UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

RHEOLOGICAL PROPERTIES OF POLYMER AND RAP MODIFIED ASPHALT BINDERS USING MULTIPLE STRESS CREEP AND RECOVERY METHOD

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE

By

SYED ASHIK ALI
Norman, Oklahoma
2016

RHEOLOGICAL PROPERTIES OF POLYMER AND RAP MODIFIED ASPHALT BINDERS USING MULTIPLE STRESS CREEP AND RECOVERY METHOD

A THESIS APPROVED FOR THE
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE

BY

____
Dr. Musharraf Zaman, Chair

____
Dr. Gerald A. Miller

____
Dr. Rouzbeh Ghabchi

Dedicated

to

My Beloved Parents

Acknowledgements

At the beginning, I would like to thank God, The Almighty, for His countless blessings in every step of my life. Secondly, I want to thank my parents and siblings, who have always encouraged me and sacrificed everything to fulfil my dream.

I would like to express my deepest appreciation, sincere gratitude, and heartiest thanks to my advisor and chair of my thesis committee, Dr. Musharraf Zaman, whose direction and encouragement have been truly inspiring in my social, academic and professional endeavor. Dr. Zaman has been an invaluable help, a source of inspiration, and a constant support throughout my study. It was him who helped me to grow into a researcher.

I would like to acknowledge and thank Dr. Rouzbeh Ghabchi from the bottom of my heart for his help in my research works in every way possible. Dr. Ghabchi was always there to guide me in the laboratory work, to help me in developing ideas and to encourage me throughout my study. His valuable suggestions and comments helped improve my research work and writing skill. I am grateful to his mentorship and leadership that were instrumental to making this thesis work successful. I also want to express my sincere thanks to my other committee member, Dr. Gerald A. Miller for offering his time and valuable input in completing this thesis. I want to thank Dr. Amy B. Cerato, Dr. Kianoosh Hatami and Dr. Dominique M. Pittenger for helping me with their knowledge and experience through their coursework at the University of Oklahoma. I would like to express my sincere gratitude to all the staff of the School of Civil Engineering and Environmental Science and the Southern Plains Transportation

Center (SPTC) for their help and support. Special thanks are extended to Mr. Michael Schmitz (Mike) for his technical support in the laboratories.

I want to thank every member of Dr. Zaman's Research Group specially Ms. Shivani Rani who helped me unselfishly throughout my research. Her assistance came in various forms: in laboratory testing, answering my questions, and educating me on different aspects of asphalt research and education. Also, I want to offer my special thanks to Dr. Amir Arshadi for his great help and cooperation throughout my thesis research. I am grateful to Dr. Zahid Hossain and his research group at the Arkansas State University for their support in conducting this research.

The financial support provided by the Oklahoma Department of Transportation (ODOT) and the Southern Plains Transportation Center (SPTC) are gratefully acknowledged. I am thankful to ODOT staff, especially Mr. Kenneth Hobson, for their assistance. Thanks are also extended to all the material suppliers in Oklahoma, New Mexico and Texas for their help throughout this study.

Finally, I want to thank my wife, Syeda Abida Sulatana, who was always beside me with her love, encouragement, support and prayers. Thanks to all of my friends in Bangladesh and the USA for their wishes.

Table of Contents

List of Tables

List of Figures

Abstract

In recent years, asphalt modifications have become increasingly popular in asphalt pavement construction. Also, in view of technical, environmental and economic benefits, the pavement industry is in favor of using high amounts of Reclaimed Asphalt Pavement (RAP) in asphalt mixes for pavement construction. Consequently, accurate rheological characterization of asphalt binders containing polymer modifiers and RAP binder is important because pavement performance is largely influenced by asphalt binder properties.

A number of test methods have evolved over the last three decades for evaluating the rutting susceptibility of asphalt binders. The objective of the current study was to use a simple Dynamic Shear Rheometer-based (DSR) test method as an alternative to the Superpave® Performance Grade (PG) tests or “PG plus” tests to accurately evaluate high-temperature performance of asphalt binders. To achieve this objective, the rheological characteristics of asphalt binders were evaluated using the Multiple Stress Creep and Recovery (MSCR) and Superpave® test methods. For this purpose, polymer-modified binders were collected from different sources located in Oklahoma, New Mexico and Texas. Also, binders were extracted from two RAPs and blended with a commonly used PG 64-22 binder at selected rates, namely 0%, 25%, 40% and 60% by the weight of the binder. Furthermore, four different asphalt mixes containing polymer-modified binders and different amounts of RAP were tested for rutting performance in the laboratory. The rutting parameter ($|G^*|/\sin\delta$), fatigue parameter ($|G^*|.\sin\delta$), viscosity, high- and low-temperature PG grades of all modified and unmodified binders were evaluated based on the Superpave® test methods. The

MSCR tests were conducted to determine high-temperature MSCR grades and to evaluate the effects of the addition of polymer and RAP binder on non-recoverable creep compliance (J_{nr}) and %Recovery values of the binders.

The polymer-modified binders were found to meet the Superpave® specifications and exhibited satisfactory rutting and fatigue resistance. The high- and low-temperature PG grades of the RAP binder blends were observed to increase with an increase in the RAP binder content. From the MSCR test results, the minimum %Recovery requirement based on the J_{nr} criteria suggested in AASHTO TP 70 was found to be appropriate for differentiating polymer-modified binders from non-polymer modified binders. Also, the addition of a higher stress level, such as 10 kPa to the MSCR test method, was found to help understand the nonlinear viscoelastic behavior of the polymer-modified binders. Furthermore, the J_{nr} value decreased and MSCR grades increased with an increase in the amount of RAP binder, which indicated an improved resistance to rutting for the RAP binder blends. The rutting and moisture susceptibilities of the asphalt mixes with high RAP content were found to be satisfactory from Hamburg Wheel Tracking (HWT) tests. A comparison of the Superpave®, MSCR and HWT test results is also presented in the present study.

CHAPTER ONE: INTRODUCTION

1.1 Background

Asphalt mix is a viscoelastic material consisting of mineral aggregates and asphalt binder. Asphalt binder, a viscoelastic and thermoplastic material is responsible for the viscoelastic behavior of the mix (Anderson et al., 1994). Many aspects of pavement performance such as resistance to permanent deformation (rutting), low-temperature cracking and fatigue life are known to be influenced significantly by the mechanical properties of the asphalt binder (Yildirim, 2007). The quest to improve binder characteristics and pavement performance has led to the evaluation, development and use of a wide range of asphalt binder modifiers such as Styrene-Butadiene-Styrene (SBS), Ethylene-Vinyl-Acetate (EVA), and plastics (Bahia et al., 2001).

The penetration grading system was introduced by the Bureau of Public Roads in 1918 and the viscosity grading system was initiated by a number of state highway departments in the 1960s to characterize asphalt binders. These grading systems were empirical in nature and were not directly related to the pavement performance (Brown et al., 2009). In the early 1990's, a new set of performance-based specifications and test methods, namely the Superpave® (Superior Performing Asphalt Pavements), was developed by the Strategic Highway Research Program (SHRP) for evaluating both asphalt binders and asphalt mixes. Although the goal of the program was to create specifications and test methods for all types of binders, the main focus of the SHRP asphalt research program was unmodified asphalt binders. In the Superpave® specifications, a Dynamic Shear Rheometer (DSR)-based test method (AASHTO T 315, 2012) was introduced to evaluate binder characteristics at high and intermediate temperatures. A new parameter called the rutting parameter ($|G^*|/\sin\delta$), which can be obtained from a DSR test, was introduced to determine the high-temperature Performance Grade (PG) and rutting resistance of asphalt binder (Anderson et al., 1994). Until now, the $|G^*|/\sin\delta$ has been widely used for the characterization of modified and unmodified binders with respect to their ability to resist rutting.

Despite several advantages of the Superpave® specifications over other methods, there are concerns associated with the capability of this method for proper characterization of modified asphalt binders. Also, a poor correlation between the rate of accumulated strain in asphalt mixes and the rutting parameter, $|G^*|/\sin\delta$, of asphalt binders measured at 10 rad/s, was reported by Bahia et al. (2001) in a study conducted for the National Cooperative Highway Research Program (NCHRP) project 9-10 (Bahia et al., 2000). The shortcomings of the Superpave® specifications in capturing the performance properties of modified asphalt binders have resulted in developing new test methods for modified binders. Consequently, a number of Departments of Transportation (DOTs) have started using different test methods such as elastic recovery (AASHTO T 301, 2013) and forced ductility (AASHTO T 300, 2011), in addition to the Superpave® tests. These tests are referred to as the Superpave® “PG Plus” tests. However, the empirical nature of these tests, variations in specifications used by the state DOTs and inability of empirical test methods in characterizing all modified binders adequately limit their use (Bahia et al., 2001; D’Angelo and Dongre, 2004). In addition to the PG plus tests, a number of mechanistic test methods such as the Repeated Creep and Recovery Test (RCRT) (Bahia et al., 2001) and Multiple Stress

Creep and Recovery (MSCR) (D'Angelo et al., 2007) test have been proposed to address the abovementioned problems.

The MSCR test was proposed to replace the Superpave® PG and PG plus tests in order to determine the high-temperature characteristics of modified asphalt binders. The advent of MSCR test greatly improved the characterization of rutting susceptibility of modified asphalt binders. This test is based on the RCRT test (Bahia et al., 2001) and was developed by the Federal Highway Administration (FHWA) (D'Angelo et al., 2007). The current MSCR test method involves testing asphalt binders at two stress levels (0.1 and 3.2 kPa) and corresponding high environmental temperature of a given climatic region. The advantage of the MSCR test is the use of creep and recovery method that better represents the loading conditions in a real pavement (D'Angelo, 2010). Many studies have reported good correlations between the non-recoverable creep compliance (J_{nr}) obtained from the MSCR test and the rutting measurements of asphalt pavements in the field (D'Angelo et al., 2007; D'Angelo, 2010; Zhang et al., 2015; Laukkanen et al., 2015). Despite the advantages of MSCR test method, there are still important concerns about the current test methods and analysis procedures. Some of the important concerns regarding the MSCR test method are listed below:

(i) *Stress level for MCSR test:* The current MSCR test method involves testing asphalt binders at two specified stress levels, namely 0.1 and 3.2 kPa. These two stress levels are arbitrarily chosen and do not appear to have any clear relationships with the stresses a binder experiences in actual pavements. Unlike unmodified binders, polymer-modified binders are very sensitive to stress levels and they exhibit non-linear response. According to D'Angelo et al. (2006), the evaluation of the non-linear viscoelastic properties of the binder is important because the rutting itself is a non-linear viscoelastic phenomenon. Also, the rutting performance of asphalt mixes is known to be highly dependent on the stress level. Furthermore, previous studies reported better correlations between mix performance data and MSCR test results at higher stress levels (Dreessen et al., 2009; Wasage et al., 2011). Therefore, it is important to determine the appropriate stress levels for the MSCR tests to characterize the non-linear viscoelastic properties of the polymer-modified binders.

(ii) *%Recovery requirement:* One important parameter obtained from the MSCR test is MSCR percent recovery (%Recovery), as it represents the elastic behavior of the asphalt binder. The elasticity of a binder is generally evaluated using the polymer curve noted in the American Association of State Highway and Transportation Officials (AASHTO) TP 70 (2009) standard "Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)." The polymer curve is constructed by plotting the minimum %Recovery requirement for elastomeric modification of an asphalt binder with respect to non-recoverable creep compliance (J_{nr}) value. The %Recovery requirement for polymer-modified binders can vary significantly from one state to another. Therefore, it is important to evaluate the minimum %Recovery requirements for polymer-modified binders.

(iii) *Correlation of MSCR test results with mix performance results:* A limited number of studies have been conducted to evaluate correlations of MSCR test results for laboratory produced and plant-produced mixes. Also, no previous studies, thus far, has established any correlations between MSCR test results of binders and performance data of asphalt mixes commonly used in Oklahoma. In order to compare the effectiveness of the MSCR test method in evaluating the rutting resistance of Oklahoma asphalt binders, it is important to compare the binders' properties with the performance of asphalt mixes available in this region. It is also important to understand the behavior of asphalt mixes containing high amount of RAP and their relations with the MSCR parameters.

(iv) *Characterization of RAP binder blends*: In response to increasing demands for green paving materials for sustainable developments, the pavement industry is using RAP materials in pavement construction. The pavement industry is heavily in favor of using high amounts of RAP in asphalt mixes due to the associated technical and economic benefits. However, no previous studies, thus far, have evaluated the rheological properties of the high RAP binder blends using the MSCR method. The rheological characterizations of the RAP binder blends using the Superpave® and MSCR test methods are expected to generate important performance data, which will help understand the performance of asphalt mixes containing high amount of RAP.

1.2 Research Objectives

The specific objectives of this study were as follows:

(i) Evaluating the MSCR parameters i.e., J_{nr} and MSCR %Recovery for polymer-modified asphalt binders available in Oklahoma, New Mexico and Texas.

(ii) Characterizing the rheological properties of the polymer-modified binders using the MSCR test method.

(iii) Assessing the effects of the addition of RAP binder on the properties of RAP binder blends using the Superpave® and MSCR test methods.

(iv) Determining the relationship between the MSCR parameter (J_{nr}) and rutting performance of asphalt mixes containing polymer-modified binders and RAP.

1.3 Significance of this Study

The present study was pursued to generate useful test results of polymer-modified binders and RAP binder blends available in Oklahoma as well as in New Mexico and Texas. The test results are expected to help in the implementation of the MSCR test methods by the DOTs of Oklahoma, New Mexico and Texas by replacing the time-consuming and costly “PG Plus” tests. The rutting performances of the polymer-modified binders are expected to be better understood by using the MSCR parameters. The Superpave® and MSCR grades of the RAP binder blends, determined in the present study, are expected to help pavement engineers in selecting the proper RAP content for asphalt mixes. In addition, the outcomes of this study are expected to help the pavement engineers gain an understanding on the effect of using high amounts of RAP on the rutting potential of asphalt mixes commonly used in Oklahoma.

1.4 Thesis Organization

The presentation of the materials in this thesis is organized in the following order:

Chapter 1: Introduction – This chapter includes a background on the conventional test methods available for characterizing asphalt binders. The background is followed by the research objectives, significance of the study, and thesis organization.

Chapter 2: Literature Review – The first part of this chapter presents a summary of the literature review conducted with a focus on the rheological and mechanical properties of polymer-modified binders and RAP binder blends. This chapter also summarizes previous studies related to the conventional binder characterization methods and their limitations. A review of literature focusing on the development, advantages, implementation and interpretations of the MSCR test method is presented in the last part.

Chapter 3: Materials and Methods – This chapter describes the selection, collection and preparation of polymer-modified binders and RAP binder blends and asphalt mixes. Descriptions of various test methods such as Superpave® tests, conventional and non-conventional MSCR tests and Hamburg Wheel Tracking (HWT) tests are also presented in this chapter.

Chapter 4: Test Results of Asphalt Binders- Analyses of the Superpave® and MSCR test results conducted on polymer-modified binders and RAP binder blends are presented in this chapter. Also, comparisons between the Superpave® and MSCR test results, the applicability of the MSCR test methods to characterize polymer-modified binders and RAP binder blends and effects of the addition of high amount of RAP are described in Chapter 4.

Chapter 5: Test Results of Asphalt Mixes- The HWT test results conducted on the asphalt mixes containing polymer-modified binders and RAP are presented in this chapter. The relations of the HWT test with the Superpave® and MSCR test methods are also discussed in this chapter.

Chapter 6: Conclusions and Recommendations– Important findings of this study and the recommendations based on these findings are presented in this chapter. The recommendations for future studies are also included in this chapter.

The details of the abbreviations used in this thesis can be found in the Appendix A: List of Abbreviations.

CHAPTER TWO: LITERATURE REVIEW

2.1 Rheological and Mechanical Properties of Polymer-modified Binders

Over the past three decades, the asphalt industry has used asphalt binder modification with polymers as an effective tool for producing mixes with better performance and improved service life. Continuously increasing traffic and axle load in recent years have led to the search for new types of asphalt binders with better performance (Maccarrone et al., 1995; Airey, 2002; Golalipour, 2011; Khadivar and Kavussi, 2013). For this reason, researchers have started to evaluate, develop and use a wide range of modifiers to improve characteristics of asphalt binders and enhance performance of asphalt pavements (Bahia et al., 2001; Golalipour, 2011; Khadivar and Kavussi, 2013).

Several studies have been conducted to characterize the viscoelastic properties and to evaluate performance of polymer-modified asphalt binders (Collins et al., 1991; Sargand and Kim, 2001; Chen et al., 2002). Plastics, elastomers, fibers and additives are the four major groups of polymer used for the modification of asphalt binders. In general, elastomers (75%) are known to be the most popular modifiers followed by plastomers (15%). Rubber, fibers and other polymer products are also used for asphalt binder modification, but to a limited degree (Diehl, 2000).

Asphalt binder consists of three major fractions, namely asphaltenes, resins, and oils. According to Airey (2011), some portions of maltenes (consisting of resins and oils) can be absorbed by the polymer during mixing and experience swelling. Due to the chemical dissimilarities of the binder and polymer, a two-phase structure (a “polymer-rich phase" and an “asphaltene-rich phase”) can be observed in the blended binder at service temperature. The polymer-rich phase consists of all of the polymers added to the binder, while the “asphaltene-rich phase” contains all of the heavy fractions (i.e., asphaltenes). However, these two phases can exhibit properties that are different from those of the base binder. Performance of blended binders is reported to be affected by the distribution, continuity and homogeneity of these phases. According to Airey (2003) and Elseifi et al. (2003), at sufficient high polymer concentrations, a continuous polymer-rich phase can be developed that would dominate performance of the binder. A dominating polymer-rich phase can make a binder soft, flexible, and elastic, whereas the asphaltene-rich phase can make it hard, brittle, and inelastic. Figure 2.1 shows a schematic of the colloidal structure of the binder and the effect of polymer modification.

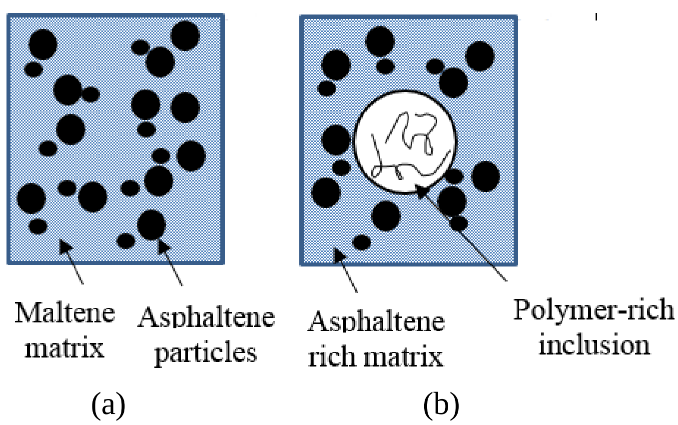


Figure 2.1 Schematic of the colloidal structure of binder and the effect of polymer modification: (a) base binder; (b) polymer-modified binder (after Zhu et al., 2014)

Airey (2003) evaluated the effects of binder source, polymer content, binder–polymer compatibility and aging on the rheological properties of the polymer-modified binders. Significant improvements in the rheological properties of binders were observed due to SBS polymer modification from the penetration, softening point, elastic recovery and DSR test results. It was also reported that the nature of the network established within the binder due to polymer modification depends on the nature of the base binder, the nature and content of the polymer and the binder-polymer compatibility. Furthermore, the binder with a high polymer content was observed to exhibit a more viscous behavior than the elastic response after oxidative aging.

Several studies have been conducted to determine the effect of modifiers on the rheological properties of asphalt binders and asphalt mixes (Read and Whiteoak, 2003; Airey, 2004). It has been observed that addition of polymers to asphalt binders helps mitigate major pavement distresses such as rutting at high temperature, low-temperature cracking, and fatigue cracking (Yildirim, 2007).

The effects of aging and polymer content on the performance of the binders were investigated by Elseifi et al. (2003). The rheological and physical changes associated with the modification of two elastomeric polymers, namely SBS linear block copolymers and Styrene Ethylene Butylene Styrene (SEBS) linear block copolymers, were analyzed. The dynamic mechanical tests were performed using a DSR apparatus at temperatures ranging from 5° to 75 °C. The binders modified with both SBS and SBES were found to exhibit an increase in the rutting resistance at service temperatures above 45 °C. A significant improvement in the fatigue resistance was observed for SBS-modified binders at intermediate service temperatures. The low-temperature performance grade was found to remain unchanged after binder modification.

Kumar et al. (2010) studied the effect of addition of Crumb Rubber (CR), Ethylene Vinyl Acetate (EVA) and SBS modifiers to neat binder on its aging, temperature susceptibility and fatigue life. It was observed that the temperature susceptibility of the binder decreased as the modifier content increased. A SBS-modified binder was found to exhibit a lower viscosity temperature susceptibility than EVA- and CR-modified binders. The EVA-modified binder was observed to show a higher rutting resistance value than SBS- and CR-modified binders, while adding each of the modifiers in the same amount. In addition, the SBS-modified binder exhibited maximum elastic recovery than the CR- and EVA-modified binders. The results of the Tensile Strength Ratio (TSR) of asphalt mixes exhibited that the asphalt mix containing EVA was more resistant to moisture-induced damage than any other modified binders. From wheel-tracking test results, the EVA- and SBS-modified asphalt mixes were found to exhibit a better resistance to rutting than mixes containing neat binder.

The high-temperature rheological properties of SBS-, oxidized polyethylene-, propylene-maleic anhydride-, and recycled crumb rubber-modified binders with and without PPA were investigated by Xiao et al. (2014). It was observed that the rubber-modified binder containing PPA showed greater viscosity than the binders modified using other compounds. The polymer-modified binders produced with oxidized polyethylene and propylene-maleic anhydride was found to exhibit the potential of reducing the energy demand during mixing and compaction of the mixes. The failure temperature and $|G^*|/\sin\delta$ of tested polymer-modified binders were found to be dependent on the binder source. Furthermore, from the phase angle results it was found that the polymer type had a significant effect on the viscoelastic characteristics of the modified binders. Moreover, the results of viscometry, amplitude sweep, frequency sweep, creep and creep recovery, and relaxation spectrums of polymer-modified binders were found to get affected by polymer types, asphalt sources, and test temperatures.

Rahi et al. (2014) evaluated the effectiveness of the Styrene-ethylene/propylene-styrene (SEPS) modification of asphalt binders with respect to two different specification parameters, namely the $|G^*|/\sin\delta$ and the Zero Shear Viscosity (ZSV). The frequency sweep test was conducted at 40°, 50°, and 60 °C under controlled-strain conditions at frequencies between 0.1 and 100 Hz to determine the high-temperature characteristics of the asphalt binders. The results of the $|G^*|/\sin\delta$ and ZSV indicated that the rutting resistance of the asphalt binders increased constantly with an increase in SEPS concentration in asphalt binder.

2.2 Rheological and Mechanical Properties of RAP Binder Blends

The use of RAP has become an important part of the pavement construction practice in recent years due to environmental concerns, scarcity of high-quality aggregates and increased cost of virgin asphalt binder. The Annual Asphalt Pavement Industry Survey (2013) reported a significant growth in the use of RAP from 2009 to 2012. It was also reported that the asphalt industry remained the country’s number-one recycler by reusing RAP at a rate of over 99 percent. More than 98 percent contractors were reported to use RAP in 2012. The amount of RAP used in asphalt mixes increased form 56 million tons in 2009 to 68.3 million tons in 2012. Approximately, 3.4 million tons of asphalt binder was conserved during 2012. The amount of savings in asphalt binder was estimated to worth over $2 billion (Hansen and Copeland, 2013). As the use of RAP is increasing rapidly, it is important to evaluate the performance of asphalt mixes containing RAP.

A number of studies have been conducted to evaluate performance of asphalt binders with the addition of different amounts of RAP binder (Daniel et al., 2010; Kim et al., 2009; Colbert and You, 2012). The high-temperature PG grades of the RAP binder blends were observed to increase or remain unchanged compared to that of the neat binder. However, the low-temperature PG grades of the RAP binder blends were found to remain the same or increase maximum by one grade compared to the unmodified binder (Daniel et al., 2010).

Kim et al. (2009) investigated the rutting and fatigue performances of RAP binder- and SBS-modified binders. The rutting and fatigue parameters were found to increase with an increase in the amount of RAP binder. The indirect tensile strength of asphalt mixes containing RAP was also found to increase with an increase in RAP content. All mixes containing RAP showed relatively low creep compliance values. It was also reported that a mix containing RAP and SBS polymer may lead to a better resistance to fatigue cracking.

Colbert and You (2012) studied the performance of the RAP binder blends using Superpave® binder characterization tests. Effects of short-term and long-term aging on the binders' viscosity and stiffness were evaluated. A PG 58-28 binder was used as the neat binder to blend with different amounts of RAP binder, namely 50%, 70% and 100% by weight of the binder. It was found from the Rotational Viscosity (RV) test results that the workability and pumping potential of the RAP binder blends reduced as the amount of RAP binder increased. Low-temperature frequency sweep tests were conducted at six different frequencies: 0.01, 0.1, 1, 5, 10, and 25 Hz at reference temperatures of 13°, 28°, 40°, 58° and 70 °C to develop shear modulus master curves for the RAP binder blends. The results showed that the shear modulus of the binder blends increased with an increase in RAP binder in the blend. The shear moduli of the blended binders were observed to remain unchanged as the amount of RAP binder increased from 50% to 70%. Also, the shear moduli of the blended binders were found to increase significantly due to RTFO- and PAV-aging.

The rutting susceptibility of asphalt binders and asphalt mixes containing different polymer modifiers and RAP binder from different sources was evaluated by Bernier et al. (2012). The rutting resistance of the asphalt mixes was determined from Asphalt Pavement Analyzer (APA) testing and was compared with the binder performance measured using MSCR and frequency sweep tests. The Fourier Transform Infrared Spectroscopy (FTIR) tests were also conducted to determine oxidation levels of different RAP binders. It was found that the binder from a basalt RAP source exhibited significantly higher $|G^*|$ values than any other binders at low frequencies. It was also observed that the addition of 10% RAP binder exhibited greater rutting resistance than other binder blends.

2.3 Asphalt Mixes with High Amounts of RAP

In view of the benefits associated with incorporating RAP in asphalt mixes, the paving industry is in favor of using higher amounts of RAP in asphalt pavement construction. However, concerns of state DOTs over the long-term effects of using high amounts of RAP on the performance of asphalt pavements have limited its use (Daniel et al., 2010; Hossain et al., 2012; Boriack et al., 2014; Ghabchi et al., 2016). These concerns are mainly due to the lack of enough mechanistic performance data and proper specifications for mixes containing RAP (Hossain et al., 2012). The Oklahoma Department of Transportation (ODOT) specifications limit the maximum amount of binder replacement by RAP or Recycled Asphalt Shingles (RAS) for surface courses and other Superpave® mixes as 12% and 30%, respectively (ODOT, 2013).

West et al. (2009) evaluated the performance of asphalt mixes containing moderate (i.e., 20%) and high (i.e., 45%) amounts of RAP under accelerated loading and determined the applicability of laboratory tests to predict field performance of asphalt mixes containing RAP. Test sections were constructed at the National Center for Asphalt Technology (NCAT) test track using a 50-mm thick surface course mix. The test sections constructed using asphalt mixes containing RAP were found to perform well for rutting under heavy loading conditions. It was also concluded from the indirect tensile strength test results that the use of RAP improved the tensile strength of asphalt mixes.

A New Hampshire Department of Transportation (NHDOT) study examined the effect of high percentages of RAP binder on the properties of the binder blends. Tests were conducted on asphalt binders extracted from 28 different asphalt mixes to determine their PG grades and critical cracking temperatures. The high- and low-temperature PG grades were observed to remain the same or increase by only one PG grade with the addition of different amounts of RAP binder. It was also observed that the high temperature PG grades for several RAP binder blends exhibited a grade bump with the addition of 20% RAP binder. The change in the failure temperature with respect to the percent binder replacement was found to decrease as the amount of RAP binder increased in the RAP binder blends (Daniel et al., 2010).

Another study conducted by Hong et al. (2010) evaluated the long-term performance of Hot Mix Asphalt (HMA) containing high percentages of RAP. For this purpose, FHWA's Long-Term Pavement Performance (LTPP) test sections in Texas were investigated for transverse cracking, rut depth and ride quality over sixteen years. With regards to transverse cracking, it was observed that, using 35% RAP in the HMA led to faster pavement deterioration than that with only virgin materials. Also, the asphalt mix with 3% latex-modified binder was found to exhibit less transverse cracks than asphalt mixes containing RAP. However, the asphalt mixes with 35% RAP were found to be more rut resistant than the asphalt mixes with virgin binders. Furthermore, the addition of RAP to the asphalt mixes was found to have no significant effect on the ride quality. It was reported that the pavement with high RAP content (e.g., 35%) are expected to perform well during its life span.

Ghabchi et al. (2014) evaluated the effect of addition of different amounts of RAP binder to virgin binders on the moisture-induced damage potential of the asphalt mixes using the Surface Free Energy (SFE) approach. For this purpose, two binders (a PG 64-22 and a PG 76-28) were blended with different amounts of RAP binder (0%, 10%, 25% and 40%). A Dynamic Contact Angle (DCA) analyzer was used to determine the SFE components (non-polar, acid and base) of the binder blends. It was found that, for both the binders, the addition of RAP binder increased the acid SFE components of the RAP binder blends, while the base SFE components remained almost unchanged. Also, the wettability, work of adhesion, work of debonding and energy parameters of the RAP binder blends with six different types of aggregates were evaluated in that study. The wettability and the work of adhesion of the RAP binder blends over the aggregates were found to increase with an increase in the amount of RAP binder. However, the blending of RAP binder with the PG 64-22 binder was found to result in a higher work of adhesion. Evaluating the energy parameters of the asphalt aggregate system, it was observed that the moisture-induced damage potential of the both binders reduced with an increase in the RAP binder content.

Sabouri et al. (2015) investigated the performance of the asphalt mixes containing RAP with respect to amount of RAP, total asphalt content and various base binders. The rutting performance of the asphalt mixes was evaluated with a permanent deformation model developed by Choi and Kim (2013). The Simplified Viscoelastic Continuum Damage (S-VECD) model was used to evaluate the fatigue properties of asphalt mixes. Nine laboratory-produced asphalt mixes were tested for this purpose. The Triaxial Stress Sweep test, Dynamic Modulus (DM) test and the Cyclic Direct Tension tests were also used to evaluate the rutting and fatigue properties of the asphalt mixes. The high- and low-temperature PG grades of the binder blends were found to increase with an increase in RAP binder. The use of soft binder with RAP in the asphalt mixes resulted in improved fatigue resistance without compromising the rutting resistance of the mixes. These researchers suggested to use either a soft base binder, maintain the optimum asphalt binder content or increase asphalt layer thickness while incorporating high amounts of RAP in asphalt mixes.

In a recent study, Ghabchi et al. (2016) evaluated the effects of RAS and RAP on the fatigue cracking, low-temperature cracking and stiffness of HMA mixes. A nation-wide survey was conducted among the DOTs to find out the major concerns of incorporating RAP and RAS in asphalt mixes. The fatigue cracking was found to be a major concern among all the state DOTs while using RAP and RAS. The resistance to fatigue cracking, low-temperature cracking and stiffness of the asphalt mixes containing different amounts of RAS (0 to 6%) and/or RAP (0 to 30%) with two types of binders (PG 64-22 and PG 70-28) were evaluated in the laboratory using Four-point Bending Beam Fatigue, DM test, Creep Compliance, and Indirect Tensile Strength tests. The maximum increase in the fatigue life was observed for the asphalt mixes with PG 64-22 binder and 5% RAS and 5% RAP. Also, the dynamic moduli of the asphalt mixes were observed to increase with the addition of RAS and/or RAP indicating a better rutting performance of mixes. However, the low-temperature cracking potential of the asphalt mixes was found to increase with an increase in the RAP and RAS content in the mixes.

2.4 Conventional Asphalt Binder Test Methods

2.4.1 Superpave® Performance Grade (PG) and Its Limitation

Before implementation of the Superpave® system, characterization of asphalt binders was mainly based on empirical methods. Different empirical tests such as penetration, ductility, softening point and viscosity were used for the characterization of asphalt binders. These empirical tests were reported to have no direct correlations with the HMA pavement performance. Also, these tests were conducted at one standard temperature without considering binder properties at other temperatures pertaining to climatic conditions. Furthermore, there was no scope for testing binder properties at low temperatures to determine binders’ resistance to thermal cracking. To address these limitations, the Superpave® PG system was developed to characterize asphalt binders based on their performance (McGennis, 1994).

The DSR test, introduced by the Superpave®, is able to characterize the rheological properties of the asphalt binders. In the DSR test, a cylindrical binder sample of desired shape is sandwiched between two parallel plates (Figure 2.2). Torque is applied to the plate to create sinusoidal, oscillatory stresses or strains on the binder sample at required temperatures and loading frequencies. The DSR test is conducted at a relatively low stress level to ensure linear viscoelastic behavior of the asphalt binder (Delgadillo, 2006). Figure 2.2 presents a schematic of the DSR test. The total dissipated energy can be calculated from the stress-strain curve of the DSR test using Equation (2.1). According to Anderson et al. (1994), the rutting can be related to the total dissipated energy keep from a DSR test. The term |G*|/sin δ was identified as the rutting parameter and was used to determine the high-temperature performance grade of the binder being tested (Bahia and Anderson, 1995).

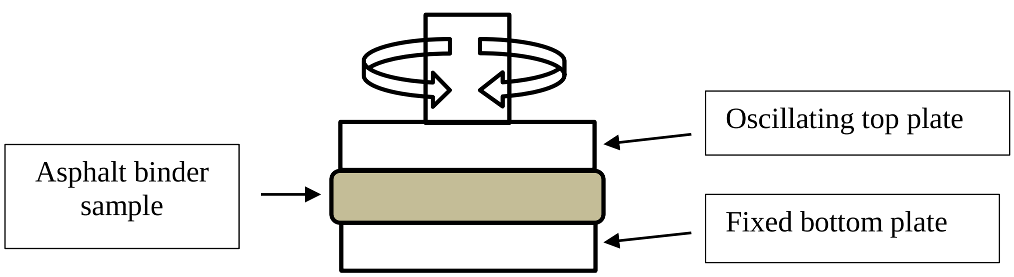


Figure 2.2 Schematic of DSR test setup (after Delgadillo, 2006)

$$W_i = \Pi * \tau_0^2 * \frac{1}{|G^*| / \sin\delta} \tag{2.1}$$

where,

W_i = Total dissipated energy,

τ_0 = Maximum applied stress,

$|G^*|$ = Shear modulus of asphalt binder, and

δ = Phase angle of asphalt binder.

The NCHRP project 9-10 (2001), "Superpave® Protocols for Modified Binders," was conducted to investigate the suitability of the test protocols proposed in the Superpave® specifications for characterizing modified asphalt binders. A wide range of commonly used modified asphalt binders were tested in that study. It was observed that the mechanical behavior of many modified binders could be highly non-linear and very sensitive to stress level, speed, and traffic volume. It was also reported that the simplifying assumptions used for the Superpave® test methods restricted their applicability for modified asphalt binders. The Superpave® test methods such as AASHTO T 315 (AASHTO, 2012) was found to be inadequate for measuring the non-linear viscoelastic properties of polymer-modified binders. The correlation between rutting properties of asphalt mixes and the $|G^*|/\sin\delta$ of asphalt binders was found to be poor (with a coefficient of determination, R^2, equal to 23.77%). It was concluded that the Superpave® specifications that were mainly developed for characterizing unmodified asphalt binders are inadequate for proper characterization of modified binders (Bahia et al., 2001).

2.4.2 Other Test Methods and Their Limitations

Consequently, many researchers and DOTs started searching for additional test methods for characterizing polymer-modified binders. This quest resulted in the introduction of Superpave® "PG Plus" test methods such as ER (AASHTO T 301, 2013), Tenacity (ASTM D 5801, 2012), and Forced Ductility (FD) (AASHTO T 300, 2011) tests (Kamel et al., 2004).

Shenoy (2001) proposed a refinement of the Superpave® high-temperature specification parameter using basic principles. A new high-temperature parameter called Shenoy's parameter ($|G^*|/(1-1/(\tan\delta.\sin\delta))$) was proposed to replace the $|G^*|/\sin\delta$. It was proposed that the permanent deformation could be minimized by maximizing Shenoy's parameter. Experimental data of some typically used binders with widely different rheological characteristics were used for the verification of the prediction. It was observed that the Shenoy's parameter correlated well with actual experimental data more than the $|G^*|/\sin\delta$, suggested by Superpave® specifications.

Dongré and D'Angelo (2003) correlated high-temperature specification parameters obtained from different asphalt binder tests with the rutting performance data from an Accelerated Loading Facility (ALF) at the FHWA's Turner-Fairbank Highway Research Center located in Virginia. The ZSV was determined using the Carreau model (Carreau et al., 1968) at different creep stress levels and by conducting multicycle creep-recovery test on the asphalt binders (Dongré and D'Angelo, 2003). The frequency sweep data at the high temperature PG grades were also used to obtain the ZSV values. Among these parameters, the ZSV determined from the Carreau model was found to exhibit a good correlation with the rutting performance of the asphalt mixes.

However, this method was found to be time-consuming. It was recommended that the ZSV determined from the single frequency sweep test can be used as a possible replacement of rutting parameter.

Dongré et al. (2004) conducted another study to evaluate the adequacy of storage viscosity (η′) as a replacement for the Superpave® high-temperature rutting parameter (|G*|/sinδ). It was found that the accumulated strain, ZSV, and η′ showed reasonable correlations with rut depths measured in a HWT test. The η′ value was found to be the most promising binder parameter for characterizing the rutting resistance of asphalt mixes. The temperature at which η′ becomes equal to a viscosity of 220 Pascal-seconds (Pa-s) was proposed as a new specification criterion.

A study conducted by Virginia Department of Transportation (VDOT) identified the presence of polymer modifiers in binders by Fourier Transform Infrared (FTIR) Spectroscopy and Elastic Recovery (ER) techniques. It was found that both of these techniques were not capable of identifying polymers in modified binders (Diefenderfer, 2006).

Zoorob et al. (2012) investigated the effects of frequency sweep test on the penetration grade binders (40/50 and 20/30) and a SBS block copolymer-modified binder at different temperatures. The measured shear modulus (|G*|) and phase angle (δ) values were found to indicate the differences between the SBS-modified binder with other non-modified binders. A Low Shear Viscosity (LSV) temperature sweep test was also conducted to obtain Equi-Viscous Temperature (EVT) at 2 kPa-s viscosity. Frequency sweep tests conducted at EVT on SBS-modified binders showed that the

LSV concept was not applicable to modified binders in which no viscosity plateau can be obtained.

The advantages and disadvantages of different test parameters namely, penetration, softening point, |G*|/sin δ, Shenoy's parameter, zero-shear viscosity, storage viscosity (η') and the J_{nr} were investigated by Domingos and Faxina (2015). A 50/70 penetration grade asphalt binder was used as the base binder and to prepare crumb rubber-, SBS-, and Poly Ethylene (PE)-modified asphalt binders of similar high-temperature PG grade (PG 76-XX). The rutting resistance of these binders were evaluated using different parameters at 64° and 70 °C. It was observed that the |G*|/sinδ exhibited more conservative results in predicting rutting susceptibility than the Shenoy's parameter. Some similarities in the ranking of the asphalt binders' susceptibility to rutting were observed while considering the |G*|/sinδ, Shenoy's parameter and J_{nr} parameter. However, the creep and recovery test method was found to detect substantial differences among the rheological responses of the modified binders, which were not clearly observed in other test procedures.

2.5 Multiple Stress Creep and Recovery (MSCR) Method

2.5.1 Development of MSCR Test Method

Outcomes of the NCHRP project 9-10 suggested that the repeated loading can be used for the characterization of the PMA binders (Bahia et al., 2000). Consequently, a new test method, called the Repeated Creep and Recovery Test (RCRT), was proposed by Bahia et al. (2000). The rate of permanent strain accumulation in the asphalt binder as a result of repeated loading was estimated by this test method. In this method, a creep load of 0.3 kPa was applied for 1 second to the asphalt binder, followed by a recovery period of 9 seconds. The main drawback of the RCRT test method was its low stress level compared to the actual field conditions (D'Angelo et al., 2006).

The stress dependency of binders in the RCRT and the relationship of this test method with the asphalt mixes' performance were evaluated by Delgadillo et al. (2006). Different polymer-modified and aged asphalt binders were used to evaluate the non-linearity of the RCRT test. Binders were tested at six different stress levels, namely 0.025, 0.1, 0.4, 1.6, 6.4 and 10 kPa. The stress sensitivity of the RCRT test was found to vary with asphalt binder type, modification type and temperature. Also, the RCRT test was found to be more sensitive to stress level than the stress sweep test. Furthermore, the permanent deformation of the asphalt mixes was found to have a good correlation with the RCRT parameter. Moreover, it was observed that the behavior of the binder at a high stress level may be used as an indicator of the rutting resistance of the asphalt mixes.

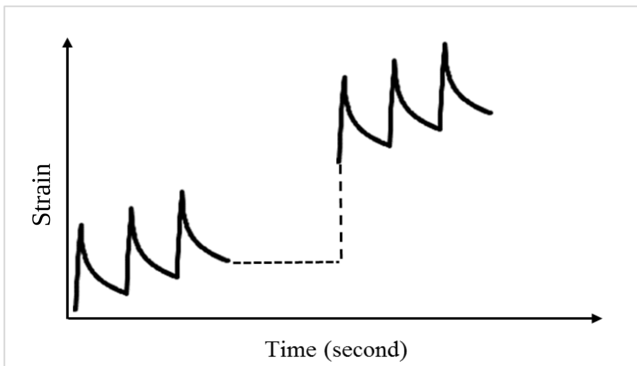
D'Angelo et al. (2006) evaluated the applicability of the RCRT method on modified binders as an alternative to Superpave® PG plus tests. A complete RCRT protocol was developed for testing asphalt binders. In that study, two stress levels (0.1 and 3.2 kPa) were proposed for testing. Binders with less networked structure were found to exhibit an increase in compliance at 3.2 kPa stress level. It was also observed that the analysis of RCRT data can provide useful information on the polymer network within the binder. It was reported that a relationship existed between percent recovery values obtained from the RCRT and elastic recovery tests. Also, tests on the field cores indicated that unlike the elastic recovery test, the RCRT was capable of identifying the presence of polymer(s) in a binder. A new parameter called non-recoverable creep compliance (J_{nr}) was introduced to determine the rutting potential of the polymer-modified asphalt binders.

A study conducted by D'Angelo (2010) evaluated the high-temperature rutting properties of both unmodified and polymer-modified asphalt binders. The outcomes of that study were used for the development of the MSCR test method. The relationship between the existing Superpave® grading and the J_{nr} parameter at 3.2 kPa stress level was evaluated using multiple unmodified and polymer-modified asphalt binders. Unmodified binders used in this study exhibited a linear behavior up to a stress level of 3.2 kPa, whereas the polymer-modified binders showed a non-linear behavior at a low stress level. The two-phase nature of the polymer-modified binders was reported to be responsible for this phenomenon. Also, the variation of rutting with J_{nr} was exhibited using the results from other studies. A new high-temperature binder specification, based on MSCR test method, was proposed for asphalt binders as a replacement for grade bumping procedure. It was also observed that the stress dependency of polymer-modified binders was affected by the stiffness of base binder, amount of polymer and extent of the polymer network in the binder.

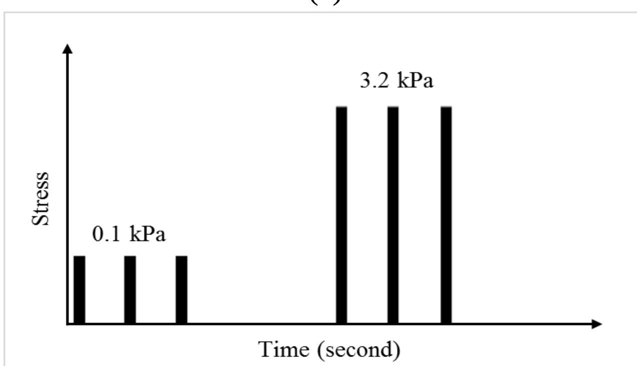
Reinke (2010) investigated the suitability of the J_{nr} parameter to predict the high-temperature performance of asphalt mixes. The J_{nr} values of all modified binders tested in that study were found to increase with an increase in the stress level. It was also found that the different polymer systems responded differently to the applied stress. It was concluded that an understanding of the stress sensitivity of the asphalt binders would be necessary to evaluate their rutting potential. It was also recommended that the

J_{nr} value of the binders be determined at the climatic temperature using a range of stress levels to evaluate their rutting resistance.

Figure 2.3 presents a schematic of the MSCR test at 0.1 and 3.2 kPa stress levels (after D'Angelo and Dongre, 2009). The non-recoverable creep compliance is calculated by dividing the non-recoverable strain after each creep and recovery cycle with the corresponding applied stress. For example, the J_{nr} at 0.1 kPa is calculated by dividing the non-recoverable strain after each creep and recovery cycle by 0.1 kPa. Equations (2.2) and (2.3) present the calculation procedure for the J_{nr} at 0.1 kPa. The J_{nr} for 3.2 kPa stress level can be calculated using similar procedure (AASHTO TP 70, 2013).



(a)



(b)

Figure 2.3 Schematic of MSCR test method (a) strain vs time and (b) stress vs time (after D'angelo and Dongre, 2009)

$$J_{nr} = \frac{\varepsilon_{10}}{0.1} \tag{2.2}$$

$$J_{nr,0.1} = \frac{\sum(J_{nr,0.1}, N)}{10} \tag{2.3}$$

where,

$\varepsilon_{10} = \varepsilon_r - \varepsilon_0$,

$\varepsilon_r =$ Strain at the end of the recovery portion of each cycle, and

$\varepsilon_0 =$ Initial strain at the beginning of the creep portion of each cycle.

2.5.2 Studies Related to MSCR Test

D'Angelo and Dongré (2009) evaluated the compatibility of the linear and radial SBS polymers with the binders using MSCR and ER test methods. It was found that the ER tests could not differentiate between different levels of polymer modifications, whereas the MSCR test was able to determine the extent of the polymer network in the binders. Also, the binder with radial SBS polymer was found to exhibit a higher recovery than the binder with linear SBS modification. Furthermore, the MSCR test results were verified with the fluorescence micrographs of the binders. It was found that the MSCR test was a convenient and less time-consuming test for optimum polymer-modified binders.

Tabatabaee and Tabatabaee (2010) evaluated the effectiveness of the current Superpave® specifications, time sweep and MSCR tests with respect to the performance of the asphalt mixes. A PG 58-22 binder was modified by adding 3%, 6%, 9%, 12%, and 15% ground crumb rubber using a laboratory scale mixer. The highly Crumb

Rubber-Modified (CRM) binders were observed to exhibit a better rut resistance from the MSCR results. It was observed that both MSCR and $|G^*|/\sin\delta$ parameters can be used in predicting permanent deformation behavior of asphalt binders modified with the CRM.

Adorjányi, and Füleki (2011) studied the performances of different hard, polymer-modified and penetration grade (35/50, 50/70) binders typically used in Hungary using MSCR test. The MSCR tests were conducted on RTFO-aged binders at high temperature (60 °C) and three different stress levels, namely 0.1, 3.2, and 6.4 kPa. It was found that the average recoverable strains of the polymer-modified and hard binders were independent of the stress level. However, the binder with a higher penetration value exhibited a lower recoverable strain and higher stress sensitivity. Significant differences in the non-recoverable creep compliance values were also observed for the asphalt binders with the same penetration grade. A good correlation was found between the average recoverable strain and average non-recoverable compliance at all stress levels for tested binders.

Wasage et al. (2011) investigated the results of the MSCR test for several conventional, polymer- and crumb rubber-modified asphalt binders to evaluate the suitability of J_{nr} as a new parameter for the prediction of rutting. Four different asphalt binders within same high-temperature PG grade were selected. Asphalt mixes were prepared using the same aggregate gradation, asphalt content and air voids. Relatively low recovery was observed for the conventional binder while polymer-modified binder showed a high recovery at all stress levels. The J_{nr} of polymer-modified binder was found to be weakly dependent on the stress up to a level of 12.8 kPa at a temperature of

40 °C. After that stress level, an increased stress dependency was observed with an increase in stress level. A stress of about 1 kPa at 40 °C was found as a common lower boundary of the linear viscoelastic behavior for all of the tested binders. The best correlation between the rut depth and the J_{nr} value was observed at a stress level of 12.8 kPa. Also, a linear viscoelastic model was developed for MSCR test. The model was reported to be capable of describing the MSCR test for all binders.

Shirodkar et al. (2012) studied the behavior of both in-house and industry-produced polymer-modified binders by characterizing creep and recovery curves obtained from the MSCR test. A methodology was developed to determine the different components, such as linear viscoelastic, non-linear viscoelastic, and permanent strain from the creep and recovery curve. Cycle 6 of 0.1 kPa stress level and cycles 1, 6, and 10 of 3.2 kPa stress level were used to determine the linear and non-linear viscoelastic parameters, respectively. It was found that the non-linear viscoelastic parameters and permanent strain were not affected by the cycles of the MSCR test but were influenced by the type of base binder. Also, the MSCR parameter, J_{nr} was found to be affected by the type of base binders and polymers.

