastic recovery and force ductility test data with the MSCR test data [60, 61].

The AI has developed a database with an interactive map to provide current information on the status of implementation of the MSCR test method for each state [58]. This map is reproduced in Figure 2.8. Since no analyses have been done for commonly used binders and conditions prevailing in Oklahoma other than the present study, no guidelines are currently available for Oklahoma. Like several other states, ODOT is in the process of implementing the MSCR test method as a quality assurance process, and the agency needs actual test data for better confidence. The present study seeks to produce the necessary MSCR test data for different types of polymer-modified binders in Oklahoma. These data may be used to develop necessary guidelines for ODOT.

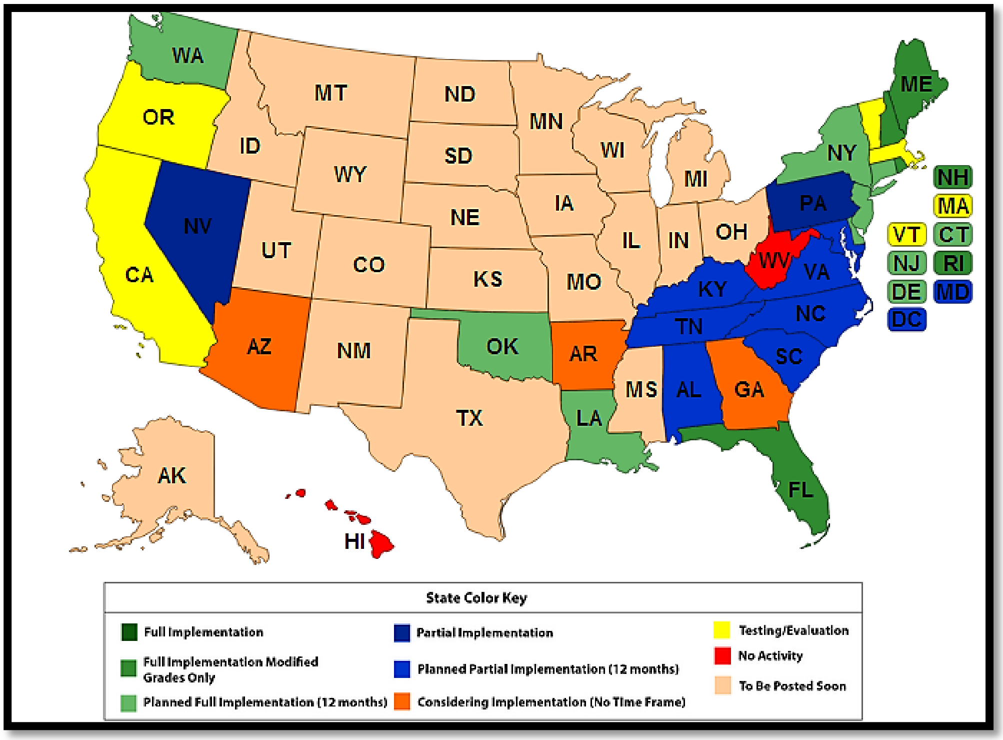


Figure 2.0-8 Current Status of MSCR Test Method Implementation [58].

2.5 MSCR-Related Studies

As noted earlier, the MSCR test method has been used in recent years as an important tool to characterize binders at high service temperatures [62-80]. This method is being established as a quality control and quality assurance tool to characterize various polymer-modifiers and warm mix additives. Various studies have reported that the MSCR test method has a better relationship to binder performance than other traditional test methods (e.g., DSR or ER). The aforementioned studies reflect the importance of the MSCR test method along with the disadvantages of elastic recovery tests.

2.5.1 Polymer and Acid Modified Binder

Santagata *et al.* [62] explained that it is crucial to consider percent strain recovery values derived from MSCR tests in order to identify the possible existence or absence of true interactions between the employed additives and the surrounding bituminous matrix. These researchers evaluated and compared effects of different nano-sized (on the order of 10^{-9} m) additives on the high-temperature properties of binder. In another study, Santagata *et al.* [63] showed that creep-recovery tests are not onlysimple and quick to perform, but also allow for the assessment of rutting potential. These researchers reiterated that the MSCR test method yielded results that were sensible for such important factors in binder modification as polymer type, composition, molecular configuration, and dosage. Moreover, by using MSCR test results, the effects of temperature-dependency and aging can be captured.

D'Angelo and Dongre [16] presented important observations regarding the optimization of polymer-modified asphalt blending using the MSCR method. The evaluation of the morphology of polymer network using a Van Guard 1200 ECM microscope verified that the %Recovery values reflect the extent of the polymer network in a binder [16]. In another study, Kadrmas [64] reported that the MSCR test has great potential to be used in the identification of appropriate polymers used in the micro-surfacing emulsion. Li *et al*. [65] used the MSCR test method to evaluate the properties of binder modified with Polyphosphoric Acid (PPA) alone, polymer alone (styrene–butadiene styrene and SBS), and with a combination of polymer and PPA, namely PPA+SBS, and PPA+Evaloy. This study used binders sampled at the plant and extracted from the loose asphalt mixes. The plant-sampled binder was tested under original, RTFO-aged, and PAV-aged conditions. These researchers concluded that all four types of binders met the J_{nr} criteria for the heavy traffic. More careful and detailed observations reveal that RTFO-aged binders meet the J_{nr} criteria for heavy traffic when $J_{nr} < 2\ kPa^{-1}$, whereas extracted binders are satisfactory for very heavy traffic when $J_{nr} < 1.0 kPa^{-1}$. Elastic recovery measured in the DSR (ER-DSR) showed a good correlation with %Recovery at 3.2 kPa for polymer-modified binder and mastics [66]. As a consequence, the MSCR test method was considered as a standard in selecting ER-DSR; it replaced elastic recovery measured in a ductility bath [66]. In a more recent study, Domingos and Faxina [67] investigated the creep-recovery behavior of 12 modified binders using the MSCR test method. It was reported that susceptibility to rutting can easily be identified with the changes of MSCR parameters (MSCR %Recovery and J_{nr}) with temperature.

2.5.2 Binder Modified with Reclaimed Materials

Wu *et al.* [68] used the MSCR test method as an important tool to investigate the performance of binder used in hot mix asphalt (HMA) with and without reclaimed asphalt shingles (RAS). These researchers tested binder recovered from field cores obtained from four experimental pavement sections. Abbas *et al*. [71] conducted a study where MSCR testing was used to evaluate the effect of reclaimed asphalt shingles (RAS) on the physical and chemical properties of virgin binders. Cheng *et al*. [72] used the MSCR test method as a tool to investigate the physical properties and evaluate the performance of Asphalt Rubber (AR) used in California. Baumgardner and D’angelo [73] investigated the ability of the cup-and-bob geometry to test neat, polymer-modified, and crumb rubber-modified (CRM) binders to determine if it could provide similar rheological results for both Superpave® and MSCR tests. Hanz *et al*. [74] used the MSCR test method, along with strain sweep, frequency sweep, and BBR tests to develop an emulsion residue-testing framework for improved chip seal performance.

2.5.3 Warm Mix Asphalt (WMA)

By lowering the viscosity of binder and/or increasing the workability of asphalt mixes using reduced heat, WMA technologies allow for mixing, transporting, and paving processes to occur at significantly lower temperatures. Many studies have been conducted on the development and use of the WMA technologies worldwide [75]. Some studies performed the MSCR tests on binders modified with WMA additives such as Advera® and Sasobit®. Unlike polymer-modified binders, the MSCR test method has not been explored for various WMA technologies.

Zeleew *et al*. [76] and Bower [77] presented a comparative evaluation of MSCR test results on four WMA technologies: three foaming processes, namely Advera®, Low Emission Asphalt (LEA), and Gencor, and an organic additive, Sasobit®. These researchers used a PG 64-22 binder as a control binder to understand the properties of WMA technologies under creep conditions. The WMA technologies exhibited lower stiffness (i.e., high compliance) when tested at higher stress levels and test temperatures. These researchers also reported the MSCR test method as a suitable tool for ranking deformation properties of WMA technologies. Hesp *et al*. [78] examined the effect of ten commercial warm mix additives (seven surfactant-based and three wax-based) on the quality and durability of Cold Lake Asphalt Cement in Canada to assist users and producers of WMA to select appropriate formulations for cold climates. Seven out of ten WMA technologies maintained a “Heavy” grade in the MSCR grading system, indicating that performance in service would be similar if the seven-day maximum temperature did not exceed 46°C. This study concluded that caution is warranted when using wax-based WMA in thin pavements and/or in northern climates where cracking is a concern with respect to long term pavement performance. Due to the difficulties in generalizing the effects of the WMA modification, it is recommended to assess both the quality and durability of an asphalt mix using improved tests such as the Ontario methods LS-228, LS-299, and LS-308 [78]. Morea *et al*. [79] conducted frequency sweep and MSCR tests to investigate rheological properties of extracted binders from three different asphalt mixes (HMA, WMA, and WMA with tensoactive additives). Based on the MSCR test results, there were clear differences among the rheological properties of neat and polymer-modified binders extracted from HMA, WMA (without additive), and with two types of chemical tensoactive additives extracted from the WMAs (with additives). The MSCR tests showed a significant reduction of accumulated strain and J_{nr} values for the polymer-modified binders when extracted from WMAs (with tensoactive additives) compared to the other extracted neat binders (from HMA, WMA, and WMA with additives) or extracted polymer-modified binders (from HMA and WMA). Liva and McBroom [80] reported significant difference in %Recovery values at 3.2

kPa and 0.1 kPa between the neat binder and the WMA binder (Sasobit®, Evotherm® 3G, Evotherm® DAT, and Rediset® WMX).

2.6 Data Interpretation of MSCR Test

2.6.1 Polymer Method

The strain response is generally nonlinear and sensitive to the stress level of a test in the case of a polymer-modified binder. The J_{nr} value obtained from the MSCR test has been found to provide a good correlation with high-temperature rutting for both neat and polymer-modified binders. The %Recovery can identify and quantify how the polymer works in a binder. In current practice, no widely accepted specifications are available for the %Recovery. Many agencies recommend a minimum value that suits their need, as described in the AASHTO T 350 procedure [20]. A typical MSCR curve, relating the %Recovery and J_{nr}, is shown in Figure 2.9. The relationship shown in the MSCR curve can be expressed by Equation 2.1 [20].

$$y = 29.37x^{-0.2633}$$

(2.1)

where y = MSCR %Recovery at 3.2 kPa, and x = Non-recoverable creep compliance at 3.2 kPa, $J_{nr,\ 3.2\ kPa}$.

It is important to note that the curve stops at J_{nr} = 2 kPa^{-1}. Anderson [24, 27, 29] mentioned that J_{nr} values greater than 2 kPa^{-1} are not required to have any minimum value of %Recovery. The curve in Figure 2.9 shows a range of elasticity. The data points above the MSCR curve indicate a binder of high elasticity or a binder that is modified with elastomeric polymers. The data points below the MSCR curve indicate a binder of poor elasticity or a binder that is not modified with enough elastomeric polymers. The current study uses the Polymer method along with “the Quadrant method” (described next) to analyze the MSCR test results.

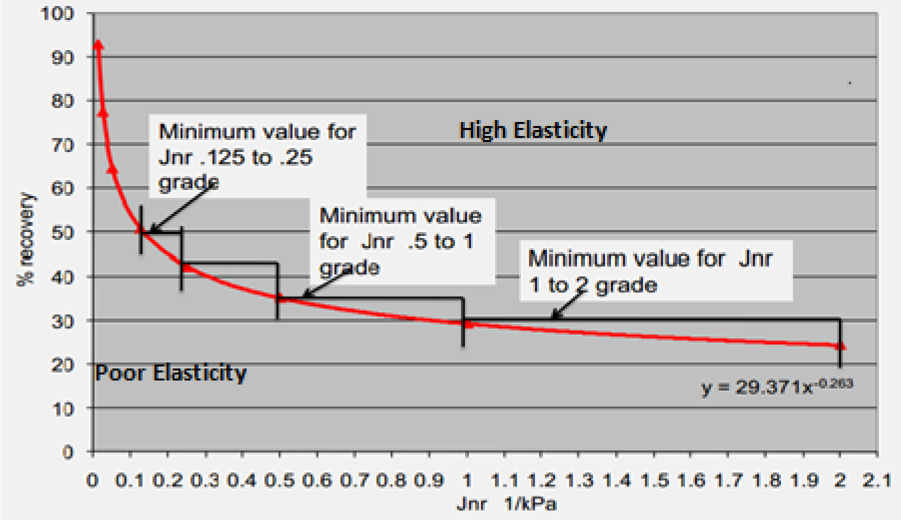


Figure 2.0-9 Scale of Minimum MSCR %Recovery for Measured J_{nr} [20].

2.6.2 Quadrant Method

The quadrant analysis is a simple way to organize customer satisfaction data. An agency could use this analysis to identify how and where to improve its operations. Figure 2.10 shows a typical quadrant plot, in which ER is plotted along the X-axis and %Recovery is plotted along the Y-axis. The four quadrants in this plot are named as follows: 1st (meets both ER and %Recovery targets; Neither User nor Supplier Risk), 2nd (User Risk), 3rd (fails both ER and %Recovery targets; Both User and Supplier Risk), and 4th (Supplier Risk). The term ‘User risk’ is used to indicate a situation where the MSCR %Recovery value meets the proposed specifications while not meeting the ER or phase angle (δ) criterion. By contrast, the ‘Supplier Risk’ is used to indicate a situation where the current ER or δ-criterion is met, but the %Recovery value does not meet the proposed specifications. In both cases, the term 'Risk' applies only to comparisons between the %Recovery and the ER, and it does not imply any increased risk of reduced performance. Also, it is seen that the minimum %Recovery values vary among different binder types.

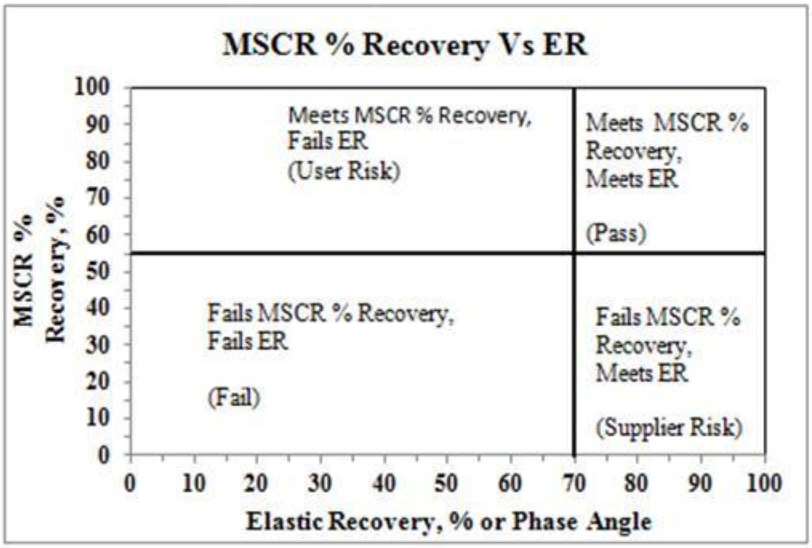


Figure 2.0-10 Analyses of MSCR Test Results: Quadrant Plot for MSCR%Recovery vs. % Elastic Recovery or Phase Angle [36].

The minimum ER requirement can vary from one DOT to another depending on its own minimum ER requirement, and is used in the comparison graph along with the %Recovery data. The limit for the phase angle represents the maximum phase angle a state DOT allows for polymer-modified binders. According to Anderson [36], when evaluating the data graphically in a four-quadrant plot, the minimum %Recovery requirement should be established in a manner where the "User Risk" is approximately equal to the "Supplier Risk." As per AI [26, 35], an appropriate %Recovery (at 3.2 kPa) at 64^{o}C is 15% less than the current ER criterion, provided that the Elastic Recovery value at 25°C is used. The four-quadrant method claims to have an equal risk for the user and the supplier of the binder. The present study aims to investigate whether the four-quadrant method is applicable for ODOT. The present study also seeks to establish specification limit(s) for %Recovery at 3.2 kPa, for possible use by the agency.

2.7 Summary

The MSCR test protocols and specifications are the results of a large number of investigations, as described above. A sequence of increasing shear stresses is considered in the MSCR test method that can capture the field condition. Pavement researchers and practitioners studied and explored various protocols to characterize polymer-modified, WMA additive-modified, and reclaimed binders in the non-linear viscoelastic range, and the most common are the ER and MSCR methods. The ER test method (ASTM D6084 or AASHTO T 301) can only detect the presence of polymer without distinguishing the polymer system. However, the MSCR test method (AASHTO T 350) is capable of capturing the actual situation of the pavement under repeated loading and at high temperatures. The MSCR parameters (J_{nr} and %Recovery) are capable of identifying the presence of polymer in binders and depicting the rutting potential in asphalt mixes.

3 METHODOLOGY, MATERIAL SELECTION AND TESTING

3.1 Introduction

This chapter includes an overview of the project flow chart, material selection process, test matrices, and performance tests. A flow chart summarizing the tasks is presented in Figure 3.1. As shown in Figure 3.1, this study involved the following major steps: (i) collection of test materials (virgin binders and HMA mixes); (ii) recovery of binders from the simulated RAPs; (iii) preparation of Sasobit®-modified binder; (iv) determination of Superpave® performance grading of the virgin binder; and (v) execution of the MSCR tests on virgin binders, recovered binders from RAPs, and Sasobit®-modified binders as well as analysis and interpretation of test data. Each of these steps along with the procedures used for the evaluation of test data is discussed in this chapter.

3.2 Material Selection and Preparation

3.2.1 Virgin Binder

In consultation with ODOT, three types of binder from five different sources (suppliers) were selected for laboratory testing at the University of Oklahoma Materials Laboratory [81]. To this end, six refineries from different geological regions were selected for this study. Table 3.1 shows the selected regions along with the types of binder collected from each source. The source locations are also marked in Figure 3.2. The selected binders include the following: one neat binder (PG 64-22) and two polymer-modified binders (PG 70-28 and PG 76-28). It should be noted that this study also analyzed another set of MSCR data (ODOT In-house MSCR data) for these binders from the aforementioned sources along with a few other sources as explained in Section 3.4.1, named ODOT MSCR Database.

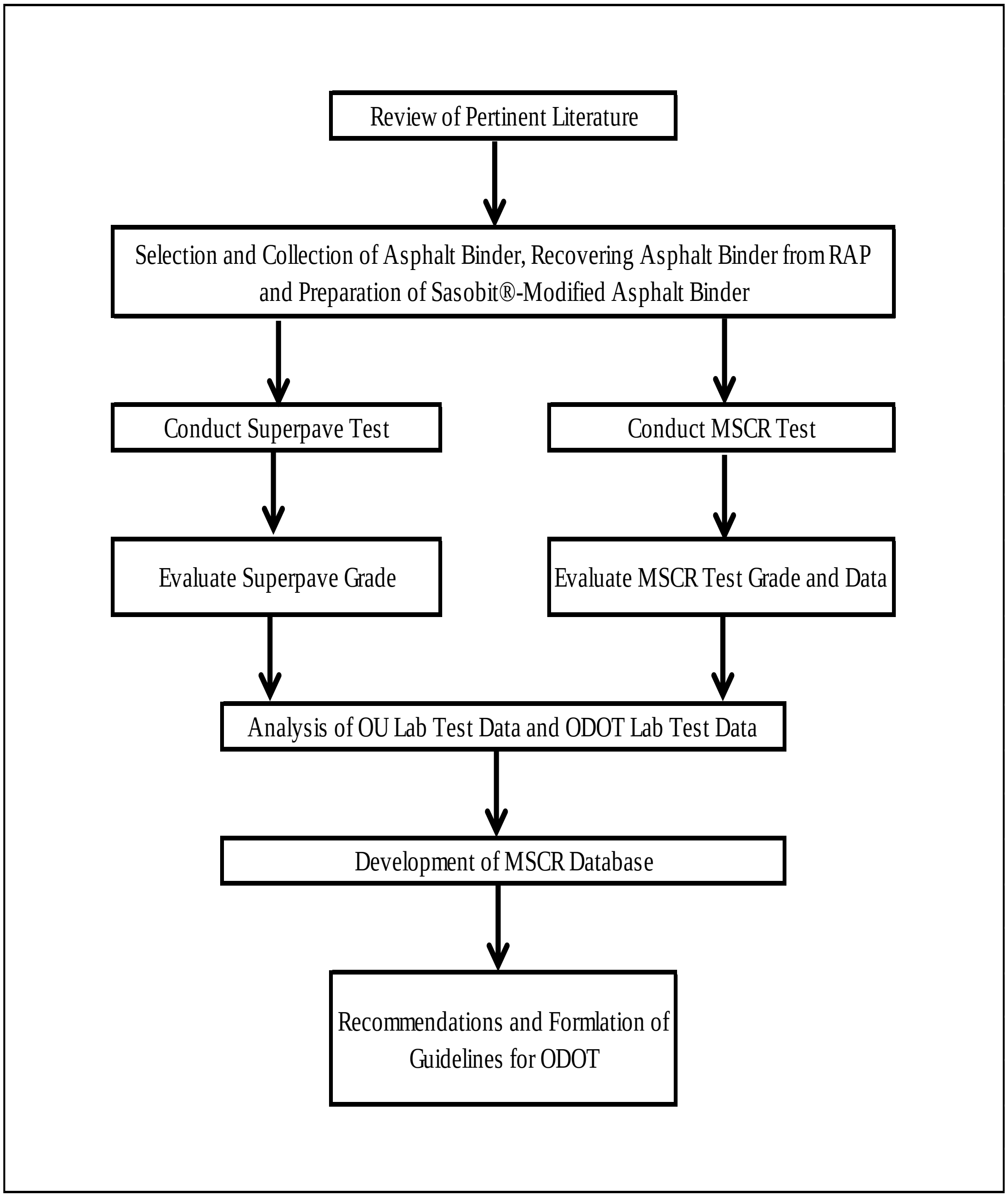


Figure 3.1 Flow Chart of the Present Study.

Table 3.1 Types and Source-Location of Binders

ODOT Specified Source Designation	**Source Designation Used in the Report Corresponding to ODOT**	**Region**	**Binder types**
A4	S1	Northeast	PG 64-22, PG 70-28
A1	S2	Northeast	PG 64-22, PG 70-28, PG 76-28
A3	S3	Northeast	PG 64-22, PG 70-28, PG 76-28
A7	S4	Southwest	PG 64-22, PG 76-28
A10	S5	Northeast (out-of-state from Kansas)	PG 70-28
	S13	North East	PG 64-22
S = Source			

Figure 3.2 Location of Selected Sources on Map for OU Lab Test.

3.2.2 Recovered Binder

Recovered binders from simulated RAP rather than field RAP were preferred in this study because, unlike field RAP, ingredients (binder type and content, aggregates, additives, etc.) of simulated RAPs are known and the mixes are prepared in a controlled environment. Three HMA mixes were collected from two different plants for subsequent aging and recovery of binders. The first of these mixes was collected from a Haskell Lemon Construction plant located in Oklahoma City, Oklahoma, the second one was from a T&G Construction plant located in Lawton, Oklahoma, and the final one was from Silver Star Construction in Moore, Oklahoma. One of these mixes (HMA Mix1) was an Oklahoma surface course (S4) mix with a PG 76-28 OK binder without RAP. The second HMA mix (HMA Mix2) type was unknown to the research team. The final mix was an S4 type mix with RAP with PG 64-22 OK binder. Long-term accelerated aging of these mixes was performed in order to obtain simulated RAP, called SRAP1, SRAP2, and SRAP3 in this study. The fourth recovered binder was obtained from field RAP (FRAP). The AASHTO R 30 (*Standard Practice of Mixture Conditioning of Hot Mix Asphalt (HMA)*) method was followed for the long-term conditioning of the HMA mixes. This method simulates the field aging from seven to ten years of service. In this process, the HMA mixes were aged in a force drift oven for 120±0.5 hours at a temperature of 85±3°C.

Binders were recovered from SRAPs by using a Rotavapor in accordance with the AASHTO T 319 (*Standard Method of Test for Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*) method. It is mentioned in AASHTO T 319 that this method has minimal effects on the physical and chemical properties of the recovered binder. For the first step, about 1,000 g of loose asphalt mix sample is placed in an extraction vessel (centrifuge) containing the extraction solvent. After running at 30 revolution/min for 5±1 min, the extractor is attached to two consecutive filtrate-receiving flasks, one after another. A vacuum of 93.3±0.7 kPa is applied to both filtrate-receiving flasks until there is no noticeable amount of solution remaining in the extractor or in the first flask. After the filtration process is complete, the solution is transferred to a recovery flask for primary distillation. The primary distillation is conducted at 100±2.5°C (oil bath temperature) and at a vacuum of 93.3±0.7 kPa. The content of the recovery flask is distilled until it is one-third full. After primary distillation is complete, the contents are transferred to the centrifuge bottles and the oil bath temperature is increased to 174±2.5°C. The bottles are then allowed to centrifuge at 3600 revolution/min for 25 minutes. The centrifuge bottles are emptied back into the recovery flask next, which is then attached to the rotary evaporator. A vacuum of 93.3±0.7 kPa is then applied to the rotary evaporator. When the condensation rate falls below one drop every 30 seconds, nitrogen gas is introduced at a rate of 1000 mL/min. The gas flow, vacuum, and bath temperature are maintained for 30±1 min to reduce the residual solvent concentration to near zero, and thus, the extracted binder is recovered from the solution.

3.2.3 Sasobit®-Modified Binder

An additional investigation was performed on Sasobit®-modified binders which was not included in the project proposal. Neat and polymer-modified binders were blended with Sasobit® in order to obtain desired mixtures. The neat binder, PG 64-22, from four different sources was blended with 2%, 3%, and 4% Sasobit® (by the weight of binder). The polymer-modified binders, PG 70-28 and PG 76-28, were blended with only 3% Sasobit® (by the weight of the binder). In the blending process, the binder was heated in a tin canister at 150°C for 2 hours. The Sasobit® additive was then added to the canister containing the heated binder, and the mixture was stirred for about a minute and put in a mechanical oven for about 10 minutes. The binder and Sasobit® mixture was then stirred for about a minute and then put back in the oven. These steps were continued for an hour. During this time the binder was covered in the oven using aluminum foil. The RTFO-aging (AASHTO T 240) was performed for all the Sasobit®-modified binders prior to the MSCR testing.

3.3 Laboratory Testing

3.3.1 Superpave® Grading of Virgin Binder

While performing the MSCR tests, the virgin binders from the aforementioned five selected sources were also evaluated for viscosity and Superpave® performance grading. The Superpave® binder test methods conducted in this study are listed in Table 3.2.

3.3.1.1 Rotational Viscosity Testing

Viscosity tests were conducted on virgin binder (both un-aged and RTFO-aged) by using a Brookfield rotational viscometer (RV) in accordance with the AASHTO T 316 method (*Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer*). The RV test helps ensure that the binder is sufficiently fluid for pumping and mixing. The viscosity of binder was determined for temperatures ranging from 135°C to

180°C at intervals of 15°C. The temperature controller is set to the desired temperature, allowing the sample chamber to be preheated. The binder sample is placed in the sample chamber after temperature equilibrium is obtained. The sample is then allowed to equilibrate at the desired test temperature for at least 10 minutes before starting the measurement. After reaching equilibrium, the speed of the viscometer is set to a speed that develops a resisting torque between 10% and 98% of the full-scale instrument capacity. The resisting torque required to maintain the constant rotational speed of 20 revolution/min of a submerged cylindrical spindle in the binder at a constant temperature is then measured and reported as viscosity.

Table 3.2 Superpave® Test Matrix

Test Name and Designation	**Test Conditions**	**Virgin Binder from (Sources)**		
		PG 64-22 from (S1, S2, S3, S4, S13)	**PG 70-28 from (S1, S2, S3, S5)**	**PG 76-28 from (S2, S3, S4)**
PG grade: AASHTO M 320		Yes	Yes	Yes
RV: AASHTO T 316	Un-aged	From 135°C to 180°C @ 15°C	From 135°C to 180°C @ 15°C	From 135°C to 180°C @ 15°C
	RTFO-aged	From 135°C to 180°C @ 15°C	From 135°C to 180°C @ 15°C	From 135°C to 180°C @ 15°C
DSR: AASHTO T 315	Un-aged	@61°C, 64°C, 67°C	@ 67°C, 70°C, 73°C	@73°C, 76°C, 79°C
	RTFO-aged			
	PAV-aged	@ 19°C, 22°C, 25°C	@ 25°C, 28°C, 31°C	@25°C, 28°C, 31°C
RTFO: AASHTO T 240		Yes	Yes	Yes
PAV: AASHTO R 28		Yes	Yes	Yes
BBR: AASHTO T 313	PAV-aged	@ -9°C, -12°C, -15°C	@ -15°C, -18°C, -21°C	@ -15°C, -18°C, -21°C
Note: RV= Rotational Viscometer, DSR= Dynamic Shear Rheometer, RTFO= Rotational Thin Film Oven, PAV= Pressure Aging Vessel, and BBR= Bending Beam Rheometer.				

3.3.1.2 Short Term and Long Term Aging

Short term aging of the virgin binder was performed using a Rotational Thin Film Oven (RTFO) in accordance with the AASHTO T 240 (*Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)*) test method. The RTFO test helps simulate the binder's aging during manufacturing and placement in the field. The RTFO aging procedure requires that the un-aged binder samples be placed in bottles and the bottles be placed in the RTFO, which has a rotating carriage. The carriage rotates within the oven, which maintains a temperature of 325°F (163°C) and an air flow of 4 liters/minute. The sample is then aged for 85 minutes.

Long-term aging of the binder was performed in accordance with the AASHTO R 28 (*Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV*)) test method. The PAV aging is conducted on binder residue obtained from the RTFO test method. This practice helps simulate oxidative aging of the binder due to field service. The PAV procedure requires that the RTFO-aged binder samples be placed in stainless steel pans and then aged in a pre-heated vessel pressurized to 305 psi (2.10 MPa) at 100^{o}C for 20 hours.

3.3.1.3 Dynamic Shear Rheometer Testing

Characterization of viscous and elastic behavior of binder at intermediate to high temperatures was done in accordance with the AASHTO T 315 (*Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*) test method. The DSR test method helps determine the high temperature rutting factors of un-aged and RTFO-aged binders as well as the intermediate temperature fatigue factor of PAV-aged binders. Binder samples were prepared by using two different sizes of silicon rubber molds. Molds with 19-mm diameter and 1.5-mm depth were used for preparing un-aged and RTFO-aged samples. Molds with 8-mm diameter and 3-mm depth were used for preparing PAV-aged samples. The un-aged and RTFO-aged samples were tested using 25-mm diameter parallel plates, whereas the PAV-aged samples were tested using 8-mm diameter parallel plates. One of the parallel plates was allowed to oscillate with respect to the other at pre-selected frequencies and angular rotation (i.e., torque). The required amplitude depends upon the value of the complex shear modulus of the binder being tested. The DSR samples were tested in a thermally controlled test chamber, capable of maintaining the desired testing temperature within a tolerance of ±0.1°C. The DSR test was performed at a loading frequency of 10 rad/s. The complex modulus (G*) and phase angle (δ) are calculated automatically as part of the operation of the rheometer using a proprietary computer software supplied by the instrument manufacturer. The complex shear modulus and the phase angle are defined as the resistance to shear deformation of the binder in the linear viscoelastic region.

3.3.1.4 Bending Beam Rheometer Testing

Low temperature stiffness and relaxation properties of binder are determined as per the AASHTO T 313 (*Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending*

Beam Rheometer (BBR)) test method. These parameters helped identify the binder's ability to resist low temperature cracking. In this method, simply supported asphalt beam samples (length = 127 mm, width = 12.7 mm, and thickness = 6.35 mm) were subjected to a constant load (980 ± 50 mN) applied at the beam's mid-point at low temperatures. The beam samples were placed in a fluid (methanol) bath at a controlled temperature and loaded for 240 seconds. The stiffness (S) (maximum bending stress divided by the maximum strain) and the rate of stress relaxation (m-value) (slope of stiffness versus time) were calculated for loading times 8, 15, 30, 60, 120, and 240 seconds. These values at time t = 60 seconds were used to quantify thermal cracking resistance of the binder.

3.3.2 MSCR Testing

3.3.2.1 MSCR versus Elastic Recovery Test

The elastic recovery test has been proved inefficient to characterize the nonlinear properties of polymer-modified binder, despite being widely used by various state agencies. Consequently, the MSCR test is being recommended as a replacement of time-consuming elastic recovery testing. The elastic recovery test is performed in accordance with the ASTM D6084 (*Standard Test Method for Elastic Recovery of Asphalt Materials by Ductilometer*) test method. Some agencies like ODOT runs this test on RTFO aged material. The sample is temperature equlibriated after trimming and cooling in the testing machine at $25±0.5^{\circ}$C for 85 to 95 minutes before it is elongated to 20 cm at a speed of 5 cm/min ± 5.0%. After 5 minutes, with the sample reaching an elongation of 20 cm, it is cut at its midpoint with scissors into two halves. The total length of the specimen, with the severed ends just touching each other, is reported and elastic recovery is calculated as the difference between this total length and the original length (20 cm), expressed as a percentage. This test method is able to identify if a modifier has been added to the binder, and if the modifier provides significant elastomeric characteristic. However, it does not necessarily identify the type or amount of the modifier added. ER tests were conducted on 34 samples of PG 70-28 binders from five different sources and 34 samples of PG 76-28 binders from four different sources tested at the ODOT Materials Laboratory.

3.3.2.2 Conventional MSCR Testing

Conventional MSCR tests on the virgin, recovered, and Sasobit®-modified binder were conducted at 64°C and at two stress levels (0.1 kPa and 3.2 kPa), in accordance with the AASHTO T 350 (*Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Binder Using a Dynamic Shear Rheometer*) test method. This test method is used to determine the presence of an elastic response in a binder under shear creep and recovery at two stress levels (0.1 kPa and 3.2 kPa), at 64°C. Sample preparation and apparatus are set in accordance with AASHTO T 315. Two parallel plates, each having a diameter of 25 mm, were used in the MSCR testing. The gap between the plates was maintained at 1 mm. As outlined in Chapter 2, the MSCR test method consists of a one-second constant stress interval followed by a nine-second zero-stress recovery period. The loading and recovery interval is repeated 30 times. The first 10 cycles are performed at 0.1 kPa stress level to condition the sample, followed by 10 more cycles at 0.1 kPa stress level and 10 cycles at 3.2 kPa stress level. Details of the experimental process are described in Appendix D. The MSCR test results were then used to grade the tested binders in accordance with AASHTO T 332 (*Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test*). Table 3.3 shows the conventional MSCR test matrix of the current study.

3.3.2.3 Non-Conventional MSCR Testing

The MSCR tests were performed on selected RTFO-aged binders (PG 70-28 from all four sources and PG 76-28 from three sources, namely S2, S3, and S4) at higher temperatures (70ºC, 76ºC) and at a higher stress level (10 kPa). These tests were conducted to evaluate the effects of higher temperature and stress level on the nonlinearity of polymer-modified binders. Table 3.4 shows the test matrix for the non-conventional MSCR tests.

3.4 Analysis of MSCR Test Data

3.4.1 ODOT MSCR Database

A significant portion of the MSCR (AASHTO T 350) and elastic recovery (ASTM D6084) test data was obtained from ODOT. The laboratory testing was conducted in multiple laboratories including the ODOT Liquid Laboratory, as part of a round robin study within the Southeastern Asphalt User/Producer Group (SEAUG). The test results for the PG 64-22 binders from 11 sources (S1-S6, S8-S12), the PG 70-28 binders from five sources (S1, S2, S3, S5, S7), and the PG 76-28 binders from four sources (S1, S2, S3, and S4) were analyzed. These sources are marked in Figure 3.2 except for S9, which was selected from Louisiana. Analyses were performed on the MSCR and ER test results for these binders based on the Polymer and Quadrant methods described earlier in Chapter 2 under the section "MSCR Test Data Interpretation." The MSCR test results obtained from ODOT are designated as the ODOT MSCR database throughout this report.

Table 3.3 Conventional MSCR Test Matrix

Materials (Sources)	Conventional MSCR Tests @ 64ºC at stress levels	
	0.1 kPa	3.2 kPa
PG 64-22 (S1,S2, S3, S4, S12) (RTFO-aged)	Yes	Yes
PG 70-28 (S1,S2, S3, S4) (RTFO-aged)	Yes	Yes
PG 76-28 (S2, S3, S4) (RTFO-aged)	Yes	Yes
SRAP1	Yes	Yes
SRAP2	Yes	Yes
PG 64-22 (S1,S2, S3, S4)+ 2% Sasobit® (RTFO-aged)	Yes	Yes
PG 64-22 (S1,S2, S3, S4)+ 3% Sasobit® (RTFO-aged)	Yes	Yes
PG 64-22 (S1,S2, S3, S4)+ 4% Sasobit® (RTFO-aged)	Yes	Yes
PG 70-28 (S1,S2, S3, S4)+3% Sasobit® (RTFO-aged)	Yes	Yes
PG 76-28 (S2, S3, S4)+ 3% Sasobit® (RTFO-aged)	Yes	Yes

Table 3.4 Non-Conventional MSCR Test Matrix

Non-Conventional MSCR Testing Conditions	Other Conditions	Materials (Sources)
At Higher Stress Level (10 kPa)	RTFO-aged binder @ 64ºC, 70ºC, 76ºC	PG 70-28 (S1, S2, S3, S4) PG 76-28 (S2, S3, S4)
At Higher Temperatures (70ºC, 76ºC)	RTFO-aged binder @ 0.1 kPa, 3.2 kPa, 10 kPa	PG 70-28 (S1, S2, S3, S4) PG 76-28 (S2, S3, S4)

Figure 3.3 Map with the Locations of Selected Sources by ODOT.

3.4.2 Tests Conducted at the OU Asphalt Binder Laboratory

The MSCR test results obtained from the OU Asphalt Laboratory (also called OU-Lab in this report) were analyzed based on the Polymer method. Since the ER test data was not available for the binders tested in the OU-Lab, the Quadrant method analysis for these data was considered outside the scope of the current study. The effects of Sasobit® modification on the MSCR test parameters, namely J_{nr} and %Recovery, were also analyzed. A comparative analysis of MSCR test results for virgin binders and Sasobit®-modified binders was performed to check any statistical differences. Moreover, the MSCR test results of polymer-modified binders at a higher stress level (10 kPa) and higher temperatures (70°C and 76°C) were analyzed to determine stress sensitivity and to evaluate nonlinearity of rheological properties as a function of stress and temperature. The MSCR test data and rheological properties of the tested binders, obtained from laboratory tests, were summarized in the form of charts and tables. Statistical significance of these test results was also evaluated. The MSCR test results obtained from the OU-Lab is referred to as the OU database throughout this report.

3.4.3 Statistical Analyses

Three samples were tested at each temperature and condition to check if the data were repeatable and standard deviation were in acceptable limit. To validate the reproducibility of test data, statistical analyses of the ODOT database and OU database were performed using box plots with three or more test results for each selected source. A box-plot provides a graphical overview of how data is distributed over the number line. It shows the central value, margin of error, and mean of the data set together. A sample box plot without an axis is presented in Figure 3.4. Each box in the box plot represents a set of MSCR test data from an individual source. The height of the box represents the interquartile range, which means the box runs from 1st quartile of the data set to the 3rd quartile of the data set. Each box has a separator, indicating the median of the data set. The diamond shape (yellow marker) in the box shows the position of the average value of the data set for a specific source. The bold black line represents the margin of error from the average value with a 95% confidence level. The red line shows the range of the data set running from the minimum value to the maximum value. The dotted blue line indicates the limit for acceptable data, i.e., the outliers of the data set limit. The red dot represents the sample position for a given source.

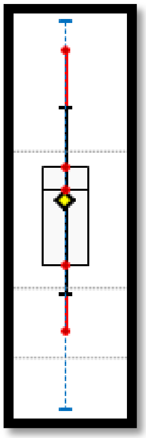


Figure 3.4 Sample Box-Plot Defining Data Set Summary.

To evaluate statistical variations, of test data, two major MSCR parameters ($J_{nr,\ 3.2\ kPa}$ and %Recovery at 3.2 kPa) were considered relevant to the statistical analysis. Outliers for each dataset are identified based on John Tukey's Inter-quartile Range Method [82]. In this method, a test data is considered an outlier if the reference test data of the data set is either less than (1st Quartile -1.5*IQR) or greater than (3rd Quartile +1.5*IQR). The term IQR is defined as inter-quartile range, which is the difference between the 1st quartile and 3rd quartile of the data set for a specific source.

The acceptable range of the test results of samples from an individual source is then checked in accordance with ASTM C670 (*Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials*). This method also describes a check for the existence of bias based on a two-tailed Student's t-test with a confidence limit of 95%. Statistical analyses were also performed to check if the data range of a reference material from a given source met the acceptable limit of the data range recommended by ASTM C670. As shown in Equation 3.1, the critical t-value is calculated and a check is then performed as to whether the value falls within the range of $-t_{\alpha/2} <$ calculated $t < t_{\alpha/2}$.

$$t = \frac{Mean\ of\ Data\ Set - Reference\ Value}{\frac{Standard\ Deviation\ of\ the\ data\ set}{\sqrt{Sample\ Size}}} \qquad 3.1$$

The value of $t_{\alpha/2}$ is determined for a given confidence limit (usually 95%) and a degree of freedom of N-1, where N is the sample size. No bias exists within the data set if the calculated critical t-value is in between $-t_{\alpha/2}$ and $t_{\alpha/2}$.

3.4.4 Long Term Pavement Performance Bind Software Analysis

The Long Term Pavement Performance (LTPP) Bind software (Version 3.1) was used for climatic data analysis [83]. There are four ways to select a station of interest for performing the analysis: by temperature, by location (states), by coordinate, and by performance grade. In the selection process, %reliability can be fixed at 50% or 95% to run the analysis for selecting a binder performance grade. The LTPPBind software allows for applying regional temperature and traffic conditions to selected Superpave® PG binders. This study also investigated if the MSCR grade can be selected using this tool.

3.5 Summary

This chapter presents a summary of the tests performed. Test matrices (Tables 3.2 and 3.4) included in this chapter provide a better understanding of the performed tests on selective binders. Superpave® tests were performed on three types of binders from five different sources as an indicator of quality assurance at OU-Lab along with both conventional and non-conventional MSCR tests. Conventional MSCR tests were also conducted in this study on Sasobit®-modified binders and recovered binders from SRAPs. The MSCR test data of three types of binders and ER test data for polymer-modified binders from twelve different sources were provided by ODOT. A combined analysis was performed on MSCR test data from both OU and ODOT MSCR databases. These analyses, presented in Chapter 4, will help to establish recommendations toward implementing the MSCR test method for ODOT.

