

Modification of Multiple Stress Creep and Recovery Test Procedure and Usage in Specification

By

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To all those who believe in God, to all those who have faith.

"The future belongs to those who believe in the beauty of their dreams."

(Eleanor Roosevelt)

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Abstract

Since the emergence of Superpave® equipment and specifications in the pavement industry in 1993, researchers and practitioners have found tools to understand characteristics and behavior of paving materials in better ways. Permanent strain or rutting is one of the most important pavement distresses. Due to its complexity and importance many studies were conducted to understand and alleviate this problem. Rutting or channeling can be classified as one of three types: 1) mechanical deformation (rutting) in subgrade or base, 2) plastic shear flow in asphalt layer and 3) wheel path consolidation (volume reduction) in asphalt layer. The plastic flow and volume consolidation of asphalt mixtures depends on a few factors, including the type of asphalt binder used in the mixture.

It is believed that the accumulated strain in asphalt binder, as a consequence of traffic, is mainly responsible for the rutting of asphalt pavements (Phillips and Robertus, 1996; Sybilski, 1996). There have been attempts to formulate a specification parameter that can describe the affinity of a binder to the increase of accumulated deformation under periodic loading. The Dynamic Shear Rheometer (DSR) was introduced as tool to measure the binder contribution to rutting.

In Superpave® specification, it was assumed that rutting is caused by the total dissipated energy. The Superpave® specification parameter $|G^*|/\sin \delta$ was identified as the term to be used for high temperature performance grading of paving asphalts in rating the binders for their rutting resistance (Anderson et al., 1994). Although used for many years as a rutting parameter, different researcher have shown the poor relationship between $|G^*|/\sin \delta$ and rutting. This term was found to be inadequate in describing the rutting performance of certain binders, particularly, the polymer modified ones. In the 9-10 project of National Cooperative Highway Research Program (NCHRP), researchers evaluated the direct correlation between mixture's rutting properties and $|G^*|/\sin \delta$ on Rotational Thin Film Oven (RTFO) aged binders, tested at the same temperature at which the mixture Repeated Shear Constant Height (RSCH) test were conducted. They found a poor correlation between the mixture rate of accumulated strain and the parameter $|G^*|/\sin \delta$ measured at 10 rad/s (Bahia et al., 2001).

In recent years many studies on bituminous binders have dealt with the inability of the original Performance Grade binder specification (PG) to correctly capture the performance properties of modified binders. Some agencies augmented the PG specifications with empirical, simple tests such as the elastic recovery, forced ductility, etc. and called it PG-plus. In addition to these, some more fundamentally

correct tests such as the repeated creep and recovery (RCR) and multiple stress creep and recovery (MSCR) have been proposed.

MSCR is a test that has received a lot of attention and significant acceptance by experts but still there is ongoing dialogue about shortcomings of this test. Some of these concerns are related to number of cycles and stress levels used in this test. Besides the testing protocol, binder selection criteria that is being proposed to reduce permanent deformation in asphalt mixtures under service load is of concern to many agencies due to the stress levels selected, relation to actual traffic speed, and traffic volume.

This research attempts to factually address the relevance of these concerns and propose measures and procedures to rectify them with a particular consideration of changes to the current MSCR test and criteria. This study includes analysis of results for binders and mixtures collected to show the role of binders in mixtures' rutting resistance and the effects of temperature, stress level, and number of cycles.

The research shows that the 10 cycles in the test are not sufficient to reach a stable secondary creep and a higher stress level will be useful to characterize modified binder behavior more clearly. A relatively simple nonlinear viscoelastic model is available (Delgadillo et al., 2011) and experimental results show that it can be used to estimate binder response to changing temperatures, loading time, and stress level. This model can be used for a more efficient selection of criteria for selecting binders in practice.

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I. Introduction

1. Background

Rutting, defined as accumulated permanent deformation, is a common form of distress in asphalt pavements. Rutting appears as longitudinal surface depressions along the wheel path in pavement. Rutting failure leads to poor serviceability of the pavements, making vehicles' ride rough and unsafe (Fahim & Bahia, 2004).

There are two basic rutting mechanisms. The first is compressive permanent deformation of the subgrade or the underlying pavement layer. The second rutting mechanism, and the main focus of this work, is the permanent deformation of the asphaltic layer near the surface. The majority of rutting problems result from plastic deformation of the surface course, and it is believed that the accumulated strain in asphalt binder is mainly responsible for that. Rutting is characterized by shear deformation inside the asphalt mixture (Centeno et al., 2008). This phenomenon is more critical during the hot season of the earlier period of pavement life, because the asphalt binder is less aged and softer.

Asphalt concrete is a viscoelastic material that contains mineral aggregates, asphalt binder and air voids. Asphalt binder, as one of the load carrying components of the asphalt mixtures, is a viscoelastic, thermoplastic material characterized by a certain level of rigidity of an elastic solid body, but, at the same time, flows and dissipates energy by frictional losses as a viscous fluid (Anderson et al., 1994). As asphalt binder is responsible for the viscoelastic behavior of all bituminous materials, it plays a dominant part in determining many of the aspects of pavement performance, such as resistance to permanent deformation. Therefore, binder has a critical role against rutting in mixture. Also, as with any viscoelastic material, asphalt's response to stress is dependent on both temperature and loading time (Anderson et al., 1994). Therefore, permanent deformation in asphalt binder is highly dependent on factors such as temperature, stress level, loading time, etc.

For many years, asphalt binders used in highway application were characterized using empirical methods (A.A.P.T.P.P., 2008). The most common tests used included penetration, ductility, softening point and viscosity. The major problem with these empirical tests is the temperature at which the tests were performed. All of these test were conducted on one or two temperatures which did not represent the

range of temperatures for pavement asphalt. Also, there were no specific requirements for asphalt cement stiffness at low temperature to control thermal cracking.

Recognizing the limitations of the traditional asphalt binder characterization procedures, the Federal Highway Administration initiated a nationwide research program called the Strategic Highway Research Program (SHRP). The introduction of Superpave® in 1993 provided a useful method of evaluating and understanding the mechanism of rutting. The Dynamic Shear Rheometer (DSR) was introduced as tool to measure the binder contribution to rutting. It was assumed that rutting is caused by the total dissipated energy (Anderson et al., 1994).

In Superpave® specification, Complex modulus (G^*) and phase angle (δ) were defined as important parameters to characterize viscoelastic behavior of binder. In viscoelastic materials, after applying an oscillating sinusoidal strain, stress response will lag behind the strain. It will vary in a similar sinusoidal fashion, but out of phase with applied strain. The amount of phase lag in such material is defined by the phase angle (δ). The phase angle is a measure of the proportions of the overall resistance caused by the viscous response and by the elastic response (Lakes, 1999). For viscoelastic material both an elastic modulus and an “imaginary” viscous modulus may be defined on a complex scale. The viscoelastic material behavior at any given time or stress state is a complex conjugate of the elastic and viscous moduli. Complex modulus can be calculated by dividing maximum stress over maximum strain. Complex modulus (absolute value) is a measure of the overall resistance to deformation under dynamic shear loading (Lakes, 1999).

The Superpave® specification parameter, $|G^*|/\sin \delta$, was identified as the term to be used for high temperature performance grading of paving asphalts in rating the binders for their rutting resistance. Although used for many years as a rutting parameter, it has been demonstrated that the relationship between $|G^*|/\sin \delta$ and rutting is poor. This term was found to be inadequate in describing the rutting performance of certain binders, particularly polymer modified binders. In NCHRP 9-10 project, Bahia et al. evaluated the direct correlation between mixture’s rutting properties and $|G^*|/\sin \delta$ on RTFO aged binders, tested at the same temperature at which the mixture test was conducted. The results indicated a poor correlation ($R^2=23.77\%$) between the mixture rate of accumulated strain, S , and the parameter $|G^*|/\sin \delta$ measured at 10 rad/s (Bahia et al., 2001). Other researchers have confirmed this conclusion (D’Angelo et al., 2006). Consequently, many agencies introduced additional tests to the standard PG specifications to overcome this limitation, known as PG-plus.

The repeated creep test was developed during the NCHRP 9-10 project to identify non-viscous flow that contributes to the permanent deformation from the total dissipated energy (Delgadillo et al., 2006).

The repeated creep and recovery test utilizes DSR to measure the accumulated strain in the binder under a given stress level for a prescribed cycles of strain creep for one second followed by stress recovery of 9 seconds. At least 100 cycles of loading are recommended. Tests have been conducted at stress levels as low as 25 Pa to as high as 25.6 kPa (Delgadillo et al., 2006,b). The irreversible nature of stress-controlled RCR test (not being cyclic like for $|G^*|/\sin \delta$) makes it possible to differentiate between the plastic strains that contribute to pavement rutting, and delayed elastic strain that are recoverable and overcome the limitation of strain-controlled $|G^*|/\sin \delta$ testing in evaluating the rutting susceptibility of the binder.

D'Angelo et al. (2007) showed that a single stress level does not completely account for the stress dependency of polymer modified binders. Testing binders at multiple stress levels using RCR test requires an extensive amount of time. These stresses should be selected to capture the properties of the asphalt in linear and in nonlinear domain. These led to the development of Multiple Stress Creep and Recovery (MSCR) test.

The MSCR is being proposed as a better test to evaluate modified binders and estimate their role in pavement performance. The MSCR has particularly received a lot of attention and holds a great promise, but it still has its own challenges with regard to its implementation, analysis of the result and its interpretation.

2. Problem Statement

While results of the MSCR test are promising, there are important concerns about current testing and analysis protocols. These issues can be categorized as follows:

- **Variability:** Observations show that data variability is more critical for binders that have high delayed elastic response. The challenge with such behavior is that taking the average of the 10 cycles, as required in the MSCR standard procedure, could be misleading as the response is significantly changing with cycles. Therefore, there is a need to find an alternative way of calculation rutting parameter to have more reliable results.
- **Steady state:** The number of cycles and the time of loading do not cover a wide span, which is necessary to characterize long-term deformation in the material (Delgadillo et al., 2006). In NCHRP 9-10 project, it was also reported that the initial cycles are not

consistent and that the delayed elasticity can play an important role in changing the response. Also, it was noted that the test should include a certain number of cycles for conditioning to get to steady state before the response should be calculated. Therefore, there is still question about the binder's capability to reach steady state after 10 cycles (Bahia et al., 2001).

- **Stress sensitivity:** It is not clear that testing at a low stress level is the best way to characterize the rutting resistance of the asphalt binder. Permanent deformation is not a linear viscoelastic phenomenon and therefore measurement of linear viscoelastic binder properties does not allow for proper rutting resistance characterization (D'Angelo et al., 2006). The stresses and strains in the binder can be high, much higher than the linear limit for the material. Permanent deformation in asphalt binder is highly dependent on the stress level. Determining the stress level at which the binder is exposed in the mixture is an important matter. Some researchers showed that MSCR results at higher stress levels have better correlation with mixture's data (Dreessen et al., 2009; Wasage et al., 2011). The two selected stress levels (0.1 and 3.2 kPa) are arbitrarily and do not necessarily represent the stress of the binder inside the pavement.
- **Percent Recovery (R%):** R% is representative of elastic behavior of binder under loading. Elasticity is an important property that measures the ability of materials to recover after deformation. There is a chart for minimum requirement percent recovery in American Association of State Highway and Transportation Officials (AASHTO) TP70-09 standard "Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)", but it does not give the clear explanation of chart purpose and possibly clarifying that if percent recovery is needed for rutting or not. Several studies indicated that there is a somewhat good correlation between elasticity and fatigue resistance, but the relation between elasticity and rutting resistance is not still fully clear (Bahia et al., 1997; Kamel et al., 2004). Therefore, it is essential to investigate the relationship between percent recovery and binder rutting resistance. In addition, it is necessary to effectively quantify the contribution of the asphalt binder elasticity to asphalt mixture permanent deformation.
- **Conversion of PG grade shift for traffic:** Elevated traffic loading requires a higher rut resistance at the distress temperature. The current grade bumping procedure assumes that elevated traffic loading is equivalent to raising the test temperature. This is a fallacy

because the temperature susceptibility among binders varies significantly. A binder that is not very temperature susceptible may have a higher Superpave specification temperature, but at the same time, it may be softer than a more temperature-susceptible binder at the distress temperature. The experts agree that the conversion from the old PG grade shift to the new system is not consistent for all binders and modifiers and there is also lack of clear guidance on speed and traffic volume.

MSCR has become a popular and well used test in the asphalt community, believed by many to capture essential rut resistance properties of the material. The purpose of this study is to identify the sources of variations in the MSCR results and propose remedies for improvement. This thesis attempts to factually address the relevance of these issues and propose measures and procedures to rectify them by suggesting appropriate revisions to test procedure and specification.

3. Research Hypothesis

It is hypothesized that by increasing the number of cycles and testing at a higher stress level in the MSCR test, the stress sensitivity and binder rutting resistance may be more accurately characterized.

4. Research Objectives

The purpose of this study is to investigate the need of modification of the current MSCR test procedure and its specification. The general objective of the present work is to develop a test and method to characterize asphalt binders rutting resistance more accurately; and to explain how the response of asphalt binders at different stress levels and temperature is related to the binder contribution of mixture rutting resistance measurements.

The specific objectives are:

- Variability and steady state: Propose a new calculation method of MSCR test results to reduce the variability of results and also propose number of cycles to reach the steady state condition at

each stress level. This will improve the test procedure to give more accurate results with less variability.

- Stress sensitivity and effect of percent recovery: Investigate the effect of adding a higher stress level and how it will effect elasticity of the binder and provide a clear explanation of chart of percent recovery requirement in AASHTO TP 70-09 standard and possibly clarifying if percent recovery is needed for rutting or not.
- PG grade shift for traffic: Propose criteria that represent the relation between Jnr dependency on loading time, traffic volume and/or speed to select the appropriate Jnr maximum limits shift. The criteria will be based on rheological modeling of binder response to loading and temperature changes. This will clarify the effect of speed and traffic volume on MSCR results and propose a better way to quantify this effect.

5. Thesis Outline

This thesis is structured into five main sections with the following content:

Chapter I: Introduction – This chapter includes a background on rutting in asphalt mixtures. The background is followed by the problem statement, research hypothesis and research objectives.

Chapter II: Literature Review – This chapter is divided into three sections. The first section presents a literature review of the rutting mechanisms. The second discusses binder characterization and the tests for rutting. The third part discuss the effect of binder modification and the last section addresses the Multiple Creep and Recovery test method for rutting characterization, its limitations and challenges.

Chapter III: Materials and Methods – In this part various neat and modified binders will be tested at different temperatures and stress levels using the Dynamic Shear Rheometer. Since asphalt binders are isotropic incompressible materials, the extensional properties can be calculated from the shear properties. The binders were subjected to primary aging, using the Rotational Thin Film Oven (RTFO). The aging of the binders in the RTFO test represents the aging that happens during the mixing and compaction of asphalt mixture samples. Therefore, it was necessary to age the binders to make them representative of the binder characteristics inside the mixtures. Test methods such as repeated creep and recovery (RCR) and multiple stress creep and recovery (MSCR) will be used to characterize the binder deformation by calculating Jnr (non-recoverable creep compliance) and percent recovery. Table I-1 shows the design of experiment.

Table I-1. Design of Experiment for Binder testing.

Variables	Levels	Description
Base Binder	2	PG 64-22, PG 58-28
Type of Modification	6	SBS, Elveloy, PE1 (CBE), PPA, GTR, PE2
Cross Linking	2	With or without
Testing Temperature	5	46,58,64,70 and 76°C
Stress Levels	3	100, 3200 and 10000 Pa
Type of Binder Test	2	MSCR, RCR
Type of MSCR test	3	different number of cycles and stress levels
Replicate	2	

Chapter IV: Evaluation and Modification of the Current MSCR Test Procedure – This chapter presents an extensive evaluation of current MSCR test procedure from different aspects. Different issues with current MSCR test procedure are investigated by testing different modified binders, identifying the critical issues to be addressed in this study. In the next stage, different procedures are evaluated to get more accurate results and to correct these issues in the MSCR test procedure. Statistical analysis will be performed to verify reproducibility and repeatability of the MSCR test. Also, a factorial design and analysis of variance (ANOVA) of the factors that influence rutting damage is included in this section and findings with regards to variability, number of cycles, stress levels and effect of elasticity are summarized. Also, results available for a limited number of mixtures tested using the Flow Number (FN) procedure are used to validate the developed procedure. Two different stress levels are used in the mixture testing to represent the different levels of traffic loading on the pavement at only one temperature. Finally, the relationship between the new developed procedure and the mixture permanent deformation is analyzed, and the suitability of the modified test specification and criteria for determination of binder rut resistance is validated based on mixture performance results.

Chapter V: Investigation of MSCR Test and Criteria with Modeling – This chapter is divided into three sections. The first part compares binder's rutting resistance measurements obtained from the MSCR test with fundamental parameters that quantify the characteristic of binders. In the second section the compatibility of new and old shifting system is investigated. In last part, the effect of traffic volume and vehicle's speed on binder's rut resistance is studied and the relation between these factors to binder's

rutting criteria is defined. Furthermore, the characteristics of different modified binders related to binder's rut resistance will be defined and criteria that represent the rutting behavior of the asphalt binder is going to be developed upon different conditions.

Chapter VI: Conclusions and Recommendations – Conclusions gathered from the most relevant testing and modeling results and recommendations based on these conclusions are offered in this section. Direction for future work is also provided in this section.

II. Literature Review

This chapter includes four sections to cover the topic of fundamental principles of binder's rutting resistance. These sections are as follows: definition and background of rutting, binder characterization and tests for rutting, effect of modifiers on binder performance, and MSCR tests and its limitations and challenges.

1. Rutting

Asphalt pavements are granular composites that contain mineral aggregates, asphalt binder and air voids. The two load-carrying components of the asphalt mixtures are the mineral aggregates and the binder. Asphalt binders are obtained from the refining of crude oil. They are produced from the heavy residue after the refining of fuels and lubricants. Bitumens are thermoplastic materials that demonstrate viscoelastic properties under most pavement operating conditions (Van der Poel, 1954). It is this fundamental property that makes them versatile binders for asphalt mixtures with the viscoelastic characteristics of the bituminous binders directly and significantly influencing the performance of the mixtures.

One of the distress modes of asphalt pavements is permanent deformation or rutting that occurs at high operating temperatures, and it is believed that the accumulated strain in asphalt binder is mainly responsible for the rutting. Rutting is defined as longitudinal surface depressions along a pavement's wheel paths. In asphalt pavements, rutting is defined as the progressive accumulation of longitudinal depressions in a wheel path under repetitive loading (Fahim & Bahia, 2004).

The possible causes for this phenomenon are the deformations in the asphalt pavement layer, in the underlying layer, or in multiple layers. The permanent deformation per wheel passage correlates with the stiffness of the asphalt binder used, and decreases with increasing number of wheel passages (Hofstra & Klomp, 1972).

There are two basic rutting mechanisms. The first one is the compressive permanent deformation of the subgrade or the underlying pavement layer. The second rutting mechanism is the permanent deformation of the asphaltic layer near the surface. The majority of rutting problems result from plastic

deformation of the surface course. It is characterized by shear deformation inside the asphalt mixture. When asphalt mixtures have low shear strength, rutting accumulates after each vehicle loading during the first months or few years of the pavement service life until it becomes noticeable and hazardous. Rutting failure leads to poor serviceability of the pavements, making vehicles ride rough and unsafe. This phenomenon is more critical during the hot season of the earlier period of pavement life because the asphalt binder is less aged and softer. Also, permanent deformation in asphalt binder is highly dependent on the stress level. The plastic flow of bituminous mixture depends on many factors; one is the type of asphalt used in the mixture (Centeno et al., 2008). One of the most recent areas of investigation in pavement engineering is the relationship between asphalt rheology and rutting in pavements. These investigations try to measure the contribution of asphalt to mixture's stability.

Asphalt concrete is a viscoelastic material that contains mineral aggregates, asphalt binder and air voids. Asphalt binder, as one of the load carrying components of the asphalt mixtures, is a viscoelastic, thermoplastic material that is characterized by a certain level of rigidity of an elastic solid body, but, at the same time, flows and dissipates energy by frictional losses as a viscous fluid (McGennis, 1994). Its characteristics are dependent on time and temperature (Anderson et al., 1994). With higher temperatures and longer loading times, the asphalt becomes softer and behaves more like a viscous fluid. With lower temperatures and faster loads, the asphalt becomes stiffer and more elastic. Because of this, rutting is more critical in the hotter summer months and under slower moving traffic.

As the asphalt binder is responsible for the viscoelastic behavior of all bituminous materials, it plays a dominant part in determining many of the aspects of pavement performance, such as resistance to permanent deformation. Therefore, binder has a critical role against rutting in mixture. Also, as with any viscoelastic material, asphalt's response to stress is dependent on both temperature and loading time (McGennis, 1994). Therefore, permanent deformation in asphalt binder is highly dependent on the factors such as temperature, stress level, loading time etc.

To strengthen asphalt pavements against damage, modifiers are sometimes added to the asphalt binder. Polymers, which are long-chain molecules of very high molecular weight, used by the binder industry are classified based on different criteria. The polymers that are used for bitumen modification can be divided into two broad categories; namely, plastomers and elastomers. Plastomers modify bitumen by forming a tough, rigid, three-dimensional network to resist deformation, while elastomers have a characteristically high elastic response, and therefore resist permanent deformation by stretching and recovering their initial shape (Bahia et al., 1998).

2. Binder Characterization and Tests for Rutting

Recognizing the limitation of the traditional asphalt binder characterization procedure in 1987, the Federal Highway Administration initiated a nationwide research program called the Strategic Highway Research Program, usually referred to as SHRP (Anderson et al., 1994). The final product of the SHRP research program was Superpave® (Superior Performance Asphalt Pavements). The Superpave® was designed to provide performance-related properties that can be related in a rational manner to pavement performance (McGennis, 1994).

NCHRP Project 9-10, “Superpave® Protocols for Modified Asphalt Binders,” was initiated to confirm whether the current Superpave® protocols are suitable for use with modified asphalt binders (Bahia et al., 2001). The conclusion drawn from reviewing the protocols was that the existing protocols cannot be used to fully characterize all asphalt binders modified with different additives. The main reason is that they are based on simplifying assumptions that cannot be reliably extended to modified binders. (Kim, 2008).

The Dynamic Shear Rheometer (DSR) was introduced in 1993 by Superpave® as a tool to measure the binder mechanical characterization. This device provided a useful method to evaluate binder rutting resistance capability. The principle used with the DSR is to apply sinusoidal, oscillatory stresses or strains over a range of temperatures and loading frequencies to a thin disc of bitumen, sandwiched between the two parallel plates of the DSR. Anderson et al. (1994) assumed that rutting is caused by the total dissipated energy as calculated from the strain-stress curve.

$$W_i = \pi * \tau_0^2 * \frac{1}{\frac{G^*}{\sin \delta}} \quad (\text{II-1})$$

Where:

W_i = total energy dissipated at the i^{th} cycle

τ_0 = maximum stress applied

G^* = complex modulus

δ = phase angle

$|G^*|/\sin \delta$ was introduced as the rutting parameter. Equation II-1 shows that increasing the rutting parameter $|G^*|/\sin \delta$ causes dissipated energy to decrease and, as a consequence, more rutting occurs.

The Superpave® specification parameter $|G^*|/\sin \delta$ was identified as the term to be used for high-temperature performance grading of paving asphalts in rating the binders for their rutting resistance. Although used for many years as a rutting parameter, different researchers have shown poor relationship between $|G^*|/\sin \delta$ and rutting. This term was found to be inadequate in describing the rutting performance of certain binders, particularly, the polymer modified ones. In NCHRP 9-10 project, Bahia et al. evaluated the relation between mixture's rutting and binders' mechanical properties, tested at the same temperature. The authors correlated $|G^*|/\sin \delta$ of RTFO aged binders with mixture Repeated Shear Constant Height (RSCH) test data and found a poor correlation ($R^2=23.77\%$) between the mixture rate of accumulate strain, S, and the parameter $|G^*|/\sin \delta$ measured at 10 rad/s (Bahia et al., 2001). RSCH test is defined in AASHTO TP7, and the accumulated permanent strain is used to measure the effect of modified binders on rutting behavior of asphalt mixtures. The accumulated permanent strain was defined according to the following equation:

$$\log \varepsilon_p = \log \varepsilon_{pl} + S_F \log N \quad (\text{II-2})$$

where:

ε_p =total accumulated permanent strain

ε_{pl} =initial strain factor

S_F = slope factor

N = number of cycles.

In addition to finding that $|G^*|/\sin \delta$ did not have strong correlation with mixture rutting data, it was found that binder characteristic is derived from linear viscoelastic behavior and it cannot include the contribution of binder damage behavior. Also, Bahia et al. (2001) reported to better simulate traffic condition, repeated creep loading should be used instead of cyclic reversible loading that does not allow direct measurement of binder rutting resistance.

A refinement of the Superpave® specification parameter for performance grading of asphalt led to the evolution of the term $|G^*| / (1 - (1/\tan \delta \sin \delta))$. This performance-based specification (PBS) term was shown to be more sensitive to the variations of the phase angle δ than the Superpave® specification parameter and thus was found to describe the unrecovered strain in the binders more accurately, especially in the case of polymer-modified asphalts (Shenoy, 2001).

Using cyclic reversible loading for viscoelastic materials can be misleading because although this test has the capability of estimation the total energy dissipated during a loading cycle, as it is unable to separate permanent deformation and delay elasticity in these materials. Rutting is a repeated mechanism with sinusoidal loading pulse in which the pavement layer is not forced back to zero deflection but would

recover some deformation due to elastic stored energy in the material of the layers. Under this type of loading, the energy is dissipated in damping and in permanent flow (Kim, 2008). It was proposed that a creep and recovery test in the DSR could solve the above problems (Bahia et al., 2001). To fill the gap in the SHRP specification, other test methods were developed.

2.1 Christensen-Anderson-Marasteanu (CAM) method

This method was developed by the Pennsylvania State University research group to estimate the accumulated deformation from the initial cycles in the test. Checking the influence of the test data in the first five cycles on the final prediction indicated that the convergence of the model parameters was good. Bahia et al. (2001) reported several problems related to this method:

- It does not give a direct measurement of the viscosity, which is the main parameter in viscous flow and permanent strain deformations.
- There is an essential need to use the model to get a creep and recovery response.
- Delay elasticity can play a major role in changing the response from one cycle to the next and first few cycles are not consistent.

2.2 Repeated Creep and Recovery (RCR) test

The repeated creep test is proposed as a method of separating the dissipated energy and estimating the resistance to accumulation of permanent strain for asphalt binders. The RCR test was developed during the NCHRP 9-10 project. Bahia et al. (2001) recommended the repeated creep recovery test (RCR) using the dynamic shear rheometer (DSR) to evaluate the resistance of asphalt binders to permanent deformation. The NCHRP 9-10 project recommend a shear stress in the range of 30 Pa to 300 Pa for 100 cycles at a rate of 1(s) loading time followed by a 9 (s) unloading time (Bahia et al., 2001).

This project introduced a new parameter G_v to characterize the rutting resistance of asphalt binders. This new parameter was derived from the four-element Burger model, which is a combination of a Kelvin model and Maxwell model. The total shear strain versus time is expressed as follows:

$$\gamma(t) = \gamma_1 + \gamma_2 + \gamma_3 = \frac{\tau_0}{G_0} + \frac{\tau_0}{G_1} \left(1 - e^{-\frac{tG_1}{\eta_1}}\right) + \frac{\tau_0}{\eta_0} t \quad (\text{II-3})$$

where,

$\gamma(t)$ =total shear strain

γ_1 =elastic shear strain

γ_2 =delayed elastic strain

γ_3 =viscous shear strain

τ_0 =constant stress

G_0 =spring constant of Maxwell model

tG_1 =spring constant of Kelvin model

η_1 =dashpot constant of Kelvin model

t =time

η_0 =dashpot constant of Maxwell model

Dividing Equation (II-3) by the constant stress leads to the following equation:

$$J(t) = J_e + J_{de}(t) + J_v(t) \quad (\text{II-4})$$

where,

J_e =elastic creep compliance

$J_{de}(t)$ =delayed elastic creep compliance

$J_v(t)$ =viscous creep compliance

Instead of using J_v which has a unit of 1/Pa, the inverse of compliance G_v is used. G_v is defined as the viscous component of the creep stiffness (Bahia et al., 2001).

D'Angelo showed that a single stress level did not completely account for the stress dependency of polymer modified binders and multiple stress levels need to be used (D'Angelo et al., 2007). Testing binders at multiple stress level using the RCR test would require an extensive amount of time.

It is not clear that testing at a low stress level is the best way to characterize the rutting resistance of an asphalt binder. The stresses and strains in the binder can be high, much higher than the linear limit for the material. Permanent deformation in asphalt binder is highly dependent on the stress level. Determining the stress level at which the binder is exposed in the mixture is an important matter (Delgadillo et al., 2006b). Permanent deformation is not a linear viscoelastic phenomenon and therefore measurement of linear viscoelastic binder properties are not likely to correlate with it (D'Angelo et al., 2007b).