A study funded by the New Jersey Department of Transportation was conducted to verify the suitability of MSCR parameters as a standard measure to evaluate the performance of polymer-modified binders (Mehta et al., 2013). It was found that the MSCR test could be used as a replacement of more time intensive elastic recovery and force ductility tests. It was also reported that using the MSCR test resulted in a reduction of capital cost and expenses associated with characterization of asphalt binders. Furthermore, a database containing properties of asphalt binders and mixes properties was developed to help engineers in selecting appropriate binders and mixes that can meet the required criteria in the specifications. A J_{nr} value of less than 0.5 kPa^{-1} showed a better high-temperature performance. It was also reported that an MSCR %Recovery value greater than 40% at 3.2 kPa stress level might meet the elastic recovery requirements of the binder. It was further suggested that a low J_{nr} value with a high MSCR %Recovery and a high |G*|/sinδ value would ensure the binders' capability to withstand heavy and extreme traffic loads.

DuBois et al. (2014) conducted a study to establish correlations between the parameters from the MSCR test with the laboratory measured high-temperature properties of asphalt mixes. A total of ten different asphalt mixes were evaluated for this purpose. Binder of each mix was tested in accordance with the Superpave® and MSCR tests to measure |G*|/sinδ and J_{nr}. The J_{nr} values were found to correlate well with the rutting performance of asphalt mixes measured using a flow time test. It was also observed that the rutting resistance of the asphalt mixes improved as the J_{nr} value of the binder decreased. Asphalt binders were found to exhibit a better rutting performance as the J_{nr} values approached 0.5 kPa^{-1} or lower. Furthermore, the flow time result was found to exhibit poor correlations with the |G*|/sinδ and MSCR %Recovery.

The high-temperature performance of highly modified asphalt binders was investigated by Mohseni and Azari (2014) using the Incremental Repeated Load Permanent Deformation (iRLPD) and the MSCR test method. The MSCR and iRLPD tests were conducted at PG, PG-6 °C and PG-12 °C temperatures. The iRLPD tests were performed at 1.0, 3.2, and 5.0 kPa shear stress levels, each consisting of 20 cycles. The relationship between the loading time and permanent strain was found to be linear for neat binders, whereas it was observed to be highly non-linear for polymer-modified binders. It was also observed that the permanent strain of polymer-modified binders was time-dependent and the non-linearity of strain increased with the level of modification. A comparison of average recovery values between both tests showed that the MSCR %Recovery was significantly less than that of the iRLPD test. The variability of the MSCR test on highly modified binders was found to be dependent on the binder type. The MSCR, LTPPBind and iRLPD Traffic Models were developed to relate the binders' test parameters to Equivalent Single Axle Load (ESAL). The iRLPD and LTPPBind estimated similar ESAL values for most of the modified binders, whereas the iRLPD and MSCR traffic estimates were found to be different for the modified binders.

Domingos and Faxina (2014) evaluated the effect of longer creep-recovery times on the MSCR test parameters using a number of modified asphalt binders. A 50/70 penetration grade binder which is equivalent to a PG 64-XX binder was used as a base binder to prepare PPA-, SBS- and SBS+PPA-modified binders. The modifier contents were selected to achieve a binder grade of PG 76-XX. Standard MSCR tests along with non-conventional tests were conducted at a creep and recovery times of 2 and 18 seconds, respectively. It was found that the PPA-modified binders exhibited the highest %Recovery and the lowest J_{nr} values. However, the highest $J_{nr\ diff}$ values were observed for the PPA-modified binder. It was also observed that an increase in creep-recovery time decreased the %Recovery and increased the non-recoverable compliance of all modified binders. The effect of an increase in both creep and recovery times was found to be more pronounced for SBS-modified binders. It was suggested that the addition of

PPA might be a good alternative to reduce the susceptibility to rutting at longer creep-recovery times.

Zhang et al. (2015) evaluated the MSCR and DSR test methods in characterizing the rutting properties of asphalt binders used in HMA mixes. A good correlation ($R^2 > 0.75$) was found between the J_{nr} values of binders and the rut depths of HMA obtained from a HWT test. Also, the rutting parameter, |G*|/sinδ, was found to exhibit a relatively poor correlation ($R^2 < 0.5$) with the rut depths. This study showed that the MSCR test has potential to serve as a surrogate for the rutting parameter, |G*|/sinδ.

A study was conducted by Hossain et al. (2015) to produce a MSCR database for different types of polymer-modified binders used in Oklahoma. Asphalt binders from different sources in Oklahoma were collected and tested at 64 °C and at 0.1 and 3.2 kPa stress levels. The asphalt binders were then graded using the MSCR grading system. The results from the quadrant plot indicated that both supplier and user may not be at risk if they use PG 76-28 asphalt binders. It was also recommended that an MSCR %Recovery value of 50 % could be adopted for PG 70-28 binders without putting many suppliers at risk. Furthermore, the MSCR %Recovery was found to decrease with temperature but increase with aging. It was suggested that the MSCR test method could be adopted by ODOT in its quality assurance process to characterize the high-temperature performance of asphalt binders.

Stevens et al. (2015) developed a MSCR database for Arizona DOT to determine the impacts of changing the grading system from Superpave® to MSCR-based system. The AASHTO T 350 (AASHTO, 2014) test method and AASHTO M 332 (AASHTO, 2014) specification were followed for conducting the DSR and MSCR tests, respectively. The database of three separate groups (A, B, and C) of asphalt binders consisting of 375 individual asphalt binder samples were evaluated in this study. It was observed that although the binders used in Arizona were produced according to AASHTO M 320 (AASHTO, 2010) specification, they met the standard traffic requirements of the AASHTO M 332 (AASHTO, 2014). Adopting the MSCR specification for grading of asphalt binders was found to increase the number of asphalt binder grades used by Arizona DOT from 8 to 13.

A study conducted by Yang and You (2015) used both DSR and MSCR tests to determine the high-temperature performance of bio-oil modified asphalt binders. A PG 58-28 binder was blended with 5% and 10% of three types of bio-oils generated from waste woods, namely untreated bio-oil, treated bio-oil and polymer-modified bio-oil. From the DSR test results it was found that the addition of bio-oil to binder increased the |G*| value and reduced the phase angle. The rutting resistance of the binder was found to increase with the addition of bio-oil. A decrease in the J_{nr} value and an increase in the %Recovery were also observed with the addition of bio-oil to binder. The MSCR test results showed that the polymer-modified bio-oil performed worse than untreated and treated bio-oil-modified binders.

The effect of stress level on the creep and recovery behavior of SBS- and PPA-modified binders was investigated by Jafari et al. (2015). Asphalt binders of same continuous PG grade were selected as base binder and mixed with 2%, 4%, and 6% SBS and required amounts of PPA to achieve the same continuous high temperature PG grade. The MSCR tests were conducted at 55°, 70 °C and at the high temperature PG grade of each binder and at a stress level of 12.8 kPa in addition to the standard MSCR procedure. It was found that the J_{nr} values at low stress levels (0.1 and 3.2 kPa) were almost independent of stress at any temperature indicating linear viscoelastic characteristics of asphalt binders. However, the stress sensitivity of the modified binders was observed to be more prominent at a high temperature and a high stress level (12.8 kPa). The SBS-modified binders were found to exhibit significantly less sensitivity to stress levels than the PPA-modified binders of the same PG grade. It was also observed that the asphalt binder modified with PPA exhibited a higher stress-sensitivity than others. Furthermore, the PPA-modified binders exhibited much lower recovery values than the corresponding SBS-modified binders. It was recommended that a stress level higher than 3.2 kPa be used to evaluate the J_{nr} values of the SBS- and PPA-modified binders in the non-linear viscoelastic region.

The creep-recovery behavior of various elastomer and/or wax modified binders was evaluated by Laukkanen et al. (2015). Different linear viscoelastic parameters, namely $|G^*|/\sin\delta$, ZSV and LSV were calculated for tested asphalt binders. It was observed that, all the rutting parameters except $|G^*|/\sin\delta$, ranked highly modified binders as the most rut resistant and unmodified binders as the most rut susceptible binders. From the MSCR ranking, it was found that the modified binders were much more rut resistant compared to the unmodified binders of same penetration grade. It was observed that the non-recoverable creep compliance at 3.2 kPa and the accumulated strain at the end of the MSCR test were able to predict binder's contribution to rutting of asphalt mixes. Also, the relationships between these two parameters and rutting of asphalt mixes were found to be linear. It was reported that the highly modified binders, especially those modified with wax, were more stress sensitive compared to unmodified and moderately modified binders.

Saboo and Kumar (2016) evaluated the rutting performance of unmodified and polymer-modified asphalt binders using different rut prediction parameters and compared their results with the rutting performance of the associated asphalt mixes. Two viscosity graded binders and two polymer-modified binders (SBS- and EVA-modified) were selected for that study. The temperature sweep test at 10 rad/s, steady-shear viscosity test at a shear rate varying from 0.1 to 100 s^{-1} and MSCR test were conducted to evaluate various rutting susceptibility parameters. A laboratory wheel-tracking device was used to measure the rutting performance of prepared HMA. From the binder tests results, it was found that the polymer-modified binders showed a better rutting performance than conventional binders. It was also observed that the rutting performance of the binders evaluated using different methods provided similar rankings. However, the amount by which one binder was superior to the other varied with the method. The MSCR test was found to be the more fundamental test method and was reported to provide more information about the viscoelastic nature of the asphalt binder than other test methods.

2.6 Interpretation of MSCR Test Data

2.6.1 Polymer Method

A %Recovery vs. J_{nr} plot is a very useful tool for characterizing asphalt binders at high temperature. This plot is known as the “polymer method” of MSCR data analysis (Anderson, 2011). In the present study, the MSCR test data was analyzed using the the polymer method. The MSCR parameters, namely J_{nr} and %Recovery obtained from the 3.2 kPa stress level at 64 °C, were plotted to characterize the binders by locating it on the polymer plot. The AASHTO TP 70 (AASHTO, 2013) provisional specification introduced a typical curve called the "MSCR curve" as a borderline between elastomeric polymer-modified and unmodified binders (Anderson, R. M., 2011). The equation of the MSCR curve is given in Equation (4.4).

$$y = 29.37x^{-0.2633} \tag{4.4}$$

where,

y = MSCR %Recovery at 3.2 kPa, and

x = Non-recoverable creep compliance at 3.2 kPa.

An asphalt binder can be defined as a highly elastic binder if the plot of the %Recovery vs. J_{nr} falls above the MSCR curve. This highly elastic binder can be modified with high amounts of elastomeric polymers. If the plot of %Recovery vs. J_{nr} falls below the MSCR curve, then it indicates that the binder will exhibit low elasticity. Such a binder is not expected to be modified with enough elastomeric polymers. Figure 2.4 presents a typical plot of the polymer method.

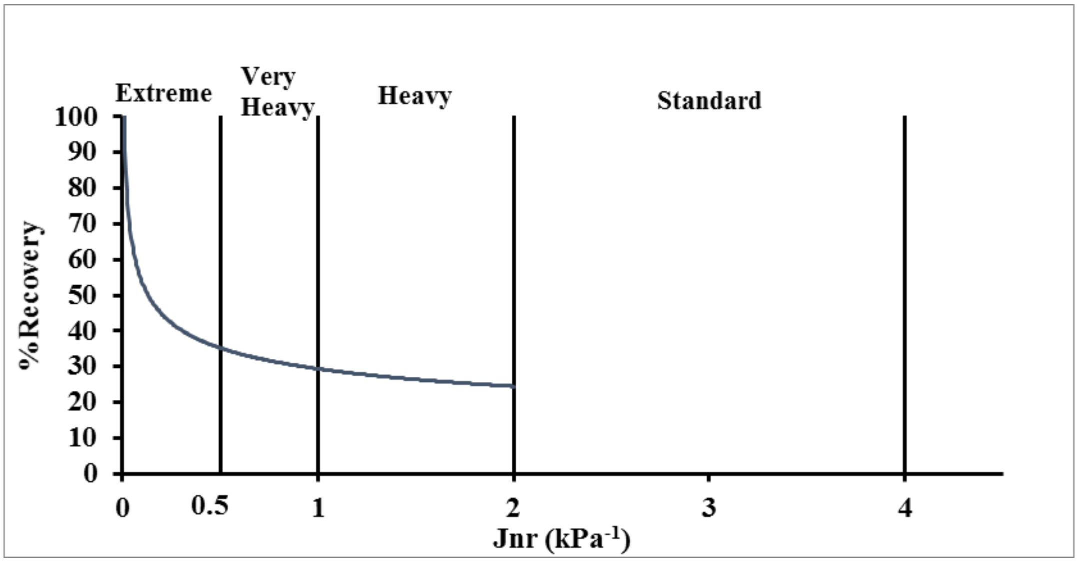


Figure 2.4 Polymer method of MSCR analysis (after AASHTO TP 70, 2013)

2.6.2 Stress Sensitivity

Stress sensitivity ($J_{nr\ diff}$) is another important parameter that can be determined from the MSCR test results. A binder's performance at a higher temperature or at a higher stress level than expected can be evaluated with the help of the stress sensitivity parameter (Hossain et al., 2015). In the MSCR test method, the $J_{nr\ diff}$ is calculated based on the difference in J_{nr} values at two stress levels. According to the AASHTO MP 19 (AASHTO, 2010), the increase in J_{nr} due to an increase in stress level from 0.1 kPa to 3.2 kPa must be less than or equal to 75% of the J_{nr} at 0.1 kPa. The equation for calculating $J_{nr\ diff}$ is given below:

$$J_{nr\ diff} = \frac{J_{nr,\,3.2\,kPa} - J_{nr,\,0.1\,kPa}}{J_{nr,\,0.1\,kPa}} 100 \leq 75\% \quad (4.5)$$

2.6.3 MSCR Grading

The MSCR grading system can be used to characterize the performance of unmodified and polymer-modified binders. The MSCR grade of a binder is calculated based on the J_{nr} values at 3.2 kPa stress level. In this grading system, the J_{nr} values are used as an indicator of the level of traffic that a binder can sustain at a given temperature. Four traffic levels are considered in the J_{nr}-based grading system, namely Standard (S), Heavy (H), Very Heavy (V) and Extreme (E). For example, at 64 °C, the four MSCR grades are PG 64S-XX (Standard), PG 64H-XX (Heavy), PG 64V-XX (Very Heavy), and PG 64E-XX (Extreme). Table 2.1 presents the MSCR grading of binders according to the AASHTO MP 19 (AASHTO, 2010) provisional specification.

Table 2.1 MSCR grades based on J_{nr} (AASHTO MP 19, 2010)

J_{nr} (kPa^{-1}) criteria	**MSCR Grading**
$2.0 < J_{nr} \leq 4.0$	PG 64S-XX (S: Standard)
$1.0 < J_{nr} \leq 2.0$	PG 64H-XX (H: Heavy)
$0.5 < J_{nr} \leq 1.0$	PG 64V-XX (V: Very Heavy)
$J_{nr} \leq 0.5$	PG 64E- XX (E: Extreme)

2.7 Implementation of MSCR Method

Publications by the Asphalt Institute (AI) have identified the benefits of adopting the MSCR test method over the “PG Plus” tests. For example, the AI published an implementation document for the MSCR test, named “*Implementation of the Multiple Stress Creep Recovery Test and Specification,”* to help the asphalt industry with the implementation of the MSCR test method (AI, 2010). Although the ultimate goal of the AI was the full implementation of this relatively new binder specification, the Asphalt Institute Technical Advisory Committee recognized that many agencies might be uncomfortable in transitioning to a system that uses different grade names (AI, 2010). A number of meetings, presentations and webinars were conducted by the AI, FHWA, and state DOT engineers to facilitate implementation of the MSCR test method (Anderson, 2011; Gierhart, 2011; Anderson, 2012(a); Anderson, 2012(b); Horan, 2012; Karl Zipf, 2014; Anderson 2014; Anderson, 2015; Corun, 2015). A number of inter-laboratory studies were also conducted by the AI to determine the precision of the AASHTO TP 70 (AASHTO, 2013) test method for the Southeastern Asphalt User/Producer Group (SEAUPG) and the North East Asphalt User Producer Group (NEAUPG). The Inter-Laboratory Study (ILS) by NEAUPG to evaluate the repeatability and reproducibility of the AASHTO TP 70 (AASHTO, 2013) test method involved twenty-eight laboratories located in the NEAUPG region. In addition to the 2010 ILS, the NEAUPG also conducted a second ILS involving twenty-eight laboratories from users, producers and industry/academia (Anderson, 2013). In 2011, the SEAUPG conducted a similar study involving twenty-three laboratories located in the SEAUPG region (Anderson, 2012(c)).

The implementation status of the MSCR test method of each state can be found in the AI's interactive database (www.asphaltinstitute.org, 2016). A highlight of the status of implementation in Oklahoma, New Mexico and Texas DOTs is presented below (www.asphaltinstitute.org, 2016):

The Oklahoma Department of Transportation (ODOT) is in the process of full implementation of the MSCR test method for all PG binders. The minimum MSCR %Recovery requirements for PG 70-28 OK, PG 76-28 OK, and PG 76E-28 binders have been set in the specifications. The Texas Department of Transportation (TxDOT) is in the process of setting minimum %Recovery requirements for different binders. The

TxDOT is planning to replace the elastic recovery with the MSCR %Recovery. Currently, the New Mexico Department of Transportation (NMDOT) is testing all binders under the MSCR specification. The NMDOT has been conducting MSCR tests for several years as a part of the Western Co-ops efforts with University of Wisconsin (www.asphaltinstitute.org, 2016).

2.8 Hamburg Wheel Tracking Test

In an attempt to identify the rutting potential of HMA mixes, many transportation agencies have started using Loaded Wheel Testers (LWT) as a supplement to their mix design procedure. It was found that the LWTs allow for an accelerated evaluation of rutting potential of the designed asphalt mixes. Several LWTs are currently being used in the United States, which include the following: Georgia Loaded Wheel Tester, Asphalt Pavement Analyzer (APA), Hamburg Wheel Tracking device (HWT), Laboratoire Central des Ponts et Chausées (French) Wheel Tracker, and Purdue University Laboratory Wheel Tracking Device (PURWheel) (Miller et al., 1995; Choubane et al., 2000; Cooley et al., 2000; Corte, 2001; Kandhal and Cooley, 2002). Results obtained from the wheel tracking devices were found to correlate well with the actual field performance when the loading and environmental conditions of a given location were considered (Miller et al., 1995; Cooley et al., 2000; Kandhal and Cooley, 2002).

The capability of the HWT test to determine the moisture sensitivity of asphalt mixes were evaluated by Lu and Harvey (2006). For this purpose, both laboratory test and field performance data were used on a large scale. Asphalt mixes were prepared using two types of aggregates, two types of binders and three different additive contents. The HWT test was found to overestimate the performance of the asphalt mixes containing the conventional binders and underestimate the performance of mixes containing polymer-modified binders.

Grebenschikov and Prozzi (2011) compared the rut depths obtained from the HWT test with the rut depths from the Mechanistic-Empirical Pavement Design Guide (MEPDG). The results of two types of asphalt mixes (Type C and Type D) from a previous TxDOT project were used for this purpose. Each mix was prepared using three aggregate gradation levels, namely fine, target and coarse and five binder contents. It was found that both the MEPDG and the HWT test ranked the mixes in the same order with respect to rutting.

Walubita et al. (2012) evaluated three laboratory tests, namely the DM test, Repeated Load Permanent Deformation (RLPD) test, and HWT test, for characterizing the permanent deformation response of HMA mixes relative to the field performance under both conventional traffic loading and Accelerated Pavement Testing (APT). It was observed that all three test methods provided consistent results in terms of rutting behavior. Also, the Superpave® mixes generally was found to exhibit higher moduli values with greater rutting resistance potential than the conventional mixes. The HWT test was found to exhibit the best repeatability and the lowest variability in the test results, compared to the DM and RLPD tests. It was suggested to use the HWT test for routine stripping assessment and rutting performance prediction of HMA.

Differences in rutting performance between laboratory and field compacted asphalt mixes were studied by Howard and Doyle (2013) using APA and HWT devices.

A total of 398 field cores and laboratory produced samples were tested in that study. No significant differences were observed between the rut depths of plant produced and laboratory produced mixes determined by APA rut tests. However, the rut depths of plant produced mixes obtained from the HWT test were observed to be higher than that of the laboratory produced mixes. Also, the rutting performance of laboratory produced mixes was found to decrease significantly with a reduction in mixing temperature.

Sel et al. (2014) evaluated the effect of test temperature on the rut depths of asphalt mixes obtained from a HWT test. The Hamburg test database and Aggregate Quality Monitoring Program database of TxDOT were used for this purpose. Statistical analyses of the collected data showed that the binder grade influenced the HWT rut performance of asphalt mixes. Binders with a higher PG grade were found to accumulate less deformation than the binders with a lower PG grade. Significant differences in the performance were observed when the samples were tested at 40° and 50 °C. The average deformation was found to exhibit an increasing trend in rutting with an increase in test temperature.

2.9 X-ray Diffraction (XRD) Analysis of Asphalt Binder

The knowledge of the type of molecular structure and the atomic arrangement present in asphalt is very important for proper characterization of asphalt binders (Halstead, 1984). The chemical composition of asphalt binders varies with the source of crude oil and the refining process. The physical properties of a particular asphalt binder depend on the amount and characteristics of asphaltenes, resins and oils (Halstead, 1984). Asphalt binder is considered a colloidal or a micellar system where the colloids or micelles are dispersed in an oily medium (Nellensteyn, 1928). According to Rostler (1979), the asphaltene fraction stays dispersed in asphalt binder and is responsible for its colloidal behavior. Generally, asphaltene consists of flat sheets of condensed aromatic systems which may be interconnected by sulfide, ether as aliphatic chains or naphthenic ring linkages. Gaps and holes in the aromatic system with heterocyclic atoms coordinated by transition metals such as vanadium (V), nickel (Ni) and iron (Fe) are most likely caused by free radical attack. The flat sheets of aromatic hydrocarbon generally stacked one above another (Yen, 1992).

McNally (2011) reported the use of nuclear magnetic resonance spectroscopy, gel permeation chromatography, ultraviolet spectroscopy and gas chromatography-mass spectrometry among other methods for characterizing the asphalt fraction, as well as the structure of the asphalt binder. However, X-ray Diffraction (XRD) technique has shown potential for determining the molecular structure and crystallite parameters for different materials (Siddiqui et al., 2002). The XRD test has been used to determine the aromaticity and crystallite parameters of petroleum asphaltenes and petroleum resin by several researchers (Yen et al., 1961; Siddiqui et al., 2002). In a study conducted by Yen et al. (1961), different crystallite parameters such as layer diameter, inter-lamellar distance, and the height of the unit cell were calculated and their relationships to different physical and chemical properties were determined. The same analysis technique was also used to determine the aging characteristics of asphalt binders (Siddiqui et al., 2002). Significant differences in crystallite parameters and molecular structure were reported for unaged and aged asphalt binders. It was also reported by Siddiqui et al. (2002) that the major factors affecting the aging behavior were sources and chemistry of the base asphalt binder. The XRD was reported to be an effective tool in evaluating the aging patterns of asphalt binder (Cardoso et al., 2009). It was found that the crystallinity of asphalt binder may increase due to the weather exposed aging. Cardoso et al. (2009) also concluded that the increased viscosity due to aging may be resulted from the increased crystallinity of the asphalt binder. The effect of using different XRD profile fitting functions (Pearson VII, Pseudo-Voigt, etc.) to determine the binder aromaticity and crystallite parameters were also studied by Gebresellasie et al. (2012). A study conducted by Ali et al. (2015) reported semi-crystalline behavior of the asphalt binder in XRD analysis due to polymer modification. In that study, the XRD analysis technique used by other researchers for asphaltenes was adopted to characterize asphalt binders as asphaltenes act as a "bodying" fraction of the asphalt binder. In the present study, XRD technique was applied to characterize the polymer- and poly-phosphoric acid-modified binders. The aging pattern of different types of binders was also investigated using XRD technique.

2.10 Summary

Polymer-modified binders have been reported to exhibit better rutting and fatigue performances in the pavement than the unmodified binders. The MSCR test method was developed by recognizing the limitations of traditional test methods to characterize polymer-modified binders. The current MSCR test method and specification are the results of a large number of laboratory and field investigations. The MSCR test method has been found to be capable of characterizing the rheological properties of binders modified with different types and amounts of polymers. Also, the

MSCR parameters have been found to better reflect field rutting performance than the Superpave® test method parameters. The scarcity and increased cost of the components of asphalt mixes has led to the incorporation of high amounts of RAP in asphalt mixes. The RAP binder blends have been reported to exhibit better rutting resistance than the unmodified binders. Also, the pavement sections with high RAP content have been found to perform well during their service life. Furthermore, the HWT test was reported to be appropriate for evaluating the rutting performance of asphalt mixes. The XRD test has been found to be capable of determining the molecular structure and the atomic arrangement of binders.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Introduction

This chapter presents an overview of the material selection process, test matrices, and performance tests for both asphalt binders and asphalt mixes. The test matrices included testing polymer-modified binders, RAP binder blends and asphalt mixes containing polymer-modified binders and different RAP contents. The major tasks of this study are to: (i) collect unmodified and polymer-modified asphalt binders from different refineries in Oklahoma, New Mexico and Texas; (ii) extract binder from selected RAPs; (iii) prepare asphalt binder samples containing RAP binder; (iv) determine Superpave® performance grade (PG) of unmodified and polymer-modified binders; (v) perform MSCR tests on unmodified and polymer-modified binders and analyze the test results; (vi) collect plant produced asphalt mixes with different RAP contents; and (vii) perform HWT tests on collected mixes and analyze the test results. A flow chart of the work flow pursued for this study is given in Figure 3.1.

3.2 Material Collection and Sample Preparation

3.2.1 Collection of Asphalt Binders

As noted previously, some commonly used asphalt binders in Oklahoma, Texas and New Mexico were evaluated in this study. Asphalt binders were collected from seven different sources; four of these sources were located in Oklahoma, one in New Mexico and two in Texas. Since the main focus of this study was to evaluate the polymer-modified binders, PG 70-XX and PG 76-XX binders were collected from these sources. The type and amount of polymer modification were not shared by the suppliers with the research team. An unmodified asphalt binder, PG 64-22, was also collected from an Oklahoma refinery for blending with the RAP binder. It is important to note that the PG grading system of the asphalt binder represents the maximum high and low temperatures it can sustain. For example, for a PG 64-22 binder, the number 64 indicates that the binder can be used in areas where the maximum seven-day average pavement temperature could be as high as 64 °C. The number -22 means that the binder is capable of withstanding a temperature as low as -22 °C, without experiencing any low-temperature cracking (Brown et al., 2009). Table 3.1 presents the types and locations of the collected binders.

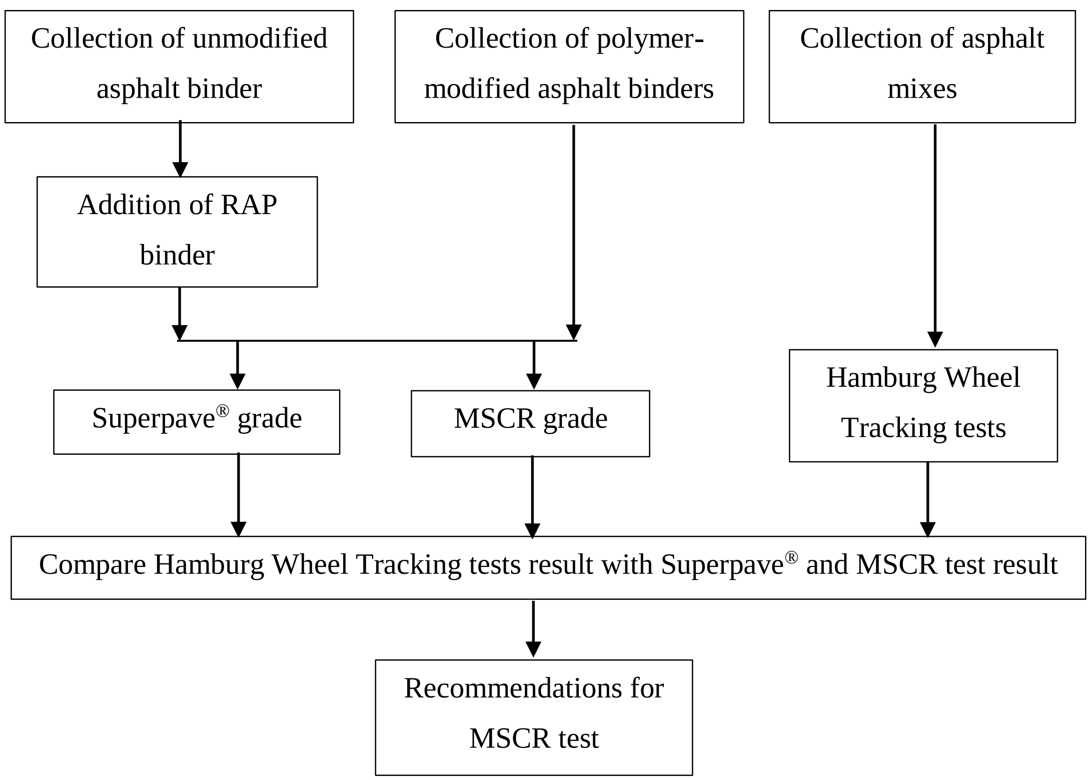


Figure 3.1 Work flow of the present study

Table 3.1 Sources and types of the binders collected for study

Source	Source locations	Binder types
S1	Oklahoma	PG 64-22, PG 70-28, PG 76-28
S2	Oklahoma	PG 70-28, PG 76-28
S3	Oklahoma	PG 70-28, PG 76-28
S4	Oklahoma	PG 76-28
S5	New Mexico	PG 70-28, PG 76-28
S6	Texas	PG 70-28, PG 76-28
S7	Texas	PG 70-22

3.2.2 Extraction of Binder from RAP

Approximately 25 kg of fine RAP was collected from two local suppliers in Oklahoma for extraction of binder. The RAP samples were collected from two sources, namely Silver Star Construction Co., located in Moore, OK and Haskell Lemon Construction Co., located in Norman, OK. For convenience, these materials were designated as RAP1 and RAP2, respectively. The collected RAPs were shipped to Arkansas State University (ASU) for binder extraction. The binder recovery from RAP was performed using a Rotary Evaporator available at the ASU Materials Laboratory in accordance with the AASHTO T 319 (Standard Method of Test for Quantitative Extraction and Recovery of Binder from Asphalt Mixtures) method (AASHTO, 2015). Approximately 320 g of RAP1 and 258 g of RAP2 binders were obtained after extraction. The RAP binders were shipped back to the OU Asphalt Binder Laboratory.

3.2.3 RAP Binder Blends

The RAP binders (RAP1 and RAP2) were blended with the unmodified PG 64-22 binder at four different amounts, namely 0%, 25%, 40% and 60% (by weight of total binder). The blending of the PG 64-22 binder and RAP binders was performed using a hand mixing process. For this purpose, the PG 64-22 binder and the RAP binders were heated to 150 °C for an hour prior to blending. The required amount of RAP binder was then weighed and added to the unmodified binder. The binder blend was mixed for one minute at every 10 minutes for an hour to consistency. For future reference in this study, the 25%, 40% and 60% RAP1 binder blends are defined as PG 64-22-R1-25, PG 64-22-R1-40 and PG 64-22-R1-60 binder, respectively. Similarly, PG 64-22-R2-25, PG 64-22-R2-40 and PG 64-22-R2-60 are used to represent 25%, 40% and 60% RAP2 binder blends, respectively.

3.2.4 Collection of Asphalt Mixes

Asphalt mixes containing polymer-modified binders and different amounts of RAP were selected to evaluate the rutting susceptibility of the asphalt mixes. For this purpose, asphalt mix design sheets required for the production of asphalt mixes were collected from Silver Star Construction Co. After evaluating these mix designs, a total of four asphalt mixes were selected for this study. Table 3.2 presents the properties of the selected asphalt mixes. Since the production of asphalt mixes with high RAP content (e.g., 35% RAP) is not very common in Oklahoma, the asphalt mixes with polymer-modified binder (MIX-1) and 25% RAP (MIX-2) were collected from the aforementioned asphalt plant, but those containing 35% RAP (MIX-3 and MIX-4) were produced in the laboratory. For laboratory produced mixes, asphalt binders, RAP and aggregates were collected from the same plant to maintain consistency.

Table 3.2 Properties of selected asphalt mixes

Asphalt plant	**Mix ID**	**Mix type**	**Nominal maximum aggregate size NMAS (mm)**	**Binder type**	**RAP content (%)**
Silver Star Construction Co. (Moore, OK)	MIX-1	S4	12.5	PG 76-28	0%
	MIX-2	S3	19	PG 64-22	25%
	MIX-3	S3	19	PG 64-22	35%
	MIX-4	S4	12.5	PG 64-22	35%

3.3 Laboratory Testing

3.3.1 Superpave® Grading of Asphalt Binders

The polymer-modified binders and the RAP binder blends were evaluated using the Superpave® grading system. The Superpave® test methods consist of conducting DSR tests, Rotational Viscometer (RV) test, and Bending Beam Rheometer (BBR) test, in accordance with AASHTO M 320 (AASHTO, 2010). The test matrix used for this purpose is presented in Table 3.3.

3.3.2 Short-term and Long-term Aging of Asphalt Binders

The short-term aging of the asphalt binders was simulated in the laboratory by conducting Rolling Thin Film Oven (RTFO) tests according to the AASHTO T 240 (AASHTO, 2013) test method (Standard Method of Test for Effect of Heat and Air on a Moving Film of Binder). The RTFO-aging simulates the oxidation and aging of asphalt binders during mixing in the asphalt plant and compacting in the field. During RTFO-aging, the oven temperature was kept constant at 163 °C and the air flow rate was maintained at 4 liters/minutes for 85 minutes.

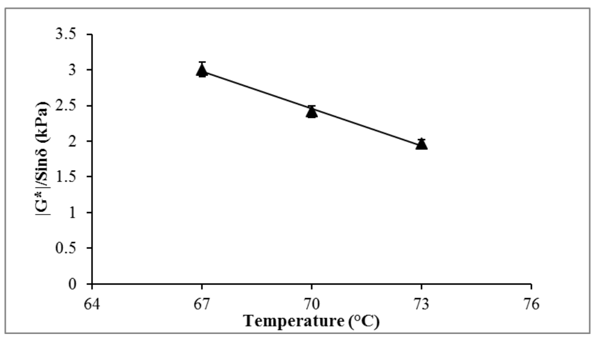
Table 3.3 Test matrix for Superpave® tests

Test name and designation	**Test conditions**	**Binders from Oklahoma**			**Binders from outside of Oklahoma**	
		PG 64-XX from (S1)	**PG 70-XX from (S1, S2, S3)**	**PG 76-XX from (S1, S2, S3, S4)**	**PG 70-XX from (S5, S6, S7)**	**PG 76-XX from (S5, S6)**
RAP blending		RAP1 and RAP2 (25%, 40% and 60%)	No	No	No	No
Superpave® grade: AASHTO M 320		Yes	Yes	Yes	Yes	Yes
RV: AASHTO T 316	Unaged	From 135 °C to 180 °C @ 15 °C				
DSR: AASHTO T 315	Unaged RTFO-aged	@61 °C, 64 °C, 67 °C	@ 67 °C, 70 °C, 73 °C	@73 °C, 76 °C, 79 °C	@ 67 °C, 70 °C, 73 °C	@73 °C, 76 °C, 79 °C
DSR: AASHTO T 315	PAV-aged	@ 19 °C, 22 °C, 25 °C	@ 25 °C, 28 °C, 31 °C	@25 °C, 28 °C, 31 °C	@ 25 °C, 28 °C, 31 °C	@25 °C, 28 °C, 31 °C
RTFO: AASHTO T 240		Yes	Yes	Yes	Yes	Yes
PAV: AASHTO R 28		Yes	Yes	Yes	Yes	Yes
BBR: AASHTO T 313	PAV-aged	@ -9 °C, -12 °C	@ -18 °C, -21 °C	@ -18 °C, -21 °C	@ -18 °C, -21 °C	@ -18 °C, -21 °C

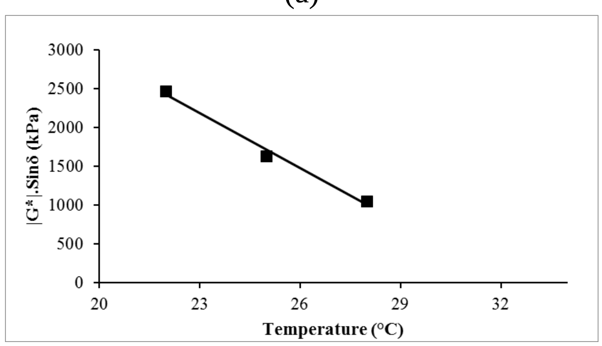
The AASHTO R 28 (AASHTO, 2012) (Standard Practice for Accelerated Aging of Binder Using a Pressurized Aging Vessel) was followed to simulate long-term aging of asphalt binders in the field using a Pressure Aging Vessel (PAV). This aging is intended to simulate 5 to 10 years of service life in the field. The PAV-aging was conducted on binder residues obtained from the AASHTO T 240 (AASHTO, 2013) (RTFO) test method. The RTFO-aged binder samples were placed in stainless steel pans and were aged in a pre-heated vessel at 100 °C for 20 hours under an air pressure of 2.10 MPa.

3.3.3 Dynamic Shear Rheometer (DSR) Test

The DSR test was conducted in accordance with the AASHTO T 315 (AASHTO, 2012) (Standard Method of Test for Determination of Rutting and Fatigue Factors Using a Dynamic Shear Rheometer) test method. The DSR test was conducted in a thermally-controlled test chamber with a temperature tolerance of ±0.1 °C. It is an oscillatory test which is conducted at a loading frequency of 10 rad/s (AASHTO T 315, 2012). For this purpose, unaged and RTFO-aged binder samples were prepared by using a silicon rubber mold having a diameter of 19 mm and a thickness of 1.5 mm. A mold with 8 mm diameter and 3 mm thickness was used to prepare PAV-aged binder samples for DSR testing. The unaged and RTFO-aged samples were tested using 25 mm diameter parallel plates with 1 mm gap, while PAV-aged samples were tested using 8 mm diameter parallel plates with 2 mm gap. The DSR tests on unaged and RTFO-aged binders were conducted under three different temperatures, namely performance grade (PG), PG+3°, and PG-3 °C. The PAV-aged samples were tested under three different temperatures, namely intermediate PG, intermediate PG+3°, and intermediate PG-3 °C. The shear modulus (|G*|) and phase angle (δ) were calculated using the software supplied by the instrument manufacturer. The rutting parameter (|G*|/sinδ) of unaged and RTFO-aged binders at high temperatures were determined. In addition, the fatigue parameter (|G*|.sinδ) for PAV-aged binders at intermediate temperatures were determined as well. Generally, a higher value of |G*|/sinδ is an indication of higher rutting resistance and a higher |G*|.sinδ value is an indicator of lower fatigue resistance (Bahia, and Anderson, 1995). The lowest temperature corresponding to a |G*|/sinδ value of 1.0 kPa for unaged or 2.20 kPa for RTFO-aged binders was considered as the continuous high PG temperature for the tested asphalt binders (AASHTO M 320, 2010). Figure 3.2 presents typical plots of DSR test results.



(a)



(b)

Figure 3.2 Typical plots from DSR tests on asphalt binder samples: (a) |G*|/sinδ vs temperature; (b) |G*|.sinδ vs temperature

3.3.4 Rotational Viscosity (RV) Test

The Rotational Viscosity (RV) tests were conducted on unaged asphalt binders using a Brookfield Rotational Viscometer. The AASHTO T 316 (AASHTO, 2013) (Standard Method of Test for Viscosity Determination of Binder Using Rotational Viscometer) test method was followed to conduct the RV tests. The workability of the asphalt binders during mixing and compaction in the field was evaluated using this test method. Approximately 10 g of asphalt binder sample is needed for conducting a RV test. For this purpose, a standard cylindrical spindle was submerged in the liquid asphalt binder and was rotated at a constant speed of 20 revolutions/minute (rpm). The torque required for the spindle to maintain a constant rotational speed of 20 rpm was measured and reported as the rotational viscosity. In this study, the rotational viscosities of the binders were determined at 135°, 150°, 165° and 180 °C. Figure 3.3 presents a typical plot of RV test results.

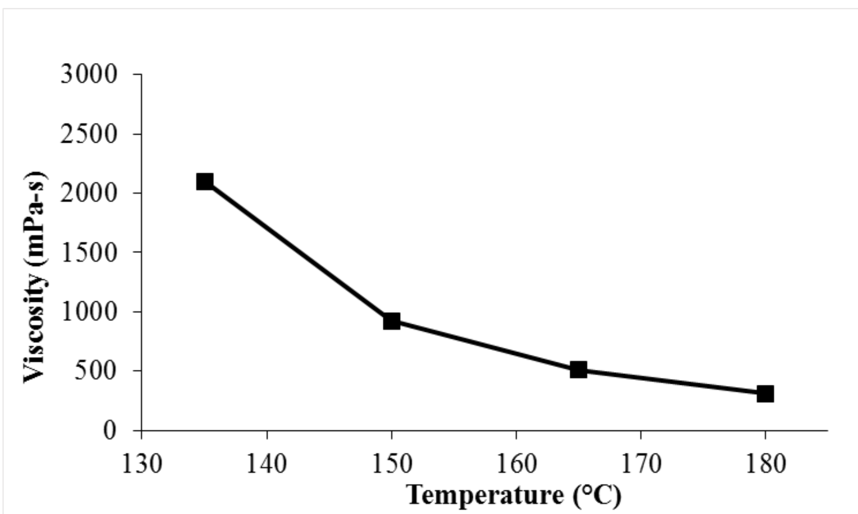
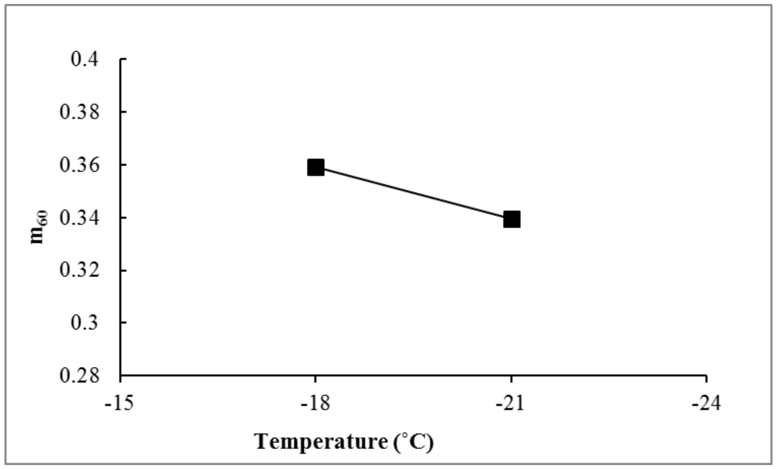


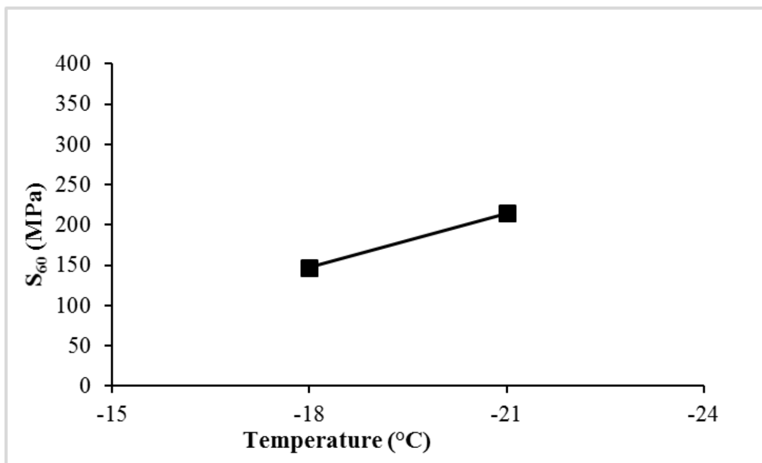
Figure 3.3 A typical plot of the RV test conducted on asphalt binder sample

3.3.5 Bending Beam Rheometer (BBR) Test

The AASHTO T 313 (AASHTO, 2013) (Standard Method of Test for Determining the Flexural Creep Stiffness of Binder Using the Bending Beam Rheometer) test method was followed to conduct the BBR test on asphalt binders. The BBR test was performed on the PAV-aged asphalt binders to determine their resistance to thermal cracking at low temperature. An Asphalt beam sample having a length of 127 mm, width 12.7 mm, and thickness 6.35 mm was prepared for this test. The sample was subjected to a constant load of 980 ± 50 mN applied at the mid-span of the beam for 240 seconds. The stiffness, S_{60} (maximum bending stress divided by the maximum strain), and the rate of stress relaxation, m_{60} (slope of stiffness versus time), were calculated for specified loading times (t) of 8, 15, 30, 60, 120, and 240 seconds. The values of the stiffness and the rate of stress relaxation at t = 60 seconds were used to quantify the thermal cracking resistance of the binders. The continuous low-temperature PG grade of the binders were determined based on the results from the BBR tests, following the Superpave® specifications (AASHTO M 320, 2010). The highest temperature corresponding to an m_{60} of 0.30 or a S_{60} of 300MPa was reported as the low temperature PG grade. Figure 3.4 presents typical plots of BBR test on asphalt binder.



(a)



(b)

Figure 3.4 Typical plots from BBR test on asphalt binder sample: (a) m_{60} vs temperature: (b) S_{60} vs temperature

3.3.6 Multiple Stress Creep and Recovery (MSCR) Test

The MSCR tests were conducted on asphalt binders, following both "conventional" and "non-conventional" procedures. The "conventional" method refers to the MSCR test performed using the AASHTO TP 70 procedure (AASHTO, 2013) (Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Binder Using a Dynamic Shear Rheometer) at a high environmental temperature. The high environmental temperature of Oklahoma (64 °C), as noted by Hossain et al. (2015), was used in this study.

The "non-conventional" MSCR test method refers to conducting the MSCR tests at a higher stress level (10 kPa) and at high temperatures (70° and 76 °C) to characterize the non-linear viscoelastic properties of polymer-modified binders and RAP binder blends (Gollalipour, 2011). Each stress level consists of ten loading-unloading cycles. Each cycle consists of a one-second creep loading and a nine-second recovery period. The non-recoverable creep compliance (J_{nr}) and the %Recovery were calculated from the MSCR test results. Figure 3.5 shows a typical plot of MSCR test conducted on asphalt binder. The test matrix for MSCR test followed in this study is presented in Table 3.4. The MSCR parameters of the binders were determined using both conventional and non-conventional MSCR test methods.

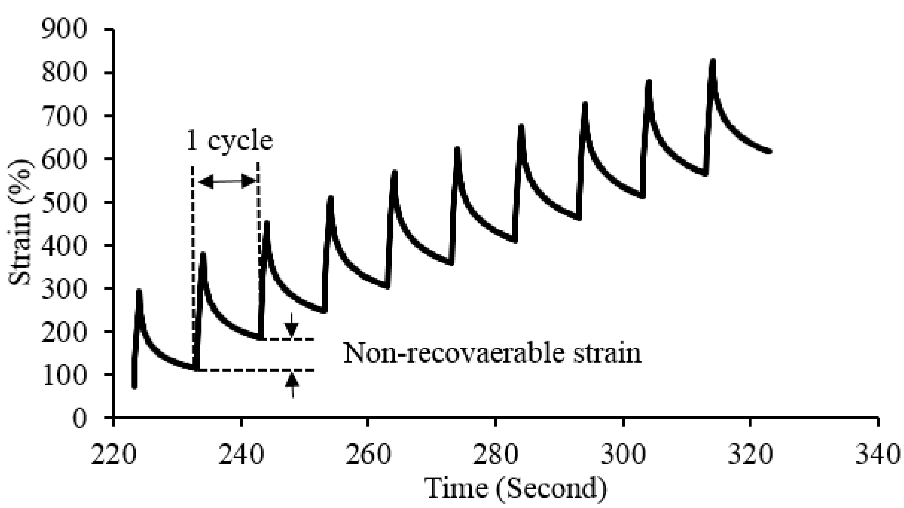


Figure 3.5 Example of stress response of a binder in MSCR test

Table 3.4 Test matrix for MSCR test

Test name and designation	Test conditions	Binders from Oklahoma			Binders from outside Oklahoma	
		PG 64-XX from (S1)	**PG 70-XX from (S1, S2, S3)**	**PG 76-XX from (S1, S2, S3, S4)**	**PG 70-XX from (S5, S6, S7)**	**PG 76-XX from (S5, S6)**
MSCR: conventional AASHTO TP 70 (AASHTO, 2013)	RTFO-aged	0.1 kPa and 3.2 kPa @ 64 °C				
MSCR: Non-conventional	RTFO-aged	10 kPa @ 64 °C, 70 °C and 76 °C 0.1 kPa, 3.2 kPa @ 70 °C,76 °C				

3.3.7 Hamburg Wheel Tracking (HWT) Test

The HWT tests were conducted on samples of asphalt mixes collected and produced for this study, in accordance with the AASHTO T 324 (AASHTO, 2014), to determine their rutting susceptibility and moisture-induced damage potential. Samples for the HWT test were prepared in the laboratory by using a Superpave® gyratory compactor. The diameter and height of the compacted samples were 150 mm and 60 mm, respectively. The bulk specific gravity values (G_{mb}) of the compacted cylindrical samples were determined in accordance with the AASHTO T 269 (Standard Method of Test for Percent Air Voids in Compacted Dense and Open Asphalt Mixtures) test method (AASHTO, 2014). The compacted samples with an air void of 7 ± 0.5% were selected for conducting HWT tests. In this method, two cylindrical samples were cut to a desired shape to place them in the plastic molds and mounting tray. The mounting tray was then placed in the HWT machine for testing. In this study, the HWT tests were conducted at 50 °C with a wheel pass frequency of 52 passes/minute and a wheel load of 705 N. The average linear speed of the wheel was approximately 1.1 km/h and traveling approximately 230 mm (9.05 in.) before reversing the movement direction. The test was automatically terminated after reaching a maximum rut depth of 20 mm or 20,000 wheel passes, whichever reached first. Deformations were measured along the length of the wheel path at 11 equally-spaced points. The rut depth at the mid-point of the sample was considered for further analysis. From the HWT test result, the post-compaction consolidation, creep slope, stripping slope, and stripping inflection point were determined. Figure 3.6 shows a typical plot of a HWT test. Important parameters such as the post-compaction consolidation, creep slope, stripping slope and stripping inflection point are noted in Figure 3.6. Table 3.5 presents the test matrix for the HWT test. Two sets of samples were tested for each mix type to ensure repeatability.