4 TEST RESULTS FOR NEAT AND POLYMER-MODIFIED BINDERS

4.1 Introduction

The test results for Superpave® and MSCR tests conducted on neat and polymer-modified binders in the current study are presented in this chapter. The findings of the MSCR test data were analyzed and guidelines were developed for the implementation of the MSCR test method for conditions prevailing in Oklahoma. Further, this chapter provides statistical analyses of test results to evaluate reproducibility and biases of test results. Finally, the viability of the use of the MSCR grading system into the Federal Highway Administration (FHWA) suggested LTPPBind software is discussed in this chapter.

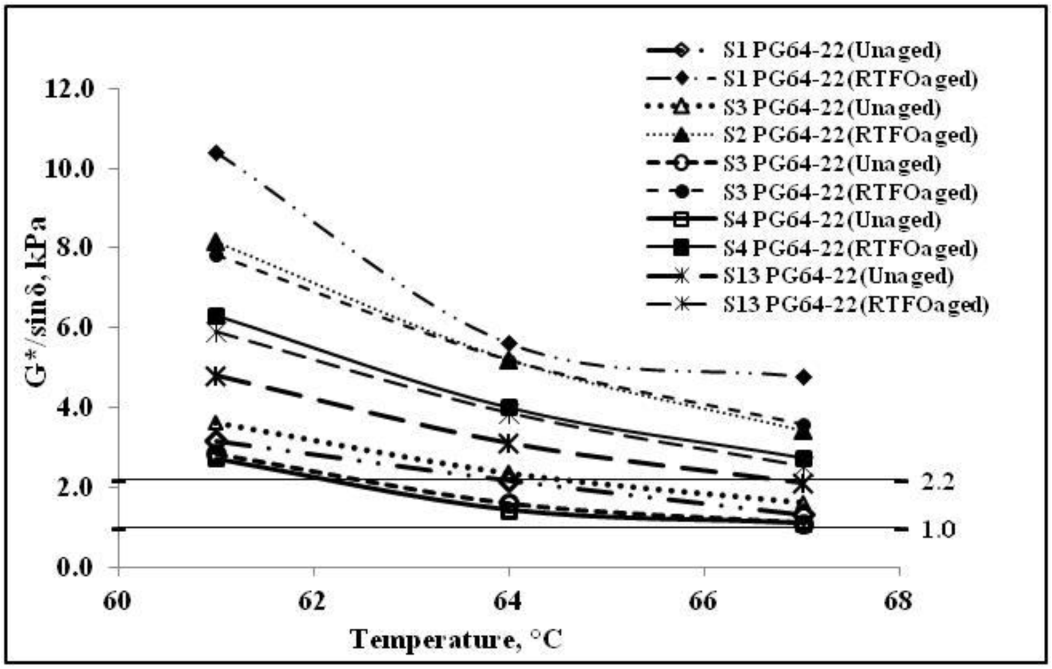
4.2 Superpave® Test Results

4.2.1 DSR Test

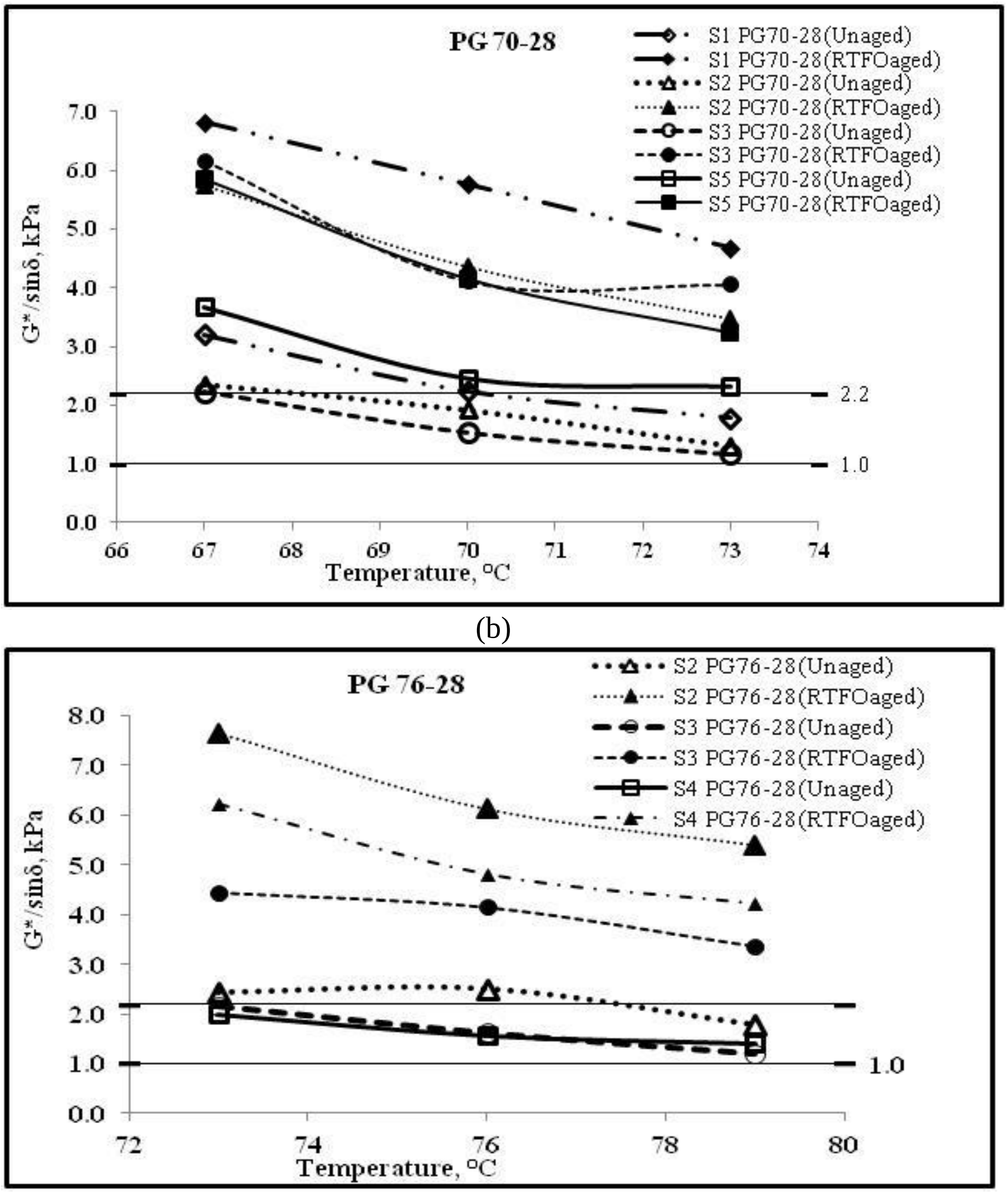
Based on the Superpave® acceptance criteria for rutting factor (G*/sinδ), the high PG temperatures corresponding to the G*/sinδ values were determined. As shown in Figure 4.1, all three types of binders from all sources, under both un-aged and RTFO-aged conditions, met the Superpave® suggested rutting factor. Based on these criteria, the rutting factors (G*/sinδ) should be at least 1.0 kPa and 2.2 kPa for un-aged and RTFO-aged conditions, respectively. As expected, the G*/sinδ value increased with a reduction in the DSR testing temperature (Figure 4.1). Since binders are viscoelastic materials, with a reduction in temperature they become stiffer due to the increase of their dynamic modulus values. As a consequence, G*/sinδ increases, and so does the rutting resistance. This observation was made for both neat and polymer-modified binders tested in this study. For instance, the G*/sinδ values of the PG 64-22 binder from S3 under the un-aged condition were 2.86 kPa, 1.61 kPa, and 1.12 kPa at 61°C, 64°C, and 67°C, respectively. Thus, the G*/sinδ value for the PG 64-22 binder from S3 was found to increase by 43% when the testing temperature was reduced from 67°C to 64°C. With further reduction in the testing temperature of the same binder from 64°C to 61°C, the G*/sinδ value was observed to increase by 77%. In the case of PG 64-22 binders under the RTFO-aged condition, the highest rutting factor was found to be 5.62 kPa for the binders from S1.

As expected, polymer-modified binders were found to have higher rutting factors at a particular testing temperature than those of neat binders. For example, at 67°C, the G*/sinδ values (under the RTFO-aged condition) of PG 70-28 and PG 64-22 binders from S2 were found to be 5.74 kPa and 3.42 kPa, respectively. The increased rutting factor for the PG 70-28 and PG 76-28 binders was due to polymeric modification with one or more elastomers. The presence of polymers in PG 70-28 and PG 76-28 binders is expected to be seen in the MSCR test results, which will be discussed later in this chapter.

As shown in Figure 4.2, at intermediate temperatures, the G*•sinδ values, an indicator of fatigue performance, for all PAV-aged PG 70-28 and PG 76-28 binders were found to be under 5,000 kPa, indicating that they met the Superpave®-specified allowable maximum fatigue factor. In general, the fatigue factor increased with a decrease in testing temperature, which was expected for viscoelastic binders. For example, the G*•sinδ of PG 76-28 from S2 at 31°C, 28°C, and 25°C were found to be 762 kPa, 980 kPa, and 1370 kPa, respectively. From Figure 4.2, it is evident that neat binders (PG 64-22) from all sources except S1 passed the Superpave-specified fatigue factor criterion at intermediate temperature (25°C). Among all tested binders, at any specific test temperature, the highest fatigue factor was obtained for the PG 70-28 binder from S1 at 28°C. The highest observed fatigue factor was 2,235 kPa.



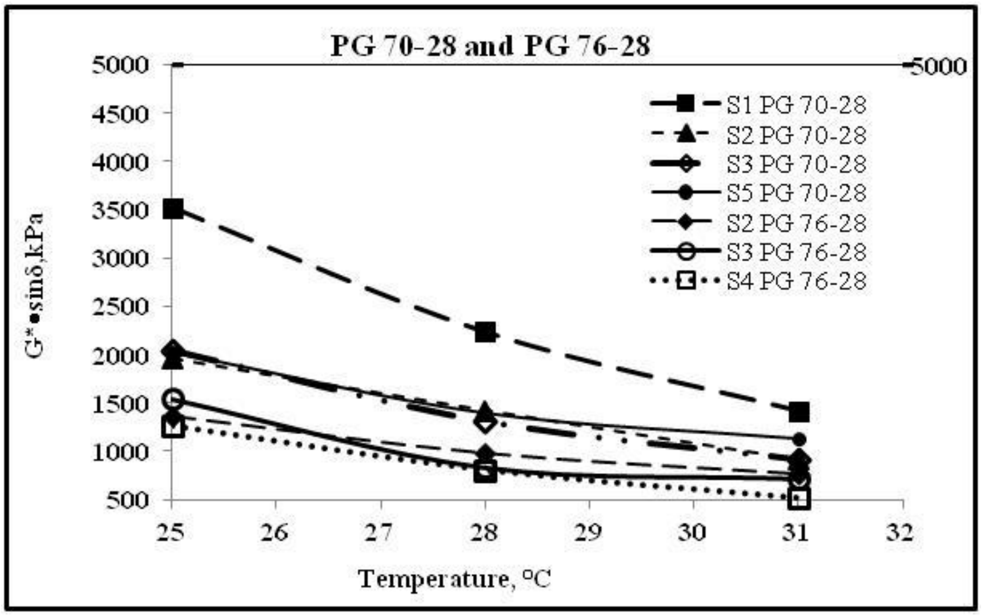
(a)



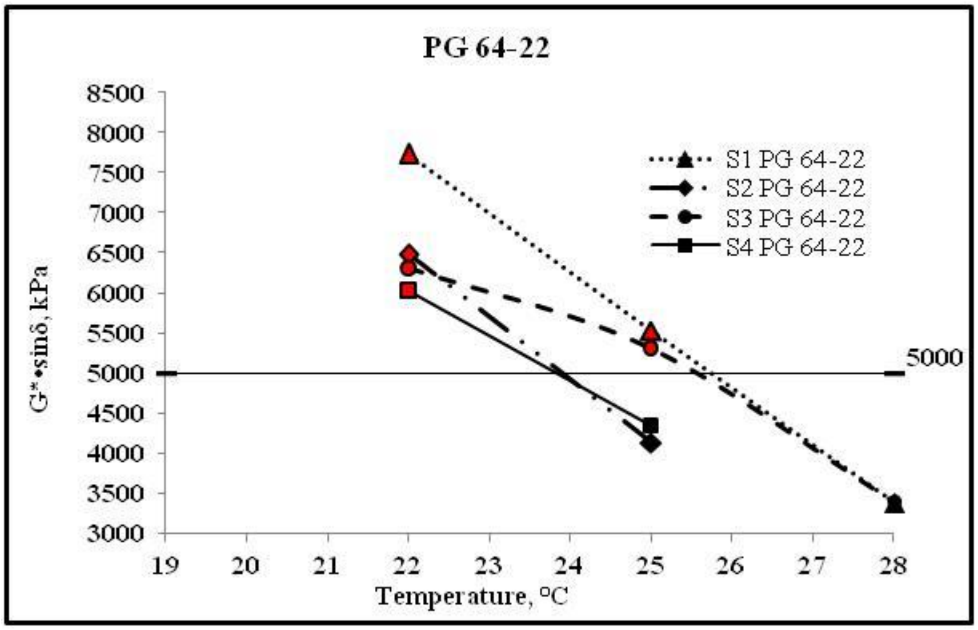
(b)

(c)

Figure 4.1 G*/sinδ vs. Temperature for (a) PG 64-22; (b) PG 70-28; and (c) PG 76-28.



(a)

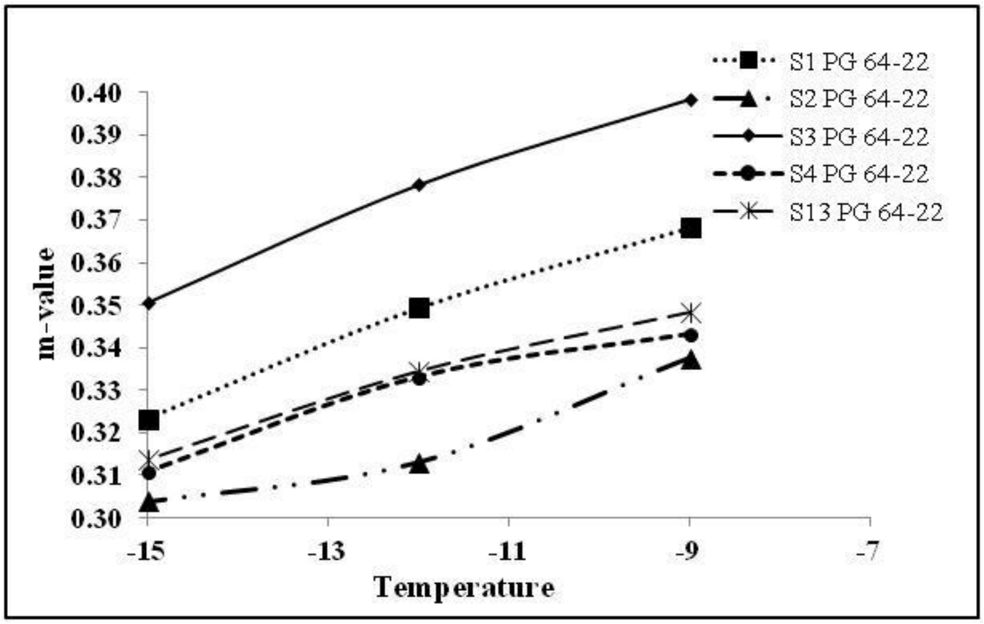


(b)

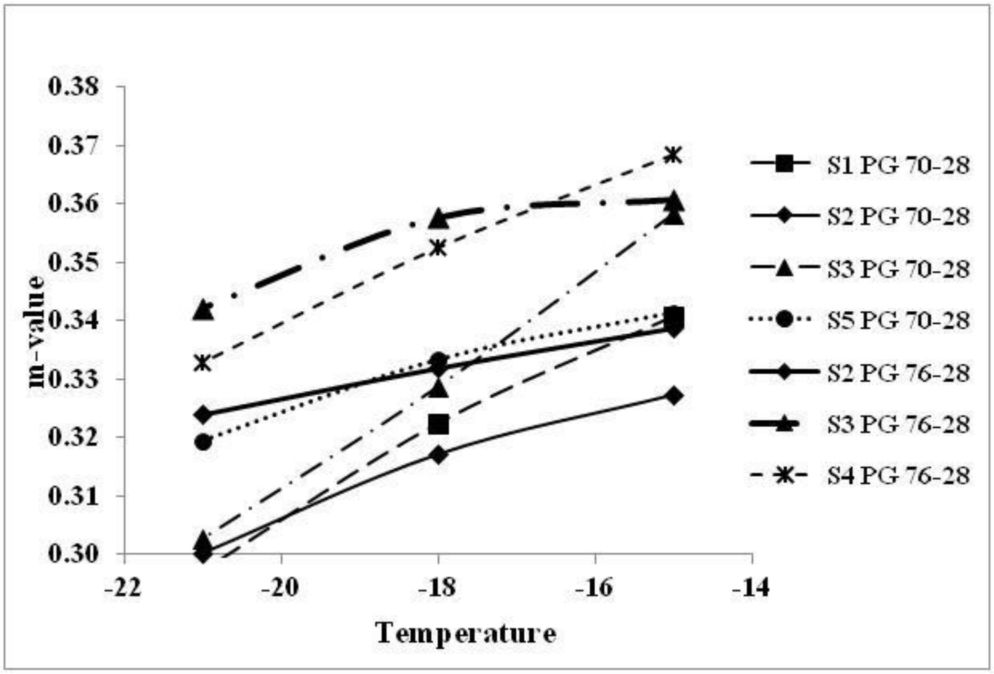
Figure 4.2 G*•sinδ vs. Temperature for PAV-aged binders: (a) PG 70-28, PG 76-28; and (b) PG 64-22.

4.2.2 BBR Test

It should be noted that the rate of stress relaxation (m-value) and stiffness (S-value) parameters obtained from the BBR test results are indicators of a binder's ability to resist low temperature cracking. With respect to thermal cracking, at low critical temperatures, the m-value (the slope of the stiffness versus loading time curve) and the S-value were found to be 0.300 and 300 MPa, respectively. Binders that are not too stiff at low temperatures and are able to relax built-up stresses are desirable. From Figure 4.3, it was observed that the m-value decreased and the S-value increased with a decrease of the BBR testing temperature, as expected. For example, the m-value of the PG 76-28 binder from S4 was observed to be 0.368, 0.352, and 0.332 at low critical temperatures of -25°C, -28°C, and -31°C, respectively. Among all PG 64-22 binders, PG 64-22 binder from S3 had the highest m-value at any particular testing temperature. On the other hand, as seen in Figure 4.4, the S-value of PG 64-22 binder from S1 was found to be higher than that of any other sources. As shown in Figure 4.4, lower stiffness values were observed in the cases of polymer-modified binders (both PG 70-28 and PG 76-28) compared to the neat (PG 64-22) binders. For example, at -25°C (BBR tests conducted at -15°C, which is 10°C warmer than the low service termperature of the pavement), the stiffness value for the PG 64-22 binder from S1 was found to be 265 MPa, whereas it was only 127 MPa for the PG 70-28 binder from the same source. By considering S-values and m-values, the low PG temperatures of tested binders were estimated and are discussed next.



(a)



(b)

Figure 4.3 m-value vs. BBR Temperature (°C) for (a) PG 64-22; and (b) PG 70-28, PG 76-28.

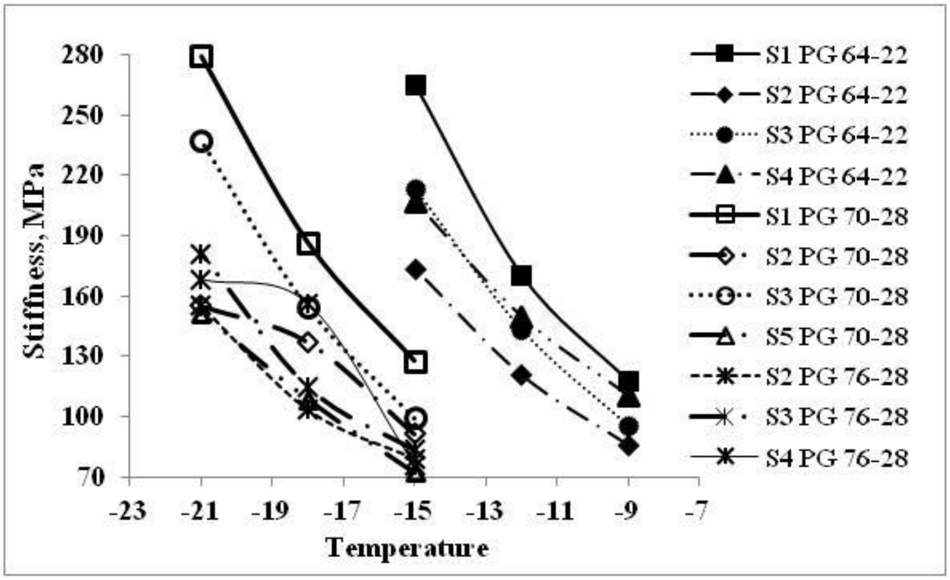


Figure 4.4 Stiffness vs. BBR Test Temperature (°C).

4.2.3 Superpave® PG Grading

Based on the DSR and BBR test results, the actual high and low PG temperatures of the tested binders were estimated and are presented in Table 4.1. The shaded rows in Table 4.1 represent the calculated, actual high PG temperatures based on the G*/sin□ values obtained from DSR tests of un-aged and RTFO-aged binders, and low PG temperatures corresponding to m-values and S-values obtained from BBR tests of PAV-aged binders. As noted earlier, according to the Superpave® specifications, the G*/sinδ values for un-aged and RTFO-aged binders are 1.0 kPa and 2.20 kPa, respectively, and the m-value and the S-value for the PAV-aged binders are 0.300 and 300 MPa, respectively. The actual high and low PG temperatures that met these Superpave® criteria were estimated through extrapolation or interpolation of laboratory test data at three different temperatures. As shown in Table 4.1, all tested binders passed the manufacturers' labeled PG grades. For instance, the actual PG grades of the PG 64-22, PG 70-28, and PG 76-28 from S2 were found to be PG 69-26, PG 74-31, and PG 82-31, respectively. It was also observed that some binders were significantly superior to their marketed PG grades than others. For example, the continuous (1°C interval) PG grade of the PG 76-28 binder from S4 was found to be PG 86-32. Likewise, the continuous PG grade of the PG 70-28 binder from S5 was PG 76-35. These findings imply that significantly high %Recovery values are expected for these stiff binders.

Table 4.1 Superpave® Test Result and Actual Grading of Selective Binders

Source	Binder Type	Superpave® Test Results (performance grading verification)								Actual PG Grading
		DSR Test				BBR Test				
		Temp (°C)	Un-aged G*/sinδ (kPa)	Temp (°C)	RTFO-aged G*/sinδ (kPa)	Temp (°C)	m-value at 60 sec	Temp (°C)	Stiffness at 60 sec, (MPa)	
S1	**PG 64-22**	61.0	3.2	61.0	10.4	-9.0	0.37	-9.0	118.1	**PG 68-26**
		64.0	2.2	64.0	5.6	-12.0	0.35	-12.0	170.8	
		67.0	1.3	67.0	4.8	-15.0	0.32	-15.0	265.4	
		68.2	1[a]	76.3	2.2[b]	-17.7	0.3[c]	-16.1	300[d]	
						-27.7		-26.1		
S1	**PG 70-28**	67.0	3.2	67.0	11.9	-15.0	0.34	-15.0	127.6	**PG 75-26**
		70.0	2.2	70.0	8.8	-18.0	0.32	-18.0	186.6	
		73.0	1.8	73.0	5.3	-21.0	0.30	-21.0	279.4	
		78.1	1[a]	75.6	2.2[b]	-20.7	0.3[c]	-21.7	300[d]	
						-27.7		-26.1		
S2	**PG 64-22**	61.0	3.7	61.0	8.2	-9.0	0.34	-9.0	86.4	**PG 69-26**
		64.0	2.4	64.0	5.2	-12.0	0.31	-12.0	121.2	
		67.0	1.6	67.0	3.4	-15.0	0.30	-15.0	173.9	
		69.6	1[a]	69.1	2.2[b]	-16.3	0.3[c]	-22.2	300[d]	
						-26.3		-32.2		
S2	**PG 70-28**	67.0	2.4	67.0	5.7	-15.0	0.33	-15.0	91.4	**PG 74-31**
		70.0	1.9	70.0	4.4	-18.0	0.32	-18.0	137.2	
		73.0	1.3	73.0	3.5	-21.0	0.30	-21.0	155.2	
		74.5	1[a]	77.2	2.2[b]	-21.0	0.3[c]	-23.3	300[d]	
						-31.0		-33.3		
S2	**PG 76-28**	73.0	2.4	73.0	7.7	-15.0	0.34	-15.0	79.2	**PG 82-31**
		76.0	2.5	76.0	6.1	-18.0	0.33	-18.0	103.6	
		79.0	1.8	79.0	5.4	-21.0	0.32	-21.0	155.4	
		82.8	1[a]	92.1	2.2[b]	-21.0	0.3[c]	-23.3	300[d]	
						-31.0		-33.3		
S3	**PG 64-22**	61.0	2.9	61.0	7.8	-9.0	0.40	-9.0	95.5	**PG 67-28**
		64.0	1.6	64.0	5.2	-12.0	0.38	-12.0	143.3	
		67.0	1.1	67.0	3.6	-15.0	0.35	-15.0	213.2	
		67.8	1[a]	69.6	2.2[b]	-20.5	0.3[c]	-18.7	300[d]	
						-30.5		-28.7		
S3	**PG70-28**	67.0	2.2	67.0	6.2	-15.0	0.36	-15.0	99.6	**PG 74-31**
		70.0	1.5	70.0	4.1	-18.0	0.33	-18.0	154.6	
		73.0	1.2	73.0	4.1	-21.0	0.30	-21.0	237.4	

Source	Binder Type	Superpave® Test Results (performance grading verification)								Actual PG Grading
		DSR Test				BBR Test				
		Temp (°C)	Un-aged G*/sinδ (kPa)	Temp (°C)	RTFO-aged G*/sinδ (kPa)	Temp (°C)	m-value at 60 sec	Temp (°C)	Stiffness at 60 sec, (MPa)	
		74.3	1[a]	161.1	2.2[b]	-21.0	0.3[c]	-23.3	300[d]	
						-31.0		-33.3		
S3	**PG 76-28**	73.0	2.2	73.0	4.5	-15.0	0.36	-15.0	83.4	**PG 80-36**
		76.0	1.6	76.0	4.2	-18.0	0.36	-18.0	114.8	
		79.0	1.2	79.0	3.4	-21.0	0.34	-21.0	181.2	
		80.5	1[a]	83.3	2.2[b]	-29.4	0.3[c]	-26.4	300[d]	
						-39.4		-36.4		
S4	**PG 64-22**	61.0	2.7	61.0	6.3	-9.0	0.32	-9.0	110.5	**PG 67-26**
		64.0	1.4	64.0	4.0	-12.0	0.33	-12.0	150.0	
		67.0	1.1	67.0	2.8	-15.0	0.31	-15.0	207.5	
		68.0	1[a]	68.3	2.2[b]	-16.4	0.3[c]	-19.8	300[d]	
						-26.0		-29.0		
S5	**PG 70-28**	67.0	3.7	73.0	5.9	-15.0	0.34	-15.0	72.4	**PG 76-35**
		70.0	2.5	76.0	4.2	-18.0	0.33	-18.0	108.7	
		73.0	2.3	79.0	3.2	-21.0	0.32	-21.0	151.5	
		101.3	1[a]	76.4	2.2[b]	-25.2	0.3[c]	-30.4	300[d]	
						-35.2		-40.4		
S4	**PG 76-28**	73.0	2.0	73.0	6.2	-15.0	0.37	-15.0	76.0	**PG 86-32**
		76.0	1.6	76.0	4.8	-18.0	0.40	-18.0	156.3	
		79.0	1.4	79.0	4.2	-21.0	0.33	-21.0	168.2	
		86.5	1[a]	89.3	2.2[b]	-22.5	0.3[c]	-54.2	300[d]	
						-32.5		-64.2		
S13	**PG 64-22**	61	4.81	61	5.93	-9	0.35	-9	65.33	**PG 68-27**
		64	3.11	64	3.89	-12	0.33	-12	99.91	
		67	2.11	67	2.56	-15	0.31	-15	145.77	
		70	1[a]	68	2.2[b]	-17	0.3	-25.1	300	
						-27		-35		

[a]: AASHTO T315 Un-aged Binder Performance Criterion: G*/sinδ >= 1.00kPa

[b]: AASHTO T315 RTFO-aged Binder Performance Criterion: G*/sinδ >= 2.20kPa

[c]: AASHTO T313 PAV-aged Binder m-value @ 60 sec : 0.300

[d]: AASHTO T313 PAV-aged Binder Stiffness @ 60 sec: 300MPa

4.3 MSCR Test Data

The MSCR and pertinent ER test results of binders from different sources are analyzed in this section. Both “conventional” and “non-conventional” MSCR test data of neat and polymer-modified binders were analyzed to develop MSCR implementation guidelines. The “conventional” MSCR test refers to the MSCR test conducted at 64°C on RTFO-aged binders at stress levels of 0.1 kPa and 3.2 kPa, which is essentially the AASHTO T 350 method. On the other hand, the “non-conventional” MSCR tests were conducted at a higher stress level (10 kPa) and at higher temperatures (70°C and 76°C) to examine the nonlinear viscoelastic properties of the polymer-modified binders. The MSCR grade, along with the $J_{nr,0.1\ kPa}$, $J_{nr,3.2\ kPa}$, $J_{nr,diff}$, R100, and R3200 values, as well as "Stress Sensitivity" of the tested binders are presented in tabular form in Tables 4.5, 4.8, and 4.9. The term "R100" denotes the MSCR %Recovery at 0.1 kPa, whereas R3200 refers to the MSCR %Recovery value at 3.2 kPa. These properties are presented in these tables. A majority of columns in these tables are self-explanatory or have been defined earlier. A few important parameters (Column 5, Column 9, and Column 10) presented in these tables are described next.

"Stress Sensitivity" in Column 5 and "MSCR %Recovery" (also called %Recovery in this report) in Column 9 are used here to determine if the binder meets the AASHTO T 332 and AASHTO T 350 specifications.

4.3.1 Stress Sensitivity

As described in Chapter 2, for a polymer-modified binder, the strain response is nonlinear with increasing stress levels and the polymer chains in the binder can be rearranged substantially when the stress level is increased. The Stress Sensitivity essentially checks a binder's performance when it experiences a higher temperature or a higher stress level than expected. With respect to the MSCR test data, "Stress Sensitivity" (Column 5) determines the percent increase in the J_{nr} value with an increase in stress level from 0.1 kPa to 3.2 kPa. This is illustrated in Equation 4.1 and Table 4.2. According to AASHTO T 332, the percent increase in J_{nr} of a binder due to increased stress levels from 0.1 kPa to 3.2 kPa must be less than or equal to 75% of the J_{nr} at 0.1 kPa. This check ensures that the binder will not be overly stress-sensitive to unexpected heavy loads or unusually high temperatures [18].

$$\mathrm{J_{nr,diff}} = \frac{\mathrm{J_{nr\,,\,3.2\;kPa}} - \mathrm{J_{nr\,,\,0.1\;kPa}}}{\mathrm{J_{nr\,,\,0.1\;kPa}}} * 100 \leq 75\% \tag{4.1}$$

Table 4.2 Stress Sensitivity Criteria

Column 4 : $\mathbf{J_{nr,diff}} = \frac{\mathrm{J_{nr,\,3.2\;kPa}} - \mathrm{J_{nr,\,.1\;kPa}}}{\mathrm{J_{nr,\,.1\;kPa}}} * \mathbf{100}$	**Column 5: Stress Sensitivity (Meets AASTHO T 332 Criterion)**
$\leq 75\ \%$	Yes
$> 75\ \%$	No

4.3.2 MSCR %Recovery

The MSCR %Recovery (Column 9) indicates whether a binder meets the second AASHTO T 350 criterion pertaining to %Recovery, which is illustrated in Table 4.3. Previous studies have established the J_{nr} as a better indicator of rut resistance for a binder than the rutting factor, G*/sinδ. However, J_{nr} alone is not sufficient to identify the presence of an elastomeric polymer in the binder [16-19]. D’Angelo [18] mentioned that the recovery portion of the creep and the recovery curve at the high-temperature range has to be used to evaluate rutting potential as it provides significant information on how polymers react with the base binders. Further, the %Recovery measured in the MSCR test measures the elastomeric response of the polymer in the binders [18]. Thus, the %Recovery check helps one to understand how reliable a binder is in terms of recovery. This is because the %Recovery check ensures that the obtained %Recovery from the MSCR test is greater than the expected value at 3.2 kPa. The expected %Recovery is calculated with the help of Equation 2.1, which uses the $J_{nr,3.2\ kPa}$ value, obtained from the MSCR test. The polynomial expression of the MSCR Line Equation shown in Column 1 in Table 2 was elaborated on in Chapter 2.

Table 4.3 MSCR %Recovery Criterion (AASHTO T 350)

MSCR Line Equation: $29.371*(J_{nr\ 3.2\ kPa})^{-0.2633}$	**Column 9: MSCR %Recovery (Meets AASTHO T 350)**	**Remarks**
< R3200 (Column 7)	Yes	Within the obtained limit
> R3200 (Column 7)	No	Beyond the obtained limit
If $J_{nr\ ,3.2\ kPa} > 2\ kPa^{-1}$	N/A	Insignificant recovery noticed

4.3.3 MSCR Grading System

As explained in Chapter 2, the SHRP grade-bumping concept is actually inappropriate for a high-temperature binder specification, where the binder is tested at temperatures far above the field temperature. The MSCR grading (Column 10) of an RTFO-aged binder is calculated based on the J_{nr} value. In this grading method, the J_{nr} values are used as an indicator of the level of traffic a binder can withstand. Four levels of traffic are considered in the J_{nr}-based grading. These levels are: Standard (S), heavy (H), very heavy (V), and extreme (E), as described in Table 4.4. It is evident from Table 4.4 that the four MSCR grades are PG 64S-XX (Standard), PG 64H-XX (Heavy), PG 64V-XX (Very Heavy), and PG 64E-XX (Extreme).

Table 4.4 MSCR Grade Based on J_{nr} (AASHTO T 332)

J_{nr} (kPa^{-1}) Criteria (Column 3)	**MSCR Grading (Column 10)**
$2.0<J_{nr} =< 4.0$	PG 64S-XX (S: Standard)
$1.0<J_{nr} =< 2.0$	PG 64H-XX (H: Heavy)
$0.5<J_{nr} =< 1.0$	PG 64V-XX (V: Very Heavy)
$J_{nr} =< 0.5$	PG 64E- XX (E: Extreme)

4.3.4 Polymer Method

Analyses were performed on the ODOT MSCR database and the OU database containing laboratory data on neat and polymer-modified binders, in accordance with the Polymer method. The results are summarized in Figures 4.5, 4.10, and 4.11 and are discussed in relevant sections. It should be noted that in the Polymer method, %Recovery values are plotted against J_{nr} values for tests conducted at the 3.2 kPa stress level. The %Recovery vs. J_{nr} plot is also very useful for characterizing a polymer-modified binder through visual observation of its location within the plot. The location (i.e., quadrant) of a binder in the plot helps to identify if the binder contains any polymer modifier. Moreover, it helps quantify the amount of polymer. In view of its simplicity and effectiveness, the Polymer method is becoming increasingly popular in characterizing polymer-modified binders.

In the Polymer method, the MSCR curve represents a borderline above which a binder exhibits a high level of elasticity and below which it is expected to exhibit a low level of elasticity. Thus, the presence of polymer in a binder can be easily detected using this method. This information is particularly helpful when using binders from unknown sources. Moreover, the %Recovery obtained from the MSCR test provides an indication of the amount of polymer in a polymer-modified binder.

4.4 MSCR Test Data of Neat Binder

4.4.1 MSCR Database

Due to a large amount of data present in the MSCR database, a snapshot of the MSCR database is presented in Table 4.5. The entire dataset is presented in Appendix A. The MSCR database contains MSCR test data of 63 PG 64-22 binders from 11 ODOT approved sources. There were no PG 64-22 binder from S7. Binders from 4 of these 11 sources were also tested in the OU Asphalt Binders Laboratory. Definitions of Columns 3, 4, 5, 9, and 10 were provided in Section 4.3.

Table 4.5 MSCR Database for PG 64-22 at 64°C

1	2	3	4	5	6	7	8	9	10
Source ID	**$J_{nr,0.1}$ kPa**	**$J_{nr,3.2}$ kPa**	**$J_{nr,diff}$**	**Stress Sensitivity (Meets AASTHO T 332)**	**R100**	**R3200**	**R_{diff}**	**%Recovery (Meets AASTHO T 350)**	**MSCR GRADE**
S1	2.10	2.39	13.59	YES	7.61	1.51	80.2	N/A	PG 64S-22
S1	1.90	2.31	21.64	YES	12.97	2.99	76.9	N/A	PG 64S-22
S1	2.12	2.52	18.66	YES	9.40	2.40	74.5	N/A	PG 64S-22
S1	2.59	2.96	14.20	YES	7.65	1.29	83.2	N/A	PG 64S-22
S1	2.53	3.05	20.43	YES	10.30	2.19	78.8	N/A	PG 64S-22
S1	2.29	2.82	23.45	YES	12.39	2.50	79.8	N/A	PG 64S-22
S1	1.83	2.29	25.08	YES	13.37	3.56	73.4	N/A	PG 64S-22
S1	1.51*	1.64*	8.95*	YES	5.41*	1.94*	64.1*	NO	PG 64H-22
…	…	…	…	…	…	…	…	…	…
S11	4.22	4.38	3.67	YES	-1.29	0.06	105	N/A	N/A
S11	4.14	4.29	3.72	YES	-0.14	0.07	148	N/A	N/A
S11	3.82	4.07	6.60	YES	2.29	0.11	95	N/A	N/A
S11	3.67	3.95	7.60	YES	3.00	0.16	95	N/A	PG 64S-22
S12	2.20	2.52	14.79	YES	8.13	1.81	78	N/A	PG 64S-22

*: OU Laboratory Data
… : Continuation of MSCR Test Results, Detail is Presented in Table A.1 of Appendix A

About 92% of binders (58 binders out of 63) were characterized as “N/A” in Column 9 of Table 4.5, which denotes insignificant recovery. Insignificant recovery is considered when $J_{nr,3.2\ kPa}$ is greater than 2 kPa^{-1}, which was discussed in Section 2.6.1. Thus, about 92% of the tested PG 64-22 binders were expected to exhibit very low rutting resistance because of their high J_{nr} values. Further, an increasing trend of J_{nr} and a decreasing trend of %Recovery were observed with an increase in stress level for 94% (59 out of 63) of binders (PG 64-22) tested herein. An increase in stress level results in an increased rate of strain accumulation, indicating poor rutting resistance. Such behavior is expected when a binder undergoes repetitive loading and unloading due to vehicular traffic in an actual pavement. Thus, a very high J_{nr} and insignificant %Recovery signifies that PG 64-22 binders are expected to have very poor rutting resistance and recovery characteristics for high levels of traffic if used at or near the surface of the pavement.

4.4.2 Polymer Method

A detailed analysis of the MSCR database was performed based on the Polymer method, which was described in Section 4.3.4. This plot is a visual representation of Table 4.5. As shown in Figure 4.6, about 94% (59 out of 63) of the tested PG 64-22 binders were plotted under the polymer curve, indicating a very low recovery, which is an indication of low elasticity as well. Further, the MSCR curve stops at a J_{nr} value of 2 kPa^{-1}, and 90% (57 out of 63) of the tested binders were observed to have their $J_{nr,3.2\ kPa}$ values beyond this curve. The reason behind this was described in Section 4.4.1. Wasage et al. [22] reported similar observations in their study, in which very small recovery was visible in neat binders (PG 64-22) even under a low stress level.

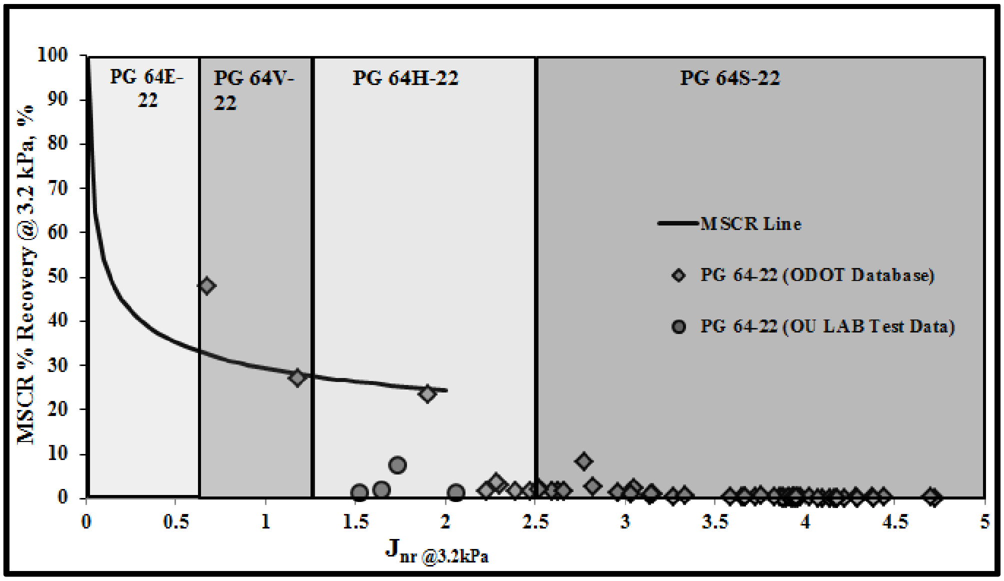


Figure 4.5 MSCR %Recovery % vs. J_{nr} @ 3.2 kPa for PG 64-22.

