MULTIPLE STRESS CREEP RECOVERY (MSCR) CHARACTERIZATION OF POLYMER MODIFIED ASPHALT BINDER CONTAINING WAX ADDITIVES

by

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DEDICATION

I would like to dedicate this to my parents, Farid Ahmed and Sarwat Farid. Though, no dedications and appreciations can cater for the sacrifices they have made to make me what I am today. This effort is highly dedicated to them for their love, support and believe on me and my hard-work throughout my entire life.

I would also like to dedicate it to my maternal Uncle and Aunt, Iqbal Raza and Tazeen Iqbal for the continuous love, support, and encouragement they have given me throughout my graduate study.

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ABSTRACT

The effect of wax additives on the characteristics of polymer modified asphalt (PMA) binders (SIS, SBS and CRM) was investigated in this study. The binders were blended using the two wax additives (LEADCAP and Sasobit) and then artificially aged using rolling thin film oven (RTFO) and pressure aging vessel (PAV) procedures. Superpave binder tests were conducted to determine viscosity, G*/sin δ, G*sin δ and stiffness values. Multiple Stress Creep Recovery (MSCR) test was carried out to evaluate the rutting resistance properties, in original and RTFO aged states. In general the results showed that (1) after the addition of wax additives, the viscosity of PG 64-22 and PMA binders was decreased; (2) higher cracking resistance (i.e., lower stiffness and G*sin δ values) was observed at the binders with LEADCAP; (3) by adding the wax additives, the percentage increase of rutting resistance (G*/sin δ) was found to be higher for PG 64-22 binder, compared to the PMA binders; (4) it was found that the effect of wax additives cannot be identified using MSCR test results; (5) the MSCR test was observed to be potentially inappropriate to measure the rutting performance of CRM binder.

1. INTRODUCTION

1.1. Background

The actual traffic load applied on the highway pavement may exceed the projected design load which increases the stresses and strains in the pavement and further causes a premature failure of the pavement (T. Fwa, 2006). This phenomenon accelerates the deterioration process in the asphalt pavement and expedites the distress mechanism which reduces the pavement's performance. In order to withstand the measured and projected traffic loads, highway pavements are designed by providing a high-quality level of service during their expected design life. Several researchers have focused on describing the behavior of pavements to explain deviations in the actual and predicted behavior. However, the forensic investigation of pavements is a complex subject that requires a thorough investigation of each variable which influences pavement performance. For that purpose, the researchers have been investigating to determine the origin of distress mechanism in pavements (D. Chen, 2007).

Asphalt binder, due to its viscoelastic properties, is an important material used in road paving which affects the pavement performance. But due to the high stresses exerted on the asphalt surface, most of the road systems experience distress and deterioration before it can achieve the design service life (Nicholls, 1998). To improve the pavement performance, it is valuable to modify the asphalt binder by adding polymers with it. The modification of asphalt binder using polymers offer a promising way to improve pavement performance and help in prolonging the service life of the road system even though the road experiences unexpected increase in number of traffic volume. The use of polymer modified asphalt (PMA) in the pavement exhibits greater resistance to rutting and thermal cracking and decreased fatigue damage, stripping and temperature susceptibility (Shafi et al., 2011).

Although, polymer modification of asphalt binder enhances the performance of asphalt pavement, it also increases the fuel consumption and production temperature of asphalt binder after modification. According to Chamoun (2013), to reduce the production temperature, PMA binders are produced and placed for their potential impact on the performance of asphalt pavement using the technology called Warm Mix Asphalt (WMA). Over the last decade, the use of WMA has gained popularity among authorities and pavement industry, as this technology reduces emissions and fuel consumption during the production and construction of asphalt mixes. With the decreased production temperature comes the benefit of reduced emissions, fumes, dust production and odors, as well as an extended mix haul distance, but it creates two major concerns: the reduction of the moisture loss from the aggregates which might lead to an increase potential of moisture damage in asphalt pavement, and the decrease in the hardening of the bitumen which can lead to early permanent deformation failure (cracking) of the pavement.

Studies have shown that the use of WMA technology has significantly improved the performance of pavements (Abdullah et al., 2016). According to Edwards et al. (2006), there are certain risks, such as change in structure, that should be considered when using wax additives in cold climatic conditions. Almost all binders show some degree of reversible structuring or ageing when stored at cold temperature. Below the laying and compaction temperatures, there is an increase in viscosity due to wax crystallization, which in turn could increase the asphalt pavement resistance to plastic deformation. Other asphalt pavement properties such as susceptibility to low temperature cracking, resistance to fatigue and adhesion properties may be affected in a negative way. Therefore, it is recommended to incorporate both polymer modification and WMA additives mixing technologies to improve the resistance to plastic deformation and reduce the early permanent deformation cracking failure of the pavement. In this study two wax warm additives, LEADCAP and Sasobit, are used. According to Mazumder et al. (2016), the addition of wax additives (i.e. LEADCAP and Sasobit) in the control and PMA binders reduced the viscosity and increased the rutting resistance. The binders mixed with Sasobit showed less resistant to fatigue cracking and have significantly higher stiffness value. Whereas, the binder mixed with LEADCAP improved the fatigue cracking resistance and significantly reduced the stiffness values.

In this study, asphalt binder was modified using three different polymers: Styrene-Isoprene-Styrene (SIS), Crumb Rubber Modifier (CRM) and Styrene-Butadiene-Styrene (SBS) polymers. According to Raghu et al. (2003), the addition of SIS polymers in asphalt binder increases the toughness properties, elongation properties and impact strength and also reduces the yield stress, while the addition of SBS enhances the toughness, ductility, and impact strength. Researchers have been studying for compatibilizers for long time and come up with the conclusion that the use of styrene-butadiene-styrene (SBS) and styrene-isoprene-styrene (SIS) have effectively improved the mechanical properties and dispersion as compared to the unmodified state. According to Shang et al. (2011), SBS has become the most appropriate polymer for asphalt modification, as the pavement with SBS modified asphalt exhibits greater resistance to rutting and thermal cracking, decreased fatigue damage, stripping and temperature susceptibility. According to Mazumder et al. (2016), SBS results in excellent bonding strength to aggregate and create a three-dimensional network with virgin asphalt phase. PMA pavements have better pavement performance under high traffic application due to high viscosity and better binder coating. Polymer modification shows properties such as better resistance to rutting, stripping, fatigue damage, and thermal cracking in asphalt pavements.

According to AASHTO T 315-10, the Dynamic Shear Rheometer (DSR) test helps in determining the dynamic shear modulus (G*) and phase angle (δ) of the asphalt binder. This test is compatible to asphalt binders having dynamic shear modulus value in the range from 100 Pa to 10 MPa. The dynamic modulus and phase angle depend upon the magnitude of the shear strain; the modulus and phase angle for both unmodified and modified asphalt binder decrease with increasing shear strain. This test method leads to determine the linear viscoelastic properties of asphalt binders according to the specification testing. The test temperature for this test is related to the temperature experienced by the pavement in the geographical area for which the asphalt binder is intended to be used.

The Federal Highway Administration (FHWA) developed a Performance Grade (PG) binder test based on performance, called Multiple Stress Creep Recovery (MSCR) test to characterize the properties of asphalt binder related to HMA rutting. According to Behnood (2016), MSCR test uses the DSR, the same equipment used in the current PG specification with updated software. The MSCR is a creep and recovery performance test conducted on asphalt binder samples, which can characterize both the recovery and non-recovery compliances of the asphalt binder. One advantage of the MSCR test is that it eliminates the need to run tests such as elastic recovery, toughness and tenacity, and force ductility. The results obtained from the MSCR test will provide additional information, which can be helpful in determining suitable binder to use in asphalt mixtures.