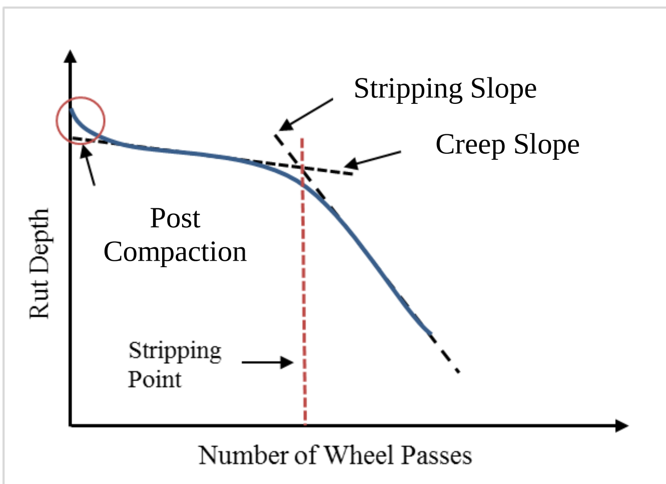


Figure 3.6 A typical plot of HWT rut depths vs. number of wheel passes (After www.pavemetinteractive.com)

Table 3.5 HWT test matrix

Mix ID	Mix type	Binder type	RAP content (%)	Sample dimensions	No. of samples	Test temperature (°C)	Failure criteria
MIX-1	S4	PG 76-28	0%	Diameter: 150 mm Height: 60 mm	2	50	Max. rut depth 20 mm or 20,000 wheel passes
MIX-2	S3	PG 64-22	25%		2	50	
MIX-3	S3	PG 64-22	35%		2	50	
MIX-4	S4	PG 64-22	35%		2	50	

3.3.8 X-ray Diffraction (XRD) Test

The XRD technique has been used by several researchers to characterize properties and molecular structure of asphalt binders (Yen et al., 1961; Siddiqui et al., 2002). In the present study, the molecular structure, aromatic and crystalline properties of an unmodified, a polymer- and a poly-phosphoric acid-modified binders were determined using the XRD technique. The specific objectives of the XRD analyses were to evaluate the effects of short-term and long-term aging on the molecular structure and rheological properties of unmodified, polymer- and poly-phosphoric acid-modified binders. For this purpose, two types of asphalt binders, namely PG 58-28 (a non-modified binder), PG 76-28 (a polymer-modified binder), and a 105% poly-phosphoric acid-modified asphalt binders were tested in an XRD. Asphalt binders and 105% PPA were collected from local suppliers in Oklahoma. The 105% PPA was added by mixing 2% PPA (by weight of asphalt binder) with the asphalt binder using a high shear mixer at a speed of 550 rpm for 1 hour at 155 °C. For this purpose, the PG 58-28 asphalt binder was heated in an oven to 155 °C. Then the PPA was weighed and added to asphalt binder and mixed in the shear mixer.

The XRD samples were prepared by putting a thin deposit of asphalt binder onto glass slides and cooled under room temperature. A total of nine samples of unmodified, polymer- and poly-phosphoric acid-modified binders, under three aging conditions (unaged, RTFO-aged and PAV-aged), were prepared and tested using the XRD method. Figure 3.7 presents an asphalt binder sample prepared for the XRD testing. The XRD tests were conducted using a Rigaku Ultima IV diffractometer by applying monochromatic Cu-Kα radiation (40 kV and 44 mA). The scan range (2θ) varied between 2° and 70° at a scan rate of 0.002° (2θ) per second and detector count time of 2 seconds/step. The XRD spectra were then analyzed using the MDI Jade 2010 software suite. The profile fitting for the XRD spectra was performed using the Pearson VII (fixed background) model. The peaks, 2θ, area of the peaks and full width at half-maximum (FWHM) were determined from the XRD profile fitted curve.

Figure 3.7 Asphalt binder sample for XRD test

The typical XRD patterns and different crystallite parameters of binders are illustrated in Figures 3.8 and 3.9. The aromaticity (f_a) and crystallite parameters of the binders were calculated using Equations (3.1) to (3.5), as noted below (Siddiqui et al., 2002).

$$f_a = \frac{A(\text{graphene})}{A(\text{graphene}) + A(\gamma)} \tag{3.1}$$

where, A is the area under the corresponding peaks. The f_a is not a true representation of the aromaticity as it does not include all the aromatic carbon of binder.

The layer distance, d_m, between aromatic sheets is given by

$$d_m = \frac{\lambda}{2 \sin\theta} \tag{3.2}$$

where,

λ = the wavelength of the Cu Kα radiation, and

θ = Bragg angle of graphene band.

The inter-chain layer distance, d_γ, is given by

$$d_\gamma = \frac{5\lambda}{8 \sin\theta} \tag{3.3}$$

where,

θ = Bragg angle of γ band.

The average height of the stack of aromatic sheets perpendicular to the plane of the sheet is obtained from Equation (3.4):

$$L_c = \frac{0.45}{B_{1/2}} \tag{3.4}$$

where,

$B_{1/2}$ = Full width of the graphene band at half maximum.

The number of aromatic sheet in a stack cluster is given by Equation (3.5):

$$M=\left(\frac{L_c}{d_m}\right)+1 \tag{3.5}$$

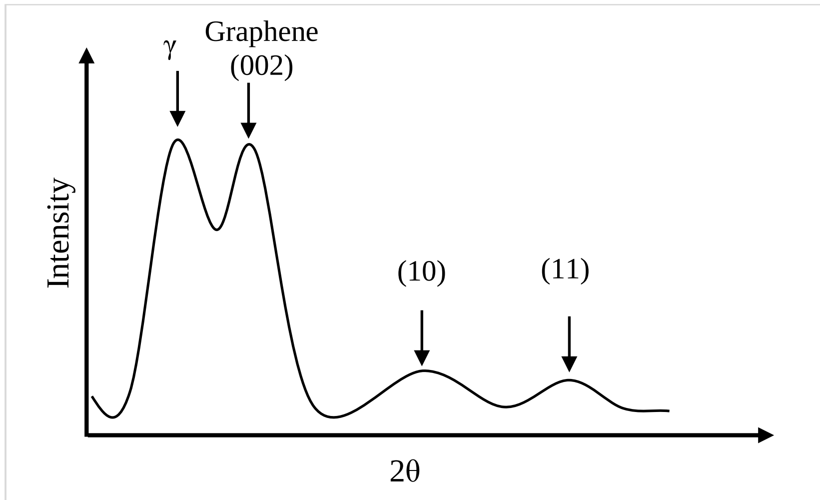


Figure 3.8 Schematic XRD pattern (after Siddiqui et al., 2002)

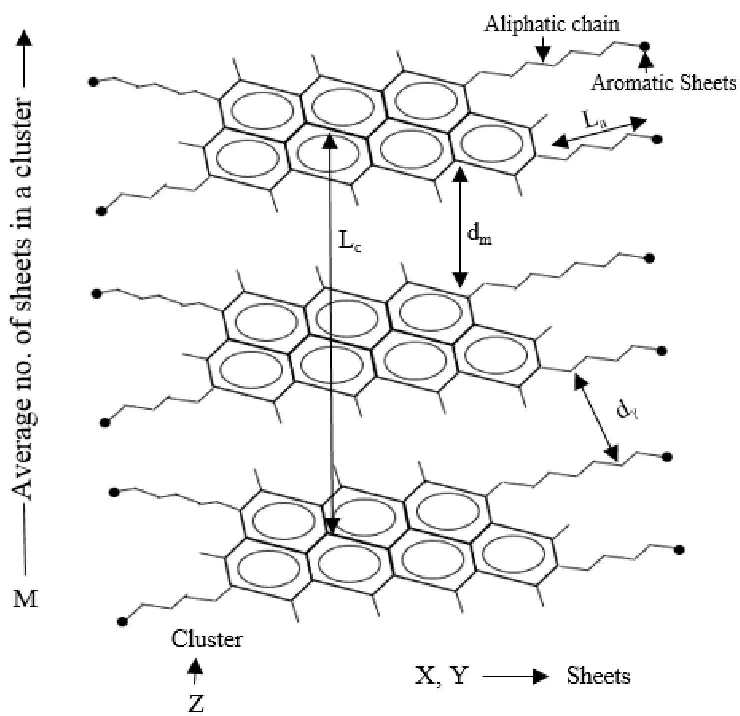


Figure 3.9 Different crystallite parameters from cross section of asphaltene model (after Siddiqui et al., 2002)

3.4 Comparative Analysis of the Superpave®, MSCR and HWT Test Results

In order to compare the results of the Superpave® and MSCR tests for evaluating the rutting resistance of an asphalt mix, the HWT rut results were used as a benchmark of the rutting performance. For this purpose, the $|G^*|/\sin\delta$ parameter obtained from the DSR test and the J_{nr} parameter obtained from the MSCR tests conducted under different temperatures and different stress levels were used for the comparative analyses. An attempt was made to find out a parameter that best predict the rutting performance of the asphalt mixes. Also, a one-to-one comparative assessment of the DSR and MSCR test methods was conducted in this study. Some testing aspects such as test repeatability, variability of results, and advantages and limitations of the test methods were also assessed.

CHAPTER FOUR: TEST RESULTS OF ASPHALT BINDERS

4.1 Introduction

This chapter presents the Superpave® and MSCR test results conducted on polymer-modified binders and RAP binder blends. A comprehensive analysis of the Superpave® and MSCR test results is also presented. Furthermore, the suitability of both methods for characterizing the polymer-modified binders and RAP binder blends was evaluated.

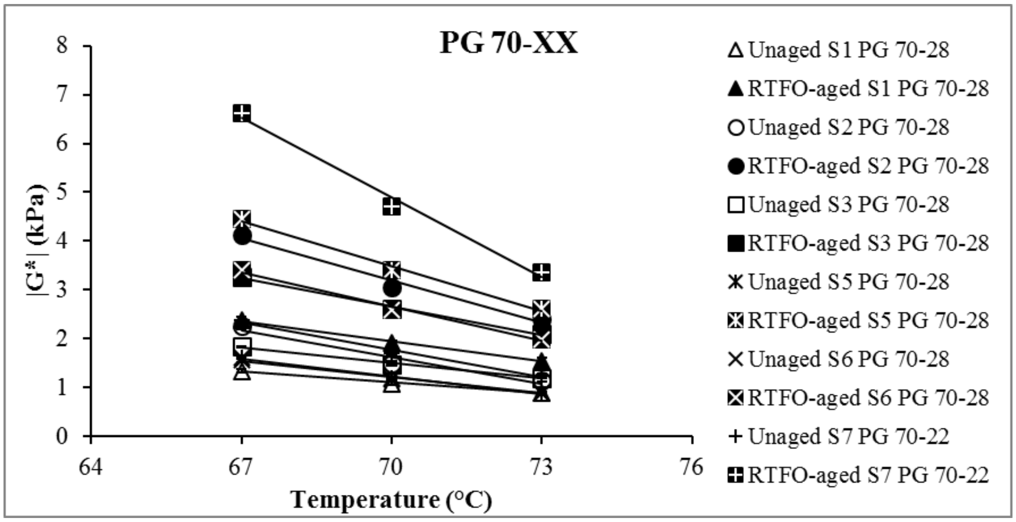
4.2 Superpave® Test Results

4.2.1 Polymer-modified Asphalt Binders

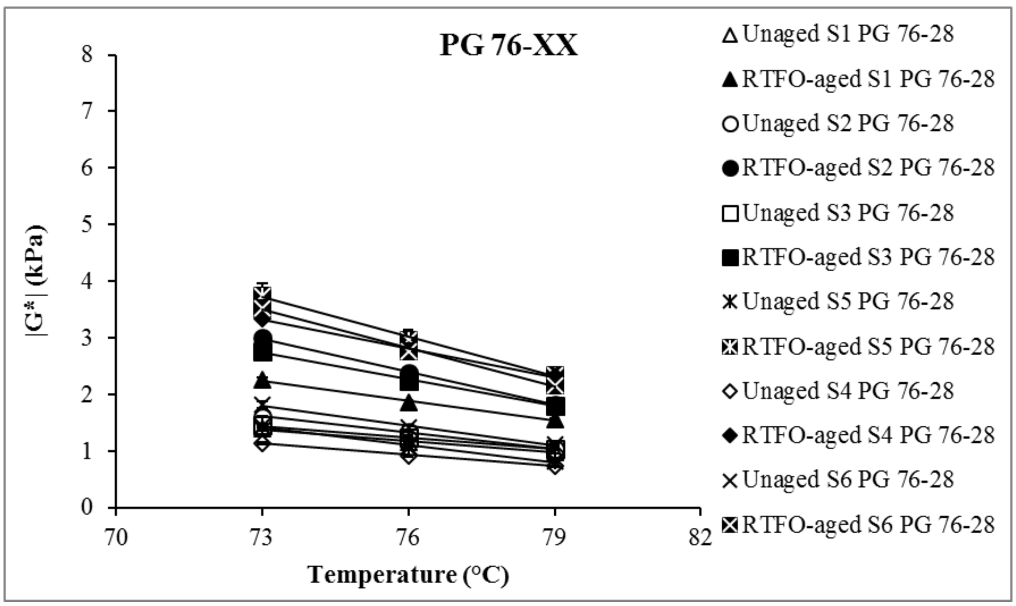
4.2.1.1 DSR test results

Figures 4.1 (a) and 4.1 (b) present the variation of |G*| values of the polymer-modified PG 70-XX and PG 76-XX binders, respectively, at different temperatures. The DSR test on unaged and RTFO-aged binders were conducted at their corresponding high performance grade (PG), PG+3° and PG–3 °C temperatures. From Figures 4.1 (a) and 4.1 (b), it was observed that the |G*| values decreased with an increase in temperature for all aging conditions and binder types. For example, the |G*| value of the unaged S1 PG 70-28 binder was found to be 1.34 kPa at 67 °C, where S1 indicates Source 1. The |G*| values for the same binder were 1.08 kPa (19% reduction) and 0.89 kPa (34% reduction) at 70 °C and 73 °C, respectively. In the case of the PG 76-XX binders, a similar trend of reducing |G*| with increasing temperature was observed. Also, the RTFO-aged binders exhibited a similar reducing trend of |G*| with temperatures although the |G*| values measured for the RTFO-aged binders were found to be higher than unaged binders, as expected. The |G*| value of the RTFO-aged S1 PG 70-28 binder was found to increase by approximately 91% of that for the unaged binder at high PG temperature (70 °C). Therefore, it can be concluded that the shear modulus as well as the stiffness of the asphalt binder are expected to increase with aging. Furthermore, the |G*| values for the PG 70-XX binders were found to vary from 1.08 to 1.70 kPa under unaged condition and from 1.91 to 4.72 kPa under RTFO-aged condition at high PG temperature (70 °C). The S7 PG 70-22 binder, where S7 indicates Source 7, was found to exhibit the highest |G*| values under both unaged and RTFO-aged conditions among all of the PG 70-XX binders. For the PG 76-XX binders, the |G*| values varied from 0.92 to 1.42 kPa under unaged conditions and from 1.86 to 2.97 kPa under RTFO-aged conditions at 76 °C.

As shown in Figures 4.2 (a) and 4.2 (b), the phase angles of the PG 70-XX and PG 76-XX binders, respectively, were found to increase with an increase in temperature. The phase angles measured for the unaged S1 PG 70-28 at 67°, 70° and 73 °C were found to be 54.83°, 54.87° and 54.90°. However, the level of increase was not the same for all binders. Also, from Figures 4.2 (a) and 4.2 (b), the phase angles of the PG 70-XX and PG 76-XX binders were found to reduce with aging. For example, the phase angle measured for the RTFO-aged S1 PG 70-28 binder was found to be 52.03° at 70 °C, which is 5% lower than that of the unaged S1 PG 70-28 binder at the same temperature. Thus, it can be concluded that, asphalt binders become stiffer with aging, as reported by other researchers (Lu and Isacsson, 1997; Tarefder and Yousefi, 2015).



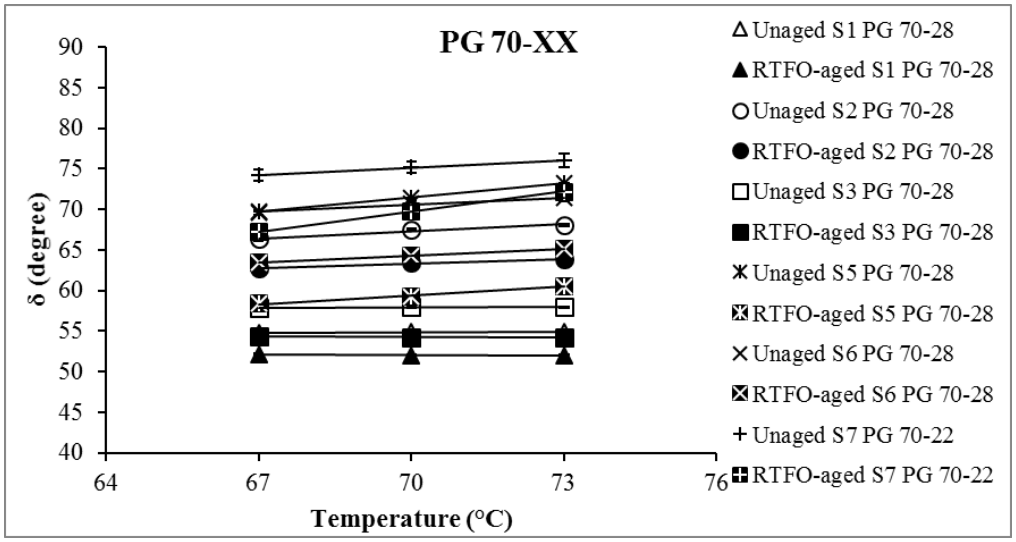
(a)



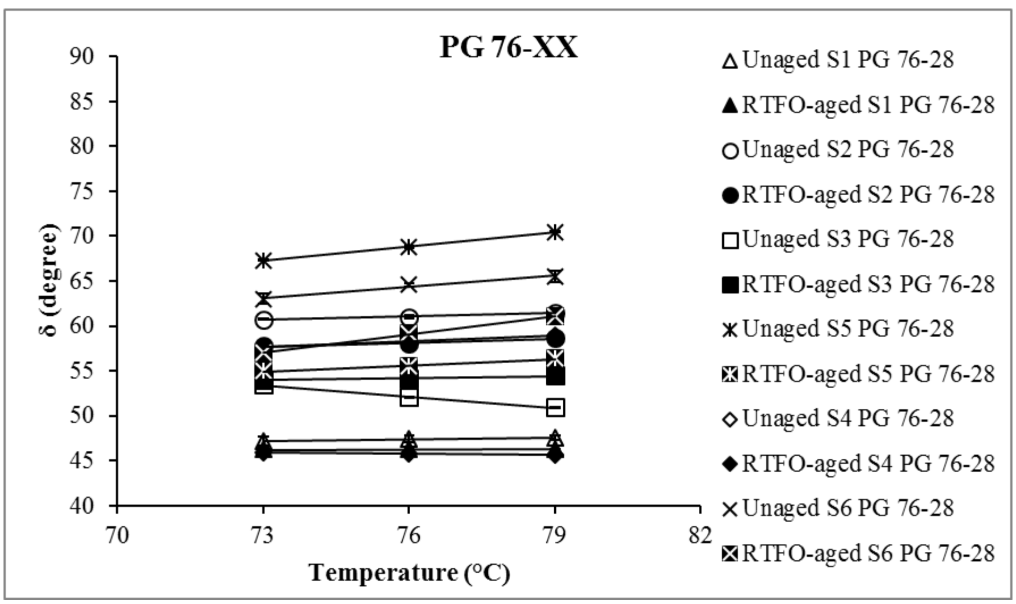
(b)

Figure 4.1 Variation of |G*| with temperature for unaged and RTFO-aged conditions: (a) PG 70-XX binders; (b) PG 76-XX binders

The phase angles of the PG 70-XX binders were found to vary from 54.87° to 75.20° under unaged conditions, and from 52.03° to 69.73° under RTFO-aged conditions at a high PG temperature (70 °C). The S7 PG 70-22 binder was found to exhibit the highest and the S1 PG 70-28 binder exhibited the lowest phase angle values among all of the tested PG 70-XX binders under both aging conditions. For the PG 76-XX binders at 76 °C, the phase angle values were observed to vary from 47.47° to 68.83° under unaged conditions and from 45.17° to 59.17° under RTFO-aged conditions.



(a)

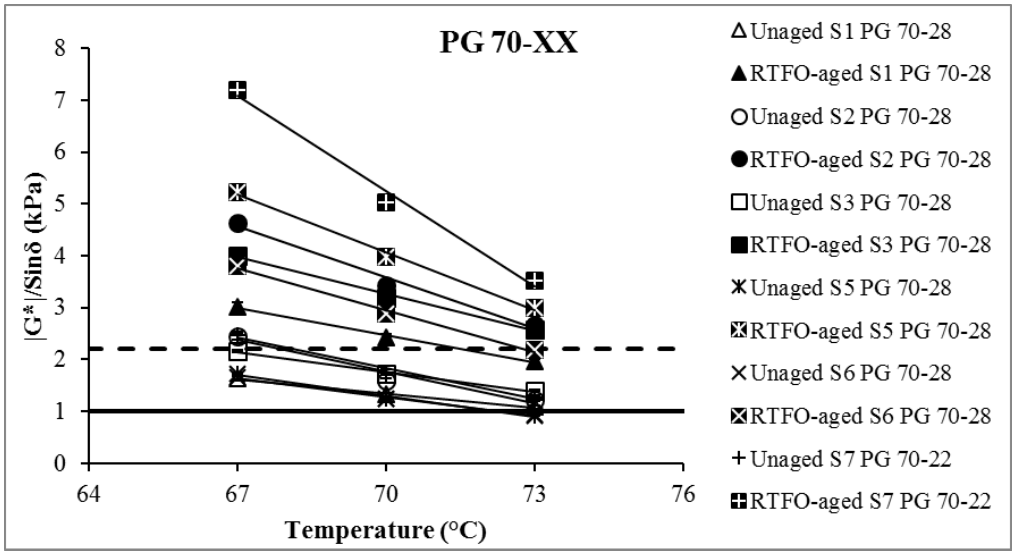


(b)

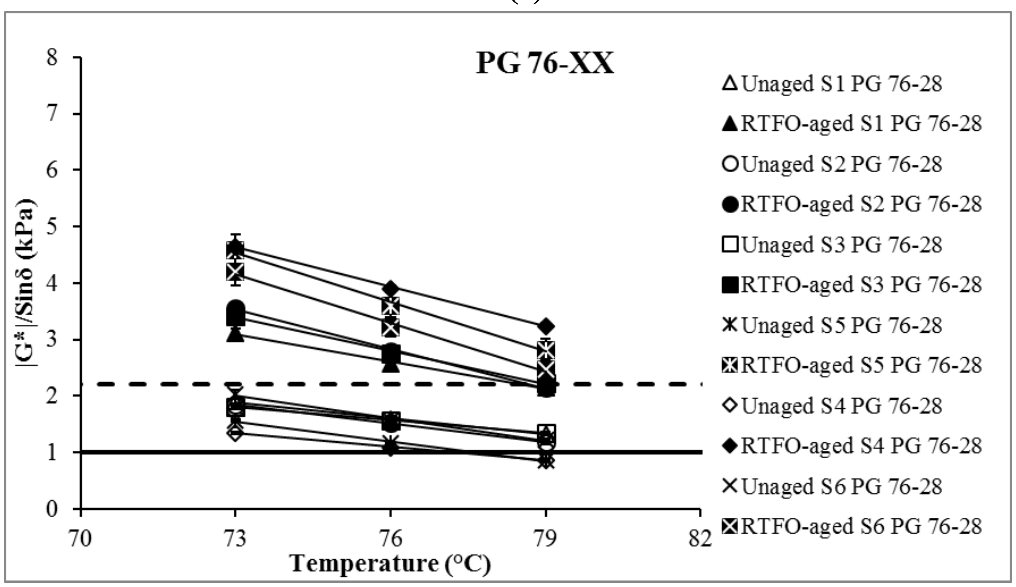
Figure 4.2 Variation of phase angle with temperature for unaged and RTFO-aged conditions: (a) PG 70-XX binders; (b) PG 76-XX binders

Figures 4.3 (a) and 4.3 (b) present the variations of rutting parameters for the PG 70-XX and PG 76-XX binders at their corresponding high PG, PG+3° and PG-3 °C temperatures, respectively. It was observed that the |G*|/sinδ value decreased with an increase in testing temperature for all aging conditions and binder types. From Figures 4.3 (a), the |G*|/sinδ values of the unaged S1 PG 70-28 binder at 67 °C was found to be 1.63 kPa. However, the |G*|/sinδ values were 1.32 kPa (19% reduction) and 1.08 kPa (38% reduction) at 70° and 73 °C temperatures, respectively. Generally, a higher value of |G*|/sinδ is an indicator of a higher rutting resistance (Bahia, and Anderson, 1995). According to the Superpave® binder specifications, the |G*|/sinδ values of the binder under unaged and RTFO-aged conditions should be greater than 1.0 and 2.2 kPa at high PG temperature, respectively. All tested binders were found to meet these Superpave® specifications requirements under unaged and RTFO-aged conditions. The |G*|/sinδ values for the unaged PG 70-XX binders were found to vary from 1.24 to 1.76 kPa. For the same binders (PG 70-XX) under RTFO-aged condition, the |G*|/sinδ values varied from 2.42 to 5.03 kPa at high PG temperature (70 °C). The S7 PG 70-22 binder was found to exhibit the highest and the S1 PG 70-28 binder showed the lowest |G*|/sinδ values under RTFO-aged condition, among all of the tested PG 70-XX binders. Also, all of the polymer-modified PG 76-XX binders were found to meet the Superpave® specifications requirement of rutting parameter at high PG temperature. For the PG 76-XX binders at 76 °C, the |G*|/sinδ values were found to vary from 1.08 to 1.58 kPa under unaged condition and from 2.57 to 3.90 kPa under RTFO-aged condition. Among all of the PG 76-XX binders tested in this study, the S4 PG 76-28 binder was found to exhibit the highest and the S1 PG 76-28 binder exhibited the lowest |G*|/sinδ values under RTFO-aged condition. Therefore, the polymer-modified S7 PG 70-22 and S4 PG 76-28 binders, are expected to exhibit relatively better rutting resistance than the PG 70-XX and PG 76-XX binders, respectively, when used in a mix. An improvement in the rutting resistance of polymer-modified binders was also reported by others (e.g., Lu and Isacsson, 1997; Elseifi et al. (2003); DuBois et al. (2014); Xiao et al. (2014); Domingos and Faxina, 2016). According to Airey (2003), the rheological characteristics of the polymer-modified binders are functions of the combined effects of the composition of the binder and polymer and the amount of polymer used in the binder. It was also observed that the binders modified with highly elastomeric polymer, such as SBS exhibited a better rutting performance at high temperatures due to the formation of a continuous polymer network when dissolved/dispersed in the binder (Lu and Isacsson, 1997; Airey, 2003).

Figures 4.4 (a) and 4.4 (b) present the variation of fatigue parameter (|G*|.sinδ) with temperature for the PAV-aged PG 70-XX and PG 76-XX binders, respectively. A lower value of fatigue parameter is an indicator of a higher fatigue resistance (Bahia and Anderson, 1995). The Superpave® binder specifications require that the |G*|/sinδ value of the PAV-aged binders be less than 5,000 kPa at intermediate PG temperature. From Figures 4.4 (a) and 4.4 (b), the |G*|.sinδ values were found to decrease with an increase in temperature. For example, from Figure 4.4 (a), the average |G*|.sinδ for the S1 PG 70-28 binder at 22 °C was observed as 2,330 kPa. However, at 25 °C and 28 °C, the average |G*|.sinδ values were 1,743 kPa (25% reduction) and 1,123 kPa (52% reduction), respectively. Also, the |G*|.sinδ values for the PG 70-28 binders collected from S1, S2, S3, S4, S5, and S6 sources were found to vary between 1,217 and 1,900 kPa at 25 °C. The |G*|.sinδ values for the S7 PG 70-22 binder was measured as 2,370 kPa at 28 °C.



(a)

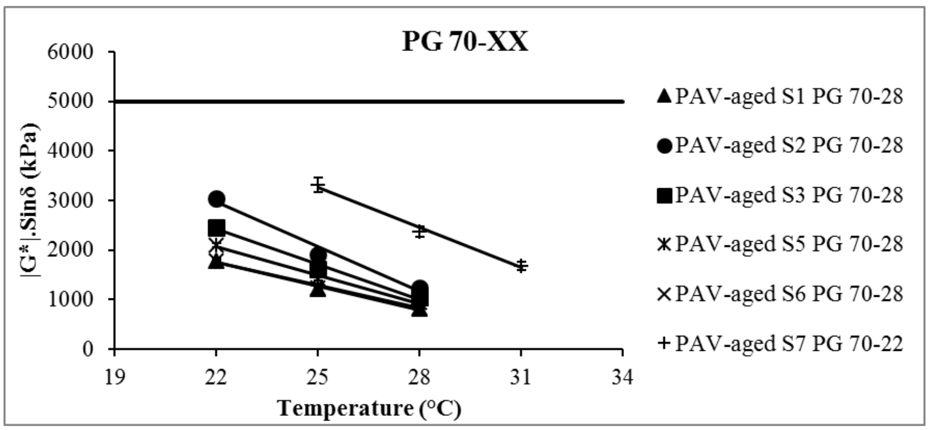


(b)

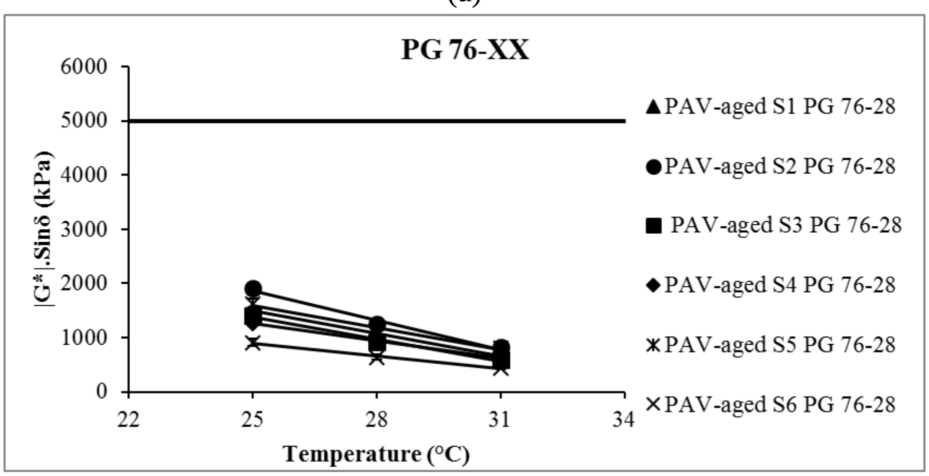
Figure 4.3 Variation of |G*|/sinδ with temperature for unaged and RTFO-aged conditions: (a) PG 70-XX binders; (b) PG 76-XX binders

Therefore, the S7 PG 70-22 binder was found to exhibit the highest and the S1 PG 70-28 binder was found to show the lowest |G*|.sinδ values among all of the PG 70-

XX binders at their corresponding intermediate temperatures. This indicates that the S1 PG 70-28 binder is expected to have a better fatigue performance than the other PG 70-XX binders. Also, the |G*|.sinδ value of the PG 76-XX binders were found to vary from 910 to 1,250 kPa at 28 °C. Among the tested PG 70-XX binders, the S4 PG 76-28 binder was found to exhibit the lowest |G*|/sinδ value at intermediate temperature. The results indicate that the S4 PG 76-28 binder is expected to provide a better fatigue resistance when used in a mix. All the PG 70-XX and 76-XX binders were found to satisfy the Superpave® specifications requirement of the fatigue parameter.



(a)

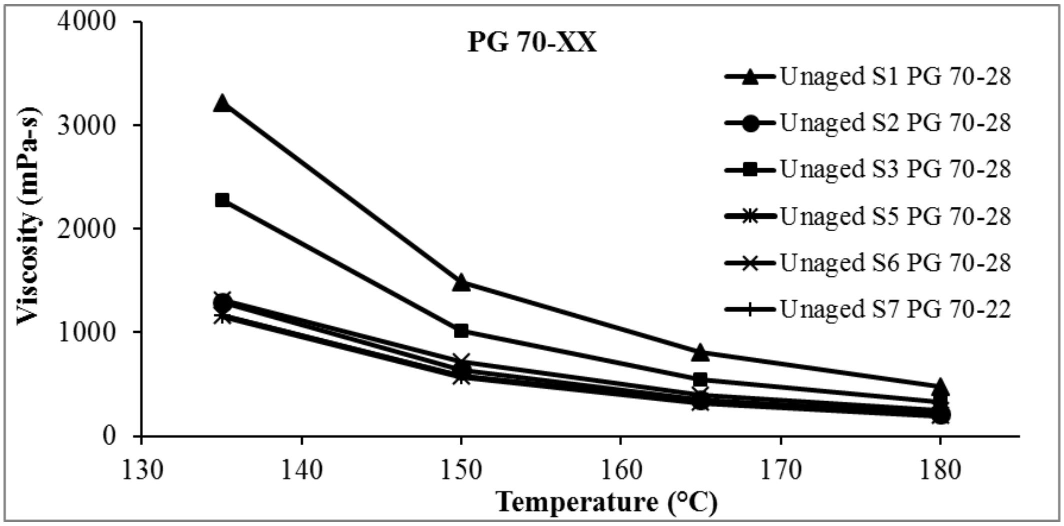


(b)

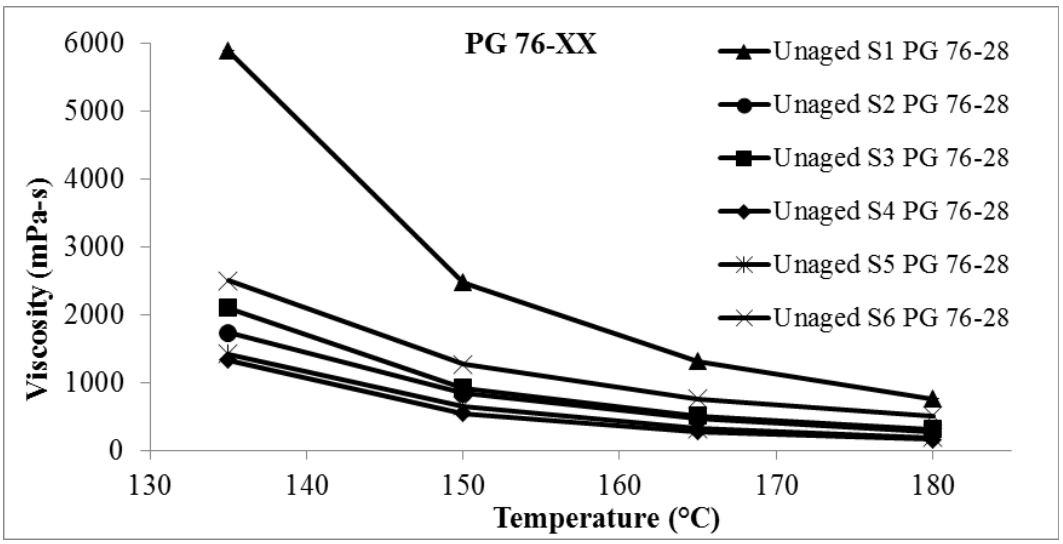
Figure 4.4 Variation of |G*|.sinδ with temperature for PAV-aged condition: (a) PG 70-XX binders; (b) PG 76-XX binders

4.2.1.2 RV test results

Figures 4.5 (a) and 4.5 (b) present the results of the rotational viscosity test conducted on the unaged PG 70-XX and PG 76-XX binders, respectively. From Figures 4.5 (a) and 4.5 (b), it is evident that the viscosity of all tested binders reduced with increasing test temperatures. For example, the viscosity of the S1 PG 70-28 binder was found to be 3213 mPa-s at 135 °C, and it decreased to 1487 mPa-s (54% reduction), 812.5 mPa-s (75% reduction) and 475 mPa-s (85% reduction) at 150°, 165° and 180 °C, respectively. Also, comparing Figures 4.5 (a) and 4.5 (b) reveals that, except binders from S3 source, the viscosities of the PG 76-XX binders are higher than those measured for the PG 70-XX binders from identical sources, as expected. For example, the viscosity of the S1 PG 76-28 binder at 135 °C was found to be 83% higher than that of the S1 PG 70-28 binder at the same temperature. Furthermore, the viscosities of the PG 70-XX binders were found to vary from 1163 to 3213 mPa-s at 135 °C, while the S1 PG 70-28 binder exhibited the highest and both the S5 PG 70-28 and S7 PG 70-22 binders exhibited the lowest viscosity values. Therefore, it can be concluded that the S1 PG 70-28 and S1 PG 76-28 binders are expected to require more compaction efforts in the field among other tested binders when used in a mix. These observations were found to be consistent with the findings reported in previous studies (Lu and Isacsson, 1997; Airey, 2003). Also, a number of studies have reported that the viscosities of the modified binders are influenced by the polymer structure and binder source (Lu and Isacsson, 1997; Airey, 2003; Xiao et al. (2014)). As reported by Lu and Isacsson (1997), the relatively high viscosity observed for the polymer-modified binders are resulted from a strong interaction between the polymer particles in the binder.



(a)

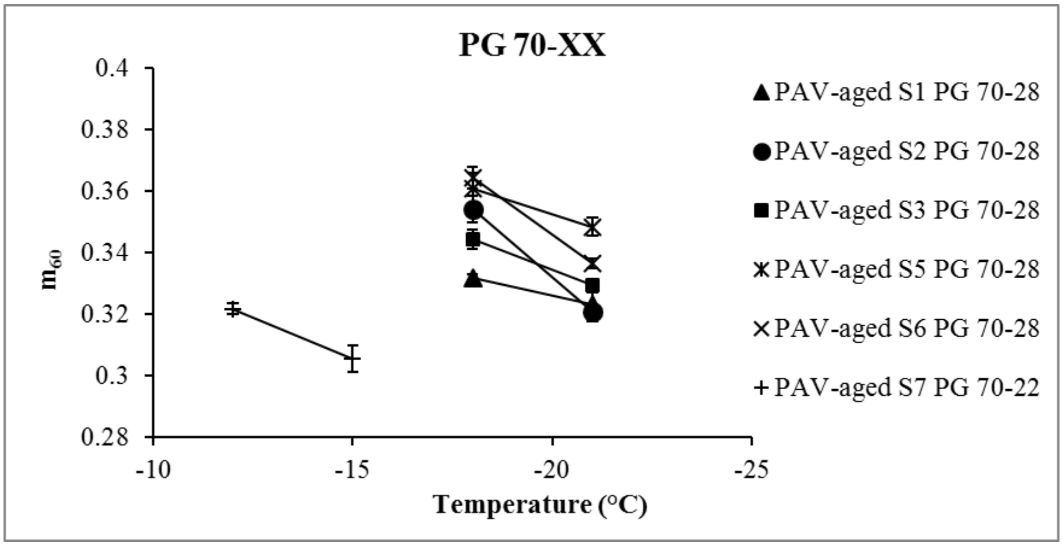


(b)

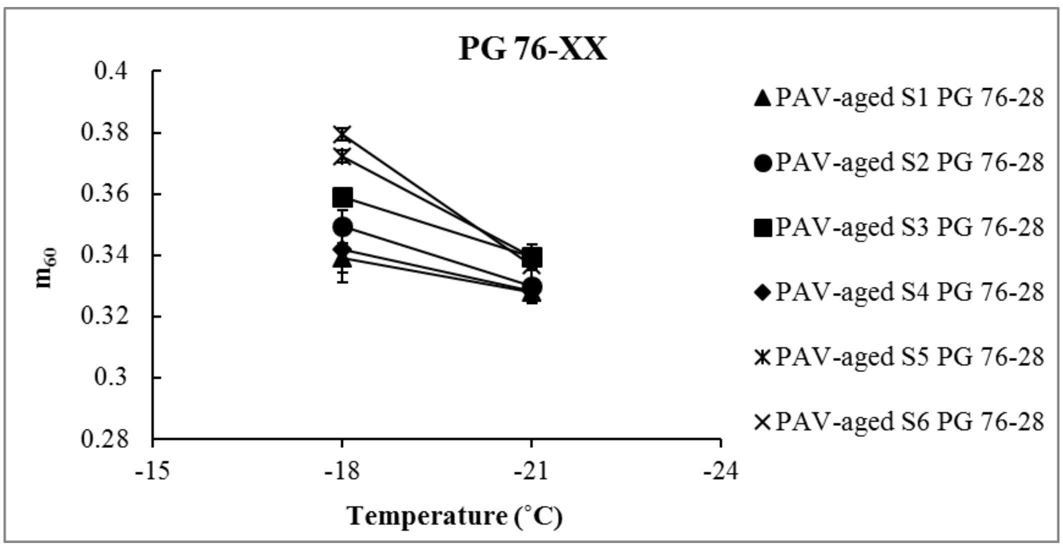
Figure 4.5 Variation of viscosity with temperature for unaged condition: (a) PG 70-XX binders; (b) PG 76-XX binders

4.2.1.3 BBR test results

Figures 4.6 (a) and 4.6 (b) present the m_{60} values and Figures 4.7 (a) and 4.7 (b) present the S_{60} values measured from BBR tests conducted on the PAV-aged PG 70-XX and PAV-aged PG 76-XX binders, respectively. From Figures 4.6 and 4.7, it can be observed that the m_{60} values reduced and the S_{60} values increased with a reduction in testing temperatures. For example, the m_{60} value of the S1 PG 70-28 binder was found to be 0.332 at -18 °C, while it decreased to 0.323 at -21 °C. The S_{60} values of the same binder were observed to increase from 131.4 MPa to 192.10 MPa when the temperature changed from -18° to -21 °C. According to the Superpave® binder specifications, the m_{60} values should be greater than 0.3 and the S_{60} values should be less than 300 MPa at low PG temperature. All of the tested binders were found to meet the Superpave® specifications requirement at low PG temperature. The improved low-temperature rheological properties of the modified binders were also reported by Lu and Isacsson (1997). It was reported that, at low temperature, polymer-modified binders exhibited a lower complex modulus and a lower reduction rate in phase angle with temperature than unmodified binders. This, in turn, helps to improve the low-temperature rheological properties of polymer-modified binders.

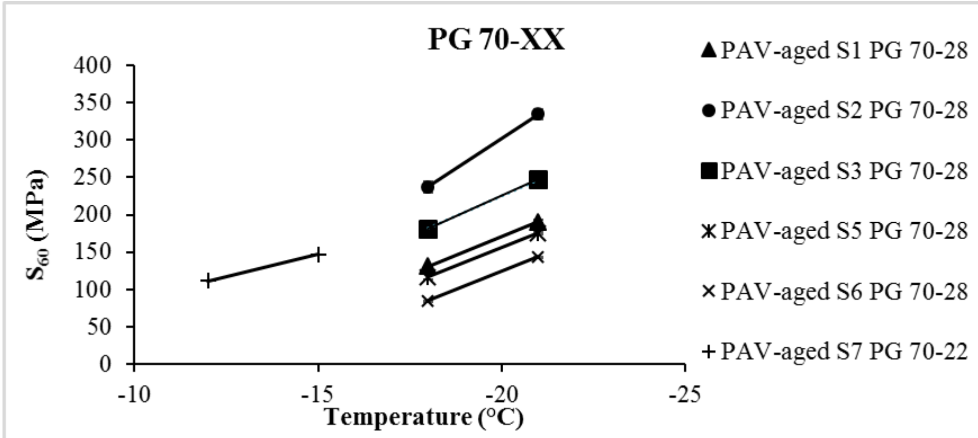


(a)

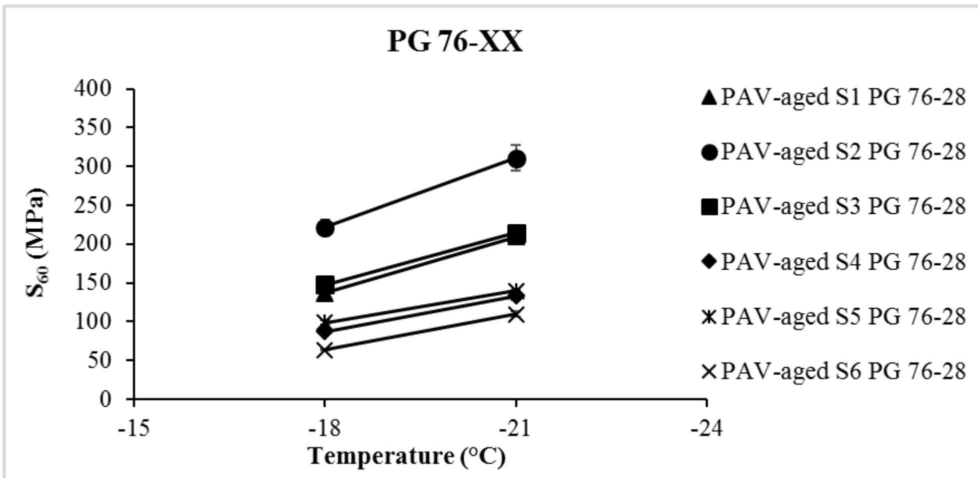


(b)

Figure 4.6 Variation of m_{60} with temperature for PAV-aged condition: (a) PG 70-XX binders; (b) PG 76-XX binders



(a)

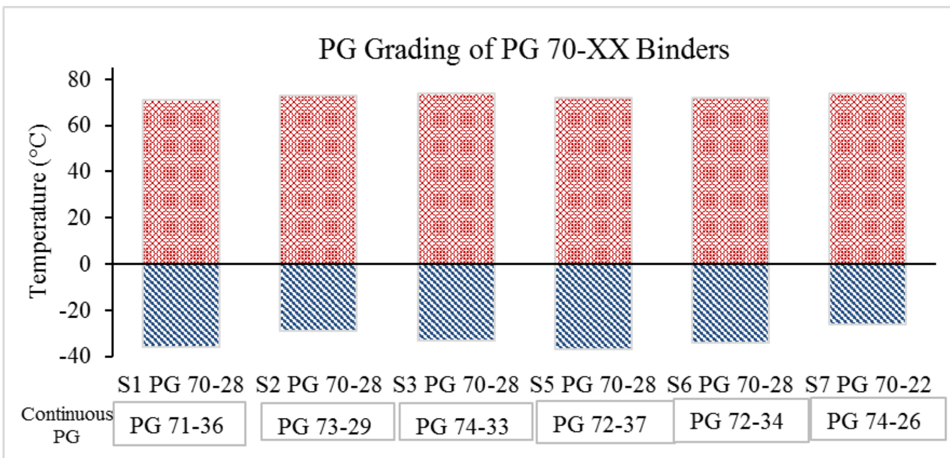


(b)

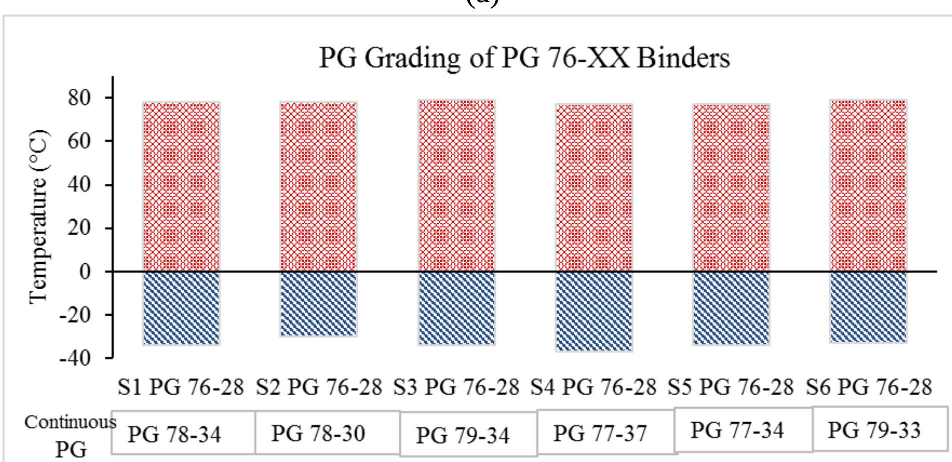
Figure 4.7 Variation of S_{60} with temperature for PAV-aged condition: (a) PG 70-XX binders; (b) PG 76-XX binders

4.2.1.4 Superpave® PG grading

The continuous high- and low-temperature PG grades of all of the binders were determined based on the results of the DSR and BBR tests, respectively. According to the Superpave® specifications, the temperature corresponding to a $|G^*|/\sin\delta$ value of 1.0 kPa for unaged or 2.20 kPa for RTFO-aged asphalt binders (whichever is the lowest) was considered as the continuous high-temperature PG grade. From the BBR test results, the temperature corresponding to an m_{60} value of 0.30 or a S_{60} value of 300 MPa (whichever is the highest) was considered as the low PG temperature. Tables 4.1 and 4.2 present the continuous high- and low- temperature PG grades of the tested binders. Figures 4.8 (a) and 4.8 (b) show graphical representations of the continuous PG grades of the PG 70-XX and PG 76-XX binders, respectively. From Figures 4.8 (a) and 4.8 (b), it can be observed that the label used by the manufacturer meets the minimum specifications requirements to be graded as advertised. For instance, the continuous PG temperature of the S1 PG 70-28 binder was found to be PG 71-36.