4.4.3 MSCR Grade

The %Recovery vs. J_{nr} plots, as shown in Figure 4.5, are also helpful in grading binders. As explained earlier (Table 4.4), the AASHTO T 332 method grades a binder based on its J_{nr} value. The MSCR grades of all tested PG 64-22 binders and their frequency distributions (bar charts) are presented in Figures 4.5 and 4.6, respectively. From the statistical frequency bar chart (Figure 4.6), it was seen that 65% of the tested PG 64-22 binders were graded as PG 64S-22. These binders were sufficient to support standard traffic, as expected, within the limit of 2 kPa^{-1} up to 4 kPa^{-1}. The PG 64S-22 binders were followed by the next highest frequency of 25% of binders, which fell beyond the limit of 4 kPa^{-1}. These binders could not possibly be graded as PG 64S-22 and perhaps a new MSCR grade name such as "Sub-Standard" can be introduced to consider binders with very high $J_{nr,3.2\ kPa}$ values. From Figures 4.5 and 4.6, it was evident that only five out of 63, and one out of 63 binders were graded as PG 64H-22 and PG 64V-22, respectively. Since, they were plotted below the MSCR curve and a very low %Recovery was noticed, grading these binders as PG 64H-22 or PG 64V-22 might not be a safe choice, considering the need to withstand heavy and very heavy traffic conditions. D'angelo [18] also indicated that a neat PG 64-22 binder would be equivalent to a PG 64S-22 based on the MSCR specification ($J_{nr,3.2\ kPa}$ value of 4.0 kPa^{-1}). After the current research was nearly completed, AASHTO T 350 replaced TP 70. The maximum J_{nr} at 3.2 kPa was changed from 4.0 to 4.5 kPa^{-1} , which significantly changes our initial findings for PG 64-22. Most of PG 64-22 binders would then be an S grade.

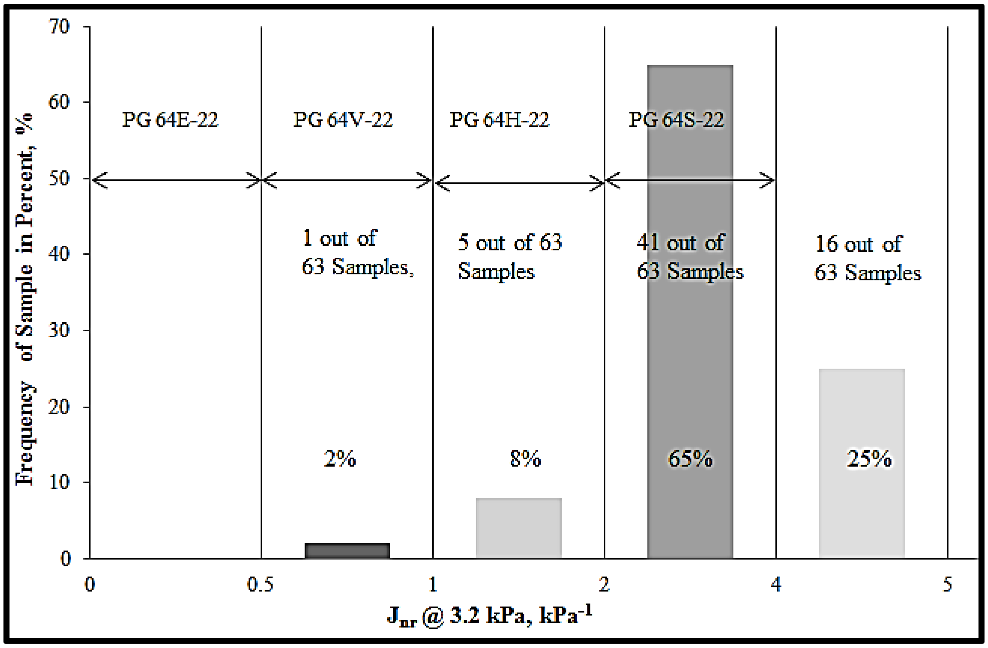


Figure 4.6 Frequency of Sample vs. J_{nr} @ 3.2 kPa for PG 64-22 Binders.

4.4.4 Stress Sensitivity

All 63 binders met the AASHTO T 332 Stress Sensitivity criterion ($J_{nr,diff}$<75%); (Table 4.5). For all binders, the percentage increase in J_{nr} while increasing the stress level from 0.1 kPa to 3.2 kPa was less than 75% of the J_{nr}

at 0.1 kPa. These observations indicate that the neat binders were not overly stress sensitive to unexpected heavy loads or unusually high temperatures. Stress Sensitivity of the tested PG 64-22 binders is presented in Figure 4.7, in which $J_{nr,diff}$ is plotted against R_{diff}. The R_{diff} represents the reduction in %Recovery with increased stress level from 0.1 kPa to 3.2 kPa. This plot was constructed to establish a relationship between $J_{nr,diff}$ and R_{diff} that might provide an insight into how a binder responds in an actual pavement when it experiences high stress levels. However, no particular trend is observed in the $J_{nr,diff}$ and R_{diff} plot.

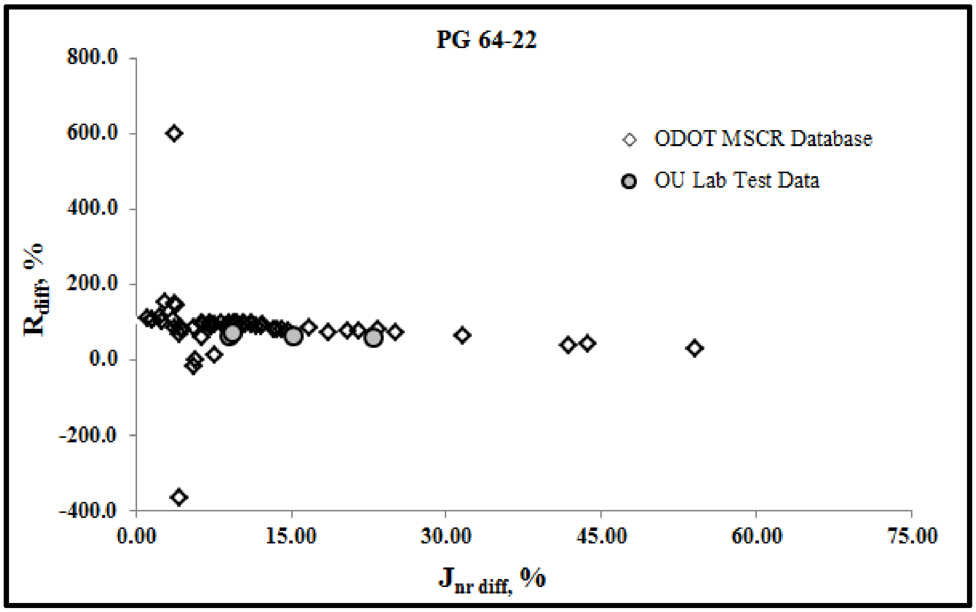
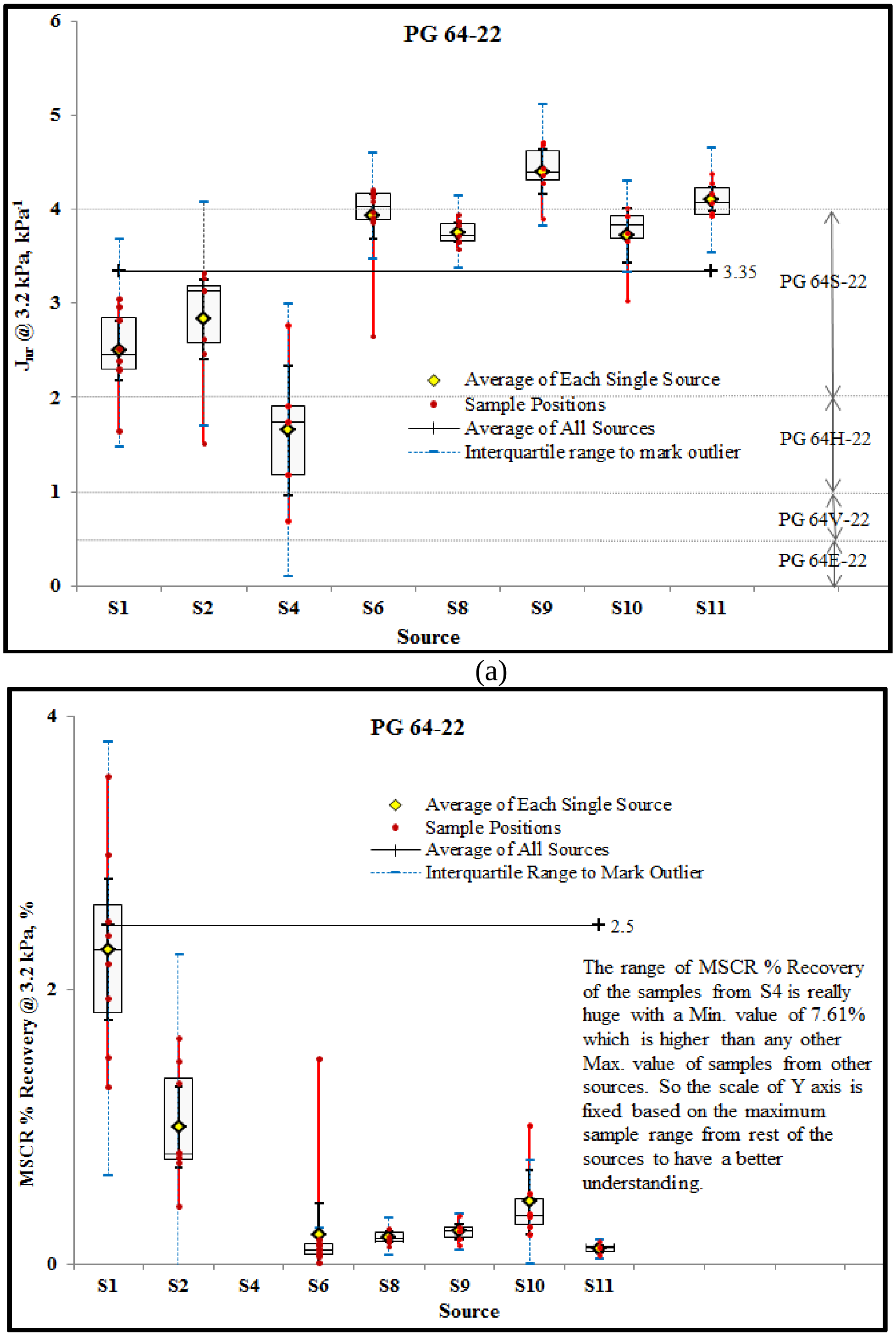


Figure 4.7 R_{diff} (%) vs. $J_{nr,\ diff}$ (%) for PG 64-22.

4.4.5 Statistical Summary of MSCR Database

Statistical analyses were conducted to establish reliability of the test data generated in the current study. The statistical analyses used herein were described in Chapter 3. As shown in Figure 4.8a, J_{nr} values for binders from 6 out of 7 sources fell within the range 2 to 5 kPa^{-1}. Also, it was seen that each of the three (S2, S6, and S10) other sources had an outlier (i.e., significantly large range of J_{nr} values). As shown in the box plot in Figure 4.8a, binders from source S4 had a large margin of error with a large range of J_{nr} values. Binders from this source had a higher standard deviation and a higher coefficient of variation than those from other sources (Table 4.6). Moreover, a significant variation was noticed in the %Recovery data of the PG 64-22 binders from S4 compared to those from other sources (Figure 4.8b). Although the binders were obtained from multiple refineries and crude oil sources, the MSCR test data exhibited a good level of consistency in most cases. The horizontal black line across the box plots indicates the average value of J_{nr} (Figure 4.8a) or %Recovery (Figure 4.8b) of binders from all sources. From Figure 4.8b, it was seen that the average %Recovery for the PG 64-22 binders from all sources was only 2.5%, which indicates a very low elasticity, as expected.

Snapshots of statistical parameters (mean, standard deviation, etc.) are presented in Tables 4.6 and 4.7. The entire dataset is presented in Appendix B (Tables B.1 and B.2). These parameters are used to check reproducibility and bias of test results and to identify outliers for the PG 64-22 binders. Due to a considerable volume of data, only a portion of test data is shown in these tables, and the entire dataset is presented in Appendix B. Again, although crude oil sources were likely different and multiple laboratories were involved in conducting the tests, the coefficient of variation (CV) for the $J_{nr,\ 3.2\ kPa}$ values was found to be less than 1 for the PG 64-22 binders from all 11 sources. Also, 10 out of 11 sources showed consistent results for %Recovery at 3.2 kPa (Tables 4.6 and 4.7).



(a)

The range of MSCR % Recovery of the samples from S4 is really huge with a Min. value of 7.61% which is higher than any other Max. value of samples from other sources. So the scale of Y axis is fixed based on the maximum sample range from rest of the sources to have a better understanding.

(b)

Figure 4.8 Box-plot of PG 64-22 from All Sources for (a) J_{nr} @ 3.2 kPa; (b) MSCR %Recovery @3.2 kPa.

The CV values less than one (1) indicate a low variance. A high variance (CV greater than 1) was observed for %Recovery at 3.2 kPa for the PG 64-22 binders from S6 (Table 4.7). This was expected as the average %Recovery at 3.2 kPa of the tested binders from S6 was less than 1%. A higher coefficient of variation was evident for %Recovery than for $J_{nr,\ 3.2\ kPa}$.

Column 9 in Tables 4.6 and 4.7 helps to identify if the data range of each source is within the acceptable limit recommended by ASTM C670. It was seen that the $J_{nr,3.2\ kPa}$ values from all 11 sources and the %Recovery values from all sources, except S4, met the ASTM C670 criteria for an acceptable data range (Table 4.6). The source S4 was also found to have a high range of %Recovery whose minimum value was even higher than the maximum %Recovery value of PG 64-22 binders from other sources at 3.2 kPa. Such variation was also depicted in the box-plot analysis (Figure 4.8). Although not from the same source, only three outliers of 63 binders were detected by considering both $J_{nr,\ 3.2\ kPa}$ and %Recovery values.

The t-values from the t-table are presented in Column 10 of Tables 4.6 and 4.7. These values are based on 95% confidence level and N-1 degree of freedom. The parameter N denotes the sample size. Column 11 shows the level of bias within a dataset for a given source, compared to Column 10. Based on this approach, only S1 and S11 had more than two bias values within the dataset for both %Recovery and $J_{nr,3.2kPa}$.

Table 4.6 Detection of Outlier and Bias for J_{nr} @ 3.2 kPa of PG 64-22

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	J_{nr} (3.2 kPa)	Outlier[a]	Sample Size, N	Mean	SD[b]	CV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S1	2.39	No	8.00	2.50	0.45	0.18	1.41	Yes	2.365	0.661	No
S1	2.31	No								1.190	No
S1	2.52	No								-0.134	No
S1	2.96	No								-2.876	Yes
S1	3.05	No								-3.429	Yes
S1	2.82	No								-2.024	No
S1	2.29	No								1.289	No
S1	1.64*	No								5.324	Yes
S2	3.27	No	8.00	2.83	0.61	0.22	1.81	Yes	2.365	-2.020	No
S2	2.47	No								1.660	No
S2	3.15	No								-1.489	No
S2	3.14	No								-1.402	No
S2	3.14	No								-1.443	No
S2	3.33	No								-2.307	No
S2	2.63	No								0.944	No
S2	1.52*	Outlier								6.057	Yes
…	…	…	…	…	…	…	…	…	…	…	…
S11	4.18	No	7.00	4.11	0.18	0.04	0.44	Yes	2.45	-1.015	No
S11	3.94	No								2.530	Yes
S11	3.96	No								2.215	No
S11	4.38	No								-4.034	Yes
S11	4.29	No								-2.682	Yes
S11	4.07	No								0.562	No
S11	3.95	No								2.425	No
S12	2.52	N/A	1.00	2.52	Not Applicable						

[a]: John Tukey's Inter-Quartile Range Method for Outlier Filter [82]

[b] : Standard Deviation [c] : Coeffcient of Variation

[d]: (Maximum J_{nr} -Minimum J_{nr}) for Each Source

[e]: If Column 8 < Column 6* Multiplier from Table 1 of ASTM C670(for Number of test results): Yes, otherwise No.

[f,g,h]: Described in section 4.3

*: OU Asphalt Laboratory Data

... : Continuation of MSCR Test Results, Detail is Presented in Table B.1 of Appendix B

Table 4.7 Detection of Outlier and Bias for MSCR %Recovery @ 3.2 kPa of PG 64-22

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	R3200	Outlier[a]	Sample Size, N	Mean	SD[b]	CV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S1	1.51	No	8.00	2.30	0.75	0.32	2.27	Yes	2.365	2.980	Yes
S1	2.99	No								-2.637	Yes
S1	2.40	No								-0.384	No
S1	1.29	Outlier								3.822	Yes
S1	2.19	No								0.416	No
S1	2.50	No								-0.774	No
S1	3.56	No								-4.776	Yes
S1	1.94*	No								1.352	No
S2	0.42	No	8.00	1.00	0.43	0.43	1.23	Yes	2.365	3.819	Yes
S2	1.48	No								-3.163	Yes
S2	0.80	No								1.281	No
S2	0.77	No								1.484	No
S2	0.81	No								1.254	No
S2	0.73	No								1.745	No
S2	1.65	No								-4.293	Yes
S2	1.32*	No								-2.126	No
…	…	…	…	…	…	…	…	…	…	…	…
S11	0.12	No	7.00	0.11	0.04	0.32	0.10	Yes	2.45	-0.756	No
S11	0.12	No								-0.613	No
S11	0.13	No								-1.539	No
S11	0.06	No								3.680	Yes
S11	0.07	No								3.276	Yes
S11	0.11	No								-0.260	No
S11	0.16	No								-3.788	Yes
S12	1.81	N/A	1.00	2.52	N/A						
[a]: John Tukey's Inter-Quartile Range Method for Outlier Filter [82]											
[b] : Standard Deviation [c] : Coeffcient of Variation											
[d]: (Maximum J_{nr} -Minimum J_{nr}) for Each Source											
[e]: If Column 8 < Column 6* Multiplier from Table 1 of ASTM C670(for Number of test results): Yes, otherwise No.											
[f,g,h]: Described in section 4.3											
*: OU Asphalt Laboratory Data											
... : Continuation of MSCR Test Results, Detail is Presented in Table B.2 of Appendix B											

At least three samples were tested at each condition to check if the MSCR test data was repeatable and the coefficient of variation was within the limit. The highest coefficient of variation of %Recovery at 3.2 kPa observed for PG 64-22 binder was 5.4% from S2. This was within the specified limit described at ASTM D7405, which gives the specified limit as 6.5% for

%Recovery at 3.2 kPa. The highest coefficient of variation of J_{nr} at 3.2 kPa was observed to be 3.9% for PG 64-22 from S4 whereas the specified limit is 15.2%. So the MSCR test data of PG 64-22 is highly repeatable. As mentioned earlier, the MSCR database consisted of test results of PG 64-22 binders from 11 sources, and MSCR tests were conducted in multiple laboratories.

The reproducibility analysis of test data between the OU Lab and each of the other selected laboratories from the ODOT MSCR database is presented in Table 4.8. Additionally, the reproducibility analysis between two laboratories (between Lab 1 and each of the other labs) within the ODOT MSCR database is presented in Table 4.9. To this end, test results for the PG 64-22 binders from only source S2 were considered. The estimated statistical parameters are shown in Tables 4.8 and 4.9. The MSCR test results for binders from S2 for the OU database are the average of three replicates. As per ASTM C670, two results submitted by two different operators testing the same material in different laboratories should not be considered suspect if the difference two-sigma limit (d2s%) (Column 3 and Column 7) meets the acceptable limit (Column 5 and Column 8). The d2s% parameter is defined as the difference limit in two results and this difference is expressed as a percent of their mean. Acceptable limits are set by ASTM D7405 (*Standard Test Method for Multiple Stress Creep and Recovery (MSCR) of Binder Using a Dynamic Shear Rheometer*) and is given in the Table 1 of ASTM D7405.

As shown in Tables 4.8 and 4.9, the data were not reproducible for %Recovery of PG 64-22 binders from S2 at 3.2 kPa between two laboratories.

The $J_{nr,\ 3.2\ kPa}$ values for the PG 64-22 were also not reproducible between the OU Asphalt Laboratory and each of the selected laboratories from the ODOT MSCR database. A number of factors may be responsible for this: (i) the sources of crude oils of these binders were likely different even though they were from the same refinery, (ii) different testing devices (DSRs) and operators used in different laboratories, and (iii) differences in RTFO-aging and other sample preparation details. $J_{nr,3.2\ kPa}$ values for the PG 64-22 binders were found to be reproducible among all laboratories except Lab2 within the ODOT MSCR database (Table 4.9).

Table 4.8 Reproducibility Analysis for PG 64-22 from S2 Between OU Database and ODOT Database

PG 64-22 from S2									
J_{nr} (3.2 kPa)					MSCR %Recovery				
1		2	3	4	5		6	7	8
Multiple Lab Data(ODOT Database)		OU Lab data	Obtained d2s%[a]	Acceptable Range of Two Test Results (ASTM D7405)	Multiple Lab Data(ODOT Database)		OU Lab data	Obtained d2s%[a]	Acceptable Range of Two Test Results (ASTM D7405)
Lab 1	3.269	1.52	73	22	Lab 1	0.42	1.32	103	18.1
Lab 2	2.472	1.52	48	22	Lab 2	1.48		11	
Lab 3	3.154	1.52	70	22	Lab 3	0.80		49	
Lab 4	3.135	1.52	69	22	Lab 4	0.77		52	
Lab 5	3.144	1.52	70	22	Lab 5	0.81		48	
Lab 6	3.331	1.52	75	22	Lab 6	0.73		57	
Lab 7	2.627	1.52	53	22	Lab 7	1.65		22	
[a]These limits represent the d2s% limits prescribed in Practice ASTM C670.									

Table 4.9 Reproducibility Analysis for PG 64-22 from S2 Between Two Labs within ODOT Database

PG 64-22 from S2									
J_{nr} (3.2 kPa)					MSCR %Recovery				
1		2	3	4	5		6	7	8
Multiple Lab Data (ODOT Database)		Lab 1 (ODOT Database)	Obtained d2s%[a]	Acceptable Range of Two Test Results (ASTM D7405)	Multiple Lab Data (ODOT Database)		Lab 1 (ODOT Database)	Obtained d2s%[a]	Acceptable Range of Two Test Results (ASTM D7405)
Lab 2	2.472	3.269	28	22	Lab 2	1.48	0.42	111	18.1
Lab 3	3.154	3.269	4	22	Lab 3	0.80	0.42	63	
Lab 4	3.135	3.269	4	22	Lab 4	0.77	0.42	59	
Lab 5	3.144	3.269	4	22	Lab 5	0.81	0.42	63	
Lab 6	3.331	3.269	2	22	Lab 6	0.73	0.42	54	
Lab 7	2.627	3.269	22	22	Lab 7	1.65	0.42	119	

[a] These limits represent the d2s% limits prescribed in Practice ASTM C670.

4.5 Polymer-Modified Binder

4.5.1 MSCR Database

Snapshots of the MSCR test results for the PG 70-28 and PG 76-28 binders are presented in Tables 4.10 and 4.11, respectively. The entire dataset of these binders is presented in Appendix A (Tables A.2 and A.3). The MSCR database contains test results of PG 70-28 and PG 76-28 binders from nine (9) and seven (7) sources, respectively.

About 99% of the tested polymer-modified binders met both the AASHTO T 332 criterion for Stress Sensitivity ($J_{nr,diff}$ < 75%) and the AASTHO T 350 criterion for minimum %Recovery. Specifically, all 46 tested PG 70-28 binders and 42 out of 43 PG 76-28 binders satisfied the aforementioned criteria;

the only binder that did not meet the MSCR criteria was from S2. Unlike the neat binders described in Section 4.4, a very high %Recovery was noticed for both PG 70-28 and PG 76-28 binders, as expected. This may be an indicator that the PG 70-28 and PG 76-28 binders were modified with elastomeric polymers. Elastomers are amorphous polymers that have the ability to stretch and return to their original shape at temperatures above their glass transition (T_g) temperatures. At a temperature below T_g, the amorphous domain lose the structural mobility of the polymer chains and become rigid glasses [93]. For example, one of the most commonly used elastomers is styrene-butadiene-styrene (SBS) copolymer blocks. The glass transition of SBS is around -65°C [93]. A roadway pavement undergoes temperatures higher than -65°C, and the elastomers help increase a binder’s elasticity. Moreover, elastomers exhibit high strain behavior, which induces temporary chain orientation and alignment under stress applications [93]. Upon removal of stress, the polymer chains come back from the temporary crystalline structures to the previous amorphous state. As indicated earlier, the %Recovery is the percentage of the ratio of recoverable strain to the total strain. So, a high %Recovery is expected from binders modified with elastomeric polymers. Use of such binders is expected to result in low rut depth. The average %Recovery for the PG 70-28 binders was about 75%, and that of the PG 76-28 binders was 90%.

In general, for PG 70-28 binders, an increasing trend of J_{nr} and a decreasing trend of %Recovery were noticed with an increase in stress level from 0.1 kPa to 3.2 kPa (Table 4.10), as expected. Such an increasing trend of the J_{nr} with an increase in the stress level was also observed for only 30% (13 out of 43) of PG 76-28 binders. An increasing J_{nr} represents an increasing rut depth as described in Section 4.4. At 0.1 kPa stress level, however, an opposite trend was observed for 45% (21 out of 46) of tested PG 70-28 binders till the J_{nr} was less than 0.2 kPa^{-1} at 0.1 kPa stress level. Further, about 80% of tested PG 70-28 binders from S1 and S2 exhibited either no decrease or insignificant decrease in %Recovery with increasing stress level (Column 8 in Table 4.10).

Similar to PG 70-28 binders, an opposite trend was observed for the PG 76-28 binders when the J_{nr} was less than 0.2 kPa^{-1} at 0.1 kPa stress level. About 70% (30 out of 43) of PG 76-28 binders experienced a reduction in the J_{nr} values with an increase in stress level. As shown in Table 4.11 (Column 8), about 76% (33 out of 43) of the tested PG 76-28 binders exhibited no decrease in %Recovery with an increase in the stress level from 0.1 kPa from 3.2 kPa. In the entire MSCR database, about 55% of all tested polymer-modified binders (PG 70-28 and PG 76-28) experienced this opposite trend (i.e., no reduction in %Recovery or no increase in J_{nr} values with an increase in the stress level). Therefore, further attention will have to be given to obtain a better understanding of the characteristics of polymer-modified binders. A possible reason for this lack of reduction in the %Recovery due to an increase of the stress level could be that the binder is not getting enough time to recover fully in 10 cycles of loading and unloading at a stress level of 0.1 kPa. This is because the creep-recovery behavior of viscoelastic materials is also time-dependent. At the early stage of loading, creep decreases with time followed by a steady stage, which is known as the secondary stage. At this secondary stage, no deformation is observed. However, with time, the material reaches a tertiary stage when creep significantly increases with time and reaches fracture. If the load is removed before it reaches its fracture stage, an instantaneous elastic response is observed, which is followed by a period of slow recovery or delayed elastic response. Therefore, the steady stage creep and delayed elastic response, or a combination of these might be the cause for polymer-modified binders showing the opposite trend with increasing stress.

Moreover, it is seen that when J_{nr} is less than 0.2 kPa^{-1} at a lower stress level, such as 0.1 kPa, an increase in the stress level from 0.1 kPa to 3.2 kPa at 64°C will not significantly affect the rutting resistance of the polymer-modified binders. These observations might be helpful in selecting a polymer-modified binder so as keep the pavement rut depth low, even when the pavement is subjected to increased stress levels. Moreover, a very low J_{nr} with a very high %Recovery at high temperatures and stress levels more adequately describes the performance of polymer-modified binders than both the ER and AASHTO T 315 test methods.

Table 4.10 MSCR Test Data and Analysis for PG 70-28

1		2	3	4	5	6	7	8	9	10
Lab No.	Source ID	$J_{nr,0.1}$ kPa	$J_{nr,3.2}$ kPa	$J_{nr,diff}$	Stress Sensitivity (Meets AASTHO T 332)	R100	R3200	R_{diff}	%Recovery (Meets AASTHO T 350)	MSCR Grade
1	S1	0.13	0.12	-8.82	YES	80.61	81.48	-1.1	YES	PG64E-28
2	S1	0.15	0.13	-9.60	YES	79.17	79.97	-1.0	YES	PG64E-28
3	S1	0.20	0.23	18.00	YES	71.48	68.14	4.7	YES	PG64E-28
4	S1	0.04	0.03	-16.62	YES	94.9	95.3	-0.4	YES	PG64E-28
5	S1	0.15	0.14	-2.45	YES	79.45	78.85	0.8	YES	PG64E-28
6	S1	0.29	0.34	14.86	YES	69.45	65.21	6.1	YES	PG64E-28
7	S1	0.19	0.20	5.28	YES	80.51	79.35	1.4	YES	PG64E-28
8	S1	0.21	0.19	-8.04	YES	78.5	80.47	-2.5	YES	PG64E-28
9	S1	0.42	0.50	17.28	YES	63.95	59.16	7.5	YES	PG64E-28
OU	S1*	0.30	0.37	22.44	YES	61.71	53.44	13.40	YES	PG64E-28
…	…	…	…	…	…	…	…	…	…	…
1	S5	0.17	0.17	1.18	YES	84.44	84.03	0.5	YES	PG64E-28
2	S5	0.39	0.53	34.19	YES	61.2	51.13	16.5	YES	PG64V-28
OU	S5*	0.13	0.13	-2.06	YES	80.38	80.61	-0.29	YES	PG64E-28
1	S7	0.20	0.21	6.11	YES	73.97	71.74	3.0	YES	PG64E-28
2	S7	0.28	0.34	21.90	YES	71.35	65.96	7.6	YES	PG64E-28
3	S7	0.35	0.38	11.09	YES	69.49	66.13	4.8	YES	PG64E-28

*: OU Asphalt Laboratory Data

... : Continuation of MSCR Test Results, Detail is Presented in Table A.2 of Appendix A

Table 4.11 MSCR Test Data and Analysis for PG 76-28

1		2	3	4	5	6	7	8	9	10
Lab No.	Source ID	$J_{nr,0.1}$ kPa	$J_{nr,3.2}$ kPa	$J_{nr,diff}$	Stress Sensitivity (Meets AASTHO T 332)	R100	R3200	R_{diff}	%Recovery (Meets AASTHO T 350)	MSCR GRADE
1	S1	0.06	0.05	-12.1	YES	88.51	89.28	-0.9	YES	PG64E-28
2	S1	0.11	0.10	-10.5	YES	84.73	86.27	-1.8	YES	PG64E-28
3	S1	0.03	0.03	-20.7	YES	95.6	96.49	-0.9	YES	PG64E-28
4	S1	0.08	0.09	1.9	YES	86.94	86.93	0.0	YES	PG64E-28
5	S1	0.10	0.08	-14.4	YES	87.08	88.58	-1.7	YES	PG64E-28
6	S1	0.15	0.13	-12.9	YES	84.12	85.65	-1.8	YES	PG64E-28
7	S1	0.12	0.12	-0.7	YES	85.29	85.08	0.2	YES	PG64E-28
…	…	…	…	…	…	…	…	…	…	…
OU	S3	0.06*	0.06*	-6.13	YES	88.95*	89.32*	-0.41	YES	PG64E-28
1	S4	0.03	0.03	-3.1	YES	93.74	93.63	0.1	YES	PG64E-28
2	S4	0.02	0.02	1.9	YES	95.42	95.11	0.3	YES	PG64E-28
3	S4	0.05	0.04	-15.8	YES	94.29	94.78	-0.5	YES	PG64E-28
4	S4	0.02	0.02	-11.1	YES	95.69	95.72	0.0	YES	PG64E-28
5	S4	0.03	0.03	-10.0	YES	95.11	95.27	-0.2	YES	PG64E-28
6	S4	0.01	0.01	0.5	YES	96.79	96.75	0.0	YES	PG64E-28
OU	S4	0.02*	0.02*	0.31	YES	96.28*	96.16*	0.13	YES	PG64E-22

*: OU Asphalt Laboratory Data

... : Continuation of MSCR Test Results, Detail is Presented in Table A.3 of Appendix A

4.5.2 Polymer Method

As seen in Figures 4.9 and 4.10, all data points for both PG 70-28 and PG 76-28 binders are clustered above the MSCR curve. This is expected as both of these binders are polymer-modified. The types and amounts of polymers used by the suppliers in manufacturing the PG 70-28 and PG 76-28 binders were not available. However, it is known that polymers help change a binder’s physical properties such as its softening point, brittleness, elastic recovery, and ductility. It was evident from the %Recovery results obtained from the MSCR tests that all PG 70-28 and PG 76-28 binders tested in this study exhibited a high level of recoverable strain at the end of repeated loading and unloading cycles, indicating greater resistance to rutting than that exhibited in neat binders. Wasage et al. [22] also noted the strong recovery feature of polymer-modified binders in their study.

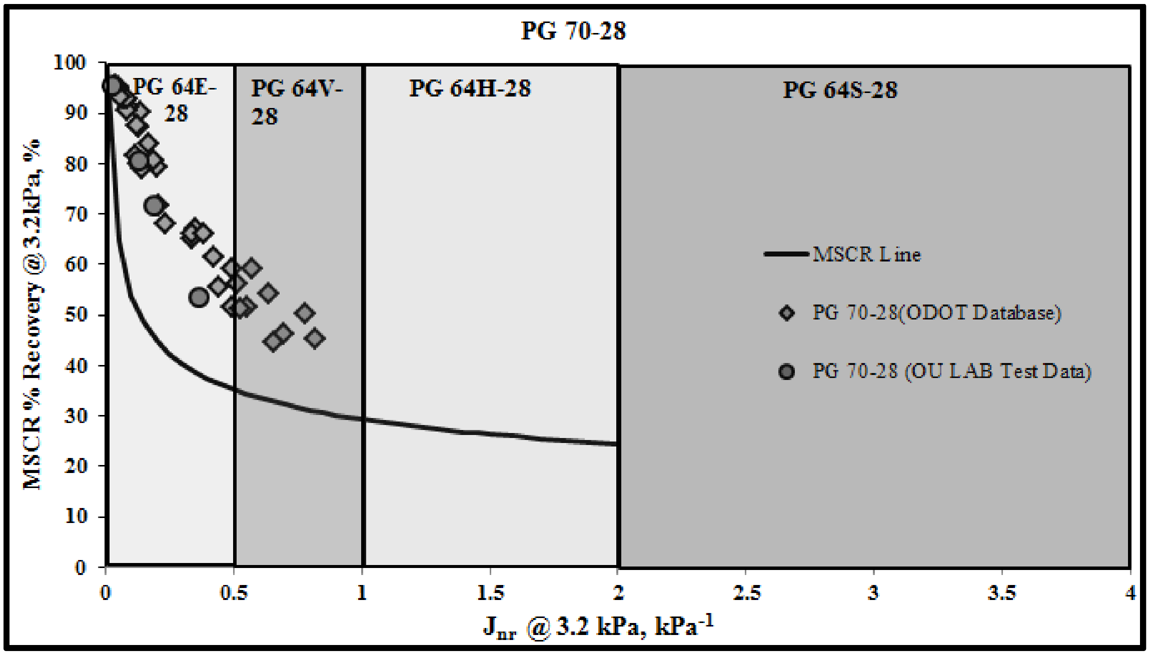


Figure 4.9 Polymer Method Analysis Plot for PG 70-28.

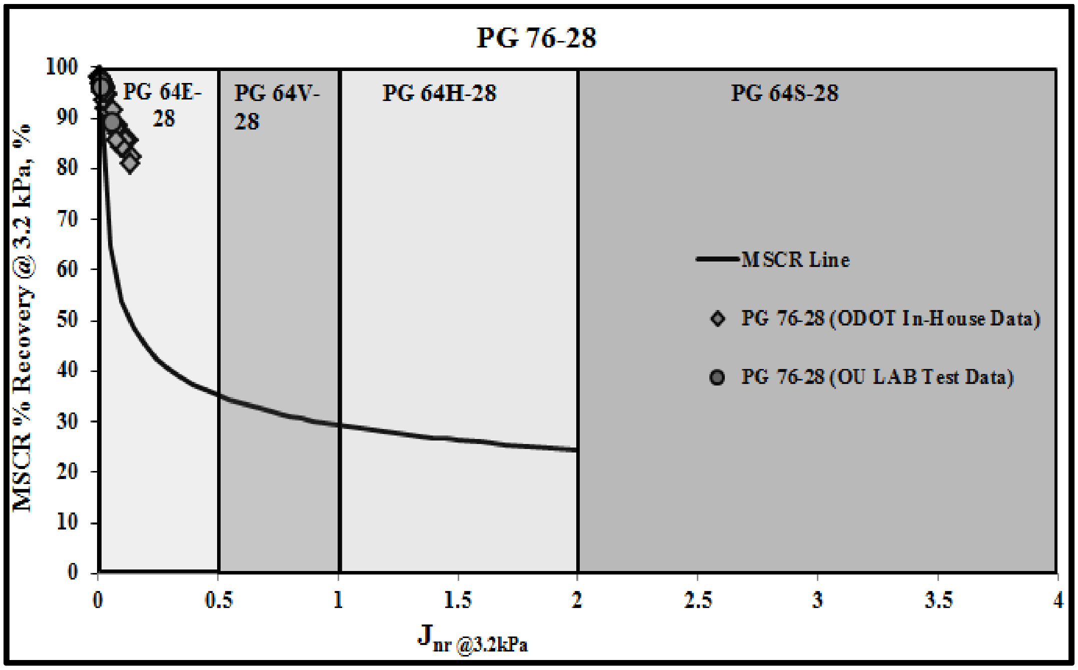


Figure 4.10 Polymer Method Analysis Plot for PG 76-28.

4.5.3 MSCR Grade

The %Recovery vs. J_{nr} plots shown in Figures 4.9 and 4.10 are helpful for grading binders in accordance with the AASHTO T 332 criteria.

PG 70-28

The MSCR grades of all PG 70-28 binders from different sources are presented in Figure 4.9 along with a statistical frequency bar chart (Figure 4.11). As shown in Figure 4.11, 80% (37 out of 46 binders) of the PG 70-28 binders were graded as PG 64E-28, indicating that these binders would be able to sustain extreme traffic condition. The remaining 20% (9 out of 46) of binders were graded as PG 64V-28, indicating that these binders would be able to sustain very heavy traffic. Thus, the equivalent MSCR grade of the PG 70-28 binders would be PG 64V-28.

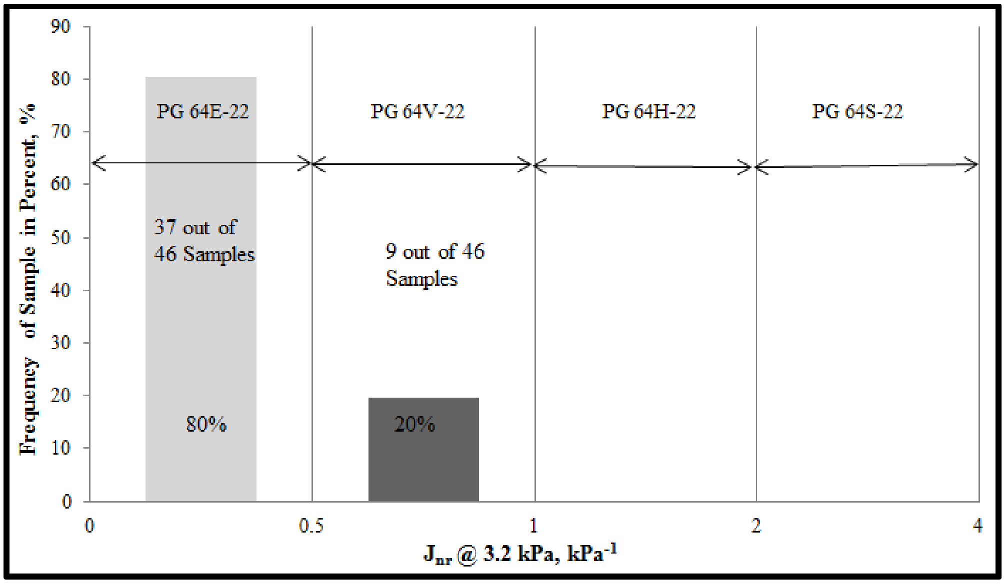


Figure 4.11 Frequency of Sample in Percent, % vs. J_{nr} @ 3.2 kPa PG 70-28.

PG 76-28

The MSCR grades of all PG 70-28 binders used in this study are summarized in Figure 4.10, along with a statistical frequency bar chart (Figure 4.12). As shown in Figure 4.12, all tested PG 76-28 binders were graded as PG 64E-28, indicating that these binders would be able to sustain extreme traffic conditions. Thus, the equivalent MSCR grade of the PG 76-28 binders would be PG 64E-28.

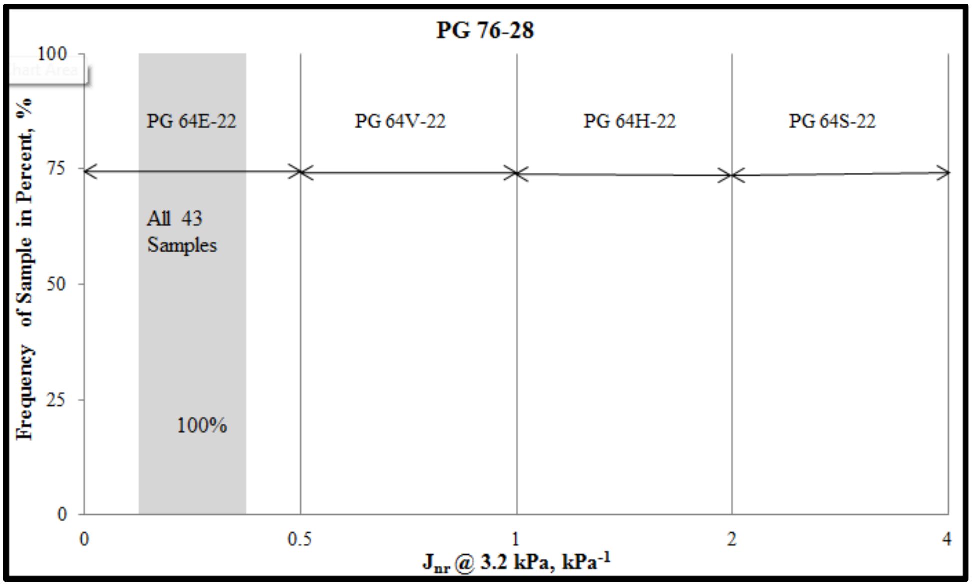


Figure 4.12 Frequency of Sample in Percent, % vs. J_{nr} @ 3.2 kPa G 76-28.