In 2001, NCHRP Report 459 based on the 9-10 project was published (Bahia et al., 2001); it proposed RCR testing with the dynamic shear rheometer (DSR) to characterize the rutting resistance of asphalt binders. From the test, a parameter called viscous component of the creep stiffness, G_v , is obtained. The parameter has been demonstrated to be an improvement in the characterization of the rutting resistance of binders, especially modified binders. The main advantages of RCR compared with the current test method and parameter $|G^*|/\sin \delta$ are described in previous work (Delgadillo et al., 2006) and can be summarized as follows:

- Repeated creep loading represents the actual loading on the pavement better than fully reversed load from dynamic testing
- RCR allows an easy identification of the permanent deformation of binders when loaded. This is especially important in modified binders, in which delayed elasticity can be significant, and the binders can recover much of their deformation when unloaded. The parameter $|G^*|/\sin \delta$ does not allow direct evaluation of delayed elasticity.

The repeated Creep test offers valuable information about the susceptibility of asphalt mixtures to rutting when changes in temperature occur (Centeno, 2001). However, in order to fully characterize the asphalt binder behavior, multiple stresses are required. These stresses should be selected to capture the properties of the asphalt in linear and in nonlinear domain.

2.3 Multiple Stress Creep and Recovery (MSCR)

The MSCR test was developed to reduce the number of samples at each stress level and it is the following development of RCR test. The test uses 1 (s) creep loading followed by 9 (s) recovery for the following stress levels: 25, 50, 100, 200, 400, 800, 1600, 3200, 6400, 12800 and 25600 Pa at 10 cycles for each stress level. The test starts at the lowest stress level and increase to the next stress level at the end of every 10 cycles, with no rest periods between creep and recovery cycles or changes in stress level. (D'Angelo et al., 2007b).

D'Angelo selected two stress levels, 0.1 kPa and 3.2 kPa, upon correlation between binder and mixture rutting results for performing the MSCR test. Ten cycles are run for each stress level for a total of 20 cycles. **Figure II-1** shows the typical results from MSCR test.

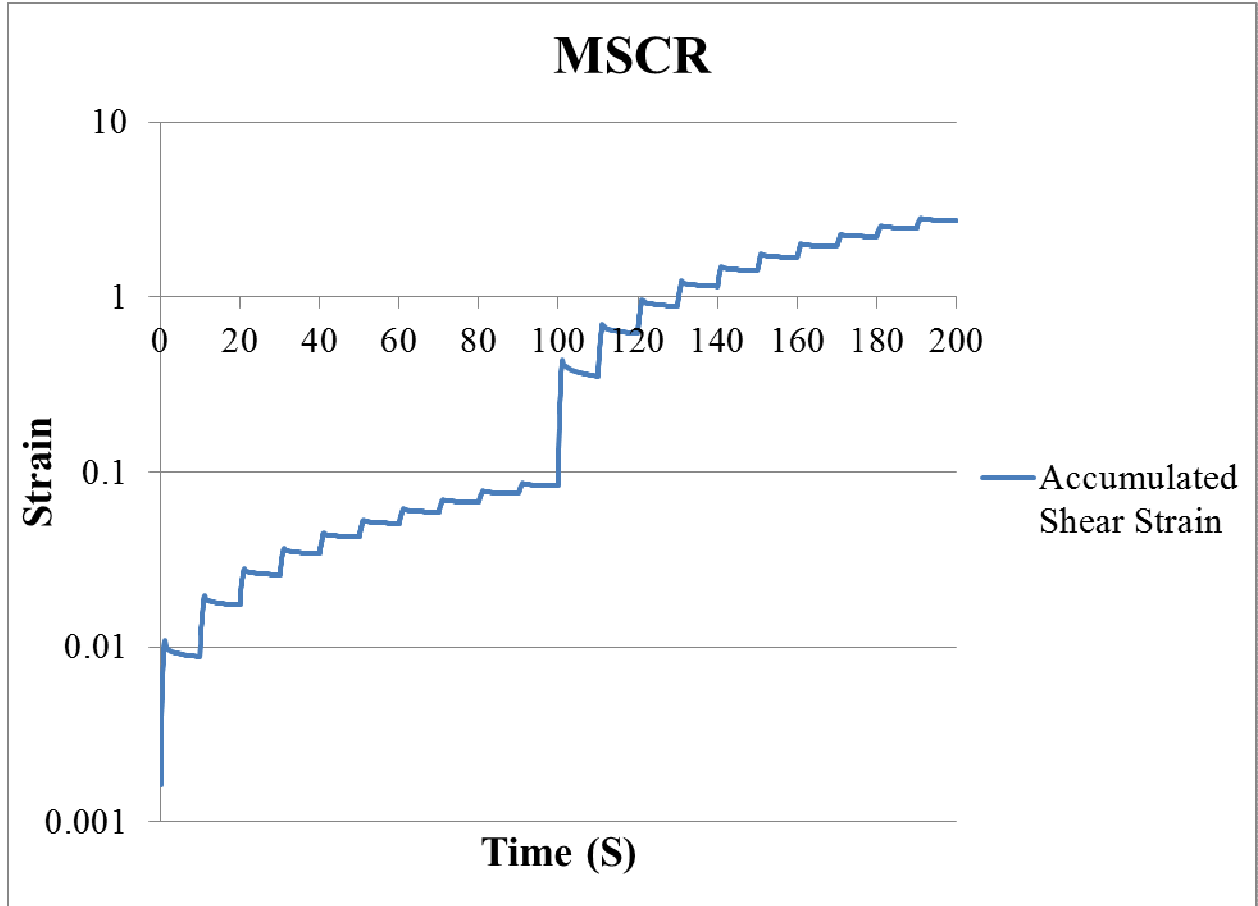


Figure II-1: MSCR Response Curve.

The average non-recoverable strain for the 10 creep and recovery cycles is then divided by the applied stress for those cycles yielding the non-recoverable creep compliance (J_{nr}). J_{nr} for 0.1kPa is calculated by divided the strain after 10 cycles to 0.1 kPa. Equations (II-5) and (II-6) show the calculation method for J_{nr} at 0.1 kPa (AASHTO TP 70).

$$J_{nr}(0.1, N) = \frac{\epsilon_{10}}{0.1} \quad (II-5)$$

$$J_{nr0.1} = \frac{\sum [J_{nr}(0.1, N)]}{10} \quad \text{for } N = 1 \text{ to } 10 \quad (II-6)$$

where,

$$\epsilon_{10} = \epsilon_r - \epsilon_o$$

ϵ_r = strain value at the end of the recovery portion (i.e., after 10.0 s) of each cycle strain

ϵ_o = initial strain value at the beginning of the creep portion of each cycle

The definition for the J_{nr} at 3.2 kPa is analogous. The J_{nr} parameter was suggested as a measure of the binder contribution to mixture permanent deformation (D'Angelo et al., 2006).

Later, Shenoy (2001) used non-recoverable compliance to characterize the propensity of asphalt binder to resist permanent deformation in the pavement. He proposed measuring the non-recoverable compliance through the dynamic oscillatory test using a frequency, time, strain or sweep test. Mathematical formula was used to calculate non-recoverable compliance from the complex modulus and phase angle. Also Shenoy showed that the unrecoverable strain in a binder that is during a creep and recovery test could be calculated directly from the dynamic oscillatory test using a frequency test (Shenoy, 2008). The percent-unrecovered strain is calculated as follows:

$$\% \gamma_{unr} = \frac{100 \sigma_0}{|G^*|} \left(1 - \frac{1}{\tan \delta \sin \delta} \right) \quad (II-7)$$

To minimize the unrecoverable strain, the following term (the inverse of the non-recoverable compliance, $\% \gamma_{unr} / \sigma_0$) needs to be maximized:

$$\frac{|G^*|}{1 - \frac{1}{\tan \delta \sin \delta}} \quad (II-8)$$

$|G^*| / (1 - (1 - \tan \delta \sin \delta))$ was proposed as a refinement to the Superpave® specification for performance grading of asphalts. The drawback of this parameter is that at $\delta < 52^\circ$, the model would predict unrealistic negatives values of $(1 - (1 - \tan \delta \sin \delta))$ (Shenoy, 2008).

Bouldin et al. (2001) developed a semi empirical method to predict the rut resistance (R) as a function of loading (time and load) and temperature from data at single frequency. This approach is based on the assumption that the strain accumulation rate depends on the binder stiffness and viscoelastic contribution $f(\delta)$, and these two contributions are independent

$$R = (1/\gamma_{acc})(t_{load}, t_{rest}) = G^*(\omega) f[\delta(\omega)] \quad (II-9)$$

$$(1/\gamma_{acc}) = k G^*(Y_0 + a \{ 1 - \exp[-|\delta - X_0 + b \ln(2)^{1/c} / b]^c \}) \quad (II-10)$$

where,

k =constant

γ_{acc} =accumulated strain

δ =phase angle

Y_0, X_0, a, b, c = empirical fitting parameters

The disadvantage of this parameter is that at phase angles between 40° and 75° this parameter does not fully capture the viscoelastic nature of many modified binders (Bouldin et al., 2001).

2.4 Zero Shear Viscosity (ZSV)

Zero Shear Viscosity (ZSV) is another method to capture the contribution to rutting of polymer modified binders. ZSV is defined as the viscosity related to a constant strain rate as the stress approaches zero (D'Angelo et al., 2007b). According to Anderson et al. (2002), Philips and Robertus used ZSV to characterize asphalt binder contribution to rutting by plotting the rut rate versus viscosity. Anderson et al. reported that ZSV can be estimated through different methods (Anderson et al., 2002): extrapolation of the dynamic viscosity to zero frequency; application of the Cross model to dynamic viscosity measurements; single creep and recovery test until a steady state flow is obtained; multiple superimposed creep and recovery tests without obtaining a state flow.

Desmazes et al. have shown that testing needed at very low (vanishing) shear rates makes it difficult and significantly time-consuming to measure ZSV (Desmazes et al., 2000). Nonetheless, the advantage of using the zero shear viscosity lies in its sensitivity toward high molecular weight (MW) additives to asphalt binder and has been shown to rank the performance of unmodified as well as modified binders adequately (Phillips and Robertus, 1996). One concern with the ZSV, however, is that its high sensitivity to MW may overestimate the performance of certain PMA binders (e.g., cross-linked styrene–butadiene–based PMA binders or other high MW-based PMA binder). Another concern is that to accurately estimate ZSV, a complicated computer software–based procedure is required (Dongre et al., 2004). Moreover, the ZSV requires more time consuming testing (frequency sweeps at multiple temperatures) and commercially available software to compute the ZSV value.

3. Modifiers

The increasing demands of traffic on road building materials in recent years has resulted in a search for binders with improved performance relative to normal penetration grade asphalt binders. This effort to obtain improved binder characteristics has led to the evaluation, development and use of a wide range of bitumen modifiers which enhance the performance of the basic bitumen and hence the asphalt on the road

(Nicholls, 1998). In recent years, there is a growing interest on asphalt modifications for use in high performance specialty pavements such as open-graded pavements (OGP) in which large gravels have been selectively utilized for creating open interconnected channels in the pavements (Bouldin, 1991).

Polymers are playing an increasingly important role in the asphalt industry and are the most technically advanced bitumen modifiers currently available. To achieve the goal of improving bitumen properties, a selected polymer should create a secondary network or new balance system within asphalt binders by molecular interactions or by reacting chemically with the binder. The strength, stiffness and adhesion of asphalt to gravel must be greatly improved to sustain the pavement performance. It is not surprising to witness various attempts to modify asphalt properties via chemical modification and/or physical blending. The major efforts have been thus far directed to viscoelastic characterization of asphalt and rubbery materials (Collins et al., 1991).

Polymers can be classified into four broad categories, namely plastics, elastomers, fibres and additives/coatings. Plastics can in turn be subdivided into thermoplastics and thermosets (or thermosetting resins) and elastomers into natural and synthetic rubber. Globally, approximately 75% of modified binders can be classified as elastomeric, 15% as plastomeric, with the remaining 10% being either rubber or miscellaneously modified (Diehl, 2000).

Elastomers polymers exhibit the ability to recover to the initial condition after an applied load is removed. The elastomers, if mixed in an appropriate amount with asphalt, can confer their elastic properties to the modified binder, thus enhancing its elastic recovery capacities and, therefore, its resistance to permanent deformations. Within the elastomeric group, styrenic block copolymers have shown the greatest potential when blended with bitumen (Airey, 2003).

Plastomers are polymers that have high early strength under deformation, but they are less flexible than elastomers and tend to fracture under large strains. Additionally, plastomers deform more slowly than elastomers under an equivalent load. Plastomers when add to asphalt confer high rigidity to the binder and strongly reduce deformations under the load. Also, plastomers increase the viscosity of the asphalt (Read and Whiteoak, 2003).

PPA is a binder modifier used for improving both high and low temperature performance. The reported advantage of using PPA is that while the viscosity is significantly increased, the penetration of the binder remains approximately the same (Edwards et al., 2006). PPA has been used as a modifier alone or in combination with polymers. The intention of adding PPA to polymer modified binder is to reduce

the polymer content leading to improved processing conditions, high temperature viscosity and storage stability (Daranga et al., 2009).

Polymer-modified binders obtained by mixing plastomeric or elastomeric macromolecular materials with traditional pure road asphalt binders have been available for more than 20 years. An ideal binder should have enhanced cohesion and very low temperature susceptibility throughout the range of temperatures to which it will be subject in service, but low viscosity at the usual temperatures at which it is placed. Its susceptibility to loading time should be low, whereas its permanent deformation resistance, breaking strength, and fatigue characteristics should be high. At the same time, it should have at least the same adhesion qualities (active and passive) as traditional binders. Lastly, its aging characteristics should be good, both for laying and in service (Brule, 1996).

Several studies have been conducted to investigate the relationship between effect of modifiers on mixture's performance. The apparent benefit of polymer modification is a reduction in the amount and severity of distresses and thereby an extension in the service life of hot-mix asphalts (HMA) pavements and overlays. From the engineering point of view, PMAs are materials with superior rheological properties (Read and Whiteoak 2003; Airey 2004; Lu and Isacsson 1998; Zanzotto et al. 2000) with respect to the unmodified asphalt binders, and they are currently used more and more in the construction of modern asphalt pavements. The addition of polymers, chains of repeated small molecules, to asphalt has been shown to improve performance. Pavement with polymer modification exhibits greater resistance to rutting and thermal cracking, decreased fatigue damage, stripping and temperature susceptibility. Polymer-modified binders have been used with success at locations of high stress, such as intersections of busy streets, airports, vehicle weigh stations, and race tracks. Different kinds of modifiers have been used to modify asphalt binder such as SBS (styrene-butadiene-styrene), SBR (styrene-butadiene-rubber), EVA, rubber and others. Desirable characteristics of polymer modified binders include greater elastic recovery, a higher softening point, greater cohesive strength and greater ductility. Modifying asphalt binders enhances their performance characteristics, including rutting resistance. Kamel et al. showed that asphalts modified with polymer addition and by refining processes produced improved binder performance. Results indicated that modification by selecting the right crudes and engineering the refining process could be very effective in improving rutting and fatigue resistance of binders (Kamel et al., 2004). Also McDaniel and Bahia have found that the use of modified binders improve the field cracking performance over that of unmodified binders (McDaniel and Bahia., 2003).

4. MSCR Test

The Multiple Stress Creep and Recovery (MSCR) test was developed as a replacement for the existing AASHTO M-320 high-temperature binder test. The results from the MSCR test may also be used as an alternative to the various SHRP+ tests. In addition to characterizing fundamental properties, the MSCR is an easy-to-use performance-related test. Multiple binders both neat and polymer-modified were evaluated in the development of a new binder test to determine high-temperature rutting property for binders. Equipment for testing of the binders was focused on the existing dynamic shear rheometer (DSR). This equipment has been widely accepted by highway agencies for use in determining rheological properties of binders in specifications. The DSR measures fundamental properties, related to the stress strain response of viscoelastic materials and is ideally suited to evaluate asphalt binders.

In its final shape, according to AASHTO TP70 standard “Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)” or American Society for Testing and Materials standard (ASTM) 7405, the test consists of 10 cycles of 0.1 kPa stress creep and recovery, followed immediately by another 10 cycles of 3.2 kPa stress creep and recovery. Each cycles consists of one second of loading and 9 seconds of recovery upon instantaneous unloading. The non-recoverable creep compliance, J_{nr} , and the percent recovery, $R\%$, are two of the parameters calculated from the measured strain under different stress cycles (D’Angelo et al., 2007,b).

The J_{nr} parameter was suggested as a measure of the binder contribution to mixture permanent deformation. The duration of the creep interval, the duration of the recovery interval, the number of loading cycles and, of course, the entity of the applied shear stress unequivocally cooperate to the control of J_{nr} . In other words, J_{nr} depends on the mechanical history of the experiment.

The MSCR is proposed as a better test to evaluate modified binders and estimate their role in pavement performance. The MSCR has particularly received a lot of attention and holds a great promise, but it still has its own challenges with regard to its implementation, analysis of the result and interpretation.

While results of the MSCR test are promising (D’Angelo et al., 2006; 2007,b; 2006,b; 2009), there are important concerns about current testing and analysis protocols. It is not clear that testing at a low stress levels (0.1 and 3.2 kPa) is the best way to characterize the rutting resistance of an asphalt binder. The stresses and strains in the binder can be high, much higher than the linear limit for the material. Permanent deformation in asphalt binder is highly dependent on the stress level. Determining the stress

level at which the binder is exposed in the mixture is an important matter (Dreessen et al., 2009; Wasage et al., 2009). Permanent deformation is not a linear viscoelastic phenomenon and, therefore, measurement of linear viscoelastic binder properties are not likely to correlate with it (D'Angelo et al., 2006). The two selected stress levels are arbitrarily and do not necessarily represent the stress of the binder inside the pavement. The number of cycles and the time of loading do not cover a wide span, which is necessary to characterize long term deformation in the material. The recovery time allowed in the test is not long enough; modified binders are still recovering after 9 (s) of recovery (Delgadillo, 2008).

III. Materials and Methods

1. Binder Tests

1.1 Materials

The test matrix included conventional asphalts (hard-soft and inelastic) and elastomeric (soft and elastic) and plastomeric (very hard and low elasticity) polymer-modified asphalts (PMAs). Two asphalt binders commonly used in the Mid-west region of the United States were selected in this study: Flint Hills (FH) PG 64-22 and CRM PG 58-28.

The neat binder samples were obtained from asphalt paving contractors, and were received in either five-gallon or one-gallon cans. The samples were heated and divided into quarter-gallon cans for handling. These neat binders were used as the base for preparation of modified binders.

Since the rheological properties of asphalt binders change with time because of oxidation, characterization is needed at different stages of the binder life. Current asphalt binder specifications consider three stages in the life of the material: a) original binder, which represents the asphalt stored before mixing with aggregates; b) primary-aged binder, or binder aged during the mixing and compaction process; and c) secondary-aged binder, which is the binder aged after several years of service life in the pavement. By aging the binder, we are achieving conditions that are closer to those seen in the actual field conditions.

Current specifications consider two laboratory procedures specially designed to simulate the aging of the binders. Rolling Thin Film Oven (RTFO) simulates primary aging (Roberts et al., 1996). A specific amount of asphalt cement (35 g) is poured into a bottle, which is placed into an oven at 163°C for 85 minutes. The oven is designed with a rotating rack that allows continuous exposure of fresh asphalt. An air jet is used to inject air inside the orifice of the bottle for further oxidation. The Pressure Aging Vessel (PAV) (Roberts et al., 1996) simulates the secondary aging during five to ten years of in-service asphalt pavements. A 50-g sample of binder already aged in the RTFO is poured into a pan, which is placed inside a pressure vessel at 100°C and 2070 kPa for 20 hours.

As pavement engineers are primarily concerned with the binder's behavior at the beginning of pavement life with respect to rutting, the binders should be subjected to standard short-term, RTFO ageing (ASTM D 2872) prior to dynamic rheological testing. Therefore, the binders were subjected to primary aging, using the RTFO in this research. The aging of the binders with the RTFO test represented the aging that happens in the binder during the mixing and compaction of asphalt mixture samples. In the field, aged binders are used; Therefore, RTFO binders are considered as more appropriate to determine the binder rutting performance (Kamel et al., 2004). Therefore, it was necessary to age the binders to make them representative of the binder characteristics inside the mixtures.

Polymer modification of asphalts is not a new phenomenon, but interest of this technique has increased considerably due to the increased performance-related requirements on asphalt pavements. Polymers used in the asphalt industry are often classified as elastomers, plastomers, rubbers and acids, with the most commonly used being the elastomers.

Asphalt Sample Modification

Two complete full factorial test matrix for binder modification is used for binder preparations. In the first test matrix, the neat binder and the three modified versions of that binder were tested. Three trial blends of the elastomeric (linear styrene-butadiene-styrene block copolymer), plastomeric modifier (polyethylene, CBE) and ground tire rubber (GTR) were produced and the true grade was determined. The targeted grades include two grade bumps $+0.5^{\circ}\text{C}$ for each neat binder. The neat binder PG grade was 64-22. This allows for comparison of the binders based on traditional selection criteria of PG. The targeted true grade was PG 76.5 $+ 0.5^{\circ}\text{C}$. The elastomeric, plastomeric and GTR at calculated percentages to target 76.5 $+ 0.5^{\circ}\text{C}$ resulted in 79.3, 74.0 and 79.3, respectively. Finally modifier quantities for blending of modified binders resulting in similar high-temperature Performance Grade (PG) were achieved. After several trials blends to determine the nonlinear relationship between percent modifier and high-temperature grade, blends were produced to exhibit grades within $+ 0.25^{\circ}\text{C}$ of one another. The required percentage of each modifier and resulting grade can be seen in **Table III-1**.

Table III-1. Percent modifier used to get high-temperature grade for modified binders.

Modifier	Percent	True Grade (°C)
SBS	3.2	77.88
CBE	4.7	78.08
GTR	7.1	77.87

After aging, the binder samples were poured into small silicone molds of 25-mm diameter and approximately 2-mm height. The sample was taken from the silicone mold and placed on the bottom plate of the DSR, which was kept at a temperature around 45°C. The top plate was then lowered, squeezing the sample down to the required thickness, (1 mm), and the edges were trimmed. After this, the chamber was placed on the testing fixture, and the temperature conditioning began. After the desired temperature was reached and had become steady (after approximately 10 minutes), the loading began.

In the second test matrix, materials selected for this study consisted of two neat binders plus different binder-modifier-concentration combinations as follows:

- Two different base neat binders; Flint Hills (FH) which is a PG 64-22, and CRM which is a PG 58-28.
- Five modifier types; linear styrene-butadiene-styrene block copolymer, terpolymer-Elvaloy 4170, two oxidized polyethylene generically called PE1(CBE) and PE2, and polyphosphoric acid.
- Two levels of modification; causing one and two HT-grade jumps (HT+6°C and HT+12°C).

The required amount of polymer to achieve the one and two HT-grade jumps was determined based on trial and error experiments. The elastomeric combined with a cross-linking agent and the commercial name of the sulfur used in this study is Butafalt. 0.123% Butaphalt per 1% LSBS (by weight of the binder) was added to the blend. The combination of the two base binders, five modifiers, and two grade jumps resulted in 22 different binders, all the binders were then tested to characterize their rutting

properties. **Table III-2** shows the summary of test matrix. The rest of preparation was the same as first test matrix.

Table III-2. Percent modifier used to achieve grade bumps for modified binders.

Polymer	FH or CRM	
	% Polymer for one grade jump	% Polymer for two grade jump
SBS	2	4
Elvaloy	0.7	1.5
PE1 (CBE)	2	3.5
PE2	2	3.5
PPA	1	1.5

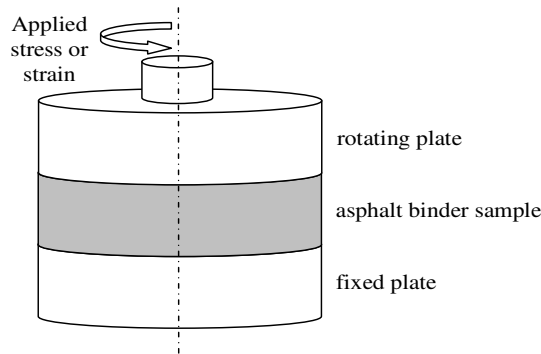
Another subset binder test matrix from the Western Cooperative Testing Group (WCTG) of the Rocky Mountain Asphalt User Producer Group (RMAUG) is used. The data collected for six binders (Binder Code: 515- 520) by the WCTG was used in this study to evaluate the variability of the MSCR test results for testing a number of modified asphalts. The other tests include the conventional PG grading as well as some of the PG Plus tests such as ductility, elastic recovery, and forced ductility.

Two replicates were tested for each binder. In the case of good repeatability, the average of the two replicates was used for the analysis of results. Good repeatability was assumed when the differences between the two replicates were lower than 10%. In the case of larger differences between replicates, a third replicate was run. Good repeatability was achieved for all binders.

1.2 Testing Device and Procedure

The Superpave parameter for rutting resistance is obtained by testing the asphalt binder using a device called the Dynamic Shear Rheometer (DSR). Since asphalt binders are isotropic incompressible materials, the extensional properties can be calculated from the shear properties. A cylindrical asphalt sample is sandwiched between two plates, one fixed and one oscillating, as shown in **Figure III-1 (a)**. Torque is applied to the oscillating plate. The temperature and stress level of testing can be adjusted according to

the expected pavement temperatures and vehicle speeds. A DSR, produced by the former Bohlin (Malvern), model CVO rheometer was used for the binder testing shown in **Figure III-1 (b)**.



(a) Dynamic Shear Rheometer Setup (Delgadillo, 2008)



(b) Dynamic Shear Rheometer machine

Figure III-1. Binder Testing setup and device.

The principle used with the DSR is to apply sinusoidal, oscillatory stresses or strains over a range of temperatures and loading frequencies to a thin disc of bitumen, which is sandwiched between the two parallel plates of the DSR. In general, two testing (plate) geometries are used with the DSR, namely an 8-mm diameter plate with a 2-mm testing gap and a 25-mm diameter plate with a 1-mm testing gap. The selection of the testing geometry is based on the operational conditions with the 8-mm plate geometry generally being used at low and intermediate temperatures (-5 – 30°C) and the 25-mm geometry at high temperatures (30 – 90°C).

Since the properties of asphalt change with temperature, the testing temperature for characterizing the binder must be the same temperature as the temperature experienced by the binder in the field. The pavement temperature depends on environmental factors like the weather and solar radiation. For this reason, pavement temperatures vary for different locations. Pavement temperatures in Florida are higher than pavement temperatures in Minnesota, for example. This means that stiffer binders will be needed in Florida than in Minnesota. The temperatures that are more relevant for rutting characterization are the summer temperatures. Permanent deformation is more critical when the asphalt is softer during the hot season. The Superpave procedure specifies that the temperature for rutting testing should be the average temperature of the seven consecutive hottest days of the summer. Direct pavement temperature

measurements are not available in most locations, so equations are used to convert the air temperature and latitude into pavement temperature. Usually, records from 30 years are taken into account to perform statistical analysis and reliability calculations for the temperatures.

Repeated Creep test offers valuable information about the susceptibility of asphalt mixtures to rutting when changes in temperature occur (Delgadillo, 2008; Centeno et al., 2008). Repeated Creep test has capability of measuring the elastic recovery of asphalt binder under different levels of stress. This fact is important because when using this test as a complement of another asphalt characterization like specification SUPERPAVE, is possible to establish differences between modified asphalts. PMB are characterized to have a greater elastic recovery than virgin asphalts. Therefore, data for binder testing was collected from RCR and MSCR tests on the various binders at different temperatures.

In this study, the DSR tests were performed using a parallel plate arrangement. The diameter of the plate was 25 mm and the gap between top and bottom plate was set at 1 mm. In this study, the tests were performed at various temperatures regardless of modifier type or test type. The repeated creep tests were performed at a constant stress which is applied for 1-s followed by a 9-s rest period of which no stress is applied, thus completing one cycle. During the 9-s rest period the specimen recovers some of the strain that was developed during the 1-s stress period before it is loaded again (Button, 2004).

2. Mixture Test

2.1 Materials

The binders from the first test matrix were used to prepare limited mixture data set. Four neat and modified binders were used to make mixture samples. The asphalt mixtures commonly used in the United States for pavements can be generally divided into coarse mixtures and fine mixtures, depending on the predominant aggregate size of the gradation. For this reason, two different aggregate gradations were used in the mixture sample preparation: one coarse and one fine. Gradations were determined for limestone aggregates to be used for production of asphalt concrete mixtures. Two gradations, fine and coarse, corresponding to the boundaries of WisDOT specifications envelop for the Nominal Maximum Aggregate Size (NMAS) of 12.5 mm were determined by matching the broadest range allowed by WisDOT specifications. The fine and coarse grain-size distributions can be seen in **Figure III-2** accompanied by

WisDOT control points. Aggregates were washed prior to batching for precise control over the volume of mineral filler in each mixture, and **Figure III-2** shows that mineral filler (minus 0.075 mm) was adjusted to match between the two gradations, eliminating any significant influence of varying mastic properties.