(a)



(b)

Figure 4.8 Superpave® PG grading of binders: (a) PG 70-XX; (b) PG 76-XX

Table 4.1 Continuous high-temperature PG grades of PG 70-XX and PG 76-XX binders

<table>
<tr><th>Source</th><th>Binder Type</th><th>Aging Condition</th><th>Temp. (°C)</th><th>|G*|/sinδ (kPa)</th><th>Superpave® requirement |G*|/sinδ (kPa)</th><th>PG Temp. (°C)</th><th>Continuous high-temperature PG</th></tr>
<tr><td rowspan="12">S1</td><td rowspan="6">PG 70-28</td><td rowspan="3">Unaged</td><td>67</td><td>1.63</td><td rowspan="3">1</td><td rowspan="3">73.8</td><td rowspan="6">PG 71</td></tr>
<tr><td>70</td><td>1.32</td></tr>
<tr><td>73</td><td>1.08</td></tr>
<tr><td rowspan="3">RTFO-aged</td><td>67</td><td>3.01</td><td rowspan="3">2.2</td><td rowspan="3">71.5</td></tr>
<tr><td>70</td><td>2.42</td></tr>
<tr><td>73</td><td>1.96</td></tr>
<tr><td rowspan="6">PG 76-28</td><td rowspan="3">Unaged</td><td>73</td><td>1.90</td><td rowspan="3">1</td><td rowspan="3">82.4</td><td rowspan="6">PG 78</td></tr>
<tr><td>76</td><td>1.58</td></tr>
<tr><td>79</td><td>1.33</td></tr>
<tr><td rowspan="3">RTFO-aged</td><td>73</td><td>3.11</td><td rowspan="3">2.2</td><td rowspan="3">78.5</td></tr>
<tr><td>76</td><td>2.57</td></tr>
<tr><td>79</td><td>2.15</td></tr>
<tr><td rowspan="12">S2</td><td rowspan="6">PG 70-28</td><td rowspan="3">Unaged</td><td>67</td><td>2.46</td><td rowspan="3">1</td><td rowspan="3">73.6</td><td rowspan="6">PG 73</td></tr>
<tr><td>70</td><td>1.60</td></tr>
<tr><td>73</td><td>1.23</td></tr>
<tr><td rowspan="3">RTFO-aged</td><td>67</td><td>4.64</td><td rowspan="3">2.2</td><td rowspan="3">74.1</td></tr>
<tr><td>70</td><td>3.43</td></tr>
<tr><td>73</td><td>2.67</td></tr>
<tr><td rowspan="6">PG 76-28</td><td rowspan="3">Unaged</td><td>73</td><td>1.84</td><td rowspan="3">1</td><td rowspan="3">80.6</td><td rowspan="6">PG 78</td></tr>
<tr><td>76</td><td>1.52</td></tr>
<tr><td>79</td><td>1.17</td></tr>
<tr><td rowspan="3">RTFO-aged</td><td>73</td><td>3.55</td><td rowspan="3">2.2</td><td rowspan="3">78.7</td></tr>
<tr><td>76</td><td>2.80</td></tr>
<tr><td>79</td><td>2.14</td></tr>
<tr><td rowspan="12">S3</td><td rowspan="6">PG 70-28</td><td rowspan="3">Unaged</td><td>67</td><td>2.16</td><td rowspan="3">1</td><td rowspan="3">76</td><td rowspan="6">PG 74</td></tr>
<tr><td>70</td><td>1.73</td></tr>
<tr><td>73</td><td>1.40</td></tr>
<tr><td rowspan="3">RTFO-aged</td><td>67</td><td>4.00</td><td rowspan="3">2.2</td><td rowspan="3">74.4</td></tr>
<tr><td>70</td><td>3.20</td></tr>
<tr><td>73</td><td>2.58</td></tr>
<tr><td rowspan="6">PG 76-28</td><td rowspan="3">Unaged</td><td>73</td><td>1.80</td><td rowspan="3">1</td><td rowspan="3">83.3</td><td rowspan="6">PG 79</td></tr>
<tr><td>76</td><td>1.56</td></tr>
<tr><td>79</td><td>1.34</td></tr>
<tr><td rowspan="3">RTFO-aged</td><td>73</td><td>3.41</td><td rowspan="3">2.2</td><td rowspan="3">79</td></tr>
<tr><td>76</td><td>2.75</td></tr>
<tr><td>79</td><td>2.22</td></tr>
<tr><td rowspan="6">S4</td><td rowspan="6">PG 76-28</td><td rowspan="3">Unaged</td><td>73</td><td>1.34</td><td rowspan="3">1</td><td rowspan="3">77.2</td><td rowspan="6">PG 77</td></tr>
<tr><td>76</td><td>1.08</td></tr>
<tr><td>79</td><td>0.87</td></tr>
<tr><td rowspan="3">RTFO-aged</td><td>73</td><td>4.65</td><td rowspan="3">2.2</td><td rowspan="3">83.4</td></tr>
<tr><td>76</td><td>3.90</td></tr>
<tr><td>79</td><td>3.24</td></tr>
</table>

Table 4.1(continue) Continuous high-temperature PG grades of PG 70-XX and PG 76-XX binders

Source	Binder Type	Aging Condition	Temp. (°C)	|G*|/sinδ (kPa)	Superpave® requirement |G*|/sinδ (kPa)	PG Temp. (°C)	Continuous high-temperature PG
S5	PG 70-28	Unaged	67	1.72	1	72.2	PG 72
			70	1.25			
			73	0.93			
		RTFO-aged	67	5.22	2.2	75	
			70	3.97			
			73	3.00			
	PG 76-28	Unaged	73	1.56	1	77.7	PG 77
			76	1.16			
			79	0.86			
		RTFO-aged	73	4.57	2.2	81	
			76	3.60			
			79	2.82			
S6	PG 70-28	Unaged	67	1.65	1	72.3	PG 72
			70	1.24			
			73	0.94			
		RTFO-aged	67	3.79	2.2	72.8	
			70	2.88			
			73	2.18			
	PG 76-28	Unaged	73	2.04	1	80.4	PG 79
			76	1.56			
			79	1.22			
		RTFO-aged	73	4.20	2.2	79.8	
			76	3.22			
			79	2.47			
S7	PG 70-22	Unaged	67	2.46	1	74.1	PG 74
			70	1.76			
			73	1.27			
		RTFO-aged	67	7.19	2.2	74.9	
			70	5.03			
			73	3.53			

Table 4.2 Continuous low-temperature PG grades of PG 70-XX and PG 76-XX binders

Source	Binder type	BBR parameters	Temperature (°C)		Superpave® specification requirement	Temp. (°C)	Temp. – 10 (°C)	Continuous low-temperature PG grade
			-18	-21				
S1	PG 70-28	m_{60}	0.332	0.323	0.3	-29.22	-39.22	PG XX-36
		S_{60} (kPa)	131.1	190.68	300	-26.5	-36.5	
	PG 76-28	m_{60}	0.339	0.328	0.3	-28.58	-38.58	PG XX-34
		S_{60} (kPa)	136.77	209.67	300	-24.72	-34.72	
S2	PG 70-28	m_{60}	0.354	0.321	0.3	-23.16	-33.16	PG XX-29
		S_{60} (kPa)	237.46	334.58	300	-19.93	-29.93	
	PG 76-28	m_{60}	0.35	0.33	0.3	-24.33	-34.33	PG XX-30
		S_{60} (kPa)	221.74	310.99	300	-20.68	-30.68	
S3	PG 70-28	m_{60}	0.344	0.33	0.3	-26.84	-36.84	PG XX-33
		S_{60} (kPa)	181.71	246.93	300	-23.44	-33.44	
	PG 76-28	m_{60}	0.359	0.34	0.3	-27.1	-37.1	PG XX-34
		S_{60} (kPa)	147.26	212.81	300	-24.83	-34.83	
S4	PG 76-28	m_{60}	0.342	0.328	0.3	-27.33	-37.33	PG XX-37
		S_{60} (kPa)	87.25	133.47	300	-31.81	-41.81	
S5	PG 70-28	m_{60}	0.361	0.348	0.3	-32.59	-42.59	PG XX-37
		S_{60} (kPa)	116.6	175.22	300	-27.39	-37.39	
	PG 76-28	m_{60}	0.372	0.339	0.3	-24.6	-34.6	PG XX-34
		S_{60} (kPa)	98.3	139.28	300	-32.77	-42.77	
S6	PG 70-28	m_{60}	0.364	0.337	0.3	-24.93	-34.93	PG XX-34
		S_{60} (kPa)	84.98	144	300	-28.93	-38.93	
	PG 76-28	m_{60}	0.379	0.337	0.3	-23.57	-33.57	PG XX-33
		S_{60} (kPa)	63.36	109.51	300	-33.38	-43.38	
S7	PG 70-22[a]	m_{60}	0.322	0.305	0.3	-16.00	-26.00	PG XX-26
		S_{60} (kPa)	111.38	146.85	300	-27.95	-37.95	

[a] S7 PG 70-22 was tested at -12° and -15 °C as per specification requirement.

4.2.2 RAP Binder Blends

The effect of the addition of different amounts of RAP binder to the neat binder was evaluated using the Superpave® test method. The Superpave® test results of PG 64-22, PG 64-22-R1-25, PG 64-22-R1-40, PG 64-22-R2-25, PG 64-22-R2-40 binders were adopted from a previous project performed by the OU research team.

4.2.2.1 DSR test results

Figure 4.9 presents the variation of the |G*| with temperature for unaged and RTFO-aged RAP binder blends. From Figure 4.9, it can be found that the addition of RAP binder increased the |G*| value of the PG 64-22 binder, as expected. For example, the |G*| values of the unaged PG 64-22 binder at 61° and 64 °C were found to be 2.39 and 1.70 kPa, respectively. However, the |G*| values of the PG 64-22-R1-25 binder at 61° and 64 °C were found to be 4.28 and 2.80 kPa, respectively. Also, the PG 64-22-R1-40 and PG 64-22-R1-60 binders were found to exhibit an increasing trend of |G*| values with an increase in RAP1 binder. Furthermore, a similar trend of increasing |G*| values with increased amount of RAP binder was observed for the RAP2 binder blends. These results indicate that the shear modulus as well as the stiffness of the PG 64-22 binder are expected to increase with an increase in the amount of RAP binder irrespective of the RAP source (Colbert and You, 2012; Bernier et al., 2012; Hossain et al., 2013)

Figure 4.10 presents the variation of δ values of the RAP binder blends with temperature. From Figure 4.10, it can be observed that the phase angles of the PG 64-22 binder exhibited a reducing trend with an increase in the amount of RAP binder for both

RAP sources. For example, the phase angle of the unaged PG 64-22 binder was found to be 84.63° at 64 °C, whereas the same for the PG 64-22-R2-25 and PG 64-22-R2-40 binders were 84.00° and 79.50° at 64 °C at the same temperature, respectively. Therefore, it can be concluded that addition of RAP binder is expected to reduce the phase angle and change the viscoelastic properties of asphalt binders. Hossain et al. (2013) reported a similar increasing trend of |G*| and a reducing trend of δ values with an increase in the amount of RAP in the binder blends. The oxidative hardening experienced by the RAP binder throughout its service life was reported to be the reason of such observations.

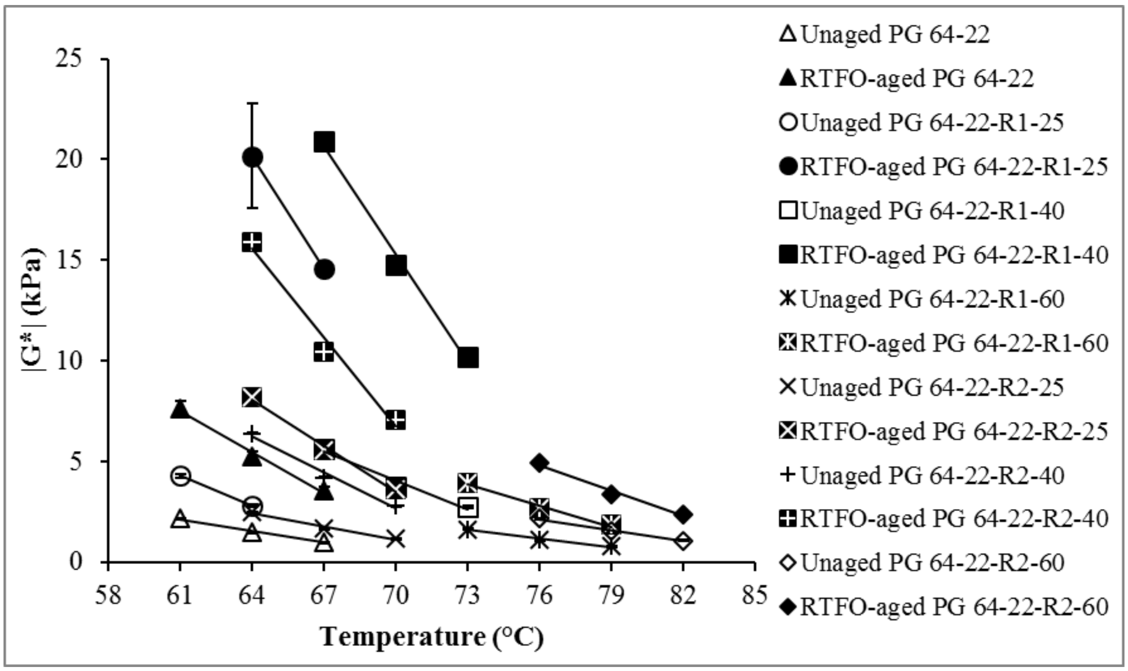


Figure 4.9 Variation of |G*| with temperature for unaged and RTFO-aged conditions and 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends

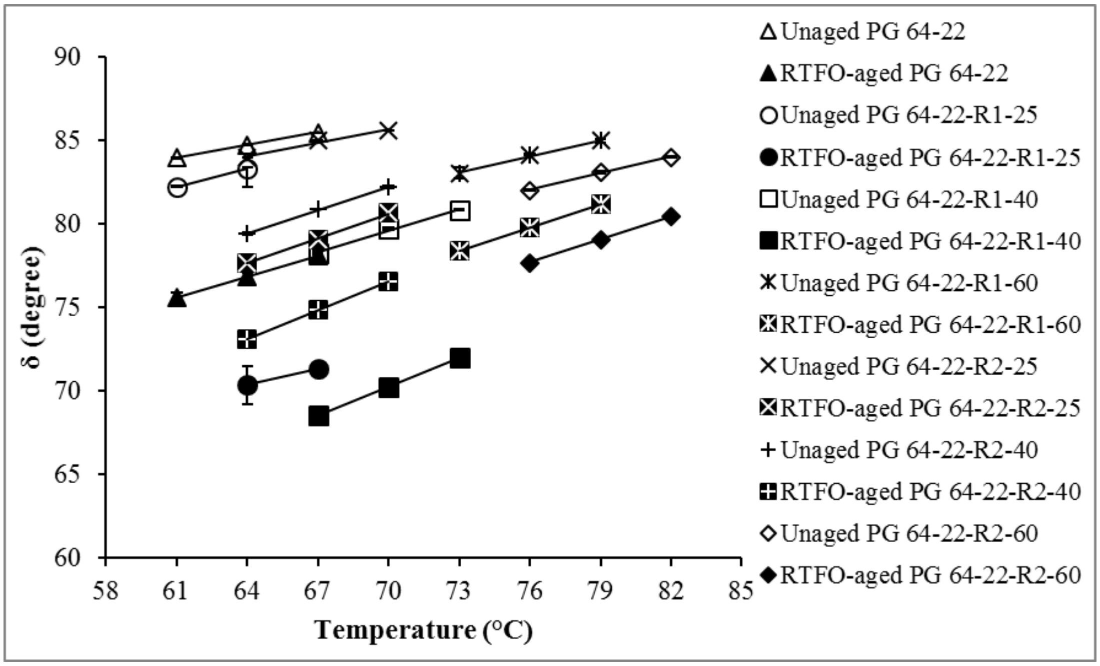


Figure 4.10 Variation of phase angle with temperature for unaged and RTFO-aged conditions and 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends

Figure 4.11 presents the effect of blending RAP1 and RAP2 binders on the |G*|/sinδ, under unaged and RTFO-aged conditions and at different temperatures. As mentioned earlier, a higher |G*|/sinδ value is an indicator of a higher rutting resistance (Bahia and Anderson, 1995). The |G*|/sinδ values were found to increase with the blending of RAP binder to the PG 64-22 binder. For example, the |G*|/sinδ values of the PG 64-22-R1-25 and PG 64-22-R1-40 binders were found to be 2.82 and 3.81 kPa at 64 °C. These values were approximately 65% and 125% higher than the |G*|/sinδ of unaged PG 64-22 binder, respectively. A similar increase in the |G*|/sinδ values was also observed for RAP2 binder blends. However, the level of increase in the |G*|/sinδ with addition of RAP binder was found to be dependent on the RAP sources. Therefore, the RAP binder blends are expected to exhibit a higher rutting resistance than those without any RAP binder, as reported by other researchers (Bernier et al., 2012; Colbert and You, 2012; Hossain et al., 2013).

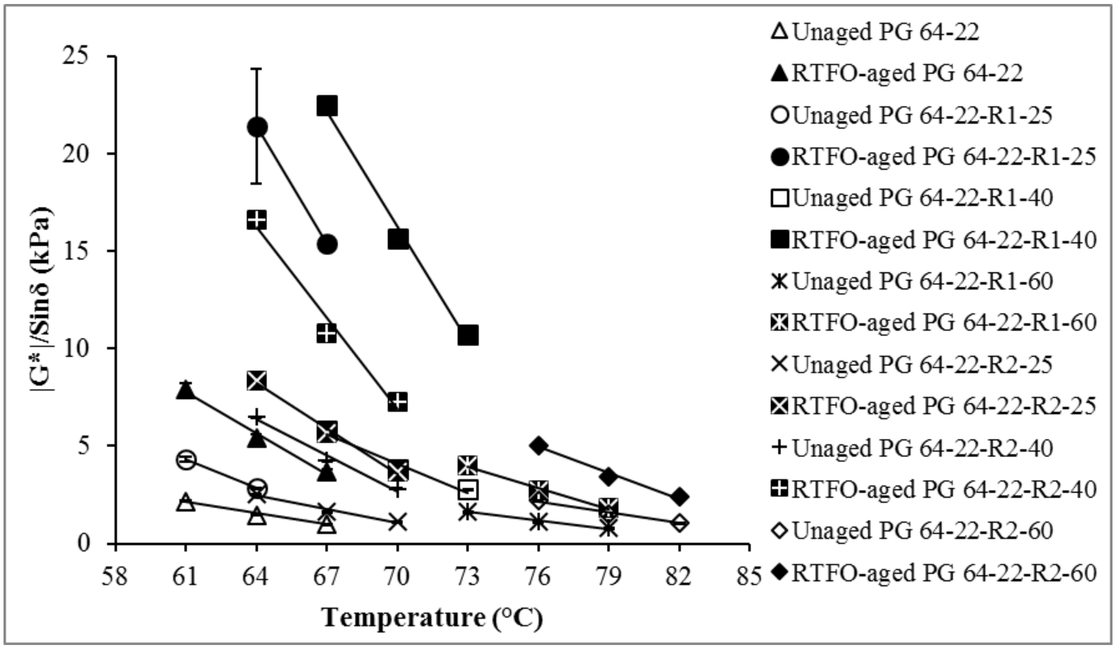


Figure 4.11 Variation of |G*|/sinδ with temperature for unaged and RTFO-aged conditions and 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends

4.2.2.2 RV test results

Rotational viscosity test results of the RAP binder blends are presented in Figure 4.12. From Figure 4.12, it can be seen that the viscosities of the RAP binder blends are higher than that of the neat PG 64-22 binder. This is due to the fact that the RAP binder experienced oxidative hardening and aging throughout its service life (Hossain et al., 2013). The viscosities of the PG 64-22 binder exhibited a continuous increasing trend with an increase in the amount of RAP binder. For example, the viscosity of the PG 64-22 binder was found to be 518.75 mPa-s at 135 °C and it increased to 1,054.5 mPa-s (103% increase) and 1237 mPa-s (138% increase) for the PG 64-22-R1-25 and PG 64-

22-R1-40 binders, respectively. However, the PG 64-22-R1-60 binder was observed to exhibit a lower viscosity than those of the PG 64-22-R1-25 and PG 64-22-R1-40 binders. With the addition of RAP2 binder to the neat binder, the viscosity follows a similar increasing trend, as observed for RAP1binder blends. The viscosity values were approximately 25%, 105% and 153% higher than that of the neat binder for PG 64-22-R2-25, PG 64-22-R2-40 and PG 64-22-R2-60 binders. This indicates that the RAP binder blends are expected to result in a reduced workability, when used in a mix. Colbert and You (2012) also reported that the amount of RAP binder added to the neat binder had an effect on the viscosity and pumping ability of associated asphalt mixes. It was also reported that the workability and the pumping potential based on viscosity of the binder significantly reduced as the amount of RAP binder increased.

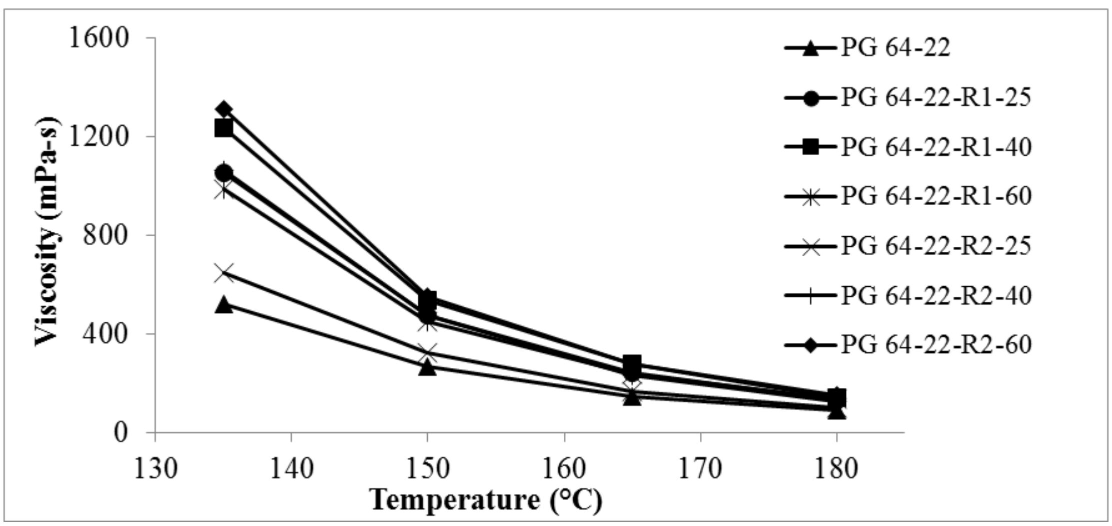


Figure 4.12 Variation of viscosity with temperature for unaged condition and 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends

4.2.2.3 BBR test results

For an improved resistance to low-temperature cracking, binders should not be too stiff at low temperatures and need to have the ability to relax of built-up stresses in a reasonable amount of time (Bahia and Anderson, 1995). Figures 4.13 and 4.14 present the m_{60} and the S_{60} values measured by conducting the BBR tests on RAP binder blends. From Figures 4.13 and 4.14, it was observed that the m_{60} values reduced and the S_{60} values increased with the addition of RAP1 and RAP2 binder to the PG 64-22 binder. For example, the m_{60} value for neat binder was found to be 0.329 at -12 °C. It reduced to 0.315, 0.299 and 0.302 for the PG 64-22-R2-25, PG 64-22-R2-40 and PG 64-22-R2-60 binders, respectively, at the same testing temperature. Also, the S_{60} values of the neat binder were found to increase from 127.24 MPa to 142.24, 155.67 and 196.10 MPa for the PG 64-22-R2-25, PG 64-22-R2-40 and PG 64-22-R2-60 binders, respectively, at -12 °C. Similar trends of variation in m_{60} and S_{60} values were observed for RAP1 binder blends except for the PG 64-22-R1-60 binder. It is suspected that some anomalies related to operator, machine or a combination of both had some roles behind such discrepancies in the test results for the PG 64-22-R1-60 binder. As the stiffness of the binder increased and the stress relaxation factor reduced with the addition of RAP binder, the binder blends are expected to exhibit a higher susceptibility to low-temperature cracking. These observations comply with the findings of an earlier study conducted by Daniel et al. (2010).

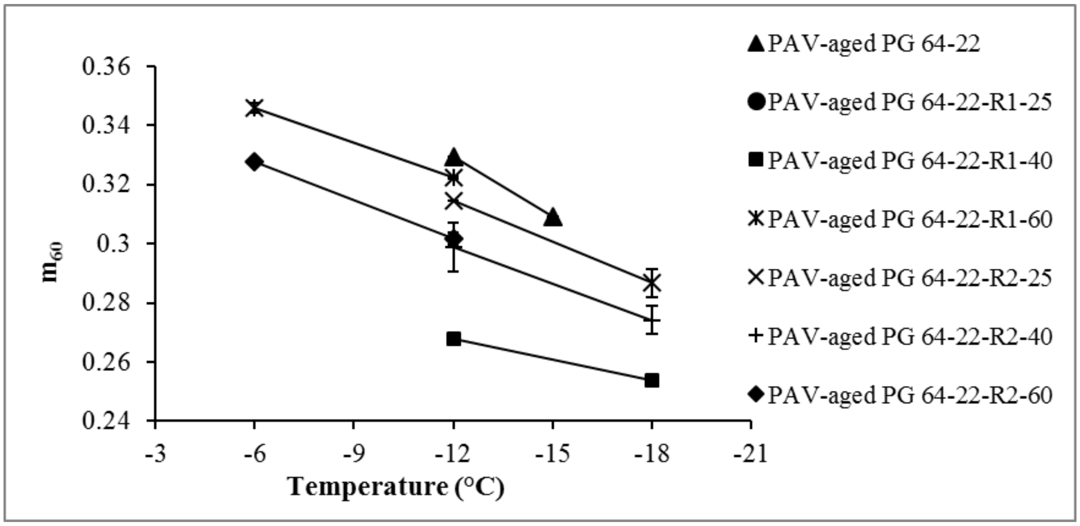


Figure 4.13 Variation of m_{60} with temperature for PAV-aged condition and 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends

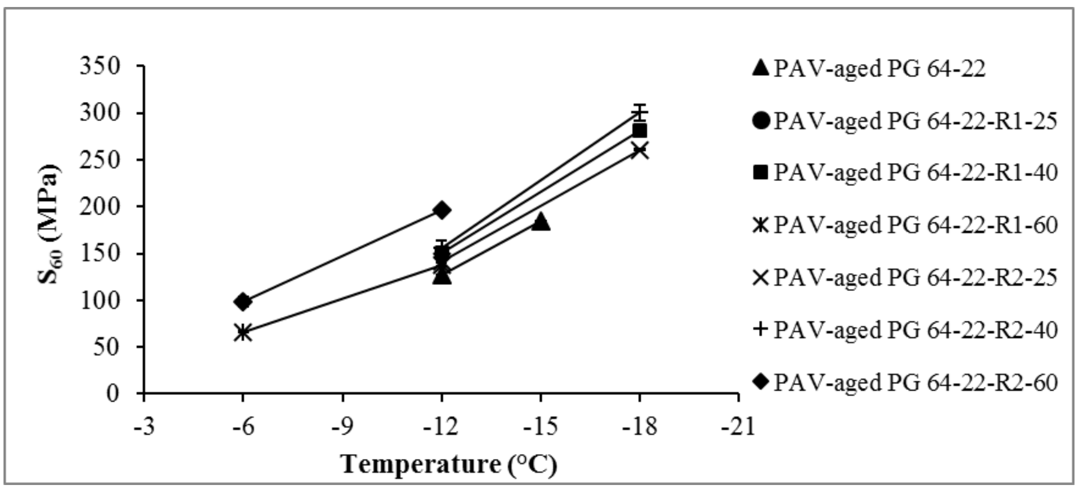


Figure 4.14 Variation of S_{60} with temperature for PAV-aged condition and 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends

4.2.2.4 Superpave® PG grading

The continuous PG grades of the RAP binder blends were determined based on the DSR and BBR test results in accordance with the Superpave® specifications. Tables 4.3, 4.4 and Figure 4.15 present the continuous high-and low-temperature PG grades of the RAP binder blends. It can be observed that the high-temperature PG grade increased with an increase in the RAP binder. As seen in Figure 4.15, the high-temperature PG grade of neat binder changes from PG 66 to PG 67, PG 76 and PG 77 with the addition of 25%, 40% and 60% RAP1 binder, respectively. Also, the high-temperature PG grades were found to be PG 69, PG 71 and PG 82 for the PG 64-22-R2-25, PG 64-22-R2-40 and PG 64-22-R2-60 binders, respectively. Therefore, the change in the high-temperature PG grades was found to be insignificant for the PG 64-22-R1-25 and PG 64-22-R2-25 binders. However, the addition of 40% and 60% RAP1 binders to the neat binder resulted in a bump of about two PG grades. Also, the high-temperature PG grades were observed to be one and three grades higher than that of neat binder for the PG 64-22-R2-40 and PG 64-22-R2-60 binders, respectively. Furthermore, it was found that the continuous low-temperature PG grade of the PG 64-22 binder increased from PG -26 to PG -22 and PG -8 (three PG grade reduction) with the addition of 25% and 40% RAP1 binder. The PG grade of the PG 64-22-R1-60 binder was found not to follow this trend as a new batch of neat binder was used for blending. The low-temperature PG grades of the PG 64-22-R2-25, PG 64-22-R2-40 and PG 64-22-R2-60 binders were found to be PG -25, PG -21 and PG -22, respectively. Therefore, only one grade increase in the low-temperature PG grade was observed due to the addition of 60% RAP2 binder to the PG 64-22 binder. Overall, these results indicate that the addition of RAP binder to neat binder is expected to decrease the rutting susceptibility of the binder blends and increase the possibility of low-temperature cracking of the binder, when used in a mix (Daniel et al., 2010; Bernier et al., 2012; Hossain et al., 2013).

Table 4.3 Continuous high-temperature PG grades of 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends

Binder type	RAP type	RAP binder (%)	Aging condition	Temp. (°C)	|G*|/sinδ (kPa)	Superpave® requirement |G*|/sinδ (kPa)	Temp. (°C)	Continuous high- temp. PG grade
PG 64-22		0	Unaged	61	2.16	1	66.7	PG 66
				64	1.47			
				67	1.00			
			RTFO-aged	61	7.88	2.2	69.6	
				64	5.38			
				67	3.66			
PG 64-22	RAP 1	25	Unaged	61	4.31	1	67.7	PG 67
				64	2.82			
				67	9.52			
			RTFO-aged	61	19.57	2.2	73.6	
				64	21.40			
				67	15.40			
PG 64-22	RAP 1	40	Unaged	67	5.77	1	76.0	PG 76
				70	3.81			
				73	2.78			
			RTFO-aged	67	22.50	2.2	77.1	
				70	15.67			
				73	10.73			
PG 64-22	RAP 1	60	Unaged	73	1.64	1	77.25	PG 77
				76	1.12			
				79	0.79			
			RTFO-aged	73	4.00	2.2	77.81	
				76	2.71			
				79	1.85			
PG 64-22	RAP 2	25	Unaged	64	2.53	1	69.26	PG 69
				67	1.66			
				70	1.15			
			RTFO-aged	64	8.38	2.2	71.65	
				67	5.64			
				70	3.66			
PG 64-22	RAP 2	40	Unaged	64	6.49	1	71.35	PG 71
				67	4.25			
				70	2.82			
			RTFO-aged	64	16.60	2.2	72.89	
				67	10.75			
				70	7.27			
PG 64-22	RAP 2	60	Unaged	76	2.19	1	82.21	PG 82
				79	1.53			
				82	1.08			
			RTFO-aged	76	5.02	2.2	82.2	
				79	3.45			
				82	2.39			

Table 4.4 Continuous low-temperature PG grades of 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends

Binder Type	**RAP type**	**RAP binder (%)**	**BBR parameters**			**Standard specifica-tion**	**Temp. (°C)**	**Temp. – 10 (°C)**	**Continuous low-temp. PG grade**
			Temp. (°C)	-12	-15				
PG 64-22		0	m_{60}	0.329	0.309	0.3	-16.4	-26.4	PG XX-26
			S_{60} (kPa)	127.24	184.19	300	-21.1	-31.1	
PG 64-22	RAP 1	40	Temp. (°C)	-12	-18				PG XX-8
			m_{60}	0.268	0.254	0.3	1.8	-8.17	
			S_{60} (kPa)	151.27	280.92	300	-18.9	-28.9	
PG 64-22	RAP 1	60	Temp. (°C)	-6	-12				PG XX-27
			m_{60}	0.346	0.322	0.3	-17.7	-27.7	
			S_{60} (kPa)	66.6	136.47	300	-25.6	-35.6	
PG 64-22	RAP 2	25	Temp. (°C)	-12	-18				PG XX-25
			m_{60}	0.315	0.287	0.3	-15.1	-25.1	
			S_{60} (kPa)	142.24	260.51	300	-20	-30	
PG 64-22	RAP 2	40	Temp. (°C)	-12	-18				PG XX-21
			m_{60}	0.299	0.274	0.3	-11.7	-21.7	
			S_{60} (kPa)	155.67	300.56	300	-18	-28	
PG 64-22	RAP 2	60	Temp. (°C)	-6	-12				PG XX-22
			m_{60}	0.328	0.302	0.3	-12.4	-22.4	
			S_{60} (kPa)	98.6	196.1	300	-18.4	-28.4	

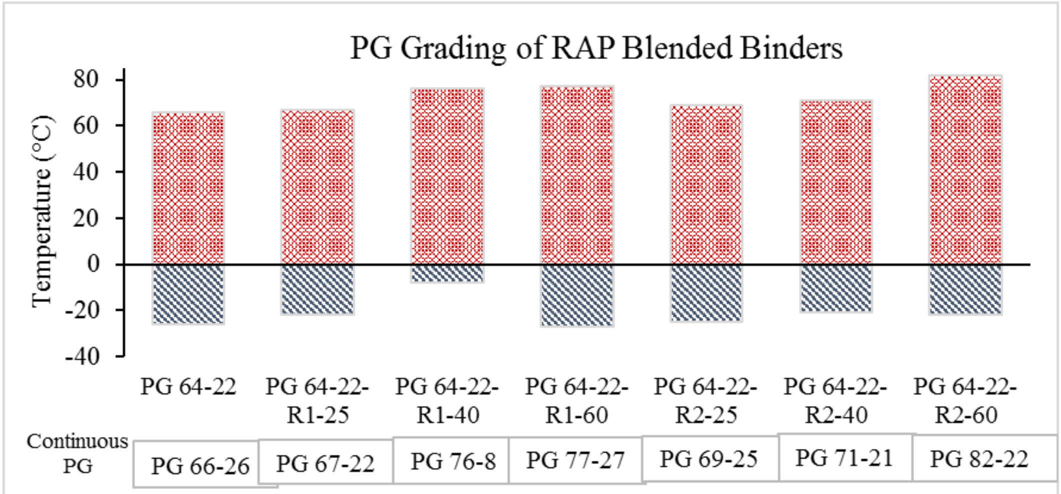


Figure 4.15 Superpave® PG grading of 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends

4.3 MSCR Test Results

4.3.1 Polymer-modified Binders

The MSCR tests on the RTFO-aged polymer-modified PG 70-XX and PG 76-XX asphalt binder samples were conducted at a temperature of 64 °C. Pertinent results of the J_{nr} (0.1 kPa), J_{nr} (3.2 kPa), $J_{nr\ diff}$, R_{100} and R_{3200} values, as well as the R_{diff} of the PG 70-XX and PG 76-XX binders, are presented in Table 4.5. The term "R_{100}" denotes the MSCR %Recovery at 0.1 kPa, whereas J_{nr} (0.1 kPa) refers to the non-recoverable creep compliance obtained from the MSCR test at 0.1 kPa. The $J_{nr\ diff}$ refers to the percent difference in J_{nr} values as the stress level changes from 0.1 kPa to 3.2 kPa.

4.3.1.1 Non-recoverable creep compliance (J_{nr})

The results of the J_{nr} values of the PG 70-XX and PG 76-XX binders at 0.1 and 3.2 kPa stress levels and 64 °C are presented in Figures 4.16 (a) and 4.16 (b). Generally, a lower J_{nr} value for binder represents a higher rutting resistance when used in a mix (D'Angelo, 2010). From Figures 4.16 (a) and 4.16 (b), relatively low J_{nr} values were observed for both PG 70-XX and PG 76-XX binders and they fell below 0.5 kPa^{-1}. For both PG 70-XX and PG 76-XX binders, it can be observed that the J_{nr} value measured at 3.2 kPa stress level was unchanged or higher compared to that measured at 0.1 kPa stress level. For example, the J_{nr} for the S5 PG 70-28 binder was found to increase from 0.25 to 0.33 kPa^{-1} when the stress level increased from 0.1 to 3.2 kPa. However, the J_{nr} value of the S1 PG 76-28 remained unchanged with a change in the stress level.

Table 4.5 MSCR test results for PG 70-XX and PG 76-XX binders at 64 °C

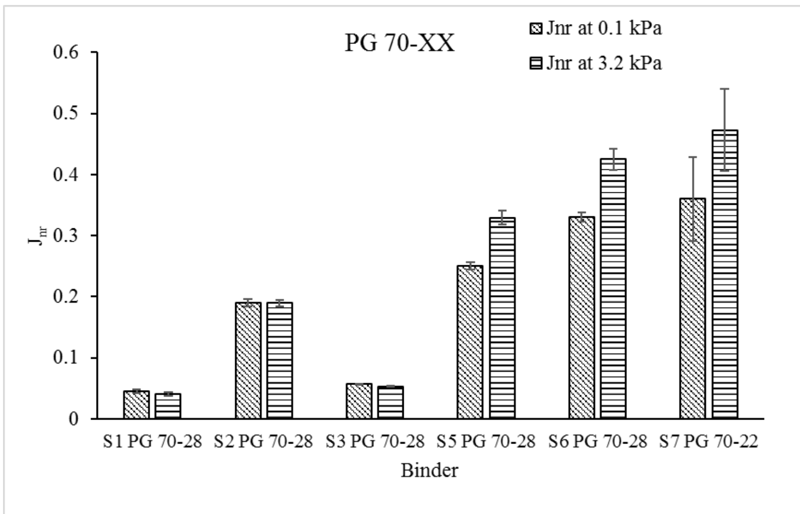
Binder Type	**Temp (°C)**	**J_{nr} (0.1 kPa) kPa^{-1}**	**J_{nr} (3.2 kPa) kPa^{-1}**	**$J_{nr\ diff}$ (0.1-3.2)**	**Stress sensitivity (Meets AASTHO MP 19)**	**R_{100} (%)**	**R_{3200} (%)**	**R_{diff} (0.1-3.2)**	**%Recovery (Meets AASTHO TP 70)**	**MSCR grade**
S1 PG 70-28	64	0.05	0.04	-8.95	Yes	96.15	95.8	0.36	Yes	PG 64E-XX
S1 PG 76-28	64	0.02	0.02	-6.30	Yes	97.29	97.24	0.05	Yes	PG 64E-XX
S2 PG 70-28	64	0.19	0.19	2.10	Yes	77.79	77.4	0.44	Yes	PG 64E-XX
S2 PG 76-28	64	0.06	0.06	-1.65	Yes	89.56	89.8	-0.32	Yes	PG 64E-XX
S3 PG 70-28	64	0.06	0.05	-5.75	Yes	94.05	94	0.05	Yes	PG 64E-XX
S3 PG 76-28	64	0.06	0.06	1.94	Yes	91.89	91.9	-0.05	Yes	PG 64E-XX
S4 PG 76-28	64	0.03	0.03	-2.35	Yes	94.71	94.45	0.28	Yes	PG 64E-XX
S5 PG 70-28	64	0.25	0.33	31.89	Yes	71.41	63.8	10.60	Yes	PG 64E-XX
S5 PG 76-28	64	0.08	0.10	28.03	Yes	81.84	76.4	6.63	Yes	PG 64E-XX
S6 PG 70-28	64	0.33	0.43	28.66	Yes	71.31	64.68	9.29	Yes	PG 64E-XX
S6 PG 76-28	64	0.11	0.14	30.02	Yes	80.32	75.74	5.69	Yes	PG 64E-XX
S7 PG 70-22	64	0.36	0.47	31.21	Yes	42.77	30.27	29.22	No	PG 64E-XX

Therefore, selecting the right stress level of the MSCR test is important to predict the rutting susceptibility of the binder with respect to the J_{nr} value. Furthermore, from Figures 4.16 (a) and 4.16 (b), variations in J_{nr} values can be observed for the binders of same PG grade but different sources. For example, the PG 70-XX binders were found to exhibit J_{nr} values ranging from 0.05 kPa^{-1} (S1 PG 70-28) to 0.36 (S7 PG 70-22) at 0.1 kPa and from 0.04 kPa^{-1} (S1 PG 70-28) to 0.47 (S7 PG 70-22) at 3.2 kPa stress levels. Also, the J_{nr} values for the PG 76-XX binders were observed to vary from 0.02 kPa^{-1} (S1 PG 76-28) to 0.11 (S6 PG 76-28) at 0.1 kPa and from 0.02kPa^{-1} (S1 PG 76-28) to 0.14 (S6 PG 76-28) at 3.2 kPa stress levels. Thus, it can be concluded that, the J_{nr} values as well as the rutting performance of the binders can vary although they have the same Superpave® PG grade. These observations were found to be consistent with the findings of the other studies (e.g., Jafari et al., 2015; Domingos and Faxina, 2016).

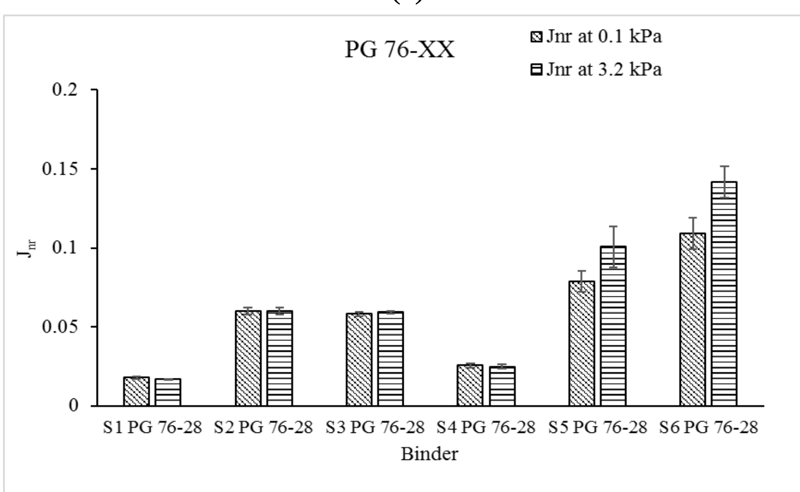
4.3.1.2 MSCR %Recovery

Figures 4.17 (a) and 4.17 (b) present the %Recovery values of the PG 70-XX and PG 76-XX binders from MSCR tests conducted at a temperature of 64 °C. According to D'Angelo (2010), the %Recovery value obtained from the MSCR test at high temperatures can be used to evaluate the rutting performance of a pavement. This parameter can also provide useful information regarding the reaction of base binder with polymer and formation of the polymer network (D'Angelo, 2010). The %Recovery value measured at the 3.2 kPa stress level was found to be unchanged or lower than that measured at the 0.1 kPa stress level for both polymer-modified binders. For example, the S1 PG 70-28 binder was found to exhibit an insignificant reduction (0.36%

difference) in the %Recovery with an increase in the stress level from 0.1 kPa to 3.2 kPa. A reason for such a low reduction in the %Recovery may be attributed to the linear viscoelastic behavior of the binder at both stress levels. Another reason can be the shortness of the rest period in the test procedure, which may cause the binder not to have enough time to fully recover at the end of loading and unloading cycles at 0.1 kPa stress level (Delgadillo et al., 2012; D'Angelo et al., 2007).



(a)

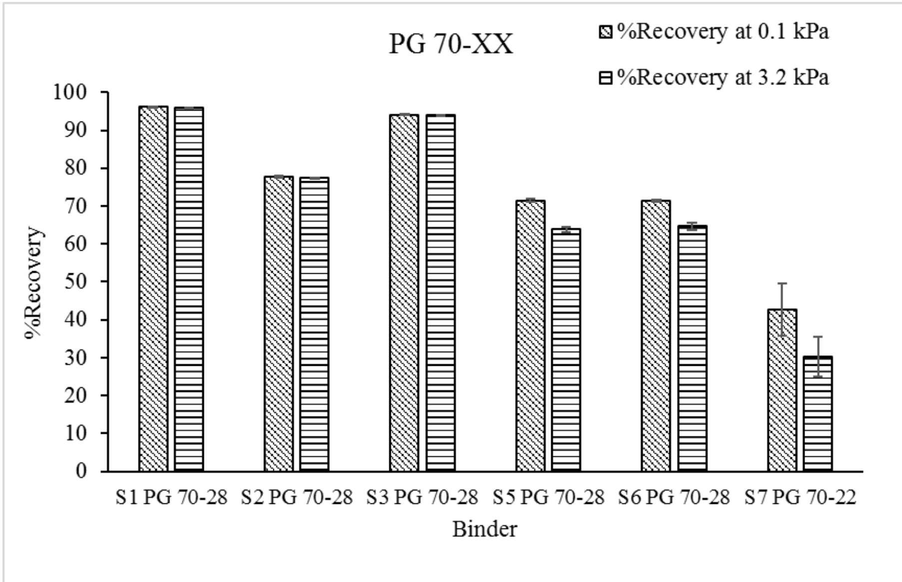


(b)

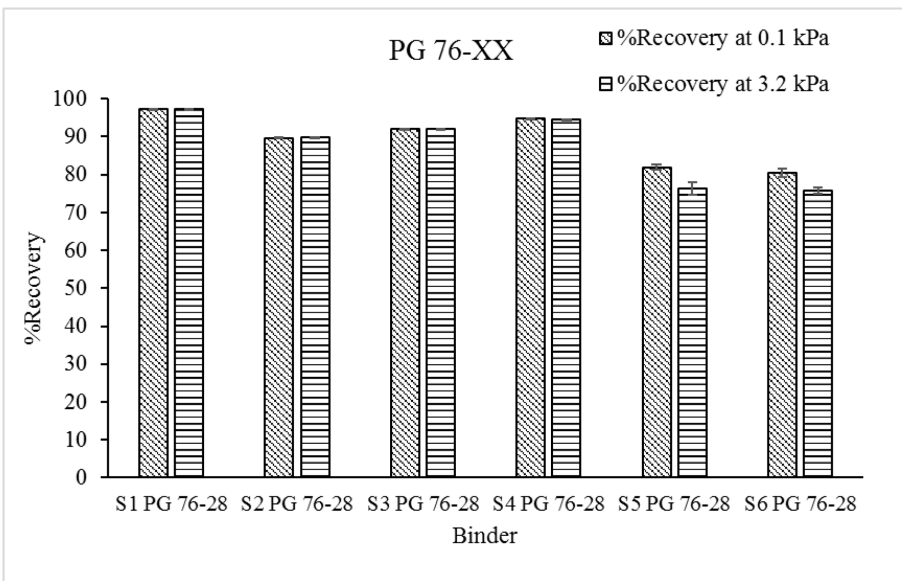
Figure 4.16 Effect of source on J_{nr} values at 64 °C: (a) PG 70-XX binders; (b) PG 76-XX binders

However, the %Recovery value of the S7 PG 70-22 binder was found to reduce by approximately 29.22% when the stress level increased from 0.1 to 3.2 kPa. Also, from Figures 4.17 (a) and 4.17 (b), relatively high %Recovery values were observed for both PG 70-XX and PG 76-XX binders from all sources except for the S7 PG 70-22. D'Angelo (2010) reported that a high %Recovery value obtained from an MSCR test can be used as an indication of strong polymer network in the binder at the corresponding high temperature. D'Angelo (2010) also tested the PPA-, SBS linear polymer- and SBS radial polymer-modified binders under fluorescence micrographs to establish relationship between %Recovery and polymer network. The polymers in the binders with low %Recovery were found to simply float in the asphalt. On the other hand, the binders with a high %Recovery were found to exhibit a strong polymer network with a leathery look indicating extensive cross-linking and well-dispersed concentrations of polymers (D'Angelo, 2010). Therefore, it can be concluded that all the PG 70-XX and PG 76-XX binders except S7 PG 70-22 are expected to have a strong polymer network at 64 °C. Furthermore, similar to J_{nr} values, binders with the same PG grade were found to exhibit variations in %Recovery values. For example, the %Recovery of PG 70-XX binders were found to vary from 96.15% (S1 PG 70-28) to 42.77% (S7 PG 70-22) at 0.1 kPa and from 95.8% (S1 PG 70-28) to 30.27% (S7 PG 70-22) at 3.2 kPa stress levels. The %Recovery values for the tested PG 76-XX binders were observed to be as high as 97.24% for the S1 PG 76-28 binder and as low as 75.74% for the S6 PG 76-28 binder at 3.2 kPa stress level. Therefore, in spite of having the same PG grade, the %Recovery values at certain stress levels and temperatures can vary depending on the viscoelastic behavior of a particular binder and binder source.