The MSCR test is conducted at the high PG temperatures and takes approximately the same amount of time as the current Superpave DSR test. Comparison of test results between the MSCR and elastic recovery (ER) has shown a good correlation for some binders, but not for all (De'Angelo et al., 2006). Both ASTM and AASHTO standard test methods (ASTM D7405-08 and AASHTO TP70) have been implemented and are being used in the United States by various user producer groups and lead state agencies to verify MSCR reproducibility and specification criterion (De'Angelo et al., 2007). It has been found that Superpave PG specification is not able to quantify the performance of modified binders. Generally, the rutting resistance of asphalt binder was evaluated through G*/ Sinδ measured by traditional DSR test based on PG system. However, there are several researches which reported low relation between G*/sin δ and real field (Behnood, 2016; Zhang et al., 2015; Tabatabaee and Tabatabaee, 2010; Behnood et al., 2016; Soenen et al., 2013). To overcome the issues mentioned in these researches, FHWA introduced Superpave plus testing protocol for better characterization of these materials. MSCR is one of the various new test methods which were introduced and showing good performance to evaluate the rutting property of PMA binders compared to G*/sin δ. Therefore, the objective of this research is to investigate the characterization of PMA binders containing wax warm additives using MSCR test. Also, other properties of PMA with wax additives are evaluated through Superpave binder test.

1.2. Research Objectives and Hypothesis

The objective of this research is to investigate PMA binder containing wax additives using a technology, which is the latest refinement of the Superpave performance graded asphalt binder specification, called Multiple Stress Creep Recovery (MSCR). This research was initiated to determine the effect of wax warm additives on the characteristics of polymer modified asphalt. Two commercial warm wax additives, LEADCAP and Sasobit, were used to study the effect of SIS, SBS, and CRM on the properties of asphalt binder. These binders were artificially aged using pressure aging vessel (PAV) and rolling thin film oven (RTFO) procedures. MSCR test was conducted to evaluate the rutting resistance properties, in the original state and after RTFO aging. The viscosity properties for the binders were evaluated in the original state. The G*/sin δ value, first in the original state, then after RTFO aging, and the low temperature stiffness properties, after

RTFO+PAV aging method, and the G*sin δ value at intermediate temperature after RTFO+PAV aging methods were evaluated.

The following has been hypothesized to investigate the objectives of this study:

- The addition of wax warm additives in the PMA binder has an impact on the performance of the modified binders which can lead towards a better pavement design.

2. LITERATURE REVIEW

2.1 Modification of asphalt binder

The increase of traffic loading on road building materials in recent years has been increased which resulted in a search for binders with improved performance relative to normal penetration grade asphalt binders. This effort to attain improved binder characteristics has led to the evaluation, development and use of a wide range of bitumen modifiers which improve the performance of the basic bitumen and hence the asphalt on the road (Nicholls, 1998). In recent years, there is a rising interest on asphalt modifications for use in high performance specialty pavements such as open-graded pavements (OGP) in which large gravels have been selectively used for creating open interconnected channels in the pavements (Bouldin, 1991).

Polymer-modified binders, which are obtained by mixing plastomeric or elastomeric macromolecular materials with traditional pure road asphalt binders, have been available for more than 20 years. An ideal binder should have enhanced cohesion and very low temperature susceptibility throughout the range of temperatures to which it will be subject in service, but low viscosity at the usual temperatures at which it is placed. At the same time, it should have at least the same adhesion qualities (active and passive) as traditional binders. Lastly, its aging characteristics should be good, both for laying and in service (Brule, 1996). According to Diehl (2000), polymers can be classified into four broad categories, namely plastics, elastomers, fibers and additives/coatings. Plastics can in turn be subdivided into thermoplastics, thermosets (or thermosetting resins) and elastomers into natural and synthetic rubber. Globally, approximately 75% of modified binders can be classified as elastomeric, 15% as plastomeric, and the remaining 10% being either rubber or miscellaneously modified (Diehl, 2000).

Several studies have been conducted to examine the relationship between the effect of modifiers on mixture's performance. The advantage of polymer modification is a reduction in the amount and severity of distresses and thereby an extension in the service life of hot-mix asphalt (HMA) pavements and overlays. From the engineering point of view, PMAs are materials with superior rheological properties (Read and Whiteoak 2003; Airey 2004; Isacsson and Lu 1998) with respect to the unmodified asphalt binders, and they are currently used increasingly in the construction of modern asphalt pavements. According to them, polymer-modified binders have been used with success at locations of high stress, such as intersections of busy streets, airports, vehicle weigh stations, and race tracks. Various kinds of modifiers have been used to modify asphalt binder such as styrene-butadiene-styrene (SBS), styrene-butadiene-rubber (SBR), ethylene-vinyl-acetate (EVA), rubber and others. Desirable characteristics of polymer modified binders include greater elastic recovery, a higher softening point, greater cohesive strength and greater ductility. Modifying the asphalt binder improves their performance characteristics, including the rutting resistance.

2.2 Wax Warm Additives

Over the last decade, the use of WMA has gained popularity among authorities and pavement industry, as this technology reduces emissions and fuel consumption during the production and construction of asphalt mixes without affecting the properties of the mixes. Previous studies on the production of WMA mix focused on modifying base asphalt binders through the addition of WMA additives. Currently, the modification of base asphalt binders with WMA additives could be done through three different processes, namely through the foaming process, the addition of organic additives, and the addition of chemical additives. Studies have shown that the use of WMA technology has significantly improved the performance of pavements (Abdullah et al., 2016).

Warm mix asphalt (WMA) technology developed in Europe, has been gaining a significant attention from industries, agencies, and academia in the United States and in Asia. The WMA permits the producers of asphalt mix to reduce the temperatures at which the material is mixed and placed on the road. The temperature reductions up to 100°F (38°C) have the obvious benefits of cutting fuel consumption and diminishing the production of greenhouse gases. Additionally, other benefits include better compaction on the road, the ability to haul paving mix for longer distances, and extending the paving season by being able to pave at lower temperatures (Kim et al., 2014).

Though, wax crystallization improves rutting resistance, other asphalt properties such as susceptibility to low temperature cracking, resistance to fatigue and adhesion properties may be affected in a negative way. However, the addition of CRM into the asphalt binder increases the asphalt pavement resistance to cracking in low temperature. If the wax additives and the crumb rubber particles are used together, the asphalt pavement resistance to plastic deformation and cracking is likely to be improved. Also, with the wax additives, the mixing and compaction temperatures of CRM mixes can be reduced (Kim et al., 2014). According to Amirkhanian and Corley (2004), the use of rubberized mixes might result in several problems with lower compaction temperatures such as inadequate volumetric properties (i.e., high air voids) and poor short-term and long-term performances. Therefore, if the technologies of WMA are incorporated into the rubberized binder, optimum mixing and compaction temperatures of the rubberized mixes are expected to decrease and be comparable to those of conventional asphalt mixes.

According to Kim and Lee (2016), wax additive is mainly used as a flow improver in asphalt concrete and mastic asphalt. Wax is known to have a softening effect on the binder and asphalt mix at high-temperature, resulting in improved compaction. With the wax additive, the viscosity of asphalt is decreased at high-temperatures (above 80°C), which improve the flow properties of asphalt (Xiao et al., 2012). The greatest advantage of this kind effect is that the mixing temperature of the asphalt is reduced, and the energy consumption and emissions are also reduced. According to Yi-qiu et al. (2012), the construction period can be extended by adding wax additives in asphalt binder.

Zhao et al. (2011) studied the effects of various warm additives on the rutting performance of traditional asphalt mixture with different binders and mixing temperature applications. Lowering mixing temperatures can increase the rutting susceptibility due to less aging occurring in the binder during mixing. The results of the study indicated that the addition of warm wax additive can stiffen the binder and increase the mixture rutting resistance. According to Kim and Lee (2016), several WMA additives have been introduced since 2000. Their study included an evaluation of two wax additives, LEADCAP and Sasobit. The LEADCAP is classified as an organic WMA additive, which is a wax-based structure including crystal controller to adjust crystalline degree of wax material at the low temperature and adhesion promoter to enhance adhesion between asphalt and aggregate (Kim et al. 2013). According to Kim and Lee (2016), Sasobit is a product of Sasol Wax. It is a long chain aliphatic hydrocarbon obtained from coal gasification using the Fischer-Tropsch process. After crystallization, it forms a lattice structure in the binder which is the basis of the structure stability of the binder containing Sasobit (or Sasol Wax).

2.3 SUPERPAVE binder characterization and testing

Federal Highway Administration initiated a nationwide research program called the Strategic Highway Research Program (SHRP) upon recognizing the limitations of the traditional asphalt binder characterization procedures. The introduction of Superpave® in 1993, provided a valuable method of evaluating and understanding the mechanism of rutting. The Dynamic Shear Rheometer

(DSR) was introduced as tool to measure the binder contribution to rutting. The rutting was assumed to be caused by the total dissipated energy (Anderson et al., 1994).