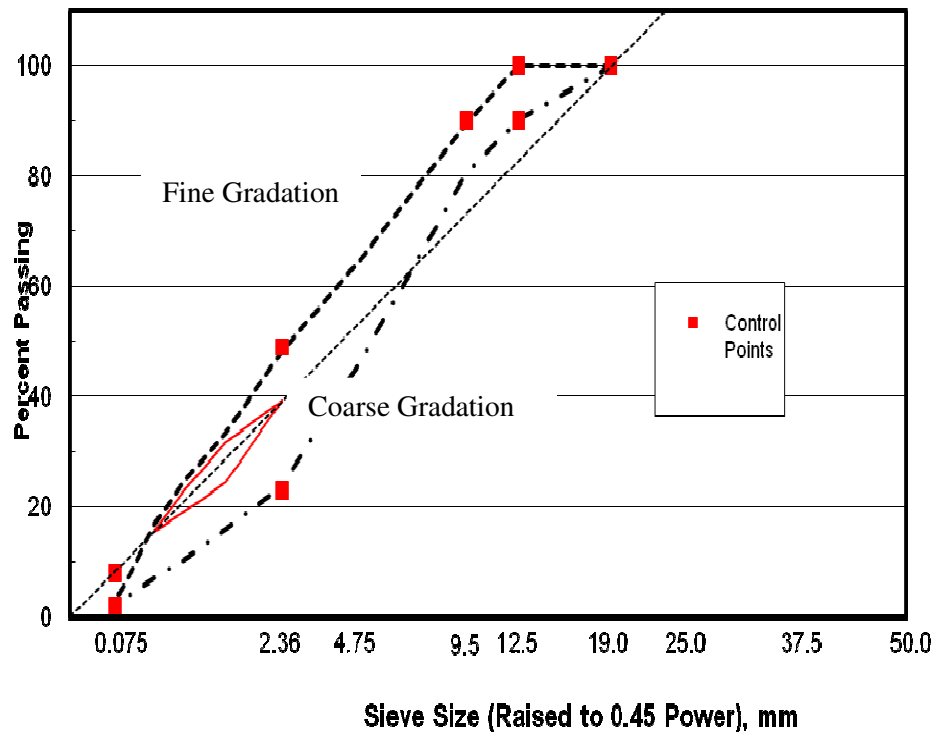


Figure III-2. Fine and coarse grain-size distributions used in production of asphalt mixtures (Coenen, 2011).

2.2 Testing Procedure

Mechanical testing of mixtures was conducted in accordance with standard protocol AASHTO TP 79 for repeated creep testing “Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)”, commonly known as flow number (FN). To characterize the mixture’s resistance to rutting, unconfined compression test with repeated creep and recovery loading was selected. The reasons for selecting this type of test can be summarized as follow: i) creep and recovery loading closely represents the loading pattern that the asphalt pavement undergoes during service, ii) it is a well-known test commonly used for

the evaluation of mixture rutting susceptibility, and iii) the test correlates well with asphalt rutting in the field (Witczak et al., 2002).

The flow number is defined as the number of cycles required for the sample to begin exhibiting tertiary creep, or flow, which is more clearly defined as the number of cycles which corresponds to the minimum rate of change in permanent axial strain of the specimen under a repeated load test. By plotting the total accumulated strain versus number of cycles, three different zones are realized. Primary, secondary and tertiary zones are identified on the creep curve (**Figure III-3**). The transition from secondary to tertiary creep corresponds to the minima of the rate of change of axial strain as shown in **Figure III-4**.

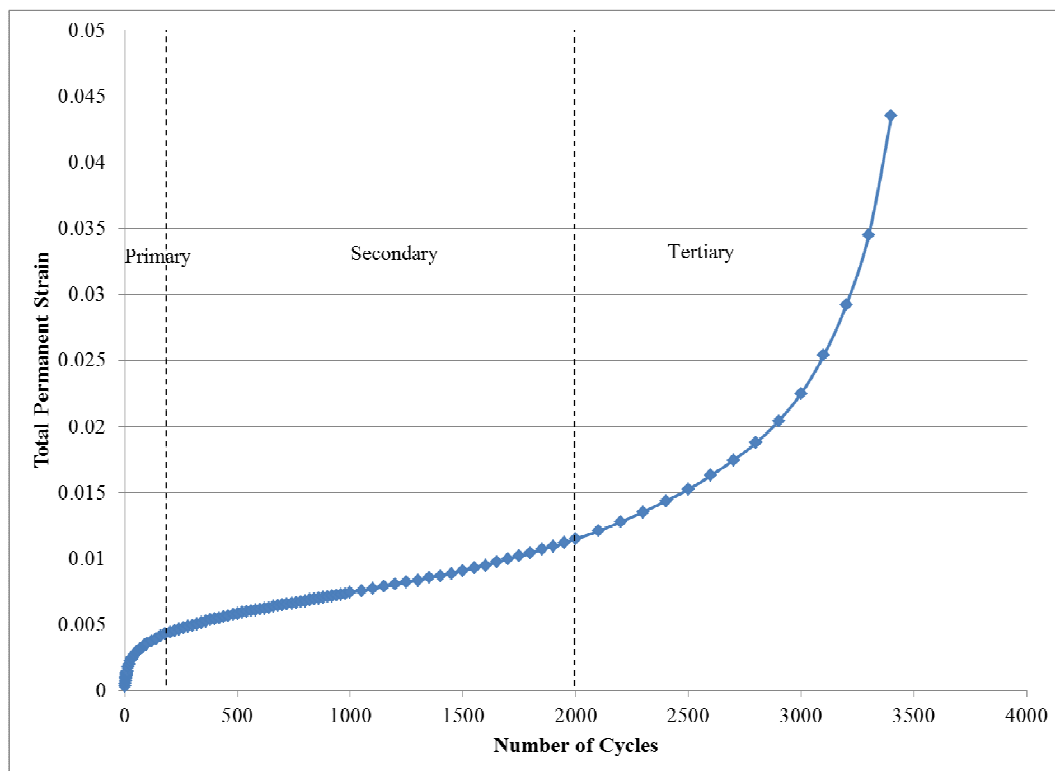


Figure III-3. Typical creep curve for HMA mixture.

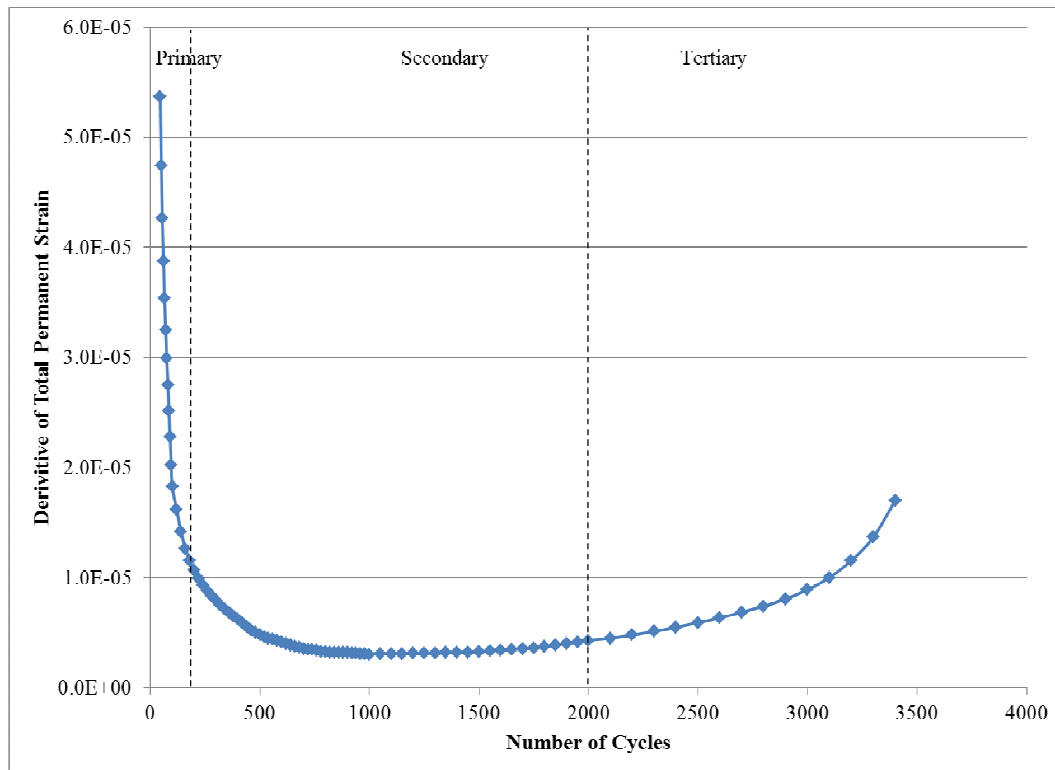


Figure III-4. Plot of rate of change of permanent axial strain versus cycles.

The flow number test consists of repeatedly loading a sample under stress control, with a 0.1-s pulse of a prescribed stress, followed by a 0.9-s rest period. This cyclic compressive loading is intended to simulate repeated passing of traffic/vehicles over the roadway and this test is used to determine mixture's resistance to permanent deformation continued until sample failure. Failure is defined by clearly exceeding the transition from secondary to tertiary creep, and when the sample has lost the capacity to withstand the prescribed stress. The test is performed on a 100-mm-diameter specimen of 150-mm-height, produced by cutting and coring a standard gyratory specimen. Specimens for this study were compacted to a consistent air void content or density by targeting 6.5 ± 0.5 percent air voids. Asphalt mixture testing was conducted at 46°C (i.e., the 7-day average high pavement temperature in the region where testing was conducted). The 7-day high temperature is chosen since this research focused on resistance to permanent deformation, which is a consequence of high temperatures and heavy loads. The *Heavy loads* definition is arbitrary. For this reason, mixture testing was conducted at two stress levels, 50 and 150 psi (345 and 1034 kPa) intended to span the average stress level found in field measurements.

IV. Evaluation and Modification of the Current MSCR Test Procedure

The Multiple Stress Creep and Recovery test proposed as a better method to evaluate modified binders and estimate their role in pavement performance. The MSCR has particularly received a lot of attention and holds a great promise, but it still has its own challenges with regard to its implementation, analysis of the result and its interpretation. This chapter tries to address the concerns raised about the current MSCR testing and its correlation with mixture results and propose appropriate modification for this test.

The unmodified and modified binders were tested as RTFO-aged for viscoelastic behavior defined by complex shear modulus (G^*) and phase angle (δ) at medium to high pavement temperatures using the DSR. The results are used to determine the PG grade of each material. The RCR and the MSCR tests on the various binders were performed at temperatures of 46, 58, 64, 70 and 76°C. The stress levels used were 100 and 3200 Pa for MSCR and 100, 3200, and 10000 Pa for RCR. The repeated creep tests were performed at a constant stress which is applied for 1-s followed by a 9-s rest period, of which zero stress is applied, thus completing one cycle. During the 9-s rest period the specimen recovers some of the strain that was developed during the 1-s stress period before it is loaded again (Van der Poel, 1954). A total of 1000 creep and recovery cycles were performed on RTFO aged binders. One thousand cycles were selected to capture the full behavior of modified binder over a long range of time. The lowest shear stress was 100 Pa due to the fact that testing of lower stresses could not be performed because the accumulated strain did not vary significantly from temperature to temperature. The value of 10000 Pa was selected to observe modified binder behavior at very high stress level.

Non-recoverable creep compliance (J_{nr}) and percent recovery (%R) of binders were calculated at each stress level and temperature to identify a trend related to stress or temperature sensitivity. Non-recovered compliance is presently being viewed as the most appropriate rheological parameter for evaluating the propensity of an asphalt binder to resist permanent deformation or rutting in the pavement wheel paths. In the dynamic shear rheometer, J_{nr} can be obtained using two different types of tests. First is through the dynamic oscillatory test using a frequency, time, strain or stress sweep, wherein the data generated is in terms of the complex modulus and phase angle that can be used in a proper mathematical form to obtain the J_{nr} and the second one is through the MSCR test, wherein the non-recovered strain at each stress level after 10 cycles of creep and recovery is divided by the stress value to obtain the non-recovered creep compliance (Shenoy, 2008).

1. Variability of MSCR Test Results

1.1 Review of WCTG Available Data

The MSCR test has not been fully implemented by DOTs and the paving industry to date. However, there appears to be significant interest in the test by a number of research laboratories, as well as by a few industry groups, which have started inclusion of the test in round-robin testing done periodically by the groups.

One of the groups that has collaborated with the Western Cooperative Testing Group (WCTG) is the Rocky Mountain Asphalt User Producer Group (RMAUG). The WCTG has more than 70 laboratories signed up to conduct period testing of split samples of binders used in the Rocky Mountain region. These labs receive specific instructions on testing and enter their individual data in a web based data collection system that is managed with the help of the Modified Asphalt Research Center (UWMARC.org). Some of the data collected by the WCTG was used in this study to evaluate the variability of the MSCR test results for testing a number of modified asphalts, and to compare the MSCR variability to other tests conducted by the group. The other tests include the conventional PG grading as well as some of the PG Plus tests such as ductility, elastic recovery, and forced ductility.

An example of the data collected is shown in **Figure IV-1**, which depicts the variations of Jnr values measured by the MSCR test by the Western Cooperative Testing Group (WCTG) for 6 different binders (515- 520), by different participating labs.

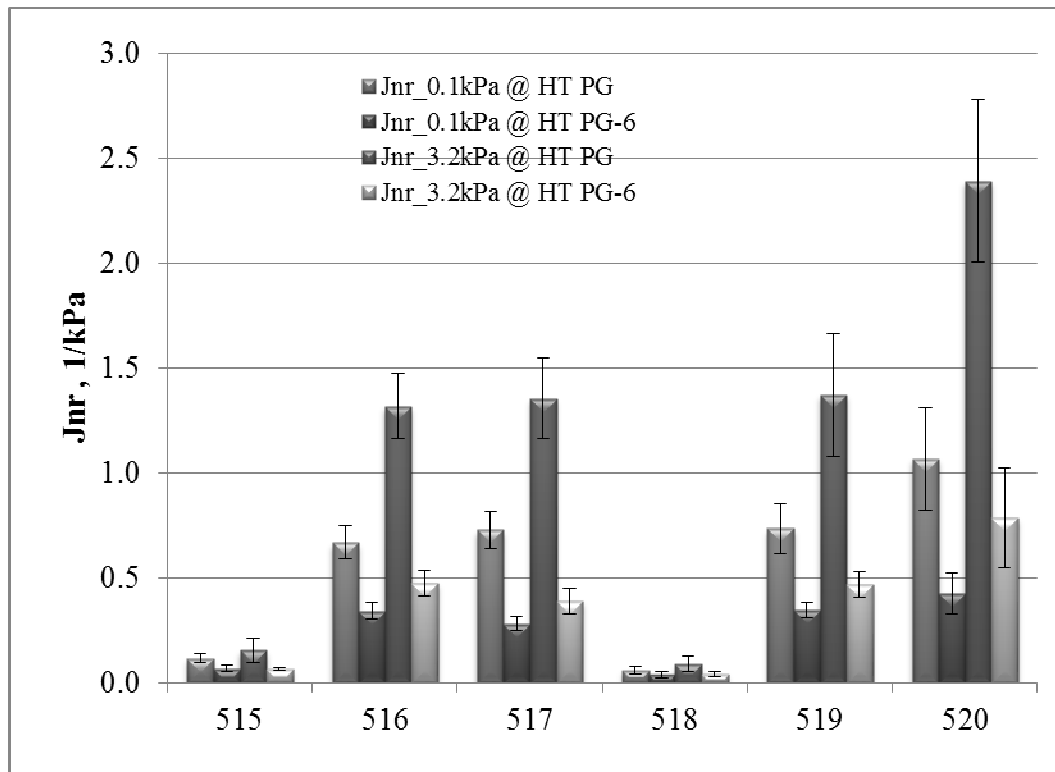


Figure IV-1. Jnr Variability in WCTG data (the range of standard deviation shown on columns).

It is clear from **Figure IV-1** that the values of Jnr vary among binders within a wide range and, more importantly, the variability shown by the range at top of the bars is dependent on stress level (0.1 kPa and 3.2 kPa), and the testing temperature (Hi PG and Hi PG-6). The range in variability represents one standard deviation above and one below the average value for each measurement. The following sections give detailed analysis and discussion about the various sources of the variability observed.

1.2 Reproducibility of MSCR Results

Reproducibility analyses of identical binders tested by different labs in the above-mentioned joint efforts in terms of coefficient of variation (COV%) are shown in **Table IV-1** and **Table IV-2** as well as **Figure IV-2**. A wide range of COV% from 4.1% to 188.2% can be seen.




Similar statistics are compiled on the tests in the PG specification (excluding the direct tension test) ranges from 2.2% to 11.5%, as shown in **Table IV-1**. This indicates that laboratory testing skills are acceptable and that the operators' error cannot be considered as the main cause of high variability of MSCR test results.

Table IV-1. Limited reproducibility data for PG tests.

Test	Maximum	Minimum	Average	Median
Viscosity, 20 rpm	11.4%	2.6%	5.6%	3.8%
Viscosity, 1 rpm	15.3%	5.0%	10.8%	11.5%
G*, Unaged	18.2%	2.1%	5.9%	3.0%
G*, RTFO @ PG Temp	35.2%	4.4%	11.1%	6.4%
G*, RTFO @ PG-6°C Temp	33.3%	3.6%	11.5%	6.2%
G*, PAV @ Intermediate Temp	22.1%	4.8%	9.8%	9.1%
BBR Stiffness, 1 hr	13.6%	2.9%	7.3%	5.8%
BBR Stiffness, 24 hr	15.7%	3.8%	7.4%	6.5%
BBR m-value, 1 hr	3.0%	1.5%	2.2%	2.1%
BBR m-value, 24 hr	4.2%	1.4%	2.5%	2.2%
DTT Stress	26.3%	1.1%	13.5%	12.1%
DTT Strain	67.3%	24.1%	40.5%	36.8%
Maximum	67.3%	24.1%	40.5%	36.8%
Minimum	3.0%	1.1%	2.2%	2.1%

PG tests
COV=2.2-11.5

Table IV-2. Limited reproducibility data for MSCR tests.

Test	Maximum	Minimum	Average	
Ductility, Unaged	59.2%	9.2%	21.5%	 Duct, T&T High COV
Ductility, RTFO	92.3%	13.4%	34.1%	
Toughness, Unaged	25.0%	9.3%	15.6%	
Tenacity, Unaged	79.5%	8.9%	33.3%	
Jnr, 3.2KPa@PG Temp.	131.5%	5.2%	39.1%	 Highest COV
Jnr, 3.2KPa@PG-6°C Temp.	42.0%	6.9%	23.6%	
%Rec, 3.2kPa@PG Temp	64.8%	4.1%	28.4%	
%Rec, 3.2kPa@PG-6°C Temp	67.4%	0.8%	15.9%	
% Elastic Recovery, 25°C	17.0%	1.0%	6.4%	 ER-COV
Maximum	188.2%	56.7%	74.7%	
Minimum	17.0%	0.8%	6.4%	

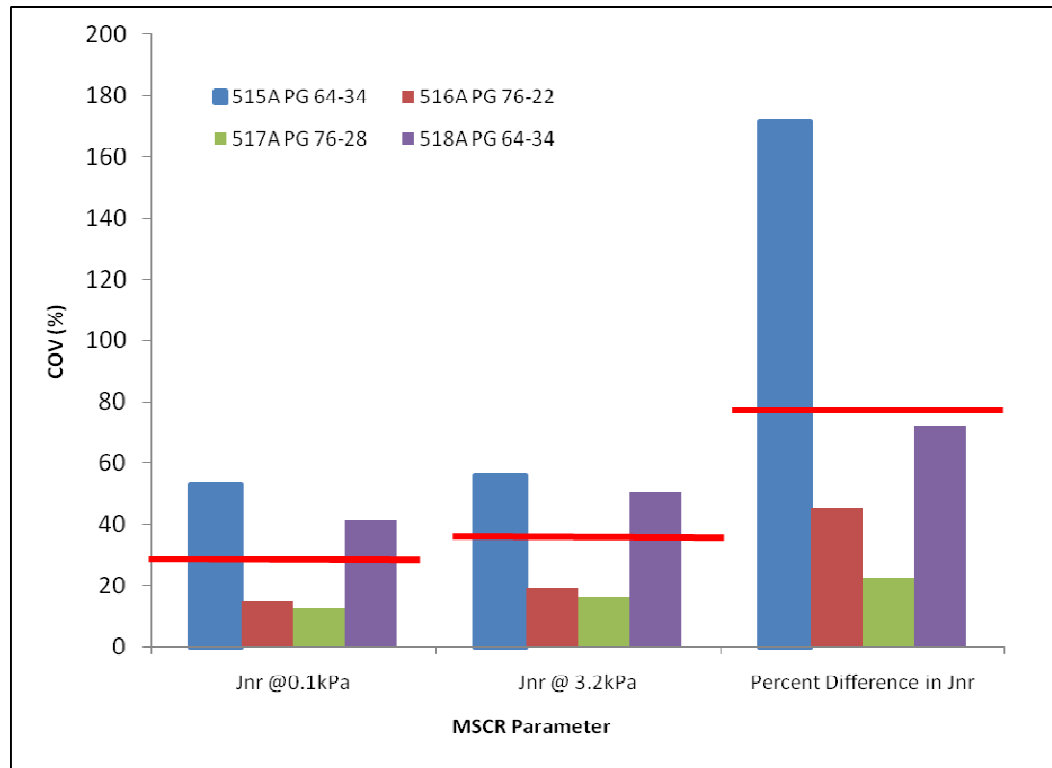


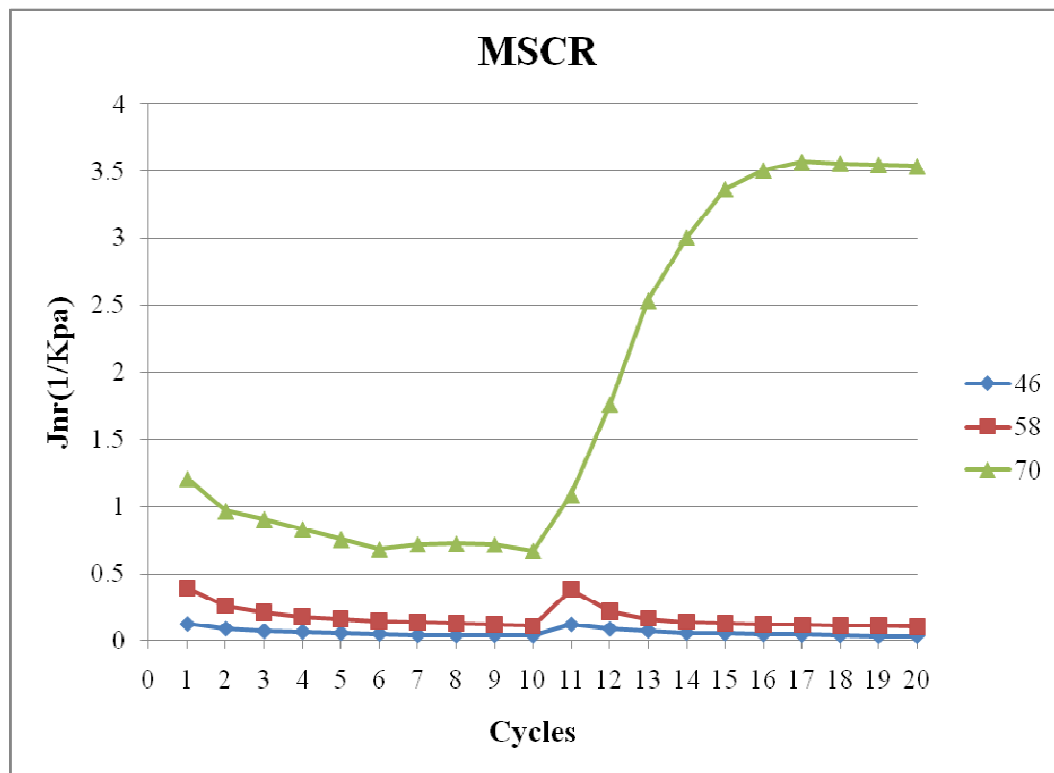
Figure IV-2. MSCR- Reproducibility Analysis without outliers (Bahia et al., 2011).

Figure IV-2 depicts a summary of the variability for 4 binders selected to have PG grades that cannot be produced without polymer modification. The plot includes the critical response parameters included in the MSCR standard (Jnr and the Jnr difference) due to change in stress. As shown in the **Figure IV-2**, the variability of MSCR test is significantly higher than the PG related parameters (shown in **Table IV-1**), and for some binders they are higher than 50%. This dependency on binder type has resulted in further investigation of the effect of elasticity on the consistency of MSCR results. This is discussed further in next section.

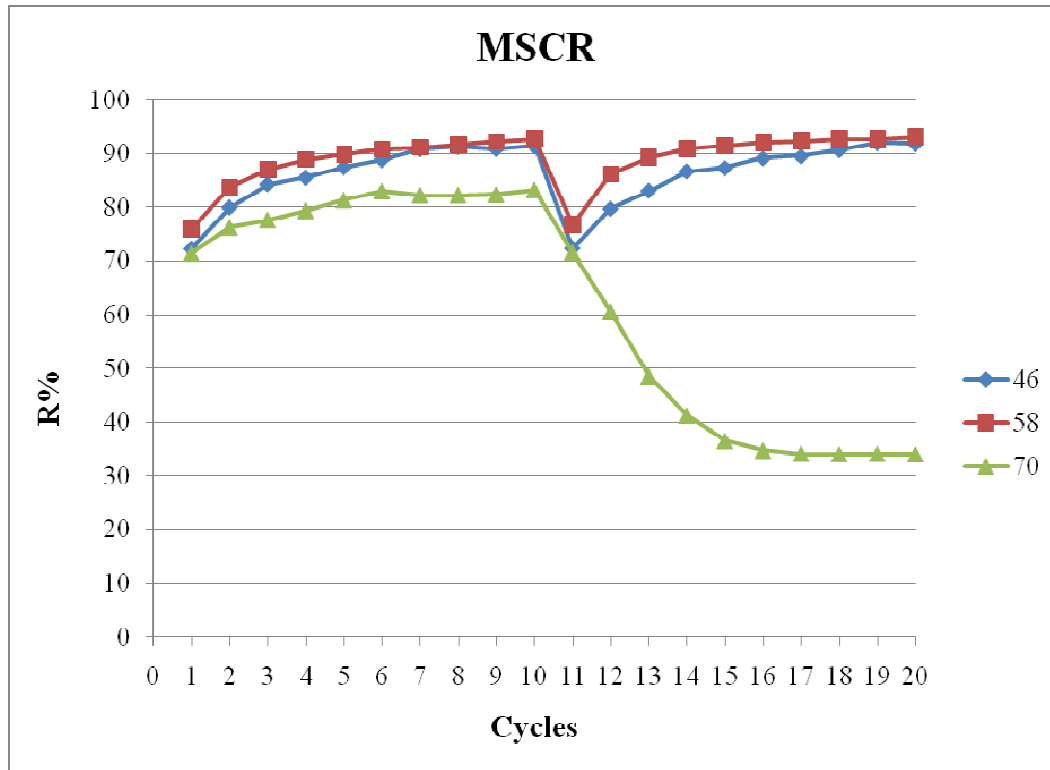
1.3 Variability within the test

Further testing was conducted at more temperatures for binder that was intentionally formulated to have high elastic recovery and a relatively low Jnr, which is typical of binder used in cold climates. **Figure IV-3** clearly shows that during the first few cycles of creep stress and recovery the binder

response rapidly changes, especially at higher stress level (cycles 11 to 20). It is during the last 5 cycles that the binder response approaches steady state.



(a)



(b)

Figure IV-3. Effect of Number of Cycles at three temperatures (46, 58 and 70°C): PG 52-34+ 4% SBS (Bahia et al., 2011).

This observation was confirmed for a few binders that have high delayed elastic response. This phenomenon is known as The Mullins effect (Diani et al., 2009). The Mullins effect is a softening that occurs in rubber-like materials during the first deformation cycles. It seemed more appropriate to relate the Mullins softening to a stress level than to a strain level, and very often the Mullins effect has been referred to as a stress-softening effect. Therefore, the response of material during the first cycles differs from cycles in the later cycles after reaching steady state. Also, Motamed et al. reported that the creep and recovery testing of binders is very helpful in understanding rutting but considering only the first part of creep, which includes only a few number of cycles, can lead to significant errors in ranking binders and mixtures (Motamed et al., 2008).