These observations support the findings of other studies (e.g., D'Angelo, 2010; Jafari et al., 2015; Stevens, 2015; Domingos and Faxina, 2016).



(a)

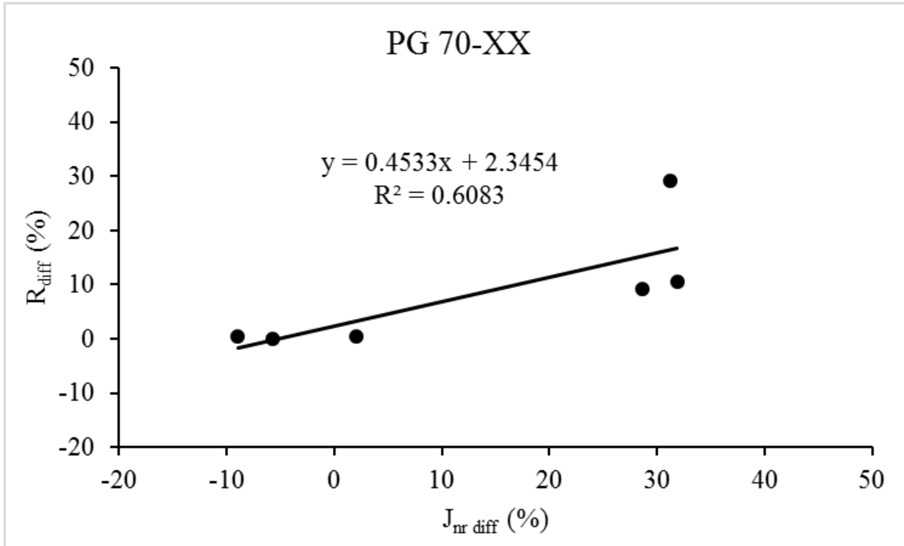


(b)

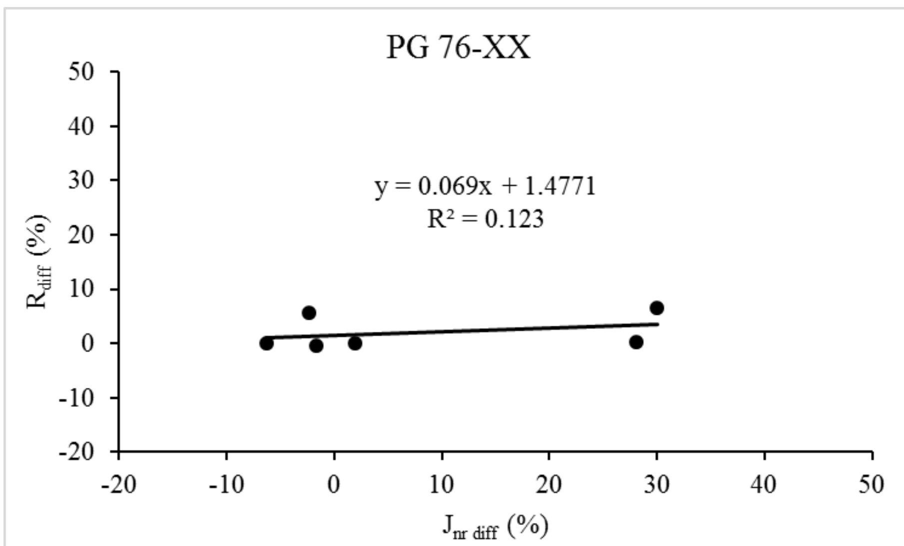
Figure 4.17 Effect of Source on %Recovery values at 64 °C: (a) PG 70-XX binders; (b) PG 76-XX binders

4.3.1.3 Stress sensitivity

Table 4.5 presents the percentage difference in J_{nr} values ($J_{nr\ diff}$) while the stress level changes from 0.1 kPa to 3.2 kPa at 64 °C. From Table 4.5 it can be observed that all of the polymer-modified binders met the minimum stress sensitivity requirement ($J_{nr\ diff}$ <75%) proposed by the AASHTO MP 19 (AASHTO, 2010) specification. The maximum increase in J_{nr} values for the PG 70-XX and PG 76-XX binders were found to be 31.89% and 28.03%, respectively. Therefore, it can be concluded that the tested polymer-modified binders were not overly stress sensitive. This means that the binders are expected not to undergo high amount of strain when subjected to unexpected heavy loads or unusually high temperatures. Figures 4.18 (a) and 4.18 (b) show the variation of $J_{nr\ diff}$ with R_{diff} values for the tested polymer-modified binders. These plots provide an insight on the trend of changes in J_{nr} with %Recovery values when subjected to a high stress level. From Figures 4.18 (a) and 4.18 (b), it can be observed that the rate of increase in %Recovery of the PG 70-XX binder has a relatively good correlation with the rate of increase in J_{nr} value. Comparatively, the PG 76-XX binder did not exhibit a good correlation. Therefore, it can be concluded that the changes in %Recovery of the PG 76-XX binders are expected to be less sensitive to the change in stress level than that of the J_{nr} value.



(a)



(b)

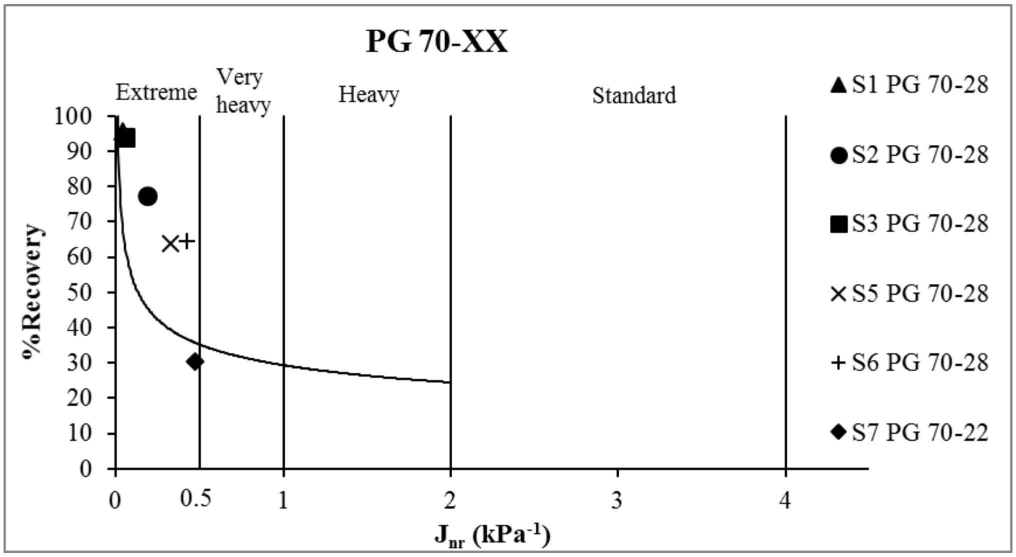
Figure 4.18 Variation of $J_{nr\ diff}$ with R_{diff} at 64 °C: (a) PG 70-XX binder; (b) PG 76-XX binder

4.3.1.4 Polymer method

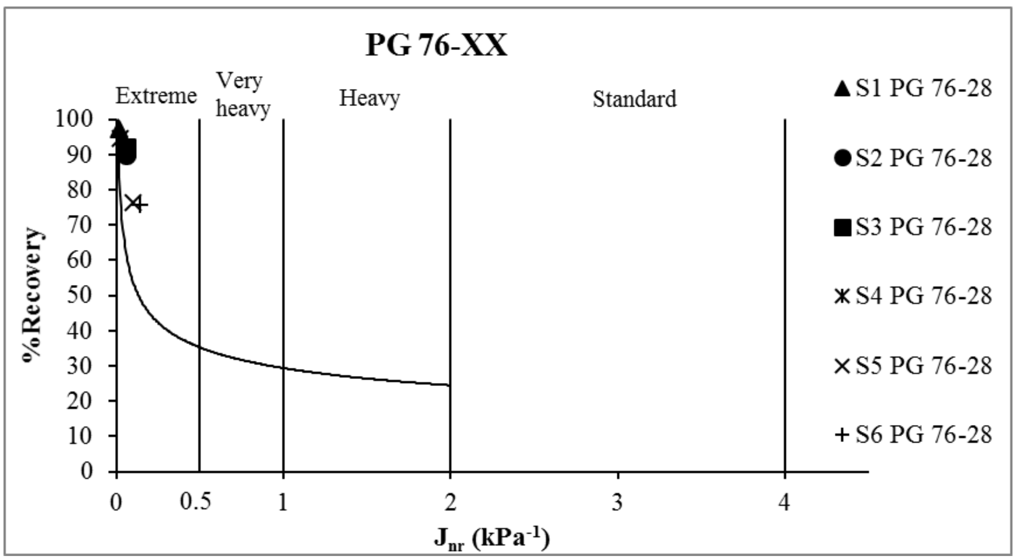
The analysis of the results of the MSCR tests conducted on the PG 70-XX and PG 76-XX binders using polymer curve are presented in Figures 4.19 (a) and 4.19 (b), respectively. In these figures, the %Recovery values at the 3.2 kPa stress level and 64 °C temperature were plotted against the corresponding J_{nr} values. From Figure 4.19 (a), all the PG 70-XX binders were found to meet the %Recovery requirement proposed by the AASHTO TP 70 (AASHTO, 2013) specification, except the S7 PG 70-22 binder. The %Recovery of S7 PG 70-22 binder was found to fall below the MSCR curve, which means either the binder was not modified with elastomeric modifiers or the modification level was low. As evident from Figure 4.19 (b), the data points for the PG 76-XX binders were found to be clustered above the MSCR curve. These results indicate that the PG 76-XX binders were modified with elastomeric polymers. No conclusive comment could be made on the effect of a particular polymer on the performance properties of the asphalt binder as the types and the amounts of polymers used by the refineries were unavailable.

4.3.1.5 MSCR grading system

The MSCR grades of the PG 70-XX and PG 76-XX binders were determined according to the AASHTO MP 19 (AASHTO, 2010) specification and are presented in Table 4.5 and Figures 4.19 (a) and 4.19 (b). From Table 4.5, it is evident that the grades of all of the tested PG 70-XX and PG 76-XX binders were found to be PG 64E-XX. This means that the tested PG 70-XX and PG 76-XX binders can sustain extreme traffic level at 64 °C without significant permanent deformation, when used in a mix. The results of the MSCR binder grade indicates that the tested polymer-modified binders are expected to exhibit high rutting resistance at 64 °C temperature and at extreme level of traffic, when used in a mix (Hossain et al., 2015).



(a)



(b)

Figure 4.19 Polymer curve analysis at 64 °C and 3.2 kPa stress level: (a) PG 70-XX binders; (b) PG 76-XX binders

4.3.1.6 Effect of increased stress level

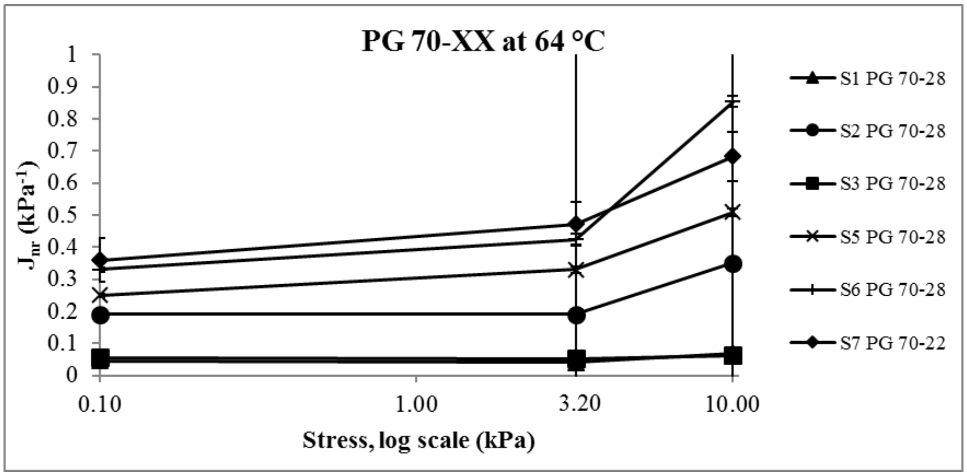
In addition to the stress levels recommended by AASHTO TP 70 (AASHTO, 2013), the MSCR tests were also conducted at the 10 kPa stress level in order to determine the stress sensitivity and non-linearity of the polymer-modified binders. Table 4.6 presents the results of the MSCR tests conducted at three different stress levels, namely 0.1, 3.2 and 10 kPa, at 64 °C.

Table 4.6 MSCR test results for PG 70-XX and PG 76-XX binders at 64 °C and 0.1, 3.2 and 10 kPa

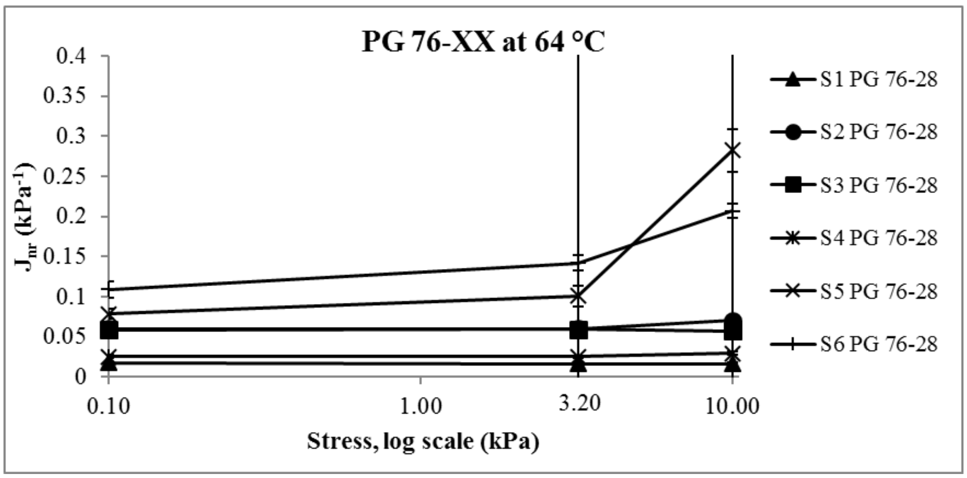
Binder Type	Temp (°C)	J_{nr} (0.1 kPa) kPa^{-1}	J_{nr} (3.2 kPa) kPa^{-1}	J_{nr} (10 kPa) kPa^{-1}	$J_{nr\ diff}$ (0.1-3.2)	$J_{nr\ diff}$ (3.2-10)	R_{100} (%)	R_{3200} (%)	R_{10000} (%)	R_{diff} (0.1-3.2)	R_{diff} (3.2-10)
S1 PG 70-28	64	0.05	0.04	0.07	-8.95	67.34	96.15	95.8	91.14	0.36	4.864
S1 PG 76-28	64	0.02	0.02	0.02	-6.3	-1.98	97.29	97.24	96.57	0.05	0.69
S2 PG 70-28	64	0.19	0.19	0.35	2.1	82.67	77.79	77.4	58.34	0.44	24.66
S2 PG 76-28	64	0.06	0.06	0.07	-1.65	3.61	89.56	89.8	88.41	-0.32	1.59
S3 PG 70-28	64	0.06	0.05	0.06	-5.75	17.24	94.05	94	91.21	0.05	2.97
S3 PG 76-28	64	0.06	0.06	0.06	1.94	-3.87	91.89	91.9	91.13	-0.05	0.87
S4 PG 76-28	64	0.03	0.03	0.03	-2.35	16.97	94.71	94.45	92.177	0.28	2.40
S5 PG 70-28	64	0.25	0.33	0.51	31.89	54.46	71.41	63.8	47.92	10.6	24.93
S5 PG 76-28	64	0.08	0.1	0.28	28.03	180.16	81.84	76.4	49.55	6.63	35.16
S6 PG 70-28	64	0.33	0.43	0.85	28.66	101.01	71.31	64.68	34.56	9.29	46.57
S6 PG 76-28	64	0.11	0.14	0.21	30.02	45.73	80.32	75.74	65.78	5.69	13.15
S7 PG 70-22	64	0.36	0.47	0.68	31.21	44.57	42.77	30.27	17.28	29.22	42.92

Figures 4.20 (a) and 4.20 (b) show the changes in J_{nr} values with stress levels at 64 °C. According to Golalipour (2011), the use of increased stress levels can help to

differentiate the rutting performance of the binders and identify the performance of the binders when used in a mix. For example, the J_{nr} values of the PG 70-XX binders were observed to remain unchanged with an increase in the stress level from 0.1 to 3.2 kPa. However, significant changes in the J_{nr} values were observed for most of the PG 70-XX binders while increasing the stress level from 3.2 to 10 kPa. According to Golalipour (2011), this rapid changing in J_{nr} value can be used as an indicator of non-linear behavior of asphalt binder. Therefore, it can be concluded that the PG 70-XX binders started exhibiting non-linear viscoelastic behavior at the 10 kPa stress level. The transition between linear and non-linear viscoelastic region of the tested binders are expected to lie at a stress level between 3.2 and 10 kPa. However, the variation in the J_{nr} values of the PG 70-XX binders from S1 and S2 sources were found to be insignificant at different stress levels. From Figure 4.20 (b), it can be observed that four out of six sources of the tested PG 76-XX binders were found not to exhibit any significant change in J_{nr} values with an increase in stress level from 3.2 to 10 kPa. This indicates that the stress sensitivities of the binders were relatively low when they were tested at stress levels up to 10 kPa. Therefore, the PG 76-XX binders were observed to behave as a linear viscoelastic material upto the 10 kPa stress level. However, the PG 76-XX binders from S5 and S6 sources exhibited a relatively high amount of change (55% for S5 and 180% for S6) in J_{nr} with an increase in the stress level from 3.2 to 10 kPa. This means that the binders from S5 and S6 sources became overly stress sensitive with an increase in stress level. The high non-linearity of these binders might result in poor performance when subjected to high stress levels in pavements (Golalipour, 2011).



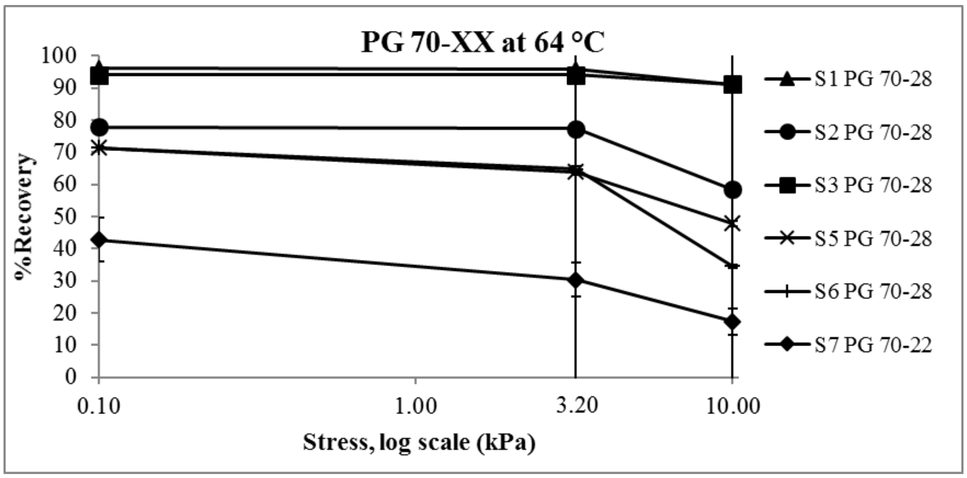
(a)



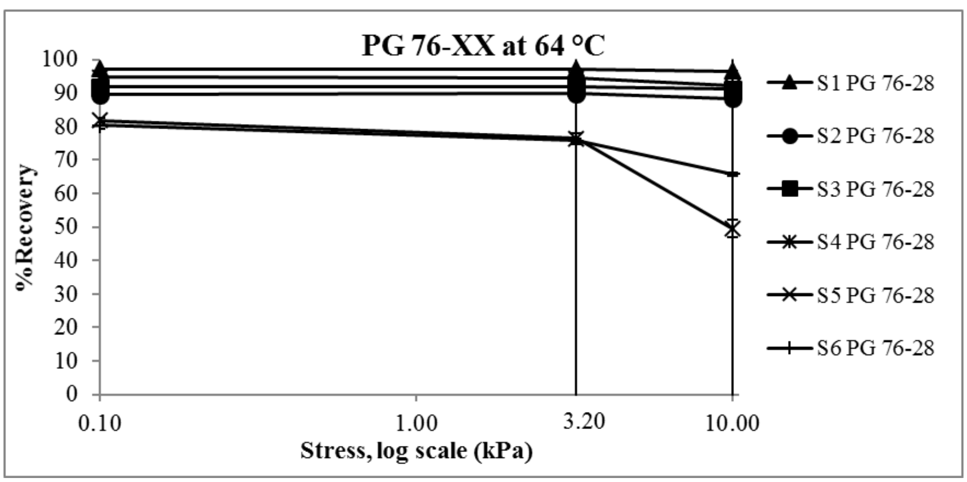
(b)

Figure 4.20 Change in J_{nr} value with stress levels at 64 °C: (a) PG 70-XX binders; (b) PG76-XX binders

The variation in %Recovery of the PG 70-XX and PG 76-XX binders at 64 °C with an increase in the stress levels is presented in Figures 4.21 (a) and 4.21 (b). As can be seen in Figure 4.21 (a), the %Recovery values of the PG 70-XX binders from S1 and S2 sources remained unchanged with an increase in stress level. However, significant changes in the %Recovery values were observed for the PG 70-XX binders from other sources (Source S3, S4, S5 and S6). Also, a sharp reduction in the %Recovery value was observed only for the S5 PG 76-28 and S6 PG 76-28 binders with an increasing stress level. Furthermore, the %Recovery of the PG 76-28 binders from other sources (S1, S2, S3 and S4) was found to exhibit a relatively low stress sensitivity. Similar to the J_{nr} parameter, the binders with highly non-linear behavior are expected to exhibit a high amount of reduction in %Recovery when the stress level increased from 3.2 to 10 kPa.



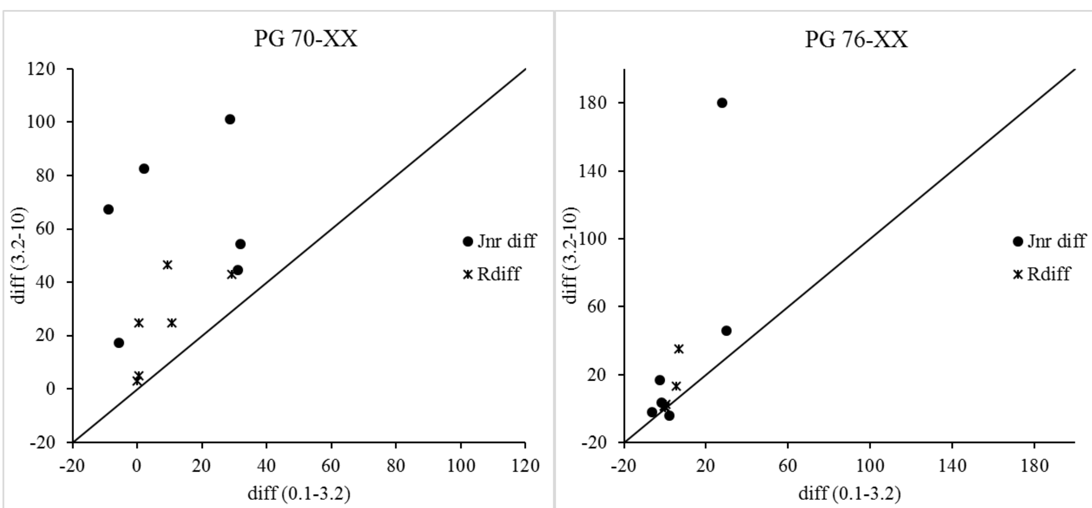
(a)



(b)

Figure 4.21 Change in %Recovery with stress levels at 64 °C: (a) PG 70-XX binders; (b) PG 76-XX binders

Figures 4.22 (a) and 4.22 (b) show variations of the $J_{nr\ diff}$ and $\%R_{diff}$ values with a change in stress level for polymer-modified binders. The $J_{nr\ diff}$ and $\%R_{diff}$ between 10 kPa and 3.2 kPa stress levels were found to be higher than those between 3.2 kPa and 0.1 kPa stress levels. This indicates that the tested binders became more sensitive to stress level with an increase in the stress level from 3.2 to 10 kPa. Also, the PG 70-XX binders were observed to become more stress sensitive than the PG 76-XX binders, except the S5 PG 76-28 binder. The high polymer modification used for the production of PG 76-XX binder are believed to be responsible for a lower stress sensitivity of binders. Therefore, conducting the MSCR test at a stress level higher than 3.2 kPa will help to understand the stress sensitivity and non-linearity of polymer-modified binders. Golalipour (2011) suggested to use 10 kPa as an additional stress level for MSCR testing of polymer-modified binders to obtain a wider spectrum of binder behavior under different stress levels.

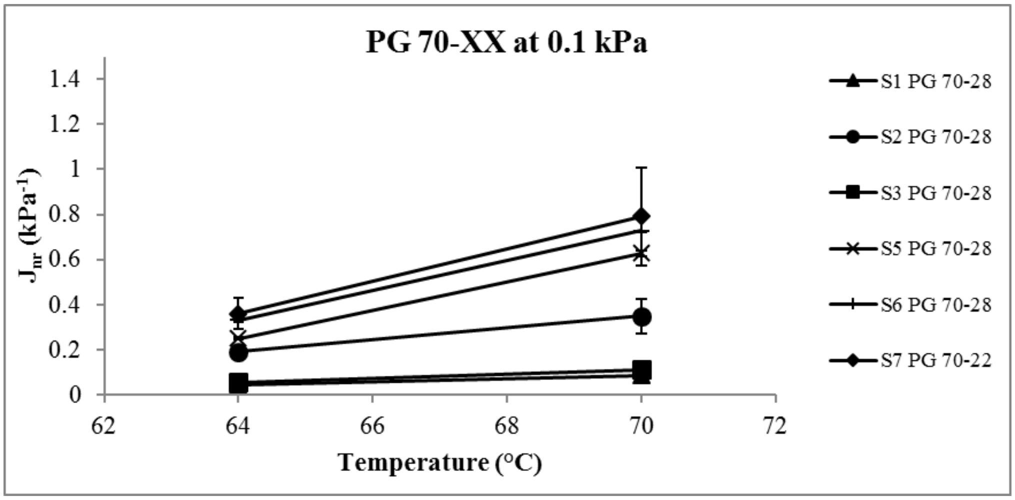


(a) (b)

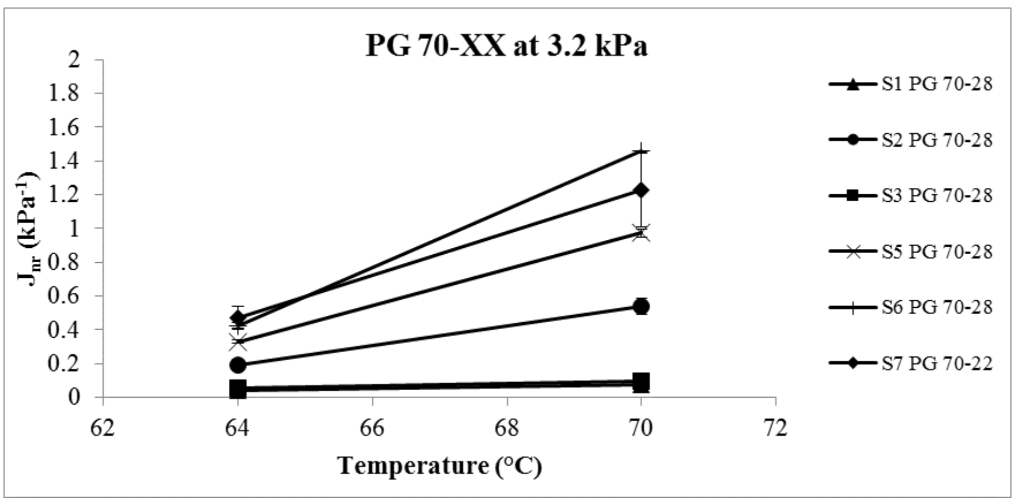
Figure 4.22 Plot of $J_{nr\ diff}$ and R_{diff} with increasing stress levels at 64 °C: (a) PG 70-XX binders; (b) PG 76-XX binders

4.3.1.7 Effect of higher temperatures

The temperature sensitivity of the J_{nr} and %Recovery parameter of the PG 70-XX and PG 76-XX binders were evaluated by conducting MSCR tests at temperatures higher than 64 °C. Specifically, the PG 70-XX binders were tested at 70° C and the PG 76-XX binders were tested at 70° and 76 °C. Figures 4.23 (a) and 4.23 (b) present the variation of J_{nr} with temperature for the PG 70-XX binders and Figures 4.24 (a) and 4.24 (b) present the variation of J_{nr} with temperature for the PG 76-XX binders at 0.1 and 3.2 kPa stress levels, respectively. From Figures 4.23 and 4.24, it is evident that the J_{nr} values of the polymer-modified binders depend on the temperature. The J_{nr} values of both the binders were found to increase with an increase in temperature. For example, the J_{nr} value of the S6 PG 70-28 at 0.1 kPa stress level was found to increase from 0.33 to 0.73 kPa^{-1} when the temperature increased from 64° to 70 °C. The effect of the temperature change on the J_{nr} value was found to be more pronounced at 76 °C for PG 76-XX binders. A similar increasing trend of the J_{nr} with an increase in the temperature was observed by other researchers (Mehta et al., 2013; Zhang et al., 2015; Jafari et al., 2015; Stevens et al., 2015). Also, from Figures 4.23 and 4.24, the differences between the J_{nr} values at 0.1 and 3.2 kPa stress levels were more significant at higher temperatures. Furthermore, the difference between J_{nr} values of asphalt binders of the same PG grade became more significant with an increase in temperature. For example, the J_{nr} values of the PG 76-XX binders from different sources were found to vary significantly from each other at 76 °C than that at 64° and 70 °C. According to Zhang et al. (2015), the temperature sensitivity of the J_{nr} parameter can be correlated with the temperature sensitivity of rutting. Therefore, binders are expected to exhibit lower rutting resistance at higher temperature and vice versa.

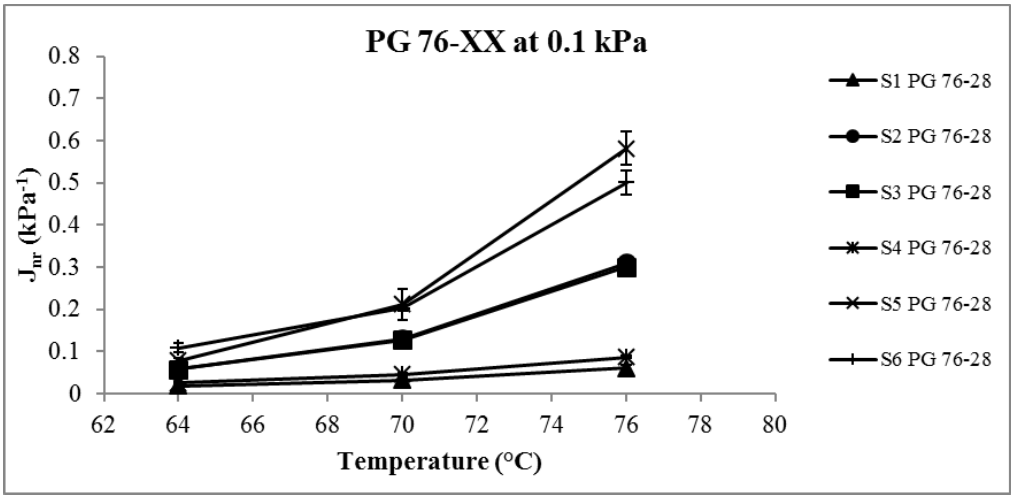


(a)

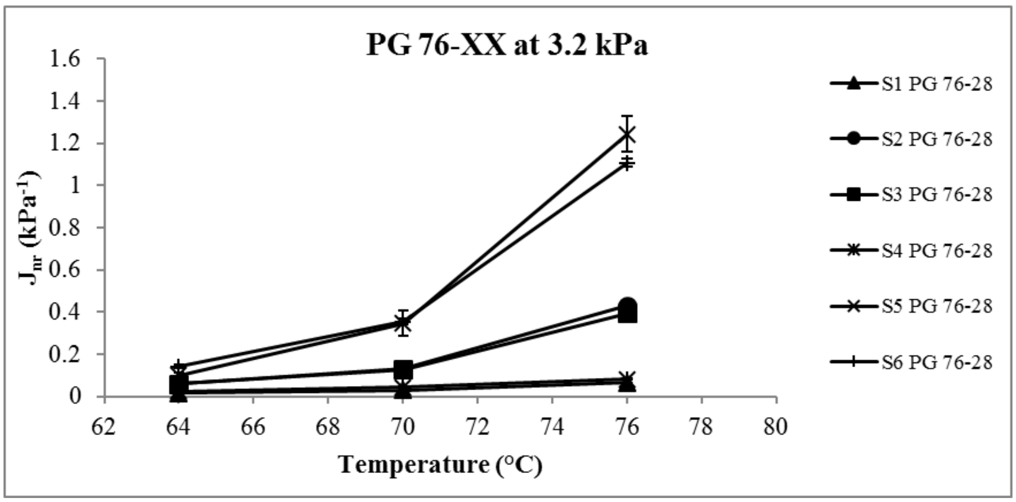


(b)

Figure 4.23 Changes in J_{nr} values with temperature for PG 70-XX binders: (a) 0.1 kPa stress level; (b) 3.2 kPa stress level



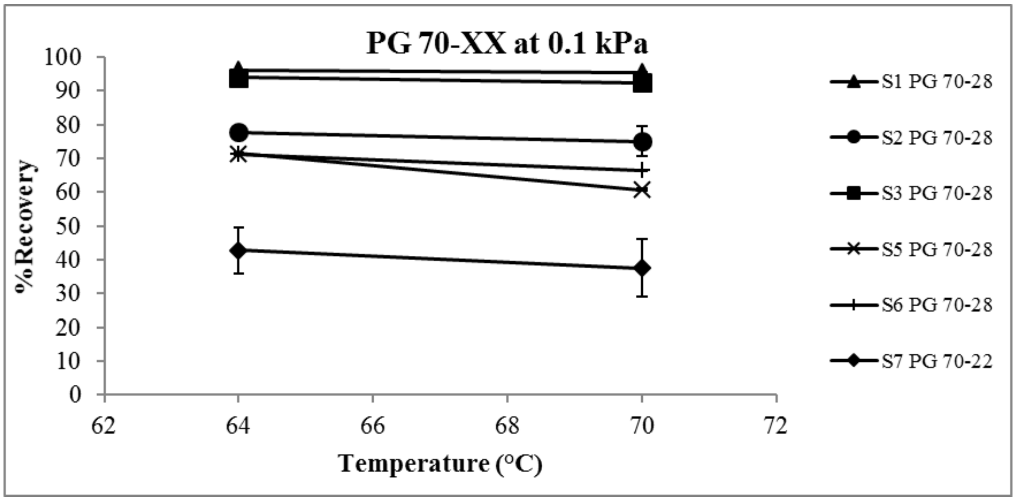
(a)



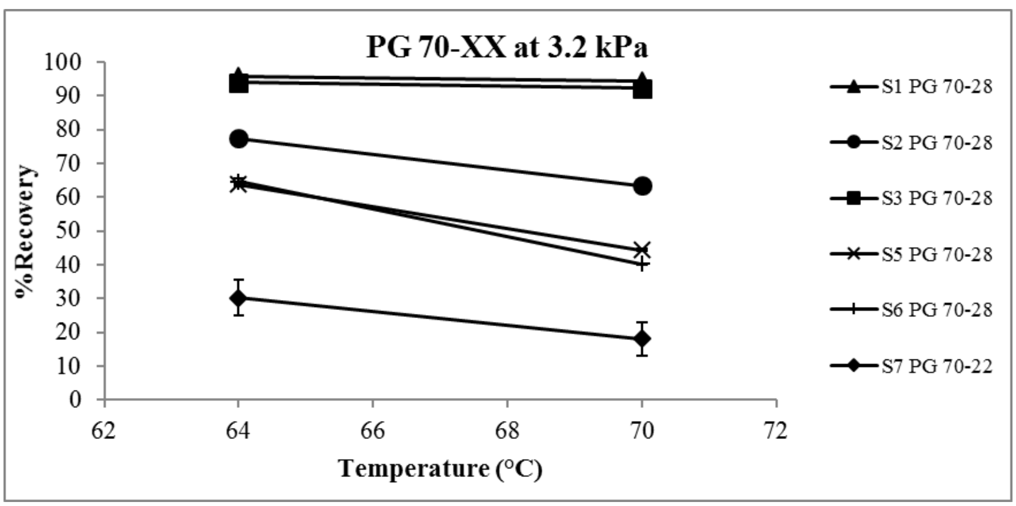
(b)

Figure 4.24 Changes in J_{nr} values with temperature for PG 76-XX binders: (a) 0.1 kPa stress level; (b) 3.2 kPa stress level

The variations in %Recovery with temperature are presented in Figures 4.25 (a) and 4.25 (b) for the PG 70-XX binders and in Figures 4.26 (a) and 4.26 (b) for the PG 76-XX binders at 0.1 and 3.2 kPa stress levels, respectively. Similar to J_{nr} parameter, the %Recovery was found to exhibit temperature sensitivity for the both the PG 70-XX and PG 76-XX binders. The %Recovery was found to reduce with an increase in temperature for all of the tested binders. At 0.1 kPa stress level, the %Recovery of the S6 PG 70-28 binder was found to be 71.3% at 64 °C whereas it reduced to 66.5% at 70 °C. Previous studies have reported a similar temperature sensitivity of %Recovery of polymer-modified binders (Mehta et al., 2013; Jafari et al., 2015; Stevens et al., 2015).

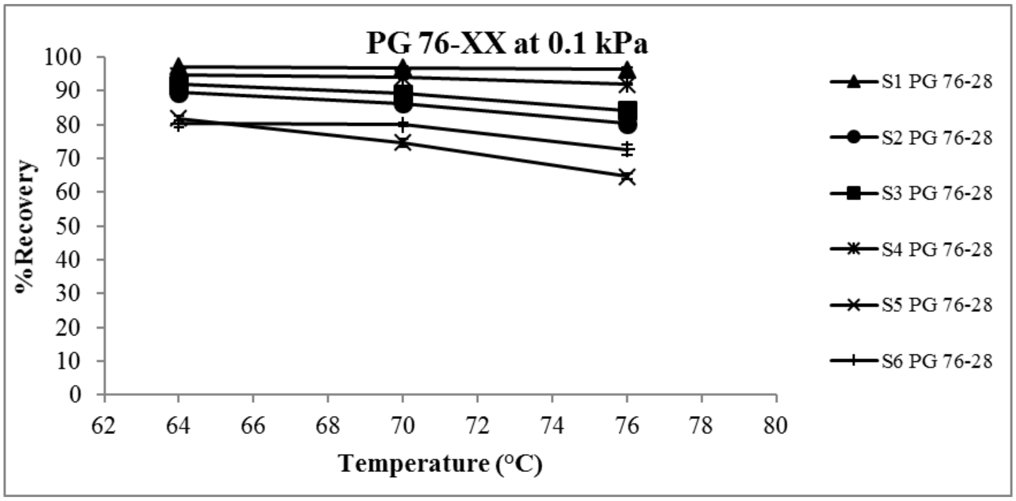


(a)

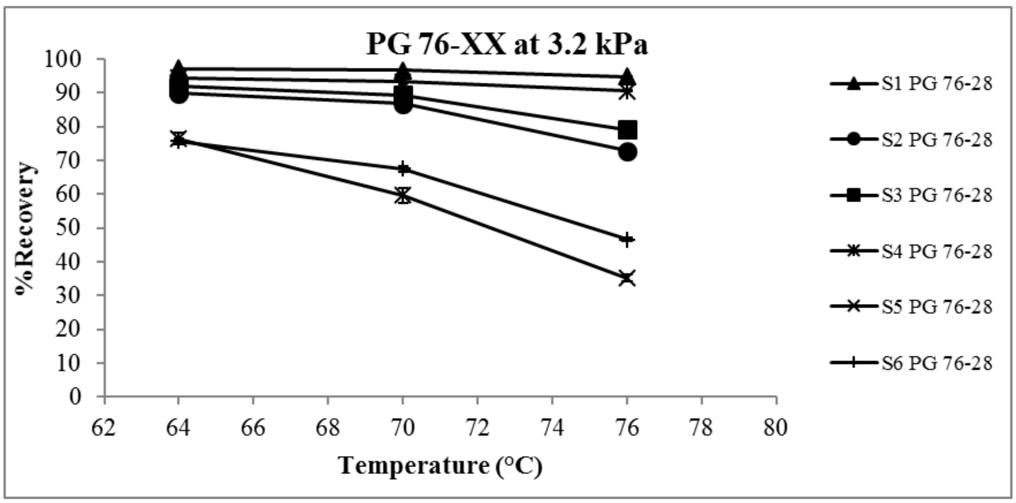


(b)

Figure 4.25 Changes in %Recovery with temperature for PG 70-XX binders: (a) 0.1 kPa stress level; (b) 3.2 kPa stress level



(a)

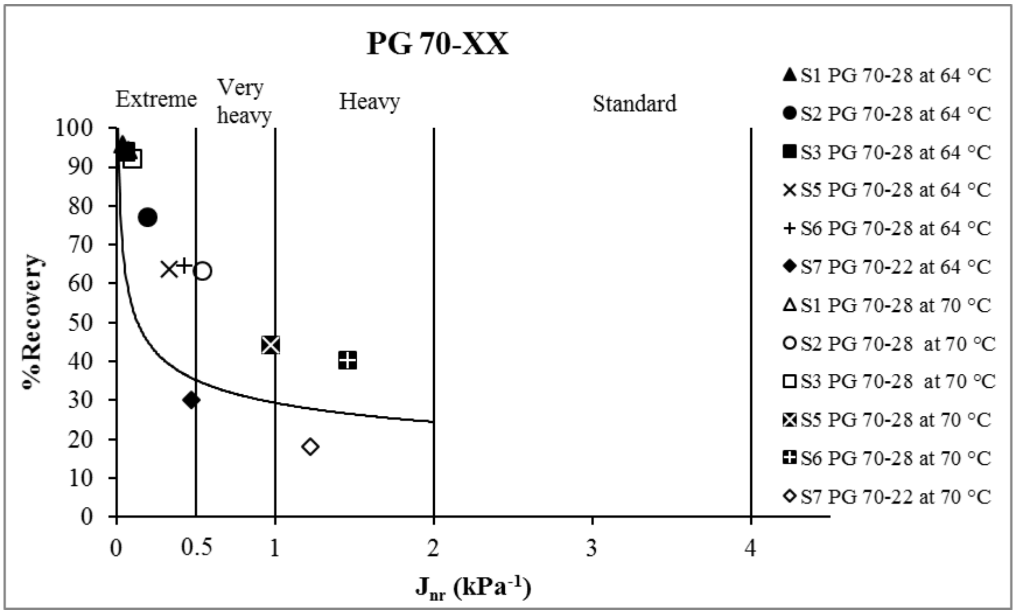


(b)

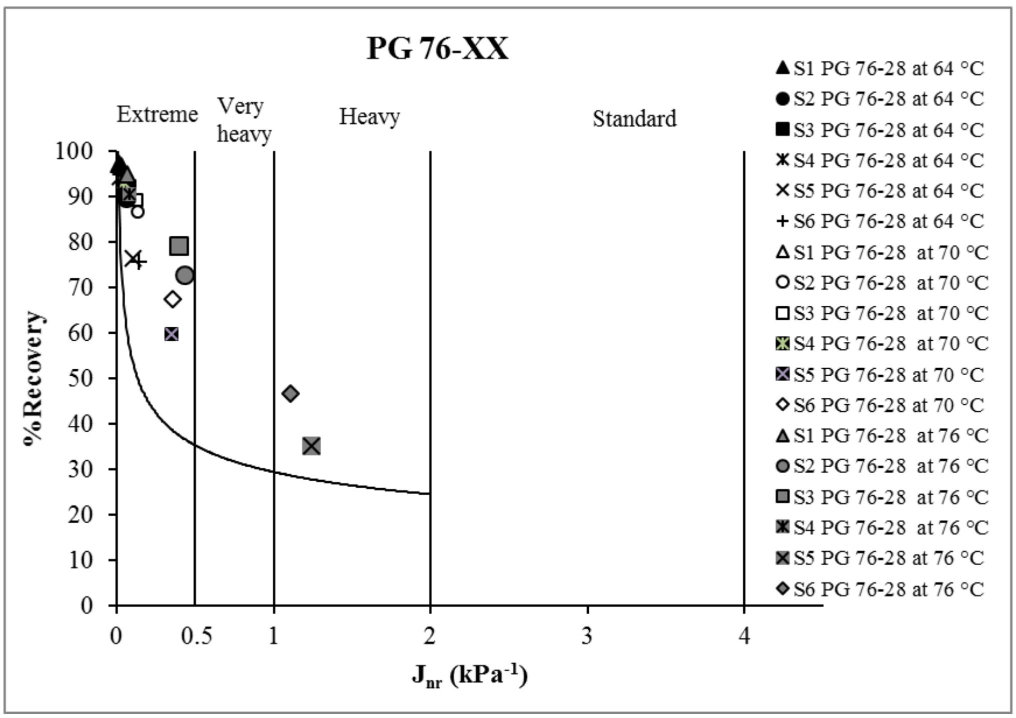
Figure 4.26 Changes in %Recovery with temperature for PG 76-XX binders: (a) 0.1 kPa stress level; (b) 3.2 kPa stress level

The polymer curve analyses of the PG 70-XX and PG 76-XX binders at higher temperature are presented in Figures 4.27 (a) and 4.27 (b). In Figure 4.27 (a), the J_{nr} values of the PG 70-XX binders at 64° and 70 °C are plotted against the corresponding %Recovery values. Likewise, in Figure 4.27 (b), the J_{nr} values of the PG 76-XX binders at 64°, 70° and 76 °C are plotted against the corresponding %Recovery values. As the

J_{nr} values of the PG 70-XX binders increased with an increase in the temperature from 64° to 70°, the MSCR grades of the binders were found to reduce. For example, the MSCR grade of the S6 PG 70-28 binder was observed to be PG 64E-28 whereas the same binder at 70 °C was found to reduce to PG 70H-28. This indicates that the binder can sustain extreme level of traffic at 64 °C but only heavy level of traffic at 70 °C, when used in an asphalt mixes. Therefore, the effect of an increase in temperature should be taken into account properly as the same binder can be graded differently at different temperatures. Stevens at al. (2015) reported that the effect of a single standard temperature drop (6 °C) might be equivalent to a single level increase in the traffic grade. However, the %Recovery requirement of all the PG 70-XX binders were found to meet the AASHTO TP 70 (AASHTO, 2013) criterion, except the S7 PG 70-22 binder. Although the PG 76-XX binders exhibited an increase in J_{nr} value with an increase in temperature, the effect of temperature change on MSCR grades was not significant. All of the PG 76-XX binders were found to meet the requirement of sustaining extreme traffic level at 64° and 70 °C. At 76 °C, only the PG 76-28 binders from S5 and S6 sources showed a reduced MSCR grade of PG 76H-28. Therefore, the PG 76-XX binders are expected to exhibit less temperature sensitivity than the PG 70-XX binders, as expected.