4.5.4 Quadrant Method

The Four-quadrant plots of the tested PG 70-28 and PG 76-28 binders are presented in Figures 4.13 and 4.14, respectively. As shown in Figures 4.13 and 4.14, a binder can be categorized as “User Risk,” “Supplier Risk,” “Both at Risk,” or “None at Risk.” If a binder meets the %Recovery but fails the ER criterion then the user is at risk (User Risk). On the other hand, if the binder meets the ER but fails the %Recovery criterion, then the supplier is at risk (Supplier Risk). If neither ER nor %Recovery criterion is satisfied, both the supplier and the user are at risk (Both at Risk). If both %Recovery and ER criteria are met, neither the supplier nor the user is at risk (None at Risk). As mentioned earlier, the MSCR test method is suggested as a replacement for the ER test method. The quadrant analysis is helpful for examining the recovery properties of the binders in terms of both the traditional elastic recovery and

%Recovery, as well as the switch from the former to the later approach. Consequently, the AI recommends that agencies use a %Recovery at 3.2 kPa 15% less than the state recommended ER value [35]. The ODOT recommended ER values for PG 70-28 OK and PG 76-28 OK binders are 65% and 75%, respectively. So, in this study it was intended to find out if the %Recovery obtained for the PG 70-28 OK and PG 76-28 OK binders were at least 50% and 60%, respectively. These analyses will help make recommendations for minimum %Recovery values for the PG 70-28 OK and PG 76-28 OK binders without putting suppliers or users at risk. If the proposed %Recovery guidelines are implemented, the ER test method will be successfully replaced by the MSCR test method.

PG 70-28

The ER and %Recovery values at 3.2 kPa ranged from 82.5% to 95%, and from 44.5% to 95.5%, respectively (Figure 4.13). Thus, the ER values met the ODOT's current ER limit of 65% for the PG 70-28 binders. Only three binders from S3 had a %Recovery value lower than 50%. These binders had a %Recovery value around 45%, which is 5% lower than the AI recommended %Recovery of 50% (65% - 15% = 50%) for the PG 70-28 binder. Thus, only one (S3) out of 5 suppliers was at risk of not meeting the %Recovery. However, a value of 45% for the %Recovery for a PG 70-28 binder appears to be a conservative approach for conditions prevailing in Oklahoma. Therefore, a %Recovery at 3.2 kPa of 50% can be adopted for PG 70-28 binders without placing many suppliers at risk.

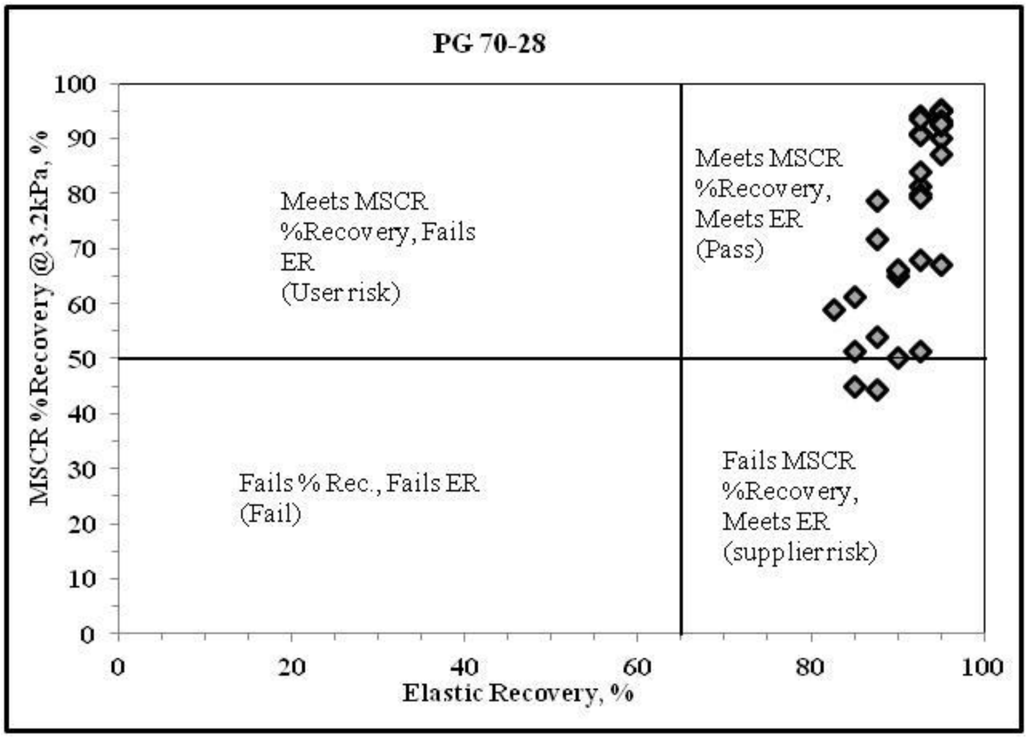


Figure 4.13 Quadrant Plot for PG 70-28.

PG 76-28

As shown in Figure 4.14, the %Recovery and ER values ranged from 92.5% to 100% and from 80.9% to 98.1%, respectively. So, the ER values met the ODOT's current ER limit of 75% for a PG 76-28 binder. Thus, the %Recovery at 3.2 kPa of 60%, based on the AI recommendations and ODOT's current ER limit (75%), is applicable for the PG 76-28 binders [35]. None of the suppliers are at risk at this level. However, a value of 60% as the %Recovery for a PG 76-28 binder appears to be a conservative approach for conditions prevailing in Oklahoma. Based on the data presented in Table 4.11 and Figure 4.14, a value of 80% as %Recovery is recommended without putting any supplier or user at risk.

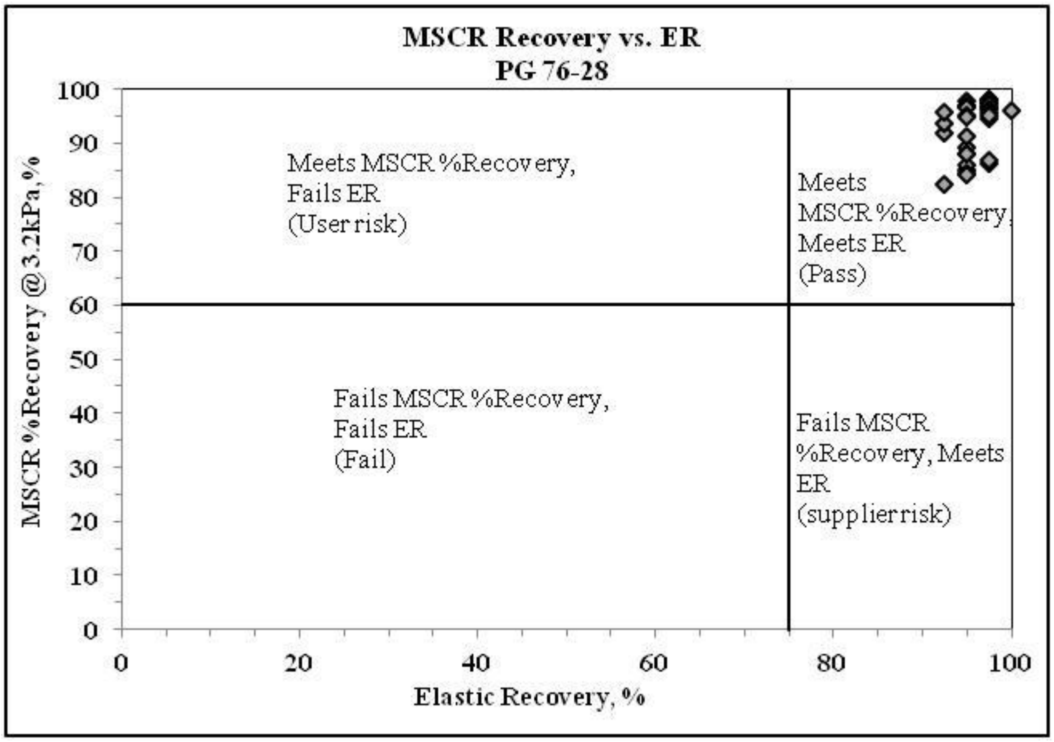


Figure 4.14 Quadrant Plot for PG 76-28.

4.5.5 Stress Sensitivity

All tested polymer-modified binders met the stress sensitivity criteria, which is a $J_{nr,diff}$ less than 75% (Figures 4.15 and 4.16). Additionally, the PG 70-28 binders were found to be more stress sensitive than the PG 76-28 binders. A high level of polymer-modification in PG 76-28 binders could be a probable cause. This is because a high level of polymer-modification might include larger polymer-chains with high molecular weight compared to PG 70-28 binders. As a result, the entanglement force is higher and the binder exhibits higher resistance to flow. A high resistance to flow results in less response to increased stress levels and rutting. Since PG 76-28 binder is used for high traffic volume, this binder is expected to perform better than a PG 70-28 binder. A respectable correlation between $J_{nr,diff}$ and R_{diff} for the PG 70-28 binders was also found, and the coefficient of determination (R^2) was found to be 0.84

(Figure 4.15). The closer the value is to 1, the more closely the data fits the curve. The developed correlation indicates an increase of R_{diff} with an increase of $J_{nr,diff}$. As seen in Figure 4.16, such a trend existed in the case of PG 76-28 binders, but the rate of increase of R_{diff} with respect to $J_{nr, diff}$ was very low. Further, the R^2 value of the R_{diff} vs. $J_{nr,diff}$ plot was found to be only 0.44, which is just below a moderate correlation. Additionally, unlike the neat binders described in Section 4.4.4, the polymer-modified binders were observed to be less stress sensitive than others in terms of R_{diff}. Even though the observations for the R_{diff} vs. $J_{nr, diff}$ plots are not conclusive at this stage of research, their relationships could provide additional insight into the stress sensitivity of polymer modified binders, which can be studied in a future project.

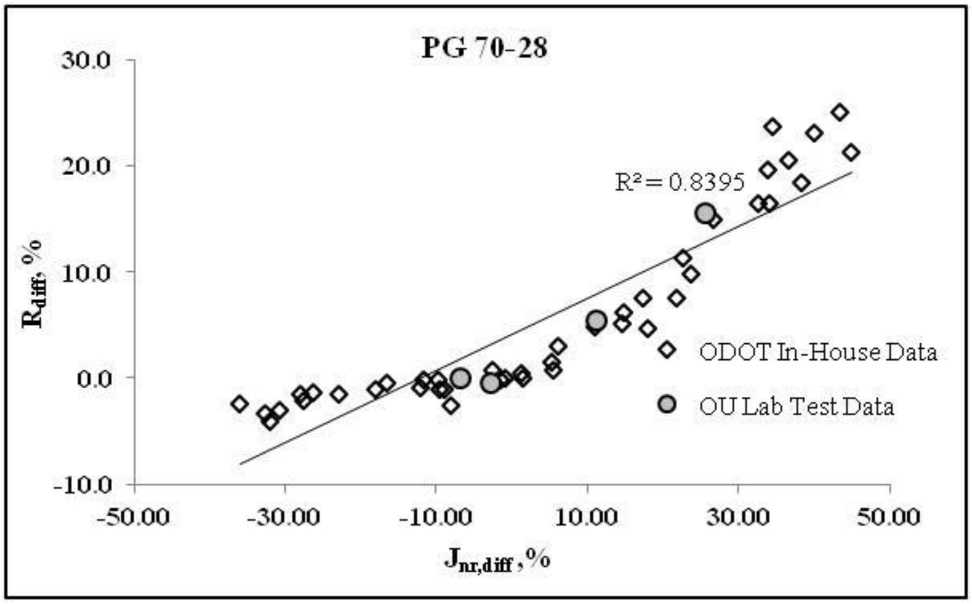


Figure 4.15 R_{diff}, % vs. $J_{nr ,diff}$, % for PG 70-28.

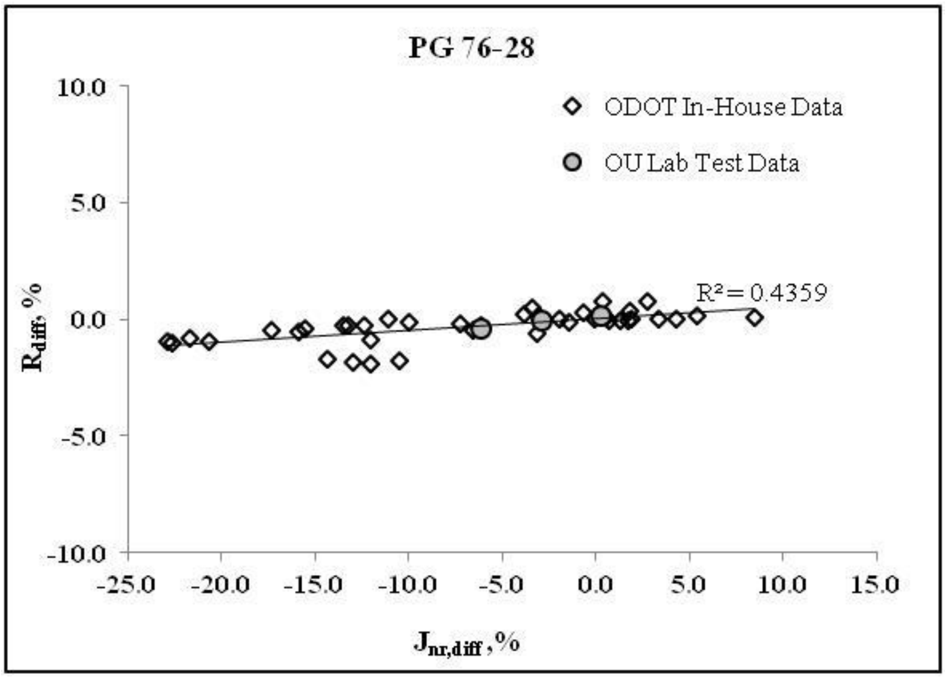


Figure 4.16 R_{diff}, % vs. $J_{nr,diff}$, % for PG 76-28.

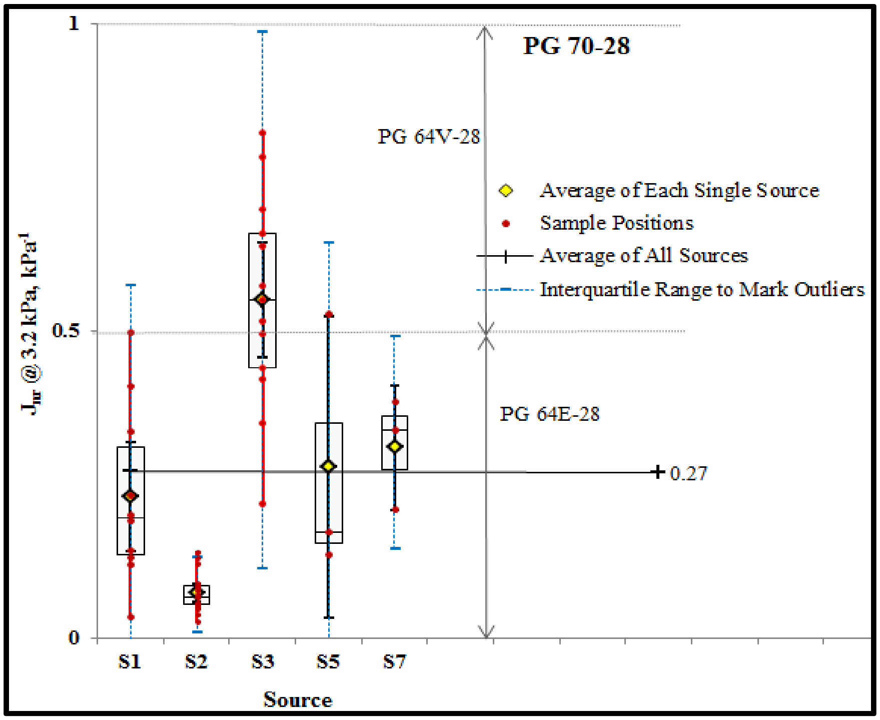
4.5.6 Statistical Summary

4.5.6.1 PG 70-28

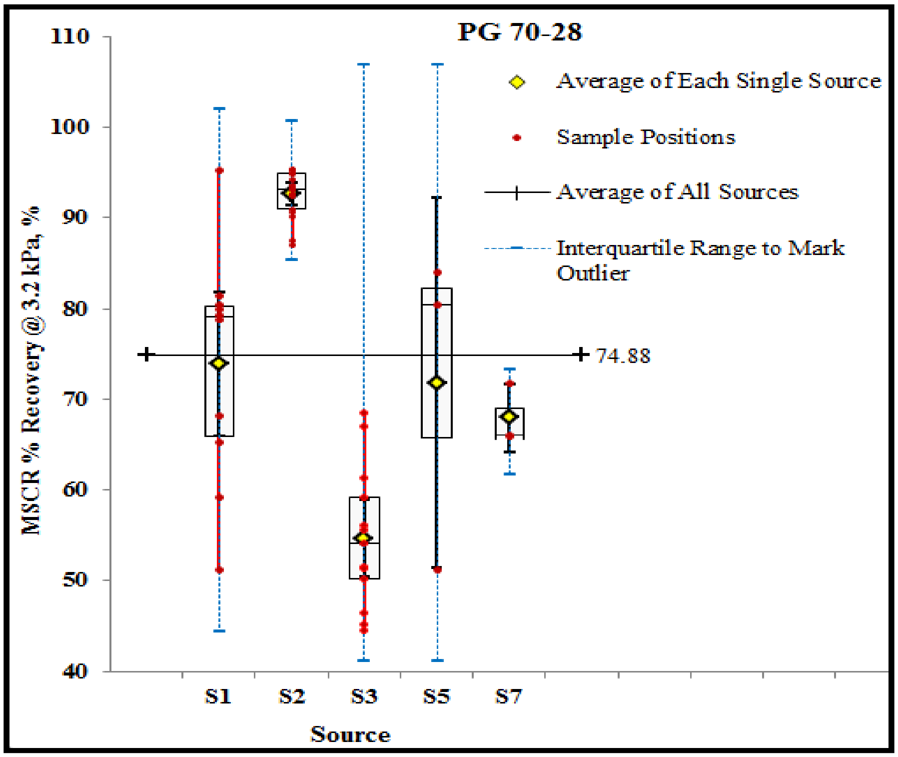
Box plot analyses of the tested PG 70-28 binders from five different sources are presented in Figure 4.17. Each source had at least three binders tested in different laboratories. Binders from only S3 were found to be in the region of PG 64V-28 grading (Figure 4.17a). Binders from S5 were found to have a high margin of error and a high standard deviation of 0.22 and 18 for $J_{nr,3.2\ kPa}$ and %Recovery at 3.2 kPa, respectively (Figure 4.17, and Tables 4.12 and 4.13). A possible reason for this high standard deviation might be the small sample size (only three binders) from this source. Results of all the tested binders, except for the three binders from S3, were found to be evenly distributed with a %Recovery ranging from 50% to 95% (Figure 4.17b). This resulted in an average %Recovery value of around 75%. No outliers were detected in the test results of PG 70-28 binders. Although they were from multiple laboratories and with different crude sources, the MSCR test data from all sources were observed to have excellent resemblances among themselves.

Snapshots of statistical test parameters pertaining to acceptable range, existence of bias in the test results, and detection of outliers for the PG 70-28 binders are presented in Tables 4.12 and 4.13. Due to the space limitation, the entire dataset is presented in Tables B.3 and B.4 in Appendix B. It is observed that the PG 70-28 binders from all five sources met the ASTM C670 criteria for an acceptable data range [93]. Out of 17 binders from S2, only one outlier was detected in the test results. The coefficient of variation (CV) was observed to be less than one (1) for both $J_{nr,3.2\ kPa}$ and %Recovery from all 5 sources, indicating a low variance. On the other hand, a CV value of less than 0.2 was observed for %Recovery at 3.2 kPa for the PG 70-28 from four out of five sources (Table 4.13). Further, having a large data range, S2 and S3 were found to have more than five (5) biased values based on two tailed t-test.

In regards to the repeatability, the highest coefficient of variations of %Recovery and J_{nr} at 3.2 kPa were observed to be 0.06 and 0.25, respectively, for PG 70-28 binder from S3. The coefficient of variation of %Recovery was found to be within the specified limit described in ASTM D7405; specifically, the specified limit is 0.065 for %Recovery at 3.2 kPa. However, the limit for J_{nr} at 3.2 kPa is 0.15, which is less than the observed limit. The PG 70-28 binders from other sources met the specified limits for the coefficient of variation for both MSCR parameters.



(a)



(b)

Figure 4. 17 Box-Plot of PG 70-28 from all Sources for (a) J_{nr} @ 3.2 kPa; (b) MSCR %Recovery @ 3.2 kPa.

Table 4.12 Detection of Outlier and Bias for J_{nr} @ 3.2 kPa of PG 70-28 Binder

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	J_{nr} (3.2 kPa)	Outlier[a]	Sample Size, N	Mean	SD[b]	CV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S1	0.12	No	10.00	0.23	0.14	0.62	0.46	Yes	2.262	2.419	Yes
S1	0.13	No								2.157	No
S1	0.23	No								-0.066	No
S1	0.03	No								4.318	Yes
S1	0.14	No								1.906	No
S1	0.34	No								-2.348	Yes
S1	0.20	No								0.626	No
S1	0.19	No								0.853	No
S1	0.50	No								-5.912	Yes
S1	0.41*	No								-3.954	Yes
…	…	…	…	…	…	…	…	…	…	…	…
S5	0.17	No	3.00	0.28	0.22	0.78	0.39	Yes	4.30	0.849	No
S5	0.53	No								-1.993	No
S5	0.14*	No								1.144	No
S7	0.21	No	3.00	0.31	0.09	0.29	0.17	Yes	4.30	1.934	No
S7	0.34	No								-0.525	No
S7	0.38	No								-1.409	No

[a]: John Tukey's Inter-Quartile Range Method for Outlier Filter [85]

[b] : Standard Deviation [c] : Coeffcient of Variation

[d]: (Maximum J_{nr} -Minimum J_{nr}) for Each Source

[e]: If Column 8 < Column 6* Multiplier from Table 1 of ASTM C670(for Number of test results): Yes, otherwise No.

[f,g,h]: Described in section 4.3

*: OU Material Laboratory Data

... : Continuation of MSCR Test Results, Detail is Presented in Table B.3 of Appendix B

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Table 4.13 Detection of Outlier and Bias for %Recovery @ 3.2 kPa of PG 70-28

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	$J_{nr,3.2\ kPa}$	Outlier[a]	Sample Size, N	Mean	SD[b]	CV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S1	81.48	No	10.00	73.91	12.87	0.17	44.10	Yes	2.262	-1.859	No
S1	79.97	No								-1.488	No
S1	68.14	No								1.418	No
S1	95.30	No								-5.255	Yes
S1	78.85	No								-1.213	No
S1	65.21	No								2.138	No
S1	79.35	No								-1.336	No
S1	80.47	No								-1.611	No
S1	59.16	No								3.625	Yes
S1	51.2*	No								5.581	Yes
…	…	…	…	…	…	…	…	…	…	…	…
S5	84.03	No	3.00	71.84	18.03	0.25	32.90	Yes	4.30	-1.171	No
S5	51.13	No								1.990	No
S5	80.3*	No								-0.819	No
S7	71.74	No	3.00	67.94	3.29	0.05	5.78	Yes	4.30	-1.999	No
S7	65.96	No								1.044	No
S7	66.13	No								0.955	No

[a] John Tukey's Inter-Quartile Range Method for Outlier Filter [85]

[b] : Standard Deviation [c] : Coeffcient of Variation; [d]: (Maximum J_{nr} -Minimum J_{nr}) for Each Source

[e]: If Column 8 < Column 6* Multiplier from Table 1 of ASTM C670(for Number of test results): Yes, otherwise No.

[f,g,h]: Described in section 4.3; *: OU Asphalt Laboratory Data

... : Continuation of MSCR Test Results, Detail is Presented in Table B.4 of Appendix B

Reproducibility of test results between the OU Asphalt Laboratory data and each of the laboratories in the ODOT MSCR database was examined for PG 70-28 binders from S2. The results are presented in Table 4.14. Further, reproducibility analysis between two laboratories from the ODOT MSCR database was performed, and data from Laboratory 1 was compared with those of the other laboratories (Table 4.15). In all cases, the reproducibility analysis of binders from S2 was considered. It can be noted that the maximum acceptable difference of a test parameter between two laboratories recommended by ASTM D7405 is 18.1%, whereas differences in %Recovery values between two laboratories never exceeded 6% (Tables 4.14 and 4.15). Therefore, %Recovery at 3.2 kPa is highly reproducible when the same binder is tested by two independent operators. However, very high d2s% values of the J_{nr} at 3.2 kPa were observed for a majority of the binders (9 out of 10), which was possibly due to a very low J_{nr} value (less than 0.1 kPa^{-1}). The ASTM D7405 method also predicts a high variability of test results due to a very low value of J_{nr}.

Table 4.14 Reproducibility Analysis for PG 70-28 from S2 Between OU and ODOT Database

PG 70-28 from S2									
$J_{nr,3.2\ kPa}$					**MSCR %Recovery at 3.2 kPa**				
1		**2**	**3**	**4**	**5**		**6**	**7**	**8**
Multiple Lab Data(ODOT Database)		OU Lab data	Obtained d2s%^{a}	Acceptable Range of Two Test Results (ASTM D7405)	Multiple Lab Data(ODOT Database)		OU Lab data	Obtained d2s%^{a}	Acceptable Range of Two Test Results (ASTM D7405)
Lab 1	0.054	0.02	92	n/a^{b}	Lab 1	94.99	95.39	0	18.1
Lab 2	0.051	0.02	87	n/a^{b}	Lab 2	95.15	95.39	0	
Lab 3	0.066	0.02	107	n/a^{b}	Lab 3	93.27	95.39	2	
Lab 4	0.141	0.02	150	42.6	Lab 4	90.18	95.39	6	
Lab 5	0.090	0.02	127	n/a^{b}	Lab 5	91.10	95.39	5	
Lab 6	0.079	0.02	119	n/a^{b}	Lab 6	92.45	95.39	3	
Lab 7	0.085	0.02	124	n/a^{b}	Lab 7	90.65	95.39	5	
Lab 8	0.056	0.02	94	n/a^{b}	Lab 8	94.33	95.39	1	
Lab 9	0.057	0.02	97	n/a^{b}	Lab 9	93.59	95.39	2	
Lab 10	0.070	0.02	111	n/a^{b}	Lab 10	92.70	95.39	3	

[a] These limits represent the d2s% limits prescribed in Practice C670.

[b] For J_{nr} values below 0.1 kPa^{-1} high variability is likely due to the very low strain values that are measured.

Table 4.15 Reproducibility Analysis for PG 70-28 from S2 Between Two Labs Within ODOT Database

PG 70-28 from S2									
Jnr (3.2 kPa)					**R3200**				
1		**2**	**3**	**4**	**5**		**6**	**7**	**8**
Multiple Lab Data(ODOT Database)		Lab 1 (ODOT database)	Obtained d2s%[a]	Acceptable Range of Two Test Results (ASTM D7405)	Multiple Lab Data (ODOT Database)		Lab 1 (ODOT database)	Obtained d2s%[a]	Acceptable Range of Two Test Results (ASTM D7405)
Lab 2	0.051	0.054	7	n/a[b]	Lab 2	95.15	94.99	0	18.1
Lab 3	0.066	0.054	20	n/a[b]	Lab 3	93.27	94.99	2	
Lab 4	0.141	0.054	89	42.6	Lab 4	90.18	94.99	5	
Lab 5	0.090	0.054	49	n/a[b]	Lab 5	91.10	94.99	4	
Lab 6	0.079	0.054	37	n/a[b]	Lab 6	92.45	94.99	3	
Lab 7	0.085	0.054	44	n/a[b]	Lab 7	90.65	94.99	5	
Lab 8	0.056	0.054	3	n/a[b]	Lab 8	94.33	94.99	1	
Lab 9	0.057	0.054	5	n/a[b]	Lab 9	93.59	94.99	1	
Lab 10	0.070	0.054	26	n/a[b]	Lab 10	92.70	94.99	2	

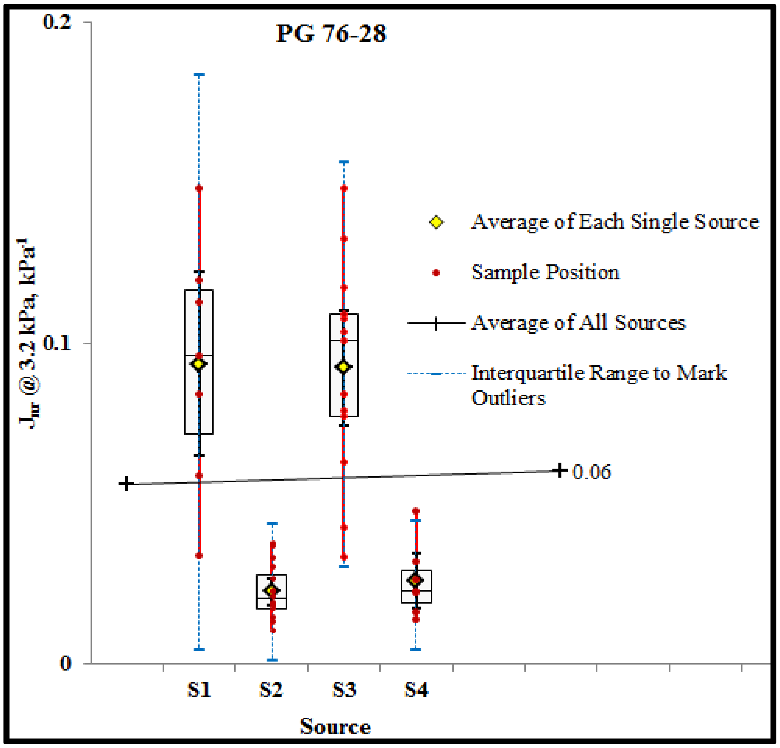
[a] These limits represent the d2s% limits prescribed in Practice C670.

[b] For J_{nr} values below 0.1 kPa^{-1} high variability is likely due to the very low strain values that are measured.

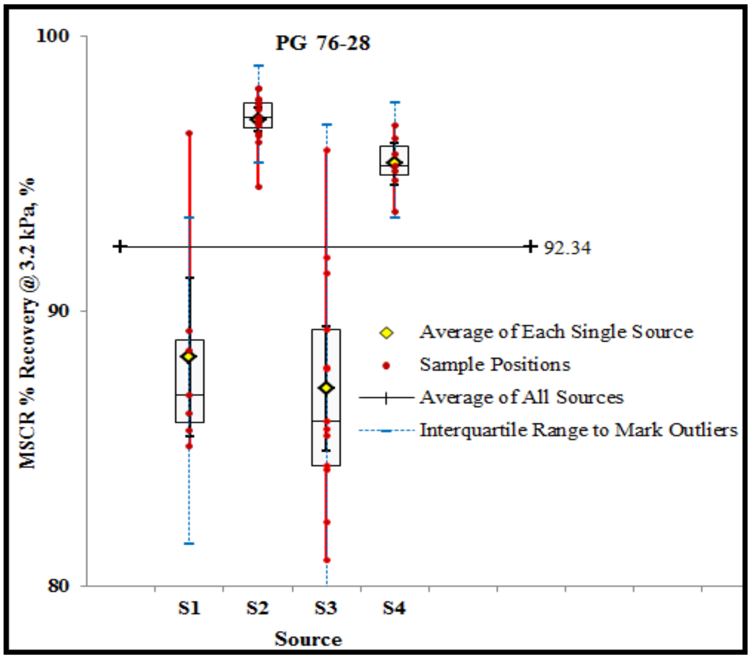
4.5.6.2 PG 76-28

It is evident from box plots presented in Figure 4.18 that tested PG 76-28 binders from S1 and S3 had a wide range of MSCR parameters. In the case of %Recovery, S1 and S2 had two outliers, whereas S4 had one outlier for the $J_{nr,3.2\ kPa}$ values. From Figure 4.18a, it is seen that the J_{nr} values of tested binders varied from 0.01 kPa^{-1} to 0.15 kPa^{-1}, indicating a grade of PG 64E-28 in accordance with the MSCR grading system. The minimum %Recovery of all PG 76-28 binders was observed to be about 81% (Figure 4.18b). As indicated earlier, PG 76-28 binders from four sources were tested, and a large number of binders (43 in total) from each source were tested in multiple laboratories.

Though tested in multiple laboratories, the MSCR test data largely exhibited a high level of consistency.



(a)



(b)

Figure 4.18 Box-Plot of PG 76-28 from all Sources of (a) J_{nr} @ 3.2 kPa; (b) MSCR %Recovery @ 3.2 kPa.

Snapshots of statistical parameters pertaining to the check for the maximum acceptable range, existence of bias in the test results, and detection of outliers for the tested PG 76-28 binders are presented in Tables 4.16 and 4.17. The entire statistical analysis is presented in Appendix B in Tables B.5 and B.6. Based on statistical analysis, a total of six outliers were detected for J_{nr} and %Recovery at 3.2 kPa. All sources met the ASTM C670 criterion for the maximum acceptable data range (Column 9 in Tables 4.16 and 4.17). The CV was found to be less than 1 for the $J_{nr,3.2\ kPa}$ and %Recovery at 3.2 kPa for binders from all 4 sources. The CV values less than one (1) indicate a low variance. Again, the observed CV values for %Recovery at 3.2 kPa for PG 76-28 binders from five sources were less than 0.05, or within 5%. It is evident from Tables 4.16 and 4.17 that the $J_{nr,3.2\ kPa}$ and %Recovery at 3.2 kPa values met the ASTM C670 criteria for the maximum acceptable data range. Out of 43 tested binders from all 5 sources, only one outlier from S2 was noticed for $J_{nr,\ 3.2\ kPa}$ (Column 3 of Table 4.16). Having a large range of data, S2 and S3 were observed to have nine (9) and six (6) biased values, respectively, in their datasets based on two-tailed t-tests.

Table 4.16 Detection of Outlier and Bias for J_{nr} @ 3.2 kPa of PG 76-28

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	J_{nr} (3.2 kPa)	Outlier[a]	Sample Size, N	Mean	SD[b]	CoV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S1	0.06	No	7.00	0.09	0.04	0.41	0.11	Yes	2.447	2.384	No
S1	0.11	No								-1.329	No
S1	0.03	No								4.081	Yes
S1	0.08	No								0.629	No
S1	0.10	No								-0.188	No
S1	0.15	No								-3.767	Yes
S1	0.12	No								-1.810	No
…	…	…	…	…	…	…	…	…	…	…	…
S4	0.03	Outlier	7.00	0.03	0.01	0.44	0.03	Yes	2.45	-0.130	No
S4	0.02	No								0.776	No
S4	0.05	No								-5.084	Yes
S4	0.02	No								0.822	No
S4	0.03	No								-1.428	No
S4	0.01	Outlier								2.743	Yes
S4	0.02*	Outlier								2.301	No

[a]: John Tukey's Inter-Quartile Range Method for Outlier Filter []

[b] : Standard Deviation [c] : Coeffcient of Variation

[d]: (Maximum J_{nr} -Minimum J_{nr}) for Each Source

[e]: If Column 8 < Column 6* Multiplier from Table 1 of ASTM C670(for Number of test results): Yes, otherwise No.

[f,g,h]: Described in section 4.3

*: OU Material Laboratory Data

... : Continuation of MSCR Test Results, Detail is Presented in Table B.5 of Appendix B

Table 4.17 Detection of Outlier and Bias for MSCR %Recovery @ 3.2 kPa of PG 76-28

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	$J_{nr,3.2\ kPa}$	Outlier[a]	Sample Size, N	Mean	SD[b]	CV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S1	89.28	No	7.00	88.33	3.91	0.04	11.41	Yes	2.447	-0.647	No
S1	86.27	No								1.393	No
S1	96.49	Outlier								-5.531	Yes
S1	86.93	No								0.946	No
S1	88.58	No								-0.172	No
S1	85.65	No								1.813	No
S1	85.08	No								2.199	No
…	…	…	…	…	…	…	…	…	…	…	…
S4	93.63	No	7.00	95.36	1.03	0.01	3.12	Yes	2.45	4.471	Yes
S4	95.11	No								0.652	No
S4	94.78	No								1.504	No
S4	95.72	No								-0.922	No
S4	95.27	No								0.240	No
S4	96.75	No								-3.579	Yes
S4	96.28*	No								-2.367	No

[a]: John Tukey's Inter-Quartile Range Method for Outlier Filter [81]

[b] : Standard Deviation [c] : Coeffcient of Variation

[d]: (Maximum J_{nr} -Minimum J_{nr}) for Each Source

[e]: If Column 8 < Column 6* Multiplier from Table 1 of ASTM C670(for Number of test results): Yes, otherwise No.

[f, g, h]: Described in section 4.3

*: OU Material Laboratory Data

... : Continuation of MSCR Test Results, Detail is Presented in Table B.6 of Appendix B

The highest coefficient of variation of %Recovery and J_{nr} at 3.2 kPa were observed to be 1.11% and 22.53%, respectively, for PG 76-28 binder from S3. The coefficient of variation of %Recovery was found to be within the specified limit described by ASTM D7405: specifically, the specified limit is 6.5% for

%Recovery at 3.2 kPa. However, the limit for J_{nr} at 3.2 kPa is "N/A" which means that for J_{nr} values below 0.1 kPa^{-1}, high variability is likely due to the low strain values that are measured. Therefore, the MSCR test results of PG 76-28 are highly repeatable. Reproducibility analyses of test results between the OU Laboratory and each of the laboratories in the ODOT MSCR database were performed and results are presented in Table 4.18. A reproducibility analysis of test results was also performed between two laboratories within the ODOT MSCR database, where data from Lab 1 was compared with that of each of the other laboratories (Table 4.19). The maximum allowable difference for %Recovery at 3.2 kPa recommended by ASTM D7405 is 18.1%, whereas the maximum estimated difference was less than 3% (Tables 4.18 and 4.19). Therefore, the %Recovery is considered to be highly reproducible whenever tested by an independent operator. On the other hand, the J_{nr} value at 3.2 kPa was observed to be lower than 0.1 kPa^{-1}, which contributed to a very high d2s%. The ASTM D7405 method also predicts a high variability of J_{nr} data in the case of a very low J_{nr} (Tables 4.18 and 4.19).

Table 4.18 Reproducibility Analysis for PG 70-28 from S2 Between OUand ODOT Database

J_{nr} (3.2 kPa)					R3200				
Multiple Lab Data(ODOT Database)		OU Lab data	Obtained d2s%[a]	Acceptable Range of Two Test Results (ASTM D7405)	Multiple Lab Data(ODOT Database)		OU Lab data	Obtained d2s%[a]	Acceptable Range of Two Test Results (ASTM D7405)
Lab 1	0.015	0.01	41	n/a[b]	Lab 1	97.73	97.07	1	18.1
Lab 2	0.010	0.01	2	n/a[b]	Lab 2	98.11	97.07	1	
Lab 3	0.014	0.01	30	n/a[b]	Lab 3	98.08	97.07	1	
Lab 4	0.021	0.01	69	n/a[b]	Lab 4	97.53	97.07	0	
Lab 5	0.026	0.01	88	n/a[b]	Lab 5	96.50	97.07	1	
Lab 6	0.021	0.01	69	n/a[b]	Lab 6	96.91	97.07	0	
Lab 7	0.039	0.01	118	n/a[b]	Lab 7	94.51	97.07	3	
Lab 8	0.020	0.01	66	n/a[b]	Lab 8	97.01	97.07	0	
Lab 9	0.016	0.01	48	n/a[b]	Lab 9	97.69	97.07	1	
Lab 10	0.018	0.01	57	n/a[b]	Lab 10	97.33	97.07	0	
[a] These limits represent the d2s% limits prescribed in Practice C670.									
[b] For J_{nr} values below 0.1 kPa^{-1} high variability is likely due to the very low strain values that are measured.									

Table 4.19 Reproducibility Analysis for PG 70-28 from S2 Between Two Labs Within ODOT Database

J_{nr} (3.2 kPa)					R3200				
Multiple Lab Data(ODOT Database)		Lab 1 (ODOT Database)	Obtained d2s%[a]	Acceptable Range of Two Test Results (ASTM D7405)	Multiple Lab Data(ODOT Database)		OU Lab data	Obtained d2s%[a]	Acceptable Range of Two Test Results (ASTM D7405)
Lab2	0.010	0.015	40	n/a[b]	Lab 2	98.11	97.73	0	18.1
Lab3	0.014	0.015	11	n/a[b]	Lab 3	98.08	97.73	0	
Lab4	0.021	0.015	30	n/a[b]	Lab 4	97.53	97.73	0	
Lab5	0.026	0.015	51	n/a[b]	Lab 5	96.50	97.73	1	
Lab6	0.021	0.015	30	n/a[b]	Lab 6	96.91	97.73	1	
Lab7	0.039	0.015	87	n/a[b]	Lab 7	94.51	97.73	3	
Lab8	0.020	0.015	27	n/a[b]	Lab 8	97.01	97.73	1	
Lab9	0.016	0.015	7	n/a[b]	Lab 9	97.69	97.73	0	
Lab10	0.018	0.015	17	n/a[b]	Lab 10	97.33	97.73	0	
[a] These limits represent the d2s% limits prescribed in Practice C670.									
[b] For J_{nr} values below 0.1 kPa^{-1} high variability is likely due to the very low strain values that are measured.									

4.6 Non-Conventional MSCR Test Data of Polymer-Modified Binder

Wasage et al. [22] reported an increased dependence of J_{nr} with increasing stress for polymer-modified binders. These researchers mentioned that the region of insensitivity to the stress level shrinks when the temperature is increased for the polymer-modified binders compared to that of neat binders. The boundary of linear viscoelastic behavior was strongly dependent on the applied stress as well as on the applied temperature [22]. A similar observation was also noticed in the present study.