Due to the complexity of the stress-strain response of rubber-like materials, which involves large deformations, non-linearity and softening, there is no general answer for The Mullins effect. To understand the pre-strain softening in rubbers, several physical interpretations have been proposed. One well-known physical interpretation is that they involve microstructural ruptures as well as microstructural

changes, but they are mainly dedicated to filled rubbers and usually do not extend to the case of crystallizing pure gums. The various explanations suggested for the Mullins effect show that there is still no general agreement on the origin of this effect at the microscopic or mesoscopic scales. According to different authors, only the irreversible, permanent, softening can be the consequence of the breakage of adsorption bonds (Diani et al., 2009).

The challenge with such behaviour is that taking the average of the 10 cycles, as required in the MSCR standard procedure, could be misleading as the response is significantly changing with cycles. It is hypothesized that such response is also a significant contributor to the variability of the MSCR results. To have an initial assessment of these effects, the Jnr values were calculated using the 10 cycles and compared with Jnr values calculated from the last 5 cycles. **Figure IV-4** shows that the percent change between two methods of calculating Jnr at 0.1 kPa stress level can be as high as 30%, and at 3.2 kPa can be as high as 20%, which is significant and can be a serious source of variability.

Figure IV-5 compares the normalized Mean Square Error (MSE) for the Jnr and %R calculated based on the average of the first and second 5-cycles. To calculate normalized MSE, first mean of Jnr for five cycles were calculated and then the error between the average and each cycle Jnr were defined. The sum of errors for 5 cycles divided by the average Jnr of five cycles will give normalized MSE. The data scatter shows that for 73% of the data points the normalized MSE for Jnr based on the average of the first 5-cycles have more variation than the ones based on the second 5-cycles. Therefore, it is expected that by taking those cycles for the calculation of Jnr, some of the variability will be removed.

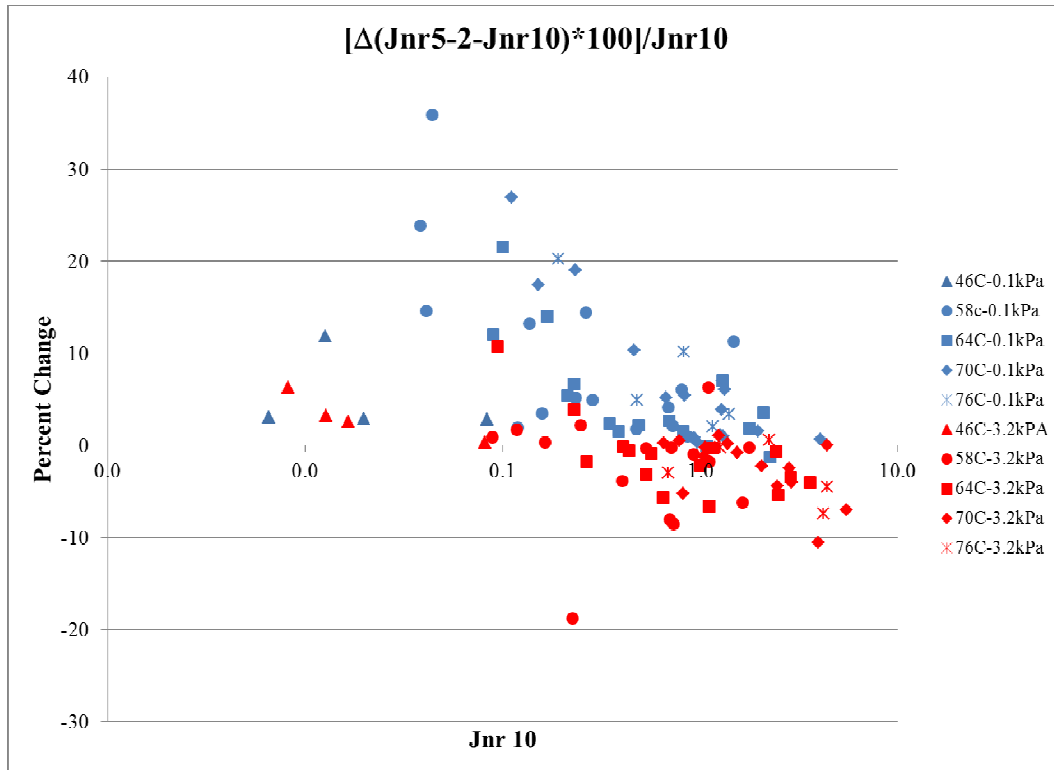


Figure IV-4. Percent change between calculating Jnr and %R based on the average of the second 5-cycles vs. the entire 10 cycles.

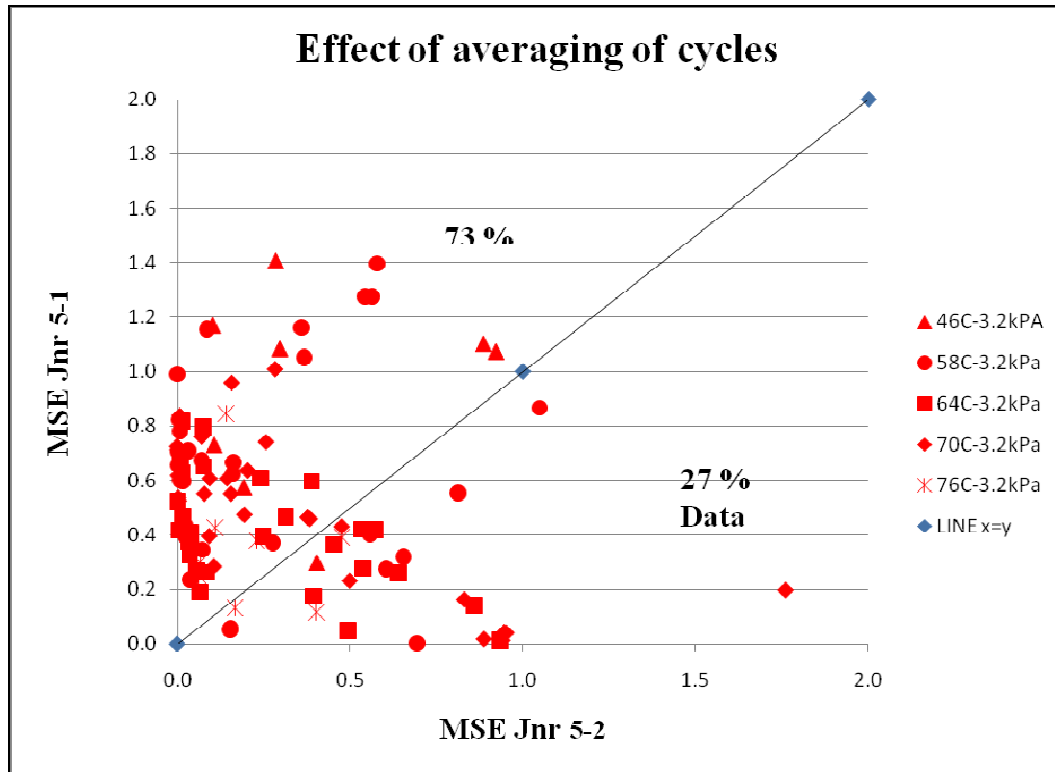


Figure IV-5. Normalized Mean Square Error between calculating Jnr and %R based on the average of the second 5-cycles vs. the first 5-cycles.

These analyses show that the method of averaging the response for 10 cycles at each of the stress levels could lead to misleading representation of actual binder response due to the changes during the cycles. To avoid the varying response that takes place during the initial cycles, it is suggested to calculate the average Jnr and %R based over the second half of the creep stress and recovery cycles at each level of stress. This should be a better representation of the binder properties, and could significantly reduce the variability of the results.

2. Effect of Number of Cycles

2.1 Investigation of effect of Number of Cycles in RCR test

Figure IV-3 clearly show that during the first five cycles of creep stress and recovery, the binder response rapidly changes, especially at higher stress level (cycles 11 to 20). It is during the last 5 cycles

that the binder response reaches a more steady state. NCHRP report 459 suggested having at least 50 cycles to get to steady state. It is reported that after 40 to 50 cycles at the high-grade temperatures, the rate of strain accumulation is constant and not dependent on the level of accumulated strain. Other research indicated the need to study creep and recovery under a larger number of cycles that better represent field conditions (Marasteanu et al., 2005).

To further investigate the cycle dependence of the materials, RCR testing was conducted, so that each material would be repeatedly loaded for an extended duration at controlled stress level. RCR tests were done for 1000 cycles at three stress levels to observe effect of number of cycles on binder behavior more clearly. Also, because these data should be correlated to mixture results, it was necessary to have a wide range of binder behavior at different stress levels. RCR tests were conducted at the same temperature of mixture testing. The **Figure IV-6** have shown RCR results at different stress levels at 46°C.

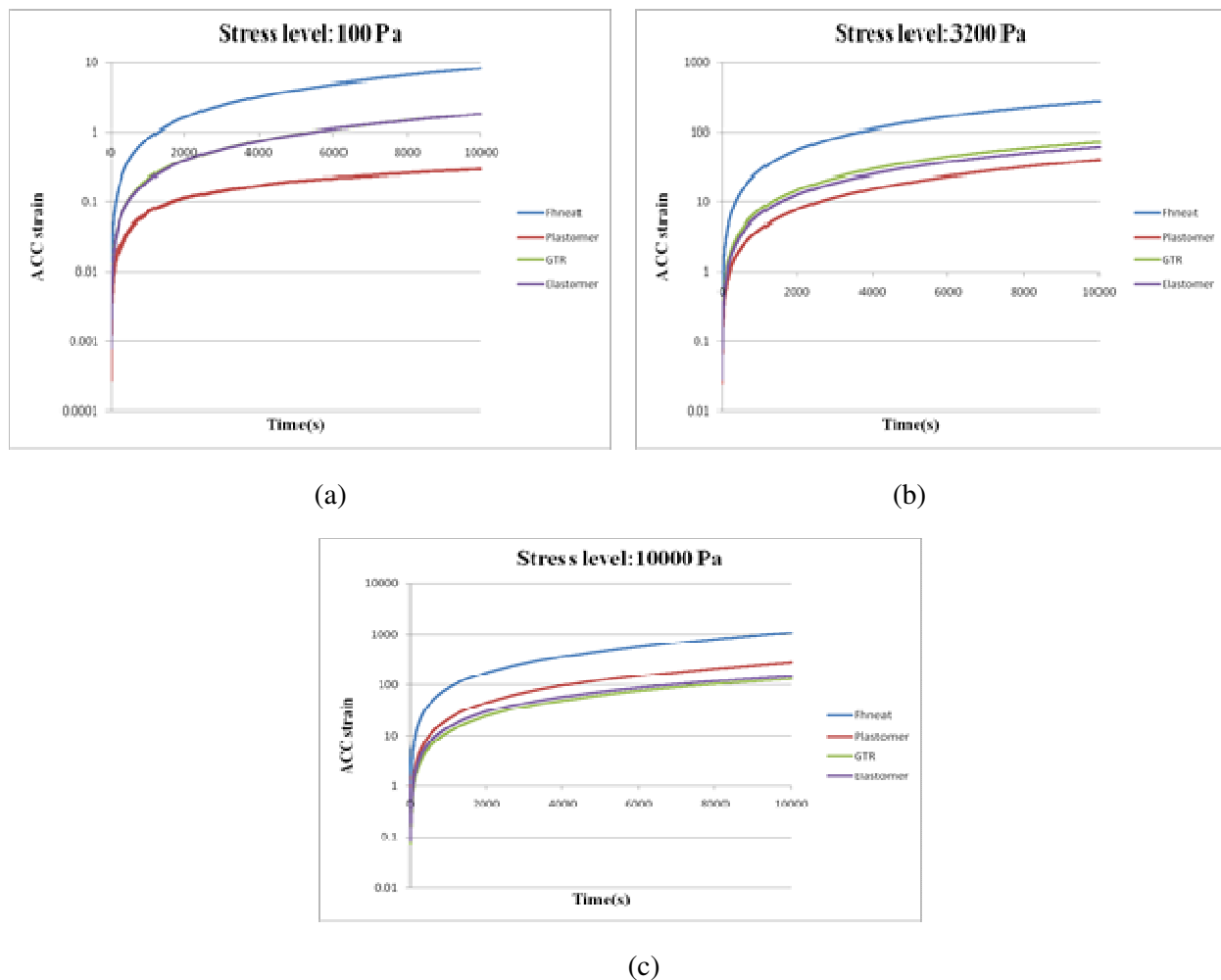
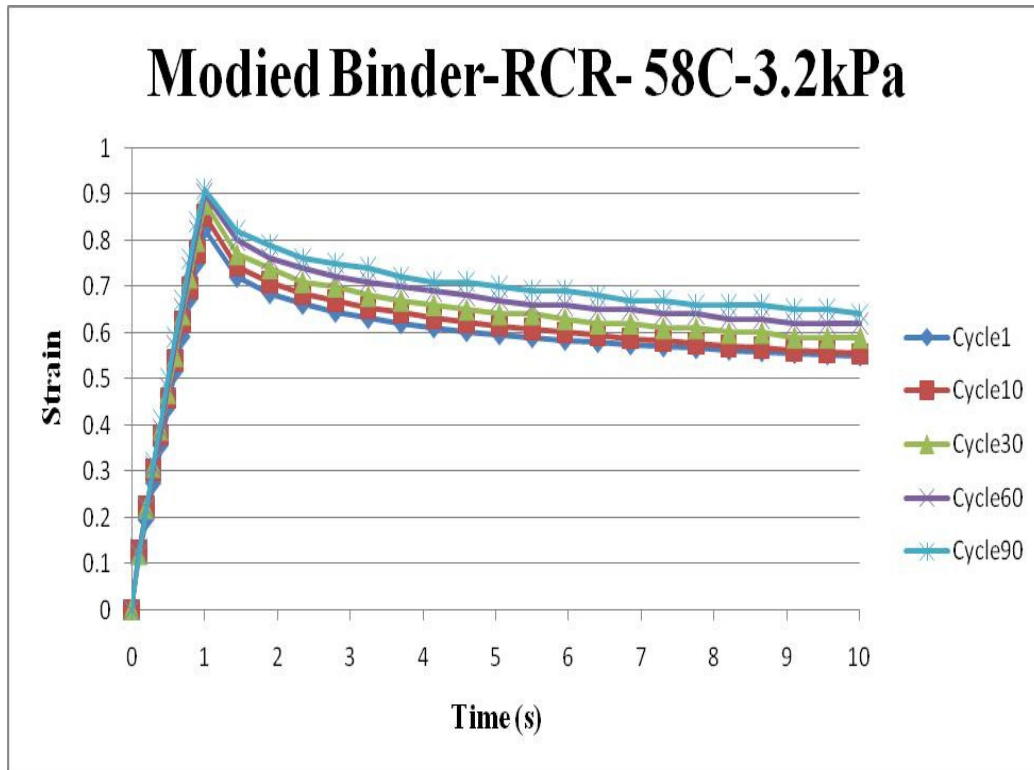
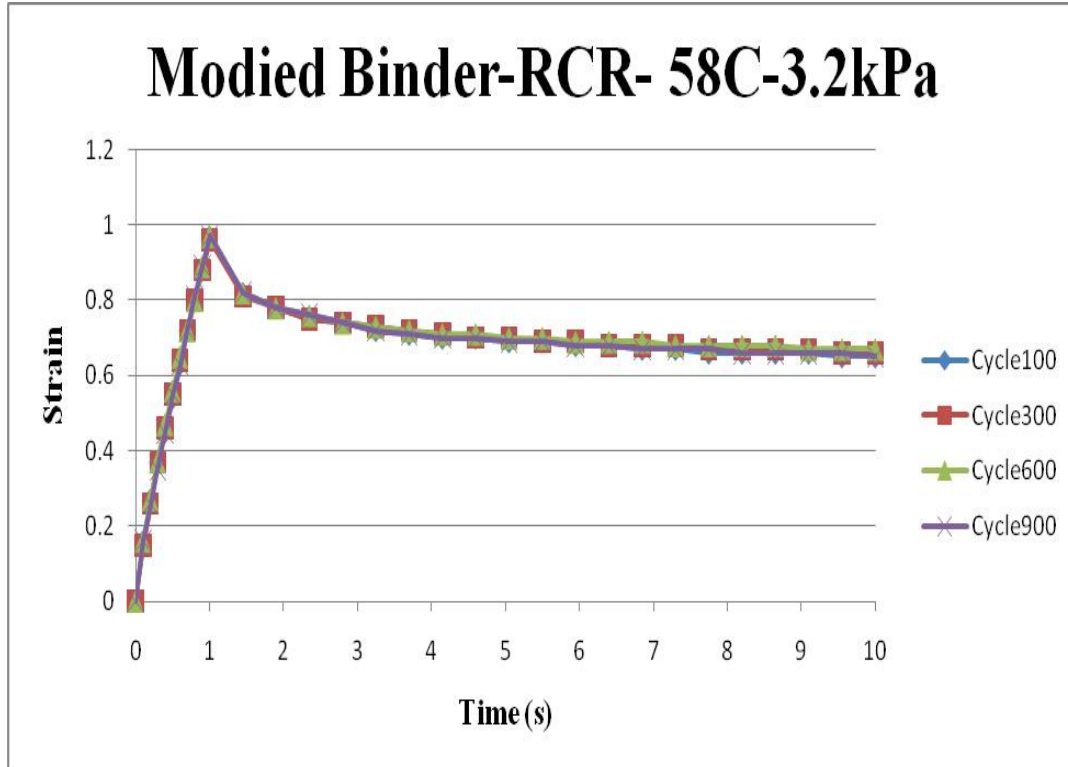


Figure IV-6: RCR (time vs. accumulated strain (ACC strain)) at 46°C for neat binder, plastomeric, elastomeric and GTR modified binders at three stress levels.

RCR results show that most change occurs before 100 cycles and after that, binder shows a constant rate of increasing strain. To check this hypothesis, more analysis on RCR results were conducted. RCR results for same binders as this research showed the same trend and the analysis confirmed the hypothesis. **Figure IV-7** shows the summary of these results.



(a)



(b)

Figure IV-7. Effect of Number of Cycles in RCR test for modified binder.

It can be clearly seen from **Figure IV-7 (a)** that the binder is in unsteady state before 100 cycles. The **Figure IV-7 (b)** shows steady state of the binder after reaching to 100 cycles. Therefore, there is a need to have enough number of cycles in MSCR test to reach this state. Also, time efficiency of the test should be considered. Therefore, 30 and 60 numbers of cycles were selected to use in the MSCR test procedure to ensure the achievement of steady state conditions for all tested material.

2.2 New Statistical Design

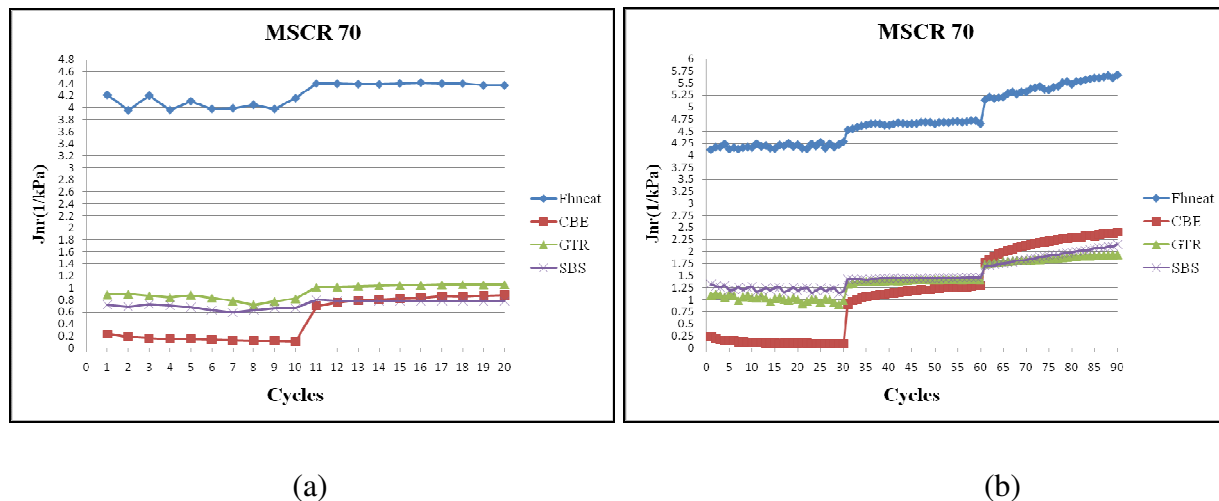
It is hypothesized that having more cycles and another stress level is helpful to exhibit better picture of binder rutting resistance, and improve overall pavement performance. A testing protocol should be developed to capture the nonlinear characteristics of asphalt binders. The test results can be used to represent more comprehensive behavior of the modified asphalt in MSCR test. The characteristics of

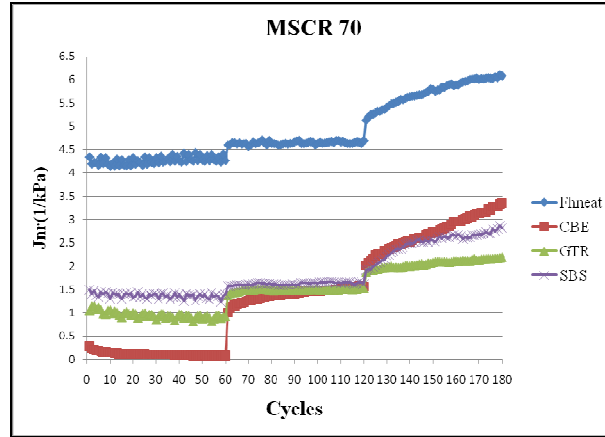
asphalt binders can be used to accurately predict the binder and mastic contribution to rutting resistance of asphalt mixtures.

To examine the effect of the number of cycles of creep and recovery, the MSCR tests were conducted according to the following methods:

- Method A - Conducting the tests for 10 cycles of creep and recovery cycles under each of the two stress levels of 0.1 kPa and 3.2 kPa, as described in AASHTO TP 70 or ASTM D7075 standards.
- Method B - Conducting the tests for 30 cycles of creep and recovery cycles under each of the three stress levels of 0.1 kPa, 3.2 kPa, and 10 kPa.
- Method C - Conducting the tests for 60 cycles of creep and recovery cycles under each of the three stress levels of 0.1 kPa, 3.2 kPa, and 10 kPa.

These modified MSCR tests were run upon first text matrix for four binders at three different temperatures. **Figure IV-8** shows the summary of various MSCR tests.





(c)

Figure IV-8. Effect of Number of Cycles in various MSCR tests for different binders.

In **Figure IV-8** the difference between these MSCR tests can be observed clearly. **Figure IV-8 (a)** shows the standard MSCR and the other two shows MSCR B and C. Comparison between **Figure IV-8 (a)** and the other two exhibit that binders ranking are changing when the binders are under more creep and recovery cycles. These results indicated that having more cycles, show a better picture of binder's behavior. In **Figure IV-8 (c)** it can be observed that binders are changing the trend around cycle 90. This mostly can be the indication of the binder being in its nonlinear region. It should be mentioned that with having more number of cycles, the binder may be get damaged especially at higher temperatures. In **Figure IV-8 (c)**, the sharp increase of Jnr at third stress levels for different binders may due to the damage. But still the results for the first two stress levels show reasonable response of binder. Also statistical analysis was performed to quantify the difference between the Standard MSCR and methods B and C. ANOVA analysis was used to determine the difference between these three types of MSCR statistically. ANOVA is capable of testing hypothesis that the statements are the same statistically. **Table IV-3** shows summary of these results.

Table IV-3. Statistical Analysis Summary.

No	Hypothesis	Stress Level (kPa)	Temperature C	p-value	Jnr (1/kPa)
1	$\mu^{A10-1}=\mu^{B10-3}=\mu^{C10-6}$	0.1	46	0.38	Accept
			58	0.31	Accept
			70	2.322E-08	Reject
2	$\mu^{A5-2}=\mu^{B5-2}=\mu^{C5-2}$	3.2	46	0.04	Reject
			58	0.007	Reject
			70	3.77E-11	Reject
3	$\mu^{A10}=\mu^{B30}=\mu^{C60}$	3.2	46	0.15	Accept
			58	0.005	Reject
			70	4.38E-12	Reject

Bahia et al. evaluated the variability of results in MSCR test and they found that there is less variability in second half of the cycles (Bahia et al., 2011). Therefore in the first hypothesis average of the last 10 cycle for each test was calculated. Then ANOVA analysis was conducted to see difference between various MSCR tests. This hypothesis shows that the effect of number of cycles at low stress level is significant at 70C. This is the indication of importance of having more number of cycles especially at high temperatures. In second hypothesis, average of Jnr value for first five cycles in each test was calculated. In this hypothesis effect of load history was examined. The entire hypothesis was rejected and it shows that the effect of load history of previous stress level is important at all temperatures. Therefore it can be seen that by adding extra number of cycles, different behaviour of binder will be observed in next stress levels. In last hypothesis, the average Jnr value for whole cycles at 3.2 kPa was calculated to examine the effect of adding number of cycles in general. Results show that the effect of number of cycles at higher temperatures is significant. Therefore overall, it can be concluded that adding more number of cycles has a significant effect on binder behaviour especially at high temperatures. Also by having more cycles, wider range of binder behaviour under creep and recovery cycles can be observed.

2.3 Burger Model Analysis

Because ANOVA is not appropriate to test difference within the test, four-element Burger model was used to show how binder behavior will change by adding number of cycles. In ANOVA analysis error terms should be independent of each other but because creep and recovery test is time domain test, the results would be dependent and the errors as well. Therefore, a four-element Burgers model, which is a combination of a Kelvin and Maxwell model in series, was selected as a good representation of the binder behavior. Burger's model consists of four mechanical components as shown in **Figure IV-9**: the two spring elements (E_M , E_K) which coincide with the Hookean principle and the two dashpots (η_M , η_K) which follow the Newtonian principle.

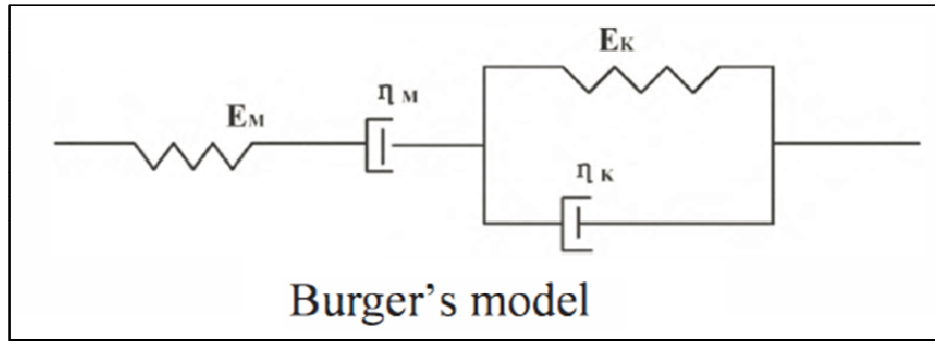
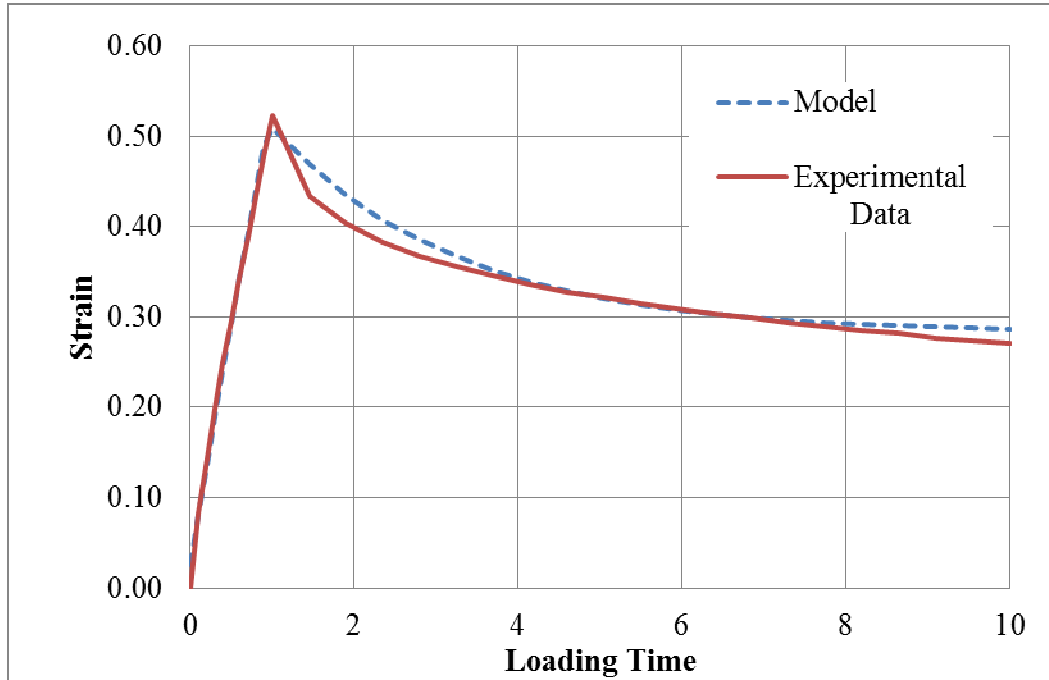


Figure IV-9. Scheme of Burger Model.