(a)

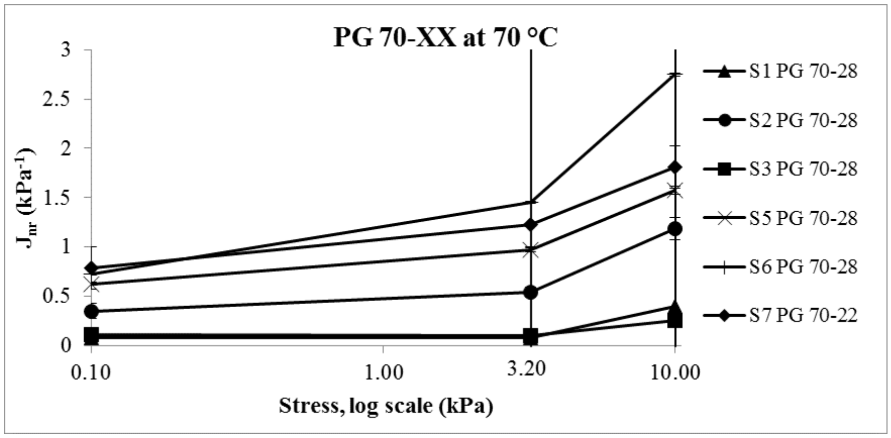


(b)

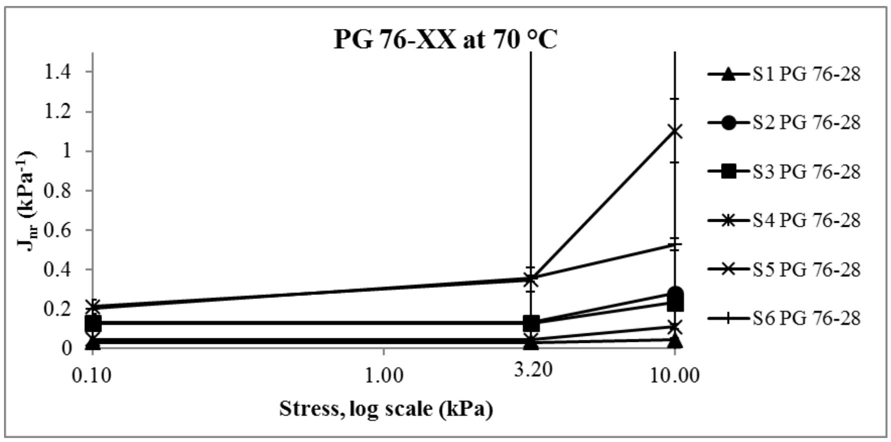
Figure 4.27 Polymer curve analyses at higher temperatures and 3.2 kPa stress level: (a) PG 70-XX binders; (b) PG 76-XX binders

4.3.1.8 Combined effect of increased stress level and higher temperature

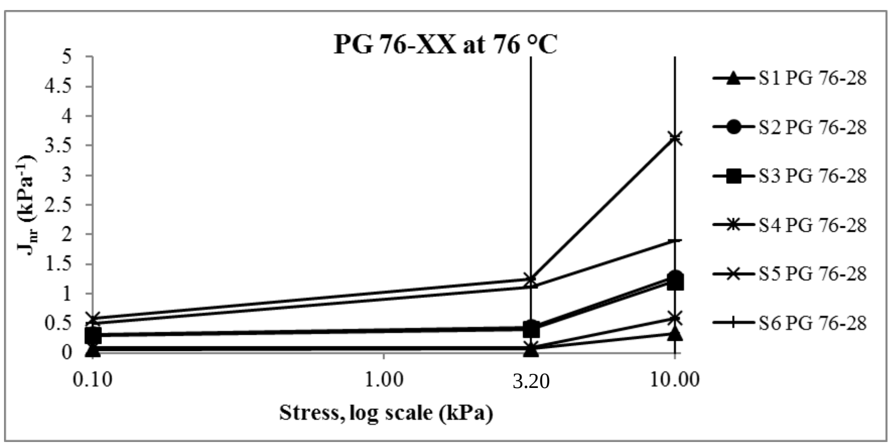
Figures 4.28 and 4.29 present the variation in the MSCR parameters of the PG 70-XX and PG 76-XX binders at different stress levels and temperatures higher than the standard procedure. As seen in Figure 4.28, the J_{nr} values were found to be almost independent of the stress levels up to 3.2 kPa, even at 70 °C for the PG 70-XX and at 76 °C for PG 76-XX binders. It is evident that at the first two stress levels, all the polymer-modified binders having the same continuous PG grade behaved very similarly. However, with an increase in the stress level to 10 kPa, the stress sensitivities of the PG 70-XX binders became clearer and the differences between the binders from different sources became prominent. However, at the 10 kPa stress level and higher temperature, the resistance to deformation of some of the binders dramatically decreased, which can be detected by a sharp increase in the J_{nr} values (Figure 4.28). Jafari et al (2015) reported that this kind of sharp increase in the J_{nr} value might be resulted from the damage of the binder structure. Furthermore, the non-linear behavior of polymer-modified binders from different sources can be better understood from the combined effect of a higher testing temperature and a higher stress level. As suggested by previous studies, an additional stress level higher than 3.2 kPa, such as 10 kPa for MSCR testing, may be helpful to characterize the non-linear behavior of the binder as well as the rutting resistance of the polymer-modified binders (Golalipour, 2011; Jafari et al., 2015).



(a)

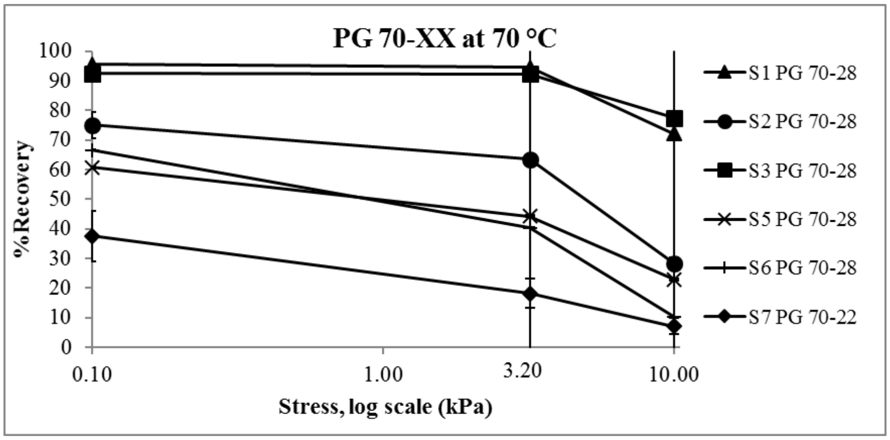


(b)

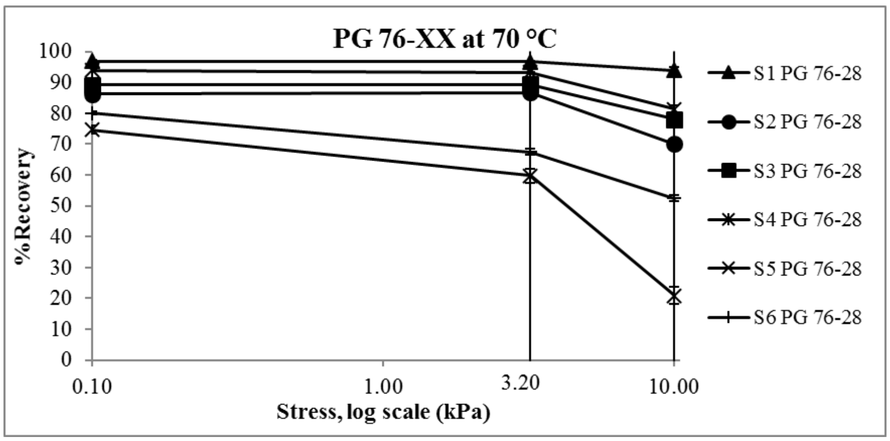


(c)

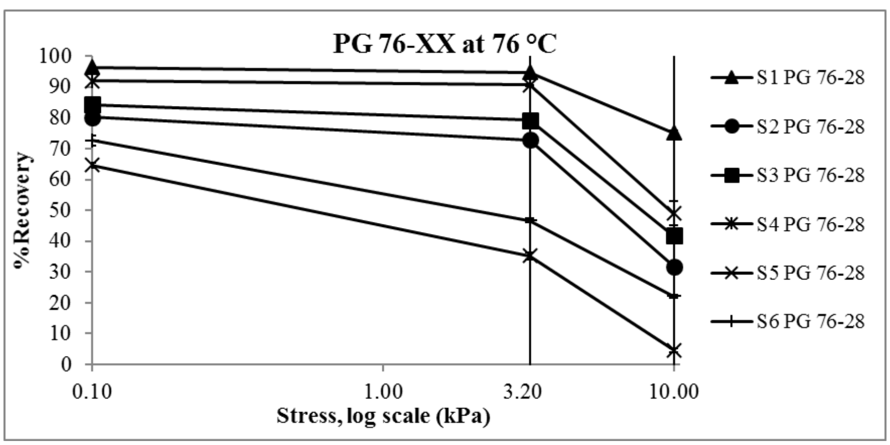
Figure 4.28 Changes in J_{nr} values with stress level: (a) PG 70-XX binders at 70 °C; (b) PG 76-XX binders at 70 °C; (c) PG 76-XX binders at 76 °C



(a)



(b)



(c)

Figure 4.29 Changes in %Recovery with stress levels: (a) PG 70-XX binders at 70 °C; (b) PG 76-XX binders at 70 °C; (c) PG 76-XX binders at 76 °C

4.3.2 RAP Binder Blends

The effect of the addition of RAP binders to the neat binder was evaluated using the MSCR test method. The MSCR tests were conducted on RTFO-aged binders' samples at 64 °C. Results of the J_{nr} (0.1 kPa), J_{nr} (3.2 kPa), $J_{nr\ diff}$, R_{100} and R_{3200} values and R_{diff} of the blended binders are presented in Table 4.7. The definition of the terms used in the table was presented in the Section 4.3.1.

Table 4.7 MSCR test results of 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends

Binder type	**Temp (°C)**	**J_{nr} (0.1 kPa) kPa^{-1}**	**J_{nr} (3.2 kPa) kPa^{-1}**	**$J_{nr\ diff}$ (0.1-3.2)**	**Stress sensitivity (meets AASTHO MP 19)**	**R_{100} (%)**	**R_{3200} (%)**	**R_{diff} (0.1-3.2)**	**%Recovery (meets AASTHO TP 70)**	**MSCR grade**
PG 64-22	64	1.46	1.80	23.13	Yes	16.44	3.60	78.05	No	PG 64H-XX
PG 64-22-R1-25	64	1.55	1.77	14.73	Yes	10.55	2.77	73.69	No	PG 64H-XX
PG 64-22-R1-40	64	0.99	1.14	15.25	Yes	15.22	5.61	63.13	No	PG 64H-XX
PG 64-22-R1-60	64	0.38	0.43	12.68	Yes	26.01	16.33	37.21	No	PG 64E-XX
PG 64-22-R2-25	64	1.17	1.35	15.35	Yes	13.43	4.53	66.25	No	PG 64H-XX
PG 64-22-R2-40	64	0.63	0.71	14.00	Yes	19.86	10.36	47.82	No	PG 64V-XX
PG 64-22-R2-60	64	0.19	0.20	7.02	Yes	31.29	26.26	16.06	No	PG 64E-XX

4.3.2.1 Non-recoverable creep compliance (J_{nr})

The J_{nr} values measured for the RAP binder blends at the 0.1 kPa and 3.2 kPa stress levels at 64 °C are presented in Figure 4.30. As noted earlier, binder with a low J_{nr} value is expected to result in a mix with better rutting resistance. From Figure 4.30, it was observed that the J_{nr} value increased with an increase in the stress level from 0.1 to 3.2 kPa. For example, the J_{nr} value measured for the PG 64-22 binder was found to increase from 1.46 to 1.80 kPa^{-1} when the stress level changed from 0.1 to 3.2 kPa. Also, from Figure 4.30, the J_{nr} values were observed to reduce with an increase in RAP binder content in the binder blends. As seen in Figure 4.30, the J_{nr} values of the PG 64-22 binder at the 3.2 kPa stress level was found to be 1.80 kPa^{-1}. It reduced to 1.77, 1.14 and 0.43 kPa^{-1} after incorporating 25%, 40% and 60% RAP1 binder, respectively. A similar reducing trend with an increase in RAP binder content was observed for RAP2 binder blends, as well. The PG 64-22-R2-25, PG 64-22-R2-40 and PG 64-22-R2-60 binders were found to exhibit J_{nr} values of 1.35, 0.71 and 0.20 kPa^{-1} at the 3.2 kPa stress level, respectively. As the J_{nr} values exhibited a reducing trend with increasing RAP binder, the binder blends are expected to exhibit a higher rutting resistance than the neat binders.

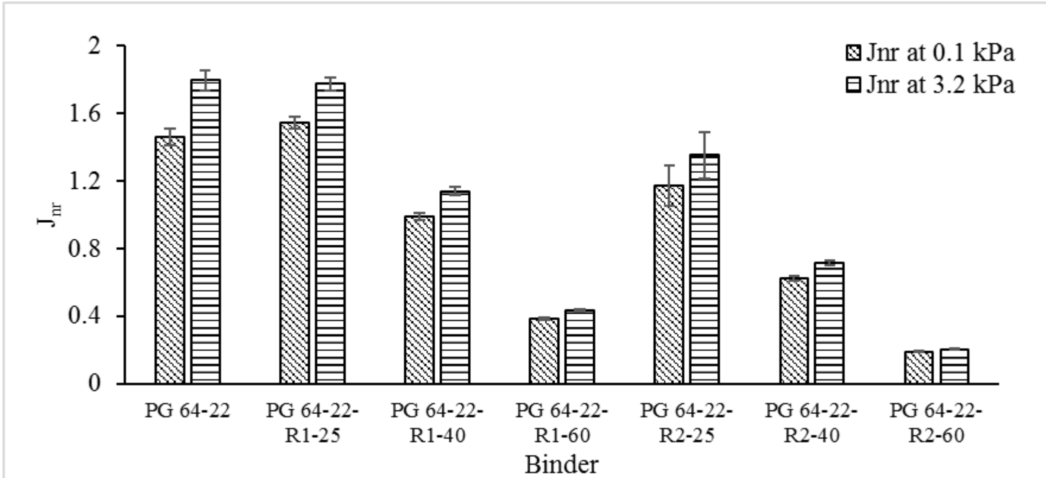


Figure 4.30 J_{nr} values of 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends at 64 °C

4.3.2.2 MSCR %Recovery

Figure 4.31 presents the %Recovery values obtained from MSCR tests conducted on RAP binder blends at 64 °C. Relatively low %Recovery values were observed as the binders were not polymer-modified. As expected, the %Recovery values at the 3.2 kPa stress level were found to be lower than that measured at the 0.1 kPa stress level for all of the RAP binder blends. Also, from Figure 4.31, it was found that the %Recovery values reduced due to the addition of 25% RAP1 binder to the blend. However, for the PG 64-22-R1-40 and PG 64-22-R1-60 binders, the %Recovery showed an increasing trend with an increase in RAP binder content. A similar increasing trend of %Recovery was also observed for RAP2 binder blends. Therefore, it can be concluded that the asphalt mixes produced with binder containing high RAP binder content are expected to exhibit a higher %Recovery at certain stress levels and temperatures than neat binders.

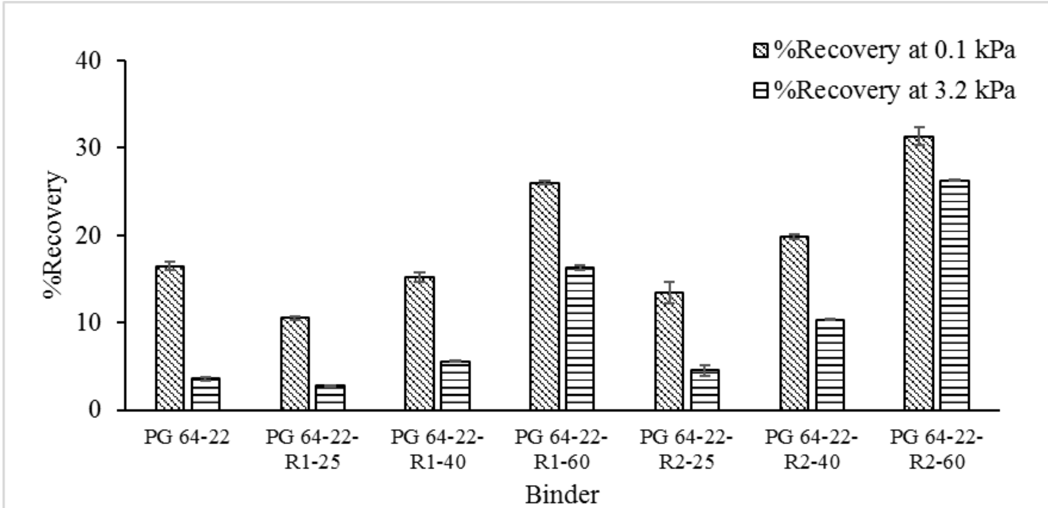


Figure 4.31 %Recovery values of 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends at 64 °C

4.3.1.3 Stress sensitivity

Figures 4.32 and 4.33 present the $J_{nr\ diff}$ and R_{diff} for RAP binder blends while the stress level changed from 0.1 kPa to 3.2 kPa at 64 °C. It can be observed from Figure 4.32 that the $J_{nr\ diff}$ values for all the RAP binder blends met the AASHTO MP 19 (AASHTO, 2010) stress sensitivity criterion ($J_{nr\ diff}$ <75%). The maximum $J_{nr\ diff}$ value was observed for the neat PG 64-22 binder (23.13%). The $J_{nr\ diff}$ values of the RAP binder blends were found to exhibit a reducing trend with an increase in the RAP binder. From Figure 4.32, the $J_{nr\ diff}$ values were found to reduce to 14.73%, 15.25% and 12.68% with the addition of 25%, 40% and 60% RAP1 binder, respectively. The RAP2 binder blends also exhibited a sharp reducing trend with an increase in RAP binder content. The $J_{nr\ diff}$ values for the PG 64-22-R2-25, PG 64-22-R2-40 and PG 64-22-R2-60 binders were observed to be 15.35%, 14.01% and 7.02%, respectively. Furthermore, from Figure 4.33, the R_{diff} values of the RAP binder blends exhibited a similar reducing trend as observed for $J_{nr\ diff}$ with an increase in RAP binder content. The R_{diff} values were found to decrease from 78.05% to 73.70%, 63.13% and 37.21% for the PG 64-22-R1-25, PG 64-22-R1-40 and PG 64-22-R1-60 binders, respectively. Therefore, it can be concluded that both MSCR parameters, namely J_{nr} and %Recovery became less sensitive to stress level with an increase in the RAP binder to the binder blend.

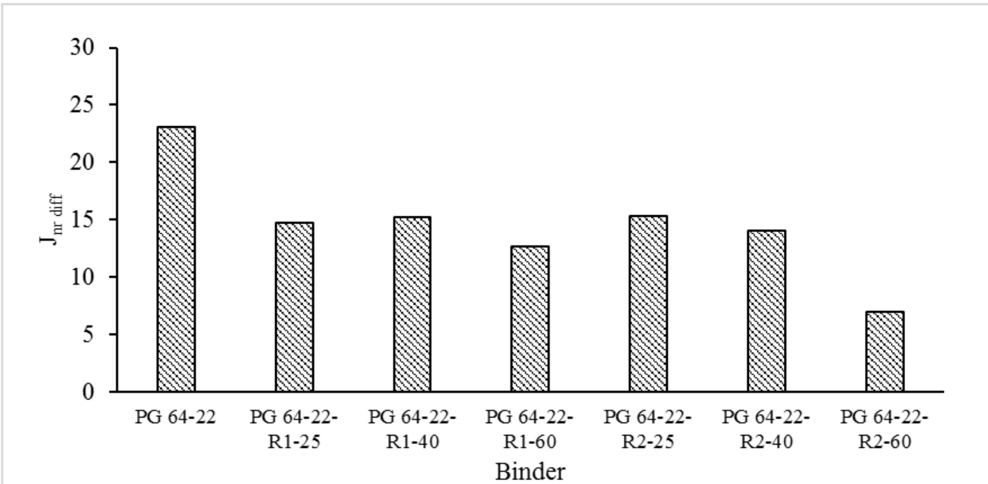


Figure 4.32 $J_{nr\ diff}$ values of 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends at 64 °C

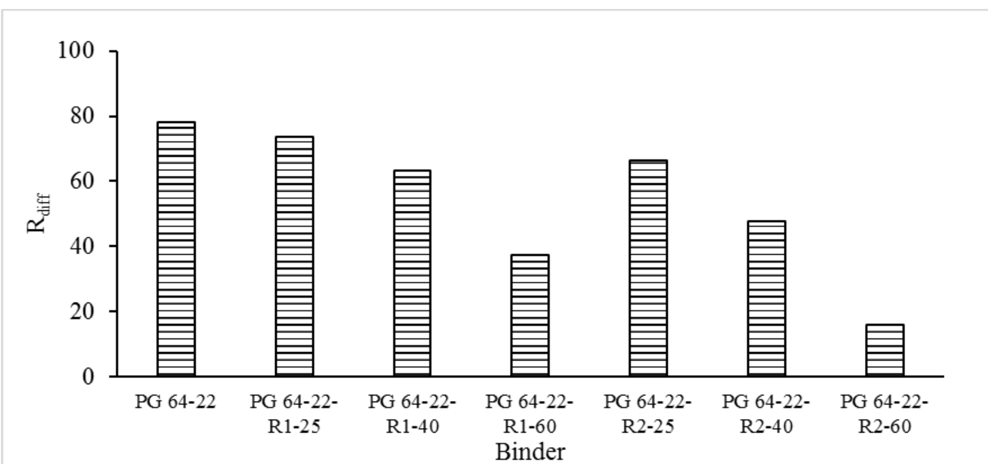


Figure 4.33 R_{diff} values of 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends at 64 °C

4.3.2.4 Polymer method

The MSCR results, analyzed using polymer curve, for RAP binder blends are presented in Figure 4.34. From Figure 4.34, it can be seen that the data points for the RAP binder blends clustered below the MSCR curve. This means that, these binders did not meet the %Recovery requirement proposed by AASHTO TP 70 (AASHTO, 2013). A low %Recovery was expected, as both the neat binder and RAP binders were not polymer-modified. The RAP binder blends are expected to perform better in rutting as the J_{nr} value reduced and %Recovery increased with an increase in the RAP binder content.

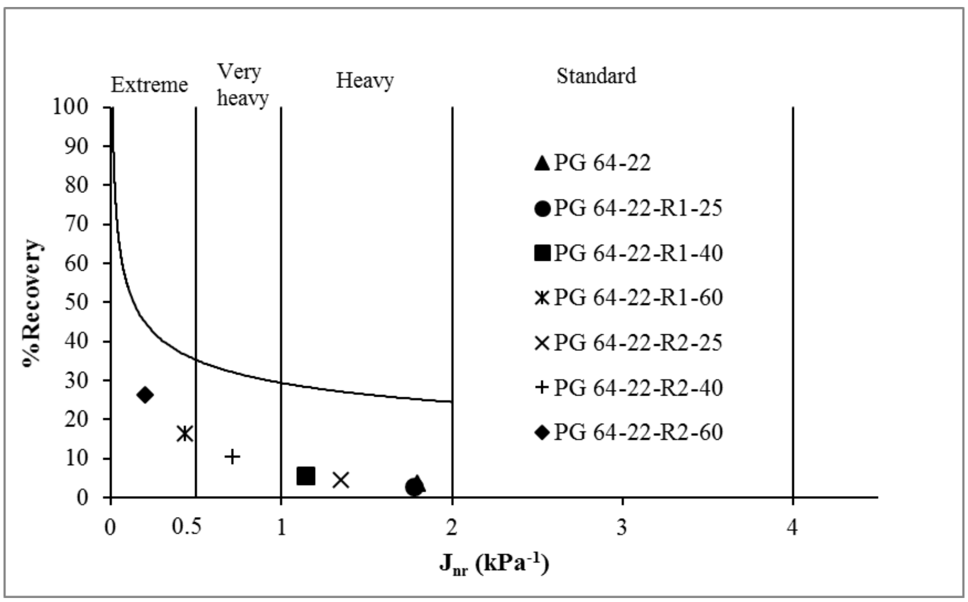


Figure 4.34 Polymer curve analysis for 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends at 64 °C and 3.2 kPa stress level

4.3.2.5 MSCR grading system

Table 4.7 and Figure 4.54 present the MSCR grading of the RAP binder blends determined according to the AASHTO MP 19 (AASHTO, 2010) specification. The

MSCR grade of the PG 64-22 binders was found to be PG 64H-XX. It means that the binder will be able to sustain heavy level of traffic at 64 °C without undergoing significant rutting, when used in asphalt mixes. Also, the equivalent MSCR grade of the PG 64-22-R1-25, PG 64-22-R1-40 binders were observed to be PG 64H-XX, the same grade as the neat binder. However, the MSCR grade of the PG 64-22-R1-60 binder was found to be PG 64E-XX, which is expected to sustain extreme level of traffic without exhibiting significant permanent deformation. The equivalent MSCR grades of the PG 64-22-R2-25, PG 64-22-R2-40 and PG 64-22-R2-60 binders were found to be PG 64H-XX, PG 64V-XX and PG 64E-XX, respectively. These results indicate that the MSCR grade of the neat binder is expected to increase with an increase in the amount of RAP binder in the blend.

4.3.2.6 Effect of increased stress level

The stress sensitivity of the RAP binder blends was determined at a higher stress level (10 kPa), in addition to the recommended stress levels in AASHTO TP 70 (AASHTO, 2013). Table 4.8 presents the MSCR test results conducted on the RAP binder blends at three different stress levels and at 64 °C.

Figures 4.35 and 4.36 show the changes in J_{nr} and %Recovery values with an increase in the stress level at 64 °C. The J_{nr} value for the neat PG 64-22 binder was observed to increase significantly with a change in the stress level from 3.2 to 10 kPa. Approximately 46% increase in J_{nr} value was observed when the stress level changed from 3.2 to 10 kPa. Also, a similar increase in J_{nr} value was observed for the other RAP binder blends. Therefore, it can be concluded that, the J_{nr} parameter of the RAP binder blends exhibited a higher stress sensitivity at 10 kPa stress levels than that at 0.1 and 3.2 kPa stress levels. Furthermore, the %Recovery of the RAP binder blends was found to exhibit sharp decrease with an increase in stress level from 3.2 to 10 kPa. As seen in Figure 4.36, the %Recovery value of the PG 64-22-R1-25 binder at 0.1, 3.2 and 10 kPa stress levels were 10.55%, 2.78%, and 0.17%, respectively. This indicates that the MSCR parameters of the RAP binder blends became overly stress sensitive with an increase in stress level.

Table 4.8 MSCR test results of 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends at 64 °C and 0.1, 3.2 and 10 kPa

Binder type	**Temp (°C)**	**J_{nr} (0.1 kPa) kPa^{-1}**	**J_{nr} (3.2 kPa) kPa^{-1}**	**J_{nr} (10 kPa) kPa^{-1}**	**$J_{nr\ diff}$ (0.1-3.2)**	**$J_{nr\ diff}$ (3.2-10)**	**R_{100} (%)**	**R_{3200} (%)**	**R_{10000} (%)**	**R_{diff} (0.1-3.2)**	**R_{diff} (3.2-10)**
PG 64-22	64	1.46	1.79	2.63	23.13	46.54	16.44	3.61	-0.34	78.05	109.30
PG 64-22-R1-25	64	1.55	1.77	2.16	14.73	22.21	10.55	2.78	0.17	73.69	94.02
PG 64-22-R1-40	64	0.99	1.14	1.40	15.25	22.96	15.22	5.62	1.28	63.13	77.23
PG 64-22-R1-60	64	0.38	0.43	0.54	12.68	26.97	26.01	16.33	5.44	37.21	66.6
PG 64-22-R2-25	64	1.17	1.35	1.63	15.35	20.98	13.43	4.53	0.89	66.25	80.15
PG 64-22-R2-40	64	0.63	0.71	0.87	14.01	22.28	19.86	10.36	3.19	47.82	69.15
PG 64-22-R2-60	64	0.19	0.20	0.25	7.02	20.82	31.29	26.26	14.15	16.06	46.09

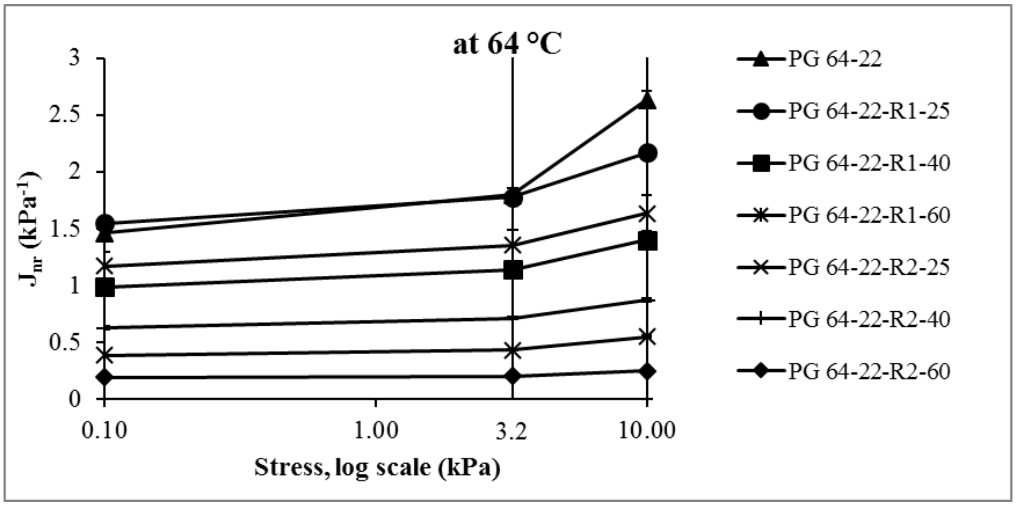


Figure 4.35 Changes in J_{nr} values with stress levels for 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends at 64 °C

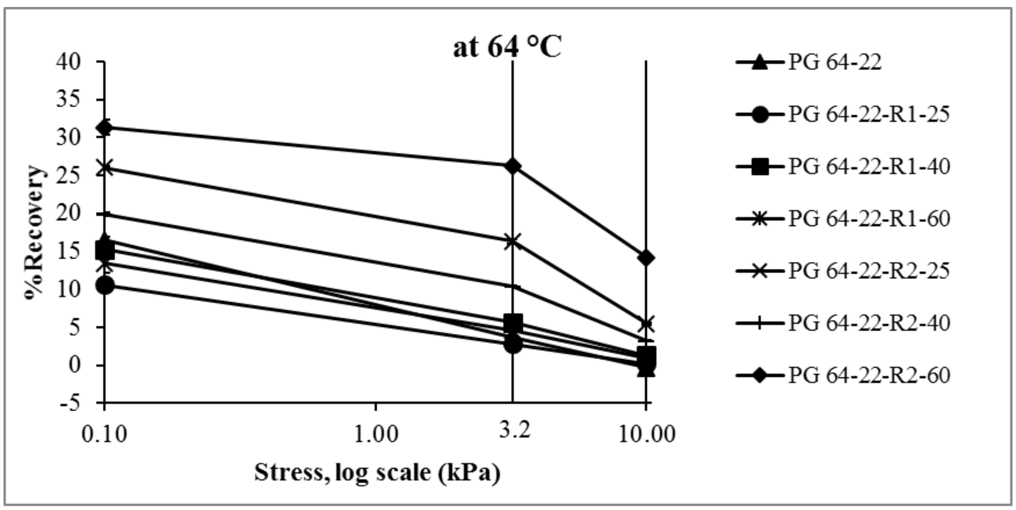


Figure 4.36 Changes in %Recovery values with stress levels for 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends at 64 °C

Figures 4.37 and 4.38 present changes in the $J_{nr\ diff}$ and $\%R_{diff}$ values with a change in stress level for RAP binder blends, respectively. The $J_{nr\ diff}$ and $\%R_{diff}$ between 10 kPa and 3.2 kPa stress levels were found to be higher than those between 3.2 kPa and 0.1 kPa stress levels. This means that the RAP binder blends became more sensitive to stress levels, when the stress level changed from 3.2 to 10 kPa. Also, the neat binder was observed to exhibit higher stress sensitivity than the RAP binder blends.

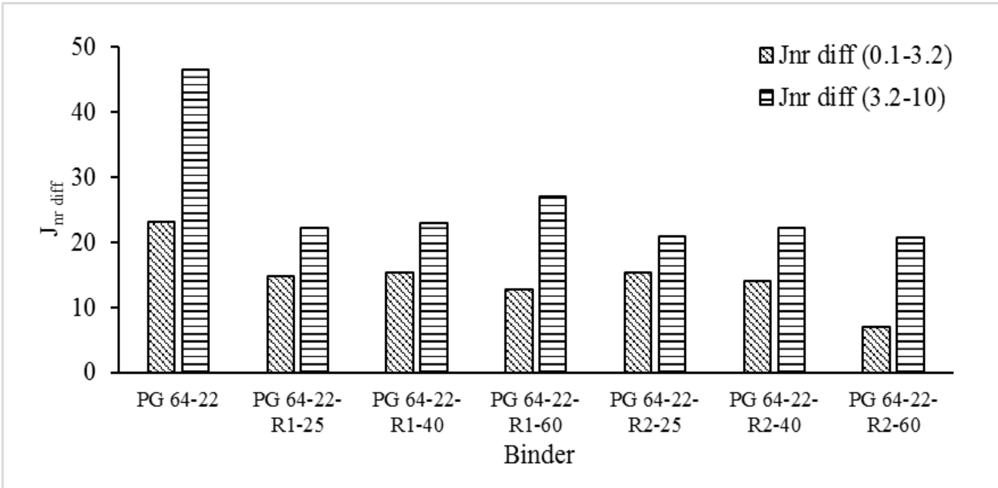


Figure 4.37 Variation in $J_{nr\ diff}$ with stress levels for 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends at 64 °C

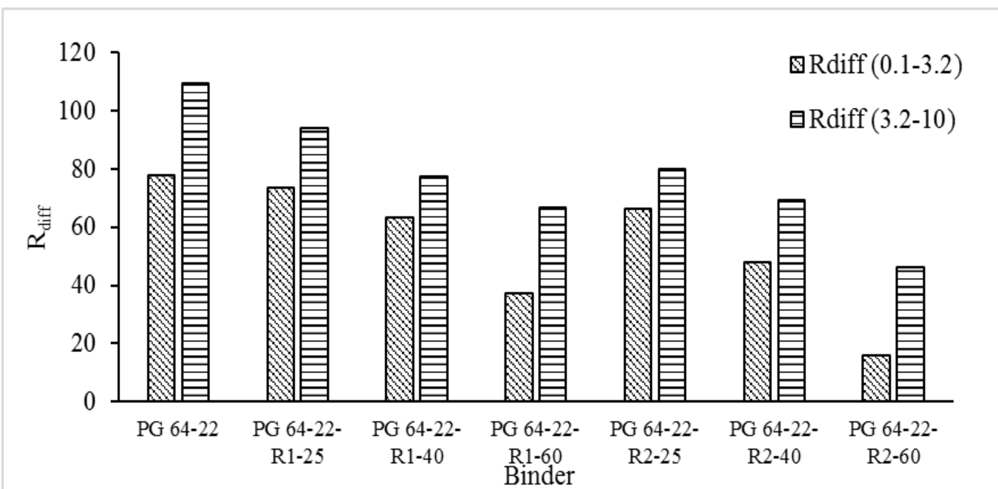
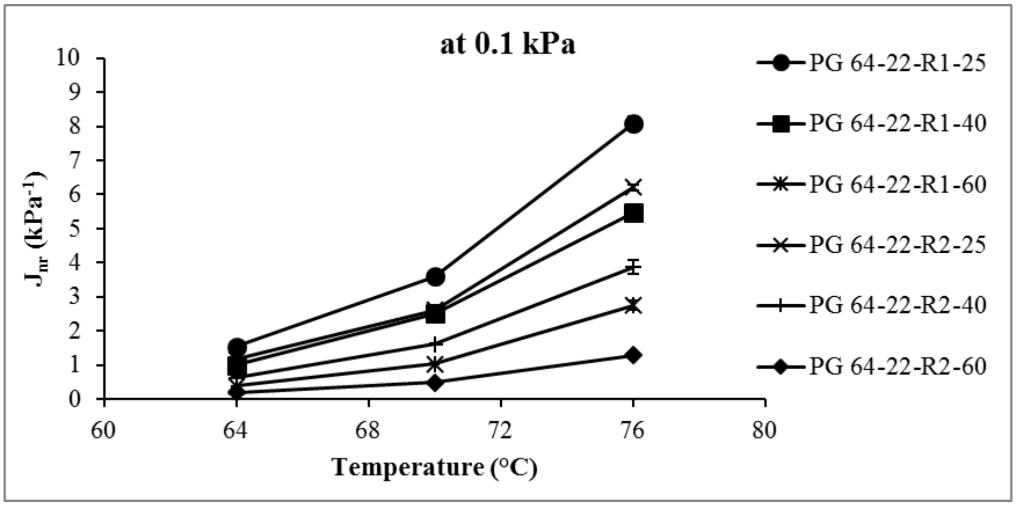


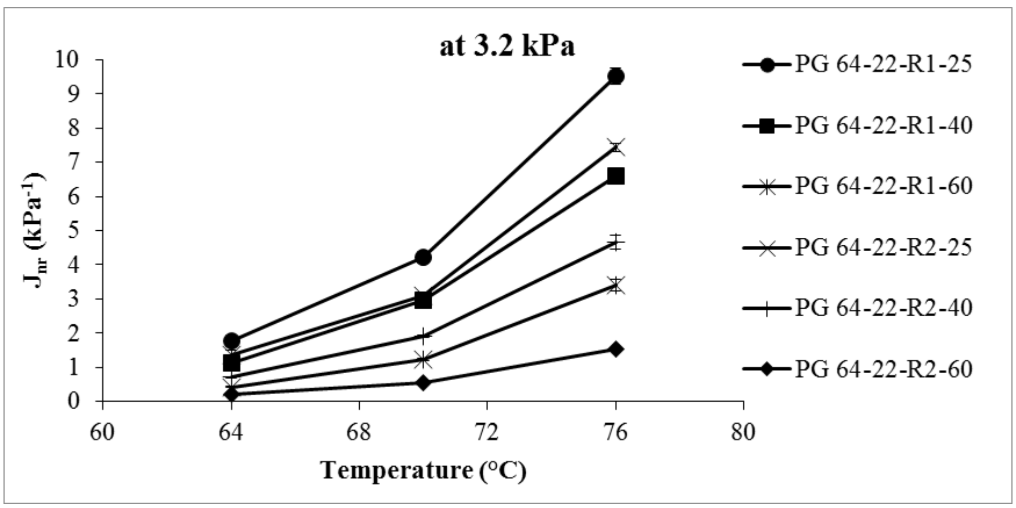
Figure 4.38 Variation in R_{diff} with stress levels for 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends at 64 °C

4.3.2.7 Effect of higher temperatures

In order to evaluate the temperature sensitivity of the MSCR parameters, the RAP binder blends were tested at temperatures (70° and 76 °C) higher than 64 °C. Figures 4.39 and 4.40 present the variation of J_{nr} and %Recovery values with temperature at 0.1 and 3.2 kPa stress levels, respectively. From Figure 4.39, it can be observed that the J_{nr} values exhibited an increasing trend with an increase in temperature. For example, the J_{nr} value of the PG 64-22-R1-25 binder at 3.2 kPa stress level was found to increase from 1.77 kPa^{-1} to 4.21 and 9.53 kPa^{-1} when the temperature increased from 64° to 70° and 76 °C, respectively. Also, from Figure 4.40, it is evident that the %Recovery reduced with an increase in temperature for all of the RAP binder blends. Furthermore, at 3.2 kPa stress level, the %Recovery for the PG 64-22-R1-25 binder was found to be 2.78% at 64 °C, whereas it reduced to 0.15% and -1.9% at 70° and 76 °C, respectively. The negative %Recovery implies that the binder underwent continuous deformation even after the removal of the load. Jafari et al. (2015) reported that the negative recovery can result from a combination of high stress level and high temperature, if it caused the binders to enter the tertiary flow level. It can be interpreted that the structure of the binder might be damaged at this temperature. Figure 4.41 presents the polymer curve analysis of RAP binder blends at 70° and 76 °C. From Figure 4.41, it can be observed that the MSCR grade of the binder reduced with an increase in temperature. For example, the MSCR grade of the PG 64-22-R1-60 binder was found to reduce from extreme to very heavy when the temperature increased from 64° to 70 °C. This means that the RAP binder blends are expected to become more susceptible to rutting with an increase in temperature.

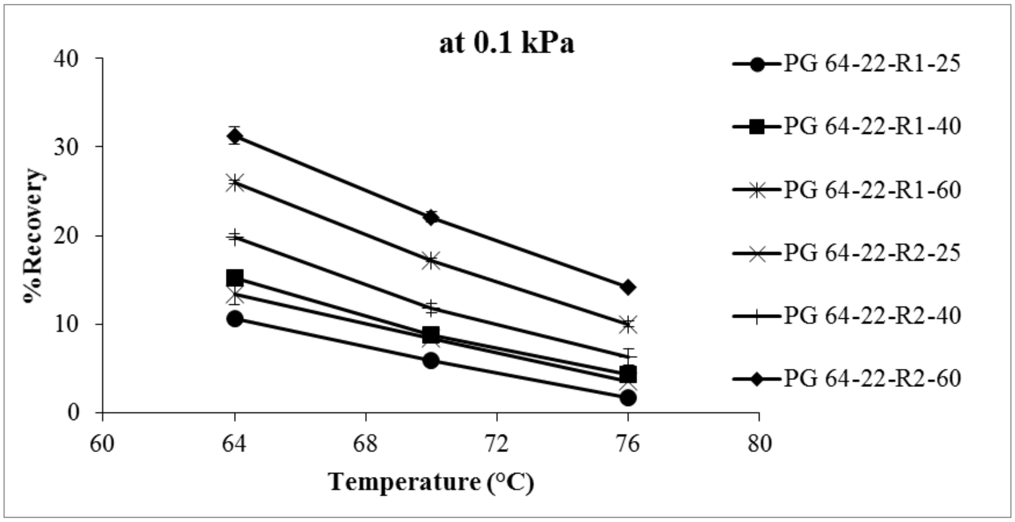


(a)

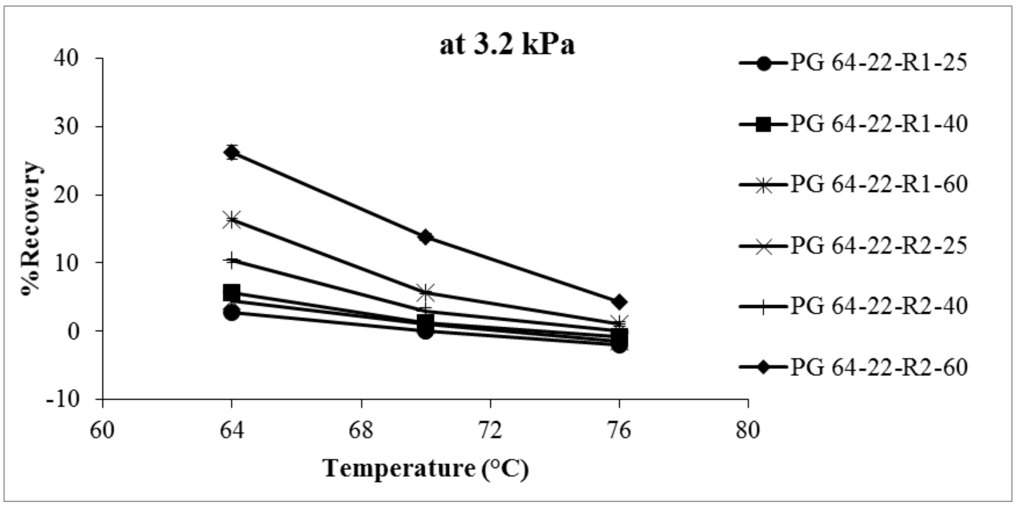


(b)

Figure 4.39 Changes in J_{nr} values with an increase in temperature for 25%, 40% and 60% RAP1 and RAP2 binder blends: (a) 0.1 kPa stress level; (b) 3.2 kPa stress level



(a)



(b)

Figure 4.40 Changes in %Recovery values with an increase in temperature for 25%, 40% and 60% RAP1 and RAP2 binder blends: (a) 0.1 kPa stress level; (b) 3.2 kPa stress level

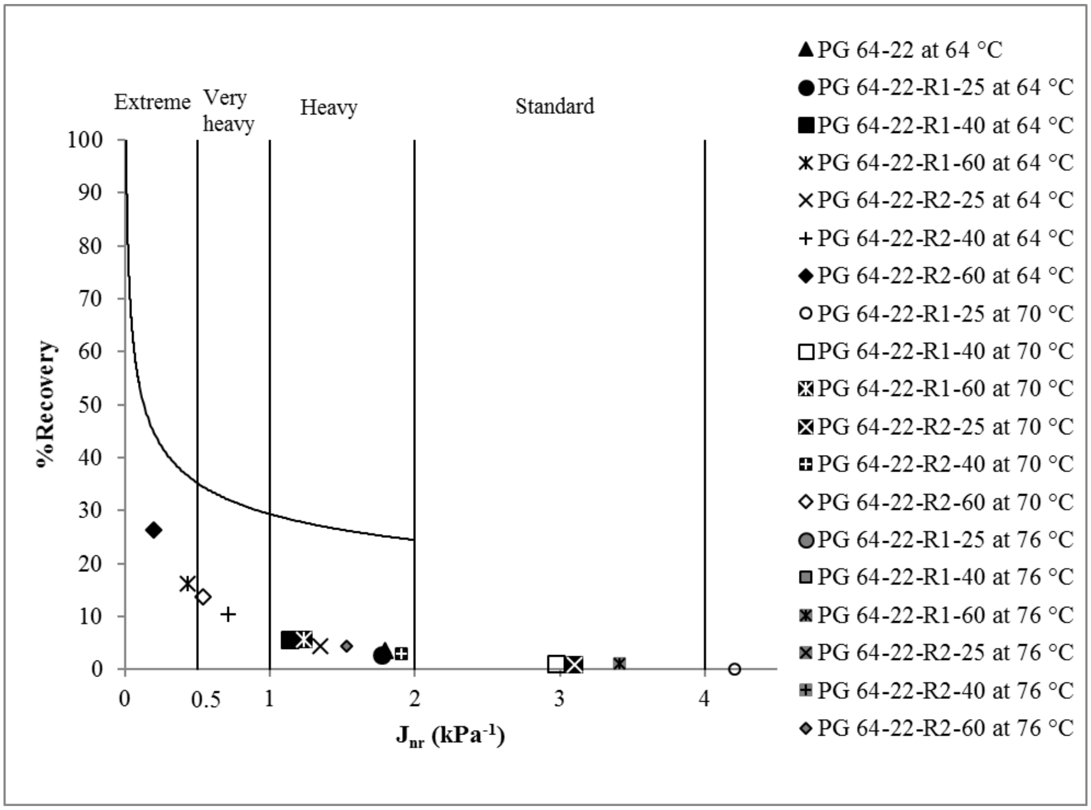
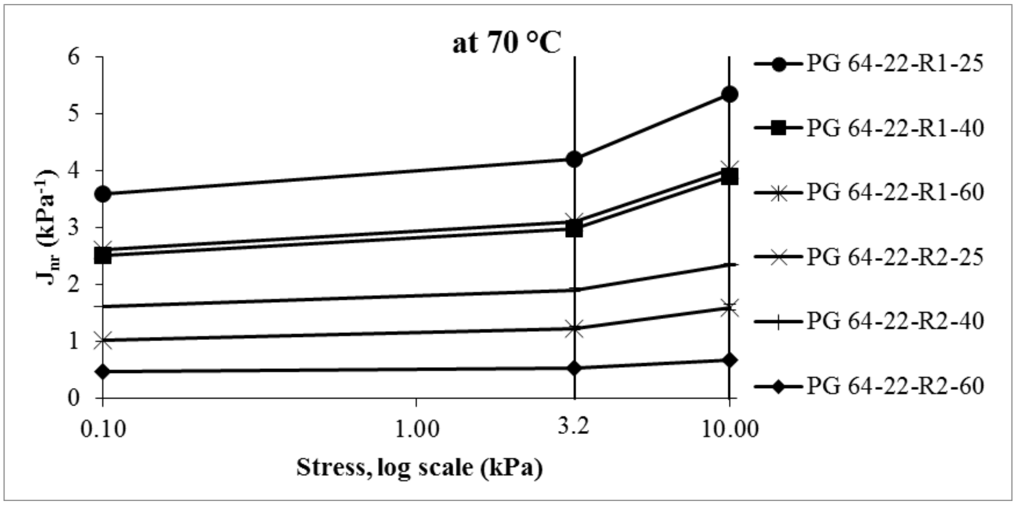


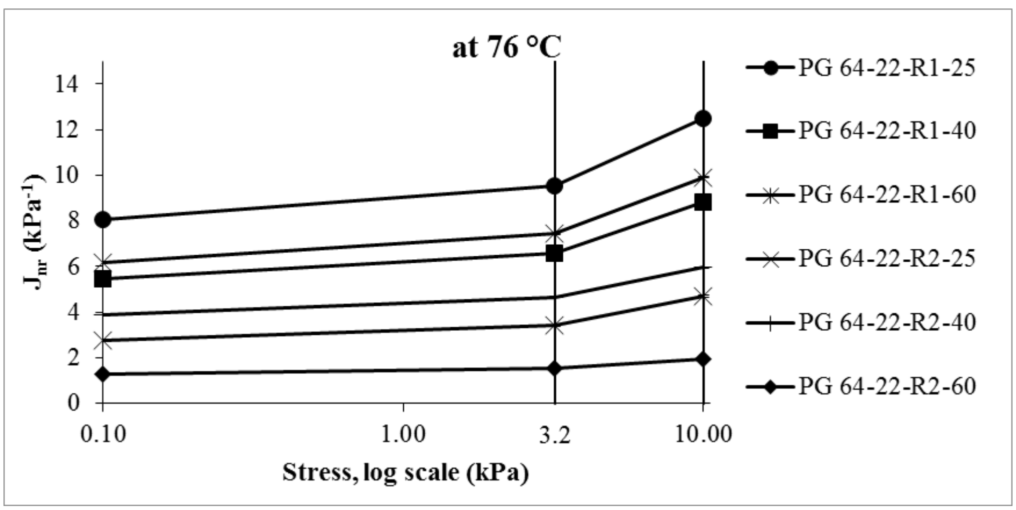
Figure 4.41 Polymer curve analysis for 0%, 25%, 40% and 60% RAP1 and RAP2 binder blends at different temperatures and 3.2 kPa stress level

4.3.2.8 Combined effect of increased stress level and higher temperature

Figures 4.42 and 4.43 present the changes in the MSCR parameters for RAP binder blends at higher stress levels and at higher temperatures than those used in conventional testing. As seen from Figures 4.42 and 4.43, the J_{nr} values increased and %Recovery values reduced with an increase in temperatures and stress levels. Also, at 70° and 76 °C, the stress sensitivities of the MSCR parameters of RAP binder blends became prominent with an increase in the stress level from 3.2 to 10 kPa. Except for the PG 64-22-R2-60 binder, all of the RAP binder blends exhibited a sharp reduction in %Recovery values at 76 °C temperature and 10 kPa stress level. Therefore, the non-linear behavior of the RAP binder blends became clearer at higher temperature and higher stress levels. This finding is expected to help understand the rutting behavior of the RAP binder blends, since the rutting itself is known to be a non-linear viscoelastic phenomenon observed in asphalt mixes.