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

The Superpave® specification parameter, |G*|/sin δ, was also identified as the term to be used for high-temperature performance grading of paving asphalts in rating the binders for their rutting resistance. Though used for many years as a rutting parameter, it has been established that the relationship between |G*|/sin δ and rutting is poor. This term was found to be inadequate in describing the rutting performance of certain binders, particularly polymer modified binders. In NCHRP 9-10 project, Bahia et al. (2001) evaluated the direct correlation between mixture's rutting properties and |G*|/sin δ on RTFO aged binders, tested at the same temperature at which the mixture test was conducted. The results indicated a poor correlation of 23.7% between the mixture rate of accumulated strain (S) and the parameter |G*|/sin δ measured at 10 rad/s. Thus, many agencies introduced additional tests to the standard PG specifications to overcome this limitation (Golalipour, 2011).

2.4 Multiple Stress Creep Recovery (MSCR)

As a consequence of traffic, it is believed that the accumulated strain in asphalt binder is mainly responsible for the rutting of asphalt pavements. There have been efforts to formulate a specification parameter that can describe the affinity of a binder to the increase of accumulated deformation under periodic loading. For example, the standard specification for performance-graded asphalt binder (AASHTO designation: M 320-05) uses the parameter $|G^*|/\sin\delta$ (= 1/J") (w= 10 rad/s) as the specification parameter for binders at high-temperatures. As the loss compliance, J", measures the energy dissipated per cycle of sinusoidal deformations (Ferry, 1980), it was assumed that a larger value of J" would cause to greater deformation in the binder. Thus, pavement with such a binder will be more subjected to rutting. However, this parameter does not give correct predictions for polymer-modified asphalts (Anderson and Kennedy 1993, Bahia et al. 2001, Bouldin et al. 2001, Shenoy 2001, D'Angelo and Dongre 2002). To replace the existing Superpave high-temperature binder parameter, $|G^*|/\sin\delta$, a new test, called MSCR, was extensively studied (D'Angelo 2009a, 2009b). This test uses a sequence of shear creep and recovery experiments. In its current form, the MSCR test consists of 1 second of creep loading followed by 9 seconds of recovery over multiple stress levels of 0.1kPa and 3.2kPa at 10 cycles for each stress level (Wasage et al., 2011).

It has been found that Superpave performance grade (PG) specification is not able to quantify the performance of modified binders. To overcome this issue, Federal Highway Administration (FHWA) introduced Superpave plus testing protocol for better characterization of these materials.

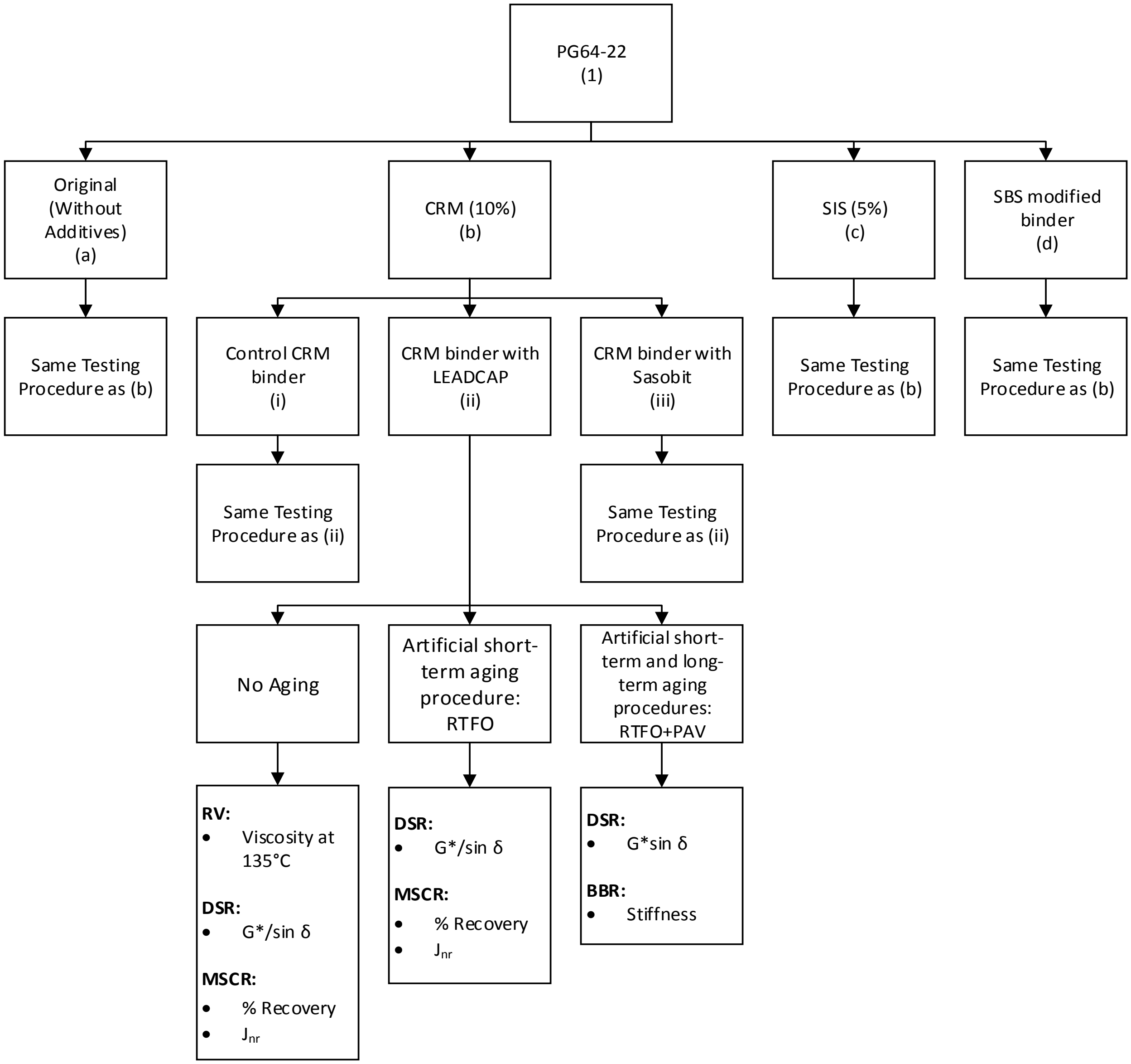
MSCR is one of the various new test methods which were introduced. According to Kumar et al. (2017), this method has been introduced as a part of new Superpave grading system (AASHTO MP 19-10) and accepted as a standard. The test is done on rolling thin film oven (RTFO) aged samples at high PG temperatures. The output of MSCR test is used to calculate nonrecoverable creep compliance (J_{nr}) and percent recovery (%Rec) for quantifying the rutting susceptibility of asphalt binders. Results from the investigations have shown that the unrecoverable creep compliance (J_{nr}) at 3.2 kPa correlates well with the actual field performance (Kumar et al., 2017).

To understand the important attributes of MSCR, consider an example of CRM binder. According to Tabatanaee and Tabatabaee (2010), as the percent of rubber contents increase, the compliance J_{nr} significantly decreases. The addition of CRM significantly improves the resistance of material to permanent deformation. A comparison of two stress level showed that CRM binders were stress sensitive, showing less recovery at 3.2kPa for each binder but more improvement as rubber content increased. According to Sadeq et al (2016), Sasobit increased the rutting factor and enhanced the PG grade of the binder by one unit (6°C), when added with asphalt binder. This stiffness increment also affected the fatigue resistance factor, which increases the possibility of having fatigue cracking at low temperature. Multiple Stress Creep Recovery (MSCR) test examined the viscoelastic behavior of asphalt binder before and after adding WMA additives. Results indicate that Sasobit would affect the fresh asphalt binder only in lowering the mixing and compaction temperatures, but would perform the same as original binder against rutting. The MSCR test showed that modification of asphalt binder caused a significant increase in binder elastic recovery, reducing the permanent deformation and thus improving rutting resistance. However, it is indicated that there are serious concerns regarding the repeatability and reproducibility of the MSCR test results for modified binders, including wax modified binders (Soenen et al., 2013).