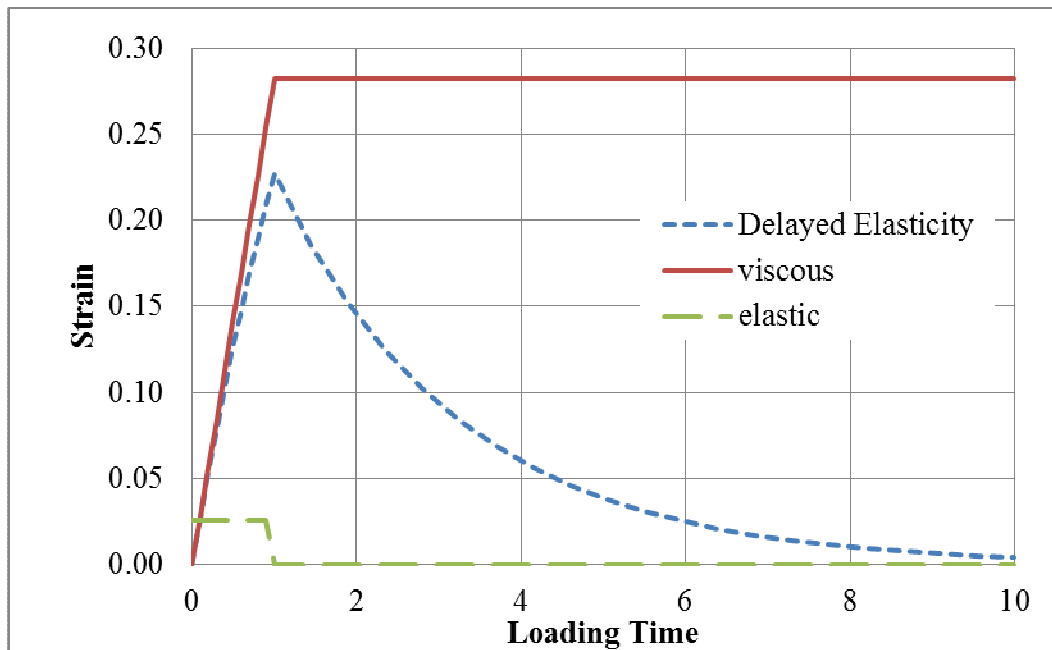
A prediction model is needed to simplify the use of the DSR and to derive a specification parameter. The equation of total shear strain in terms of Burgers model is as follows:

$$\varepsilon(t) = \sigma_0 / E_M + \sigma_0 t / \eta_M + \sigma_0 / E_K [1 - e^{-E_K t / \eta_K}] \quad (\text{IV-1})$$

The viscoelastic description of the behavior of asphalt binders in repeated creep and recovery experiments was studied. In the Burger model the response of an asphalt binder is characterized by three components. The first is the instantaneous elastic component (E_M), the second is the permanent or viscous component (η_M), and the third is the viscoelastic component (or delayed elastic) that is fully recovered where sufficient unloading time is allowed. These three components can exhibit linear or nonlinear behavior. **Figure IV-10** shows the result an example of fitted Burger model to experimental data. In the **Figure IV-10 (a)**, the fitted Burger model is shown and in the **Figure IV-10 (b)**, the decomposed elements of binder behavior are shown.



(a)



(b)

Figure IV-10. Fitted Burger Model to MSCR Experimental Data.

Also, the Burger model has the advantage of separating the binder response into elastic, viscous and delayed elastic responses and it can show binder behavior clearly. Therefore, the Burger model was fitted

to accumulated strain observed in MSCR test with 30 cycles and the changing in the value of elements was analyzed. This analysis was done to show the effect of number of cycles within the test. **Table IV-4** shows summary of findings of comparison between cycle 10 and 30 in MSCR B for all binders.

Table IV-4. Four-element Burger model analysis.

Test and Cycles	Modifier	Temp, C	Stress, kPa	E_M	E_K	η_M	η_K	R2
MSCR (B)- Cycle 10	Neat	58	0.1	179923	12345	1548	8260	1.000
MSCR (B)- Cycle 30		58	0.1	179899	12773	1506	6484	0.999
Percent difference between Cycle 10 vs. 30				0.0	3.5	-2.7	-21.5	
MSCR (B)- Cycle 10	Plastomer	58	0.1	77877	2967	22596	7443	0.982
MSCR (B)- Cycle 30		58	0.1	66635	2246	28994	6511	0.982
Percent difference between Cycle 10 vs. 30				-14.4	-24.3	28.3	-12.5	
MSCR (B)- Cycle 10	GTR	58	0.1	58840	4520	5071	6321	0.989
MSCR (B)- Cycle 30		58	0.1	52246	4178	5305	6806	0.985
Percent difference between Cycle 10 vs. 30				-11.2	-7.6	4.6	7.7	
MSCR (B)- Cycle 10	Elastomer	58	0.1	75472	7463	4420	8964	0.993
MSCR (B)- Cycle 30		58	0.1	92365	6566	4573	8681	0.993
Percent difference between Cycle 10 vs. 30				22.4	-12.0	3.5	-3.2	

This result shows that there is a considerable difference (higher than 10%) between binder behavior in those two MSCR tests. It can be seen that the difference between values of elements are large enough and it is the indication of non-steady state. Also it was observed that the difference is more significant for modified binders rather than neat one. It should be mentioned that difference between binder behavior at different cycle is shown in different elements of Burger model for different binders and it depicts that each binder shows unique change in their behavior affected by number of cycles. These results confirm that there is significant difference between binder behavior at cycle 10 and 30. Similar analysis was conducted on MSCR C to see difference of adding more cycles. **Table IV-5** shows summary of the results.

Table IV-5. Burger model analysis on MSCR with 60 cycles.

Test and Cycles	Modifier	Temp, C	Stress , kPa	E _M	E _K	η _M	η _K	R ²
MSCR (C)- Cycle 10	Neat	58	0.1	179908	11748	1576	6591	1.000
MSCR (C)- Cycle 30		58	0.1	179906	9847	1476	7414	1.000
MSCR (C)- Cycle 60		58	0.1	179908	9007	1522	8001	1.000
Percent difference between Cycle 10 vs. 30				0.0	-16.2	-6.4	12.5	
Percent difference between Cycle 30 vs. 60				0.0	-8.5	3.2	7.9	
MSCR (C)- Cycle 10	Plastomer	58	0.1	77868	2605	26565	6629	0.981
MSCR (C)- Cycle 30		58	0.1	69953	2075	57247	6605	0.985
MSCR (C)- Cycle 60		58	0.1	69989	1957	52931	6632	0.985
Percent difference between Cycle 10 vs. 30				-10.2	-20.3	115.5	-0.4	
Percent difference between Cycle 30 vs. 60				0.1	-5.7	-7.5	0.4	
MSCR (C)- Cycle 10	Neat	58	3.2	1166069	11	20276204	1416	0.997
MSCR (C)- Cycle 30		58	3.2	960505	12	19726636	1404	0.996
MSCR (C)- Cycle 60		58	3.2	960505	11	19726636	1405	0.997
Percent difference between Cycle 10 vs. 30				-17.6	6.7	-2.7	-0.9	
Percent difference between Cycle 30 vs. 60				0.0	-6.2	0.0	0.1	
MSCR (C)- Cycle 10	Plastomer	58	3.2	99573	5012	6713	10140	0.993
MSCR (C)- Cycle 30		58	3.2	129194	5276	6407	9818	0.995
MSCR (C)- Cycle 60		58	3.2	125320	5660	5962	9842	0.995
Percent difference between Cycle 10 vs. 30				29.7	5.3	-4.6	-3.2	
Percent difference between Cycle 30 vs. 60				-3.0	7.3	-7.0	0.2	

These results prove the finding from **Table IV-4**. The difference between cycle 10 and 30 is significant. But when we are going to cycle 60, it can be seen that the difference between cycle 30 and 60 is not large. These results show that after 30 cycles, changing in binder behavior in each cycle reduces and the binder behavior shows more consistency. After 30 cycles, the values for different elements in Burger model are getting very similar and the difference between cycle 30 and 60 is not considerable. Also it should be mentioned that the same results were observed for elastomer and GTR binders. These findings indicate that there is no worth to go more than 30 cycles because more consistent response is observed and also the delayed elasticity effects are reduced. Because the interest is in the viscous part of binder behavior and time efficiency of the test, the test should include a certain number of cycles for conditioning. From these analyses, it can be suggested that 30 cycles for each stress level would be good alternative for current MSCR test.

2.4 Verification with Limited Mixture Data

Flow number (FN) testing was conducted for both fine and coarse gradations of limestone using each of the four binders in the first test matrix at stress levels of 344 and 1034 kPa. Mixture testing was conducted at a temperature of 46°C. A summary of the test results for limestone mixtures is shown in **Table IV-6**.

Table IV-6. Summary of FN results for limestone mixtures compacted to 6.5±0.5% air voids.

Sample	Stress (kPa)	
	344	1034
Neat-Coarse	450	100
Neat-Fine	730	150
GTR-Coarse	690	160
GTR-Fine	1575	240
Plastomer-Coarse	3000	210
Plastomer-Fine	50000+	400
Elastomer-Coarse	1050	260
Elastomer-Fine	3150	430

Results show consistently that the fine gradation had a greater FN value than the coarse gradation for each of the binder types and at both stress levels. Also, the FN values show consistent reduction when the stress level was increased. The same as MSCR results, the mixtures with plastomer modification exhibited higher FN values than those with elastomeric modification at the lower stress level. The ranking elaborated classifies asphalts approximately in the same order, this fact shows a good correlation between the performance of the asphalt mixtures evaluated in FN test and the performance “predicted” by the rheology characterization of asphalts. However, this ranking was reversed at the increased stress level. In fact, the fine gradation with plastomeric binder did not exhibit tertiary flow within a 50000-cycle loading duration. These results suggest that there may be a shift in the component governing mixture performance, when changing from the low to high stress.

An example of the results obtained from FN testing at 344 kPa is shown in **Figure IV-11**. As shown in the plots, the plastomer with coarse gradation is performing similarly to the elastomer with fine gradation. The plastomer with fine gradation lasted more than 50000 cycles without showing tertiary flow and it can be seen in the plot with horizontal line.

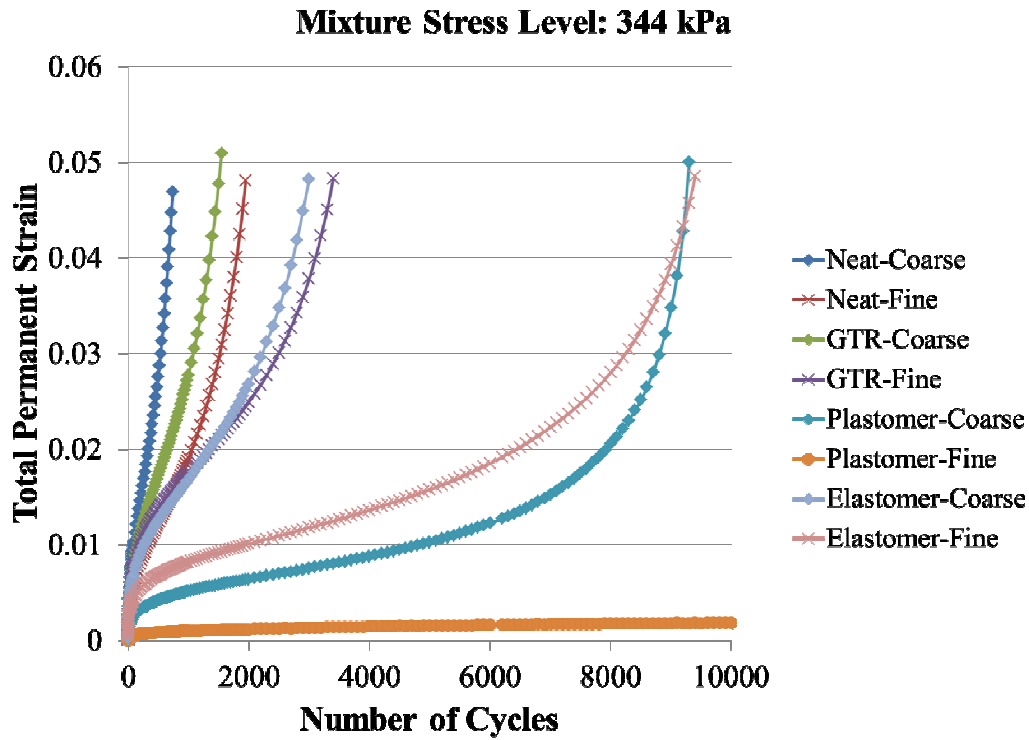


Figure IV-11. Graph. FN results for limestone mixtures at 344 kPa.

It can be seen from **Figure IV-11** and **Table IV-6** that modification improves the performance beyond that of the unmodified binder and this holds true regardless of stress level or gradation. Comparing Jnr of mixture results with Jnr of new MSCR test showed that MSCR method B correlated better to mixture results at the same temperature. Average of Jnr in secondary zone of mixtures was used to be correlated with binder results. **Figure IV-12** shows summary of some of these results.

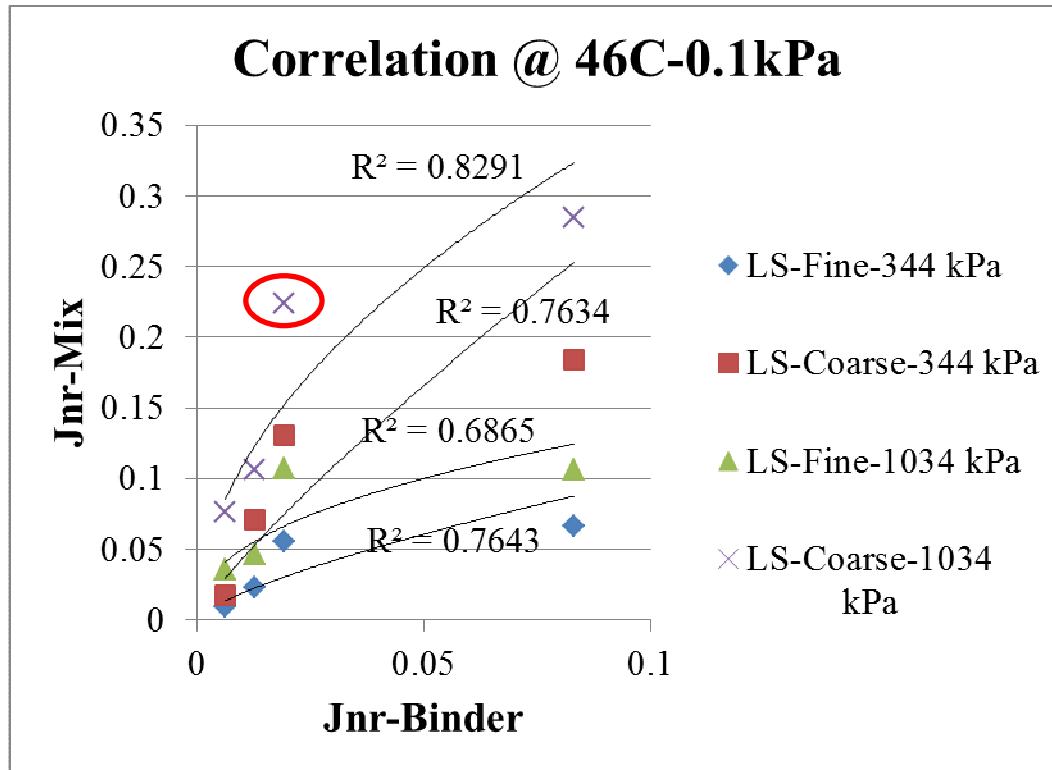


Figure IV-12. Binder-Mixture Jnr Correlation.

The point encircled corresponds to the CBE sample. This point shows the high stress sensitivity of this binder from the MSCR test, as will be further discussed in the next section. The corresponding mixture of CBE exhibited very dramatic failure at high stress level of mixture testing. This sample showed almost the same failure as neat binder and it can be concluded that stress sensitivity of binder is very critical and it needs to be considered. The next section will discuss about this issue in a detail.

Then correlation between standard MSCR and mixtures were compared to MSCR with 30 cycles and mixtures to see which one gives better correlation. For standard MSCR, average Jnr of whole 10 cycles were calculated at each stress level but in MSCR B average of last 10 cycles were used to correlate with mixture data. **Table IV-7** shows summary of this comparison.

Table IV-7. Comparison of R^2 Binder-Mixture Jnr correlation for various MSCR.

Binder Test Condition		Mixture FN @ 46C	
		Fine 344 kPa	Coarse 344 kPa
46C- 0.1 kPa	Standard MSCR	0.76	0.76
	MSCR B	0.76	0.83
46C- 3.2 kPa	Standard MSCR	0.63	0.67
	MSCR B	0.68	0.73
58C- 0.1 kPa	Standard MSCR	0.79	0.79
	MSCR B	0.82	0.89
58C- 3.2 kPa	Standard MSCR	0.64	0.58
	MSCR B	0.70	0.69

The results showed that average Jnr of last 10 cycles has better correlation to mixture data in comparison with average Jnr of whole cycles for MSCR B and standard MSCR results as well. The best correlation was at 58C at low stress level. This can be related to precision of data acquisition at this temperature for stiff binders like this or it can be explained by strain order of binders experience in mixtures. It can be seen that the correlations are not very significant. It can be explained that at the high number of cycles, the MSCR test brings the binder to the domain of nonlinear viscoelasticity, and the same must occur during the FN test in the corresponding mix but it is still difficult to imagine that Jnr and the rut depth, two quantities obtained in the domain of nonlinear viscoelasticity, can be easily correlated. Moreover the element (particles) of the mix undergoes much more complicated deformation in the FN test than the element of the corresponding binder in the MSCR test.

Finally, as a result of these analysis, it can be concluded that 30 cycles is recommended to use in MSCR in order to capture more consistent results and have less variation especially in the second half. Finally, it could be said that there is a good correlation between the susceptibility to rutting at different temperatures of the asphalt mixtures and the information provided by repeated Creep, the rheology

characterization method. The accumulated total deformation in the 30 cycles of repeated creep test increases, asphalt (or the mixture made with it), becomes more susceptible to rutting at different test temperatures.

3. Effect of Stress Level

Stress sensitivity, or non-linearity, of modified asphalt binders under increased levels of stress has been the subject of several recent investigations. One of the consequences of these research activities is the introduction of the Multiple-Stress Creep and Recovery (MSCR) for consideration as a new binder specification test. Although the MSCR is a promising test, there are questions about the justification of the stress levels selected in the test. Kose (2001) clearly indicated that finding the range in stresses or strains in binder domains is not a trivial task and no one level can be selected as most representative of what binders experience in a typical mixture. It is clear from the results that a wide range can exist and the best approach is to characterize the stress sensitivity of binders and mixtures and use the sensitivity as a performance measure (Kose, 2001). It is also important to notice that the stress dependency is not the same for all asphalts and appears to be small for the binders without additives.

Permanent deformation in modified asphalt binders can be highly dependent on stress level (Bahia et al., 2001). Delgadillo et al. (Delgadillo et al., 2006) reported that the nonlinear behavior of many modified binders suggests that the use of higher stress levels that are more representative of the state of stress between the aggregate particles in the mixture is preferred. Some researchers showed that in order to study the behavior of the binders in non-linear range, stress levels higher than 3.2 kPa seems to be needed (Wasage et al., 2009; Dreessen et al., 2006; D'Angelo et al., 2007b). Another research showed that the final accumulated creep compliance at the end of 10 cycles for the given stress level, the linear viscoelastic domain of the studied asphalt binders was near 10 kPa (Wasage et al., 2009; Reyes et al., 2009). They also reported that starting point of nonlinearity, the applicability of the linear viscoelastic theory for the description of the repeated creep and recovery experiments, was found to cover a wide range of shear stresses up to 10 kPa depending on the sample.

Delgadillo et al. (Delgadillo et al., 2006) showed that for stresses until 10,000 Pa, the correlation between RCR and mixture permanent deformation agree well regardless of selected stress level. They also reported that the ability of a binder to resist high stress levels without collapsing (continuous flow at 1.0-s loading time) appears to be a good indicator of the mixture rutting performance. Results from the

creep test confirm that the binders that were able to resist higher stress levels without failure of the sample resulted in mixtures with higher resistance to permanent deformation (Delgadillo et al., 2006). Wasage et al. showed that The variation of J_{nr} in the modified asphalt binders that it is important to understand the stress dependency of the material and they reported that most binders starting to show nonlinear behavior by stress level close to 10 kPa (Wasage et al., 2009). Therefore to investigate the effect of stress level, 10 kPa was selected to add to the MSCR test with 30 and 60 cycles as last stress level proceeding 3.2 kPa.

3.1 Adding 10 kPa

Figure IV-13 shows summary of the MSCR B and C procedures results with 10 kPa stress level added last. At lower stress level, the distinction between some modified binders is hard to determine because the modified binders behave similarly. As the testing stress levels are increased the binders begin to separate allowing us to differentiate and identify the performance of the binders. It can be seen in that the sensitivity of plastomer to the stress level is to the extent that it affects the ranking of the binders. This higher nonlinearity in this modified binder might lead to poor performance at high stress levels in pavements; therefore, stress sensitivity should be taken into account in selecting binders and type of modification.

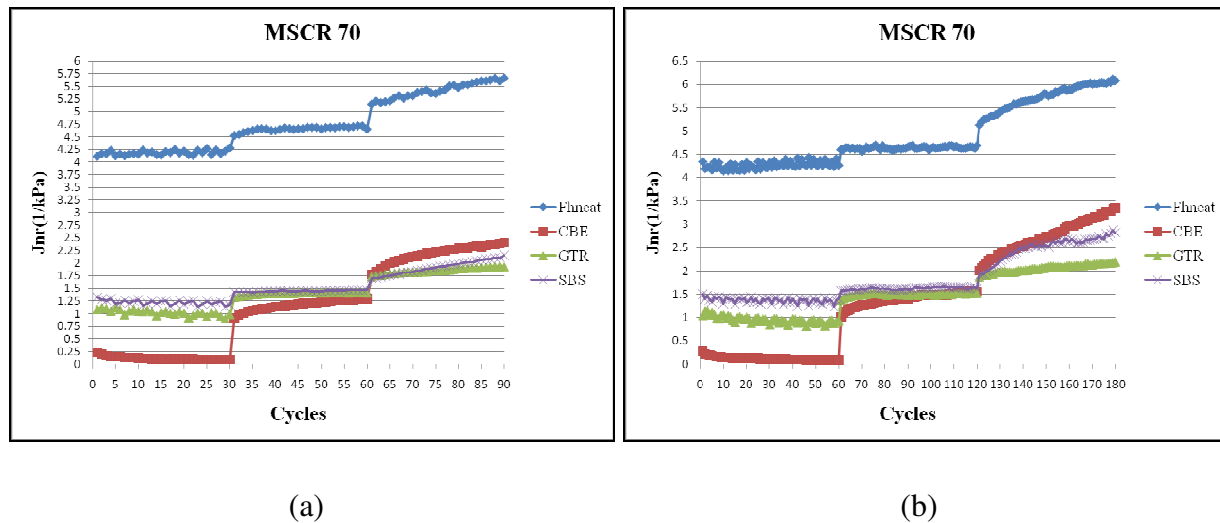


Figure IV-13. Effect of adding 10 kPa stress level in various MSCR tests for different binders.

The stress dependency of polymer-modified binders is far more complex than neat binders. Polymer-modified binders are in fact two-phase systems and the stress dependency is affected by the stiffness of

the base asphalt, the volume of polymer, and the extent of the polymer network in the binder. All of these effects should be identified by the MSCR test which improves the ability to relate binder properties of both neat and modified binders to mixture performance.

3.2 Stress Sensitivity and Nonlinearity

Some analyses were performed to see the effect of 10 kPa stress level on binder behavior. An analysis was conducted to see the stress sensitivity of binders for different stress levels. **Figure IV-14** shows the summary of this analysis.

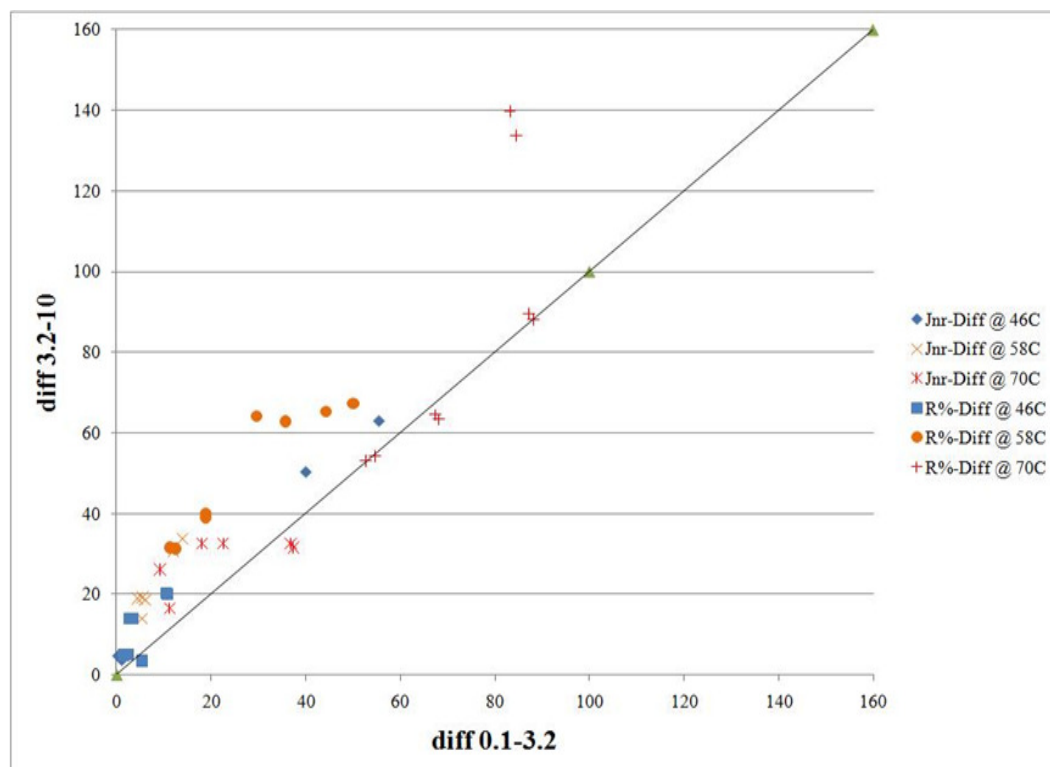
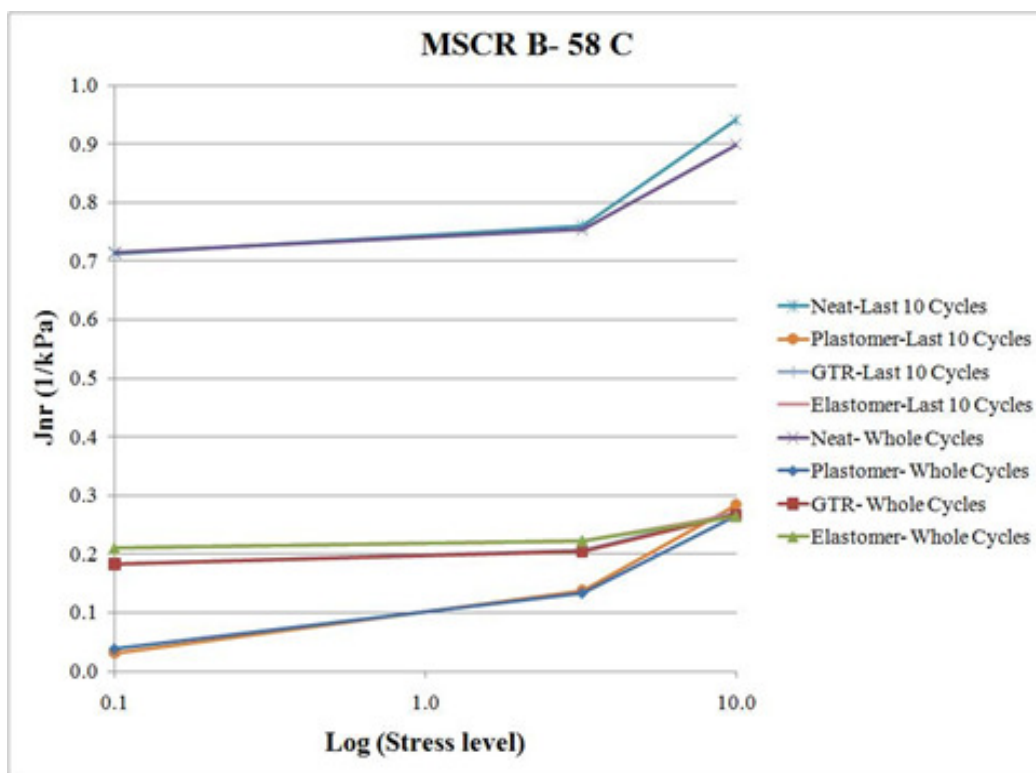


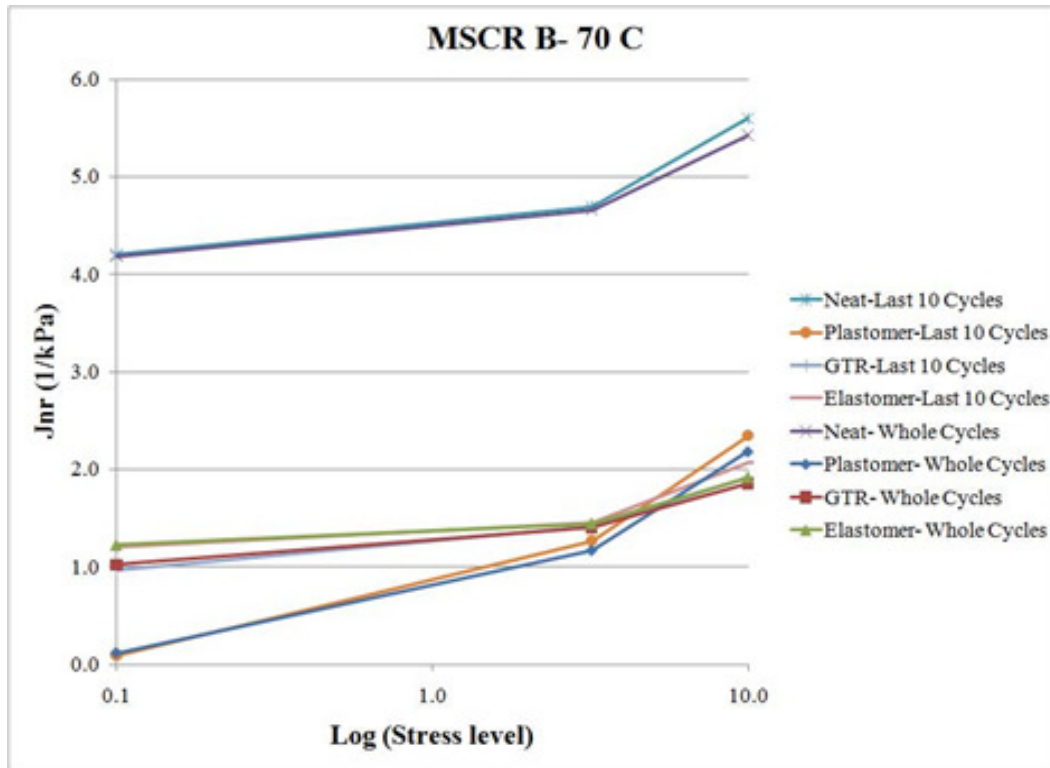
Figure IV-14. Comparison of the binder stress sensitivities between the stress levels.