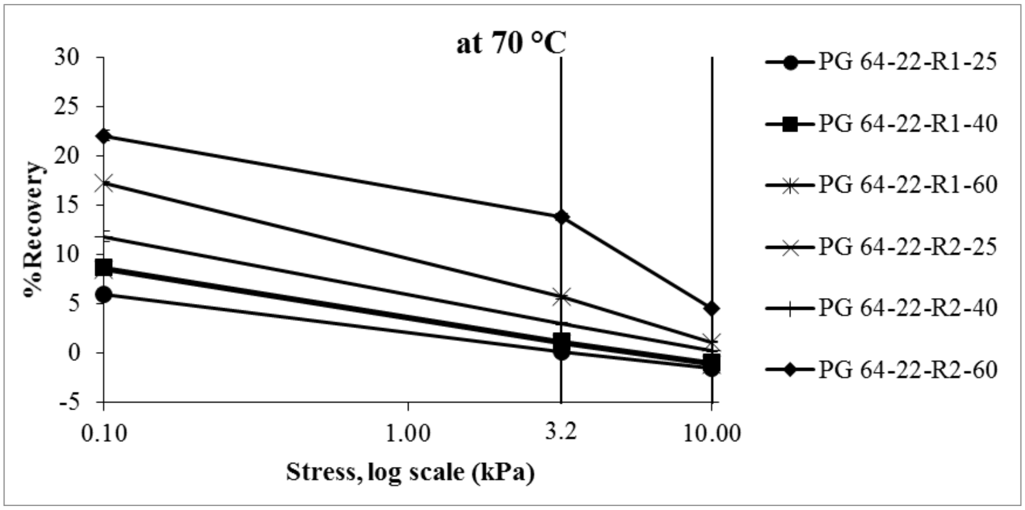


(a)

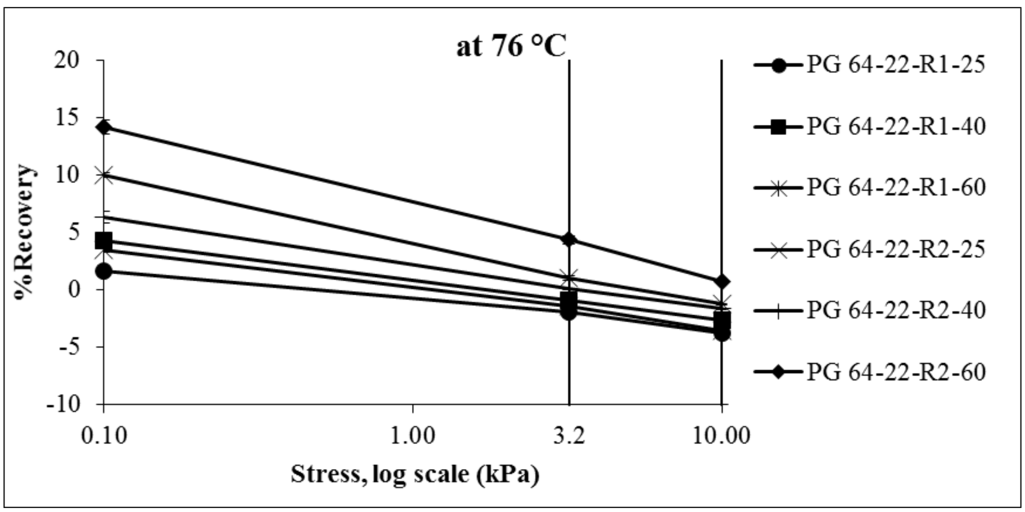


(b)

Figure 4.42 Changes in J_{nr} values with stress level for 25%, 40% and 60% RAP1 and RAP2 binder blends at 70° and 76 °C



(a)



(b)

Figure 4.43 Changes in %Recovery values with stress level for 25%, 40% and 60% RAP1 and RAP2 binder blends at 70° and 76 °C

4.4 Comparison of DSR and MSCR Test Results

4.4.1 Ranking of Binders

4.4.1.1 Polymer-modified binders

Tables 4.9 and 4.10 present the ranking of the polymer-modified binders based on their rutting performance determined from the DSR and MSCR tests. The binders were ranked based on the |G*|/sinδ value at corresponding high temperature. A lower |G*|/sinδ value was considered to be associated with less resistant to rut in this ranking system. Also, the J_{nr} values from MSCR test at different temperatures and stress levels were used to rank the binders. A binder exhibiting the lowest J_{nr} value was considered to exhibit highest rut resistant behavior and vice versa. From Tables 4.9 and 4.10, the DSR and MSCR test methods were observed to rank the polymer-modified binders differently. For example, the S1 PG 70-28 binder was ranked the lowest rut resistant binder according to the DSR test results among all the PG 70-XX binders. However, the same binder ranked differently (highest resistance to rutting), based on the J_{nr} values. The ranks of the S2 PG 70-28, S2 PG 76-28 and S6 PG 70-28 binders were found to be similar for both ranking systems. Similar differences in ranking of binders by different test methods were reported by Zhang at al. (2015). The variations in sensitivity of the |G*|/sinδ and J_{nr} to binders' viscoelastic properties are assumed to be a primary reason for such differences in binders' ranking. Previous studies have reported better correlations between J_{nr} values and field rutting performance than the |G*|/sinδ values of asphalt binders (Bahia et al., 2001; DuBois et al., 2014; Zhang at al., 2015). Therefore, the MSCR-based ranking of binders is expected to predict the rutting resistance better than the DSR-based ranking. However, no significant differences were observed in the MSCR-based ranking at different temperatures and stress levels. Therefore, the MSCR results at 64 °C and 0.1 or 3.2 kPa can be used for ranking and selection of asphalt binders with respect to their rutting resistance using the MSCR method.

Table 4.9 Ranking of PG 70-XX binders with respect to rut performance

Binder	DSR ranking based on |G*|/sinδ	MSCR ranking based on J_{nr}			
		64 °C		70 °C	
		0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa
S1 PG 70-28	6	1	1	1	1
S2 PG 70-28	3	3	3	3	3
S3 PG 70-28	4	2	2	2	2
S5 PG 70-28	2	4	4	4	4
S6 PG 70-28	5	5	5	5	5
S7 PG 70-22	1	6	6	6	6

Table 4.10 Ranking of PG 76-XX binders with respect to rut performance

Binder	DSR ranking based on |G*|/sinδ	MSCR ranking based on J_{nr}					
		64 °C		70 °C		76 °C	
		0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa
S1 PG 76-28	6	1	1	1	1	1	1
S2 PG 76-28	4	4	4	4	4	4	4
S3 PG 76-28	5	3	3	3	3	3	3
S4 PG 76-28	1	2	2	2	2	2	2
S5 PG 76-28	2	5	5	6	5	6	6
S6 PG 76-28	3	6	6	5	6	5	5

4.4.1.2 RAP binder blends

The ranking of the RAP binder blends based on the DSR and MSCR test results is presented in Table 4.11. The |G*|/sinδ values of the RAP binder blends at 64 °C were used to rank their rutting performance. Also, the J_{nr} values of the RAP binder blends at different temperatures and stress levels were used in this ranking. Similar to polymer-modified binders, the |G*|/sinδ and J_{nr} values ranked the binders differently. Based on the |G*|/sinδ results, the PG 64-22 binder ranked poorly with the lowest resistance to rutting. The same method ranked the PG 64-22-R1-40 binder superior, with the highest resistance to rutting. The PG 64-22-R2-60 binder and the neat binder were ranked as the binders with the highest and the lowest resistance to rutting based on the J_{nr} value at 64 °C and 3.2 kPa stress level, respectively. Based on these findings, it was concluded that the MSCR test results at 64 °C and 0.1 or 3.2 kPa stress levels can be used to rank binders effectively for their resistance to rutting.

Table 4.11 Ranking of the RAP binder blends with respect to rut performance

Binder	**DSR ranking based on |G*|/sinδ**	**MSCR ranking based on J_{nr}**					
		64 °C		**70 °C**		**76 °C**	
		0.1 kPa	**3.2 kPa**	**0.1 kPa**	**3.2 kPa**	**0.1 kPa**	**3.2 kPa**
PG 64-22	7	6	7	-	-	-	-
PG 64-22-R1-25	3	7	6	6	6	6	6
PG 64-22-R1-40	1	4	4	4	4	4	4
PG 64-22-R1-60	4	2	2	2	2	2	2
PG 64-22-R2-25	5	5	5	5	5	5	5
PG 64-22-R2-40	6	3	3	3	3	3	3
PG 64-22-R2-60	2	1	1	1	1	1	1

4.4.2 Repeatability of Test Results

Tables 4.12 and 4.13 present the coefficient of variation (COV) for the results obtained from the DSR and MSCR tests conducted on the PG 70-XX and PG 76-XX binders, respectively. The COV values of the DSR tests were calculated based on the |G*|/sinδ values measured for three binder samples at their corresponding PG temperature. The COV values reported for the MSCR test at each stress level and testing temperature were calculated based on the J_{nr} values measured for three binder samples. The MSCR test was found to exhibit higher COV values than the DSR test for both binder types. The COV values of the DSR test were found to vary between 0.89% and 6.54%, whereas those for the MSCR test varied from 0.08% to 27.25%. Therefore, it can be concluded that the MSCR test is expected to exhibit higher variability than the DSR test. Gollalipour (2011) also reported significantly higher variability of MSCR test parameters compared to the Superpave® parameters for the same binder.

Table 4.12 Coefficient of variation of the DSR and MSCR test of PG 70-XX binders

Binder	Coefficient of Variation of DSR Test	Coefficient of Variation of MSCR Test			
		64 °C		70 °C	
		0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa
S1 PG 70-28	3.21	6.24	6.44	4.39	4.56
S2 PG 70-28	0.89	3.03	2.80	21.85	9.06
S3 PG 70-28	1.95	1.95	1.92	3.56	3.60
S5 PG 70-28	1.00	2.35	3.41	5.89	6.31
S6 PG 70-28	2.79	2.33	4.16	0.26	0.36
S7 PG 70-22	1.82	19.07	14.26	27.25	17.86

Table 4.13 Coefficient of variation of the DSR and MSCR test of PG 76-XX binders

Binder	Coefficient of variation of DSR test	Coefficient of variation of MSCR test					
		64 °C		70 °C		76 °C	
		0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa
S1 PG 76-28	2.05	4.09	25.89	16.18	14.19	11.44	0.08
S2 PG 76-28	1.55	4.06	3.56	4.45	3.26	2.44	3.95
S3 PG 76-28	1.37	2.35	1.35	3.80	5.32	3.63	5.20
S4 PG 76-28	1.28	5.17	5.10	4.80	4.63	2.88	2.64
S5 PG 76-28	6.54	8.31	12.93	17.44	17.69	6.90	6.70
S6 PG 76-28	5.38	9.08	6.99	3.35	4.42	5.58	1.72

4.4.3 Subjective Comparison of DSR and MSCR Test Methods

A subjective comparison of DSR and MSCR test methods is presented in Table 4.14. This comparison is expected to help understand the suitability of the MSCR test in practice.

Table 4.14 Subjective comparison of the DSR and MSCR tests

DSR test	MSCR test
Simple test method	Simple DSR -based test method
Time consuming	Relatively less time consuming
Covers linear viscoelastic properties of the binders	Can be used to determine non-linear viscoelastic properties by adjusting stress level and temperature.
High repeatability and less variability	Higher variability than DSR test
Provides complex shear modulus and phase angle of binder	Determine non-recoverable creep compliance and %recovery of binders.
Cannot differentiate between polymer and non-polymer modified binders.	Differentiate between polymer and non-polymer-modified binders.

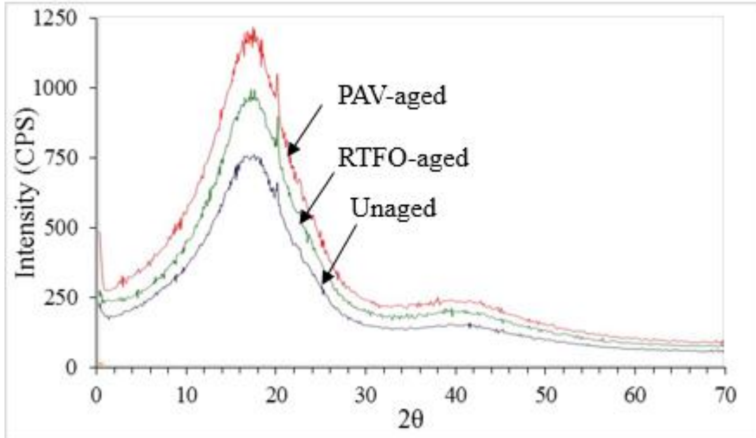
4.5 X-ray Diffraction (XRD) Test Results

The XRD spectra for the unaged, RTFO-aged, and PAV-aged samples of PG 58-28, PG 76-28, and PG 58-28 + 2% PPA binders are presented in Figures 4.44 (a), 4.44 (b), and 4.44 (c), respectively. The γ band, graphene (002), (10) and (11) bands are the four peaks generally observed after spectral analysis. The molecular structure of asphalt is the source of scattering the X-rays. The γ peak arises from X-rays scattered by aliphatic chains or condensed saturated rings. The graphene (002) band originates from the diffraction of X-rays from the stacks of aromatic molecules. The (10) and (11) bands are the first and the second nearest neighbors in the ring compounds and come from the reflections of the in-plane structure of the aromatics (Siddiqui et al., 2002). From Figures 4.44 (a), 4.44 (b), and 4.44 (c), it can be observed that, in general, the patterns of the fresh and aged binders are very similar and each contains the γ and graphene layer stacking peak and the (10) peak. The combined peak of γ and graphene (002) bands are observed between 2 to 30°. The (10) band is also observed at 2θ angle of 35° to 50°. However, since the test was limited to 2θ = 70°, the (11) band is missing from the XRD profiles. Profile fitting of the XRD spectra using the Pearson VII model was done to determine the peaks, 2θ, FWHM, peaks areas, and other parameters, including aromaticity and crystalline parameters. These parameters are discussed next.

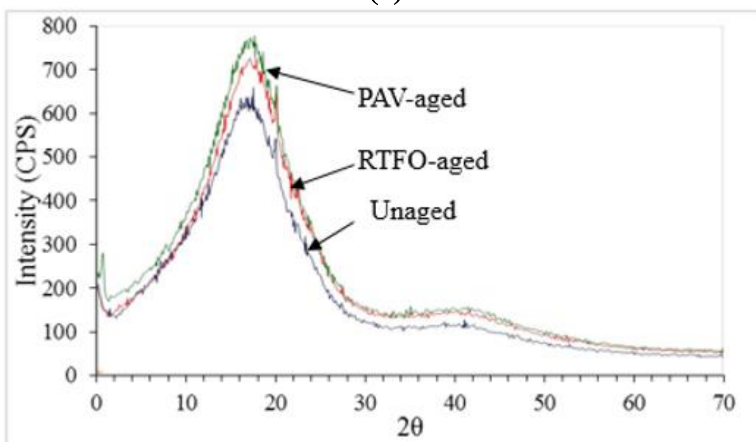
4.5.1 Aromaticity and Crystallite Parameters of PG 58-28 Binder

The aromaticity and different crystallite parameters for unaged, RTFO-aged, and PAV-aged PG 58-28 binders are presented in Table 4.15. The aromaticity (f_a) of the PG 58-28 binder is determined by calculating the areas of the γ and the (002)-graphene peaks from the profile-fitted curves. The XRD test results (Table 4.15) indicated that the unaged PG 58-28 binder had a f_a value of 0.84, which reduced to 0.79 after RTFO-aging and then increased to 0.83 after PAV-aging of the binder. This observation was found to be consistent with the findings of the previous studies (Siddiqui et al., 2002). According to Siddiqui et al. (2002), a reduction in f_a as a result of short-term aging is due to the hydrogenation of aromatic rings. The f_a results indicated that the binder lost its aromatic character after short-term aging, but it was able to regain some after long-term aging. Moreover, Siddiqui et al. (2002) suggested that the change in the reactive portion of the aromatic ring may be responsible for the change in aromaticity at different aging conditions. The layer distance between aromatic sheets (d_m) was found to decrease from 4.64 Å for an unaged binder to 4.59 Å in the short-term aged binder and then increase to 4.66 Å for the long-term aged binder. This indicated a compaction of aromatic ring as a result of short-term aging. However, it was found that the d_m increased due to long-term aging.

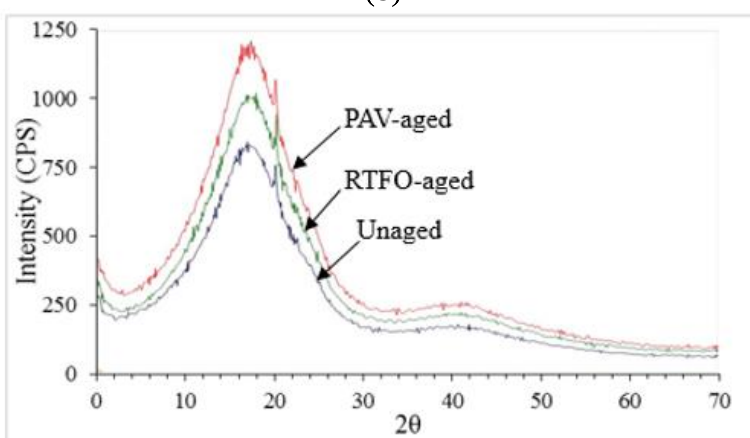
The distance between the saturated portions of the molecule known as inter-chain layer distance (d_γ) was found to decrease after short-term aging, but increase due to long-term aging of the binder. The unaged PG 58-28 binder possessed a d_γ value of 7.81 Å, which was found to reduce to 7.39 Å for the RTFO-aged binder and then increase to 4.83 Å for the PAV-aged binder. The height of the aromatic sheets (L_c) was found to decrease from 10.23 Å in the unaged binder to 8.41 Å in the RTFO-aged binder and then increase to 10.16 Å in the PAV-aged binder (Table 4.15). Siddiqui et al. (2002) suggested that this phenomenon can be seen if the aromatic ring system was not compact because of loose stacking due to oxidative aging. The number of aromatic sheets in stacked cluster, M, also exhibits a reduction due to short-term aging and then increase due to long-term aging. From Table 4.15, the M value was found to decrease from 3.20 in the unaged binder to 2.83 in the RTFO-aged binder and then increase to 3.20 in the PAV-aged binder. The M values also indicated that the compactness of aromatic sheet increased with short-term aging and then decreased with long-term aging.



(a)



(b)



(c)

Figure 4.44 XRD patterns of unaged, RTFO-aged and PAV-aged binders: (a) PG 58-28 binder; (b) PG 76-28 binder; (c) PG 58-28 binder with 2% PPA

4.5.2 Aromaticity and Crystallite Parameters of PG 76-28 Binder

Table 4.15 also presents the aromaticity and crystallite parameters for the PG 76-28 binder. According to Table 4.15, the f_a values of the unaged binder decreased consistently with aging. For example, the unaged PG 76-28 binder had a f_a value of 0.91, which decreased substantially to 0.88 and 0.87 with RTFO- and PAV-aging, respectively. These results indicated that the breaking of aromatic rings in a polymer-modified binder continues with aging. It was also observed that the d_m of the unaged binder decreased from 4.78 Å to 4.68 Å with short-term aging and remained almost unchanged (4.69 Å) with long-term aging. According to Table 4.15, aging also decreased the d_γ of polymer-modified binders. For example, the PG 76-28 binder exhibited a d_γ value of 9.58 Å that reduced to 8.56 Å for the both RTFO- and PAV-aged binders. Also, the L_c decreased substantially with aging. The L_c value varied from 14.01 Å for the unaged binder to 11.84 Å and 12.03 Å for RTFO-aged and PAV-aged binders, respectively. This indicated that the aromatic ring system became compact with aging. The M value was also found to decrease with aging. By evaluating all the aromaticity and crystallite parameters for the PG 76-28 binder, it can be observed that the differences in parameters between RTFO-aged and PAV-aged binder were negligible. Therefore, it can be concluded that for the tested polymer-modified binders, major changes in molecular structure took place during short-term aging, and the changes were negligible during PAV-aging.

Table 4.15 Aromaticity and crystallite parameters of binders

Aging condition	f_a	d_m (Å)	d_γ (Å)	L_c (Å)	M
PG 58-28					
Unaged	0.84	4.64	7.81	10.23	3.20
RTFO-aged	0.79	4.59	7.39	8.41	2.83
PAV-aged	0.83	4.66	8.25	10.16	3.18
PG 76-28					
Unaged	0.91	4.78	9.58	14.06	3.94
RTFO-aged	0.88	4.68	8.57	11.84	3.53
PAV-aged	0.87	4.69	8.56	12.03	3.57
PG 58-28 + 2% PPA					
Unaged	0.57	4.62	7.46	7.65	2.66
RTFO-aged	0.53	4.34	6.71	5.42	2.25
PAV-aged	0.53	4.34	6.66	5.20	2.20

4.5.3 Aromaticity and Crystallite Parameters of PG 58-28 + 2% PPA Binder

From Table 4.15, it was observed that the f_a value of the unaged PG 58-28 + 2% PPA binder was greater than that of RTFO- and PAV-aged binder. After short term-aging, the f_a value decreased from 0.57 to 0.53 and remained unchanged due to long term-aging. The d_m was also found to exhibit a similar trend as observed in case of aromaticity. The d_γ and L_c values of the unaged PG 58-28 + 2% PPA binder were also found to decrease with aging. The M value for the PG 58-28 + 2% PPA binder was also found to decrease significantly with aging. Considering all the parameters, it can be concluded that the major changes in molecular structure occurred during RTFO-aging. Further, changes in molecular structure due to PAV-aging were insignificant.

4.5.4 Effect of PPA and Polymer Modification on Aromaticity and Crystallite Parameters

The effect of adding PPA and polymer to the binder can be determined by comparing different aromaticity and crystallite parameters. From Figure 4.45, it is evident that the asphalt binder lost its aromatic character to some extent upon the addition of PPA for all aging conditions. From Figure 4.45, it can be observed that the f_a value of the PG 58-28 binder decreased from 0.84 to 0.57 as a result of the addition of PPA. This was attributed to the reaction of PPA with the asphalt compounds, which may cause a deterioration of aromatic rings and thus reduced aromaticity may happen. This phenomenon can be explained with the mechanism proposed by Masson et al. (2009): PPA is known to react with the functional group with high dielectric constant present in the asphalt binder. Strongly acidic PPA reacts with asphalt binder's weak base to form ionic pairs and replaces weak acids such as phenols during the reactions. A decrease in the molecular mass of the PPA-modified binder may be resulted from the loss of hydrogen bonds and release of alkylated phenol from a larger aromatic structure. Also, the disintegration of asphaltene may be responsible for the lower molecular weight asphalt compounds and change in morphology. In the present study, the decrease in aromaticity due to PPA modification may be a result of this reduction in molecular weight and change in morphology. The d_m was also found to decrease with PPA modification. Although the unmodified and the PPA-modified PG 58-28 binder showed very similar d_m values under unaged condition, significant differences in d_m values were observed due to RTFO- and PAV-aging. Another important observation was the compaction of aromatic ring of PPA-modified binder as a result of both short-term and long-term aging. However, aromatic ring compactness of the unmodified PG 58-28 binder was observed only for the short-term aged binder. The d_γ was also found to reduce with the addition of PPA. The d_γ values of the PG 58-28 + 2% PPA binder were 4.5%, 9.2%, and 19.3% lower than the corresponding values of the PG 58-28 binder under unaged, RTFO-aged, and PAV-aged conditions, respectively. The L_c values also exhibited a similar decreasing trend with PPA addition. Therefore, it is seen that the aromatic rings became more compacted with the addition of PPA. This effect was found to be more significant with aging. As noted earlier, addition of PPA results in an increase in the |G*| and a decrease in the phase angle values of the PG 58-28 binder. According to Masson et al. (2009), with the release of smaller molecules, a contracted phase of covalently bonded large molecules with restricted motion may be observed upon the addition of PPA in the binder. They also concluded that this increase in stiffer phase may increase the high temperature performance grade of a binder. This phenomenon explains the increase in |G*| as well as rutting parameter with the addition of PPA observed in this study. However, no clear correlation was observed between the crystallite parameters and |G*|.

The increase in viscosity of the PPA-modified binder may be a result of the compacting of aromatic rings with PPA modification. According to Peterson (2009), binders with highly condensed ring systems and chemical functional groups may be highly polar or polarizable which interact strongly with each other. This interaction between molecules can influence the flow behavior as well as viscosity. Therefore, it can be assumed that the compacting of aromatic rings with PPA modification may be responsible for the increased viscosity of the binder. Also, it was found that for the

PPA-modified binder, the difference in aromaticity and crystallite parameters was negligible between RTFO- and PAV-aging. This phenomenon may explain the improved fatigue parameter for PPA-modified binders when compared with the unmodified binder. However, further studies are needed to prove this hypothesis.

From Figure 4.45, it is clear that the polymer-modified binder showed a higher aromaticity than the unmodified PG 58-28 binder. This may be due to the formation of aromatic rings or splitting of aliphatic groupings during polymer modification. Also, the d_m for the PG 76-28 binder was higher than the unmodified binder. Addition of polymer may be resulted in an increase in the binder volume by absorbing maltenes fractions, which is responsible for the increase in the d_m value. The L_c value of the unmodified binder was found to increase from 10.23 to 14.06 Å with polymer modification. The same trend was observed for the M value. The polymer-modified binder also exhibited compacting of aromatic rings with aging. However, the change in the molecular structure remained almost unchanged after RTFO-aging. These observations may be used to explain the improved rutting and fatigue parameter for polymer modified binder, as discussed in the case of the PPA-modified binder (Ali et al., 2016). Soenen and Redelius (2014) reported that the binders with the compacted ring system, resulted from the interactions of aromatic molecules, are expected to exhibit reduced mobility and increased elasticity. Therefore, the compacted aromatic ring systems of PPA- and polymer-modified binders are expected to exhibit higher elasticity than the neat binder.

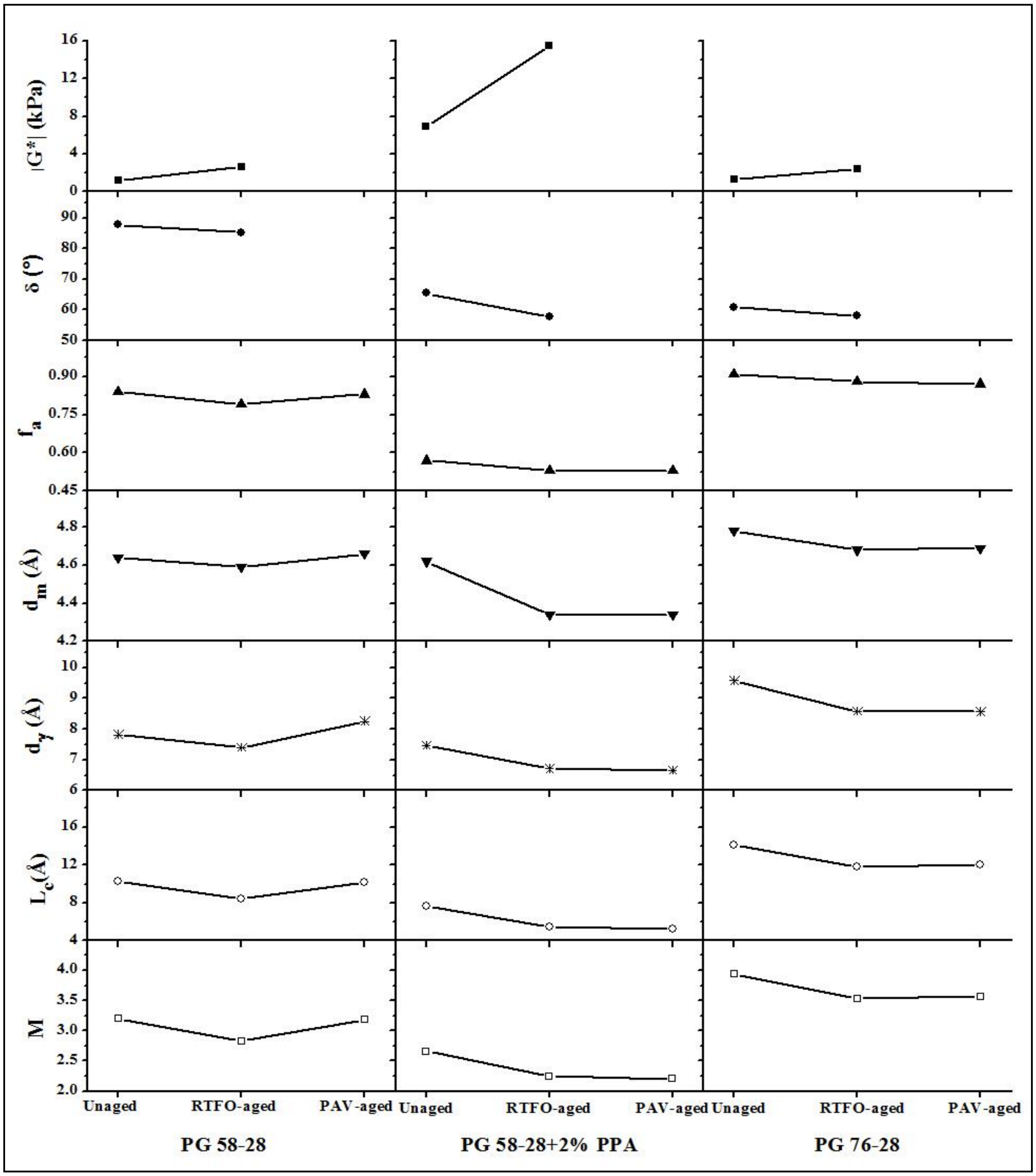


Figure 4.45 Comparisons of rheological, aromaticity and crystallite parameters for PG 58-28, PG 58-28 + 2% PPA and PG 76-28

4.6 Summary

The results of the Superpave® and MSCR tests conducted on the polymer-modified binders and RAP binder blends are presented in this chapter. Although all of the polymer-modified binders were observed to meet the continuous high- and low-temperature PG grade specification requirements as labeled by the manufacturers, significant differences in the rheological properties determined by the MSCR test were observed for binders with the same PG grade. Based on the MSCR test results, the polymer-modified binders were observed to exhibit relatively low J_{nr} and high %Recovery values. This indicates a better rutting resistance of the binder when used in an asphalt mix. Also, the non-conventional MSCR tests conducted on the polymer-modified binders at higher stress levels and temperatures provided a better understanding of the non-linear behavior of the binders. Furthermore, the Superpave® and MSCR tests were found to help understand the improvement in the rutting performance of the binder blends containing RAP binder. The DSR and MSCR test methods were found to rank the rutting performance of both polymer-modified binders and those containing RAP binder differently. The MSCR-based ranking was found to correlate better with the field rutting performance. Moreover, the XRD analyses provided an insight of the molecular structure of the unmodified, polymer-modified and PPA-modified binders.

CHAPTER FIVE: TEST RESULTS OF ASPHALT MIXES

5.1 Introduction

As discussed in Chapter 3, a total of four asphalt mixes, namely MIX-1, MIX-2, MIX-3 and MIX-4 containing polymer-modified binders and RAP, were prepared in this study for testing. This chapter presents the rutting and moisture susceptibility evaluation of the asphalt mixes using a HWT device. A comparative analysis of these Superpave® and MSCR test methods in light of the HWT rut data is discussed as well.

5.2 Volumetric Properties of Asphalt Mixes

Among the four asphalt mixes, two mixes (MIX-1 and MIX-2) were collected from a local plant and the other two mixes (MIX-3 and MIX-4) were prepared in the laboratory. The mix designs for all the mixes were provided by Silver Star Construction Co. The laboratory produced mixes were prepared by mixing different percentages of virgin aggregates, virgin binder, and RAP, as recommended in the mix design reports. The prepared asphalt mixes were then used to prepare cylindrical samples using a Superpave® Gyratory Compactor (SGC) in accordance with the AASHTO T 312 (AASHTO, 2015) test method. Four specimens with air voids of 7.0±0.5% were prepared for each mix type. The specimens were tested in a HWT device.

The MIX-1 specimens were prepared from a S4 mix, which composed of 42% of 5/8″ chips, 18% of 3/16″ screenings, 25% of manufactured sand and 15% of fine sand with a nominal maximum aggregate size (NMAS) of 12.5 mm. The design asphalt binder content of these specimens was 4.8%. The volumetric properties of the MIX-1 specimens satisfied the ODOT mix design requirements (ODOT, 2012). Tables 5.1 and 5.2 summarize the aggregates gradation and volumetric properties of MIX-1.

The MIX-2 specimens were prepared from a S3 mix, with a NMAS of 19 mm. This mix contained 25% RAP. The specimens were composed of 10% of 1″ rock, 27% of 5/8″ chips, 12% of screenings, 15% of manufactured sand and 11% of fine sand. The design asphalt binder content and the amount of binder replacement by RAP were 4.4% and 31.8%, respectively. A summary of the aggregates' gradation and volumetric properties of MIX-2 is presented in Tables 5.3 and 5.4.

The MIX-3 specimens were prepared from a S3 mix with a NMAS of 19 mm. This mix contained 35% RAP. The specimens were composed of 10% of 1″ rocks, 27% of 5/8″ chips, 19% of screening and 9% of manufactured sand. The design asphalt binder content and the amount of binder replacement by RAP were 4.5% and 44.4%, respectively. A summary of the aggregates' gradation and volumetric properties of MIX-3 is presented in Tables 5.5 and 5.6.

The MIX-4 specimens were prepared from a S4 mix with a NMAS of 12.5 mm. This mix contained 35% RAP. The specimens were composed of 10% and 20% of 5/8″ chips from two different sources, 26% of manufactured sand 9% of fine sand. The design asphalt binder content and the amount of binder replacement by RAP were 4.8% and 41.7%, respectively. A summary of the aggregates' gradation and volumetric properties of the MIX-4 specimens is presented in Tables 5.7 and 5.8.

Table 5.1 Summary of aggregates' gradation of MIX-1

Blended material	% of each aggregate	
5/8″ Chips	42	
3/16″ Screens	18	
Man. Sand	25	
Sand	15	
Gradation (sieve size, mm)	**%Passing**	**Required***
19	100	100
12.5	97	90-100
9.5	90	≤ 90
4.75	68	-
2.36	45	34-58
1.18	33	-
0.6	26	-
0.3	18	-
0.15	7	-
0.075	3.7	2-10

* ODOT specification (ODOT, 2012)

Table 5.2 Summary of aggregate properties and volumetric properties of MIX-1

Volumetric and aggregate properties	Values	Required*
G_{mm}	2.492	
G_{se}	2.691	
G_{sb}	2.671	
G_b	1.01	
Virgin Binder Type	PG 76-28	
Total Binder content (%)	4.8	
Virgin Binder Content (%)	4.8	
P_{ba}	0.28	
VMA (%)	14.7	min. 14.5
VFA (%)	72.8	72-77
DP	0.8	0.6-1.6
LA Abrasion (%)	24	max. 40
Micro Deval (%)	9.7	max. 25
Sand Equivalent (%)	93	min 50
Fractured Faces	100/100	min. 98/95
Tensile Strength Ratio	0.85	min. 0.8
Permeability (10^{-5} cm/s)	2	max. 12.5

* ODOT specification (ODOT, 2012)

Table 5.3 Summary of aggregates' gradation of MIX-2

Blended material	**% of each aggregate**	
1″ Rock	10	
5/8″ Chips	27	
3/16″ Screens	12	
Man. Sand	15	
Sand	11	
Fine RAP	25	
Gradation (sieve size, mm)	**%Passing**	**Required***
25	100	100
19	98	90-100
12.5	88	≤ 90
9.5	75	-
4.75	60	-
2.36	45	31-49
1.18	34	-
0.6	27	-
0.3	18	-
0.15	9	-
0.075	5.3	2-8

* ODOT specification (ODOT, 2012)

Table 5.4 Summary of aggregate properties and volumetric properties of MIX-2

Volumetric and aggregate Properties	**Values**	**Required***
G_{mm}	2.528	
G_{se}	2.716	
G_{sb}	2.686	
G_b	1.01	
Virgin Binder Type	PG 64-22	
Total Binder content (%)	4.4	
Virgin Binder Content (%)	3	
P_{ba}	0.42	
VMA (%)	13.5	min. 13.5
VFA (%)	71.38	70-75
DP	1.4	0.6-1.6
LA Abrasion (%)	24	max. 40
Micro Deval (%)	9.7	
Sand Equivalent (%)	79	min 40
Fractured Faces	100/100	min. 85/80
Tensile Strength Ratio	0.83	min. 0.8
Permeability (10^{-5} cm/s)	0.2	max. 12.5

* ODOT specification (ODOT, 2012)

Table 5.5 Summary of aggregates' gradation of MIX-3

Blended material	% of each aggregate	
1″ Rock	10	
5/8″ Chips	27	
Man. Sand	19	
Sand	9	
Fine RAP	35	
Gradation (sieve size, mm)	**%Passing**	**Required***
25	100	100
19	96	90-100
12.5	85	≤ 90
9.5	72	-
4.75	55	-
2.36	40	31-49
1.18	31	-
0.6	25	-
0.3	18	-
0.15	9	-
0.075	5.4	2-8

* ODOT specification (ODOT, 2012)

Table 5.6 Summary of aggregate properties and volumetric properties of MIX-3

Volumetric and aggregate properties	Values	Required*
G_{mm}	2.556	
G_{se}	2.754	
G_{sb}	2.707	
G_b	1.01	
Virgin Binder Type	PG 64-22	
Total Binder content (%)	4.5	
Virgin Binder Content (%)	2.5	
P_{ba}	0.64	
VMA (%)	13.5	min. 13.5
VFA (%)	69.9	70-75
DP	1.4	0.6-1.6
LA Abrasion (%)	24	max. 40
Micro Deval (%)	9.7	-
Sand Equivalent (%)	87	min 40
Fractured Faces	100/100	min. 85/80
Tensile Strength Ratio	0.86	min. 0.8
Permeability (10^{-5} cm/s)	5.5	max. 12.5

* ODOT specification (ODOT, 2012)

Table 5.7 Summary of aggregates' gradation of MIX-4

Blended material	% of each aggregate	
5/8″ Chips	10	
5/8″ Chips	20	
Man. Sand	26	
Sand	9	
Fine RAP	35	
Gradation (sieve size, mm)	**%Passing**	**Required***
19	100	100
12.5	95	90-100
9.5	83	≤ 90
4.75	62	-
2.36	44	34-58
1.18	33	-
0.6	26	-
0.3	19	-
0.15	9	-
0.075	5.4	2-10

* ODOT specification (ODOT, 2012)

Table 5.8 Summary of aggregate properties and volumetric properties of MIX-4

Volumetric and aggregate properties	Values	Required*
G_{mm}	2.516	
G_{se}	2.72	
G_{sb}	2.691	
G_b	1.01	
Virgin Binder Type	PG 64-22	
Total Binder content (%)	4.8	
Virgin Binder Content (%)	2.8	
P_{ba}	0.4	
VMA (%)	14.7	min. 14.5
VFA (%)	72.1	72-77
DP	1.2	0.6-1.6
LA Abrasion (%)	24	max. 40
Micro Deval (%)	9.7	-
Sand Equivalent (%)	88	min. 40
Fractured Faces	100/100	min. 85/80
Tensile Strength Ratio	0.84	min. 0.8
Permeability (10^{-5} cm/s)	2.5	max. 12.5

* ODOT specification (ODOT, 2012)

5.3 Hamburg Wheel Tracking (HWT) Test Results

All the mix samples were tested at 50 ºC using a HWT device under wet condition in accordance with the AASHTO T 324 test method (AASHTO, 2014). Samples were tested up to 20,000 wheel passes or 20 mm rut depth, whichever reached first. The rut depths at 11 points on the specimen along the wheel-path were recorded automatically for each wheel pass and were saved in a Microsoft ACCESS database. The rut depths at the mid-point of the specimen (Point No. 6) were considered for analysis. The rut depths obtained from two sets of tests conducted on the same asphalt mix were averaged and used for further evaluation. It was observed that the moving steel wheels of the HWT device vibrate vertically on the rough specimen surface which introduces noise into the rut depth readings. The moving averages of the rut depth readings along the time axis were taken to remove this noise. Lu and Harvey (2006) used the following Equations (4.1), (4.2) and (4.3) to calculate the moving averages of the HWT test results.

$$\overline{d_t} = 0.40d_t + 0.25d_{t+1} + 0.15d_{t+2} + 0.10d_{t+3} + 0.10d_{t+2} \quad (1 \le t \le 5) \tag{4.1}$$

$$\begin{aligned}\overline{d_t} &= 0.05d_{t-5} + 0.05d_{t-4} + 0.075d_{t-3} + 0.075d_{t-2} + 0.15d_{t-1} \\ &+ 0.20d_t + 0.15d_{t+1} + 0.075d_{t+2} + 0.075d_{t+3} + 0.05d_{t+4} + 0.05d_{t+5}\end{aligned} \quad (5 < t < 19{,}995) \tag{4.2}$$

$$\overline{d_t} = 0.40d_t + 0.25d_{t-1} + 0.15d_{t-2} + 0.10d_{t-3} + 0.10d_{t-4} \quad (19{,}995 \le t \le 20{,}000) \tag{4.3}$$

The important performance parameters, namely post compaction deformation, creep slope, stripping slope, and stripping inflection point were determined from the HWT test results. The post compaction deformation observed instantaneously just after starting the test simulates the densification of asphalt mix owing to initial trafficking. Yildirim and Kennedy (2002) used the rut depth at 1,000 wheel passes as the post-compaction point. The linear region of the rut progression curve after post compaction point is called creep region which represents rutting due to plastic flow. The creep slope is defined as the rut depth per wheel pass in the creep region. The stripping inflection point is used to characterize the moisture-induced damage of the asphalt mix. The stripping slope was obtained by drawing lines between the stripping inflection point and the final wheel pass. In this study, the creep and stripping slopes were defined as the number of passes per unit of rut depth for convenience.

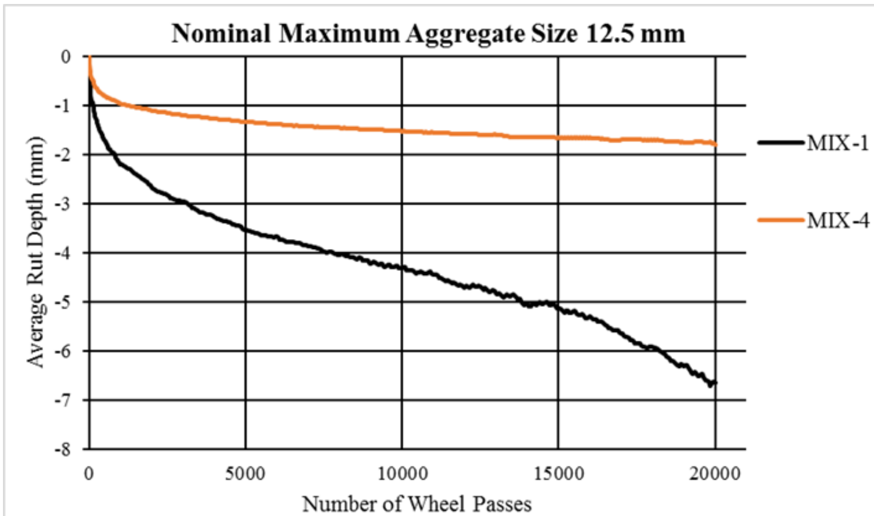
5.4 Evaluation of Rutting and Resistance to Moisture-induced Damage of the Mixes

Figure 5.1 presents the average rut depth with respect to wheel passes for all of the asphalt mix specimens. Rut depths at 1,000, 5,000, 10,000, 15,000, and 20,000 passes for all four mix specimens are presented in Table 5.9. The performance parameters were determined from HWT curves and are presented in Table 5.10. From Figure 5.1, it was observed that the rut depths at 20,000 passes for all four mix specimens were less than 10 mm. However, only the MIX-1 specimens, which contained polymer-modified PG 76-28 binder, exhibited moisture-induced damage. None of the other three mixes containing RAP were found to exhibit moisture-induced damage during the test, since no stripping inflection points were observed.

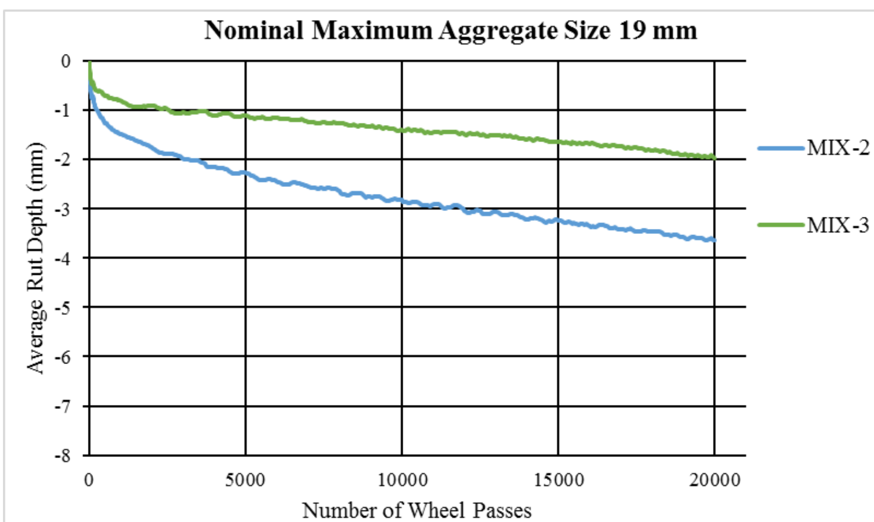
The MIX-1 and MIX-4 specimens can be compared to examine the effects of polymer-modified binder and high RAP content on rut performance. From Figure 5.1 (a) and Table 5.9, it is evident that, although both the MIX-1 and MIX-4 specimens were S4 mixes with a NMAS = 12.5 mm, the MIX-4 specimens containing PG 64-22 and 35% RAP exhibited a lower rut depth compared to the MIX-1 specimens, which contained PG 76-28 binder without any RAP. The rut depths for the MIX-1 and MIX-4 specimens after 20,000 wheel passes were found to be 6.63 and 1.77 mm, respectively. Also, the creep slopes for the MIX-1 and MIX-4 specimens were found to be 5,458 and 28,986 passes/mm, respectively. Furthermore, the MIX-1 specimens exhibited a stripping inflection point at 16,100 passes with a stripping slope of 2,952 passes/mm. Therefore, it can be concluded that MIX-1, which contained polymer-modified PG 76-28 binder, is expected to exhibit higher rutting and moisture-induced damage than MIX-3, which contained PG 64-22 binder and 35% RAP.

The effect of incorporating high amount of RAP in the mix on rutting performance can be evaluated by comparing the results of the HWT tests conducted on the MIX-2 and MIX-3 specimens. From Figure 5.1 (b) and Table 5.9, it can be observed that the average rut depth for the MIX-2 specimens, which contained 25% RAP, was higher than those measured for the MIX-3 specimens, which contained 35% RAP. The post compaction deformations for the MIX-2 and MIX-3 specimens were found to be 1.49 and 0.89 mm, respectively. Also, the creep slopes for the MIX-2 and MIX-3 specimens were found to be 9,948 and 18,770 passes/mm, respectively. These results indicate that an asphalt mix containing high RAP content is expected to exhibit a higher rutting resistance. These observations agree with the findings reported by others (Hong et al., 2010; Hossain et al., 2013; Boriack et al., 2014; Ghabchi et al., 2016).

The effect of aggregate gradation on the rut performance of asphalt mixes was evaluated using the HWT test results of the MIX-3 and MIX-4 specimens. From Table 5.9, the average rut depth measured for the MIX-3 (S3 mix) specimens was 1.95 mm, which was higher than the average rut depth measured (1.77 mm) for the MIX-4 (S4 mix) specimens. The creep slopes for the MIX-3 and MIX-4 specimens were found to be 18,770 and 28,986 passes/mm, respectively. This means that the S4 mix tested in this study is expected to perform better than the S3 mix in terms of rutting resistance.