4.6.1 Increased Stress Level

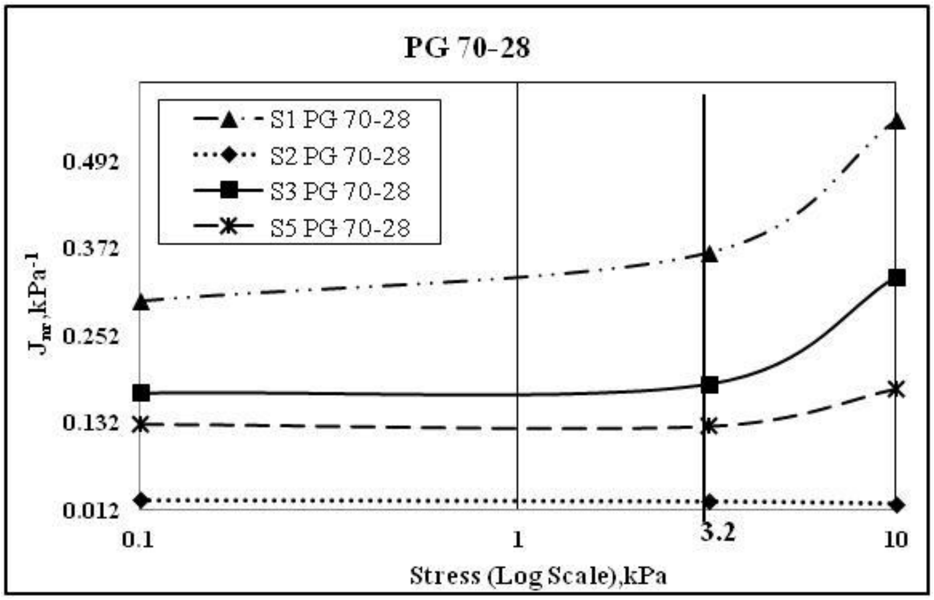
Delgadillo et al. [82] reported that the correlation between repeated creep recovery and permanent deformation of HMA mixes is strong for stresses up to 10 kPa, regardless of selected stress level. However, Wasage et al. [83] reported that most binders start to show nonlinear behavior at a stress level close to 10 kPa. Therefore, MSCR tests were conducted in this study on polymer-modified binders from four different sources at 10 kPa to observe the stress dependency of J_{nr} and %Recovery. Test results for both MSCR parameters at three different stress levels at 64°C are presented in the Table 4.20.

Table 4.20 MSCR Test Data and Analysis at Increased Stress Level forPolymer-Modified Binders

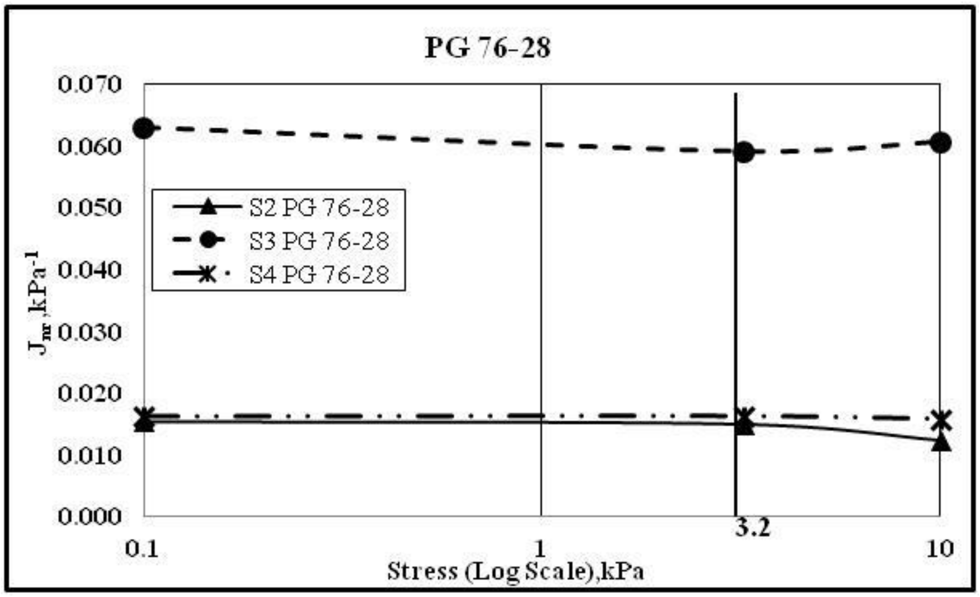
1	2	3	4	5	6	7	8	9	10	11
Source & type (RTFOaged)	**J_{nr} (0.1 kPa)**	**J_{nr} (3.2 kPa)**	**J_{nr} (10 kPa)**	**$J_{nr, diff}$ (0.1-3.2)**	**$J_{nr, diff}$ (3.2-10)**	**R100**	**R3200**	**R10000**	**R_{diff} (0.1-3.2)**	**R_{diff} (3.2-10)**
S1 PG 70-28	0.30	0.37	0.55	22.44	50.16	61.71	53.44	32.60	13.40	38.99
S2 PG 70-28	0.03	0.02	0.02	-7.42	-13.43	95.26	95.39	95.06	-0.14	0.35
S3 PG 70-28	0.17	0.19	0.33	7.25	78.95	74.59	71.81	49.45	3.73	31.14
S5 PG 70-28	0.13	0.13	0.18	-2.06	39.35	80.38	80.61	71.25	-0.29	11.61
S2 PG 76-28	0.02	0.01	0.01	-2.92	-18.06	96.98	97.07	97.20	-0.09	-0.13
S3 PG 76-28	0.06	0.06	0.06	-6.13	2.63	88.95	89.32	87.87	-0.41	1.62
S4 PG 76-28	0.02	0.02	0.02	0.31	-2.48	96.28	96.16	95.59	0.13	0.59

4.6.1.1 Effect of Increased Stress Level 10 kPa

The changes in J_{nr} and %Recovery for seven (7) polymer-modified binders with three different stress levels (0.1 kPa, 3.2 kPa, and 10 kPa) are presented in Figures 4.19 and 4.20. As the stress level is increased to 10 kPa, nonlinear behavior of J_{nr} is found to increase. No sharp changes were observed in the range of 0.1 kPa to 3.2 kPa, whereas a significant change was observed in the MSCR parameters (%Recovery and J_{nr}) within the range of 3.2 kPa and 10 kPa. Golalipour [4] also mentioned similar observations that it is hard to determine any distinction between polymer-modified binders at low stress levels because their behaviors are almost the same. Golalipour [4] also reported that the sensitivity of the polymers to the increased stress level can affect the ranking of the binders. Findings of the current study also revealed that at high stress level, the binder's resistance to deformation starts to decrease. D'Angelo [18] stated that this is due to the two-phase nature of the polymer-modified binders, with the polymer network suspended in the binder continuum. At first, when tested under a lower stress, near linear viscoelastic range, they appear much stiffer. Then, as the stress increases, the polymer chains are extended and start to disentangle. This disentanglement reduces the strength of the modified binders. This was exemplified by a sharp decrease in %Recovery (Figure 4.20a) and a sharp increase in J_{nr} (Figure 4.19a). However, this change was only evident for the PG 70-28 binders. The PG 70-28 binders from three out of four sources experienced %Recovery above 45%. PG 70-28 binder from S1 was found to have a %Recovery less than 35%. Therefore, based on the majority of the tested binders, a limit for %Recovery can be set as 45% when the MSCR test is performed at 10 kPa. This limit will only put one supplier at risk. On the other hand, the PG 76-28 binders from all three sources exhibited either no change or very insignificant change in J_{nr} when the stress level was increased from 3.2 kPa to 10 kPa (Table 4.20 and Figure 4.19b). Moreover, the PG 76-28 binders exhibited very little change in %Recovery (Table 4.20 and Figure 4.20b). Thus, a suggested limit for %Recovery of PG 76-28 binders when tested at 10 kPa would be the same as the limit recommended at 3.2 kPa. A possible reason for this trend has been discussed in Section 4.5.1 in terms of the elastomeric characteristics under applied load. Insignificant changes in MSCR parameters of the PG 76-28 binder when tested at 10 kPa indicated that the PG 76-28 binder is not as sensitive to the stress level of 10 kPa.

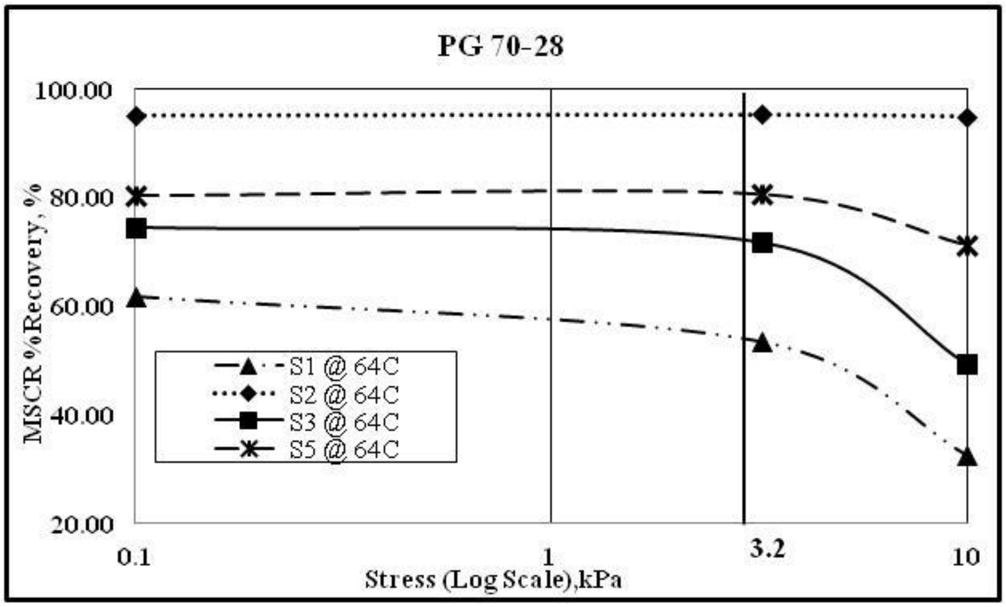


(a)

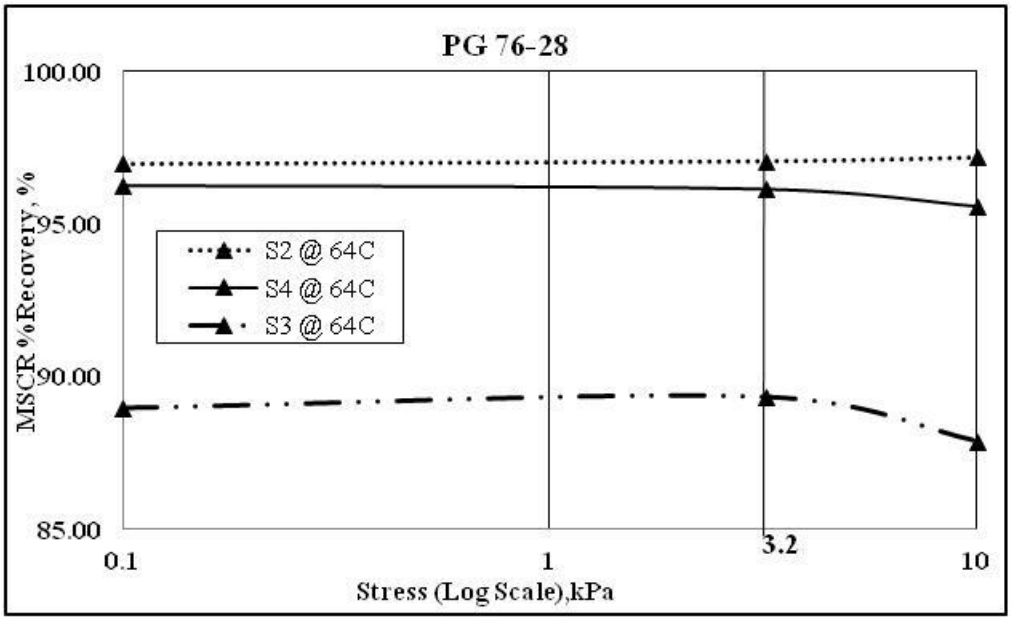


(b)

Figure 4.19 Change of J_{nr} with Stress Level for (a) PG 70-28; and (b) PG 76-28.



(a)

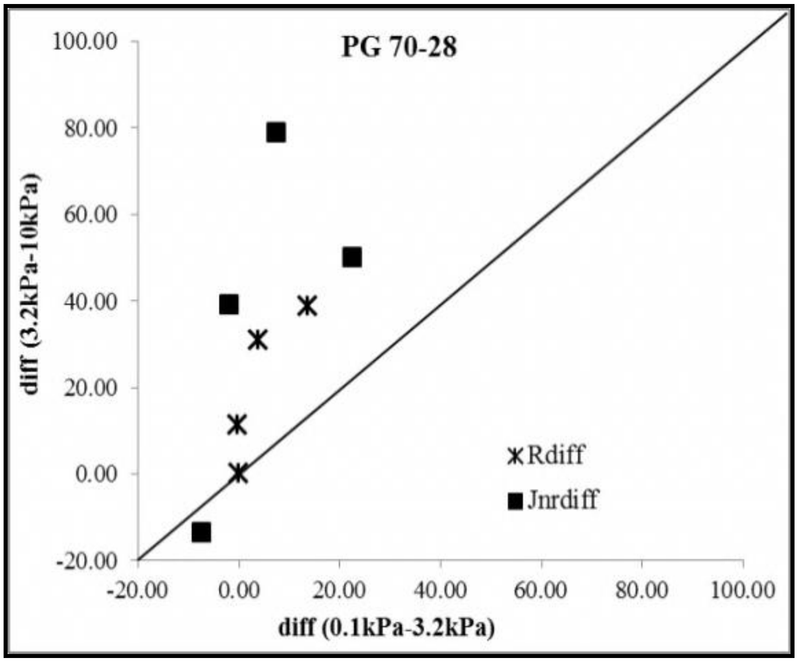


(b)

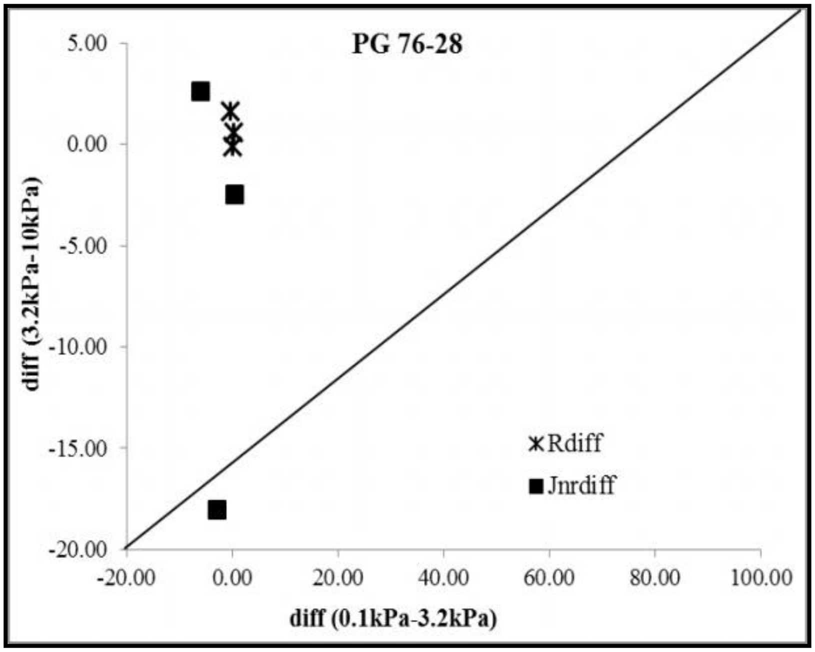
Figure 4.20 Change of MSCR %Recovery with Stress Level for (a) PG 70-28; and (b) PG 76-28.

4.6.1.2 Stress Sensitivity

Golalipour [4] mentioned that $J_{nr,\ diff}$ (%) and R_{diff} (%) values between stress levels of 10 kPa and 3.2 kPa are higher than those of 3.2 kPa and 0.1 kPa. The same scenario was observed for the polymer-modified binders tested in the current study. As shown in Figure 4.21, a majority of the evaluated polymer-modified binders exhibited high stress sensitivity at higher stress level. Moreover, the PG 70-28 binders were found to be more stress sensitive than the PG 76-28 binders. Higher polymer-modification in PG 76-28 binders than the PG 70-28 binders could be a possible reason for this, as discussed in Section 4.5.5. Golalipour [4] also suggested that adding a 10 kPa stress level in the MSCR test method can help to understand a wide spectrum of binder behavior. Adding a 10 kPa stress level also helps capture not only the stiffening effects of the polymer, but the delayed elastic effects.



(a)



(b)

Figure 4.21 Comparison of Stress Sensitivity for (a) PG 70-28; and(b) PG 76-28.

4.6.2 MSCR Tests at Higher Temperature

Performing MSCR tests at higher temperatures is helpful to understand the effect of high temperature on the J_{nr} values. Mehta et al. [61] also conducted MSCR tests at higher temperatures (64°C, 70°C, and 76°C) to observe the temperature dependency of %Recovery. These researchers reported that when the temperature was raised to 70°C and 76°C, the %Recovery decreased and the J_{nr} value dramatically increased. As shown in Figures 4.22 through 4.24, similar observations were made at higher temperatures in the current study. Santagata et al. [62] also reported a similar trend of increasing J_{nr} with an increase in MSCR testing temperature. A possible reason could be the viscoelastic properties of polymer-modified binder. At high temperatures, the polymer chains are highly affected and viscous behavior starts to become prominent. In such cases, creep behavior becomes dominant over the recovery. As a result, additional deformation takes place which is time-dependent and non-reversible. Moreover, at high temperatures, binders' stiffness reduces, which induces flow and results in permanent deformation.

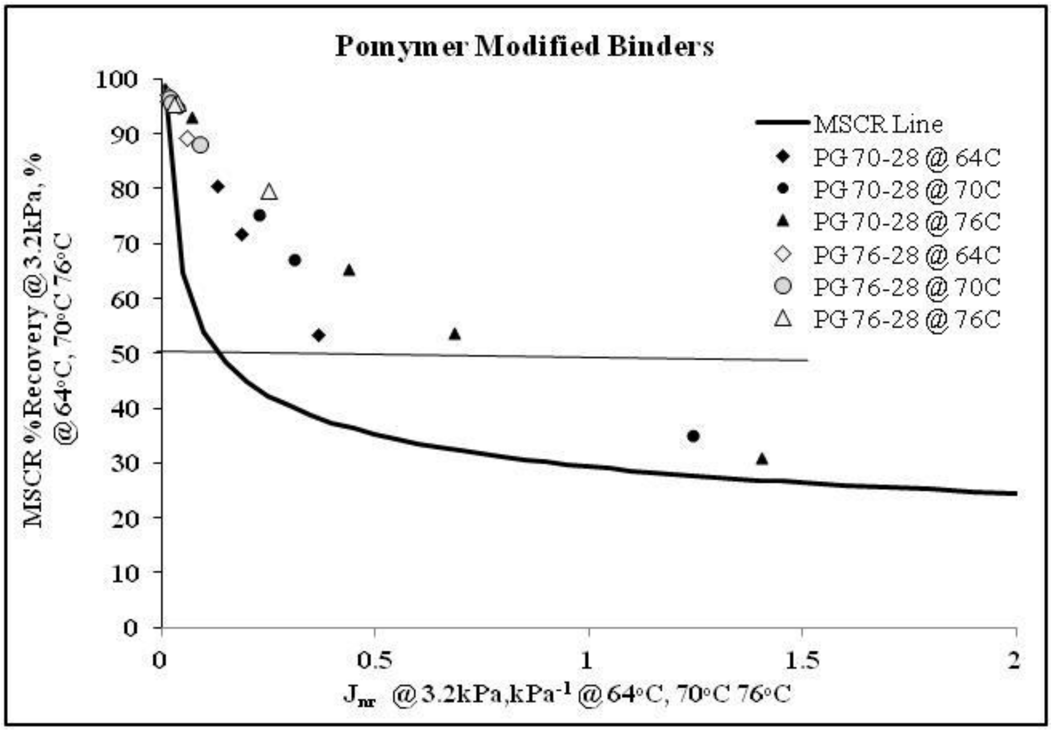
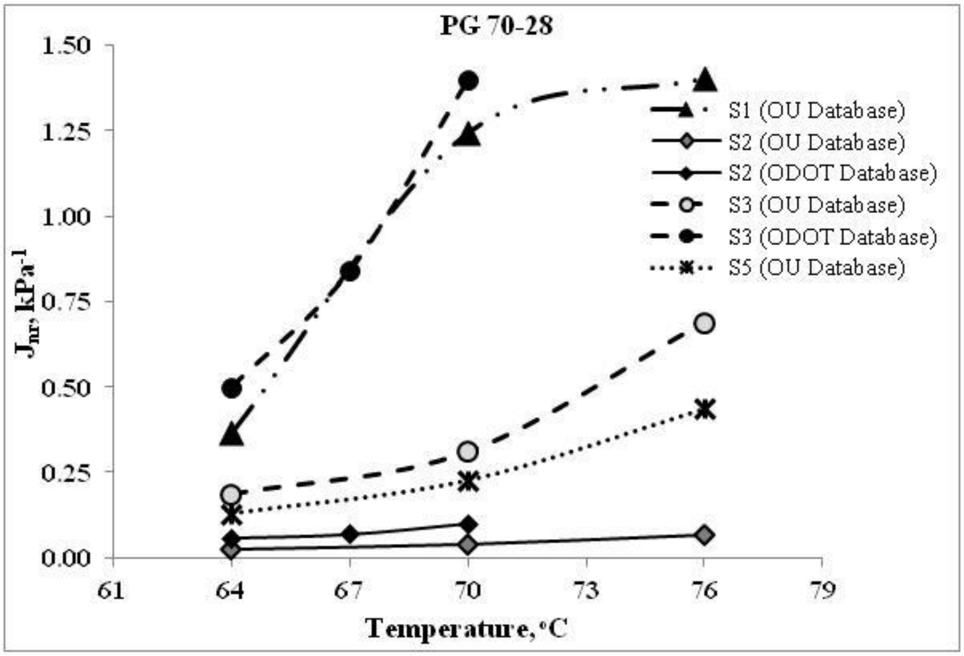
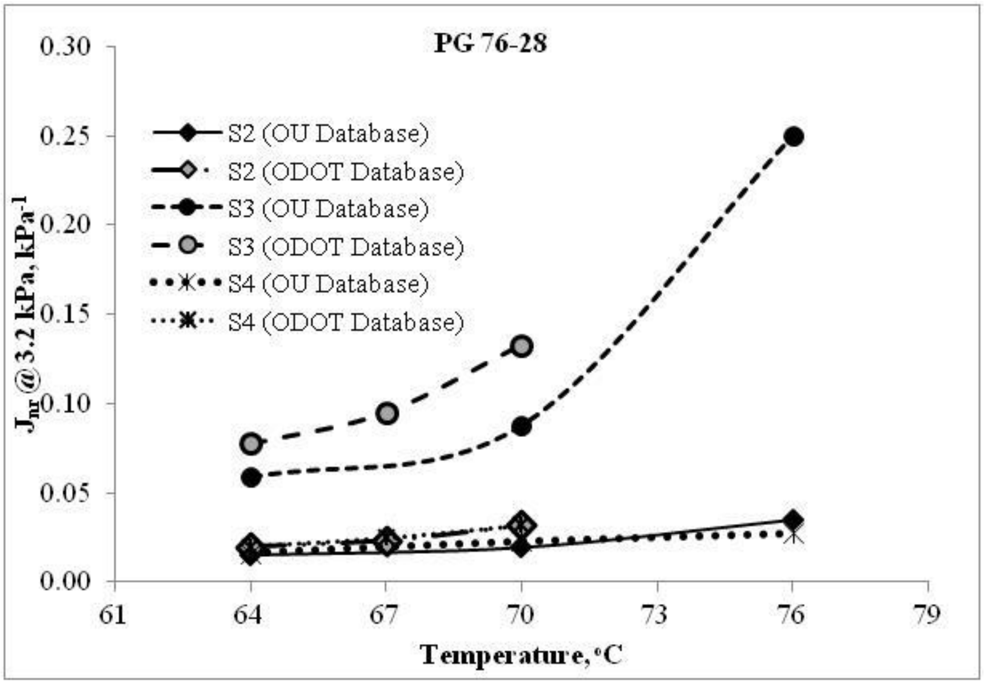


Figure 4.22 MSCR %Recovery vs. J_{nr} @ 3.2 kPa at 64°C, 70°C and 76°C.

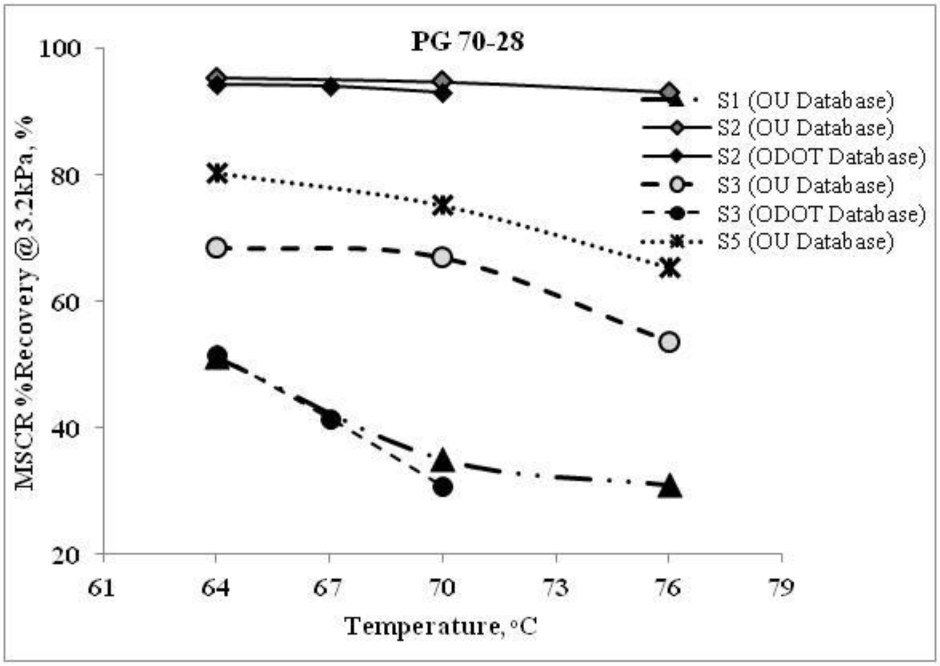


(a)

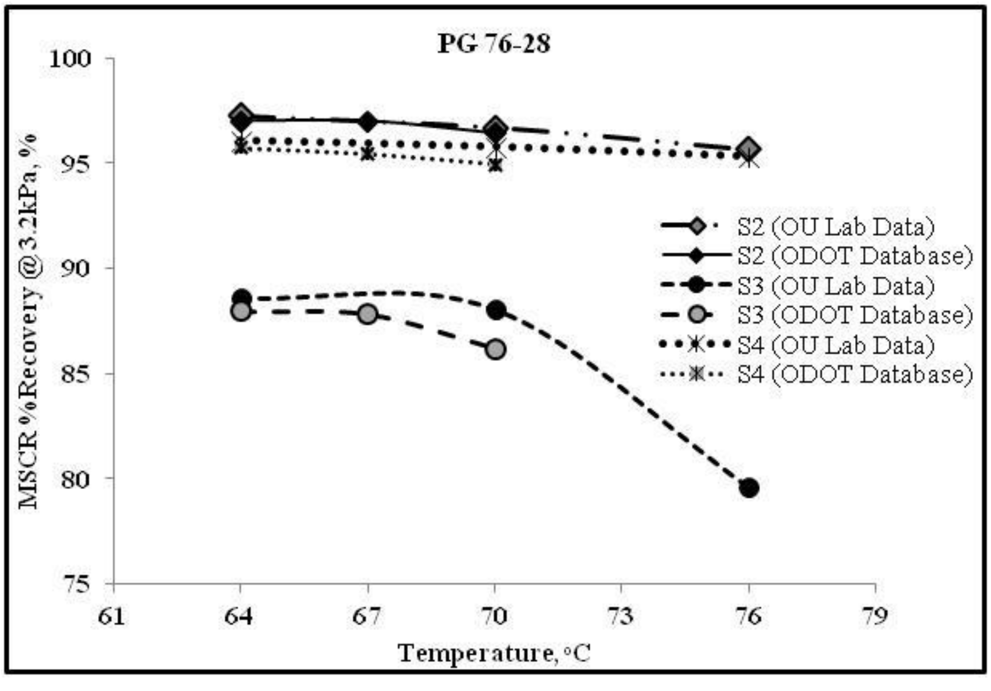


(b)

Figure 4.23 Change of J_{nr} @ 3.2 kPa,kPa^{-1} with Increase in Temperature for: (a) PG 70-28; and (b) PG 76-28.



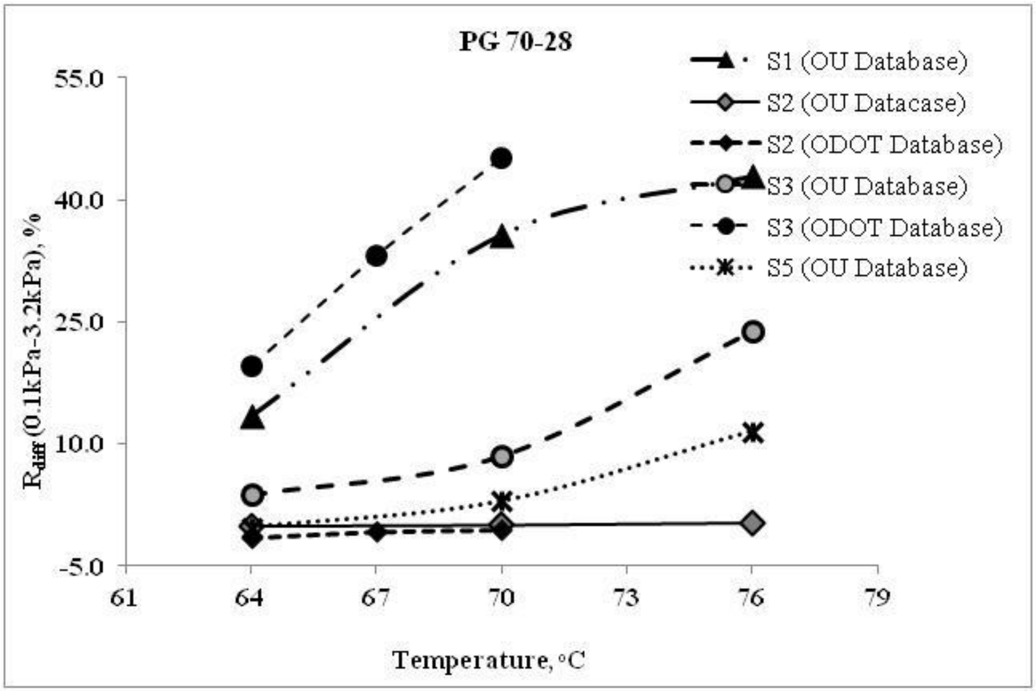
(a)



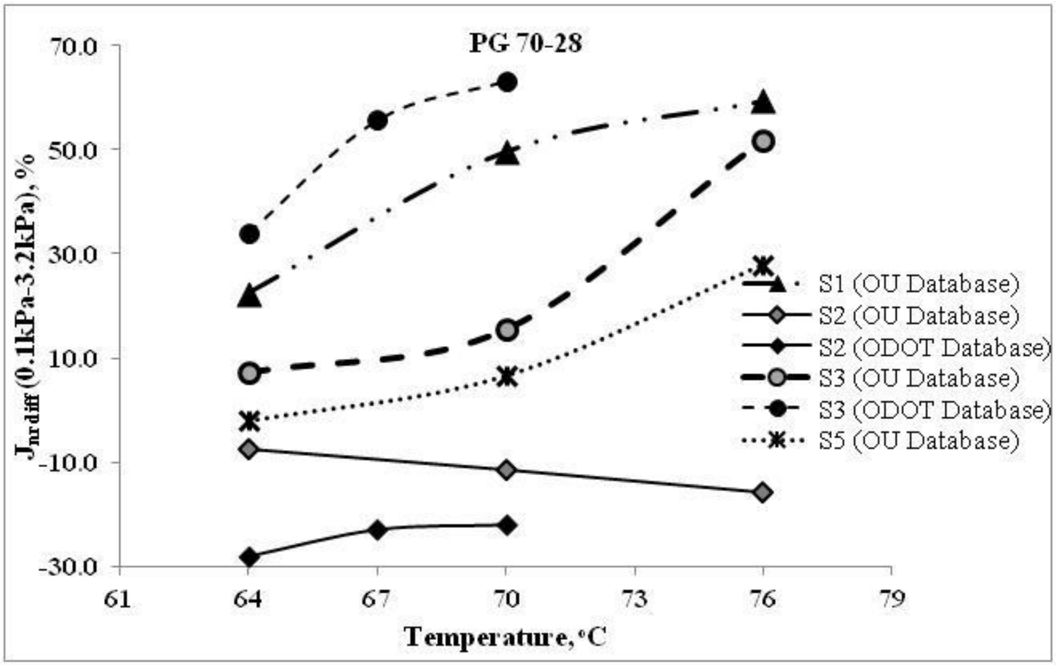
(b)

Figure 4.24 Change of MSCR %Recovery @ 3.2 kPa with Temperature for (a) PG 70-28; and (b) PG 76-28.

As noted earlier, the stress sensitivity was found to increase with an increase in temperature, indicating a binder's pronounced nonlinear viscoelastic region at temperatures higher than 64°C. The variations in the difference between the MSCR parameters (R_{diff} and $J_{nr,diff}$) for PG 70-28 and PG 76-28 binders are presented in Figures 4.25 and 4.26, respectively. The variations are more pronounced for the PG 76-28 binders than for the PG 70-28. As shown in these figures, the shape of the curves was found to be different for binders from different sources (Figures 4.25 and 4.26). This might be an indication of different types of polymers used in the polymer modification processes. Additional MSCR testing with known type and quantity of polymer should be conducted to evaluate the characteristics of R_{diff} versus temperature curves.

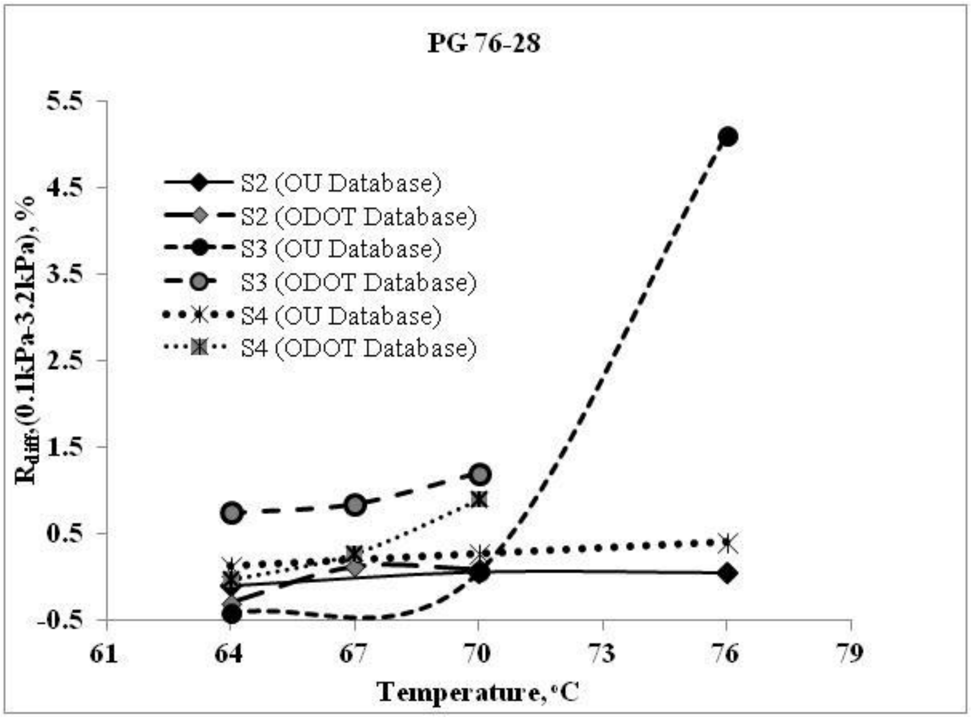


(a)

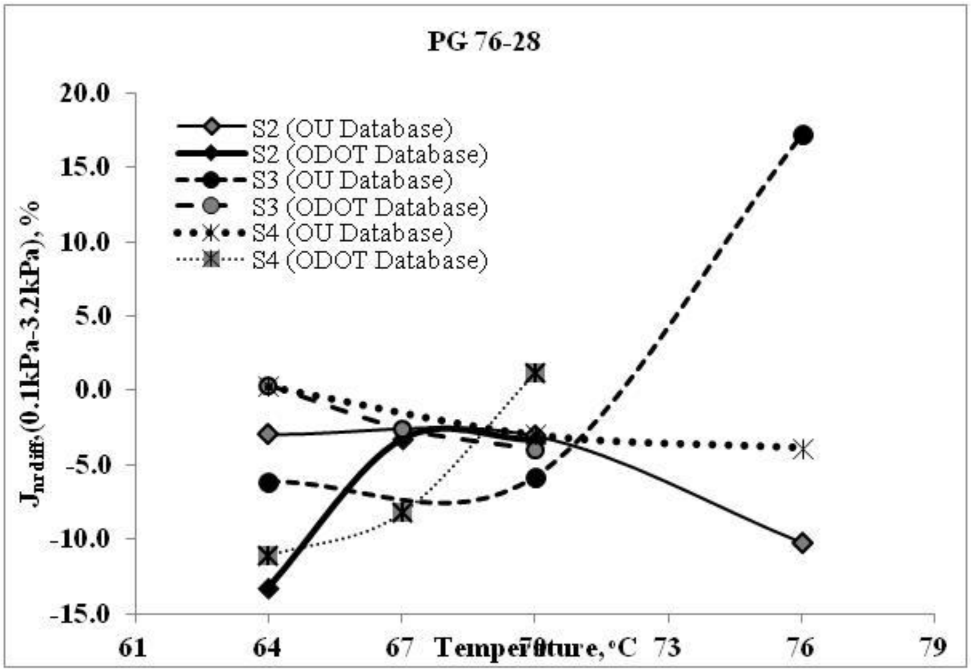


(b)

Figure 4.25 (a) R_{diff} (0.1 kPa-3.2 kPa); and (b) $J_{nr,diff}$ (0.1 kPa-3.2 kPa), % vs. Temperature for PG 70-28.



(a)

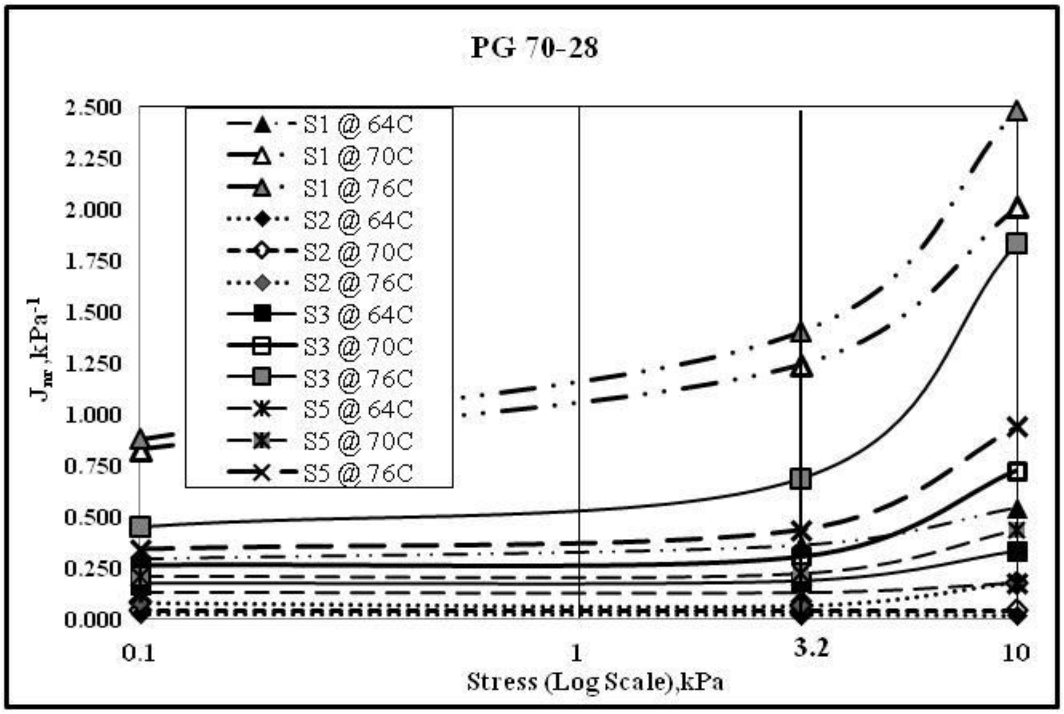


(b)

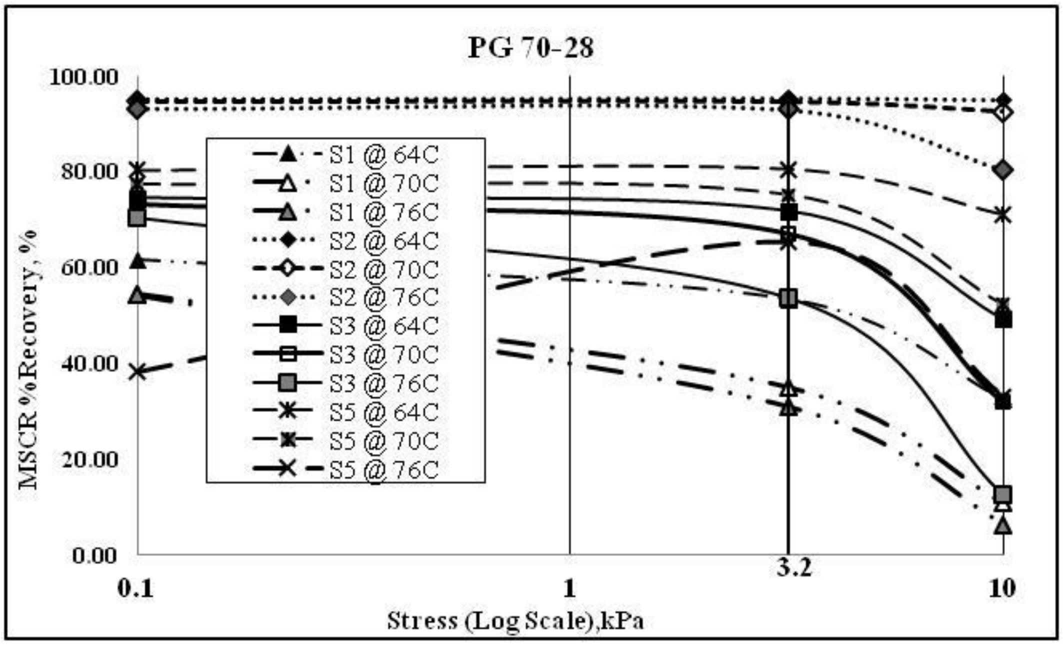
Figure 4.26 (a) R_{diff} (0.1 kPa-3.2 kPa) ; and (b) $J_{nr,diff}$ (0.1 kPa-3.2 kPa), % vs. Temperature for PG 76-28.