Figure IV-14 shows that the Jnr diff and %R diff values between stress levels of 10 kPa and 3.2 kPa is higher those of 3.2 kPa and 0.1 kPa. The plots show that majority of the evaluated binders exhibit more pronounced stress sensitivity at higher stress level testing. Adding 10 kPa stress level can help to get

wider spectrum of binder behavior under different stress levels especially between modified binders which behave very similar at low stress level. By using the higher levels of stress and strain in the MSCR test, the response of the asphalt binder captures not only the stiffening effects of the polymer, but also the delayed elastic effects (where the binder behaves like a rubber band). A new procedure of MSCR (Procedure B), performed with a DSR is developed to capture the nonlinear response of the binder and relate that response to rutting in asphalt mixtures. This affect cannot be identified by the existing SHRP binder specification where testing is done in the linear viscoelastic range. Furthermore, **Figure IV-15** shows the stress susceptibility of binders at different stress levels and temperatures.



(a)



(b)

Figure IV-15. Jnr values at three stress levels for unmodified and modified binders.

Increasing stress level, the binder sensitivity to stress becomes clearer and the difference between modifications becomes more visible. From **Figure IV-15**, it can be pointed out that in order to study the behavior of the binders in non-linear range, stress levels higher than 3.2 kPa seems to be needed. It can be seen that at high stress level, the binder resistance to deformation starts to decrease as shown by a sharp increase in Jnr. This rapid changing in non-recoverable creep compliance can be indicator that binder is in nonlinear region.

In these materials, the boundary of linear viscoelastic behavior was strongly dependent on the applied stress as well as on the applied temperature. Thus the suggestion that the MSCR test should be done at temperatures determined upon actual pavement temperature. Polymer will act like a filler and increase the overall stiffness of the binder, however the stress sensitivity of the binder will be greater than a neat binder with an equivalent stiffness. This is due to the actual lower stiffness of the base binder controlling the polymer particle interaction at higher stress. As the polymer percentage or volume is increased the particle interaction becomes greater, increasing the apparent stiffness of the binder and reducing the stress sensitivity at any particular stiffness. The rheological data indicated that strain dependent linearity criteria

for all binders (10,000 microstrain) at high stiffness values as well as a high temperature strain dependent linearity criterion (1,000,000 microstrain) for elastomeric modified binders (Airey and Rahimzadeh, 2004). Also it should be mentioned that stress sensitivity varies with temperature too. The linear limits are very different when measured at 70°C compared with measurements at 46°C and that is confirmed by other researches as well (Delgadillo et al., 2006). When the temperature is increasing, the region of insensitivity to the stress level will shrink. Therefore this is a critical factor that indicates the necessity of estimating the stress sensitivity at actual pavement temperatures.

3.3 Variability at different Stress Level

Another analysis was conducted in order to see the effect of stress level on variability. These analysis was conducted on binders in second test matrix to make sure that there is a wide range of different modified binders. These analysis showed that going to higher stress level can decrease the variability of results within test. Results values have more fluctuation at low stress level and increasing stress level can be helpful to get more repeatable results. **Figure IV-16** shows summary of this analysis and **Table IV-8** presents the binder codes.

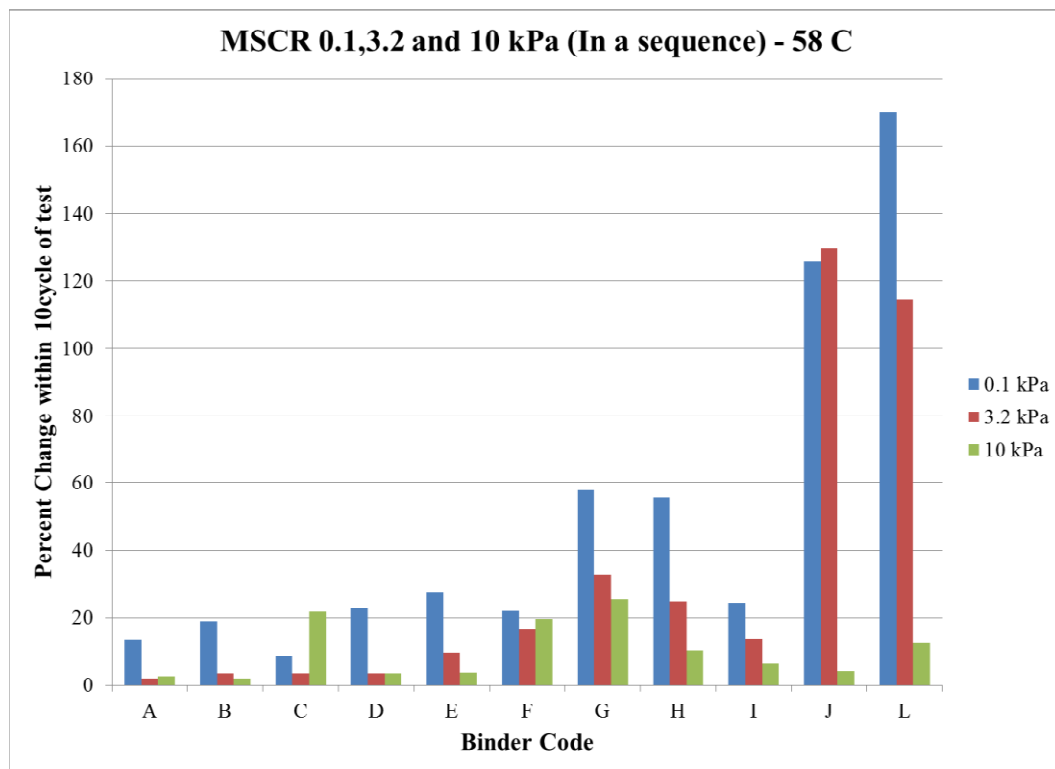


Figure IV-16. Percent change within 10 cycles for each stress level in MSCR test.

Table IV-8. Codes for Modified Binders.

Binder Code	Binder Type
A	FH + 3.2 SBS
B	FH + 4.7 CBE
C	FH + 7.1 GTR
D	FH+ 0.7 ELV
E	FH+ 1.5 ELV
F	FH+ 1 PPA
G	FH+ 1.5 PPA
H	FH+ 2 PE2
I	FH+ 3.5 PE2
J	FH + 2 SBS + BUT
L	FH + 4 SBS + BUT

Bahia et al. (Bahia et al., 2011) also showed that variability is extremely high for the low stress level of 0.1 kPa. Also, this stress level is too low and does not have a significant effect on the response at the subsequent stress level, or on proper ranking of the binder.

Finally, it can be concluded that adding 10 kPa increases binder nonlinearity and susceptibility to stress level and also shows more clear image of modified binder rut resistance. It should be mentioned that at higher stress level (10 kPa in this study) and higher temperatures the binder's behavior changes and it is strongly recommended that a new stress level be selected to measure stress sensitivity and be more repeatable in MSCR test.

4. Influence of Asphalt Binders Elasticity on Mixture Rut Resistance

To strengthen asphalt pavements against damage, modifiers are sometimes added to the asphalt binder. Several studies have been conducted to investigate the relationship between the effect of modifiers and pavement performance. Investigations suggest that the proper balance occurs when an effective elastic network is created by natural, molecular associations. The elastic network may also be created by introducing molecular entanglement in asphalt through the use of high molecular weight polymeric additives (Yildirim, 2007). The apparent benefit of polymer modification is the reduction in the amount and severity of distresses and thereby extension of the service life of hot-mix asphalts (HMA) pavements

and overlays. With proper type of modification, pavements can exhibit greater resistance to rutting, thermal cracking, fatigue damage, and stripping. Polymer modified binders have been used with success at locations of high stress, such as intersections of busy streets, airports, vehicle weigh stations, and race tracks. Different kinds of modifiers have been used to modify asphalt binder such as SBS, SBR, EVA, rubber, etc. Polymer modified binders possess higher elasticity, softening point, adhesion and ductility (Brule, 1996; Airey, 2002; Isacsson and Lu, 1998).

One of the most important characteristics of modified binders is elasticity. Elasticity is defined as the degree to which a material recovers its original shape following application and release of stress. According to the Asphalt Institute “when a tire passes over a section of pavement it is desirable for that pavement to have the ability to ‘give’, but it is equally important for it to recover to its original shape.” Technically speaking, the pavement should possess some flexibility to ‘give’ as the wheel passes, and enough elastic recovery to resume its preloading shape. Since rutting is accumulated permanent deformation in pavements, elasticity may have an enormous effect on material’s recovery after deformation and hence reducing the rutting.

Elasticity is an important property that measures the ability of materials to recover after deformation. Current methodology for measuring the elasticity of asphalt binders for rutting aspect requires running MSCR test. The procedure of this test follows the AASHTO TP70 “Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer”. AASHTO TP70-09 standard has percent recovery in its specification for modified binders. R% is calculated based on following equations at 0.1 kPa in MSCR test (AASHTO TP 70):

$$\varepsilon_r(0.1, N) = \frac{(\varepsilon_1 - \varepsilon_{10}) \times 100}{\varepsilon_1} \quad \text{for } N = 1 \text{ to } 10$$

(IV-2)

$$R_{0.1} = \frac{\text{SUM}[\varepsilon_r(0.1, N)]}{10} \quad \text{for } N = 1 \text{ to } 10 \quad \text{(IV-3)}$$

where,

$$\varepsilon_{10} = \varepsilon_r - \varepsilon_o$$

$$\varepsilon_1 = \varepsilon_c - \varepsilon_o$$

ε_c = strain value at the end of the creep portion (i.e., after 1.0 s) of each cycle strain

ε_r = strain value at the end of the recovery portion (i.e., after 10.0 s) of each cycle strain

ε_o = initial strain value at the beginning of the creep portion of each cycle

The definition for the R% at 3.2 kPa is analogous. The percent recovery measured in the MSCR test is suggested as a measure of the elastomeric response of the polymer in an asphalt binder (D'Angelo et al., 2006).

There is a chart of Jnr versus % R in this standard as it does not give the clear explanation of the chart purpose and possibly clarifying that if percent recovery is needed for rutting or not. **Figure IV-17** shows this chart. In the standard it is mentioned that being above the chart is the evidence of elastomeric presence in binder.

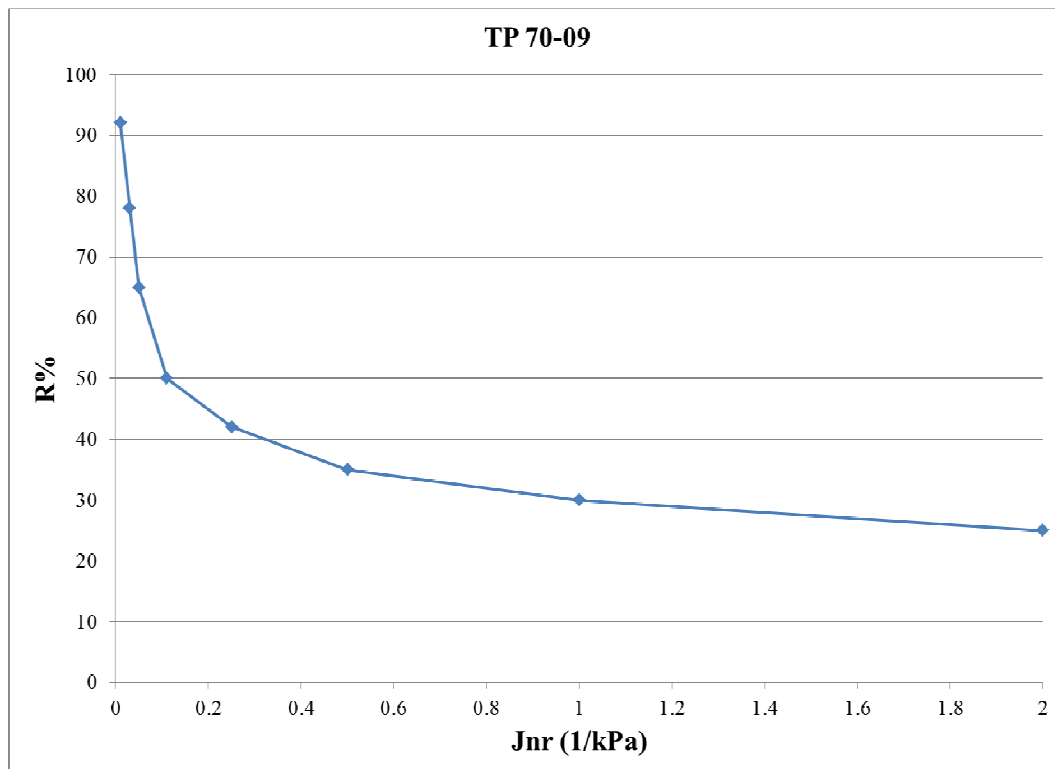


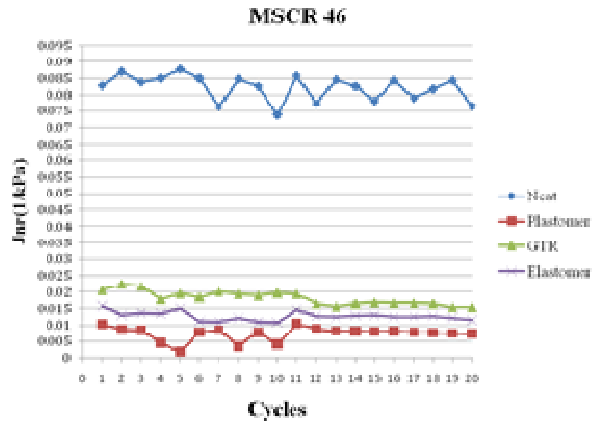
Figure IV-17. AASHTO TP 70-09 specification chart for elastic response.

The purpose of this part is to establish if this requirement is justifiable. Several studies indicated that there is a somewhat good correlation between elasticity and fatigue resistance, but the relation between elasticity and rutting resistance it is still unclear. Therefore, it is essential to investigate the relationship between elasticity and binder rutting resistance.

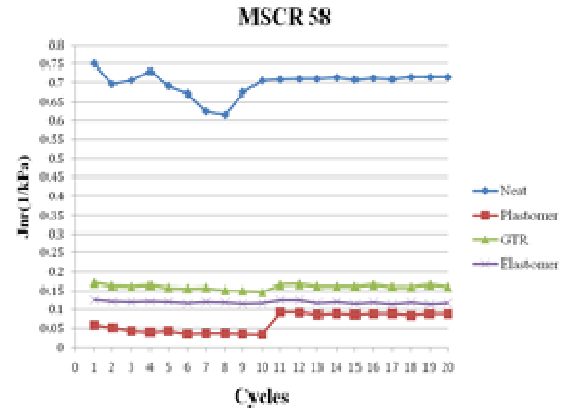
4.1 Effect of Elasticity on Binder Behavior

Elasticity has a major role in behavior of polymer-modified binder. The relationship between elasticity and asphalt binder performances in terms of rutting was investigated by many researchers. Some studies showed that elasticity is important for rutting other not. There is a lack of clarity of the elasticity and effects of that on PMA. In this part, percent recovery was selected as representing characteristic for binder elasticity.

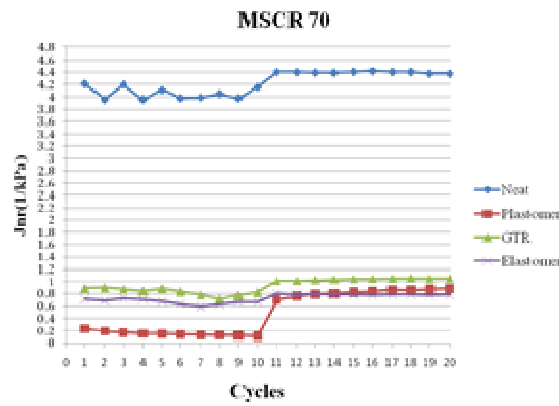
A summary of the MSCR test results for first test matrix binders can be seen in **Figure IV-18**. In general, the ranking of the performance of binders from high to low, based on the MSCR results, is plastomer, elastomer, GTR, and neat. However, it can be seen that plastomer-modified binder also exhibits stress sensitivity at high temperatures, and the ranking begins to shift, evident in the increasing non-recoverable creep compliance (J_{nr}) and a decrease in the percent recovery (%R). **Figure IV-18 (a)** and **(f)** clearly show that plastomer-modified binder is sensitive to stress level. In these graphs, it can be seen that the plastomer-modified binder recovery decreased more than the half by changing the stress level. This ranking is reporting that, counter-intuitively, the plastomer has a higher elasticity than the elastomer, but only at low stress levels. At the high stress level of the MSCR test run at 70°C, the relative ranking of the elastomer and plastomer match expectations. Unlike the elastomer- and plastomer-modified binders, the GTR-modified binder ranking does not change when increasing the stress level at higher temperature. This data shows that the addition of GTR to the asphalt binder does improve the elasticity of the binder significantly at high and low stress levels at all three temperatures when compared to the unmodified binder. The improvement, however, is not as great as that of the elastomer and plastomer modification.



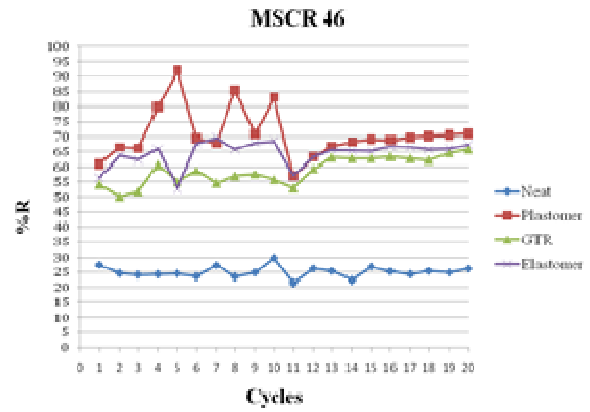
(a)



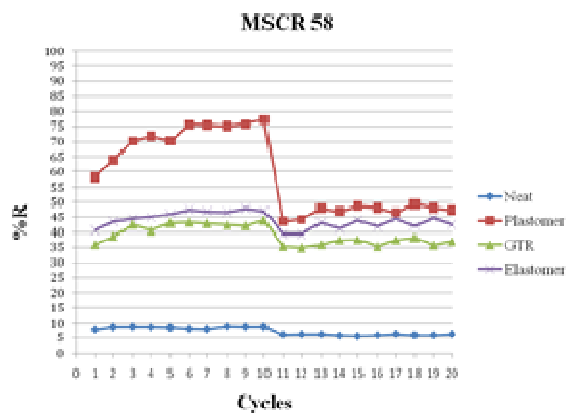
(b)



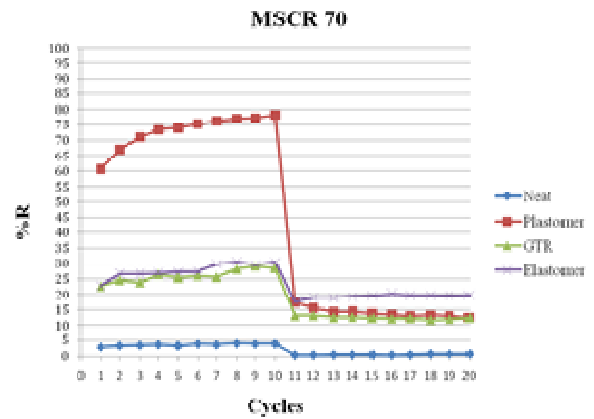
(c)



(d)



(e)



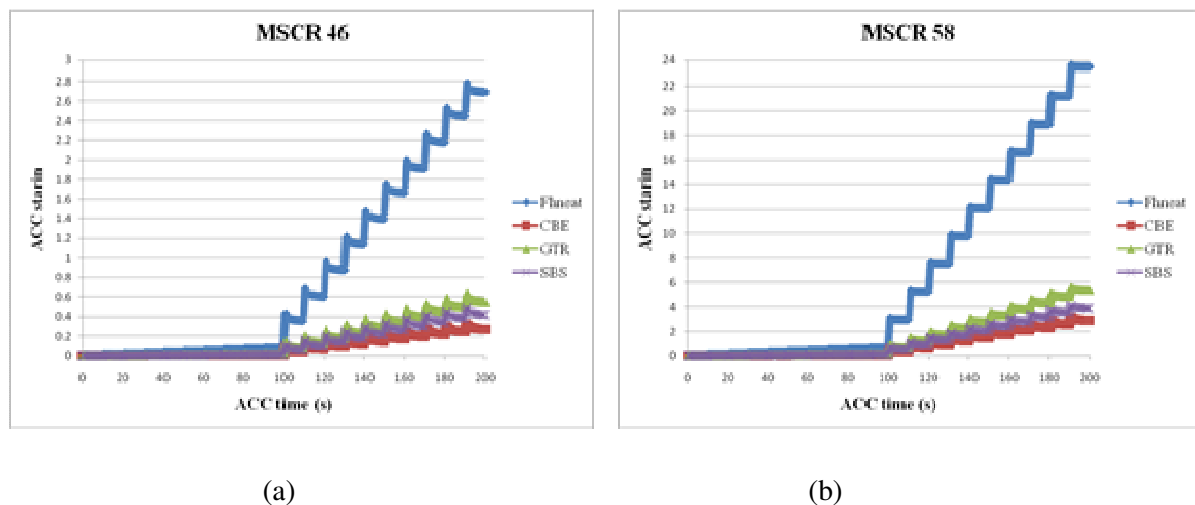
(f)

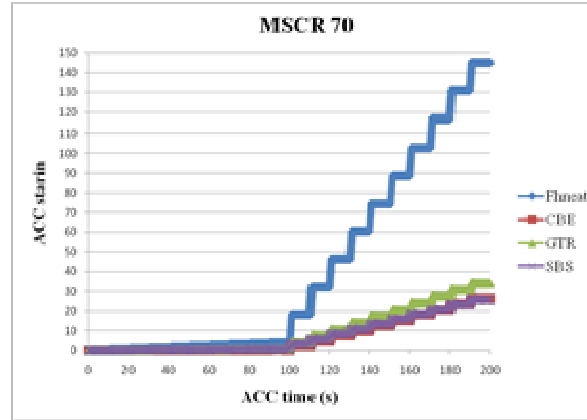
Figure IV-18. MSCR results for asphalt binders.

Figure IV-18 shows the accumulated strain results of MSCR tests for all binder. As the testing temperatures are increased the modified binders begin to separate from neat binder allowing us to differentiate and identify the performance of the modified binders. It can be observed that the elastomeric binder SBS is offering significantly higher recovery during the creep testing and thus exhibits less accumulated deformation. The plastomeric binder also offers higher recovery than does the neat binder. In addition, the ranking from the binder creep test matches well with the ranking from the mixture test results in terms of the rate of accumulation of permanent strain.

But at high temperatures, differentiation between modified binders response is getting more difficult and they show similar amount of accumulated strain. Also in **Figure IV-18**, it can be recognized that with increasing the temperature from 46 to 58 and then 70°C, the recovery amount for all binders is decreasing specially at 70°C which the recovery part is decreasing dramatically. This means that there is no significant recovery at high temperatures and high stress levels for none of the binders even modified one.

The neat binder developed the highest amount of strain with the GTR modified binder being the next highest. Plastomer modified binder proved to perform the best with the smallest amounts of accumulated strain. Thus, leaving the remaining modified binders classified between these two with strains ranging very similar to each other.





(c)

Figure IV-19. Accumulated strain results in MSCR for asphalt binders.

It can be seen that the ranking of binders is pretty much the same with increasing the temperature but at 70°C, plastomer modified binder came closer to the other modified binders. Also the binder data shows that if a low stress level is encountered, regardless of temperature, accumulated strain for all binder would be in very similar change. As stress level was raised to 3200 Pa, the ranking is going to be more clear and distinguishable. It is important to underline that the role of the applied shear stress has to be investigated more deeply because the stresses generated by moving traffic are much higher than those considered in the current form of the MSCR test for asphalt binders. Moreover, with similar applied stresses, the type of modification also plays an important role.

These results show that binder elasticity has enormous effect on binder rut resistance behavior. It is clear that the binder with higher elasticity shows less non-recoverable deformation. As the elasticity of the binder is increasing, the binder can recover more amount of deformation and it will result in less amount of permanent deformation. Therefore binder with higher elasticity, shows less J_{nr} value and more rut resistance. However the effect of binder elasticity on mixture is not simple and it contains a lot of complexity due to relation with different factors.