(a)



(b)

Figure 5.1 HWT test results of the asphalt mixes: (a) NMAS= 12.5 mm; (b) NMAS= 19 mm

Table 5.9 Rut depths of asphalt mix specimens at different number of wheel passes

MIX ID	Wheel passes				
	1000	**5000**	**10000**	**15000**	**20000**
MIX-1	2.22	3.54	4.3	5.13	6.63
MIX-2	1.49	2.27	2.85	3.24	3.64
MIX-3	0.81	1.10	1.41	1.64	1.95
MIX-4	0.97	1.34	1.53	1.67	1.77

Table 5.10 Performance parameters of asphalt mix specimens obtained from the HWT tests

MIX ID	HWT indices					
	Post-compaction (mm)	**Creep slope (mm/Pass)**	**Creep slope (Passes/mm)**	**Stripping inflection point**	**Stripping slope (mm/Pass)**	**Stripping slope (Passes/mm)**
MIX-1	2.22	0.00018	5458	16100	0.00034	2952
MIX-2	1.49	0.00010	9948	N/A	N/A	N/A
MIX-3	0.81	0.00005	18770	N/A	N/A	N/A
MIX-4	0.97	0.00003	28986	N/A	N/A	N/A

5.5 Comparison of HWT, DSR and MSCR Test Results

Table 5.11 presents a comparison of the HWT, DSR, and MSCR test results. The amount of binder replacement by RAP for each mix, as mentioned in Section 5.2, was used for this evaluation. The properties of the asphalt mixes were compared with the properties of corresponding equivalent RAP binder blends. For example, the HWT rut depth measured for the MIX-2 specimens (31.8% of binder replaced by RAP), was compared with the DSR and MSCR test results of the PG 64-22-R1-25 binder. The $|G^*|/\sin\delta$ values of the RTFO-aged binders at the corresponding high temperature were used for this comparison. Also, the J_{nr} values of the binders determined at 64 °C and 3.2 kPa stress level were used to compare with the HWT rut depths. Figure 5.2 presents a comparison of the DSR and HWT test results. It can be observed that the mixes with a NMAS = 12.5 mm, the HWT rut depth increased with a reduction in the |G*|/sinδ value. A similar increasing trend of rut depth with a reduction in the |G*|/sinδ value was observed for asphalt mixes with a NMAS = 19 mm although the amount was not the same. Figure 5.2 presents a comparison of the MSCR and HWT tests results. From Figure 5.2, it can be observed that the HWT rut depth exhibited an increasing trend with an increase in J_{nr} value for asphalt mixes with an NMAS = 19 mm. However, asphalt mixes with a NMAS = 12.5 mm exhibited a completely opposite trend. The HWT rut depth was found to increase with a decrease in J_{nr} value. As mentioned in Section 5.2, the binder properties of the two mixes were different (one polymer-modified binder and another containing RAP binder). The sensitivity of the J_{nr} parameter to polymer modification may be the reason for this discrepancy. Other studies have reported that the J_{nr} at 3.2 kPa stress level correlated well with the HWT rut test results and can be used as a parameter for characterizing the rutting resistance of asphalt binders when used in a mix (Zhang et al., 2015; D'Angelo, 2007). Additional studies are needed on asphalt mixes used in Oklahoma to develop correlations between the DSR, MSCR and HWT test results.

Table 5.11 Comparison of HWT, DSR and MSCR test results

MIX ID	NMAS	Binder type	%Binder replacement	Rut depth (mm)	Equivalent RAP binder blend	|G*|/sinδ (kPa)	J_{nr} (kPa^{-1})
MIX-1	12.5	PG 76-28	0.00	6.63	0	2.79	0.03
MIX-2	19	PG 64-22 + RAP	31.82	3.64	25	14.6	1.77
MIX-3	19	PG 64-22 + RAP	44.44	1.95	40	14.77	1.14
MIX-4	12.5	PG 64-22 + RAP	41.67	1.77	40	14.77	1.14

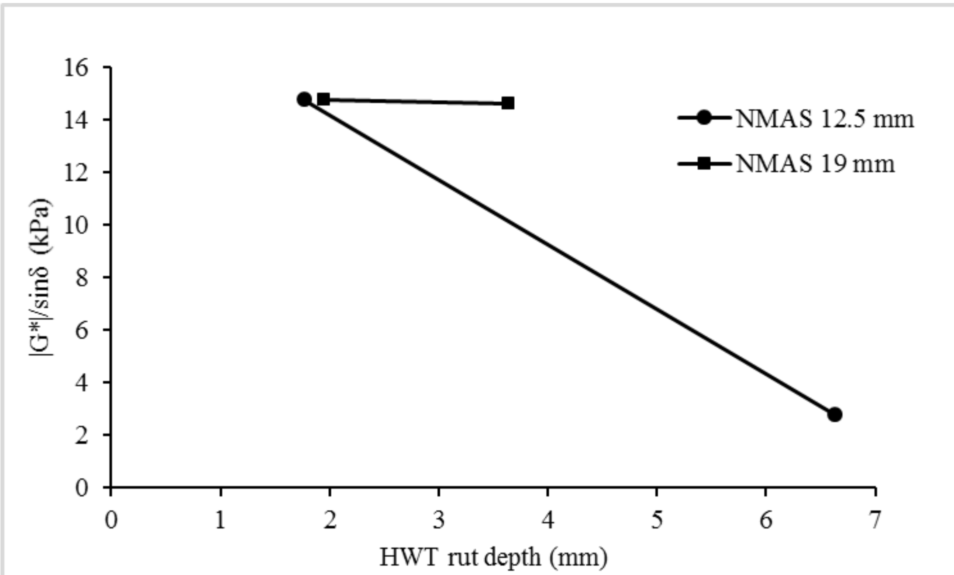


Figure 5.2 Comparison of DSR and HWT test results

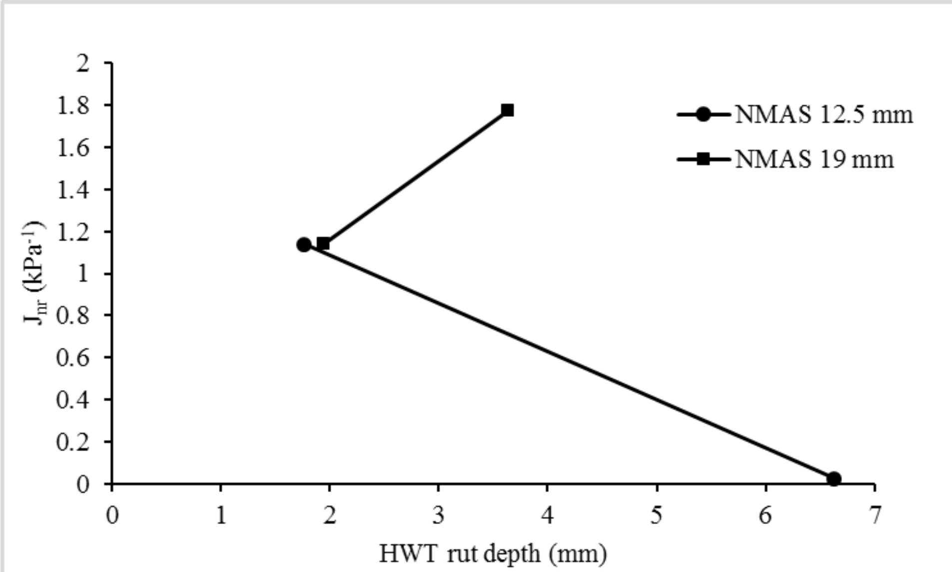


Figure 5.3 Comparison of MSCR and HWT test results

5.6 Summary

The results of the HWT tests conducted on asphalt mix specimens are presented in this chapter. Based on the HWT test results, the asphalt mixes with polymer-modified binder exhibited higher susceptibilities to rutting and moisture-induced damage than the asphalt mixes with RAP. Also, the HWT rut depths of the asphalt mixes was observed to reduce with an increase in the RAP content from 25% to 35%. Furthermore, the rutting resistance of the S4 mix with 35% RAP was found to be better than that of the S3 mix with the same amount of RAP. Based on the comparison of the HWT, DSR and MSCR test results, the HWT rut depth was observed to increase with a reduction in the $|G^*|/\sin\delta$ value and with an increase in the J_{nr} value.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

The applicability of the MSCR test method to characterize the polymer-modified binders and RAP binder blends commonly used by DOTs in Oklahoma, Texas and New Mexico was evaluated in the present study. The experimental plan comprised of conducting the Superpave® and MSCR tests on the polymer-modified PG 70-XX and PG 76-XX binders from seven different sources. The effects of blending different amounts of RAP binders, namely 0%, 25%, 40% and 60% (by weight of the binder), with a PG 64-22 binder were evaluated using both the Superpave® and MSCR test methods. The MSCR tests were conducted on the RTFO-aged binder samples at 64 °C, in accordance with the AASHTO TP 70 (AASHTO, 2013) test method. Also, the MSCR tests were conducted at a higher stress level (10 kPa) and higher temperatures (70 °C and 76 °C) to determine the stress and temperature sensitivities of the tested binders. The results of the MSCR tests were analyzed using the AASHTO MP 19 (AASHTO, 2010) specification. Furthermore, the rutting and moisture susceptibilities of the asphalt mixes containing polymer-modified binders and high amounts of RAP were determined using the HWT test. The results of the DSR, MSCR and HWT tests were compared to evaluate relationships between binders' properties and performance of asphalt mixes. Based on the results and discussions presented in previous chapters, the following conclusions can be drawn:

6.1 Conclusions

6.1.1 Evaluation of MSCR Test Method and Parameters

(i) The MSCR parameters have potential to adequately characterize the rheological properties of polymer-modified binders. The J_{nr} and %Recovery parameters were able to successfully determine the effects of different amounts of RAP binder in the binder blends. Also, the MSCR parameters provide a better understanding of the stress and temperature sensitivities of polymer-modified binders and RAP binder blends. Therefore, the MSCR parameters can be used to determine the viscoelastic behavior of the polymer-modified binders and RAP binder blends available in Oklahoma, New Mexico and Texas.

(ii) The %Recovery requirements proposed by AASHTO TP 70 (2013) were found to be adequate for differentiating the elastomeric polymer-modified binders from other binders used in this study. The polymer-modified PG 70-XX and PG 76-XX binders (except S7 PG 70-22 binder) were found to satisfy the %Recovery requirements of AASHTO TP 70 (2013). The S7 PG 70-22 binder did not satisfy the %Recovery requirements as it may not be an elastomeric polymer-modified binder.

(iii) It was found that the current MSCR test method is not sufficient to characterize the non-linear viscoelastic behavior of polymer-modified binders. The polymer-modified binders used in the present study were found to exhibit a non-linear behavior at a higher stress level (i.e., 10 kPa) than the stress levels used currently. Therefore, a 10 kPa stress level can be added to the MSCR test method in conjunction with the 0.1 and 3.2 kPa stress levels to better characterize the non-linear viscoelastic behavior of polymer-modified binders. Such characterization is important as pavement rutting is known to be a non-linear phenomenon.

6.1.2 Characterization of Polymer-modified Binders

(i) The continuous high- and low-temperature PG grades of the polymer-modified binders were found to meet the minimum specification requirements to be graded as advertised and labeled by the manufacturers. However, not all the polymer-modified binders were found to satisfy the %Recovery requirements of AASHTO TP 70 (2013). Therefore, the polymer-modified binders, which are produced to meet the Superpave® specifications, may not always satisfy the MSCR %Recovery requirements, depending on the types and amounts of polymers used for binder modification.

(ii) The J_{nr} and %Recovery parameters were able to identify the differences in the rheological properties of the polymer-modified binders of the same PG grades but from different sources. The differences in the viscoelastic properties of the same PG grade binders were found to become prominent at a higher stress level (i.e., 10 kPa) and higher temperatures (70° and 76 °C). Therefore, the responses to the permanent deformation of the binders having the same PG grade are expected to vary with the binder sources while other conditions (e.g., temperature and traffic) remain same.

(iii) The results of the DSR tests indicated that the polymer-modified PG 70-XX and PG 76-XX binders are expected to exhibit satisfactory rutting and fatigue resistance, when used in a mix. Also, the MSCR grades of all of the tested polymer-modified binders were found to be PG 64E-XX, indicating binders' ability to sustain extreme level of traffic at 64 °C. Furthermore, from the HWT test, the rut depth obtained for the asphalt mix containing polymer-modified binder was found to satisfy the ODOT specifications requirement. Therefore, a pavement constructed with asphalt mix containing polymer-modified binders is expected to perform well in terms of rutting.

(iv) All of the tested polymer-modified binders were observed to meet the AASHTO MP 19 (AASHTO, 2010) stress sensitivity criterion at 64 °C. Therefore, the polymer-modified binders are not expected to exhibit high amount of deformation when subjected to unexpected heavy loads or increase in ESALs at 64 °C. However, the stress and temperature sensitivities of the polymer-modified binders were found to increase with an increase in the stress level and temperature.

(v) The MSCR grades of the polymer-modified binders were found to reduce with an increase in temperature. For example, the MSCR grade of the S6 PG 70-28 binder was found to change from PG 64E-28 to PG 70H-28 with an increase in temperature from 64° to 70 °C. Therefore, the effect of an increase in temperature on the MSCR grade should be taken into account during construction of a pavement as the same binder can be graded differently at different temperatures.

(vi) From the XRD study, it was observed that different aromaticity and crystallite parameters of the binder can be used as an effective tool for the characterization of the molecular structure of binders. It was found that the aromatic character of the binder reduced to some extent upon the addition of PPA. The compacting of the aromatic ring system was observed with the addition of PPA. A higher f_a value of the PG 76-28 binder than the PG 58-28 binder may be due to the formation of aromatic rings or splitting of aliphatic groupings during polymer modification. It was assumed that increased layer distance of aromatic sheets of polymer-modified binder may be the result of an increase in the volume of binder after polymer-modification. The binder with polymer modification exhibited compacting of aromatic rings system with aging. The compacted aromatic ring system is expected to be responsible for a higher elasticity as well a higher MSCR %Recovery of polymer-modified binders. Therefore, the S7 PG 70-22 binder, which exhibited low %Recovery, can be assumed to have a loosely compacted aromatic rings system and/or weak interaction between molecules.

6.1.3 Characterization of RAP Binder Blends

(i) The $|G^*|$ and $|G^*|/\sin\delta$ of the RAP binder blends were observed to increase with an increase in the amount of RAP binder in the binder blends. Therefore, the RAP binder blends are expected to exhibit a higher rutting resistance than the neat binder. However, the level of increase in the rutting resistance was observed to be dependent on RAP sources. From the HWT test results, asphalt mixes with high amounts of RAP were observed to exhibit satisfactory rutting performance than the mixes with polymer-modified binders. Also, the rutting resistance of the asphalt mixes was found to increase with an increase in the RAP content from 25% to 35%. As per ODOT specifications, the maximum allowable percent binder replacement by RAP for surface courses and other Superpave® mixes are 12% and 30%, respectively (ODOT, 2013). The ODOT may consider revising the allowable limit of binder replacement as both the RAP binder blends and asphalt mixes with high RAP content were found to exhibit an improved resistance to rutting.

(ii) The high-temperature PG grades of the RAP binder blends were observed to increase with an increase in the RAP binder content. No significant changes in the PG grades of the binder blends were observed after incorporating 25% RAP1 and RAP2 binders. However, the addition of 40% and 60% RAP1 binders resulted in an increase of two grades than the neat binder. Also, the high-temperature PG grades were found to increase by one and three grades after the addition of 40% and 60% RAP2 binders, respectively. Therefore, the addition of RAP binder to the neat binder is expected to improve the resistance to rutting, when used in a mix.

(iii) The low-temperature PG grades of the RAP binder blends were found to exhibit an increasing trend with addition of RAP binder. The addition of 40% RAP1 binder to the binder blend resulted in a three grades bump of low-temperature PG grade. Also, the low-temperature PG grade of the PG 64-22 binder increased by one grade due to the addition of 60% RAP2 binder. Therefore, an increase in

RAP binder to the binder blends is expected to increase the possibility of low-temperature cracking, when used in a mix.

(iv) The J_{nr} values were found to decrease and the %Recovery values were found to increase with an increase in the RAP binder content in the binder blends, indicating a higher rutting resistance than the neat binder. Also, the MSCR grades of the RAP binder blends exhibited an increasing trend with an increase in amount of RAP binder. For example, the MSCR grade of the PG 64-22 binder was found to be PG 64H-22, which increased to PG 64E-XX after addition of 60% RAP1 and RAP2 binders. According to the AASHTO MP 19 (AASHTO, 2010) specification, a binder with an "extreme" grade is expected to sustain a traffic levels of greater than 30 million ESALs and standing traffics (< 20 km/h). Therefore, the 60% RAP1 and RAP2 binder blends can be used at places which experience extreme traffic and/or standing traffics, such as toll plazas, port facilities and intersections.

(v) The stress sensitivities of the RAP binder blends at 64 °C were found to meet the AASHTO MP 19 (AASHTO, 2010) stress sensitivity criterion. Also, the RAP binder blends were found to become less sensitive to the stress level with an increase in the RAP binder. Therefore, the RAP binder blends are expected to exhibit better resistance to the deformation when subjected to unexpected heavy loads or increase in ESALs at 64 °C.

(vi) The negative %Recovery observed at higher stress levels and temperatures indicated a continuous deformation of the binder sample after the removal of creep load. Therefore, the stress and temperature sensitivities of the RAP binder blends should be taken into consideration, although they are expected to exhibit a satisfactory rutting performance at high temperatures, based on the Superpave® test results.

6.1.4 Comparison of HWT, DSR and MSCR Test Results

(i) The DSR and MSCR test methods were found to rank the rutting performance of the polymer-modified binders differently. A similar dissimilarity in the ranking of binders based on the DSR and MSCR test methods were observed for the RAP binder blends. However, the MSCR-based ranking system is expected to predict the rutting performance of binders better than the DSR-based ranking. It was found that a combination of low stress level and temperature can be used to determine the ranking of the binders from the MSCR test method.

(ii) From the HWT test results, the rut depths for both types of asphalt mixes (NMAS=12.5 mm and NMAS= 19 mm) were found to increase with a reduction in the $|G^*|/\sin\delta$ values, although the level of increase was not the same. The HWT rut depths were found to exhibit an increasing trend with an increase in J_{nr} value for asphalt mixes with an NMAS = 19 mm. However, the rut depths of asphalt mixes with a NMAS = 12.5 mm were found to exhibit an opposite trend with J_{nr} value. The sensitivity of the J_{nr} parameter to polymer modification of binders were assumed to be the reason for this discrepancy.

6.2 Recommendations

The following recommendations were made based on the limitations and the scope of the present study:

(i) The Oklahoma DOT may consider improving its current MSCR database by including binders' results from all approved suppliers. A number of different polymers are currently being used by the asphalt binder refineries to achieve specification requirements. The effects of the types and amounts of the different polymers used by refineries located in Oklahoma on the performance of the binders were beyond the scope of the present study. A detailed rheological study using the MSCR test method is needed to characterize the polymer-modified binders with different types and amounts of polymers used in Oklahoma.

(ii) The refineries located in Oklahoma, New Mexico and Texas are producing asphalt binders following the AASHTO M 320 (AASHTO, 2012) specification. A study is needed to find out the feasibility of changing the specification of binders' production to AASHTO MP 19 (AASHTO, 2010) from AASHTO M 320 (AASHTO, 2012). Also, training of both users and producers on the MSCR test method and specification are necessary to help adopting this test method in Oklahoma, New Mexico and Texas.

(iii) The present study provides an insight on the rutting resistance of asphalt mixes containing polymer-modified binders and high amount of RAP and its relation with the DSR and MSCR rutting parameters. However, a comprehensive study is needed to establish correlations between the performance of plant and laboratory produced asphalt mixes and the DSR and MSCR test results. Based on the results of field performance, the MSCR guidelines can be evaluated and updated, periodically.

(iv) The Oklahoma DOT may consider using high amount of RAP in asphalt mixes as they exhibited a higher rutting resistance. However, the low-temperature cracking and fatigue performance should be taken into account during the selection of an asphalt mix with high amount of RAP. A study is needed to optimize the amount of RAP to be added to asphalt mixes based on their overall performance.

References

AASHTO M 320 (2010). “Standard Specification for Performance-Graded Asphalt Binder.” *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO M 322 (2014). “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 MP 19 (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 R 28 (2012). “Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV).” *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO T 240 (2013). “Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test).” *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO T 269 (2014). “Standard Method of Test for Percent Air Voids in Compacted Dense and Open Asphalt Mixtures.” *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO T 300 (2011). "Standard Method of Test for Force Ductility Test of Asphalt Materials." *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO T 301 (2013). "Standard Method of Test for Elastic Recovery Test of Asphalt Materials by Means of a Ductilometer." *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO T 312 (2015). "Standard Method of Test for Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor." *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO T 313 (2013). "Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)." *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO T 315 (2012). "Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)." *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO T 316 (2013). "Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer." *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO T 319 (2015). “Standard Method of Test for Quantitative Extraction and Recovery of Binder from Asphalt Mixtures.” *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO T 324 (2014). “Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA).” *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO TP 70 (2013). “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.

Adorjányi, K., and Füleki, P. (2011). “Performance Evaluation of Bitumens at High Temperature with Multiple Stress Creep Recovery Test.” *Hungarian Journal of Industry and Chemistry, 39(2),* 195-199.

Airey, G. D. (2002). “Rheological Evaluation of Ethylene Vinyl Acetate Polymer Modified Bitumens.” *Construction and Building Materials, 16(8),* 473-487.

Airey, G. D. (2003). “Rheological Properties of Styrene Butadiene Styrene Polymer Modified Road Bitumens”. *Fuel, 82,* 1709-1719.

Airey, G. D. (2004). “Fundamental Binder and Practical Mixture Evaluation of Polymer Modified Bituminous Materials.” *International Journal of Pavement Engineering, 5(3),* 137-151.

Airey, G. D. (2011). “Factors Affecting the Rheology of Polymer Modified Bitumen. Polymer Modified Bitumen-Properties and Characterization.” *Woodhead Publishing Limited*, Oxford, 238-263.

Ali, S.A., Ghabchi, R., Rani, S., and Zaman, M. (2016). “Characterization of Effect of Polymer Modification, Poly-Phosphoric Acid and Aging on Asphalt Binder Using X-ray Diffraction (XRD)”. Submitted to *Construction and Building Materials*.

Ali, S. I. A., Ismail, A., Yusoff, N. I. M., Karim, M. R., Al-Mansob R. A., and Alhamali D. I., (2015). “Physical and Rheological Properties of Acrylate–Styrene–Acrylonitrile Modified Asphalt Cement.” *Construction and Building Materials, 93,* 326-334.

Anderson, D. A., Christensen, D. W., Bahia, H. U., Dongre, R., Sharma, M. G., Antle, C. E., and Button, J. (1994). “Binder Characterization and Evaluation. Volume 3: Physical Characterization.” *Strategic Highway Research Program, National Research Council*, Washington, DC.

Anderson, R. M. (2011). “Understanding the MSCR Test and its Use in the PG Asphalt Binder Specification.” In *Webinar, Asphalt Institute (AI)*, Lexington, KY.

Anderson, M. (2012(a)). “Evaluation of J_{nr} Criterion for Unmodified Asphalt Binders.” In *Asphalt Binder Expert Task Group Meeting*, Minneapolis, MN.

Anderson, M. (2012(b)). “SEAUPG Evaluation of MSCR Recovery as a Replacement for PG Plus Tests.” In *Webinar, Asphalt Institute*, Lexington, KY.

Anderson, M., R. (2012(c)). "Southeast Asphalt User-Producer Group Inter Laboratory Study to Determine the Precision of AASHTO TP70 – the Multiple Stress Creep-Recovery (MSCR) Test." *Asphalt Institute,* Lexington, KY.

Anderson, M., R. (2013). "Northeast Asphalt User-Producer Group Second Inter Laboratory Study to Determine the Precision of AASHTO TP70 – the Multiple Stress Creep-Recovery (MSCR) Test." *Asphalt Institute,* Lexington, KY.

Anderson, M. (2014). "Introduction to the Multiple-Stress Creep-Recovery (MSCR) Test and its Use in the PG Binder Specification." In *54th Annual Idaho Asphalt Conference*, Moscow, Idaho.

Anderson, M. (2015). "Implementation of the MSCR Test and Specification: Questions, Clarifications, and Emphasis." In *Asphalt Binder ETG Meeting,* Oklahoma City, Ok.

Asphalt Institute Guidance Document (2010). "Implementation of the Multiple-Stress Creep-Recovery (MSCR) Test and Specification." *Asphalt Institute,* Lexington, KY, www.asphaltinstitute.org .

Asphalt Institute (2016). "State MSCR Implementation Status." *Asphalt Institute,* Lexington, KY, www.asphaltinstitute.org .

ASTM D 5801 (2012). "Standard Test Method for Toughness and Tenacity of Bituminous Materials." *ASTM International,* West Conshohocken, PA, www.astm.org.

Bahia, H. U., and Anderson, D. A. (1995). "Strategic Highway Research Program Binder Rheological Parameters: Background and Comparison with

Conventional Properties.” *Transportation research record; Journal of Transportation Research Board*, *1488*, 32-39.

Bahia, H. U., Hanson, D. I., Zeng, M., Zhai, H., Khatri, M. A., and Anderson, M. R. (2000). “A Project NCHRP 9-10 Superpave Protocols for Modified Asphalt Binders.” Draft Topical Report (Task 9), Prepared for *National Cooperative Highway Research Program*, Transportation Research Board, National Research Council, Washington, D.C.

Bahia, H. U., Hanson, D. I., Zeng, M., Zhai, H., Khatri, M. A., and Anderson, M. R. (2001). “NCHRP Report 459, Characterization of Modified Asphalt Binders in Superpave Mix Design.” Prepared for *National Cooperative Highway Research Program,* Transportation Research Board, National Research Council, Washington, D.C.

Bahia, H. U., Zhai, H., Zeng, M., Hu, Y., and Turner, P. (2001). “Development of Binder Specification Parameters Based on Characterization of Damage Behavior.” *Journal of the Association of Asphalt Paving Technologists*, *70,* 442-470.

Bernier, A., Zofka, A., and Yut, I. (2012). “Laboratory Evaluation of Rutting Susceptibility of Polymer-Modified Asphalt Mixtures Containing Recycled Pavements.” *Construction and Building Materials*, *31*, 58-66.

Boriack, P., Katicha, S., and Flintsch, G. (2014). “Laboratory Study on Effects of High Reclaimed Asphalt Pavement and Binder Content: Stiffness, Fatigue Resistance, and Rutting Resistance.” *Transportation Research Record: Journal of the Transportation Research Board*, *2445*, 64-74.

Brown, E. R., Kandhal, P. S., Roberts, F. L., Kim, Y. R., Lee, D. Y., and Kennedy, T. W. (2009). "Hot Mix Asphalt Materials, Mixture Design, and Construction." *NAPA Research and Education Foundation,* Lanham.

Cardoso, E. D. R.., Braz, D., Motta, L. M. G., Barroso, R. C., and Lopes, R. T. (2009). "Effect of the Weather in The Aging of Asphalts by XRD." In *International Nuclear Atlantic Conference–INAC.,* Rio de Janeiro, Brazil.

Carreau, P. J., MacDonald, I. F., and Bird, R. B. (1968). "A Nonlinear Viscoelastic Model for Polymer Solutions and Melts—II." *Chemical Engineering Science, 23(8),* 901-911.

Chen, J. S., Liao, M. C., and Tsai, H. H. (2002) "Evaluation and Optimization of the Engineering Properties of Polymer-Modified Asphalt." *Practical Failure Analysis, 2(3),* 75-83.

Choi, Y. T., and Kim, Y. R. (2013). "Development of Calibration Testing Protocol for Permanent Deformation Model of Asphalt Concrete." *Transportation Research Record: Journal of the Transportation Research Board, 2373,* 34–43.

Choubane, B., Page, G., and Musselman, J. (2000). "Suitability of Asphalt Pavement Analyzer for Predicting Pavement Rutting." *Transportation Research Record: Journal of the Transportation Research Board, 1723*, 107-115.

Colbert, B., and You, Z. (2012). "The Properties of Asphalt Binder Blended with Variable Quantities of Recycled Asphalt Using Short Term and Long Term Aging Simulations." *Construction and Building Materials, 26(1),* 552-557.

Collins, J. H., Bouldin, M. G., Gelles, R., and Berker, A. (1991). “Interpretation of Dynamic Mechanical Test Data for Paving Grade Asphalt Cements.” In *Proceedings of the Association of Asphalt Paving Technologists*, *60,* 43-69.

Cooley, L. A., Kandhal, P. S., Buchanan, M. S., Fee, F., and Epps, A. (2000). “Loaded Wheel Testers in The United States: State of The Practice.” *Transportation Research Circular*, *E-C016,* Transportation Research Board, Washington, DC.

Corte, J. F. (2001). “Development and Uses of Hard-grade Asphalt and of High-Modulus Asphalt Mixes in France.” *Transportation Research Circular, 503,* Transportation Research Board, Washington, DC, 12-31.

Corun, R. (2015). “Multiple Stress Creep Recovery Test for Asphalt Binders.” *PAPA RegionalTechnical Workshop*, Breinigsville, PA.

D’Angelo, J., and Dongre, R. (2004). “Development of a Performance-Based Binder Specification in the United States.” In *Proceedings of 3rd Eurasphalt and Eurobitume Congress*, *339,* Vienna, Austria.

D'Angelo, J., Dongre, R., and Reinke, G. (2006). “Evaluation of Repeated Creep and Recovery Test Method as an Alternative to SHRP+ Requirements for Polymer Modified Asphalt Binders.” In *Fifty-First Annual Conference of the Canadian Technical Asphalt Association (CTAA),* Charlottetown Prince Edward Island, Canada.

D’Angelo, J., R. Kluttz, R., Dongre, K. Stephens and L. Zanzotto. (2007). “Revision of the Superpave High Temperature Binder Specification: The Multiple Stress Creep Recovery Test.” *Asphalt Paving Technology, 76*, 123.

D’Angelo, J. and Dongr’e, R. (2009). “Practical Use of Multiple Stress Creep and Recovery Test Characterization of Styrene-Butadiene-Styrene Dispersion and Other Additives in Polymer-Modified Asphalt Binders.” *Transportation Research Board: Journal of the Transportation Research Board, 2126,* 73-82.

D’Angelo, J. (2010). “New High-Temperature Binder Specification Using Multistress Creep and Recovery.” *Development in Asphalt, Transportation Research Circular, E-C147,* Transportation Research Board, Washington, DC, 1-13.

Daniel, J., Pochily, J., and Boisvert, D. (2010). “Can More Reclaimed Asphalt Pavement Be Added? Study of Extracted Binder Properties from Plant-Produced Mixes with up to 25% Reclaimed Asphalt Pavement.” *Transportation Research Record: Journal of the Transportation Research Board, 2180,* 19-29.

Delgadillo, R., Cho, D. W., and Bahia, H. (2006). “Part 1: Bituminous Materials: Nonlinearity of Repeated Creep and Recovery Binder Test and Relationship with Mix Permanent Deformation.” *Transportation Research Record: Journal of the Transportation Research Board, 1962(1),* 3-11.

Diefenderfer, S. (2006). “Detection of Polymer Modifiers in Asphalt Binder”. *VTRC 06-R18*, Virginia Department of Transportation, 1401 East Broad Street, Richmond, VA 23219, USA.

Diehl, C. F. (2000). “Ethylene-Styrene Interpolymers for Bitumen Modification.” In *Proceedings of the Papers submitted for review at 2nd Eurasphalt and Eurobitume Congress, Held 20-22 September 2000, Barcelona, Spain., 2,* 93.

Domingos, M. D. I., and Faxina, A. L. (2014). “Creep-Recovery Behavior of Asphalt Binders Modified with SBS and PPA.” *Journal of Materials in Civil Engineering, ASCE, 26(4),* 781-783.

Domingos, M. D. I., and Faxina, A. L. (2015). “Susceptibility of asphalt binders to rutting: literature review.” *Journal of Materials in Civil Engineering, ASCE, 28(2),* 04015134.

Dongré, R., and D'Angelo, J. (2003). “Refinement of Superpave High-Temperature Binder Specification Based on Pavement Performance in the Accelerated Loading Facility.” *Transportation Research Record: Journal of the Transportation Research Board, 1829*, 39-46.

Dongré, R., D'Angelo, J. and Reinke, G. (2004). “New Criterion for Superpave High-Temperature Binder Specification.” *Transportation Research Record: Journal of the Transportation Research Board, 1875,* 22-32.

Dreessen, S., Planche, J. P., and Gardel, V. (2009). “A New Performance Related Test Method for Rutting Prediction: MSCRT. *Advanced testing and characterization of bituminous materials, 1,* 971-980.

DuBois, E., Mehta, Y., and Nolan, A. (2014). “Correlation Between Multiple Stress Creep Recovery (MSCR) Results and Polymer Modification of Binder.” *Construction and Building Materials, 65,* 184-190.

Elseifi, M. A., Flintsch, G. W., and Al-Qadi, I. L. (2003). “Quantitative Effect of Elastomeric Modification on Binder Performance at Intermediate and High Temperatures.” *Journal of Materials in Civil Engineering, ASCE, 15(1),* 32-40.

Gebresellasie, K., Shirokoff, J., and Lewis, J. C., (2012). “Effect of X-ray Line Spectra Profile Fitting with Pearson VII, Pseudo-Voigt and Generalized Fermi Functions on Asphalt Binder Aromaticity and Crystallite Parameters.” *Journal of Physics: Conference Series, 397,* 012069.

Ghabchi, R., Singh, D., & Zaman, M. (2014). “Evaluation of Moisture Susceptibility of Asphalt Mixes Containing RAP and Different Types of Aggregates and Asphalt Binders Using the Surface Free Energy Method.” *Construction and Building Materials, 73,* 479-489.

Ghabchi, R., Barman, M., Singh, D., Zaman, M., & Mubaraki, M. A. (2016). “Comparison of Laboratory Performance of Asphalt Mixes Containing Different Proportions of RAS and RAP.” *Construction and Building Materials*, *124,* 343-351.

Gierhart, D. (2011). “Simple Talking Points for Sharing Why Your State Should Be Implementing MSCR.” In *Southeastern Asphalt User-Producer Group (SEAUPG) Web Meeting, Asphalt Institute (AI),* Lexington, KY.

Golalipour, A. (2011). “Modification of Multiple Stress Creep and Recovery Test Procedure and Usage in Specification.” *Master Thesis, University of Wisconsin-Madison,* Wisconsin.

Grebenschikov, S., and Prozzi, J. (2011). “Enhancing Mechanistic-Empirical Pavement Design Guide Rutting-Performance Predictions with Hamburg Wheel-Tracking Results.” *Transportation Research Record: Journal of the Transportation Research Board, 2226,* 111-118.

Halstead, W. J. (1984). “Relation of Asphalt Chemistry to Physical Properties and Specifications.” *Publication VHTRC 84-R45*, Virginia Highway and Transportation Research Council.

Hansen, K. R., and Copeland, A. (2013). “Annual Asphalt Pavement Industry Survey on Recycled Material and Warm-Mix Asphalt Usage: 2009–2012.” *No. IS-138*, National Asphalt Pavement Association, 5100 Forbes Blvd., Lanham, MD 20706.

Hong, F., Chen, D. H., and Mikhail, M. (2010). “Long-term Performance Evaluation of Recycled Asphalt Pavement Results from Texas: Pavement Studies Category 5 Sections from the Long-Term Pavement Performance Program.” *Transportation Research Record: Journal of the Transportation Research Board, 2180,* 58-66.

Horan, B. (2012). “Multiple Stress Creep Recovery (MSCR) Task Force Overview and Recommendations.” In *Southeastern Asphalt User-Producer Group Meeting, Asphalt Institute,* Lexington, KY.

Hossain, Z., Buddhalla, A., O’Rear, A. O., Zaman, M., Laguros, J. L., and Lewis, S. (October 1-3, 2012). “Recycled Asphalt Pavement in new Asphalt Mixs: State of the Practice.” In *2nd International symposium on Asphalt Pavement and Environment*, Fortaleza, Brazil.

Hossain, Z., Zaman, M., Solanki, P., Ghabchi, S., Singh, D. V., David, A., and Lewis, S. (2013). “Implementation of MEPDG for Asphalt Pavement with RAP Final Report.” *OTCREOS10.1-45-F,* Oklahoma Transportation Center, Midwest City, Oklahoma.

Hossain, Z., Ghosh, D., Zaman, M., and Hobson, K. (2015). "Use of the Multiple Stress Creep Recovery (MSCR) Test Method to Characterize Polymer-Modified Asphalt Binders," *Journal of Testing and Evaluation, ASTM, DOI:10.1520/JTE20140061. ISSN 0090-3973.*

Howard, I. L., and Doyle, J. D. (2013). "Rutting and Moisture Damage Wheel Tracking Comparison of Laboratory and Field Compacted Asphalt Concrete." In *Green Streets, Highways, and Development 2013@ sAdvancing the Practice, ASCE,* 106-116.

Jafari, M., Babazadeh, A., and Aflaki, S. (2015). "Effects of Stress Levels on Creep and Recovery Behavior of Modified Asphalt Binders with the Same Continuous Performance Grades." *Transportation Research Record: Journal of the Transportation Research Board*, *2505*, 15-23.

Kandhal, P. S., and Cooley, L. A. (2002). "Evaluation of Permanent Deformation of Asphalt Mixtures Using Loaded Wheel Tester." *Asphalt Paving Technology*, *71,* 739-753.

Kamel, N. I., Bahai, H. U., and Cho, D. W. (2004). "Critical Laboratory Evaluation of Asphalt Binders Modified by Refining Processes." In *Proceedings of the Forty-Ninth Annual Conference of the Canadian Technical Asphalt Association (CTAA)-Montreal*, Quebec, 57-76.

Khadivar, A., and Kavussi, A. (2013). "Rheological Characteristics of SBR and NR Polymer Modified Bitumen Emulsions at Average Pavement Temperatures." *Construction and Building Materials, 47,* 1099-1105.

Kim, S., Sholar, G. A., Byron, T., and Kim, J. (2009). “Performance of Polymer-Modified Asphalt Mix with Reclaimed Asphalt Pavement.” *Transportation Research Record: Journal of the Transportation Research Board, 2126(1),* 109-114.

Kumar, P., Mehndiratta, H. C., and Singh, K. L. (2010). “Comparative study of rheological behavior of modified binders for high-temperature areas.” *Journal of Materials in Civil Engineering, ASCE, 22(10),* 978–984.

Laukkanen, O. V., Soenen, H., Pellinen, T., Heyrman, S., and Lemoine, G. (2015). “Creep-recovery behavior of bituminous binders and its relation to asphalt mixture rutting.” *Materials and Structures, 48(12),* 4039-4053.

Lu, Q., and Harvey, J. (2006). “Evaluation of Hamburg wheel-tracking Device Test with Laboratory and Field Performance Data.” *Transportation Research Record: Journal of the Transportation Research Board, 1970,* 25-44.

Maccarrone, S., Holleran, G., and Gnanaseelan, G. P. (1995). “Properties of Polymer Modified Binders and Relationship to Mix and Pavement Performance (with Discussion and Closure).” *Journal of the Association of Asphalt Paving Technologists, 64*, 209-240.

Masson, J. F., Collins, P., Woods, J. R., Bundalo-Perc, S., and Margeson, J. (2009). “Chemistry and Effects of Polyphosphoric Acid on the Microstructure, Molecular Mass, Glass Transition Temperatures and Performance Grades of Asphalts.” *Journal of the Association of Asphalt Paving Technologists, 78,* 455-490.

McGennis, R. B., Shuler, S., and Bahia, H. U. (1994). “Background of Superpave Asphalt Binder Test Methods.” *Office of Technology Applications, Federal Highway Administration.*

Mehta, Y., Nolan, A., DuBois, E., Zorn, S., Batten, E., and Shirodkar, P. (2013). "Correlation between Multiple Stress Creep Recovery (MSCR) Results and Polymer Modification of Binder." *FHWA-NJ-2014-002,* New Jersey Department of Transportation, Bureau of Research.

Miller, T., Ksaibati, K., and Farrar, M. (1995). "Using Georgia Loaded-Wheel Tester to Predict Rutting." T*ransportation Research Record: Journal of the Transportation Research Board, 1473*, 17-24.

Mohseni, A., and Azari, H. (2014). "High-temperature Characterization of Highly Modified Asphalt Binders and Mixtures." T*ransportation Research Record: Journal of the Transportation Research Board, 2444(1)*, 38-51.

Nellensteyn, F. J. (1928). "Relation of The Micelle to The Medium in Asphalt." *Journal of the Institute of Petroleum Technologist, 14,* 134-138.

Oklahoma Department of Transportation (ODOT), (2009). "2009 Standard Specifications Book." *Construction Engineering, Standards, Specifications, Materials and Testing*, Oklahoma Department of Transportation, http://www.odot.org/c_manuals/specbook/oe_ss_2009.pdf.

Oklahoma Department of Transportation (ODOT), (2012). "Oklahoma Department of Transportation Special Provision for Plant Mix Bituminous Bases and Surfaces (Superpave)." *SP No. 708-26,* Oklahoma Department of Transportation, http://www.odot.org/c_manuals/specprov2009/oe_sp_2009-708-26.pdf.

Oklahoma Department of Transportation (ODOT), (2013). "Oklahoma Department of Transportation Special Provision for Reclaimed Asphalt Pavement and

Shingles." *SP No. 708-21*, Oklahoma Department of Transportation, http://www.odot.org/c_manuals/specprov2009/oe_sp_2009-708-21.pdf.

Pavement Interactive. "Laboratory Wheel Tracking Devices." Website: http://www.pavementinteractive.org/article/laboratory-wheel-tracking-devices/

Petersen, J. C. (2009). "A Review of the Fundamentals of Asphalt Oxidation: Chemical, Physicochemical, Physical Property, and Durability Relationships." *Transportation Research E-Circular, E-C140, Transportation Research Board,* Washington, DC.

Rahi, M., Fini, E. H., Hajikarimi, P., and Nejad, F. M. (2014). "Rutting Characteristics of Styrene-Ethylene/Propylene-Styrene Polymer Modified Asphalt." *Journal of Materials in Civil Engineering, ASCE, 27(4),* 04014154.

Read, J.; and Whiteoak, D. (2003). "The Shell Bitumen Handbook". Fifth Edition, *Thomas Telford Publishing*, Heron Quay, London.

Reinke, G. (2010). "Use of Hamburg Rut Testing Data to Validate the Use of J_{nr} as A Performance Parameter for High-Temperature Permanent Deformation." *Development in Asphalt, Transportation Research Circular, E-C147*, Transportation Research Board, Washington, DC, 14-24.

Rostler, F. S., (1979). "Fractional Composition: Analytical and Functional Significance." *Bituminous Materials- Asphalts, Tars, and Pitches, Vol. II, Chapter* 6, *Robert E. Krieger Publishing Company,* Hunington, New York.

Saboo, N., and Kumar, P. (2016). "Analysis of Different Test Methods for Quantifying Rutting Susceptibility of Asphalt Binders." *Journal of Materials in Civil Engineering, ASCE,* 04016024.

Sabouri, M., Bennert, T., Daniel, J. S., and Kim, Y. R. (2015). "Fatigue and Rutting Evaluation of Laboratory-Produced Asphalt Mixtures Containing Reclaimed Asphalt Pavement." *Transportation Research Record: Journal of the Transportation Research Board, 2506*, 32-44.

Sargand, S. M., and Kim, S. S. (2001). "Performance Evaluation of Polymer Modified and Unmodified Superpave Mixes." In *Second International Symposium on Maintenance and Rehabilitation of Pavements and Technological Control*, Auburn, AL.

Sel, I., Yildirim, Y., and Ozhan, H. B. (2014). "Effect of Test Temperature on Hamburg Wheel-Tracking Device Testing." *Journal of Materials in Civil Engineering, ASCE, 26(8),* 04014037.

Shenoy, A. (2001). "Refinement of The Superpave Specification Parameter for Performance Grading of Asphalt." *Journal of Transportation Engineering, 127(5),* 357-362.

Shirodkar, P., Mehta, Y., Nolan, A., Dahm, K., Dusseau, R. and McCarthy, L. (2012). "Characterization of Creep and Recovery Curve of Polymer Modified Binder." *Construction and Building Materials, 34*, 504-511.

Siddiqui, M. N., Ali, M. F., and Shirokoff, J. (2002). "Use of X-Ray Diffraction in Assessing the Aging Pattern of Asphalt Fractions." *Fuel, Vol. 81(1)*, 51-58.

Soenen, H., and Redelius, P. (2014). "The Effect of Aromatic Interactions on the Elasticity of Bituminous Binders." *Rheologica Acta, 53(9),* 741-754.

Stevens, R., Stempihar, J., and Underwood, B. S. (2015). "Evaluation of Multiple Stress Creep and Recovery (MSCR) Data for Arizona." *International Journal of Pavement Research and Technology*, *8(5),* 337.

Tabatabaee, N., and Tabatabaee, H. A. (2010). "Multiple Stress Creep and Recovery and Time Sweep Fatigue Tests." *Transportation Research Record: Journal of the Transportation Research Board, 2180(1),* 67-74.

Walubita, L., Zhang, J., Das, G., Hu, X., Mushota, C., Alvarez, A., and Scullion, T. (2012). "Hot-mix Asphalt Permanent Deformation Evaluated by Hamburg Wheel Tracking, Dynamic Modulus, and Repeated Load Tests." *Transportation Research Record: Journal of the Transportation Research Board, 2296,* 46-56.

Wasage, T. L. J., Stastna, J., and Zanzotto, L. (2011). "Rheological analysis of multi-stress creep recovery (MSCR) test." *International Journal of Pavement Engineering, 12(6),* 561-568.

West, R., Kvasnak, A., Tran, N., Powell, B., and Turner, P. (2009). "Testing of Moderate and High Reclaimed Asphalt Pavement Content Mixes: Laboratory and Accelerated Field Performance Testing at The National Center for Asphalt Technology Test Track." *Transportation Research Record: Journal of the Transportation Research Board, 2126,* 100-108.

Xiao, F., Amirkhanian, S., Wang, H., and Hao, P. (2014). "Rheological Property Investigations for Polymer and Polyphosphoric Acid Modified Asphalt Binders at High Temperatures." *Construction and Building Materials, 64,* 316-323.

Yang, X., and You, Z. (2015). "High Temperature Performance Evaluation of Bio-Oil Modified Asphalt Binders Using the DSR and MSCR Tests." *Construction and Building Materials, 76,* 380-387.

Yen, T. F., Erdman, J. G., and Pollack, S. S., (1961). “Investigation of the Structure of Petroleum Asphaltenes by X-ray Diffraction.” *Analytical Chemistry, 33(11),* 1587-1594.

Yen, T. F. (1992). “The Colloidal Aspect of a Macrostructure of Petroleum Asphalt.” *Fuel Science & Technology International, 10 (4-6),* 723-733.

Yildirim, Y. (2007). “Polymer Modified Asphalt Binders.” *Construction and Building Materials, 21,* 66–72.

Zhang, J., Walubita, L. F., Faruk, A. N., Karki, P., and Simate, G. S. (2015). “Use of the MSCR Test to Characterize the Asphalt Binder Properties Relative to HMA Rutting Performance–A Laboratory Study.” *Construction and Building Materials, 94,* 218-227.

Zhu, J., Birgisson, B., and Kringos, N. (2014). “Polymer Modification of Bitumen: Advances and Challenges.” *European Polymer Journal, 54,* 18-38.

Zipf, K. (2014). “Grading Asphalt Binders with the Multiple Stress Creep Recovery Test AASHTO TP-70 and MP-19.” *Delaware Department of Transportation (DelDOT),* Dover, DE.

Zoorob, S. E., Castro-Gomes, J. P., Oliveira, L. P., and O’Connell, J. (2012). “Investigating the Multiple Stress Creep Recovery Bitumen Characterization Test.” *Construction and Building Materials, 30,* 734-745.

Appendix A: List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AI	Asphalt Institute
ALF	Accelerated Loading Facility
APA	Asphalt Pavement Analyzer
BBR	Bending Beam Rheometer
CR	Crumb Rubber
DCA	Dynamic Contact Angle
DOT	Departments of Transportation
DSR	Dynamic Shear Rheometer
ER	Elastic Recovery
EVA	Ethylene-Vinyl-Acetate
EVT	Equi-Viscous Temperature
ESAL	Equivalent Single Axle Load
FD	Forced Ductility
FHWA	Federal Highway Administration
FTIR	Fourier Transform Infrared
HMA	Hot Mix Asphalt
HWT	Hamburg Wheel Tracking
ILS	Inter-Laboratory Study
LTPP	Long-Term Pavement Performance
LSV	Low Shear Viscosity
LWT	Loaded Wheel Tester
MEPDG	Mechanistic-Empirical Pavement Design Guide
MSCR	Multiple Stress Creep and Recovery
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NEAUPG	North East Asphalt User Producer Group

NHDOT	New Hampshire Department of Transportation
NMDOT	New Mexico Department of Transportation
ODOT	Oklahoma Departments of Transportation
PAV	Pressure Aging Vessel
PG	Performance Grading
PURWheel	Purdue University Laboratory Wheel Tracking Device
RAS	Recycled Asphalt Shingles
RAP	Reclaimed Asphalt Pavement
RAP binder	Binder extracted from RAP
RCRT	Repeated Creep and Recovery Test
RLPD	Repeated Load Permanent Deformation
RTFO	Rolling Thin Film Oven
RV	Rotational Viscometer
S-VECD	Simplified Viscoelastic Continuum Damage
SBS	Styrene-Butadiene-Styrene
SEPS	Styrene-ethylene/propylene-styrene
SFE	Surface Free Energy
SHRP	Strategic Highway Research Program
SEAUPG	Southeastern Asphalt User/Producer Group
Superpave®	Superior Performing Asphalt Pavements
TSR	Tensile Strength Ratio
TxDOT	Texas Department of Transportation
VDOT	Virginia Department of Transportation
XRD	X-ray Diffraction
ZSV	Zero-Shear Viscosity
J_{nr}	Non-recoverable creep compliance
$J_{nr\ diff}$	Percent difference in J_{nr} values at two stress levels
%Recovery	MSCR percent recovery
η'	Storage viscosity