4.6.3 Combined Effects of Increased Stress Level and Higher Temperature

The nonlinear behavior of polymer-modified binders can be well understood from the combined effects of higher testing temperatures than 64°C and a higher stress level (10 kPa) than 3.2 kPa. As seen in Figures 4.27 and 4.28, highly polymer-modified binders such as PG 76-28 are more sensitive to high temperatures than other binders, as expected. These binders do not show the expected trend of higher J_{nr} values with higher stress levels at temperatures below 76˚C. Mehta et al. [61] also mentioned the possibility of temperature dependency in binders that exhibit high %Recovery values, which can result in reduced J_{nr} and increased %Recovery values with an increase in temperature.

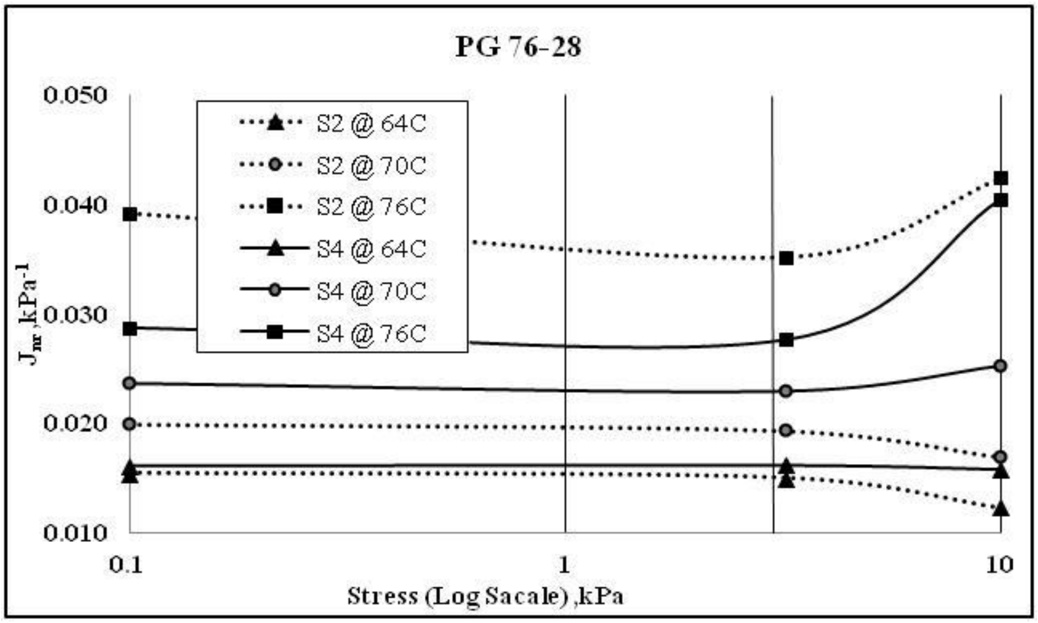


(a)

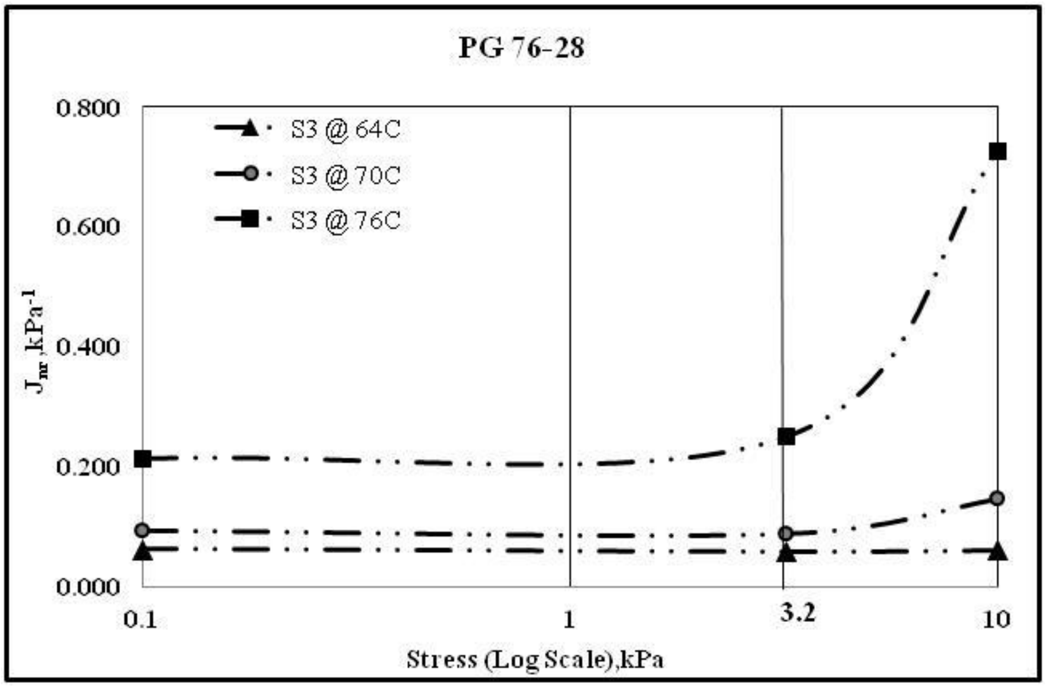


(b)

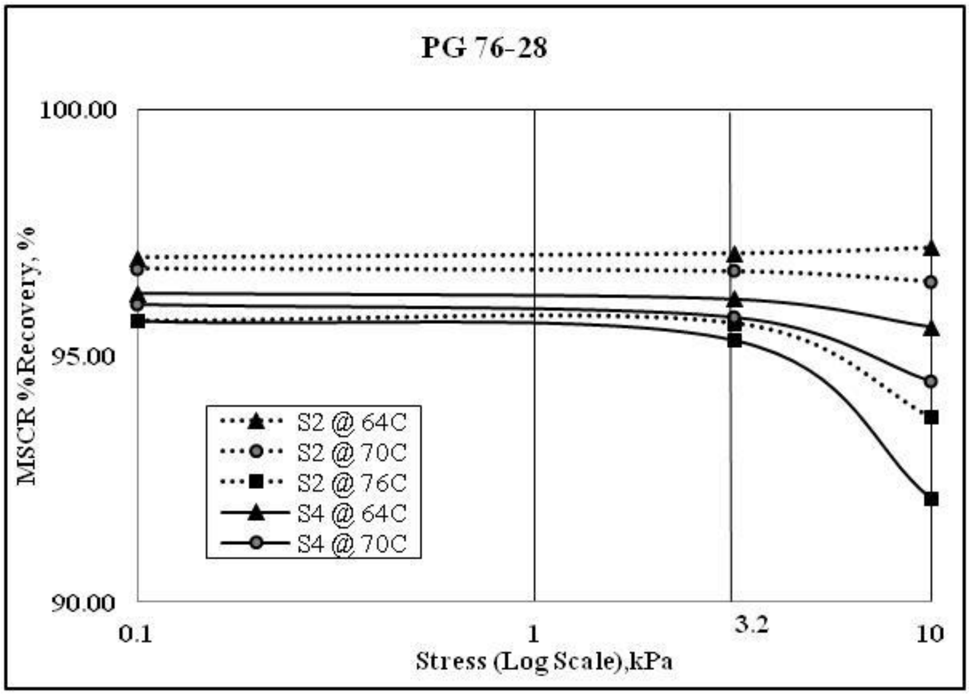
Figure 4.27 Change in MSCR Parameters with Stress levels and Temperatures for PG 70-28 (a) J_{nr} ; and (b) MSCR %Recovery.


PG 76-28
0.050
0.040
0.030
0.020
0.010
J_{nr} ,kPa^{-1}
S2 @ 64C
S2 @ 70C
S2 @ 76C
S4 @ 64C
S4 @ 70C
S4 @ 76C
0.1
1
10
Stress (Log Sacale) ,kPa

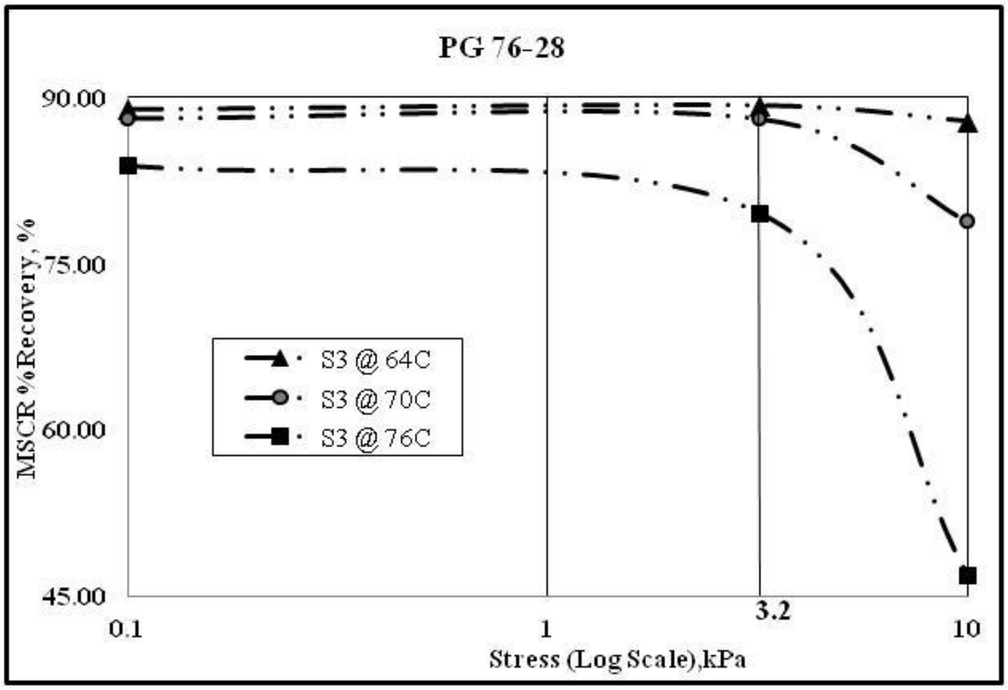
(a)


PG 76-28
0.800
0.600
0.400
0.200
0.000
J_{nr} ,kPa^{-1}
S3 @ 64C
S3 @ 70C
S3 @ 76C
0.1
1
3.2
10
Stress (Log Scale),kPa

(b)



(c)



(d)

Figure 4.28 Change in MSCR Parameters with Stress levels and Temperatures for PG 76-28 (a) and (b) J_{nr} ;(c) and (d) MSCR %Recovery.

4.7 LTPPBind Software Analysis

The LTPPBind software facilitates determining the design binder grade for a pavement section. The LTPPBind (Version 3.1) analysis was performed on four geographical locations in Oklahoma: New Mexico in the West Region (along I-40 West), Arkansas in the East Region (along I-40 East), Kansas in the North Region (along I-35 North), and Texas in the South Region (along I-35 South) (Figure 4.29). The design binder grades were estimated for all traffic conditions with reliability levels of 50% and 95%. The analysis tables are presented in Appendix C (Tables C.1 and C.2). A total of 12 types of binders (7 for 50% reliability and 5 for 95% reliability) were suggested by the LTPPBind software to be used in different regions of Oklahoma. The analysis showed that the range of binder grades is from PG 58-10 to PG 76-16 for both 50% and 95% reliabilities considering slow and fast traffic speed in four categories of traffic loading (Appendix C). Among the tested binders, with a reliability of 95%, PG 76-28 satisfies the aforementioned range obtained from the LTPPBind software analysis. If a reliability of 50% is considered, then both PG 70-28 and PG 76-28 cover the range of PG 58-10 to PG 70-10. It should be noted that Version 2.0 of this software would have shown lower grades of binder required for the same conditions.

While considering the MSCR grading, the variation in the PG grading depends on the type of traffic loading (Standard, Heavy, Very Heavy, and Extreme) only. The MSCR grading system eliminates the use of a wide range of PG grade binders such as PG 70-28, and PG 76-28. Rather, the use of PG 64(S, H, V, E)-xx depending on the traffic loading is suggested. The PG 64E-28 binder is expected to cover all four regions with both 50% and 95% reliability. Further, the analysis of the MSCR database in the current study revealed that all PG 76-28 and about 80% of PG 70-28 binders can be graded as PG 64E-28.

Figure 4.29 Map Showing the Location Used in LTPPBind Software Analysis.

4.8 Recommended MSCR %Recovery

Based on the above findings and observations of neat and polymer-modified binders, a minimum %Recovery can be suggested for all three types of commonly used Oklahoma-certified binders. As recommended by D'Angelo [18], the grading system for the neat binders should not be changed. Still, if tested under the MSCR test protocol, a PG 64-22 binder should have a minimum %Recovery of only 2%. The recommended minimum MSCR %Recovery for a PG 70-28 binder is 50% based on the 46 tested binders from 5 different sources. Based on this limit, only one supplier will be at risk and no user will be at risk with a 50% recovery limit for the PG 70-28 binders. The PG

76-28 binder is the highest binder grade that ODOT uses in highway construction projects [94]. The recommended minimum %Recovery for this polymer-modified binder (i.e., PG 76-28) is 80% based on the 43 binders tested from four different sources. No supplier or user will be at risk with an 80% recovery limit for the PG 76-28 binders. It could be noted that a PG 76E-28 binder with a minimum %Recovery of 95% was used by ODOT for the highly modified asphalt (HiMA) pavements in Oklahoma (an I-40 project) [94]. The polymer used in the PG 76E-28 binder was Kraton^{TM}, which is a new SBS product. The target of the I-40 project was to use HiMA in the pavement section to reduce the thickness of the pavement, and thus ensure cost effectiveness and long-term durability along with high resistance to rutting and fatigue cracking. The HiMA had the added benefit of eliminating concerns about the grade changes along the highway sections. The MSCR test method was stated as the best method to characterize HiMA for the I-40 project [94].

4.9 Summary

A majority (65%) of the tested PG 64-22 binders were graded as PG 64S-22. The AASTHO T 350 criteria for %Recovery marked the PG 64-22 as “insignificant recovery.” About 80% of the PG 70-28 binders were graded as PG 64E-22 with an average of 75% recovery. All 46 PG 70-28 binders from five different sources met both the AASHTO T 350 criteria for %Recovery and the AASHTO T 332 criteria for stress sensitivity. From the quadrant plot analysis, it was found that none of the tested binders were a User Risk. However, 3 binders from one source (S2) were observed to be a Supplier Risk. Forty three (43) out of 46 binders satisfied the AI recommended minimum %Recovery of

50%. The %Recovery observed for these three binders was about 45%, which was just 5% less than 50%. Therefore, the minimum %Recovery for PG 70-28 binder can be considered as 50% without putting many suppliers at risk.

All 43 PG 76-28 binders were graded as PG 64E-28 with an average %Recovery of 80%. All tested binders from all sources met the AI recommended minimum %Recovery of 75%. None of the users or suppliers of PG 76-28 binders were found to be at risk. Therefore, a %Recovery of 80% is recommended for PG 76-28 Oklahoma binders without penalizing any suppliers or putting any users at risk.

Non-conventional MSCR tests performed at a higher stress level and a higher temperature level provided a better understanding about the nonlinear viscoelastic zone of polymer-modified binders. Drastic increases in J_{nr} value and decreases in %Recovery were observed with an increase in stress levels and temperatures. Based on the findings discussed in this chapter, it is suggested that the MSCR test be performed at higher stress levels and higher temperatures for a better understanding of the non-linear behavior of polymer-modified binders, as recommended by other researchers [4, 22, 61].

5 TEST RESULTS FOR SASOBIT® -MODIFIED AND RAP BINDERS

5.1 Introduction

As noted in Chapter 3, MSCR tests were conducted on Sasobit®-modified binders as-well-as binders recovered from SRAP samples. Analyses of these test data were performed and presented in this chapter. The analyses were based on the Polymer method. Efforts were made to examine the effect of Sasobit® as well as SRAP on the MSCR grading of the associated binders.

Both neat and polymer-modified binders were blended with Sasobit® in selected amounts by weight. Specifically, the neat binder (PG 64-22) was blended with 2%, 3%, and 4% Sasobit®. The polymer-modified binders (PG 70-28 and PG 76-28) were blended with only 3% Sasobit® by weight. MSCR tests were conducted after 72 hours of RTFO aging of the prepared mixtures. The RAP binders were recovered from two simulated HMA mixes (one S4 type with PG 76-28 binder). Three replicates were tested for each mix, and the average value of the three tests is presented in Tables 5.1 and 5.4. The highest standard deviations for the %Recovery and J_{nr} at 3.2 kPa were found to be 0.54 and 0.27, respectively. As described in section 4.3 of Chapter 4, these tables include two important criteria that are reflective of binder performance. These criteria are: Stress Sensitivity (Column 5) and %Recovery (Column 9). These tables also include the new MSCR grading (Column 10).

5.2.1 Effect of Sasobit® Percentage

The MSCR %Recovery is found to increase and the J_{nr} is found to decrease with increasing Sasobit® content (Table 5.1 and Figure 5.1). A similar trend was observed for the PG 64-22 binders from all four sources. Jamshidi et al. [86] also reported that the addition of Sasobit® led to a reduction in J_{nr}, which is an indication of greater rutting resistance for Sasobit®-modified binders compared to neat binders. Previous studies have shown that the addition of Sasobit® lowers the viscosity of the binder at high temperatures and increases the viscosity at intermediate temperatures [87°C, 88°C, and 90°C]. At in-service temperatures, Sasobit® provides higher resistance to deformation and improved elasticity. This is because the service temperatures are lower than the melting point of Sasobit®. At temperatures below its melting point, Sasobit® forms a lattice structure in the binder and provides better stability to the binder. This is another reason for the increased resistance to rutting at service temperatures due to the addition of Sasobit® [88]. A number of previous studies have reported similar findings [89, 90]. One of the primary purposes of the present study was to verify that the MSCR parameters were capable of identifying the changes in rutting resistance due to Sasobit®-modification of binders from MSCR tests conducted at a high stress level of 3.2 kPa.

As noted above, J_{nr} decreased and %Recovery increased with an increase in Sasobit® content (Table 5.1). This trend was evident for both stress levels: 0.1 kPa and 3.2 kPa. Since rutting is generally prominent at high stress levels, MSCR parameters were analyzed at 3.2 kPa rather than 0.1 kPa.

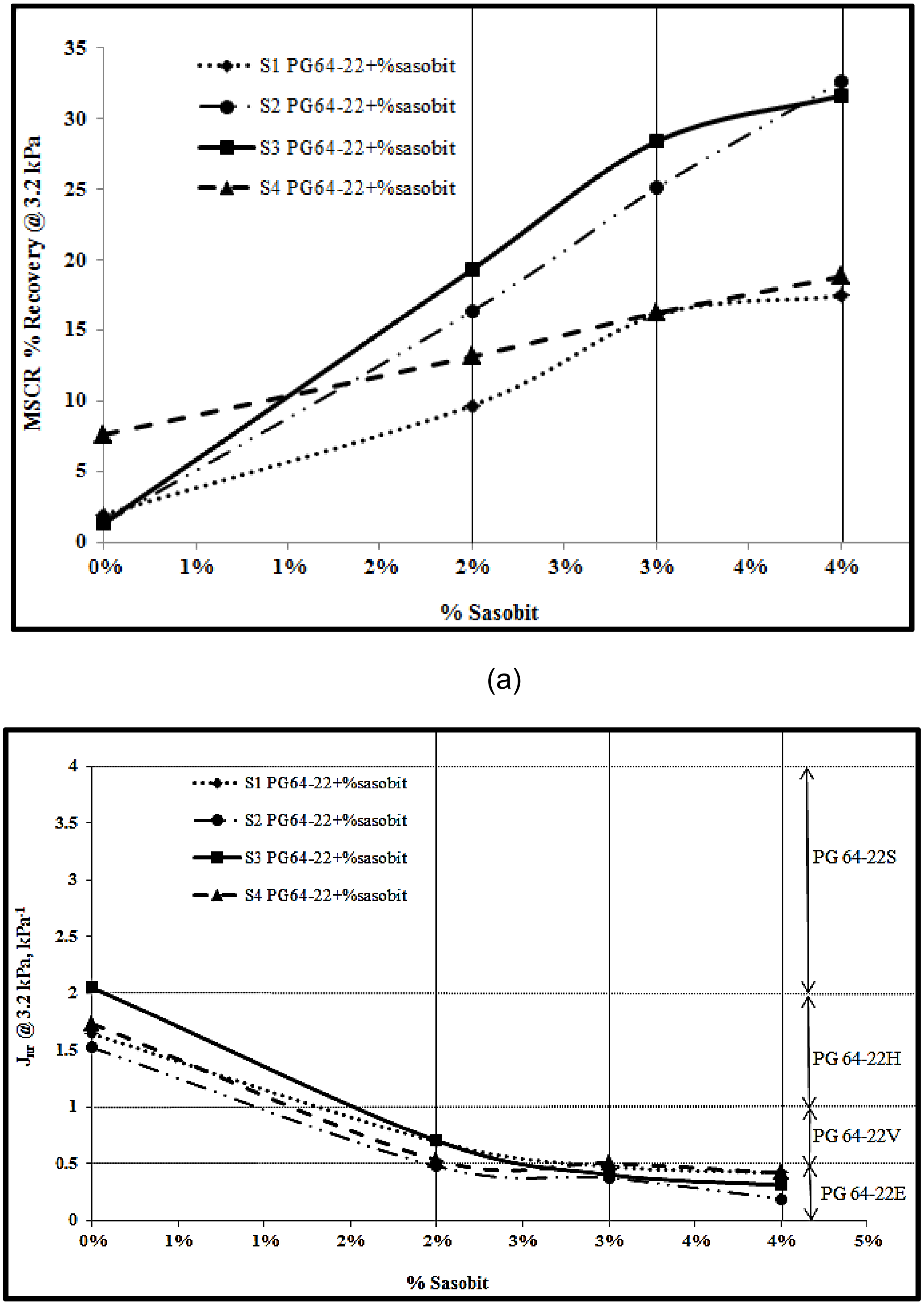
From an application standpoint, it is important to examine the degree of change in $J_{nr,\ 3.2\ kPa}$ due to changes in the Sasobit® amount (percentage). It is evident that the addition of only 2% Sasobit® reduced the $J_{nr,\ 3.2\ kPa}$ values by more than 50%, compared to the $J_{nr,\ 3.2\ kPa}$ values of PG 64-22 binders. Similar reductions were observed for the binders from all four sources. As described in Chapter 2, a 50% reduction in J_{nr} amounts to about 50% reduction in rutting. The laboratory data from the present study are in agreement with the aforementioned observations for the addition of 2% Sasobit® to the neat binders. When the amount of Sasobit® was increased from 2% to 3%, the corresponding J_{nr} decreased by about 25% for binders from three sources. For the fourth source, however, the corresponding change was only about 5%. Increasing the Sasobit® amount further (from 3% to 4%) caused changes in the $J_{nr,\ 3.2\ kPa}$ that were found to be insignificant. Based on these observations, the optimum amount of Sasobit® was found to be around 3%.

Similar observations were made for the other MSCR parameter, %Recovery. It was found that the %Recovery at 3.2 kPa increased, on average, by at least a factor of 6 to 7 due to the addition of 2% Sasobit® to the neat binders from three sources (Table 5.1). The increase of J_{nr} in the case of the binder from the fourth source was only 50%, due to the addition of 2% Sasobit®. The %Recovery at 3.2 kPa was found to increase by more than 50% when the Sasobit® content was increased from 2% to 3%. Such an increase was evident for the PG 64-22 binders from all four sources. Comparatively, a less than 10% increase was observed for %Recovery at 3.2 kPa when increasing the Sasobit® content from 3% to 4%. Again, this increase was evident for the PG 64-22 binders from all sources. Based on the tested binders from all four sources and the above discussions it is evident that the addition of 2% Sasobit® will increase

%Recovery at 3.2 kPa about 6 times for neat binders and reduce the $J_{nr,\ 3.2\ kPa}$ values by 50%.

Table 5.1 MSCR Test Data and Analysis for Sasobit®-Modified Neat Binders

1		2	3	4	5	6	7	8	9	10
Source & type (RTFOaged)	**Sasobit®**	**J_{nr} (0.1 kPa)**	**J_{nr} (3.2 kPa)**	**$J_{nr\ diff}$**	**Stress Sensitivity (Meets AASTHO T 332)**	**R100**	**R3200**	**R_{diff}**	**%Recovery (Meets AASTHO T 350)**	**MSCR GRADE**
S1 PG64-22	0%	1.51	1.64	8.95	YES	5.41	1.94	64.1	NO	PG64H-22
	2%	0.53	0.69	30.85	YES	26.69	9.67	63.8	NO	PG64V-22
	3%	0.37	0.47	28.28	YES	30.89	16.06	48.0	NO	PG64E-22
	4%	0.30	0.42	38.60	YES	37.31	17.42	53.3	NO	PG64E-22
S2 PG64-22	0%	1.32	1.52	15.15	YES	3.71	1.32	64.4	NO	PG64H-22
	2%	0.36	0.47	32.42	YES	33.32	16.36	50.9	NO	PG64E-22
	3%	0.30	0.37	25.22	YES	36.82	25.05	32.0	NO	PG64E-22
	4%	0.13	0.19	40.34	YES	49.19	32.57	33.8	NO	PG64E-22
S3 PG64-22	0%	1.88	2.05	9.35	YES	4.63	1.31	71.6	N/A	PG64S-22
	2%	0.51	0.70	37.25	YES	36.78	19.30	47.5	NO	PG64V-22
	3%	0.29	0.40	37.98	YES	44.65	28.34	36.5	NO	PG64E-22
	4%	0.19	0.31	61.39	YES	53.15	31.57	40.6	NO	PG64E-22
S4 PG64-22	0%	1.41	1.73	22.93	YES	19.62	7.61	61.2	NO	PG64H-22
	2%	0.35	0.53	51.65	YES	35.77	13.12	63.3	NO	PG64V-22
	3%	0.34	0.50	45.67	YES	36.15	16.21	55.2	NO	PG64E-22
	4%	0.26	0.42	61.96	YES	42.53	18.79	55.8	NO	PG64E-22



(a)

(b)

Figure 5.1 Change of MSCR Parameters @ 3.2 kPa with Increase in Sasobit® Content (a) MSCR %Recovery; (b) J_{nr}.

5.2.2 Polymer Method

It was observed from Column 9 of Table 5.1 that the Sasobit®-modified binders tested here did not meet the AASHTO T 350 requirement for %Recovery. Here, "No" means the obtained %Recovery at 3.2 kPa is less than the desired %Recovery at 3.2 kPa calculated by Equation 2.1. The %Recovery obtained from the MSCR tests showed that all of the neat binders with Sasobit®-modification tested herein experienced a low level of recoverable strain at the end of repeated loading and unloading cycles. As described in Section 4.3, in the Polymer method the MSCR curve represents a borderline above which binders exhibit a high level of elasticity, whereas below the curve they are expected to exhibit a low level of elasticity. Since Sasobit®-modified binders showed a low level of elasticity, they would plot below the MSCR curve (Figure 5.2). Moreover, binders containing elastomeric polymers are expected to plot above the MSCR curve. However, Sasobit®-modified binders are modified with plastomers rather than elastomers. Plastomers increase the stiffness of a binder at high temperatures to resist permanent deformation [91].

Unlike plastomers, elastomeric polymers diminish rutting by recovering elastically from temporary deformation. The main benefit of adding Sasobit® is that it reduces a binder’s viscosity and allows for a reduction in working temperature of 18°C to 54°C [90]. Thus, Sasobit® serves as a "flow improver," both during the asphalt mixing process and the laydown operation. Sasobit® has a melting point between 85°C to 115°C, and is completely soluble in binder at temperatures higher than 120°C [90]. Below its melting point and at in-service pavement temperatures, Sasobit® forms a crystalline network structure in the binder that leads to added stability [88]. As a result, when Sasobit® is used with a binder, it forms a lattice crystalline network structure. This structure adds stability to the binder, which increases stiffness and thus resistance to permanent deformation. This is a probable reason that Sasobit®–modified binders were located below the MSCR curve. A good level of upward shift in binders' location was observed in Figure 5.2 towards the MSCR curve compared to the shift for the neat binders. Sasobit®modified binders experienced low strain accumulation in terms of low J_{nr}, which resulted in a high ratio of recoverable strain to the total strain. As a consequence, 6 to 7 times higher %Recovery values were observed for modified binders compared to neat binders (Table 5.1). The highest shift in %Recovery was found to be 25 times the obtained %Recovery for PG 64-22 from S2, without Sasobit® modification. The highest shift occurred when Sasobit® content was increased to 4%.

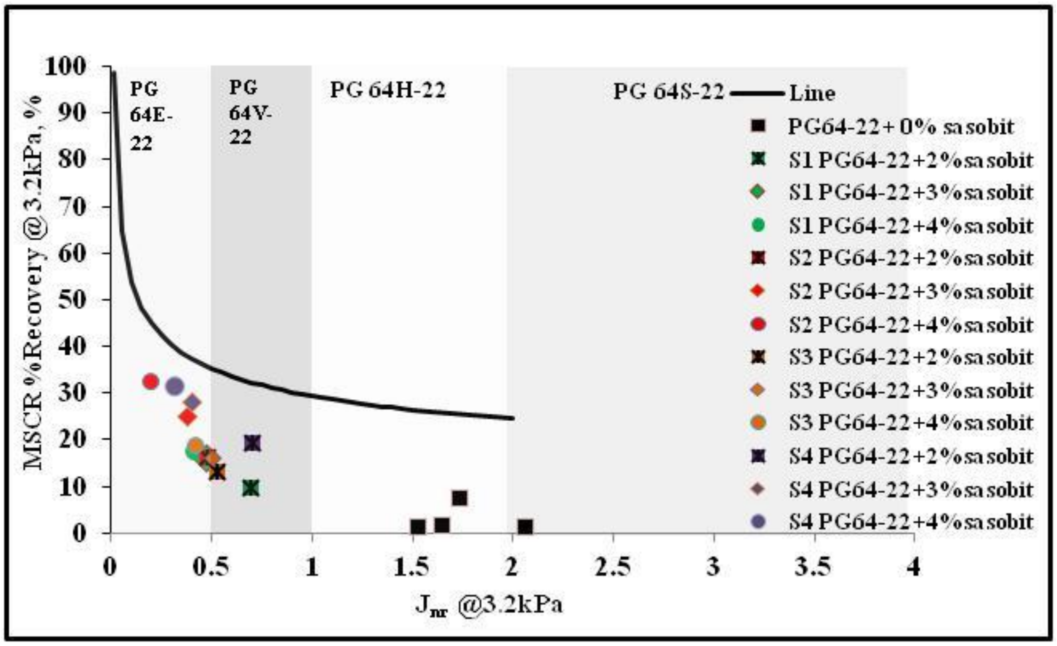


Figure 5.2 MSCR %Recovery vs. J_{nr} @ 3.2 kPa for Sasobit® - Modified Binder.

5.2.3 Effect of Modification on Binder Grade based on AASHTO MP-19

Binders from all four sources modified with Sasobit® exhibited a better MSCR performance grade than the neat binder, as reflected in the lower J_{nr} value. For example, the PG 64-22 from S1 exhibited a gradual increase in performance grade from PG 64H-22 to PG 64V-22, followed by PG 64E-22 with the addition of 2%, 3%, and 4% Sasobit®, respectively (Table 5.2). It is evident from Tables 5.1 and 5.2 that the neat PG 64-22 binder was able to sustain standard traffic condition. However, the addition of 3% Sasobit® led to an MSCR grade of PG 64E-22. This means that binders modified with 3% Sasobit® can sustain extreme traffic conditions, which is a significant improvement. Addition of 4% Sasobit® also resulted in the same grade of PG 64E-22. Thus, 3% Sasobit® is preferable to 4% Sasobit® with respect to optimization. The changes in MSCR grading with differing Sasobit® contents are presented in Table 5.2.

It can be seen in Figure 5.2 that, despite having the highest MSCR grade of PG 64E-22, a binder may not have the desired performance in terms of %Recovery and thus, attention should be given when selecting the binder. The MSCR grade PG 64E-22 is expected to sustain extreme traffic conditions. Nonetheless, a low %Recovery at 3.2 kPa cannot meet the desired performance. However, this plot provides a combined idea about the rutting resistance and MSCR grading of Sasobit®-modified binders in terms of J_{nr} and %Recovery.

Table 5.2 Change of MSCR Grading with Increase in Sasobit® Content

Source of PG 64-22 (RTFO-aged)	Sasobit® Content			
	0%	2%	3%	4%
S1	PG64H-22	PG64V-xx	PG64E-xx	PG64E-xx
S2	PG64H-22	PG64E-xx	PG64E-xx	PG64E-xx
S3	PG64S-22	PG64V-xx	PG64E-xx	PG64E-xx
S4	PG64H-22	PG64V-xx	PG64E-xx	PG64E-xx

5.3 Polymer-Modified Binder

A number of previous studies have examined the behavior of polymer-modified binders when blended with Sasobit® [89-91]. For example, Wasiuddin et al. [89] studied polymer-modified binders blended with 2%, 3%, and 4% Sasobit®. It was reported that the binder grade reached the highest level of rutting resistance when 3% Sasobit® was added to the binder [89]. Moreover, the manufacturer recommends using 3% Sasobit® by weight of the binder [89]. Adding 3% Sasobit® helps to achieve the desired reduction in viscosity. That study recommends limiting the concentration of Sasobit® to 4% by weight [89]. Exceeding the recommended limit may cause non-beneficial or harmful impacts to the low-temperature properties, such as fatigue cracking. The present study focused on the binder's high temperature characteristic of rutting resistance. Thus, the target was to observe how well the MSCR parameters can describe rutting performance of a polymer-modified binder with Sasobit® –modification. In order to realize this objective, two types of polymer-modified binders (PG 70-28 and PG 76-28) were studied herein, and the dosage was kept constant at 3%. These binders were obtained from four different sources, as noted previously.

The MSCR parameters, $J_{nr,\ 3.2\ kPa}$ and %Recovery, were evaluated for each case.

5.3.1 *Effect of Sasobit® Percentage*

The MSCR test results for polymer-modified binders modified with 3% Sasobit® are presented in Table 5.3. Saha [92] reported that the addition of Sasobit® might increase the rutting resistance at a lower stress level, while it can increase the rutting damage at a higher stress level. As noted in Section 4.6, increased stress levels reduce the rutting resistance. Addition of Sasobit® to neat binders as well as polymer-modified binders was found to be beneficial at both stress levels (Tables 5.1 and 5.3). In other words, addition of Sasobit® was always found to increase the rutting resistance for both 0.1 kPa and 3.2 kPa stress levels. Thus, MSCR tests should be performed at higher stress levels than 3.2 kPa to validate the statements of Saha [92].

Sasobit® modification of polymer-modified binders lowered the $J_{nr,\ 3.2\ kPa}$ by 50% for 5 out of 7 tested binders. So, Sasobit® modification of polymer-modified binders can decrease the rut depth to half. This observation was not valid for the PG 70-28 binder from S5 and the PG 76-28 binder from S2 because the corresponding changes in $J_{nr,3.2\ kPa}$ were much lower. However, like other binders tested in this study, the PG 70-28 binder from S5 and the PG 76-28 binder from S2 exhibited a higher %Recovery due to Sasobit® – modification. This is because Sasobit®, at temperatures below its melting point, forms a lattice structure in the binder and provides better stability according to field trials [88]. The contribution of Sasobit® modification in lowering rut depth has been described in Sections 5.2.1 and 5.2.2.

For PG 64-22 binders from all four sources, addition of 3% Sasobit® was found to lower the binder $J_{nr,\ 3.2\ kPa}$ by more than 70%, compared to the values for the neat binders (Table 5.1). In the case of polymer-modified binders, however, Sasobit®-modification by 3% lowered the J_{nr} by about 50%. This was observed for all polymer-modified binders except the PG 70-28 binder from S5 and the PG 76-28 binder from S2. It was not possible to find out the trend of increasing %Recovery with Sasobit®-modification separately for PG 70-28 and PG 76-28. This was because, for the same grade of binder, sometimes a high level of increase in %Recovery was noticed, but not consistently, due to the addition of 3% Sasobit®. For example, with 3% Sasobit®-modification, the PG 70-28 binder from S1 exhibited 30% increase in %Recovery whereas, only 0.9% increase was noticed for the same binder (PG 70-28) from S2. Possible reasons for such inconsistencies could be chain reactions of plastomers (Sasobit®) with elastomers and other types of polymer present in a particular binder. It should be mentioned here that the type of polymer used in the polymer-modified binders from different sources was unknown. It is likely that they were of different types and in different amounts. It was evident from the findings in Section 4.5 that the tested PG 76-28 and PG 70-28 binders from all the sources exhibited high elasticity. This was because they all were plotted above the MSCR curve. This indicates the presence of elastomeric polymers in binders. Due to the lack of information on the polymers present in the polymer-modified binders, it was not possible to describe the actual reactions.

Table 5.3 MSCR Test Data and Analysis of Polymer-Modified Binders

1		2	3	4	5	6	7	8	9	10
Source & type	Sasobit®	J_{nr} (0.1 kPa)	J_{nr} (3.2 kPa)	$J_{nr\ diff}$	Stress Sensitivity (Meets AASTHO T 332)	R100	R3200	R_{diff}	%Recovery (Meets AASTHO T 350)	MSCR GRADE
S1 PG70-28	0%	0.30	0.37	22.44	YES	61.71	53.44	13.40	YES	PG64E-28
	3%	0.08	0.11	37.50	YES	77.49	69.90	9.8	YES	PG64-xxE
S2 PG70-28	0%	0.03	0.02	-7.42	YES	95.26	95.39	-0.14	YES	PG64E-28
	3%	0.01	0.01	0.00	YES	104.65	96.30	8.0	NO	PG64-xxE
S3 PG70-28	0%	0.17	0.19	7.25	YES	74.59	71.81	3.73	YES	PG64E-28
	3%	0.05	0.06	20.00	YES	85.22	81.25	4.6	YES	PG64-xxE
S5 PG70-28	0%	0.13	0.13	-2.06	YES	80.38	80.61	-0.29	YES	PG64E-28
	3%	0.05	0.07	40.00	YES	86.41	83.09	3.8	YES	PG64-xxE
S2 PG76-28	0%	0.02	0.01	-2.92	YES	96.98	97.07	-0.09	YES	PG64E-28
	3%	-0.02	0.01	-150.00	YES	109.16	97.33	10.8	NO	PG64-xxE
S3 PG76-28	0%	0.06	0.06	-6.13	YES	88.95	89.32	-0.41	YES	PG64E-28
	3%	0.02	0.03	50.00	YES	94.25	91.17	3.3	YES	PG64-xxE
S4 PG76-28	0%	0.02	0.02	0.31	YES	96.28	96.16	0.13	YES	PG64E-28
	3%	-0.01	0.01	-200.00	YES	108.05	97.38	9.8	NO	PG64-xxE

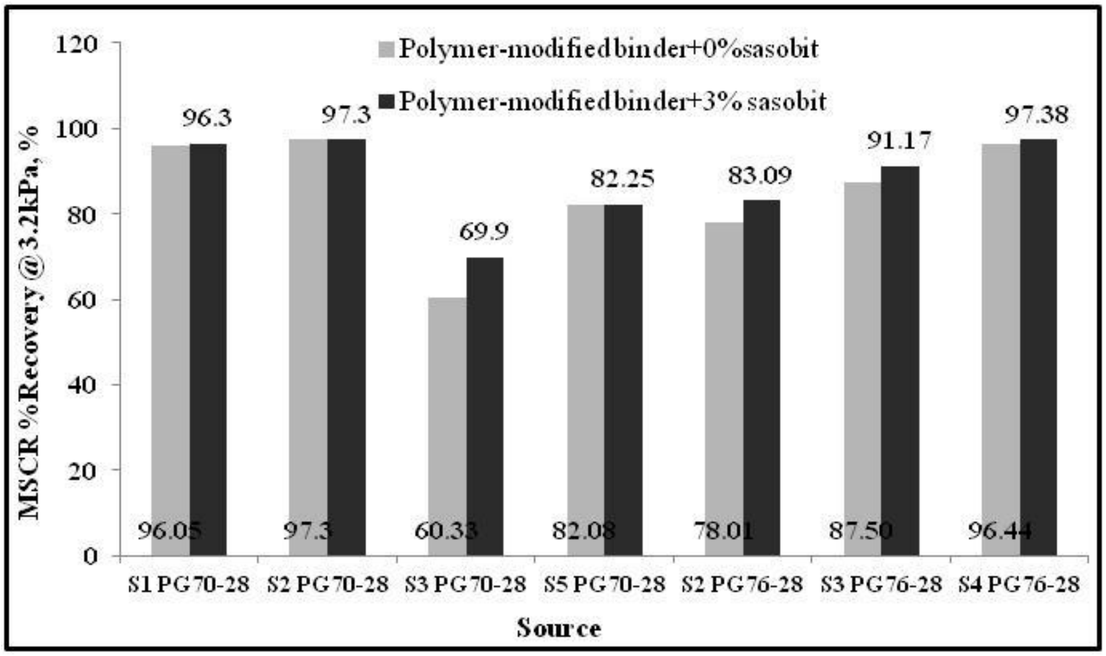


Figure 5. 3 Change of MSCR %Recovery @ 3.2 kPa with Addition of 3% Sasobit®

5.3.2 Polymer Method

The results from the Polymer method are presented in Figure 5.4. As described earlier, the %Recovery vs. J_{nr} plot is very useful in characterizing a polymer-modified binder through visual observation of the location of a binder within the plot. The polymer-modified binders without any Sasobit® modification are expressed using yellow dots in the plot (Figure 5.4). In this figure, the binders modified with Sasobit® were found to be highly elastic. This is because they were plotted above the MSCR curve. High elasticity results in lower amounts of permanent deformation [4]. Therefore, better rutting resistance of Sasobit®-modified binder is expected, as was described in the previous sections. The AASTHO T 350 criteria for MSCR %Recovery was not satisfied for three Sasobit®-modified binders. In Column 9 of Table 5.3, these binders are characterized as "No." As described in Section 4.3, this means the obtained %Recovery at 3.2 kPa is less than the desired %Recovery at 3.2 kPa calculated by Equation 2.1. The desired value of R3200 from Equation 2.1 was 98.5 % whereas, the actual R3200 from the MSCR tests was found to be about 97% for these three binders. The corresponding $J_{nr,\ 3.2\ kPa}$ value was obtained as 0.01 kPa^{-1}, for all three binders. Moreover, these three binders were found to experience higher R3200 values at 0.1 kPa than the rest of the Sasobit®-modified binders (Table 5.3).