Ultimately, the Multiple Stress Creep and Recovery (MSCR) test was established as a replacement for the existing AASHTO M 320 high-temperature binder test. The results from the MSCR test may also be used as an alternative to the various SHRP+ tests. In addition to illustrating fundamental properties, the MSCR is an easy-to-use performance-related test. According to Golalipour (2011), multiple binders both neat and polymer-modified were evaluated in the development of a new binder test to determine high-temperature rutting property for binders. Equipment for testing of the binders was focused on the existing dynamic shear rheometer (DSR). This equipment has been widely accepted by highway agencies for use in determining rheological properties of binders in specifications. The DSR measures fundamental properties, related to the stress strain response of viscoelastic materials and is ideally appropriate to assess asphalt binders (Golalipour, 2011).

3. MATERIALS AND METHODS

In this chapter, the materials used in this study and the procedures to accomplish the research objectives are described. The objective of this study is to investigate the effects of different variables on control binders and PMA binders mixed with wax additives. The flowchart of experimental design is shown in Figure 3-1. As the rheological properties of asphalt binders have different effects with respect to time due to oxidation, it is required to find the characteristics of asphalt binder at various stages throughout the binder life. There are three stages in the life of material, according to the current asphalt binder specification. The first stage is the original binder which represent the asphalt stored before mixing. The second stage is primary-aged binder which represent the binder aged during the mixing and compaction process. The third stage is secondary-aged binder which represent the binder aged after several years of service life in the pavement. The purpose of aging the binder is to achieve the conditions that are closer to those seen in the actual field conditions. To simulate the aging of the binders, the current specifications consider two laboratory procedures. Rolling Thin Film Oven (RTFO) simulates primary aging, while Pressure Aging Vessel (PAV) simulates the secondary aging during five to ten years of in-service asphalt pavement.



Key:

PG: Performance Grade
64-22: The binder meets the high temperature properties up to 64°C and low temperature properties down to -22°C
CRM: Crumb Rubber Modifier
SIS: Styrene-Isoprene-Styrene
SBS: Styrene-Butadiene-Styrene
RTFO: Rolling Thin Film Oven
PAV: Pressure Aging Vessel
RV: Rotational Viscometer
DSR: Dynamic Shear Rheometer
BBR: Bending Beam Rheometer
G*: Complex shear modulus and δ: Phase angle

Figure 3-1. Flowchart of experimental design

Materials

Asphalt binder

In this study, Performance grade (PG) 64-22 asphalt binder and PMA binders containing SIS (approximately 5% by the weight of binder), CRM (approximately 10% by the weight of binder), and SBS (approximately 5% by the weight of binder) modified binder were used. In this research, PG 64-22 binder was modified with three different modifiers to study the rheological properties and stress-dependent behavior of modified asphalt binders. Table 3-1 shows the details of the modified binders used in the study.

Table 3-1. Binder IDs and their characteristics.

Binder ID	Type of modifier	Modifier content (wt. %)
PG 64-22	-	0
SBS	SBS	5
SIS 5%	SIS	5
CRM 10%	CRM	10

For this experiment, 600gm of each CRM and SBS modified asphalt binders were heated in oven for 2 hours at 365°F, and SIS modified binder was heated in oven for 1 hour at 365°F. 5% of SIS (5% of 600gm =30gm) was added in the oven-heated sample and put on the mixer for 60 minutes at 365°F. The Crumb Rubber Modifier (CRM), passed through a 40 mesh (0.420 mm), is produced by mechanical shredding process, and the modified rubberized binder by wet process. 10% of CRM (10% of 600gm =60gm) was added in the oven-heated sample and put on the mixer for 30 minutes at 170°C mixing temperature and 700 rpm mixing speed. Since SBS modified asphalt binder is a commercially available binder, it was used in the same manner without any further modifications.

After mixing the modifiers in the oven-heated binder sample, 98.5% of binder was poured into two containers by weight, and 1.5% of wax additives i.e. LEADCAP and Sasobit, each was mixed with the modified binder in the containers. The tests were performed for binders, before and after the addition of wax additives.

The asphalt binder was passed through the aging process by using rolling thin film oven (RTFO) for 85 minutes at 163°C (ASTM D 2872) and pressure aging vessel (PAV) for 20 hours at 100°C (ASTM D 6251). The test properties of asphalt binders and the instrument used for different aging conditions are presented in Table 3-2.

Table 3-2. Properties of base asphalt binder

Aging states	Instrument	Test Properties
Unaged binder	RV	Viscosity @ 135°C (cP)
	DSR	G*/sin δ @ 64°C (kPa)
	MSCR	▪ J_{nr} ▪ %Rec
RTFO aged binder	DSR	G*/sin δ @ 64°C (kPa)
	MSCR	▪ J_{nr} ▪ %Rec
RTFO+PAV aged binder	BBR	▪ Stiffness @ -12°C (MPa) ▪ m-value @ -12°C
	DSR	G*sin δ @ 25°C (kPa)

<u>LEADCAP</u>

The LEADCAP is an organic additive of a WMA wax-based structure that consists of crystal controller and artificial materials. As polyethylene-based wax is the major component of LEADCAP, the wax material can be melted at over melting temperature due to its crystalline structure. The melting point of LEADCAP is about 110°C. Therefore, the LEADCAP in the asphalt binder at 130°C (the temperature at which the asphalt mixture is produced), is liquidized. Since the molecular weight of wax is lower than that of average asphalt molecules, LEADCAP in the asphalt binder can reduce the viscosity of the binder (Yang et al., 2012). Figure 3-2 shows LEADCAP used in this study.

Figure 3-2. LEADCAP

Sasobit

Sasobit is a long chain of aliphatic hydrocarbon obtained from coal gasification using Fischer-Tropsch process. Ultimately, it is a product of a Fischer-Tropsch (FT) wax and Sasol wax, which melted completely into the asphalt binder at 115°C and reduce the binder viscosity. Sasobit gives poor low-temperature properties because crystalline wax material is very stiff and brittle at temperature less than crystallization point, which further expedite the wax-based additive to exhibit a high potential for cracking (Yang et al., 2012). Sasobit forms a lattice structure in the binder after crystallization, which is the basis of the structural stability of the binder containing Sasobit (Kim and Lee, 2016). Figure 3-3 shows Sasobit used in this study.

Figure 3-3: Sasobit

Addition of wax additives

Two types of warm asphalt additives; Sasobit and LEADCAP, are used each with a ratio by weight of binder. These additives were added in the quantity of 1.5 percent (1.5 gm) of the binder. The tests were conducted in the original state (without additives) and with adding these two wax warm additives. The asphalt binder was mixed with the additives by hand mixing for 1 minute in order to get a consistent mixing. Table 3-3 describes the binder types used in this study and their arrangements, as mixed with wax warm additives.

Table 3-3. Description of Binders with Wax warm additives

Binder types	Description
PG 64-22	PG 64-22 binder
PG 64-22 + L	PG 64-22 binder with 1.5% LEADCAP
PG 64-22 + S	PG 64-22 binder with 1.5% Sasobit
SIS	SIS modified binder
SIS+ L	SIS modified binder with 1.5% LEADCAP
SIS + S	SIS modified binder with 1.5% Sasobit
CRM	CRM modified binder
CRM + L	CRM modified binder with 1.5% LEADCAP
CRM + S	CRM modified binder with 1.5% Sasobit
SBS	SBS modified binder
SBS + L	SBS modified binder with 1.5% LEADCAP
SBS + S	SBS modified binder with 1.5% Sasobit

Experimental Procedure

<u>MSCR Test</u>

MSCR test is conducted using the DSR, as shown in Figure 3-9, for SBS, CRM, PG 64-22, and SIS binders. The test is conducted according to AASHTO T 350-14 specification at 64°C. PMA binders were tested in original state, and with adding wax additives (i.e. LEADCAP and Sasobit). The samples are tested in creep and recovery at two stress levels: 0.1 kPa and 3.2 kPa. Two parameters are derived from analyzing the MSCR test (i.e. the non-recoverable creep compliance (J_{nr}) and percent recovery (%Rec)). The test is done on unaged, and rolling thin film oven (RTFO) aged samples at high PG temperatures. As shown in Figure 3-4, the binder is subjected to creep loading and unloading cycle of 1 second and 9 seconds respectively, at stress levels of 0.1 kPa and 3.2 kPa and ten cycles of loading are given at each stress level. The output of MSCR test is used to calculate non-recoverable creep compliance (J_{nr}) and percent recovery (%Rec) for quantifying the rutting susceptibility of asphalt binders. The non-recoverable creep compliance (J_{nr}), which is determined by dividing non-recoverable shear strain by the shear stress, is used to evaluate the rutting potential of the asphalt binder. Figure 3-5 shows the Bohlin software used to perform MSCR test.