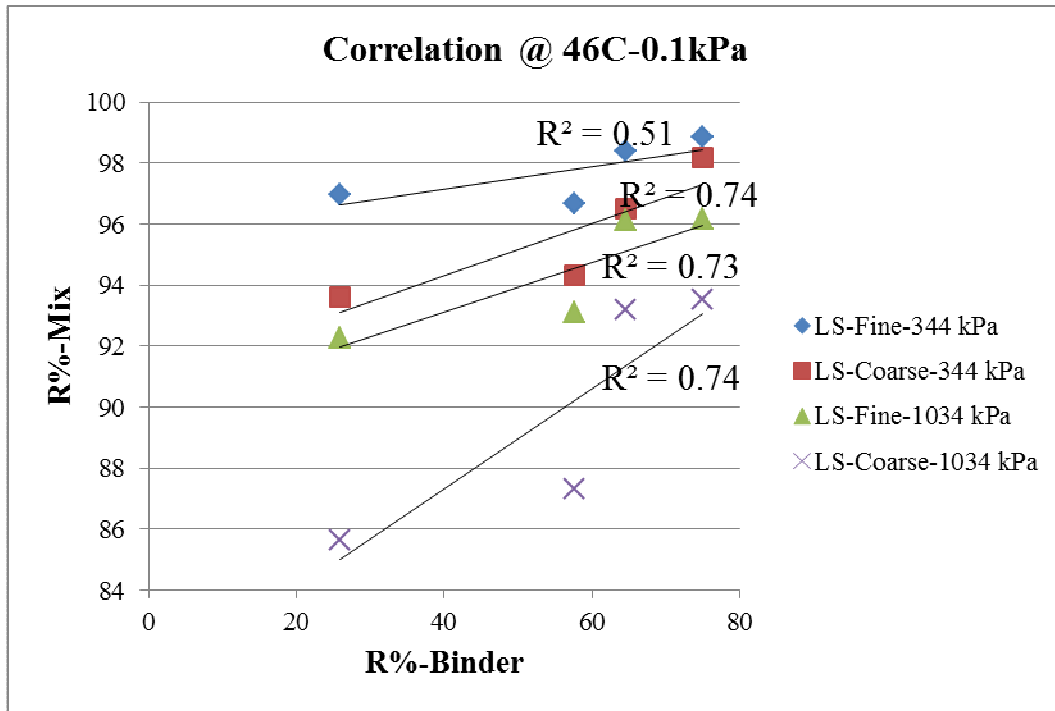
4.2 Relationship between Binder Elasticity and Mixture Performance

Asphalt pavement experience several types of distresses, of these, rutting and fatigue cracking are considered to be the most important. There are two general approaches to build asphalt pavements that are resistant to HMA confined rutting:

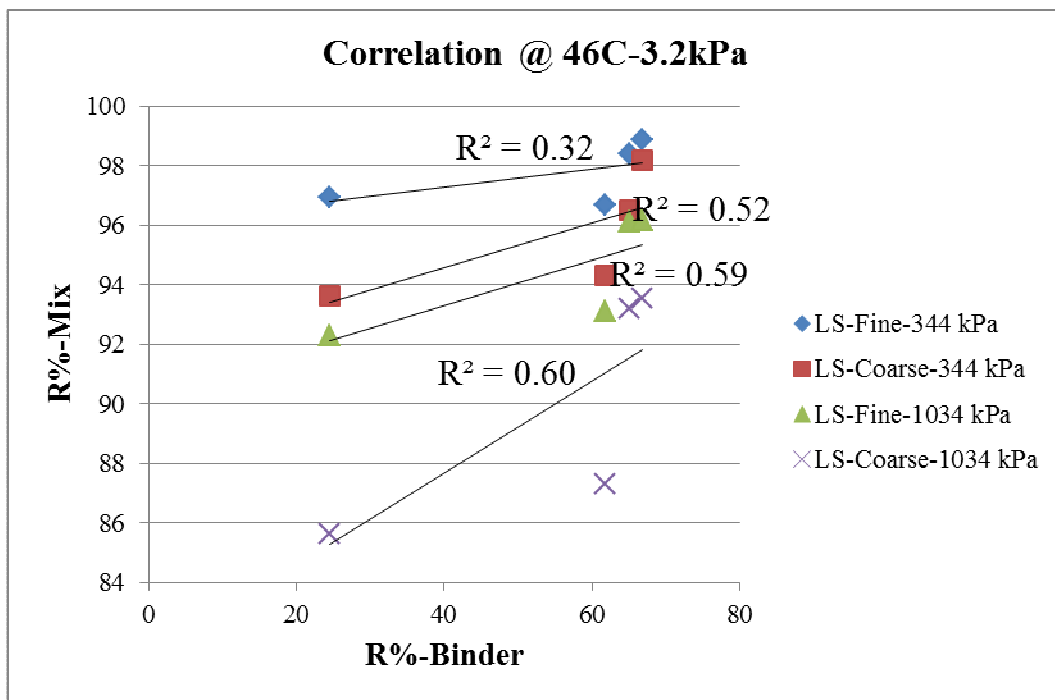
1. Make the asphalt concrete stiff to reduce the deformation, thereby less elastic recovery is needed to resume its initial shape.
2. Make the asphalt concrete more flexible and resilient to assure that there is enough elastic recovery to recover the deformation.

It was hypothesized that the binder elasticity alone is not sufficient to inhibit rutting and improve overall mixture rut resistance. Therefore it is essential to investigate the relationship between binder elasticity and mixture rutting resistance and how different modifiers fit into the above approaches. There is a need to effectively quantify the contribution of the asphalt binder elasticity to asphalt mixture permanent deformation.

In this part the effect of binder elasticity on mixture rut resistance was investigated by using MSCR test. The percent recovery, (R%) was chosen as the indicators of elasticity. A higher R% signifies superior elasticity and over all rutting resistance. Binder's MSCR results were compared with flow number results of mixtures at the same temperature to have an overview of binder and mixture relationship from the aspect of elasticity and rutting. R% of the mixture was calculated from FN test results at 46oC; The average of R% in secondary zone of mixture's response was used to be correlated with binder results.



(a)



(b)

Figure IV-20. R% of Mixture from FN tests compared to the Binder MSCR results at 46C at different stress levels.

As shown in **Figure IV-20**, direct relationship between binder elasticity and percentage recovery in the mixture FN test was observed. Binder with high elasticity would be characterized by low non-recoverable creep compliance and this means that a binder characterized with a high level of elasticity would exhibit better performance in the FN test.

A statistical relationship was found between the binder and mixture R% at the same temperature but it is not significant. This shows that there is correlation between binder elasticity and mixture performance but it is confounded with different variables. However, the relationship between binder elasticity and rutting of HMA is not a simple, direct relationship. This is because the binder does affect the aggregate structure at a given asphalt content and air voids, and the overall rutting is significantly dampened by the aggregate. However, modified binders will always reduce rutting by forming a lubricating film that effectively reduces the friction and stress concentration at which large-scale aggregate movement occurs.

The other important point that should be mentioned is the scale of percent recovery change in binder and mixture. It can be seen that R% of binder is changing from 25% to 70% but the recovery of mixture is not changing significantly for different binders. This confirms that binder elasticity alone is not sufficient to inhibit rutting and improve overall mixture rut resistance but it is very important factor. Because mixture data set in this research was limited, further investigation is needed to cover this more in details.

V. Using MSCR Results to account for Traffic

There is widespread recognition that asphalt binders play a key role in mixture behavior and pavement performance. It is believed that the accumulated strain in asphalt binder, as a consequence of traffic is mainly responsible for the rutting of asphalt pavements. There have been attempts to present a specification criteria and parameter that can describe the affinity of a binder to the increase of accumulated deformation under periodic loading. Although several researchers have tried to develop rheological binder criteria, most of the existing binder specifications are based on traditional binder measurements that either are not measured anymore or are not valid for modified binders.

Rheological and damage characterization of asphalt binders under dynamic loading and different frequencies and temperatures can simulate a wide range of traffic loads and climate conditions. Unfortunately, the characterization of asphalt binders by their rheological properties requires considerable time, financial resources, and equipment—elements that are not readily available to contractors and design engineers in most firms. Consequently, researchers have made significant attempts to develop a criteria of the dynamic properties of asphalt binder on the basis of traffic effects.

Rheological properties of asphalt binders provide a fundamental understanding of the behavior of these materials. These properties play important roles in the evaluation and selection of paving materials, and in the analysis and design of asphalt pavements. Characterizing asphalt binders in the linear and nonlinear range is critical for proper material selection. The response of the material has to be known for the range of stresses and loading times expected when used inside the pavement. Therefore there is a need to have criteria that can present binder behavior under different stress level, number of cycles and temperatures.

1. SHRP Criteria (AASHTO M 320)

Typically, polymer-modified binders are used on roadways with high traffic and heavy loads. Under the existing SHRP specifications with higher traffic levels or slower speeds grade bumping is used. In

these cases binders with a higher temperature grade would be specified. For example, on a typical freeway in a PG 64 climate if the traffic level were to be above 30 million ESALs one grade bump would be specified, increasing the required grade to a PG 70. At toll facilities or in urban areas where slow moving traffic would be expected the grade would be bumped a second time increasing the required grade to a PG 76. Therefore in the SHRP system the specification criteria would be held constant but the test temperature at which the criteria is required is increased. **Figure V-1** shows the schematic chart for this shifting system. The definition of traffic volume and traffic speed is as follow:

The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.

Standing Traffic—where the average traffic speed is less than 20 km/h.

Slow Traffic—where the average traffic speed ranges from 20 to 70 km/h.

Standard Traffic—where the average traffic speed is greater than 70 km/h.

<i>Design ESALs</i>	<i>Traffic Load Rate</i>		
	Standing	Slow	Standard
<0.3	PG 76-22	PG 64-22	PG 64-22
0.3 to < 3	PG 76-22	PG70-22	PG 64-22
3 to <10	PG 76-22	PG70-22	PG 64-22
10 to < 30	PG 82-22	PG 76-22	PG 70-22
> 30	PG 82-22	PG 76-22	PG 70-22

Figure V-1. PG Grade shifting for binder PG 64-22 under different conditions of traffic (AASHTO M 320-10).

Grade bumping based on changes in temperature is used in the SHRP binder specification. The concept is based on the idea that increasing the test temperature by 6°C and holding the criteria value the same will basically double the stiffness of the binder to resist against higher traffic level. This was developed with the assumption that the temperature susceptibility of all binders is very similar and rutting is linear phenomena. But, it has been demonstrated that rutting is a nonlinear high stress and strain phenomenon and testing at temperatures far above the temperature where the stresses and strains will occur will lead to erroneous results that will not correlate to performance. **Figure V-2** shows the Jnr susceptibility to temperature.

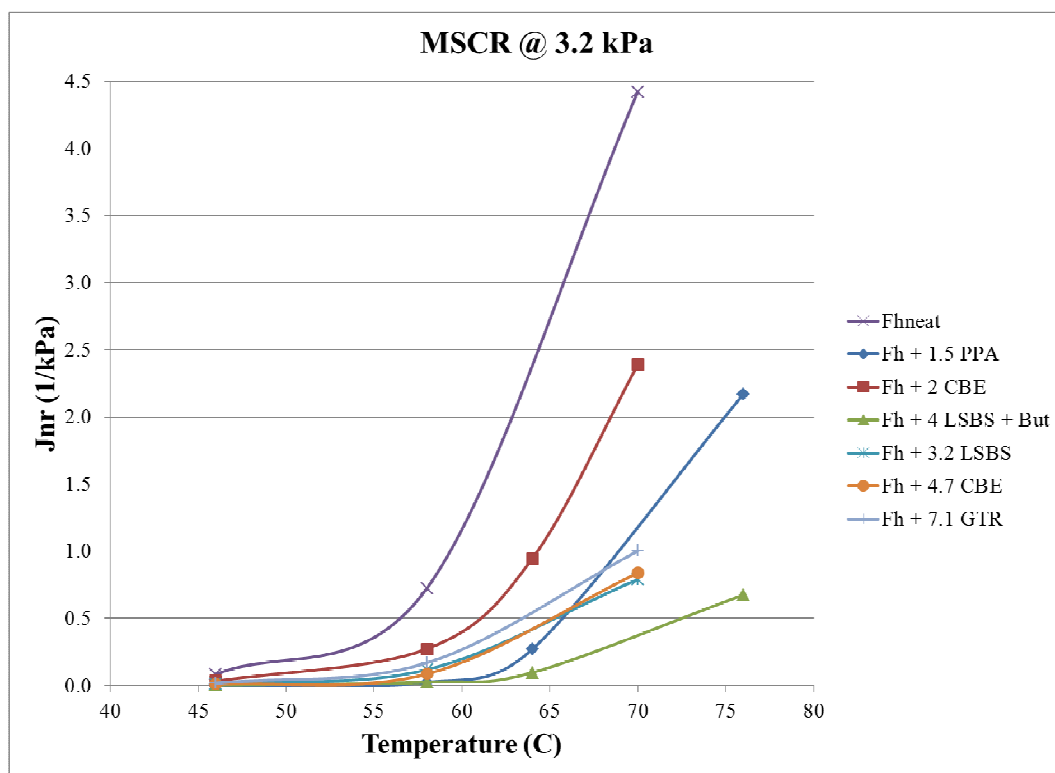


Figure V-2. Jnr values for different modified binders at different temperatures.

This results shows that the relationship between Jnr value and temperature is not linear, as assumed in the SHRP specification. It can be clearly seen that the Jnr susceptibility to temperature is nonlinear and it is different from binder to binder. This leads to the question on how should the effect of increased traffic volume or slower speeds be taken into account in a new specification?

2. AASHTO MP 19 Criteria

Researchers findings indicate that the non-recoverable compliance Jnr would be a good replacement for the SHRP high-temperature binder criteria (D’Angelo et al., 2006; 2007,b; 2006,b; 2009). A new high-temperature binder specification was developed using the compliance value Jnr measured in the MSCR test. The high pavement temperature does not change with changes in traffic volume, therefore it would be best to change the criteria used to evaluate the binder at that high temperature. Instead of increasing the testing temperature and holding the specification criteria constant, the required compliance value should be reduced to provide a more rut-resistant binder. Using a Jnr value at 3.2 kPa of 4.0 kPa⁻¹ as a basis for a standard paving grade, reductions in Jnr for grade bumping will be made for slow-speed traffic and traffic greater than 30 million ESALs (AASHTO MP 19 “Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test”). Using this approach temperature bumping would be eliminated and adjustments to the Jnr criteria would be made. **Table V-1** shows the summary of new criteria.

Table V-1. Binder Selection on the Basis of Traffic Speed and Traffic Level for MSCR (AASHTO MP 19).

Design ESALs ^a (Million)	Recommendations for the High-Temperature Grade of the Binder		
	Traffic Load Rate		
	Standing ^b	Slow ^c	Standard ^d
< 0.3	S ^e	S	S
0.3 to < 3	H	S	S
3 to < 10	V	H	H
10 to < 30	E	V	V
≥ 30	E	E	E

^a The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.

^b *Standing Traffic*—where the average traffic speed is less than 20 km/h.

^c *Slow Traffic*—where the average traffic speed ranges from 20 to 70 km/h.

^d *Standard Traffic*—where the average traffic speed is greater than 70 km/h.

^e S designates Standard Grade, H designates Heavy Grade, V designates Very Heavy Grade, E designates Extreme Grade under AASHTO MP 19 standard.

The required environmental asphalt binder grades may be selected by the procedures described in AASHTO M 320, except do not use the “grade bumping” procedure in AASHTO M 320. The different traffic levels are selected upon the appropriate “S”, “H”, “V”, or “E” grade for the expected traffic level and traffic load rate (AASHTO MP19):

- Standard Grade “S” in most typical situations will be for traffic levels fewer than 10 million Equivalent Single Axle Loads (ESALs) and less than the standard traffic load rate (>70 km/h).
- High Grade “H” in most situations will be for traffic levels of 10 to 30 million ESALs or slow moving traffic (20 to 70 km/h).
- Very High Grade “V” in most situations will be for traffic levels of greater than 30 million ESALs or standing traffic (< 20 km/h).
- Extremely High Grade “E” in most situations will be for traffic levels of greater than 30 million ESALs and standing traffic (< 20 km/h) such as toll plazas or port facilities.

As **Table V-1** shows, the new Jnr-based specification is implemented differently than the way grade bumping used in the PG high temperature specification is implemented. In the new specification, the value of Jnr determines whether a PG binder is suitable for standard, heavy, or very heavy traffic, on the basis of the traffic levels used in the current PG binder specification.

This new specification does a far better job of relating binder properties for both neat and polymer-modified binders to actual pavement rutting. Testing is done at the same environmental zones established by SHRP but temperature bumping is eliminated. To account for high traffic volumes and or slower moving traffic the compliance value is reduced (Bouldin et al., 2001). But for any climate zone all testing would be done at a constant temperature. The new Jnr-based specification specifies the test temperature as the binder high PG temperature.

Testing binder at a single temperature for different climatic conditions can be very misleading. **Figure V-3** was prepared to exemplify the relationship between the continuous grade and the non-recoverable creep compliance at 3.2 kPa for a material tested at 58C (58C represents the average 7-day maximum pavement design temperature). The results shows that an asphalt grade PG 58 could have an Jnr at 3.2 kPa between 1.78 and 2.81 kPa, which according to the AASHTO MP19-10 corresponds to standard grade "S" and high grade "H". For a PG 64 the Jnr is between 0.07 and 1.52 and corresponds to H, V or E. A PG 70 would be labeled V or E.

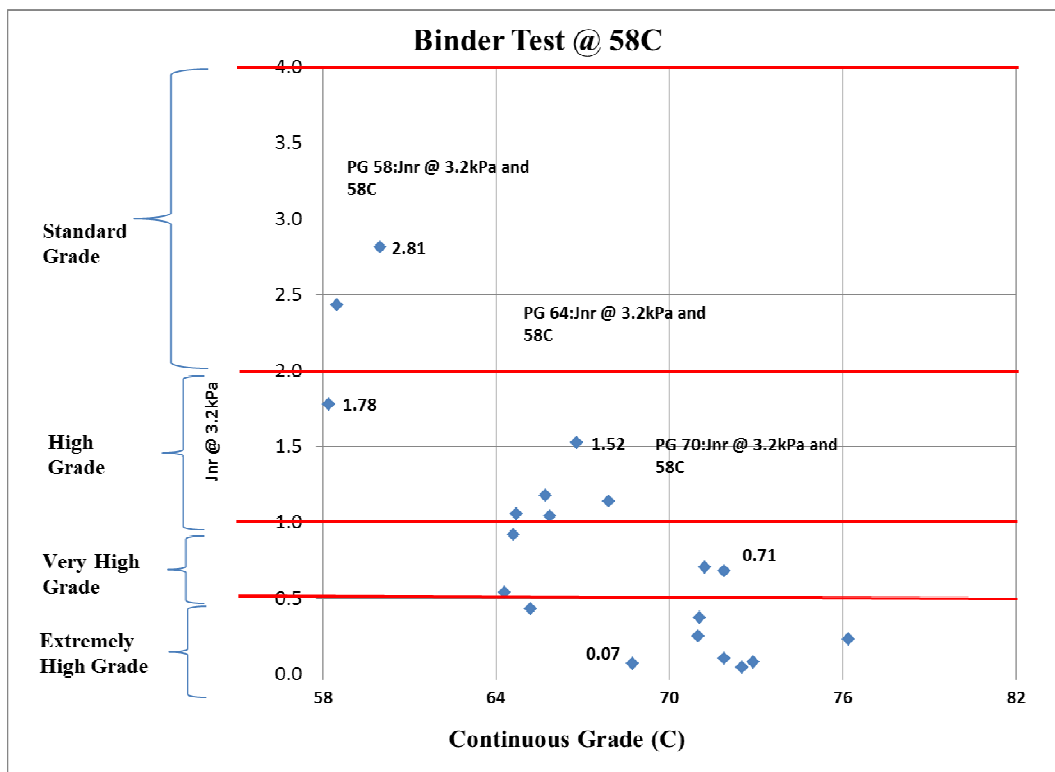


Figure V-3. Relationship between continuous grade and Jnr at 58C.

It can be seen from **Figure V-3** that binders with the same PG grade can be classified for different traffic conditions. This will bring a lot of confusion on which binder is more appropriate for specific project site and weather conditions. **Figure V-4** shown the relationship between the continuous grade and the non-recoverable creep compliance at 3.2kPa for a material tested at 64C. As shown a PG 64 could have a Jnr between 0.15 and 2.67. Based on the AASHTO MP19 this material could be labeled as S, H, V or E. A PG 70 would be labeled H, V or E.

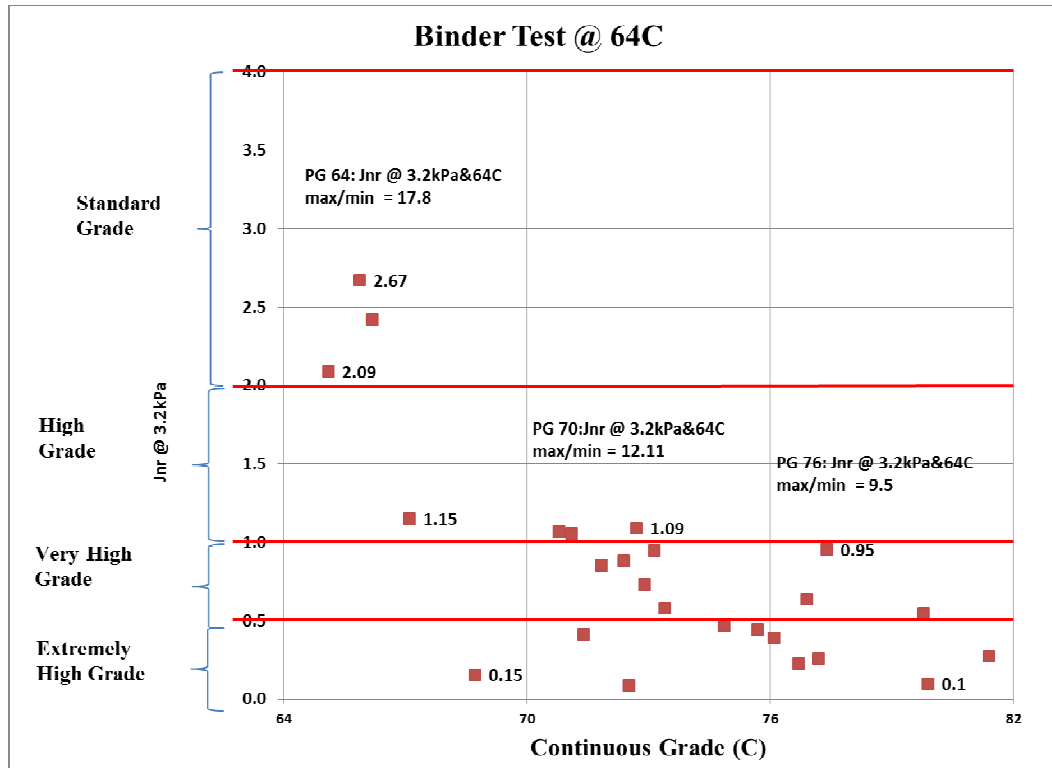


Figure V-4. Relationship between continuous grade and Jnr at 64C.

These results clearly show that the current specification of Jnr is not capable of distinguishing between binders at different traffic levels. Asphalt binder is nonlinear viscoelastic material under heavy traffic, and testing at temperatures different than service climate temperatures can give false estimation of binder behavior under specified conditions. Therefore MSCR testing temperature should be climatic temperature of area rather than High PG temperature of Binder. Implementing this method will give precise information about binder behavior under those climatic specification and traffic level.

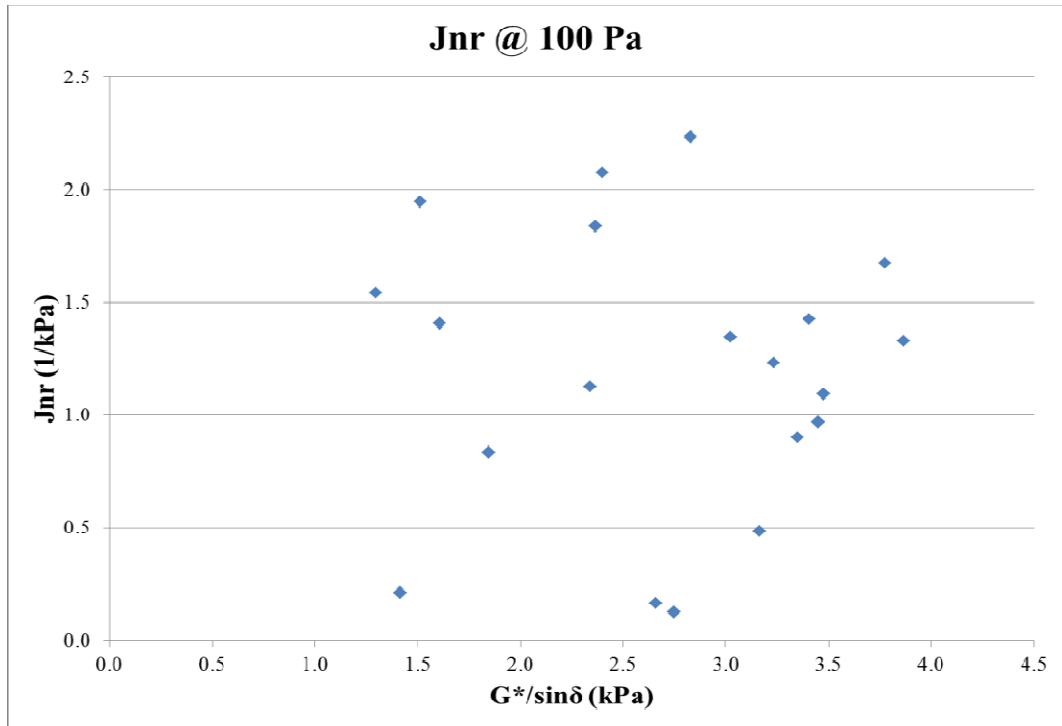
3. Accounting for Traffic Condition Effect for New Jnr Specification

The two main characteristics of the traffic loading relevant to permanent deformation are tire pressure and vehicle speed. A national rutting study conducted by Brown and Cross (Brown and Cross, 1992), compared 42 pavements in 14 states and concluded that most of the rutting was limited to the top three to four inches of the pavement. Since the distress is so close to the surface, the stresses due to traffic loading

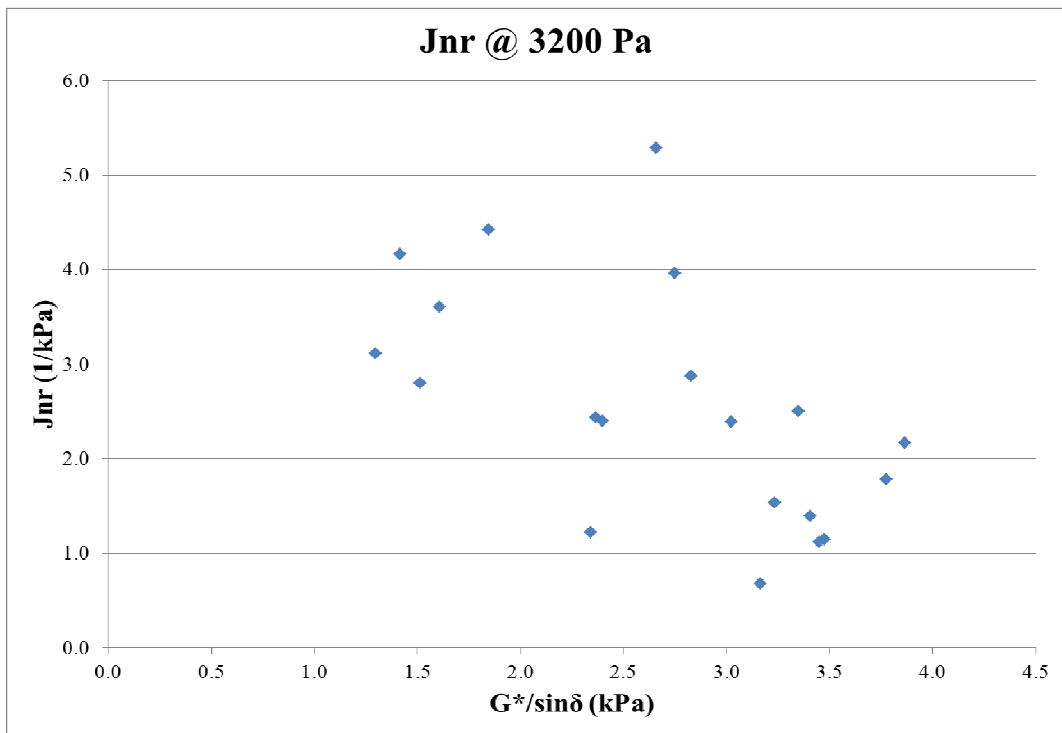
are very similar to the tire pressure of the vehicles. For this reason, tire pressure is a very important factor in rutting of pavements.

Another factor to be considered is that most of the laboratory rut testers in use today simulate slow moving or standing traffic conditions. Asphalt mixtures are viscoelastic materials. Since the time of loading influences the complex modulus of the mix, the vehicle speed is an important factor in the response of the asphalt pavement. Under slow traffic loads (longer loading time), the complex modulus of the pavement will be lower (and more viscous) than under faster traffic loads. This means that slower vehicles generate more permanent deformation than fast ones. For this reason, for the same site temperature, a stiffer binder will probably be needed for the design of a parking lot pavement than for the design of a highway pavement. However in reality, rutting in pavements occurs at varying speeds. Therefore there is essential need to take into account the effect of speed and pressure on binder rutting resistance.

In current AASHTO MP 19 Jnr specification, for higher level of traffic volume or speed, shifting upon the appropriate “S”, “H”, “V”, or “E” grade for the expected traffic level and traffic load rate will be applied. To account for the effect of traffic load, the linear viscoelastic conceptual approach is proposed and the accumulated strain is assumed to be linearly related to the traffic equivalent single-axle load levels (Bouldin et al., 2001). This method shifting showed in **Table V-1** is very similar to the linear shifting process from SHRP specification. It can be seen that for double higher traffic level, half Jnr value will be used to correspond the effect of traffic level. **Figure V-5** shows the relationship between Jnr and $G^*/\sin \delta$ for different modified binders at the same temperature for both tests.



(a)



(b)

Figure V-5. Relationship between Jnr and $G^*/\sin\delta$ for different modified binders.

It can be seen clearly in **Figure V-5** that there is no correlation between J_{nr} and $G^*/\sin \delta$ and the data are scattered. This results confirm that there is no clear relation between the new parameter of characterizing rutting (J_{nr}) and old parameter ($G^*/\sin \delta$). The reason for this observation is related to their fundamental concept. In old specification, it was tried to measure binder's susceptibility to rutting upon linear viscoelastic theory while the new specification and test is trying to have more wider spectrum of binder behavior in both linear and nonlinear region. Therefore using a similar approach for shifting to account for different traffic conditions is not meaningful, and there is an essential need to have a modification of Grade shifting upon MSCR test and J_{nr} value.