Furthermore, the corresponding $J_{nr,\ diff}$ values were found to be either zero or negative. As described in Section 4.3, $J_{nr,diff}$ relates to the "Stress Sensitivity" of a binder. A higher $J_{nr,\ diff}$ means the binder is more sensitive to stress levels and vice versa. A polymer-modified binder is generally not expected to exhibit a zero or negative $J_{nr,diff}$ value. Types of polymer used and possible reactions between Sasobit and polymer might be a probable cause for such unexpected results. More MSCR testing of polymer-modified binders with Sasobit®-modification may be performed in the future to address this issue.

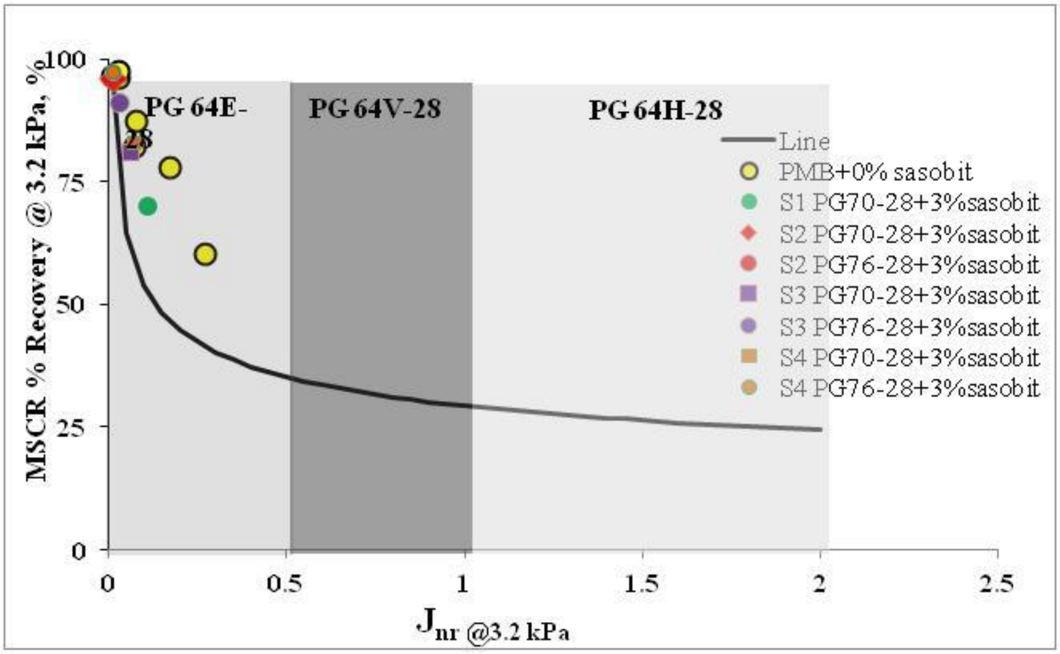


Figure 5.4 MSCR %Recovery vs. J_{nr} @ 3.2 kPa for Polymer-Modified Binder.

5.3.3 Impact of Modification on Binder Grade based on AASHTO MP-19

Figure 5.4 provided a visual understanding of the change in MSCR grading due to the addition of 3% Sasobit® in polymer-modified binders. From Figure 5.5, a significant decrease in non-recoverable creep compliance is seen due to the addition of 3% Sasobit® to a polymer-modified binder. Again, this gives an indication of having better rutting resistance. Without Sasobit® modification, polymer-modified binders were graded as PG 64E-28 (Table 5.3 and Figure 5.4). Thus, Sasobit® modification did not bring any change to this grading.

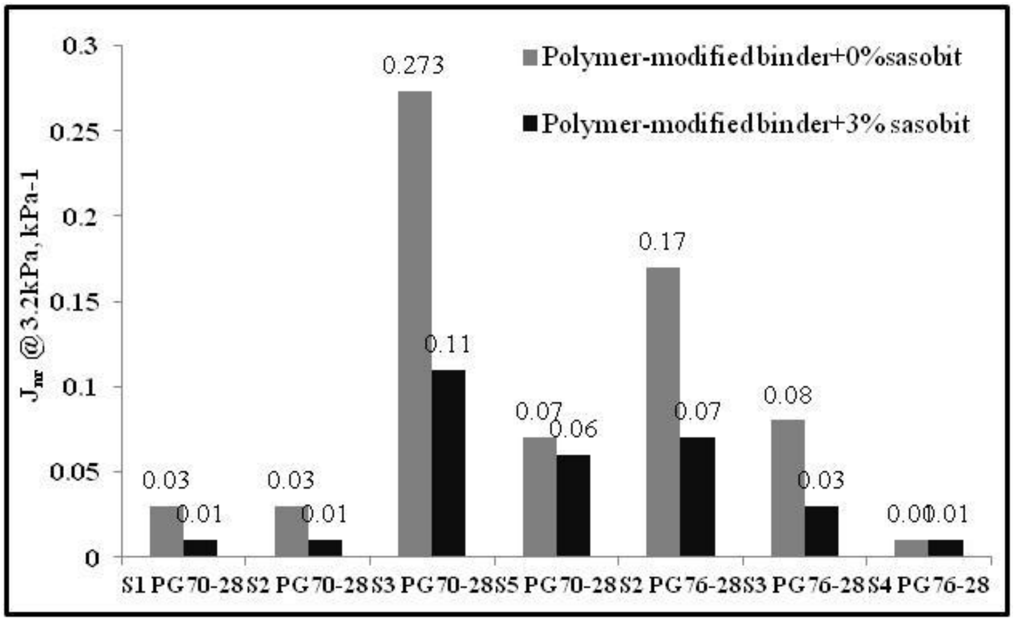


Figure 5.5 Change of J_{nr} @ 3.2 kPa with Addition of 3% Sasobit® Content.

5.4 Recovered Binder from RAP

5.4.1 MSCR Database

Because of increased construction costs and environmental awareness, the use of reclaimed asphalt pavement (RAP) is becoming a more common practice around the world. One of the main barriers to wide RAP usage is the difficulty of evaluating the properties of the binder in the RAP. Previous studies have consistently shown that chemical-based methods such as the Abson method can influence the properties of the recovered binder during solvent extraction. In the present study, MSCR tests were conducted on binders recovered from three laboratory simulated RAPs (SRAP1, SRAP2, and SRAP3) and one field RAP at three different temperatures (64°C, 70°C, and 76°C). Based on the information provided by the contractor, a PG 76-28 binder and a PG binder of unknown grade were used in the corresponding HMA mixes of SRAP1 and SRAP2, respectively. The third HMA mix was prepared with PG 64-22 OK binders. The current study utilized the Rotavapor method to recover binder from a solution, which was previously extracted in a centrifuge that used 85% toluene and 15% alcohol as solvents.

As described earlier, a binder can be graded based on the $J_{nr,\ 3.2\ kPa}$ at 64°C from the MSCR test. Thus, it was possible to document the changes in the binder grade due to long-term aging and recovery by comparing the MSCR grade of the recovered binders with that of the original binders. As done before, the replicates of each RAP were tested, and their average values are presented in Table 5.4. The recovered binders from both SRAPs exhibited a very low J_{nr} value, indicating their high resistance to rutting, as expected. A low J_{nr} value is expected because recovered binders from RAP are generally much stiffer than their original counterparts. Exposure of the pavement to atmospheric oxygen (oxidation) and weathering are the primary causes for such increased stiffness. Based on J_{nr} values and AASHTO T 350 criterion, all recovered binders from

SRAPs are graded as PG 64E-XX, which is the same as that of a typical PG 76-28 binder evaluated in this study. Another important observation is that the %Recovery at 3.2 kPa of the recovered binder from SRAP1 and SRAP3 are about 82% and 70%, respectively, which are about 8% and 20% lower than the average %Recovery of all tested PG 76-28 binders. On the other hand, the recovered binder from SRAP2 exhibited a significantly lower %Recovery of 55%, resembling a PG 70-28 binder.

The variations of J_{nr} and %Recovery values with respect to MSCR testing temperatures are also presented in Table 5.4 and Figure 5.6. In the case of SRAP1, SRAP2 and FRAP binders, it is seen that the J_{nr} increases and %Recovery values decreases with an increase in temperature. Such trends were observed for PG 70-28 and PG 76-28 binders evaluated in the current study. However, SRAP2 binders show opposite trends for both J_{nr} and %Recovery values. It should be noted that the mix design sheet along with the binder type of HMA corresponding to SRAP2 was unknown to the research team. This HMA mix could have contained RAP from an unknown source as contractors in Oklahoma usually use up to 25% RAP in base courses. The volumetric properties, RAP content, binder type and content, and additive type and content of the HMA mix, among other important factors, dictate the properties of the SRAP binder. Further, the recovery process (Rotavapor) of the binder from SRAP may have influenced the properties of the binder as a small trace of the recovery solvents (toluene and alcohol) in the residue could alter a binder’s viscoelastic properties.

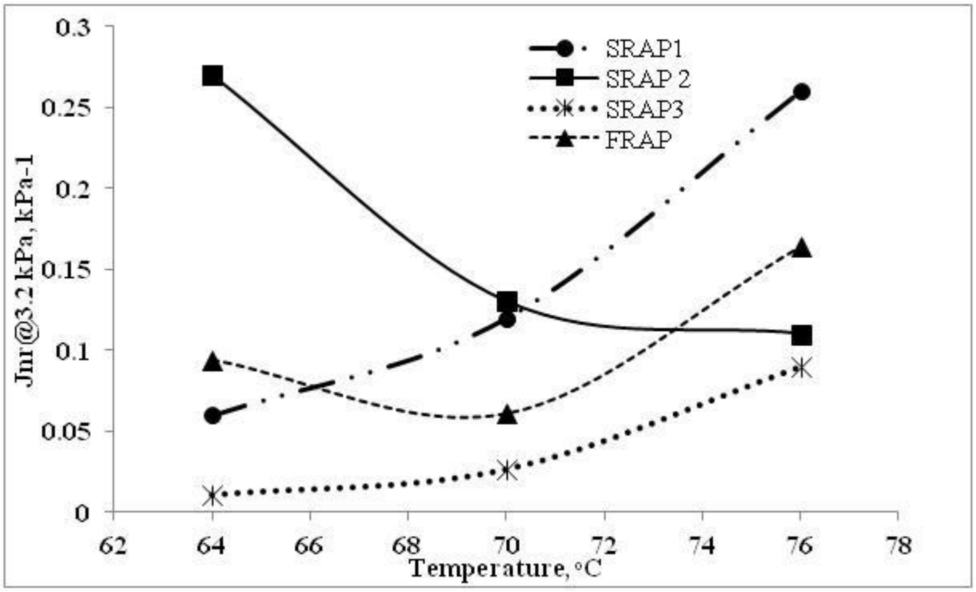
Table 5.4 MSCR Test Data and Analysis for Recovered Binders from SRAP

1		2	3	4	5	6	7	8	9	10
Source & type	temp	J_{nr} (0.1 kPa)	J_{nr} (3.2 kPa)	$J_{nr\ diff}$	Stress Sensitivity (Meets AASTHO T 332)	R100	R3200	R_{diff}	%Recovery (Meets AASTHO T 350)	MSCR GRADE
SRAP 1	64	0.064	0.061	-3.78	YES	85.73	85.37	0.4	YES	PG64E-XX
SRAP 2	64	0.24	0.27	14.85	YES	62.36	55.45	11.1	YES	PG64E-XX
SRAP 3	64	0.01	0.01	0.67	YES	73.00	72.80	0.3	NO	PG64-xxE
FRAP	64	0.09	0.09	4.05	YES	62.53	61.90	1.0	YES	PG64-xxE
SRAP 1	70	0.13	0.12	-12.07	YES	82.39	82.53	-0.2	YES	N/A
SRAP 2	70	0.13	0.13	0.00	YES	72.07	70.43	2.3	YES	N/A
SRAP 3	70	0.03	0.03	3.02	YES	66.23	65.14	0.6	NO	N/A
FRAP	70	0.1	0.1	1.89	YES	3.47	51.34	4.0	NO	N/A
SRAP 1	76	0.257	0.264	2.80	YES	78.99	74.62	5.5	YES	N/A
SRAP 2	76	0.11	0.11	-0.62	YES	72.89	71.46	2.0	YES	N/A
SRAP 3	76	0.0828	.0896	8.21	YES	57	53	7.6	NO	N/A
FRAP	76	0.15	0.16	10.59	YES	44.92	38.86	3.5	NO	N/A

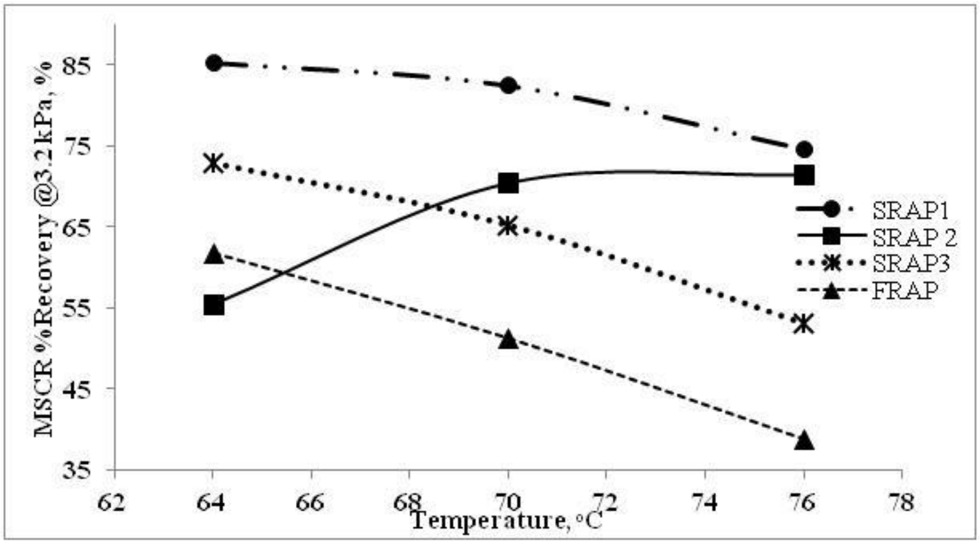
5.4.2 Polymer Method

As seen in Figure 5.7, for all three testing temperatures the data points of recovered binders from both SRAPs are scattered above the MSCR curve, which is expected for polymer-modified binders. These recovered binders also satisfy the AASHTO T 350 %Recovery criterion, excepting the SRAP3 binder. At any temperature, a higher %Recovery value was noticed for the SRAP1 binder than other RAP binders. The binder recovered from field RAP was noticed as having the lowest %Recovery values at all temperatures. Further, the SRAP1 binder exhibited a higher reduction in %Recovery when the temperature was increased from 70°C to 76°C, compared to that from 64°C to

70°C. When temperature was increased from 64˚C to 70˚C, the reduction in %Recovery at 3.2 kPa was around 4% compared to %Recovery at 64˚C. The reduction in %Recovery was found to be around 10% when the temperature was increased from 70˚C to 76˚C, compared to the %Recovery at 70˚C.



(a)



(b)

Figure 5.6 Change of MSCR Parameters @ 3.2 kPa with Increase in Temperatures for Recovered Binders (a) J_{nr}; (b) MSCR %Recovery.

As explained in Section 5.4.1, opposite trends for J_{nr} and %Recovery were observed only for the SRAP2 binder. Other RAP binders were observed to have a similar trend with increasing temperature. Moreover, the binder type and the mix type were unknown for the SRAP2.

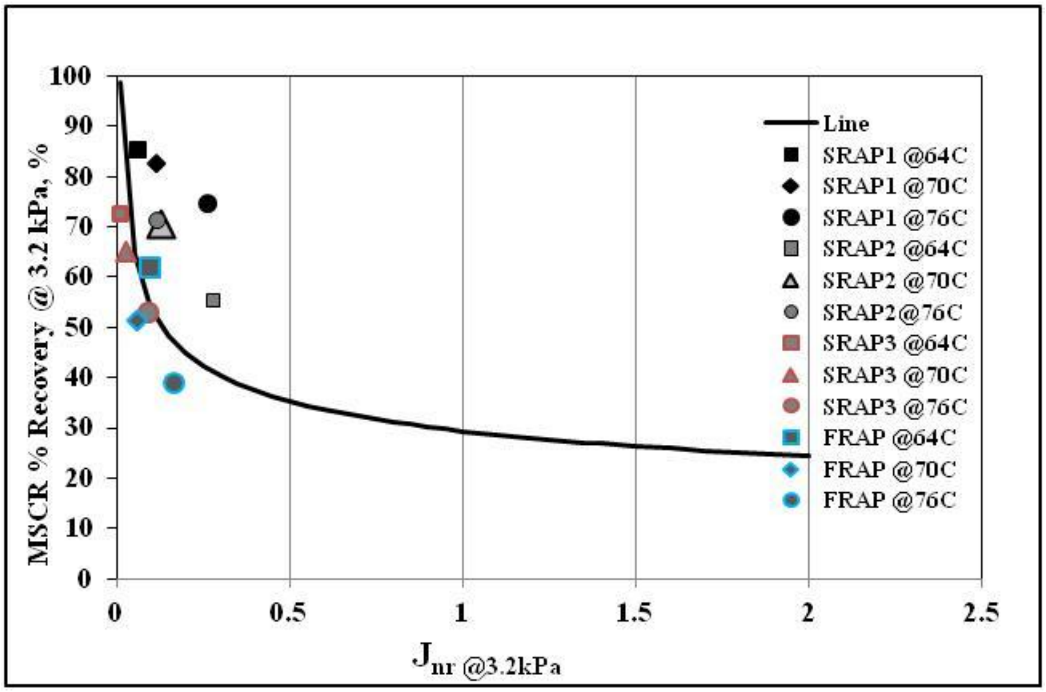


Figure 5.7 Polymer Method Analysis for Recovered Binders.

5.4.3 *Stress Sensitivity*

Only the recovered binder from SRAP3 did not meet the stress sensitivity criteria of AASTHO T 332. As shown in Figure 5.8, the recovered binders from SRAPs and FRAP exhibited prominent nonlinearity with increasing temperature. Thus, it is important to perform MSCR testing on RAP binders at higher temperatures than 64°C. The stress sensitivity was found to be negative or zero in some cases. The delayed elastic response of the binder or the steady creep stage might be a possible cause for such observations, as mentioned earlier in Section 4.5. This stress sensitivity issue should be addressed in a future study.

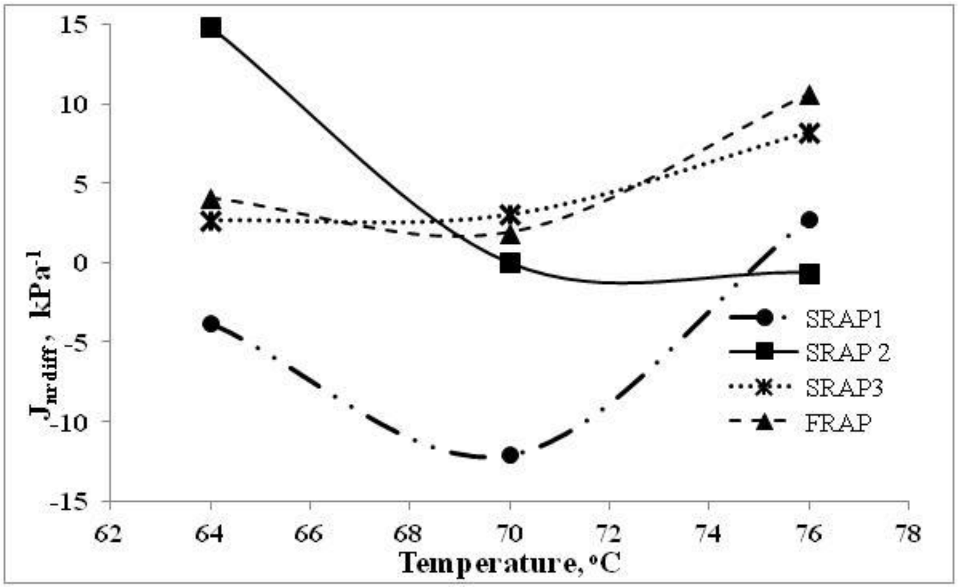


Figure 5.8 Change of Stress Sensitivity with Increase in Temperature for Recovered Binders.

5.4.4 Impact of Modification on Binder Grade based on AASHTO MP-19

The recovered binders from SRAPs and FRAP satisfied the conditions to be graded as PG 64E-XX. The maximum value of J_{nr} was found to be 0.27 kPa^{-1}. This value is much lower than the 0.5 required to reach the next lowest MSCR grade (Table 5.4). The binder used in both SRAPs was PG 76-28 binder. As discussed in Section 4.5, the PG 76-28 binders used in this study can be graded as PG 64E-28. Thus, based on these test results, the higher-temperature grade was verified by the MSCR grading. Bending Beam Rheometer (BBR) tests should be performed to determine the low temperature grade. More MSCR testing on the recovered binders from RAP could lead to more specific conclusions on grading of unknown binders.

5.5 Summary

Sasobit®-Modified Binders

- The J_{nr} was observed to decrease and the %Recovery was observed to increase with an increase in Sasobit® content in the neat binders, as expected.
- None of the PG 64-22 binders passed the AASHTO T 350 criterion for the %Recovery, even after Sasobit®-modification. The %Recovery was less than 50% for all tested Sasobit®-modified PG 64-22 binders. This indicated that the Sasobit®-modification was not enough to improve the %Recovery to a level expected for polymer modified binder. Still, Sasobit®-modification increased %Recovery by roughly more than ten times the %Recovery of neat binder. However, this was not valid for the binder from S4.
- An addition of 2% Sasobit® can lower the $J_{nr,\ 3.2\ kPa}$ values of the neat binders by 50%. Using this criterion, one can anticipate that the rut depth would be reduced to half when using only 2% Sasobit® as a modifier. However, this observation could not be supported by the test data for the binder from S4 which would require 3% Sasobit® to reduce the rut depth by half.
- Percent decrease in $J_{nr,\ 3.2\ kPa}$ and increase in %Recovery was not significant when increasing the Sasobit® content from 3% to 4% compared to that of 0% to 2% or 2% to 3%.
- An upward shift of binders' location in the MSCR %Recovery vs. J_{nr} at 3.2 kPa plot was noticed due to the addition of Sasobit®. The upward

shift towards the MSCR curve indicated a better MSCR grade and rutting resistance than a PG 64-22 binder without Sasobit®. However, this was not sufficient to meet the AASHTO T 350 criterion.

- Sasobit®-modification improved the MSCR grading from PG 64S-22 to PG 64E-22. The neat binders used herein were expected to withstand standard traffic condition. After being modified with Sasobit®, the binders were expected to withstand extreme traffic based on the $J_{nr,\ 3.2\ kPa}$ values.
- The PG 64-22 binder with 3% Sasobit® can be graded as PG 64E-22 with an average %Recovery of 20%.
- Sasobit® modification in polymer-modified binders did not cause any change in the MSCR grading, compared to binders without any Sasobit® modification. All binders were graded as PG 64E-28. However, 3% Sasobit®-modification was observed to reduce the $J_{nr,\ 3.2\ kPa}$ values by 50%. Based on this indicator, rut depths can be reduced by 50% with Sasobit® modification. Sasobit®-modification increased %Recovery in some binders by more than 30%.
- Addition of 3% Sasobit® to polymer-modified binders from S2 and S4 did not pass the AASTHO T 350 criteria for %Recovery. Stress sensitivity was observed to be either zero or negative for these binders as well. Still, these binders were plotted significantly above the MSCR curve.

<u>Recovered Binders from SRAP</u>

- Opposite trends were observed for the binders recovered from two different simulated reclaimed asphalt pavement (SRAP) samples with an increase in temperatures. The recovered binder from SRAP1 showed increasing J_{nr} with an increase in temperature, while recovered binder from SRAP2 showed an opposite trend with increasing temperature.

- Both recovered binders met the AASHTO T 332 criterion for the stress sensitivity as well as the AASHTO T 350 criteria for %Recovery.
- At 3.2 kPa, the %Recovery of the recovered binder from SRAP1 was found to be 82% at 64^{o}C, which is about 8% lower than a typical PG 76-28 binder used in the RAP mix.
- Significantly lower $J_{nr,\ 3.2\ kPa}$ values were observed for both SRAP binders. As a result, the recovered binders were graded with the highest MSCR grade of PG 64E-XX. These binders are expected to withstand extreme traffic conditions.

6 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

The study was intended to determine the feasibility of the adoption of the multiple stress creep recovery (MSCR) test method by the Oklahoma Department of Transportation (ODOT). To this end, a laboratory-based experimental study consisting of commonly used binders in Oklahoma was conducted. The experimental plan was comprised of Superpave® and MSCR testing of three selected types of performance grade (PG) binders: PG 64-22, PG 70-28, and PG 76-28. Also, the effects of a warm mix asphalt (WMA) additive, namely Sasobit®-modified binders, and binders recovered from two simulated reclaimed asphalt pavements (SRAP) on the original binders were evaluated.

The PG binders were obtained from 12 different ODOT certified sources (refineries). These sources were located throughout Oklahoma as well as in neighboring states. A significant portion of the MSCR (AASHTO T 350) and elastic recovery (ASTM D6084) test data was obtained from ODOT. The laboratory testing was conducted in multiple laboratories including the ODOT Liquid Laboratory, as part of a round robin study within the Southeastern Asphalt User/Producer Group (SEAUG). The laboratory tests conducted at The University of Oklahoma Asphalt Laboratory involved testing of the aforementioned three types of binders from five sources. Both data sources contained test results from conventional MSCR tests conducted in accordance with the AASHTO T 350 test method. In this method, tests are conducted on RTFO-aged binders at 64°C at two different stress levels, namely 0.1 kPa and

3.2 kPa. Some non-conventional MSCR tests were also conducted, in which RTFO-aged binders were tested at higher temperatures (70°C, 76°C) and a higher stress level (10 kPa) than those specified in the AASHTO T 350 test method. The MSCR test results were then analyzed in accordance with the AASHTO T 332 specifications.

In order to examine the effects of Sasobit® on J_{nr} and %Recovery, MSCR tests were conducted on neat binders (PG 64-22) modified with 2%, 3%, and 4% Sasobit® (by weight of the binder), and on polymer-modified binders (PG 70-28 and PG 76-28) with 3% Sasobit® (by weight of the binder). The simulated RAP samples investigated in this study were obtained through long term accelerated aging of two HMA mixes. Both of these mixes were of Type S4, prepared with PG 76-28 binders.

Two selected parameters, Non-Recoverable Creep Compliance (J_{nr}) and MSCR %Recovery (%Recovery) at 3.2 kPa, obtained from MSCR test data, were analyzed for MSCR grading. In addition, the Polymer method and the Quadrant method were used in the interpretation of the test data. Both of these guidelines have been suggested by Asphalt Institute (AI). To evaluate statistical variations of the test results, box-plot analysis, outlier detection, and two-tailed t-test were conducted. The box-plot analysis was conducted to examine the dispersion of data through the estimation of basic statistical parameters (average, median, 1st quartile, 3rd quartile, and margin of error) of a dataset from an individual source. The outliers in a dataset were detected based on John Tukey's Interquartile Range Rule. Two-tailed Student's t-tests were performed on a selective number of datasets to verify if one set of data significantly varies from another set of data with a confidence level of 95% (p = 0.005). Reproducibility of data obtained from the OU Asphalt Laboratory and from the ODOT MSCR database was checked. Reproducibility tests were also performed on data from sources (OU and ODOT).

6.2 Conclusions

Based on the results presented in Chapters 4 and 5 and their analyses and interpretations, the following conclusions are drawn:

- A large number of data points (59 out of 63 samples or 94%) for the PG 64-22 binders were scattered under the AASTHO T 350 MSCR curve. The average %Recovery at 3.2 kPa was found to be very low, about 2.5%, which could be considered "no recovery at all."
- All PG 70-28 binders (46 total) tested here met both the AASHTO T 332 stress sensitivity criterion ($J_{nr,\ diff} < 75\%$) and the AASTHO T 350 criterion for %Recovery. Based on the J_{nr} values, about 80% (37 out of 46) of the PG 70-28 binders were graded as PG 64E-22, which was followed by 20% (9 out of 46) of binders that were graded as PG 64V-22. According to the quadrant plot method, about 93% (43 out of 46 samples) of PG 70-28 binders met the AI recommended minimum MSCR %Recovery criterion of 50% (i.e., 15% less than the ODOT required minimum ER of 65%). All the tested PG 70-28 binders met the ODOT required minimum ER criterion of 65%. Only three binders from one source showed 45% recovery, and they resided in the "Supplier Risk" quadrant, indicating that the supplier is at risk.

- Analyses of MSCR test results show that the AASHTO T 350 recommended J_{nr} criteria could be followed in MSCR-based grading for conditions prevailing in Oklahoma and characteristics of local binders. The suggested minimum %Recovery for PG 70-28 binders would be about 50%, without penalizing a significant number suppliers and users.
- All 43 tested PG 76-28 binders met both the AASHTO T 332 stress sensitivity criterion and the AASTHO T 350 criterion for the %Recovery. Based on the J_{nr} values, all PG 76-28 binders were graded as PG 64E-22. The average %Recovery of PG 76-28 binders at 3.2 kPa was found to be 92%, which met the AI-recommended minimum %Recovery of 60% (15% less than the ODOT-required minimum ER of 75%). All tested PG 76-28 binders met the ODOT-required minimum ER of 75%. Further, all the tested binders fell in the “Pass” quadrant of the quadrant plot; none of the tested binders fell in the “Fail,” “Supplier Risk,” or “User Risk” quadrants.
- Similar to the PG 70-28 binders, the PG 76-28 binders could be graded based on the AASHTO T 350 recommended J_{nr} thresholds, along with the quadrant plots. Without penalizing any suppliers or users, the recommended minimum %Recovery for the local PG 76-28 binders would be about 80%. This approach to specifying a %Recovery is called a step approach versus the graphical method shown in AASHTO TP 70.
- The nonlinear behavior of PG 70-28 and PG 76-28 binders was more prominent at a higher stress level (10 kPa) than 3.2 kPa. Also, the

shapes of MSCR curves for these binders at higher temperatures (70°C and 76°C) were found to be different from those at 64°C. Thus, MSCR tests should be performed at 10 kPa and at higher temperatures (70°C and 76°C) to get a better understanding of nonlinearity and polymer networks in polymer-modified binders. The proposed minimum %Recovery values at 10 kPa for PG 70-28 and PG 76-28 binders would be about 45% and 70%, respectively.

- As in the case of polymer-modified binders, Sasobit®-modified binders can be evaluated by the AASHTO T 350 criterion. As expected, Sasobit® decreased J_{nr} and increased the %Recovery of both neat and polymer modified binders. With 2% Sasobit®, the MSCR grade of the PG 64-22 binders was upgraded to the next level of MSCR grade. Additionally, J_{nr} values were observed to decrease by about 70%. This indicated a reduction of rutting potential compared to the neat binder due to the addition of Sasobit®. With 3% Sasobit®, the PG 64-22 binders appeared to exhibit an MSCR grading of PG 64E-22. Modification with 3% Sasobit® did not make any change to MSCR grading of polymer-modified binders. However, 3% Sasobit® decreased the J_{nr} values of polymer-modified binders by about 50% compared with polymer-modified binders without Sasobit®. This reduction indicated a 50% reduction in rutting potential of Sasobit®-modified binders.
- Unexpectedly, the recovered binder from a RAP sample showed a reduced MSCR grade than the PG 76-28 binder used in the RAP mixes.

The recovered binders from both RAP samples were graded as PG 64E-XX. However, the recovered binder showed a significantly lower %Recovery of about 50%, compared to that of the PG 76-28 binder used in the SRAP1 mix. Such a reduction of %Recovery in RAP binders could be due to the traces of the extraction solvent in the recovered binder. Even though the reflux temperatures in the recovery process was below 150°C, polymer chains in the asphalt binders can break down at high temperatures.

- The LTPPBind software analysis revealed that at 95% reliability, the PG 76-28 binder satisfied a wide range of binders (from PG 58-10 to PG 76-16) for weather and traffic conditions prevailing in Oklahoma. If a 50% reliability is considered, then both PG 70-28 and PG 76-28 binders satisfied a larger set of binders ranging from PG 58-10 to PG 70-10. If the proposed MSCR grading was adopted, PG 64V-22 and PG 64E-22 binders would satisfy the recommended wide range of PG binders suggested by the LTPPBind software analysis. These grades would require less polymer and would need %Recovery less than the current limits recommended by this research and currently used by ODOT for PG 70-28 and PG 76-28.

6.3 Recommendations

Based on the limited scope of the present study and the assumptions made, the following recommendations are made for future studies:

- The current study did not obtain any information related to the type and amount of polymers used in polymer-modified binders. Most of the binders provided by the refinery may not have fixed and specific compositions. Some binders may have several types of polymers or additives to meet the target specifications. Thus, the influence of any specific type or amount of polymer on the non-recoverable compliance could not be identified from the present study. Therefore, it is suggested that a detailed evaluation of the impact of a broad range of polymer modifications on the non-recoverable compliance be pursued.

- The current study was limited to one loading (1 sec) and one resting (9 sec) period in each loading cycle. A future study may be pursued which incorporates different loading and unloading time periods that mimic a more realistic traffic frequency.
- The current study did not evaluate any rutting resistance of asphalt mix samples. A comprehensive study could be undertaken to establish correlation(s) between J_{nr} and rutting or MSCR %Recovery and rutting. Also, a future study could involve correlations between J_{nr} and field rutting.
- The current study evaluated only Sasobit® as a WMA additive. Other commonly used WMA additives (e.g., Advera® and Evotherm®) should be evaluated to verify if their MSCR-based J_{nr} and %Recovery values can be correlated with resistance to rutting.

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APPENDIX A: MSCR Database

The analysis of MSCR test results of three types of binders combining ODOT database and OU database is presented below in tabular format. The analysis was performed for the binders from several sources, mentioned clearly in the tables below.

Table A.1 MSCR test Data and Analysis for PG 64-22

1	2	3	4	5	6	7	8	9	10
Source ID	**J_{nr} (0.1 kPa)**	**J_{nr} (3.2 kPa)**	**$J_{nr\ diff}$**	**Stress Sensitivity (Meets AASTHO T 332)**	**R100**	**R3200**	**R_{diff}**	**%Recovery (Meets AASTHO T 350)**	**MSCR GRADE**
S1	2.10	2.39	13.59	YES	7.61	1.51	80.2	N/A	PG64S-22
S1	1.90	2.31	21.64	YES	12.97	2.99	76.9	N/A	PG64S-22
S1	2.12	2.52	18.66	YES	9.40	2.40	74.5	N/A	PG64S-22
S1	2.59	2.96	14.20	YES	7.65	1.29	83.2	N/A	PG64S-22
S1	2.53	3.05	20.43	YES	10.30	2.19	78.8	N/A	PG64S-22
S1	2.29	2.82	23.45	YES	12.39	2.50	79.8	N/A	PG64S-22
S1	1.83	2.29	25.08	YES	13.37	3.56	73.4	N/A	PG64S-22
S1*	1.51	1.64	8.95	YES	5.41	1.94	64.1	NO	PG64H-22
S2	3.28	3.27	-0.34	YES	-3.37	0.42	112.5	N/A	PG64S-22
S2	2.18	2.47	13.34	YES	7.64	1.48	80.7	N/A	PG64S-22
S2	3.07	3.15	2.87	YES	-1.47	0.80	154.8	N/A	PG64S-22
S2	2.95	3.14	6.45	YES	1.90	0.77	59.2	N/A	PG64S-22
S2	2.86	3.14	9.85	YES	4.47	0.81	81.9	N/A	PG64S-22
S2	2.97	3.33	12.12	YES	6.30	0.73	88.3	N/A	PG64S-22
S2	2.49	2.63	5.71	YES	1.68	1.65	1.9	N/A	PG64S-22
S2*	1.32	1.52	15.15	YES	3.71	1.32	64.4	NO	PG64H-22
S3	2.41	2.59	7.64	YES	1.87	1.60	14.2	N/A	PG64S-22
S3*	1.88	2.05	9.35	YES	4.63	1.31	71.6	N/A	PG64S-22
S4	1.32	1.90	43.76	YES	42.23	23.37	44.7	NO	PG64H-22
S4	0.83	1.18	41.79	YES	45.30	27.20	40.0	NO	PG64H-22
S4	0.44	0.68	54.02	YES	67.48	47.89	29.0	YES	PG64V-22
S4	2.11	2.77	31.58	YES	22.99	8.27	64.0	N/A	PG64S-22
S4*	1.41	1.73	22.93	YES	19.62	7.61	61.2	NO	PG64H-22
S5	2.14	2.23	4.26	YES	0.36	1.69	-367	N/A	PG64S-22
S6	4.04	4.22	4.43	YES	0.60	0.11	81.7	N/A	N/A
S6	3.81	3.86	1.52	YES	-2.14	0.18	108.4	N/A	PG64S-22
S6	3.82	4.18	9.42	YES	4.84	0.01	99.8	N/A	N/A
S6	3.79	3.93	3.72	YES	0.53	0.07	86.1	N/A	PG64S-22
S6	4.03	4.09	1.64	YES	-1.81	0.10	105.5	N/A	N/A
S6	3.53	3.88	9.82	YES	4.96	0.14	97.1	N/A	PG64S-22
S6	3.78	4.20	11.26	YES	6.34	0.00	100.0	N/A	N/A

1	2	3	4	5	6	7	8	9	10
Source ID	**J_{nr} (0.1 kPa)**	**J_{nr} (3.2 kPa)**	**$J_{nr\ diff}$**	**Stress Sensitivity (Meets AASTHO T 332)**	**R100**	**R3200**	**R_{diff}**	**%Recovery (Meets AASTHO T 350)**	**MSCR GRADE**
S6	3.89	4.14	6.35	YES	2.24	0.07	96.8	N/A	N/A
S6	3.89	4.17	7.21	YES	2.85	0.05	98.2	N/A	N/A
S6	3.63	3.89	7.28	YES	2.98	0.14	95.4	N/A	PG64S-22
S6	3.83	3.98	3.81	YES	-0.03	0.15	599.0	N/A	PG64S-22
S6	2.28	2.66	16.75	YES	9.18	1.50	83.7	N/A	PG64S-22
S8	3.33	3.65	9.57	YES	4.99	0.19	96.2	N/A	PG64S-22
S8	3.52	3.67	4.26	YES	0.83	0.26	68.9	N/A	PG64S-22
S8	3.51	3.88	10.36	YES	5.63	0.13	97.7	N/A	PG64S-22
S8	3.56	3.72	4.55	YES	0.87	0.17	80.5	N/A	PG64S-22
S8	3.66	3.96	8.18	YES	4.20	0.16	96.2	N/A	PG64S-22
S8	3.79	3.83	1.11	YES	-2.02	0.20	110.1	N/A	PG64S-22
S8	3.40	3.59	5.59	YES	1.76	0.26	85.3	N/A	PG64S-22
S9	4.60	4.72	2.59	YES	-3.21	0.14	104.3	N/A	N/A
S9	4.08	4.44	8.75	YES	2.39	0.24	90.0	N/A	N/A
S9	4.23	4.70	11.17	YES	4.18	0.18	95.6	N/A	N/A
S9	4.08	4.38	7.36	YES	2.21	0.27	87.6	N/A	N/A
S9	3.83	3.91	2.33	YES	-2.26	0.35	115.5	N/A	PG64S-22
S9	3.94	4.29	8.92	YES	2.38	0.24	90.0	N/A	N/A
S10	2.87	3.03	5.57	YES	0.87	1.01	-16.1	N/A	PG64S-22
S10	3.32	3.67	10.54	YES	5.11	0.36	93	N/A	PG64S-22
S10	3.67	3.93	7.23	YES	2.19	0.27	88	N/A	PG64S-22
S10	3.51	3.94	12.26	YES	5.99	0.35	94	N/A	PG64S-22
S10	3.36	3.76	11.66	YES	5.32	0.51	90	N/A	PG64S-22
S10	3.87	4.02	3.96	YES	-0.49	0.21	144	N/A	N/A
S11	3.83	4.18	9.03	YES	4.27	0.12	97	N/A	N/A
S11	3.94	3.94	-0.03	YES	-3.30	0.12	104	N/A	PG64S-22
S11	3.99	3.96	-0.75	YES	-3.91	0.13	103	N/A	PG64S-22
S11	4.22	4.38	3.67	YES	-1.29	0.06	105	N/A	N/A
S11	4.14	4.29	3.72	YES	-0.14	0.07	148	N/A	N/A
S11	3.82	4.07	6.60	YES	2.29	0.11	95	N/A	N/A
S11	3.67	3.95	7.60	YES	3.00	0.16	95	N/A	PG64S-22
S12	2.20	2.52	14.79	YES	8.13	1.81	78	N/A	PG64S-22
*: OU Laboratory MSCR Test Data									