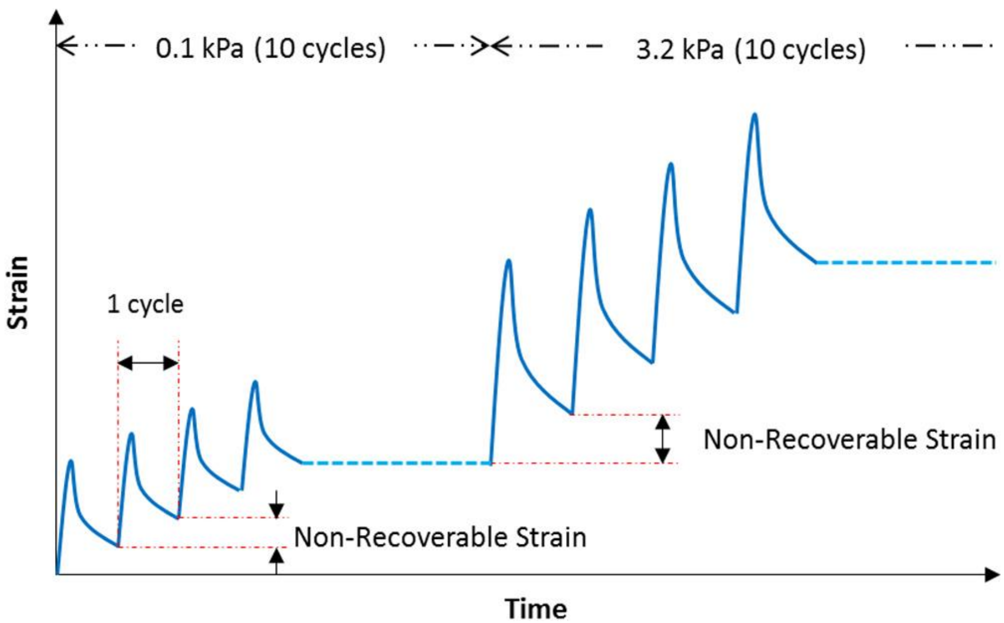


Figure 3-4. Typical MSCR test results with 10 cycles of creep and recovery at stress levels of 0.1 and 3.2 kPa (Zhang et al., 2015)

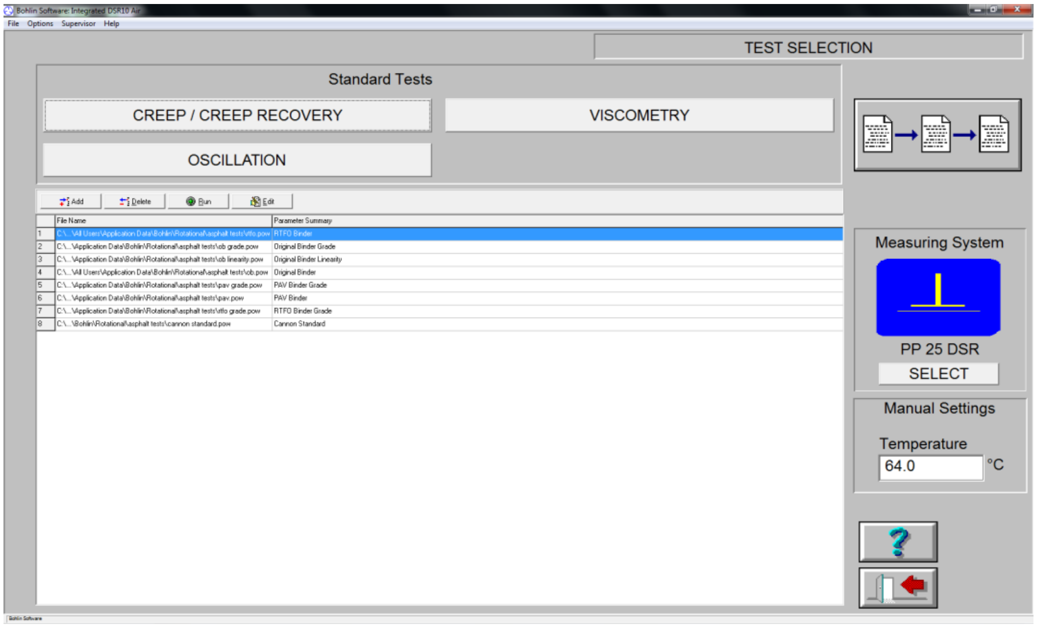


Figure 3-5. Bohlin software to perform MSCR test

<u>RV Test</u>

The viscosity is measured using a Brookfield Rotational Viscometer at the standard temperature of 135°C, according to AASHTO T 316. An 8.5 g of control binder (PG 64-22) sample and 10.5 g of PMA binders (SBS, SIS and CRM) each are tested with a number 21 and 27 spindles, respectively. The test was conducted on the original binder and by adding 1.5 % of LEADCAP and Sasobit each, using the method stated above. At a constant temperature, the viscosity is determined by measuring the torque, to maintain a constant rotational speed of a cylindrical spindle while submerged in an asphalt binder sample. Figure 3-6 shows the instrument “Rotational Viscometer”.

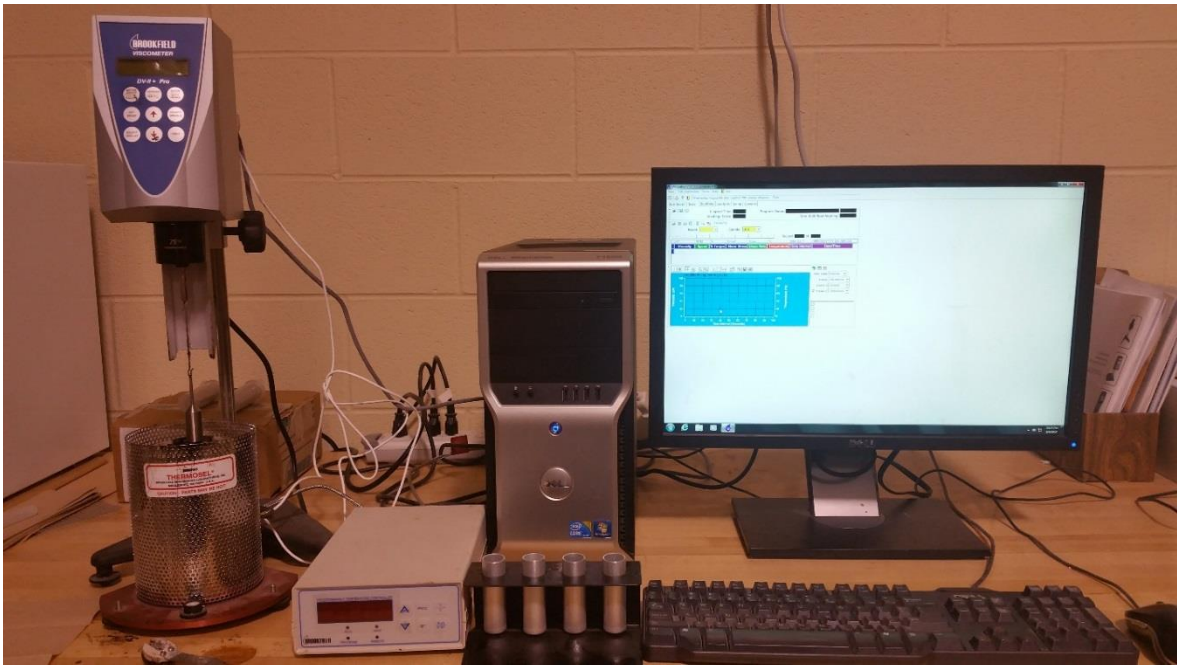


Figure 3-6. Rotational Viscometer

DSR Test

DSR test is conducted for measuring the high temperature rheological properties of each binder at a frequency of 10 radians per second (1.59 Hz), according to AASHTO T 315. For DSR test, PMA binders were used in original state, and with wax additives. The binders were tested in original state, and then artificially short-term aged through the rolling thin film oven (RTFO) aging process for 85 min at 163°C. The short-term aged binders are evaluated using DSR test, and are subjected to artificial long-term aging in Pressure Aging Vessel (PAV). The original binders and RTFO residual binders were tested with a 25 mm parallel plate at 64°C and the binders (RTFO+PAV residual) were tested using an 8 mm parallel plate at 25°C. Asphalt binder shows viscoelastic properties at temperatures where most pavements carry traffic. The relationship between the applied stress and the resulting strain quantifies the viscoelastic behavior in the DSR, and leads to the calculation of two important asphalt binder properties: the complex shear modulus (G*) and phase angle (δ). G* is the ratio of maximum shear stress (τ_{max}) to maximum shear strain (γ_{max}).