The current binder specifications for rutting have some critical gaps, most of them related with the characterization of modified binders. One of the problems with the rutting parameter is that the binders are characterized based on their linear viscoelastic properties (Delgadillo, 2008). To present the rutting response of the binder in the mix the nonlinear response has to be taken into account. Since asphalt binders behave approximately like linear viscoelastic materials only for small stresses (strains), the current parameter would be suitable only if the binder inside the pavement is subjected to stresses (strains) below its linear threshold. Nonlinearity of the creep response to the stress input can be incorporated by allowing the creep compliance to depend on both time and stress: $J(t, \sigma)$.

It appears that developing a semi empirical model that fits MSCR test data using data generated from conventional Superpave DSR tests can be pursued with the goal of revising the J_{nr} high-temperature specification. Due to the nonlinear behavior of asphalt mixtures, the loading time and stresses are highly influential in the response of the asphalt pavement. Since binders are an important factor in the nonlinear behavior of mixes, as discussed previously, the selection of the appropriate asphalt binder should be determined by the loading time and stress level to which the pavement will be subjected. This must be considered in models before final specification parameters are set.

Recently, a constitutive model was developed to predict the asphalt binder response subjected to any loading history (Delgadillo et al., 2011). This model, which is based on two argument power law, predicts the total response of asphalt binders as the summation of permanent and recoverable strain. The nonlinear power model is given by the following equation (Delgadillo et al., 2011):

$$\gamma(t, \tau) = \sum_{i=1}^n k_i \cdot t^{m_i} \cdot \tau^{p_i} \quad (V-1)$$

Where:

γ = shear strain (dimensionless)
 t = time (s)
 τ = shear stress (kPa)
 k_i, m_i, p_i = model parameters

The number of arguments n to be used depends on the material. For the polymer modified binder, a value of n equal to two was found to be enough to describe the shape of the curves. The response of asphalt binders subjected to an applied stress includes recoverable and irrecoverable strain components, which can be described as shown in Equation (V-2):

$$\varepsilon_{total} = \varepsilon_{rec} + \varepsilon_{irrec} \quad (V-2)$$

where ε_{rec} is the recoverable strain and ε_{irrec} is the irrecoverable strain. The recoverable strain component can be instantaneous (elastic) or time dependent (viscoelastic). It was shown that the total creep strain γ can be separated into recoverable strain γ_r and permanent strain γ_p (Delgadillo et al., 2011).

$$\gamma(\tau_0, t_1) = \gamma_r(\tau_0, t_1) + \gamma_p(\tau_0, t_1) \quad (V-3)$$

Where:

τ_0 = stress applied during loading phase (kPa)
 t_1 = loading time (s)
 γ = total strain after loading phase (dimensionless)
 γ_r = recoverable strain (dimensionless)
 γ_p = permanent strain (dimensionless)

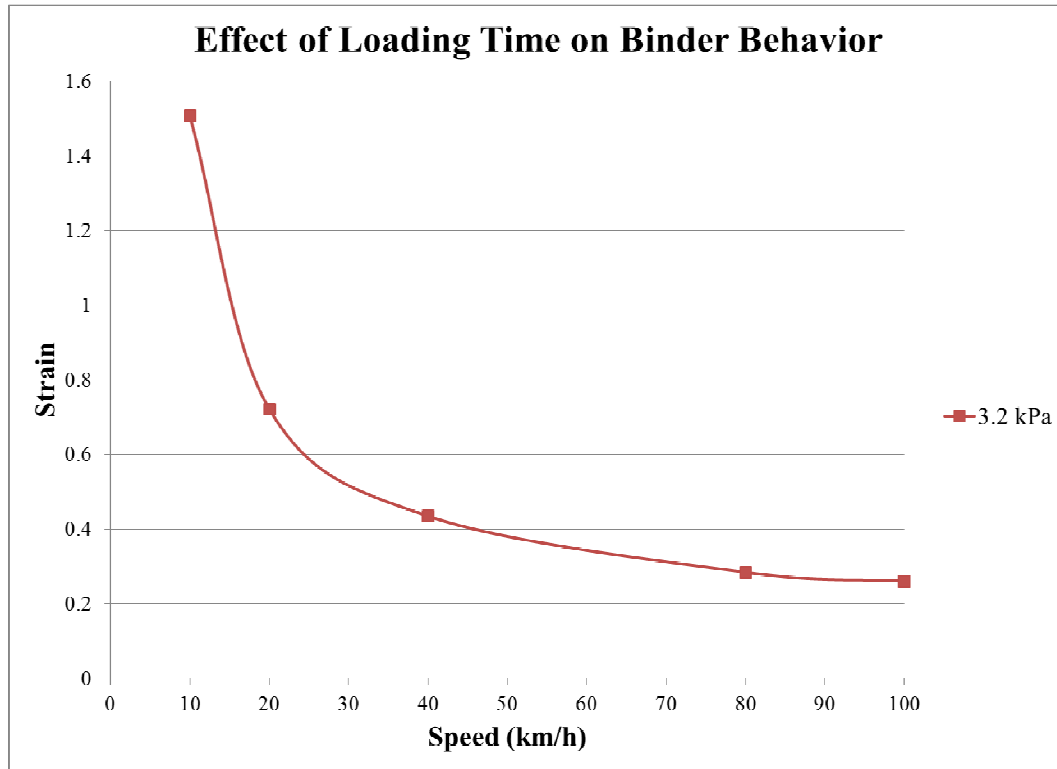
In this model, the two main characteristics of the traffic loading relevant to permanent deformation should be considered. The loading time term (t) will take into account the effect of vehicle speed. Huang proposed an equation to convert the vehicle speed to corresponding loading time (Huang, 2004). Using the following equation, different vehicles speed can be converted to corresponding loading time:

$$d = 12a / s \quad (V-4)$$

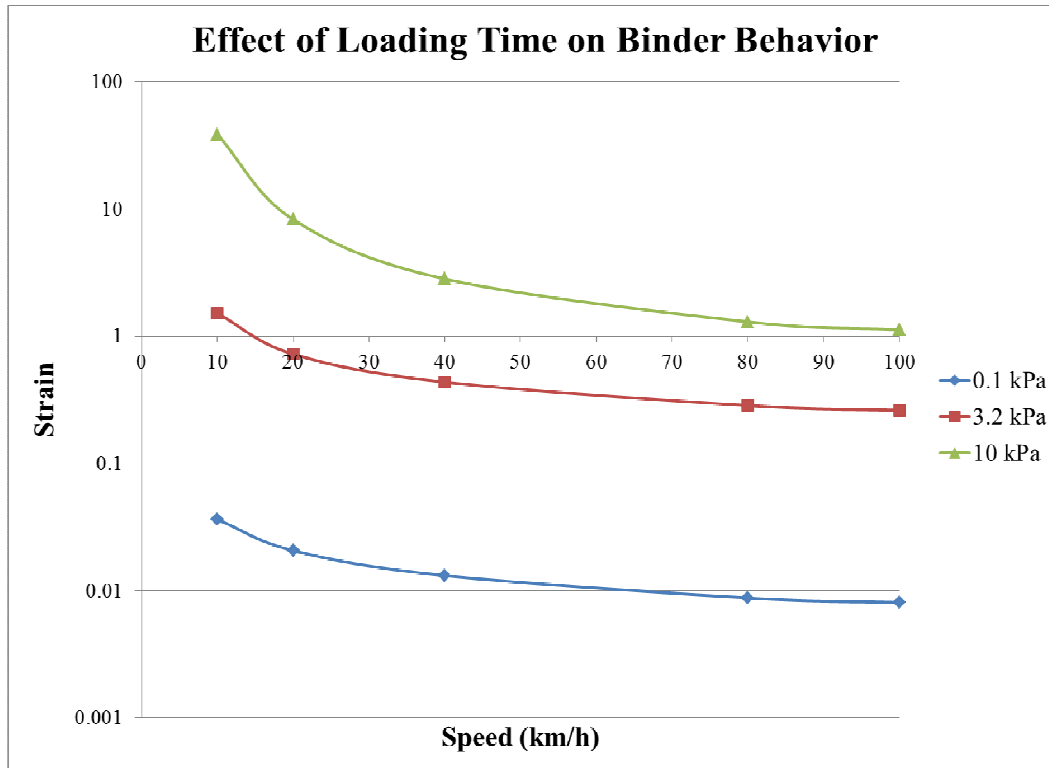
Where:

d = Duration of Load (s)
 a = tire contact radius (m)
 s = vehicle speed (m/s)

It should be mentioned that $a=6$ (in.) in pavement problems. Also the shear stress term in model will account for the tire pressure effect. The traffic volume will be taken into account by the sigma series. **Figure V-6** shows the modeling results of traffic effect on binder behavior in terms of rutting.



(a)



(b)

Figure V-6. Effect Of Various Speed on Binder Rutting Resistance.

As expected, these results clearly indicate that the effect of traffic speed on strain value is nonlinear. In addition it can be observed that the effect stress level for different vehicle speed is nonlinear. By increasing traffic speed, the rate of strain accumulation is decreasing. As expected, rutting is more critical at lower speeds because the loading time is increased. However, it is clear that rutting is happening at all various traffic speed by strain accumulation. **Figure V-7** shows the modeling results for the effect of traffic volume and speed together. The results are shown in log-log scale.

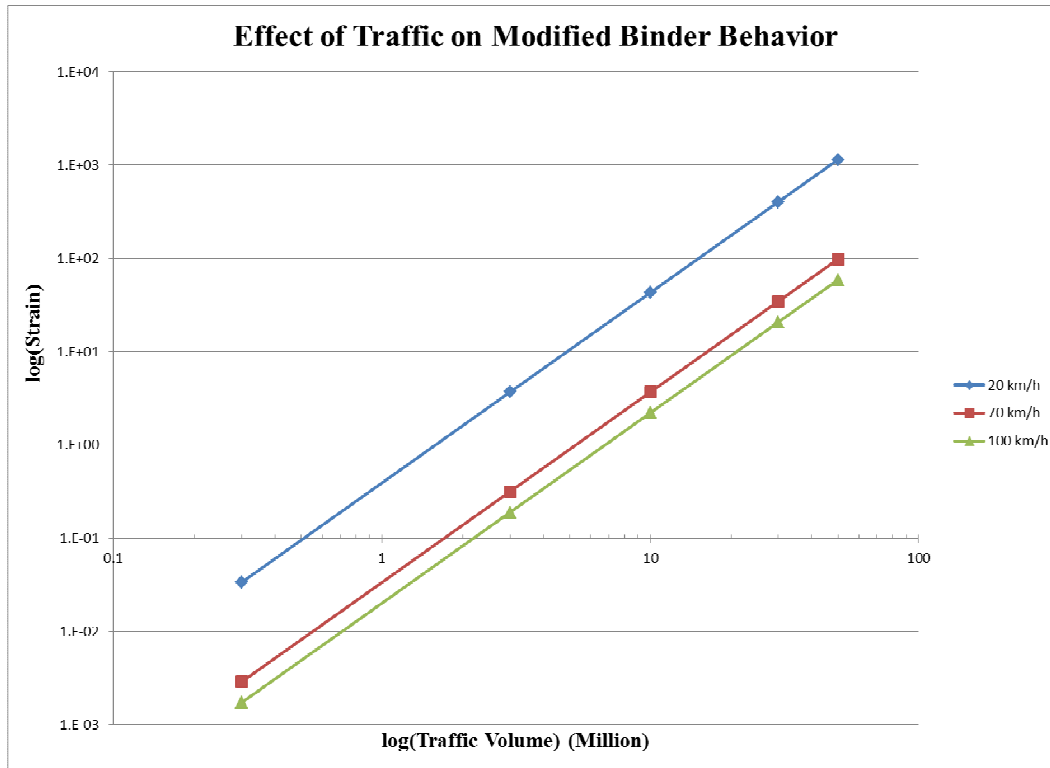


Figure V-7. Effect of Traffic Speed and Volume on Binder Rut Resistance.

The results shows that the effect of traffic volume, in log-log scale is linear, which represent the nonlinearity of binder rutting resistance at different traffic conditions. It should be mentioned that the strain in mixture would be much lower than the magnitude of the calculated strain for binder because the main load bearing part of mixture is aggregate. However, these results demonstrate the nonlinearity of binder behavior at different traffic conditions and incapability of current specification.

Finally it can be concluded that linear shifting for traffic levels is inappropriate and the nonlinearity of binder behavior should be taken into account. Modeling can be very helpful in order to define desirable limits for any specific traffic conditions. It is also important to conduct MSCR test at service climate temperature.

VI. Summary of Findings, Conclusions, and Recommendations

1. Summary of Findings

The Multiple Stress Creep and Recovery (MSCR) test has been standardized in AASHTO and ASTM standards and is used by a large number of state agencies. The main concerns about the test are higher variability, insufficient number of cycles to reach a steady state response, and the arbitrary stress levels at which the test is conducted. In this study, a comprehensive experimental test matrix was completed to investigate these concerns and offer solutions. The non-recoverable creep compliance (J_{nr}) and percent recovery (R%) for different binders at different conditions (stress levels and different number of cycles) were calculated . The results were also compared to the asphalt mixture Flow number (FN) produced with the same aggregates and different binders. Based on the results and analyses, the following conclusions can be drawn:

- This study has shown that the current method of averaging the response for 10 cycles at each of the stress levels could lead to misleading representation of actual binder response due to the changes during the cycles.
- To avoid the varying response that takes place during the initial cycles, it is recommended to calculate the average J_{nr} and %R based on the second half of the creep and recovery cycles at each level of stress. This should be a better representation of the binder properties, and could significantly reduce the variability of the results.
- Variability is extremely high for the low stress level of 0.1 kPa. Also, this stress level is too low and does not appear to offer correlation to mixture behavior. It is therefore not suitable for proper ranking of the binder with respect to binder contribution to mixture rutting.
- The results indicate that by increasing number of cycles for each stress level, the variation in J_{nr} results will decrease and binder will show more consistent response, which is an indication of reaching a steady state after experiencing conditioning in first few cycles. The number of cycles at which the MSCR test was conducted were 10, 30 and 60. ANOVA analysis showed that significant differences between the binder behavior at 10 and 30 cycles exist, while no significant differences between 30 and 60 cycles exist. Based on this, it is recommended to use 30 cycles to reach steady

state to reduce the variability of the MSCR results. Based on limited mixture results it was found that the MSCR test results at 30 cycles correlates well with mixture's rutting resistance.

- The MSCR test can be used to identify the upper bounds of the stress level below which the material behave in the linear viscoelastic region; Nonlinear viscoelasticity can be used for the description of the binder rutting resistance, depending on the temperature at which the test was performed. Thus, the ability of J_{nr} to predict the performance of different asphalt binders is strongly dependent on the testing temperature.
- Testing at higher stress levels can differentiate better among different modifiers, and it will depict the nonlinear behavior of binders more extensively. Furthermore, at higher stress level (10 kPa in this study), the binder response especially at higher temperature changes, and the stress sensitivity of modified binders will be revealed more clearly.
- A weak correlation was found between the binder elasticity and the mixture performance. This indicates that the elasticity alone is not important factor regarding mixture rutting resistance.
- A simplified form of nonlinear constitutive relationship was developed to predict the binder's response under MSCR test. The relationship, which is composed of a nonlinear viscous part and a linear viscoelastic part, is able to predict satisfactorily the repeated creep and recovery testing at multiple stress levels. This non-linear viscoelastic model allowed for an accurate prediction of the binder response to the MSCR test, for both neat and modified asphalt binders, through the use of the rheological parameters obtained from the DSR measurements. The modeling analyses show that the current criteria and shifting process to account for traffic is not appropriate and requires modification. The results indicate that the relationship between the non-recoverable creep compliance (J_{nr}) and traffic volume and speed is nonlinear. In addition it was found that binder's nonlinearity under different traffic conditions should be taken into account in order to have a better estimation of mixture's rutting performance.

2. Conclusions

This study indicates that the testing protocol for the MSCR test can be improved significant by minor modifications. Based in the results it is recommended that the current procedure be modified by testing the creep and recovery for 30 cycles at the stress levels of 3.2 and 10 kPa. The results also show that the adjustment in J_{nr} and % R limits for traffic should be changed to account for the non-linear relationship between these parameters and traffic cumulative loading time.

3. Recommendations for Future Work

This study suggests modification of the MSCR procedure for better estimation of binder rutting resistance. Many areas are still to be further investigated. The following are the recommended areas of future research:

- Different loading and unloading time need to be investigated in MSCR test procedure. This could lead to a more clear indication of the effect of binder elasticity on rut resistance.
- Binders with different levels of elasticity and stiffness should be prepared for binder and mixture testing in order to effectively quantify the contribution of the asphalt binder elasticity to the asphalt mixture permanent deformation.
- Further research on the proposed procedure and comparison with extensive mixture data needs to be performed.

VII. References

- AASHTO M320 (2010). “Standard Specification for Performance-Graded Asphalt Binder”. American Association of State Highway and Transportation Officials, Washington, D.C.
- AASHTO MP19 (2010). “Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test”. American Association of State Highway and Transportation Officials, Washington, D.C.
- AASHTO TP70 (2009). “Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)”. American Association of State Highway and Transportation Officials, Washington, D.C.
- AASHTO TP79 (2009). “Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)”. American Association of State Highway and Transportation Officials, Washington, D.C.
- A. A. P. T. P. P. (2008). “PG Binder Grade Selection for Airfield Pavements”, no.04-2.
- Aiery G.D. (2002). “Rheological evaluation of ethylene vinyl acetate polymer modified bitumens”, *Construction and Building Materials*, v16, 473-478.
- Airey, G. D. (2003). “Rheological Properties of Styrene Butadiene Styrene Polymer Modified Road Bitumens”. In *Fuel*, Vol. 82, pp. 1709-1719.
- Aiery G.D. and Rahimzadeh B. (2004). “Combined bituminous binder and mixture linear rheological properties”, *Journal of Construction and Building Materials*.
- Anderson, D. A., D. W. Christensen, H. U. Bahia, R. Dongre, M. G. Sharma, C. E. Antle and J. Button. (1994). “Binder Characterization and Evaluation. Volume 3: Physical Characterization”, *Strategic Highway Research Program, National Research Council*, Washington, DC.
- Anderson, D. A., Y. M. Le Hir, J. P. Planche, D. Martin and A. Shenoy. (2002). “Zero shear viscosity of asphalt binders”, *Transportation Research Record: Journal of the Transportation Research Board*, v1810, no. -1, 54-62.

- ASTM D2872 (2004). “Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)”. American Society for Testing and Materials, West Conshohocken, Pennsylvania.
- ASTM D7405 (2010). “Standard Method of Test for Multiple Stress Creep and Recovery (MSCR) of Asphalt Binder Using a Dynamic Shear Rheometer”. American Society for Testing and Materials, West Conshohocken, Pennsylvania.
- Bahia, H. U., D. Perdomo and P. Turner. (1997) “Applicability of Superpave binder testing protocols to modified binders”, *Transportation Research Record: Journal of the Transportation Research Board*, v1586, no.-1, 16-23.
- Bahia, H. U., W. P. Hislop, H. Zhai and A. Rangel. (1998). “Classification of asphalt binders into simple and complex binders”, *Journal of the Association of Asphalt Paving Technologists*, v67, no.1-41.
- Bahia, H. U., D. I. Hanson, M. Zeng, H. Zhai, M. A. Khatri and M. R. Anderson. (2001). “NCHRP Report 459, Characterization of Modified Asphalt Binders in Superpave Mix Design. Prepared for the National Cooperative Highway Research Program”, *Transportation Research Board, National Research Council*, Washington, D.C.
- Bahia. H. U., Tabatabaee, N., Clopotel. C. and Golalipour. A. (2011). “Evaluation of Using the MSCR test for Modified Binder Specification”, *Canadian Technical Asphalt Association*.
- Bouldin MG, Collins JH. Rubber. (1991). “*Chem. Techno*”; 64:577.
- Bouldin, M. G., R. Dongré and J. D'Angelo. (2001). “Proposed refinement of Superpave high-temperature specification parameter for performance-graded binders”, *Transportation Research Record: Journal of the Transportation Research Board*, v1766, no.-1, 40-47.
- Brown, E. R. and S. A. Cross. (1992). “A National Study of Rutting in Hot Mix Asphalt Pavements”, *Journal of the Association of Asphalt Paving Technologists*, Vol.61, pp.535–582.
- Brule Bernard. (1996). “Polymer-Modified Asphalt Cements Used in Road Construction Industry: Basic Principles”, *Transportation Research Record: Journal of the Transportation Research Board*, v1535, no.-1.

- Centeno, M., Sandoval, Cremades and Alarcon. (2008). "Assessing rutting susceptibility of five different modified asphalts in bituminous mixtures using rheology and wheel tracking test", *Transportation Research Board*.
- Coenen, A. (2011). "Image Analysis of Aggregate Structure Parameters as Performance Indicators of Rutting Resistance", Ph.D Thesis, University of Wisconsin - Madison, Madison.
- Collins J.H., Bouldin M.G., Gelles R. and Berker A. (1991). "Asphalt Paving Technol", 60:43.
- D'Angelo R., Dongre R. and Reinke G. (2006a). "Evaluation of Repeated Creep and Recovery Test Method as an Alternative to SHRP+ Requirements for Polymer Modified Asphalt Binders", *Proceedings, Canadian Technical Asphalt Association*, November.
- D'Angelo R. and Dongre R.. (2006b). "Development of a High Temperature Performance Based Binder Specification in the United States", *10th International Conference on Asphalt Pavements, Quebec City, Canada, 10th International Conference on Asphalt Pavements*.
- D'Angelo, J. A., R. Dongre and G. Reinke. (2007a). "Creep and recovery", *Public roads*, v70, no.5, 24-30.
- D'Angelo, J., R. Kluttz, R. Dongre, K. Stephens and L. Zanzotto. (2007b). "Revision of the Superpave High Temperature Binder Specification: The Multiple Stress Creep Recovery Test", *ASPHALT PAVING TECHNOLOGY*, v76, no.123.
- D'Angelo R. and Dongre R. (2009). "Practical Use of the MSCR Test: Characterization of SBS Dispersion and Other Additives in PMA Binders, *Transportation Research Board Annual Meeting*.
- Daranga, C.; Clopotel, C. S.; Mofolasayo, A.; and Bahia, H. U. (2009). "Storage Stability and Effect of Mineral Surface on Polyphosphoric Acid (PPA) Modified Asphalt Binders". *Transportation Research Board Annual Meeting*, Washington, D.C.
- Delgadillo R., Nam K. and Bahia H. U. (2006a). "Why do we need to change $G^*/\sin \delta$ and How?", *Road Materials and Pavement Design*, v7, *Hermes Science Publication*.
- Delgadillo R., Cho D. W. and Bahia H. U. (2006b). "Nonlinearity of Repeated Creep and Recovery Binder Test and Relationship with Mixture Permanent Deformation", *Transportation Research Records No. 1962, Transportation Research Board, Washington, D.C.*

- Delgadillo, R. (2008). “Nonlinearity of asphalt binders and the relationship with asphalt mixture permanent deformation”, Ph.D Thesis. University of Wisconsin - Madison, Madison.
- Delgadillo, R., H. Bahia and Lakes, R. (2011). “A Nonlinear Constitutive Relationship for Asphalt Binders”, *Journal of Materials and Structures, Springer*, Volume 1/1968, Volume 44.
- Desmazes, C., M. Lecomte, D. Lesueur, and M. Phillips. (2000). “A Protocol for Reliable Measurement of Zero-Shear-Viscosity in Order to Evaluate Anti-Rutting Performance of Binders”, *Proc., 2nd Eurasphalt & Eurobitume Congress*, Barcelona, Spain, Book 1, pp. 202–211.
- Diani J., Fayolle B. and Gilormini P. (2009). “A Review on the Mullins”, *European Polymer Journal*, 45, 601–612.
- Diehl C. F. (2000). *In Proceedings of the 2nd Eurasphalt and Eurobitume Congress*, Vol.2, p.93.
- Dongre R., D’Angelo R. and Reinke G. (2004). “New Criterion for Superpave High-Temperature Binder Specification”, Transportation Research Records No. 1875, *Transportation Research Board, Washington, D.C.*
- Dreessen A., J.P. Planche and V. Gandel. (2009). “A new performance related test method for rutting prediction: MSCRT”, *Advanced Testing and Characterization of Bituminous Materials*.
- Faheem, A., and Bahia H.U. (2004). “Using Gyrotory Compactor to Measure Mechanical Stability of Asphalt Mixtures”, *Wisconsin Highway Research Program*.
- Hofstra, A., and A.J.G. Klomp. (1972). “Permanent Deformation of Flexible Pavements under Simulated Road Traffic Conditions”, *Third International Conference on the Structural Design of Asphalt Pavements*, Vol 1., 613-621.
- Huang, Y.H. (2004). “Pavement Analysis and Design. Pearson Education”, Inc.
- Isacsson U and Lu X. (1998). “Testing and appraisal of polymer modified road bitumens”, In: Francken L, editor. *Bituminous binders and mixes, Rilem Report 17*, London: E and FN Spon.
- Kamel, N. I., H. U. Bahia and D. W. Cho. (2004). “Critical Laboratory Evaluation of Asphalt Binders Modified by Refining Processes”, 57-76.
- Kim, Y. R.. (2008). “Modeling of asphalt concrete”, McGraw-Hill Professional.

- Kose S. (2001). “Development of a Virtual Test Procedure for Asphalt Concrete”, PhD Thesis. University of Wisconsin - Madison, Madison.
- Lakes, R. (1999). “Viscoelastic Solids”, CRC Press.
- Marasteanu, M. O., Clyne, T., McGraw, J., Li, X. and Velasquez. R. (2005). “High-Temperature Rheological Properties of Asphalt Binders”, *Transportation Research Record: Journal of the Transportation Research Board*, V1901, 52-59.
- McDaniel R. S. and Bahia, H. U. (2003). “Field Evaluation of Asphalt Additives to Control Rutting and Cracking”, Transportation Research Records No. 1829, *Transportation Research Board, Washington, D.C.*
- McGennis, R. B. (1994). “Background of SUPERPAVE asphalt mixture design and analysis”, Federal Highway Administration; Available through the National Technical Information Service.
- Motamed A., Delgadillo, R., Bahia, H. U. and Zeng M. (2008). “Effects of Increased Loading Level and Time on Rutting Resistance of Modified Asphalt Binders and Mixtures”, *Proceedings, Canadian Technical Asphalt Association*.
- Nicholls C. (1998). “Asphalt Surfacing”. *London: E and FN Spon*;; p. 68-79.
- Phillips, M. C., and C. Robertus. (1996). “Binder Rheology and Asphaltic Pavement Permanent Deformation; The Zero-Shear Viscosity”, Paper No.5.134. *Presented at the 1st Eurasphalt and Eurobitume Congress, Strasbourg, France*.
- Read, J.; and Whiteoak, D. (2003). “*The Shell Bitumen Handbook*”. Fifth Edition, Edited by R. Hunter.
- Reyes, M., Kazatchkov, I.B., Stastna, J. and Zanzotto. L. (2009). “Modeling of Repeated Creep and Recovery Experiments in Asphalt Binders”, *Transportation Research Record: Journal of the Transportation Research Board*, V2126, 63-72.
- Roberts F., P. Kandhal, E Ray Brown, D. Lee and T. Kennedy. (1996). “Hot Mix Asphalt Materials, Mixture Design and Construction”, *NAPA Research and Educational Foundation*.
- Shenoy, A. (2001). “Refinement of the Superpave specification parameter for performance grading of asphalt”, *Journal of transportation engineering*, v127, no. 5, 357-362.

- Shenoy, A. (2008). “Nonrecovered compliance from dynamic oscillatory test vis-a-vis nonrecovered compliance from multiple stress creep recovery test in the dynamic shear rheometer”, *International Journal of Pavement Engineering*, v99999, no.1,1-1.
- Sybilski, D. (1996). “Zero-Shear Viscosity of Bituminous Binder and its Relation to Bituminous Mixtures Rutting Resistance”, *Transportation Research Record 1535*, pp. 15-21, TRB, National Research Council, Washington, D.C.
- Van der Poel C. (1954). “A general system describing the visco-elastic properties of bitumen and its Relation to routine test data”, *JAppl Chem*; 4:221–36.
- Wasage T. L. J., Stastna J. and Zanzotto L. (2011). “Rheological Analysis of Multiple Stress Creep and Recovery (MSCR) test”, *International Journal of Pavement Engineering*.
- Witczak MW, Kaloush KE, von Quintus H. (2002). “Pursuit of the Simple Performance Test for Asphalt Mixture Rutting”, *Journal of Association of Asphalt Paving Technologists*, 71, 671 – 691.
- Yildirim, Y. (2007). “Polymer modified asphalt binders”, *Construction and Building Materials*, v21, no. 1, 66-72.