Table A.2 MSCR Test Data and Analysis for PG 70-28

1	2	3	4	5	6	7	8	9	10
Source ID	$J_{nr,}$ 0.1 kPa	$J_{nr,}$ 3.2 kPa	$J_{nr,diff}$	Stress Sensitivity (Meets AASTHO T 332)	R100	R3200	R_{diff}	%Recovery (Meets AASTHO T 350)	MSCR Grade
S1	0.13	0.12	-8.82	YES	80.61	81.48	-1.1	YES	PG64E-28
S1	0.15	0.13	-9.60	YES	79.17	79.97	-1.0	YES	PG64E-28
S1	0.20	0.23	18.00	YES	71.48	68.14	4.7	YES	PG64E-28
S1	0.04	0.03	-16.62	YES	94.9	95.3	-0.4	YES	PG64E-28
S1	0.15	0.14	-2.45	YES	79.45	78.85	0.8	YES	PG64E-28
S1	0.29	0.34	14.86	YES	69.45	65.21	6.1	YES	PG64E-28
S1	0.19	0.20	5.28	YES	80.51	79.35	1.4	YES	PG64E-28
S1	0.21	0.19	-8.04	YES	78.5	80.47	-2.5	YES	PG64E-28
S1	0.42	0.50	17.28	YES	63.95	59.16	7.5	YES	PG64E-28
S1*	0.30	0.37	22.44	YES	61.71	53.44	13.4	YES	PG64E-28
S2	0.05	0.05	-0.88	YES	94.95	94.99	0.0	YES	PG64E-28
S2	0.05	0.05	5.48	YES	95.81	95.15	0.7	YES	PG64E-28
S2	0.09	0.07	-22.97	YES	91.90	93.27	-1.5	YES	PG64E-28
S2	0.21	0.14	-32.09	YES	86.63	90.18	-4.1	YES	PG64E-28
S2	0.10	0.09	-9.67	YES	90.93	91.10	-0.2	YES	PG64E-28
S2	0.11	0.08	-27.63	YES	90.48	92.45	-2.2	YES	PG64E-28
S2	0.12	0.09	-30.63	YES	88.04	90.65	-3.0	YES	PG64E-28
S2	0.08	0.06	-28.04	YES	92.87	94.33	-1.6	YES	PG64E-28
S2	0.08	0.06	-26.25	YES	92.33	93.59	-1.4	YES	PG64E-28
S2	0.11	0.07	-35.94	YES	90.50	92.70	-2.4	YES	PG64E-28
S2	0.15	0.13	-11.75	YES	87.1	87.2	-0.2	YES	PG64E-28
S2	0.12	0.08	-32.74	YES	89.8	92.7	-3.3	YES	PG64E-28
S2	0.14	0.12	-12.12	YES	87.0	87.7	-0.9	YES	PG64E-28
S2	0.05	0.05	-1.43	YES	94.8	94.9	-0.1	YES	PG64E-28
S2	0.07	0.06	-17.97	YES	92.1	93.1	-1.1	YES	PG64E-28
S2	0.04	0.04	1.38	YES	95.5	95.5	0.0	YES	PG64E-28
S2*	0.03	0.02	-7.42	YES	95.26	95.39	-0.14	YES	PG64E-28
S3	0.54	0.78	44.97	YES	63.8	50.2	21.3	YES	PG64V-28
S3	0.47	0.58	23.63	YES	65.5	59.1	9.7	YES	PG64V-28
S3	0.30	0.35	14.64	YES	70.7	67.1	5.2	YES	PG64E-28
S3	0.46	0.64	38.26	YES	66.3	54.1	18.5	YES	PG64V-28
S3	0.37	0.50	33.97	YES	64.0	51.5	19.6	YES	PG64E-28
S3	0.57	0.82	43.33	YES	60.27	45.14	25.1	YES	PG64V-28
S3	0.50	0.70	40.07	YES	60.34	46.39	23.1	YES	PG64V-28
S3	0.49	0.66	34.57	YES	58.28	44.52	23.6	YES	PG64V-28
S3	0.39	0.52	32.65	YES	67.05	56.05	16.4	YES	PG64V-28
S3	0.40	0.55	36.66	YES	64.75	51.42	20.6	YES	PG64V-28
S3	0.34	0.42	22.63	YES	69.08	61.30	11.3	YES	PG64E-28
S3	0.35	0.44	26.69	YES	65.31	55.53	15.0	YES	PG64E-28
S3*	0.17	0.19	7.25	YES	74.59	71.81	3.73	YES	PG64E-28
S5	0.17	0.17	1.18	YES	84.44	84.03	0.5	YES	PG64E-28
S5	0.39	0.53	34.19	YES	61.2	51.13	16.5	YES	PG64V-28
S5*	0.13	0.13	-2.06	YES	80.38	80.61	-0.29	YES	PG64E-28
S7	0.20	0.21	6.11	YES	73.97	71.74	3.0	YES	PG64E-28
S7	0.28	0.34	21.90	YES	71.35	65.96	7.6	YES	PG64E-28
S7	0.35	0.38	11.09	YES	69.49	66.13	4.8	YES	PG64E-28

*: OU Laboratory MSCR Test Data

Table A.3 MSCR Test Data and Analysis for PG 76-28

1	2	3	4	5	6	7	8	9	10
Source ID	J_{nr} (0.1 kPa)	J_{nr} (3.2 kPa)	J_{nr} diff	Stress Sensitivity (Meets AASTHO T 332)	R100	R3200	R diff	%Recovery (Meets AASTHO T 350)	MSCR GRADE
S1	0.06	0.05	-12.1	YES	88.51	89.28	-0.9	YES	PG64E-28
S1	0.11	0.10	-10.5	YES	84.73	86.27	-1.8	YES	PG64E-28
S1	0.03	0.03	-20.7	YES	95.6	96.49	-0.9	YES	PG64E-28
S1	0.08	0.09	1.9	YES	86.94	86.93	0.0	YES	PG64E-28
S1	0.10	0.08	-14.4	YES	87.08	88.58	-1.7	YES	PG64E-28
S1	0.15	0.13	-12.9	YES	84.12	85.65	-1.8	YES	PG64E-28
S1	0.12	0.12	-0.7	YES	85.29	85.08	0.2	YES	PG64E-28
S2	0.01	0.02	3.3	YES	97.7	97.7	0.0	YES	PG64E-28
S2	0.01	0.01	-7.2	YES	97.9	98.1	-0.2	NO	PG64E-28
S2	0.01	0.01	0.7	YES	98.0	98.1	-0.1	YES	PG64E-28
S2	0.02	0.02	8.5	YES	97.6	97.5	0.1	YES	PG64E-28
S2	0.03	0.03	-22.9	YES	95.6	96.5	-0.9	YES	PG64E-28
S2	0.02	0.02	5.4	YES	97.0	96.9	0.1	YES	PG64E-28
S2	0.04	0.04	1.3	YES	94.5	94.5	0.0	YES	PG64E-28
S2	0.02	0.02	-13.2	YES	96.7	97.0	-0.3	YES	PG64E-28
S2	0.02	0.02	-13.5	YES	97.4	97.7	-0.3	YES	PG64E-28
S2	0.02	0.02	1.7	YES	97.3	97.3	-0.1	YES	PG64E-28
S2	0.04	0.03	-21.7	YES	95.6	96.4	-0.8	YES	PG64E-28
S2	0.02	0.02	4.3	YES	96.8	96.8	0.0	YES	PG64E-28
S2	0.03	0.03	-0.1	YES	96.2	96.1	0.0	YES	PG64E-28
S2	0.02	0.02	-12.4	YES	96.8	97.1	-0.3	YES	PG64E-28
S2	0.03	0.02	-15.6	YES	96.4	96.8	-0.4	YES	PG64E-28
S2*	0.02	0.01	-2.92	YES	96.98	97.07	-0.09	YES	PG64E-22
S3	0.03	0.03	-3.8	YES	92.1	92.0	0.2	YES	PG64E-28
S3	0.10	0.09	-12.0	YES	86.2	87.9	-1.9	YES	PG64E-28
S3	0.10	0.10	-1.4	YES	85.9	86.0	-0.1	YES	PG64E-28
S3	0.04	0.03	-22.6	YES	94.9	95.85	-1.0	YES	PG64E-28
S3	0.08	0.07	-17.3	YES	90.9	91.36	-0.5	YES	PG64E-28
S3	0.08	0.08	0.3	YES	88.6	87.96	0.7	YES	PG64E-28
S3	0.15	0.14	-3.2	YES	81.8	82.34	-0.6	YES	PG64E-28
S3	0.13	0.14	2.8	YES	81.6	80.93	0.8	YES	PG64E-28
S3	0.11	0.10	-6.6	YES	84.0	84.36	-0.5	YES	PG64E-28
S3	0.12	0.11	-2.0	YES	85.7	85.71	0.0	YES	PG64E-28
S3	0.11	0.11	-3.4	YES	84.6	84.24	0.5	YES	PG64E-28
S3	0.08	0.08	-6.1	YES	85.3	85.49	-0.2	YES	PG64E-28
S3*	0.06	0.06	-6.13	YES	88.95	89.32	-0.41	YES	PG64E-28
S4	0.03	0.03	-3.1	YES	93.74	93.63	0.1	YES	PG64E-28
S4	0.02	0.02	1.9	YES	95.42	95.11	0.3	YES	PG64E-28
S4	0.05	0.04	-15.8	YES	94.29	94.78	-0.5	YES	PG64E-28
S4	0.02	0.02	-11.1	YES	95.69	95.72	0.0	YES	PG64E-28
S4	0.03	0.03	-10.0	YES	95.11	95.27	-0.2	YES	PG64E-28
S4	0.01	0.01	0.5	YES	96.79	96.75	0.0	YES	PG64E-28
S4*	0.02	0.02	0.31	YES	96.28	96.16	0.13	YES	PG64E-22

*: OU Laboratory MSCR Test Data

APPENDIX B: Outlier Detection, Precision and Bias Check

The analysis for detection of outlier and the check for precision and bias existence in the data set for three types of binders are presented in the tables below.

Table B.1 Detection of Outlier and Bias for J_{nr} @ 3.2 kPa of PG 64-22

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	J_{nr} (3.2 kPa)	Outlier[a]	Sample Size, N	Mean	SD[b]	CoV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S1	2.39	No	8.00	2.50	0.45	0.18	1.41	Yes	2.365	0.661	No
S1	2.31	No								1.190	No
S1	2.52	No								-0.134	No
S1	2.96	No								-2.876	Yes
S1	3.05	No								-3.429	Yes
S1	2.82	No								-2.024	No
S1	2.29	No								1.289	No
S1*	1.64	No								5.324	Yes
S2	3.27	No	8.00	2.83	0.61	0.22	1.81	Yes	2.365	-2.020	No
S2	2.47	No								1.660	No
S2	3.15	No								-1.489	No
S2	3.14	No								-1.402	No
S2	3.14	No								-1.443	No
S2	3.33	No								-2.307	No
S2	2.63	No								0.944	No
S2*	1.52	Outlier								6.057	Yes
S3	2.59	No	2.00	2.32	0.38		0.54		12.71	-0.707	No
S3*	2.05	No								0.707	No
S4	1.90	No	5.00	1.65	0.79	0.48	2.09	Yes	2.776	-0.707	No
S4	1.18	No								1.347	No
S4	0.68	No								2.757	No
S4	2.77	No								-3.167	Yes
S4*	1.73	No								-0.230	No
S5	2.23	N/A	1.00	2.23	N/A						
S6	4.22	No	12.00	3.93	0.42	0.11	1.56	Yes	2.20	-2.313	Yes
S6	3.86	No								0.562	No
S6	4.18	No								-2.043	No
S6	3.93	No								0.048	No
S6	4.09	No								-1.316	No
S6	3.88	No								0.431	No
S6	4.20	No								-2.190	No
S6	4.14	No								-1.684	No
S6	4.17	No								-1.904	No
S6	3.89	No								0.333	No
S6	3.98	No								-0.353	No
S6	2.66	Outlier								10.428	Yes
S8	3.65	No	7.00	3.76	0.13	0.04	0.37	Yes	2.45	2.582	Yes
S8	3.67	No								2.137	No
S8	3.88	No								-2.378	No
S8	3.72	No								0.659	No
S8	3.96	No								-3.936	Yes
S8	3.83	No								-1.451	No
S8	3.59	No								3.342	Yes
S9	4.72	No	6.00	4.41	0.30	0.07	0.81	Yes	2.57	-2.608	Yes
S9	4.44	No								-0.254	No

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	J_{nr} (3.2 kPa)	Outlier[a]	Sample Size, N	Mean	SD[b]	CoV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S9	4.70	No								-2.402	No
S9	4.38	No								0.240	No
S9	3.91	No								4.043	Yes
S9	4.29	No								0.981	No
S10	3.03	Outlier	6.00	3.72	0.36	0.10	0.99	Yes	2.57	4.672	Yes
S10	3.67	No								0.364	No
S10	3.93	No								-1.400	No
S10	3.94	No								-1.427	No
S10	3.76	No								-0.209	No
S10	4.02	No								-1.999	No
S11	4.18	No	7.00	4.11	0.18	0.04	0.44	Yes	2.45	-1.015	No
S11	3.94	No								2.530	Yes
S11	3.96	No								2.215	No
S11	4.38	No								-4.034	Yes
S11	4.29	No								-2.682	Yes
S11	4.07	No								0.562	No
S11	3.95	No								2.425	No
S12	2.52		1.00	2.52	Not Applicable						

[a] John Tukey's Inter-Quartile Range Method for Outlier Filter [82]

[b] : Standard Deviation [c] : Coeffcient of Variation

[d]: (Maximum J_{nr} -Minimum J_{nr}) for Each Source

[e]: If Column 8 < Column 6* Multiplier from Table 1 of ASTM C670(for Number of test results): Yes, otherwise No.

[f,g,h]: Described in section 4.3

*: OU Laboratory MSCR Test Data

Table B.2 Detection of Outlier and Bias Criteria Check for MSCR %Recovery @ 3.2 kPa of PG 64-22

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	R3200	Outlier[a]	Sample Size, N	Mean	SD[b]	CoV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S1	1.51	No	8.00	2.30	0.75	0.32	2.27	Yes	2.365	2.980	Yes
S1	2.99	No								-2.637	Yes
S1	2.40	No								-0.384	No
S1	1.29	Outlier								3.822	Yes
S1	2.19	No								0.416	No
S1	2.50	No								-0.774	No
S1	3.56	No								-4.776	Yes
S1*	1.94	No								1.352	No
S2	0.42	No	8.00	1.00	0.43	0.43	1.23	Yes	2.365	3.819	Yes
S2	1.48	No								-3.163	Yes
S2	0.80	No								1.281	No
S2	0.77	No								1.484	No
S2	0.81	No								1.254	No
S2	0.73	No								1.745	No
S2	1.65	No								-4.293	Yes
S2*	1.32	No								-2.126	No
S3	1.60	No	2.00	1.46	0.20	0.14	0.54	Yes	12.71	-0.707	No
S3*	1.31	No								0.707	No
S4	23.37	No	5.00	22.87	16.51	0.72	40.28	No	2.776	-0.068	No
S4	27.20	No								-0.586	No
S4	47.89	No								-3.388	Yes
S4	8.27	No								1.976	No
S4*	7.61	No								2.066	No
S5	1.69	N/A	1.00	2.23	N/A						
S6	0.11	No	12.00	0.21	0.41	1.95	1.50	Yes	2.20	0.856	No
S6	0.18	No								0.263	No
S6	0.01	No								1.702	No
S6	0.07	No								1.154	No
S6	0.10	No								0.935	No
S6	0.14	No								0.578	No
S6	0.00	No								1.798	No
S6	0.07	No								1.165	No
S6	0.05	No								1.335	No
S6	0.14	No								0.609	No
S6	0.15	No								0.503	No
S6	1.50	Outlier								-10.89	Yes
S8	0.19	No	7.00	0.20	0.05	0.25	0.13	Yes	2.45	0.455	No
S8	0.26	No								-4.253	Yes
S8	0.13	No								3.540	Yes
S8	0.17	No								1.395	No
S8	0.16	No								1.984	No
S8	0.20	No								-0.464	No
S8	0.26	No								-3.425	Yes
S9	0.14	No	6.00	0.24	0.07	0.31	0.21	Yes	2.57	3.328	Yes
S9	0.24	No								-0.059	No
S9	0.18	No								1.772	No
S9	0.27	No								-1.221	No
S9	0.35	No								-3.780	Yes
S9	0.24	No								-0.039	No
S10	1.01	Outlier	6.00	0.45	0.29	0.65	0.80	Yes	2.57	-4.687	Yes
S10	0.36	No								0.771	No
S10	0.27	No								1.567	No
S10	0.35	No								0.871	No
S10	0.51	No								-0.512	No
S10	0.21	No								1.990	No

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	R3200	Outlier[a]	Sample Size, N	Mean	SD[b]	CoV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S11	0.12	No	7.00	0.11	0.04	0.32	0.10	Yes	2.45	-0.756	No
S11	0.12	No								-0.613	No
S11	0.13	No								-1.539	No
S11	0.06	No								3.680	Yes
S11	0.07	No								3.276	Yes
S11	0.11	No								-0.260	No
S11	0.16	No								-3.788	Yes
S12	1.81	N/A	1.00	2.52	N/A						
[a:] John Tukey's Inter-Quartile Range Method for Outlier Filter [82]											
[b] : Standard Deviation [c] : Coeffcient of Variation											
[d]: (Maximum J_{nr} -Minimum J_{nr}) for Each Source											
[e]: If Column 8 < Column 6* Multiplier from Table 1 of ASTM C670(for Number of test results): Yes, otherwise No.											
[f,g,h]: Described in section 4.3											
*: OU Laboratory MSCR Test Data											

Table B.3 Detection of Outlier and Bias for J_{nr} @ 3.2 kPa of PG 70-28

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	J_{nr} (3.2 kPa)	Outlier[a]	Sample Size, N	Mean	SD[b]	CoV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S1	0.12	No	10.00	0.23	0.14	0.62	0.46	Yes	2.262	2.419	Yes
S1	0.13	No								2.157	No
S1	0.23	No								-0.066	No
S1	0.03	No								4.318	Yes
S1	0.14	No								1.906	No
S1	0.34	No								-2.348	Yes
S1	0.20	No								0.626	No
S1	0.19	No								0.853	No
S1	0.50	No								-5.912	Yes
S1*	0.41	No								-3.954	Yes
S2	0.05	No	17.00	0.07	0.03	0.44	0.11	Yes	2.119	1.720	No
S2	0.05	No								2.029	No
S2	0.07	No								0.674	No
S2	0.14	Outlier								-5.884	Yes
S2	0.09	No								-1.397	No
S2	0.079	No								-0.418	No
S2	0.09	No								-1.005	No
S2	0.06	No								1.599	No
S2	0.06	No								1.452	No
S2	0.07	No								0.319	No
S2	0.13	No								-5.004	Yes
S2	0.08	No								-0.836	No
S2	0.12	No								-4.221	Yes
S2	0.05	No								2.319	Yes
S2	0.06	No								1.356	No
S2	0.04	No								3.133	Yes
S2*	0.03	No								4.166	Yes
S3	0.78	No	13.00	0.55	0.17	0.31	0.22	Yes	2.18	-4.883	Yes
S3	0.58	No								-0.491	No
S3	0.35	No								4.254	Yes
S3	0.64	No								-1.804	No
S3	0.50	No								1.159	No
S3	0.82	No								-5.690	Yes
S3	0.70	No								-3.092	Yes
S3	0.66	No								-2.250	Yes
S3	0.52	No								0.740	No
S3	0.55	No								-0.001	No
S3	0.42	No								2.733	Yes
S3	0.44	No								2.346	Yes
S3*	0.22	No								6.979	Yes
S5	0.17	No	3.00	0.28	0.22	0.78	0.39	Yes	4.30	0.849	No
S5	0.53	No								-1.993	No
S5*	0.14	No								1.144	No

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	J_{nr} (3.2 kPa)	Outlier[a]	Sample Size, N	Mean	SD[b]	CoV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S7	0.21	No	3.00	0.31	0.09	0.29	0.17	Yes	4.30	1.934	No
S7	0.34	No								-0.525	No
S7	0.38	No								-1.409	No

[a] John Tukey's Inter-Quartile Range Method for Outlier Filter [82]

[b] : Standard Deviation [c] : Coeffcient of Variation

[d]: (Maximum J_{nr} -Minimum J_{nr}) for Each Source

[e]: If Column 8 < Column 6* Multiplier from Table 1 of ASTM C670(for Number of test results): Yes, otherwise No.

[f,g,h]: Described in section 4.3

*: OU Laboratory MSCR Test Data

Table B.4 Detection of Outlier and Bias for MSCR %Recovery @ 3.2 kPa of PG 70-28

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	$J_{nr\ (3.2\ kPa)}$	Outlier[a]	Sample Size, N	Mean	SD[b]	CoV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S1	81.48	No	10.00	73.91	12.87	0.17	44.10	Yes	2.262	-1.859	No
S1	79.97	No								-1.488	No
S1	68.14	No								1.418	No
S1	95.30	No								-5.255	Yes
S1	78.85	No								-1.213	No
S1	65.21	No								2.138	No
S1	79.35	No								-1.336	No
S1	80.47	No								-1.611	No
S1	59.16	No								3.625	Yes
S1*	51.20	No								5.581	Yes
S2	94.99	No	17.00	92.65	2.55	0.03	8.34	Yes	2.119	-2.599	Yes
S2	95.15	No								-2.777	Yes
S2	93.27	No								-0.692	No
S2	90.18	No								2.736	Yes
S2	91.10	No								1.715	No
S2	92.45	No								0.218	No
S2	90.65	No								2.214	Yes
S2	94.33	No								-1.867	No
S2	93.59	No								-1.046	No
S2	92.70	No								-0.059	No
S2	87.20	No								6.041	Yes
S2	92.68	No								-0.037	No
S2	87.70	No								5.486	Yes
S2	94.92	No								-2.522	Yes
S2	93.10	No								-0.503	No
S2	95.54	No								-3.209	Yes
S2*	95.44	No								-3.098	Yes
S3	50.23	No	13.00	54.68	7.72	0.14	24.03	Yes	2.18	2.079	No
S3	59.13	No								-2.077	No
S3	67.05	No								-5.775	Yes
S3	54.06	No								0.291	No
S3	51.50	No								1.486	No
S3	45.14	No								4.456	Yes
S3	46.39	No								3.872	Yes
S3	44.52	No								4.745	Yes
S3	56.05	No								-0.639	No
S3	51.42	No								1.523	No
S3	61.30	No								-3.090	Yes
S3	55.53	No								-0.396	No
S3*	68.55	No								-6.475	Yes
S5	84.03	No	3.00	71.84	18.03	0.25	32.90	Yes	4.30	-1.171	No
S5	51.13	No								1.990	No
S5*	80.37	No								-0.819	No

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	J_{nr} (3.2 kPa)	Outlier[a]	Sample Size, N	Mean	SD[b]	CoV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S7	71.74	No	3.00	67.94	3.29	0.05	5.78	Yes	4.30	-1.999	No
S7	65.96	No								1.044	No
S7	66.13	No								0.955	No

[a] John Tukey's Inter-Quartile Range Method for Outlier Filter [82]

[b] : Standard Deviation [c] : Coeffcient of Variation

[d]: (Maximum J_{nr} -Minimum J_{nr}) for Each Source

[e]: If Column 8 < Column 6* Multiplier from Table 1 of ASTM C670(for Number of test results): Yes, otherwise No.

[f,g,h]: Described in section 4.3

*: OU Laboratory MSCR Test Data

Table B.5 Detection of Outlier and Bias for J_{nr} @ 3.2 kPa of PG 76-28

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	J_{nr} (3.2 kPa)	Outlier[a]	Sample Size, N	Mean	SD[b]	CoV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S1	0.06	No	7.00	0.09	0.04	0.41	0.11	Yes	2.447	2.384	No
S1	0.11	No								-1.329	No
S1	0.03	No								4.081	Yes
S1	0.08	No								0.629	No
S1	0.10	No								-0.188	No
S1	0.15	No								-3.767	Yes
S1	0.12	No								-1.810	No
S2	0.01	No	16.00	0.02	0.01	0.37	0.03	Yes	2.131	3.834	Yes
S2	0.01	No								5.635	Yes
S2	0.01	No								4.441	Yes
S2	0.02	No								1.753	No
S2	0.03	No								-5.075	Yes
S2	0.02	No								1.532	No
S2	0.04	No								-7.463	Yes
S2	0.02	No								-0.144	No
S2	0.02	No								1.874	No
S2	0.02	No								2.370	Yes
S2	0.04	No								-6.833	Yes
S2	0.02	No								-0.322	No
S2	0.03	No								-3.765	Yes
S2	0.02	No								0.699	No
S2	0.03	No								-2.032	No
S2*	0.02	No								3.497	Yes
S3	0.03	No	13.00	0.09	0.03	0.36	0.11	Yes	2.179	6.343	Yes
S3	0.10	No								-0.930	No
S3	0.10	No								-1.243	No
S3	0.04	No								5.372	Yes
S3	0.08	No								1.422	No
S3	0.08	No								1.606	No
S3	0.15	No								-6.048	Yes
S3	0.13	No								-4.374	Yes
S3	0.11	No								-1.686	No
S3	0.12	No								-2.700	Yes
S3	0.11	No								-1.804	No
S3	0.08	No								0.873	No
S3*	0.06	Outlier								3.168	Yes
S4	0.03	Outlier	7.00	0.03	0.01	0.44	0.03	Yes	2.45	-0.130	No
S4	0.02	No								0.776	No
S4	0.05	No								-5.084	Yes
S4	0.02	No								0.822	No
S4	0.03	No								-1.428	No
S4	0.01	Outlier								2.743	Yes
S4*	0.02	Outlier								2.301	No

[a] John Tukey's Inter-Quartile Range Method for Outlier Filter [82]

[b] : Standard Deviation [c] : Coeffcient of Variation

[d]: (Maximum J_{nr} -Minimum J_{nr}) for Each Source

[e]: If Column 8 < Column 6* Multiplier from Table 1 of ASTM C670(for Number of test results): Yes, otherwise No.

[f,g,h]: Described in section 4.3

*: OU Laboratory MSCR Test Data

Table B.6 Detection and ASTM Precision- Bias Criteria Check for MSCR %Recovery @ 3.2 kPa of PG 76-28

1	2	3	4	5	6	7	8	9	10	11	12
Source ID	J_{nr} (3.2 kPa)	Outlier[a]	Sample Size, N	Mean	SD[b]	CoV[c]	J_{nr} Value Range[d]	Meets ASTM C 670 Range Criteria[e]	t-value for (N-1) df (95% Confidence Limit)[f]	Critical t-value[g]	Bias Exists[h]
S1	89.28	No	7.00	88.33	3.91	0.04	11.41	Yes	2.447	-0.647	No
S1	86.27	No								1.393	No
S1	96.49	Outlier								-5.531	Yes
S1	86.93	No								0.946	No
S1	88.58	No								-0.172	No
S1	85.65	No								1.813	No
S1	85.08	No								2.199	No
S2	97.73	No	16.00	96.98	0.88	0.01	3.60	Yes	2.131	-3.449	Yes
S2	98.11	No								-5.185	Yes
S2	98.08	No								-5.048	Yes
S2	97.53	No								-2.536	Yes
S2	96.50	No								2.170	Yes
S2	96.91	No								0.297	No
S2	94.51	Outlier								11.262	Yes
S2	97.01	No								-0.160	No
S2	97.69	No								-3.267	Yes
S2	97.33	No								-1.622	No
S2	96.36	No								2.810	Yes
S2	96.75	No								1.028	No
S2	96.14	No								3.815	Yes
S2	97.06	No								-0.388	No
S2	96.82	No								0.708	No
S2*	97.07	No								-0.434	No
S3	91.96	No	13.00	87.18	4.15	0.05	14.92	Yes	2.179	-4.149	Yes
S3	87.89	No								-0.613	No
S3	85.98	No								1.046	No
S3	95.85	No								-7.528	Yes
S3	91.36	No								-3.628	Yes
S3	87.96	No								-0.674	No
S3	82.34	No								4.208	Yes
S3	80.93	No								5.433	Yes
S3	84.36	No								2.453	Yes
S3	85.71	No								1.280	No
S3	84.24	No								2.557	Yes
S3	85.49	No								1.471	No
S3*	89.32	No								-1.856	No
S4	93.63	No	7.00	95.36	1.03	0.01	3.12	Yes	2.45	4.471	Yes
S4	95.11	No								0.652	No
S4	94.78	No								1.504	No
S4	95.72	No								-0.922	No
S4	95.27	No								0.240	No
S4	96.75	No								-3.579	Yes
S4 *	96.28	No								-2.367	No

[a] John Tukey's Inter-Quartile Range Method for Outlier Filter [82]

[b] : Standard Deviation [c] : Coeffcient of Variation

[d]: (Maximum J_{nr} -Minimum J_{nr}) for Each Source

[e]: If Column 8 < Column 6* Multiplier from Table 1 of ASTM C670(for Number of test results): Yes, otherwise No.

[f, g, h]: Described in section 4.3

*: OU Laboratory MSCR Test Data

APPENDIX C: LTPPBind Software Analysis

The analysis by LTPPbind software to check the feasibility of the MSCR grading for four different locations is presented below.

Table C.1 PG Grade Calculation by LTPPbind Software (50% Reliability)

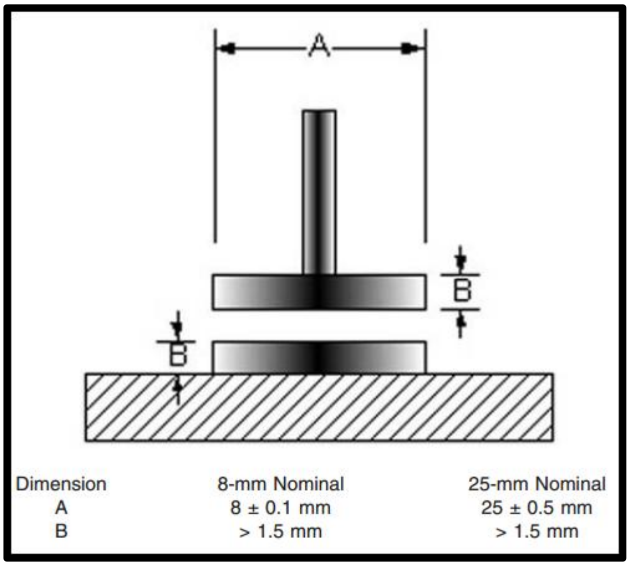
General Information						Calculated PG based on Traffic and Location				
Locateon near	**Latitude**	**Longitude**	**Elevation**	**Weather Station**	**Avg. PG (50% Reliability)**	**Traffic loading in MESAL**	**Traffic Speed**	**calculated PG grade (50% reliability)**	**Commonly used Binders**	**Proposed MSCR grades**
New Mexico, I40W	36.88	102.95	1231	kenton	64-16	0-3	fast/slow	58-16	64-22	64S-22
						3.0-10.0	slow	64-16	64-22	64H-22
							fast	64-16	64-22	64H-22
						10.0-30.0	slow/fast	70-16	70-28	64V-28
						abv 30	slow	70-16	70-28	64E-28
							fast	70-16	70-28	64E-28
Arkansas, I40E	35.9	94	283	Stillwell	64-16	0-3	slow	64-10	64-22	64S-28
							fast	58-10	64-22	64S-22
						3.0-10.0	slow	70-10	70-28	64H-28
							fast	64-10	64-22	64H-28
						10.0-30.0	slow	70-10	70-28	64V-28
							fast	70-10	70-28	64V-28
						abv 30	slow	76-10	76-28	64E-28
							fast	70-10	70-28	64E-28
Kansas, I35N	36.88	97.05	322	Newkirk	64-16	0-3	slow	64-10	64-22	64S-22
							fast	58-10	64-22	64S-22
						3.0-10.0	slow	70-10	70-28	64H-28
							fast	64-10	64-22	64H-22
						10.0-30.0	slow	70-10	70-28	64V-28
							fast	70-10	70-28	64V-28
						abv 30	slow	76-10	76-28	64E-28
							fast	70-10	70-28	64E-28
Texas, I35S	34.82	97.65	277	Lindsay 2 w	70-16	0-3	slow	64-10	64-22	64S-22
							fast	58-10	64-22	64S-22
						3.0-10.0	slow	70-10	70-28	64H-28
							fast	64-10	64-22	64H-28
						10.0-30.0	slow	70-10	70-28	64V-28
							fast	70-10	70-28	64V-28
						abv 30	slow	76-10	76-28	64E-28
							fast	70-10	70-28	64E-28

Table C.2 PG Grade Calculation by LTPPBind Software (98% Reliability)

General Information							**Calculated PG based on Traffic and Location**			
location near	**Latitude**	**Longitude**	**Elevation**	**Weather Station**	**avg PG (98% Reliability)**	**Traffic loading in M ESAL**	**Traffic Speed**	**calculated PG grade (98% reliability)**	**Commonly used Binders**	**Proposed MSCR grades**
New Mexico, I40W	36.88	102.95	1231	kenton	64-22	0-3	fast/slow	58-22	64-22	64S-22
						3.0-10.0	slow	70-22	70-28	64H-28
							fast	64-22	64-22	64H-28
						10.0-30.0	slow/fast	70-22	70-28	64V-28
						abv 30	slow	76-22	76-28	64E-28
							fast	70-22	70-28	64E-28
Arkansas, I40E	35.9	94	283	Stillwell	64-22	0-3	slow	64-16	64-22	64S-22
							fast	58-16	64-22	64S-22
						3.0-10.0	slow	70-16	70-28	64H-28
							fast	70-10	70-28	64H-28
						10.0-30.0	slow	76-16	76-28	64V-28
							fast	70-16	70-28	64V-28
						abv 30	slow	76-16	76-28	64E-28
							fast	76-16	76-28	64E-28
Kansas, I35N	36.88	97.05	322	Newkirk	64-22	0-3	slow	64-16	64-22	64S-22
							fast	64-16	64-22	64S-22
						3.0-10.0	slow	70-16	70-28	64H-28
							fast	70-16	70-28	64H-28
						10.0-30.0	slow	76-16	76-28	64V-28
							fast	70-16	70-28	64V-28
						abv 30	slow	76-16	76-28	64E-28
							fast	76-16	76-28	64V-28
Texas, I35S	34.82	97.65	277	Lindsay 2 w	70-22	0-3	slow	64-16	64-22	64S-22
							fast	58-16	64-22	64S-22
						3.0-10.0	slow	70-16	70-28	64H-28
							fast	70-16	70-28	64H-28
						10.0-30.0	slow	76-16	76-28	64V-28
							fast	70-16	70-28	64V-28
						abv 30	slow	76-16	70-28	64E-28
							fast	76-16	76-28	64E-28

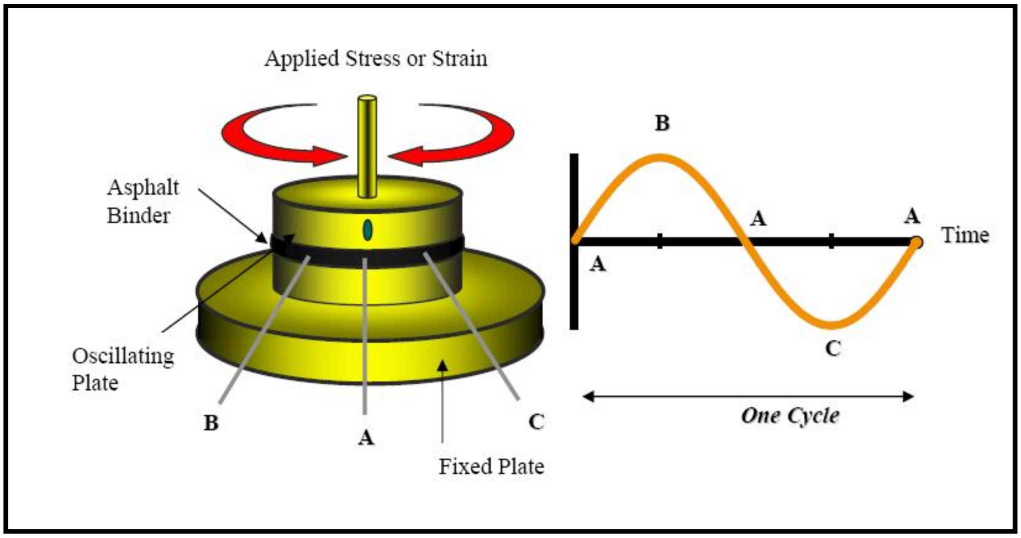
APPENDIX D: Summary of Test Method (AASHTO T 350)

The Multiple Stress Creep and Recovery test method is conducted under cyclic (oscillatory) shear using 25mm parallel plate geometry with a 1mm gap setting. A Dynamic Shear Rheometer (DSR) test system includes parallel metal plates, a means for controlling the temperature of the test specimen, a loading device, and a control and data acquisition system. Oscillatory shear refers to a type of loading in which a shear stress is applied to a test sample in an oscillatory manner such that the shear stress or strain varies in amplitude about zero in a sinusoidal manner. Parallel plate geometry describes a testing geometry in which the test specimen is sandwiched between two rigid parallel plates and subjected to shear (Figures D.1 and D.2). Metal plates are cylindrical in shape, formed from steel or aluminum, with smooth ground surfaces. During testing, one of the parallel plates is oscillated with respect to the other at pre-selected frequencies and angular deflection (or torque) amplitudes. The sample is loaded at constant stress for 1 second then allowed to recover for 9 second (Figure D.3). Ten creep and recovery cycles are run at 0.1 kPa creep stress followed by ten at 3.2 kPa creep stress. Particulate material in the asphalt binder is limited to particles with longest dimensions less than 250 μm. Particles with dimensions greater than 250 μm approach the dimensions of the gap between the two plates of the DSR machine (1000 μm). In order to accurately characterize a two-phase material containing particulate material it is well accepted that the thickness of the test specimen must be at least four times the maximum particle size.

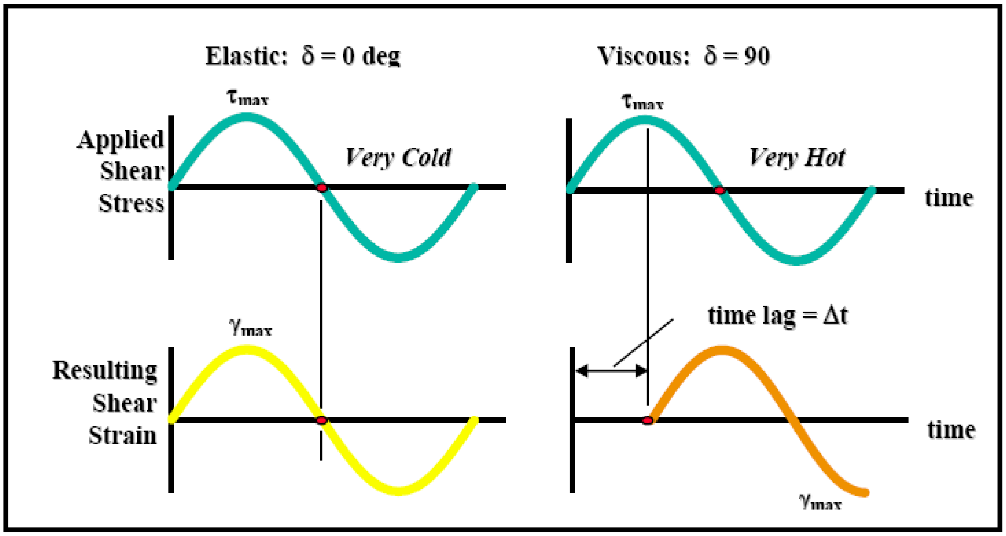


Dimension	8-mm Nominal	25-mm Nominal
A	8 ± 0.1 mm	25 ± 0.5 mm
B	> 1.5 mm	> 1.5 mm

Figure D.1 Plate Geometry and Dimension (AASHTO T 315).



(a)



(b)

Figure D.2 (a) Application of Stress, (b) Time Lagging.

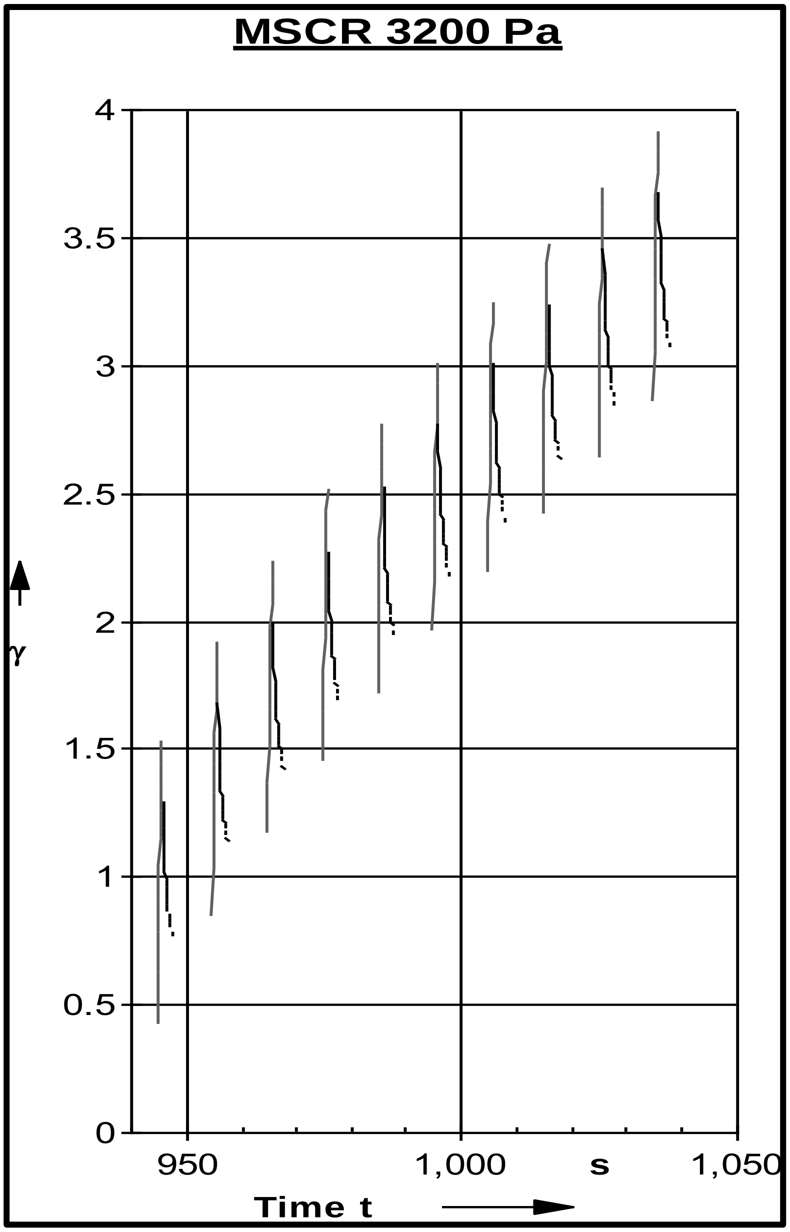


Figure D.3 Creep-Recovery Output from Software.