The phase angle (δ), the time lag between the applied stress and the resulting strain, is considered as zero degree for elastic materials, and 90 degrees for viscous materials. As shown in Figure 3-7, viscoelastic material such as asphalt, shows a stress-strain response between the two extremes in DSR.

Considering the viscoelastic nature, G* is the measure of total resistance of a material to deform when sheared repeatedly, and δ is the angle made with the horizontal axis which indicates the relative amount of temporary and permanent deformation. Figure 3-8 further illustrates the viscoelastic behavior of asphalt by considering two viscoelastic asphalts. However, both asphalts are viscoelastic, but due to smaller δ, asphalt 2 is more elastic than asphalt 1.

In this study, G*/sin δ, for each asphalt binder in both original state and short term aged state, and G*sin δ for long-term aged state are used. Figure 3-9 shows the apparatus used for DSR test in this study.

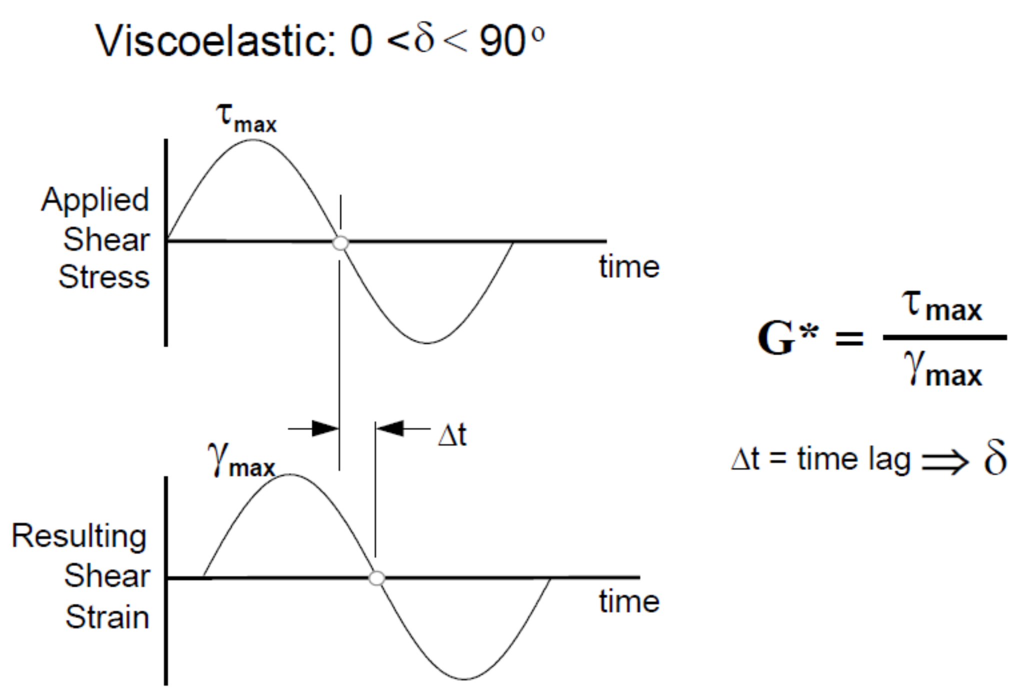


Figure 3-7. Stress-Strain response for viscoelastic materials (Superpave Fundamentals: Reference Manual)

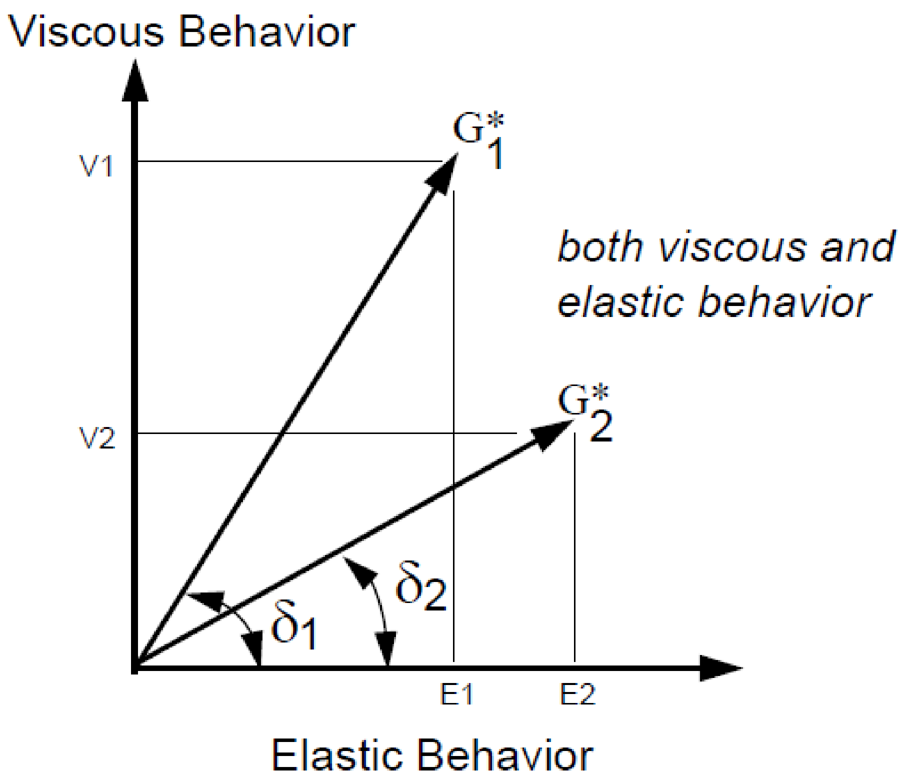


Figure 3-8. Viscous and Elastic behavior of asphalt (Superpave Fundamentals: Reference Manual)

Figure 3-9. Dynamic Shear Rheometer

BBR Test

The Bending Beam Rheometer test is conducted on asphalt beam (125 x 6.35 x 12.7 mm) to determine the stiffness at -12°C. According to AASHTO T 313, the cracking property of the asphalt binder at low temperature is evaluated using BBR test. The binders with and without wax additives were used and creep stiffness (S) of the binders were measured at a loading time of 1 min. Test was performed on RTFO+PAV residual samples. The beam of the binder was supported at both side and a constant load of 100 g applied at the center of the beam. And, the deflection of the center point and the m-value were measured. Figure 3-10 shows the apparatus used for BBR test in this study.

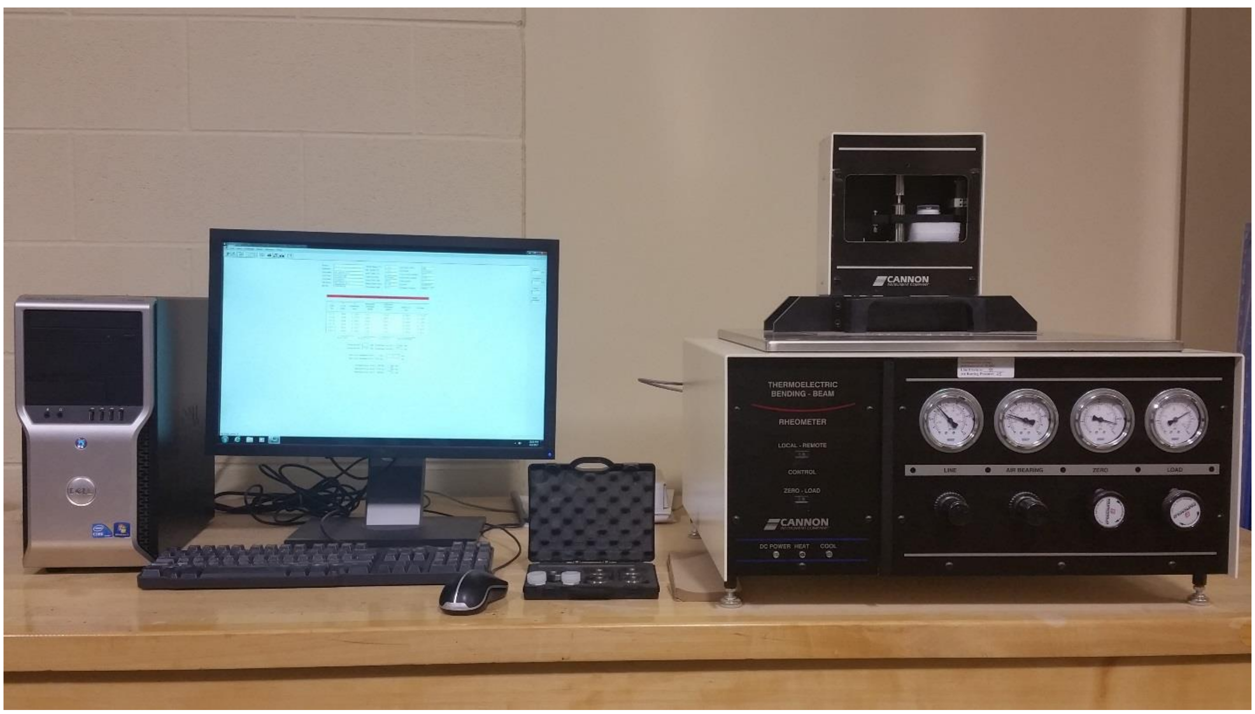


Figure 3-10. Bending Beam Rheometer

4. STATISTICAL ANALYSIS

The software "IBM SPSS Statistics" program was used to perform statistical analysis, to conduct an analysis of variance (ANOVA) and Least Significant Difference (LSD) with comparison to the significance value ($\alpha = 0.05$). In this study, the primary variables include the binder types (PG 64-22, SBS, CRM and SIS) and the wax types (Control, LEADCAP, and Sasobit).

First, to determine whether the significant difference among the sample means existed, the ANOVA was performed. The significance level of 0.95 (α=0.05) indicates that each finding had a chance of 95% to be true. After determining that there were differences among the sample means using the ANOVA, the LSD was calculated to determine the difference between two sample means required to affirm the corresponding population mean difference. After the LSD was calculated, all pairs of sample means were compared. According to Ott (2001), the difference between the LSD and two sample means is considered the determining factor to declare the statistical significance of the variables. Therefore, if the difference between two sample means was greater than or equal to the LSD, the population means were stated to be statistically different.

5. RESULT AND DISCUSSION

5.1. Rotational Viscosity test

Since the viscosity reflects the binder's ability to be pumped through an asphalt plant, it is considered as a significant factor, at high-temperature, to decide the working temperature (Asphalt Institute, 2003). The variations in the viscosities of asphalt binders using different wax warm additives and with different modifiers; such as SBS, SIS and CRM are shown in Figure 5-1. The test was conducted using Rotational Viscometer at 135°C as accordance with AASHTO T 316. The results show that using modifiers with the asphalt binder increased the viscosity of the binder. The stiffening effects of SBS modification on the viscosities can be seen easily, which shows that as compared to other modifiers, SBS increases the viscosity of asphalt binder. The addition of wax additives played a significant role in reducing the viscosities, due to its properties to decrease the mixing and compaction temperature as compared to the control binders. For the control binder, there is a slight difference in the viscosities but the addition in PMA binder shows a significant effect in reducing the viscosity, when mixed with Sasobit (Kim et al. 2014; Kantipong et al. 2007; Kim 2007; Hurley and Prowell 2005; Edwards et al. 2010; Kim et al. 2010, 2011, 2012; Jamshidi et al. 2012, 2013; Susana et al. 2008). The reduction in viscosity of SBS modified binder with LEADCAP and Sasobit was approximately 8% and 15% respectively, as compared to SBS modified binder without additives. Figure 5-1 also shows the reduction rate of viscosities for PMA binders with wax additives. It shows the percentage reduction of viscosities for LEADCAP (L) and Sasobit (S) as compared to the control binder.

The same trend was observed with SIS modified binder and CRM binder. The addition of Sasobit in SIS modified binder reduced the viscosity up to 10%, as compared to reduction of 4%, when mixed with LEADCAP. Likewise, the addition of Sasobit in the CRM binder reduced the viscosity approximately 10%, as compared to reduction of 9%, when mixed with LEADCAP. All the modified binders satisfy the current maximum requirement by Superpave (i.e. 3,000 centipoise), except for SBS modified binder without wax additives, which is slightly higher than the maximum requirement.

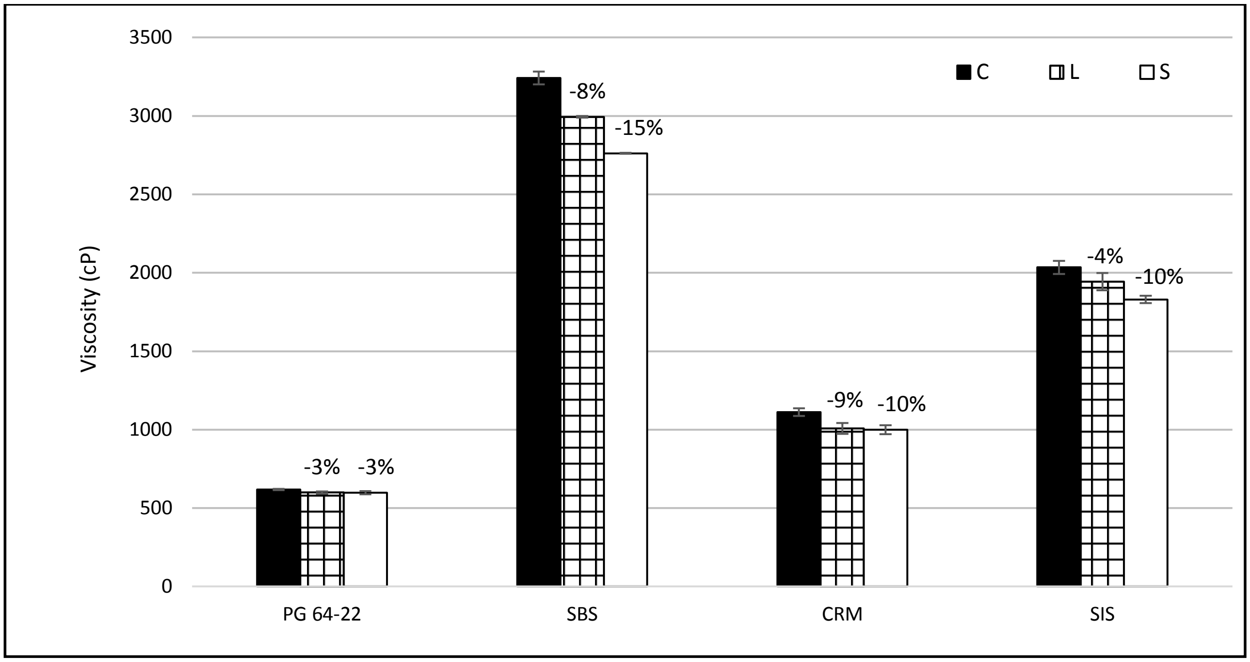


Figure 5-1. Viscosity of the binders with wax additives at 135°C

Table 5-1. Results of statistical analysis of the viscosity value as a function of the binder and wax additives at 135°C

Viscosity	PG 64-22	PG 64-22 +L	PG 64-22 +S	SBS	SBS +L	SBS +S	CRM	CRM+L	CRM+S	SIS	SIS +L	SIS +S
PG 64-22	-	N	N	S	S	S	S	S	S	S	S	S
PG 64-22+L		-	N	S	S	S	S	S	S	S	S	S
PG 64-22+S			-	S	S	S	S	S	S	S	S	S
SBS				-	S	S	S	S	S	S	S	S
SBS+L					-	S	S	S	S	S	S	S
SBS+S						-	S	S	S	S	S	S
CRM							-	S	S	S	S	S
CRM+L								-	N	S	S	S
CRM+S									-	S	S	S
SIS										-	S	S
SIS+L											-	S
SIS+S												-

S: significant N: non-significant

The statistical results of the change in the viscosity as a function of binder type and wax additive are shown in Table 5-1. It can be seen that the binder types have a significant effect on the viscosity value at 135°C. There was a statistically significant difference in the viscosity of these binders due to the addition of wax additives.

5.2. Bending Beam Rheometer test

The stiffness of asphalt binder, in original and modified states, with and without wax additives was measured using Bending Beam Rheometer at -12°C on RTFO+PAV aged binder, as accordance to AASHTO T 313. According to Asphalt Institute (2003), the decrease in stiffness leads to reduction in tensile stresses in the asphalt binder and reduces the chances of low temperature cracking. The m-value, the change in asphalt stiffness with time during loading, represents the rate of change in the creep stiffness verses time. For creep stiffness, Superpave asphalt binder specification contains a maximum requirement of 300 MPa of measured stiffness and the m-value be greater than or equal to 0.3 at 60 seconds. Figures 5-2 and 5-3 demonstrate the differences in stiffness and m-value for asphalt binders, respectively.

The addition of Sasobit with PG 64-22 binder increased the stiffness to 16% as compared to the control binder, while addition of LEADCAP reduced the stiffness up to 6%. The similar trend was observed with SBS and CRM binders. The addition of Sasobit with SBS modified binder increased the stiffness to 12% as compared to control SBS binder, whereas addition of LEADCAP reduced the stiffness up to 7%. The CRM asphalt binder with LEADCAP is found to have the lowest stiffness value of 189 MPa, which is approximately 3% lower than the stiffness value of CRM binder without additives. It was found that all the binders, except PG 64-22 binder with Sasobit and SBS modified binder with Sasobit, satisfied the maximum requirement of 300 MPa. CRM binder with LEADCAP is expected to have the best performance for low temperature cracking resistance as compared to other binder types used in this study.

It was found that all the binders showed a similar trend by showing the highest value of stiffness for Sasobit. However, the addition of LEADCAP showed an influential effect on the stiffness by reducing it approximately up to 18% compared to the control SIS binder. In general, it shows that the addition of LEADCAP increased the m-value of the binder while the addition of Sasobit decreased the m-value of the binder. This similar trend was followed by all the binders.

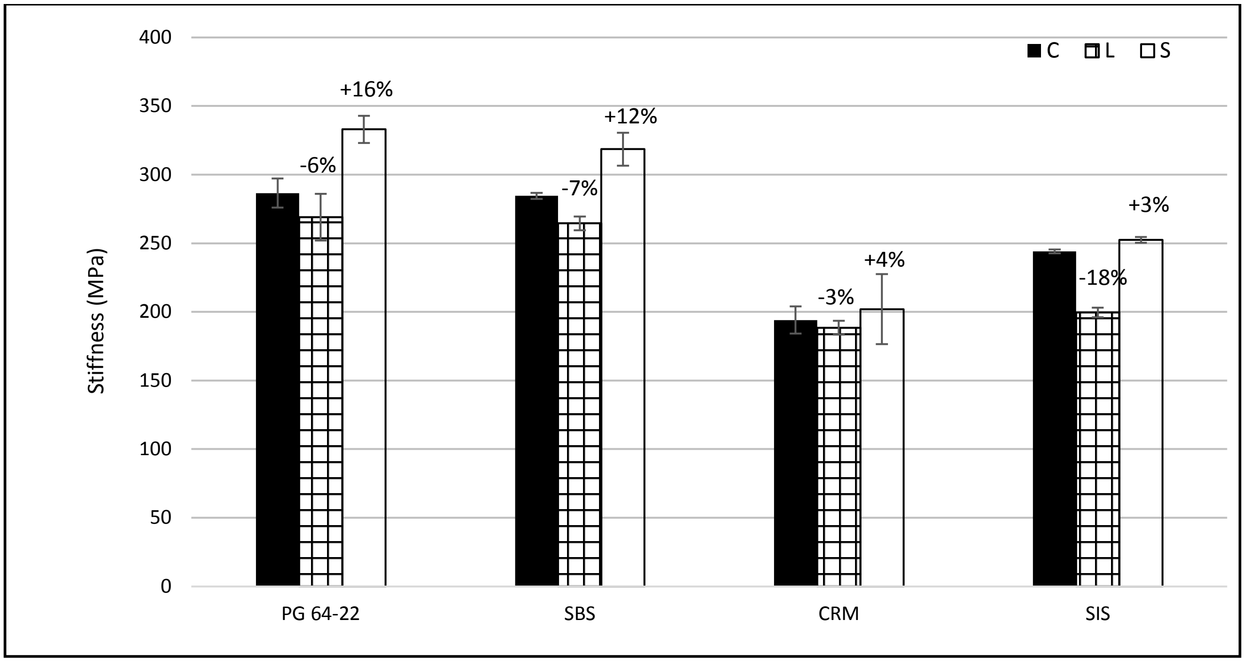


Figure 5-2. Stiffness of the binders with wax additives at -12°C (after RTFO+PAV)

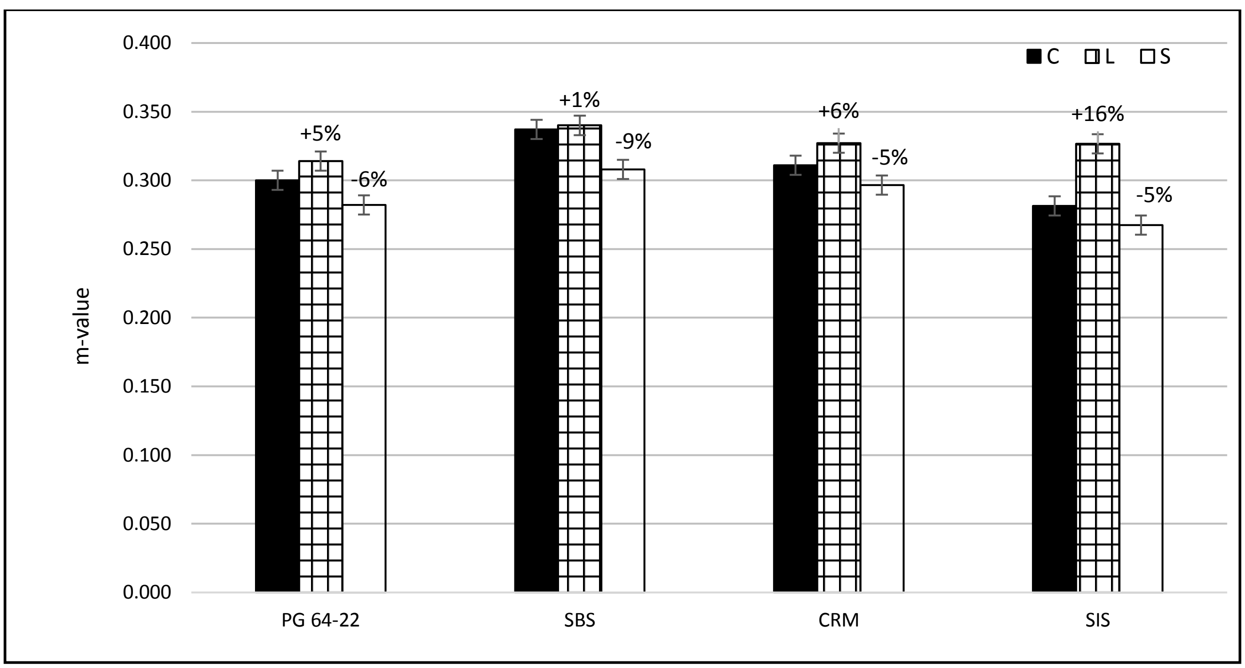


Figure 5-3. m-value of the binders with wax additives at -12°C (after RTFO+PAV)

Table 5-2. Results of statistical analysis of the stiffness value as a function of the binder and wax additives after RTFO + PAV at -12°C

Stiffness	PG 64-22	PG 64-22 +L	PG 64-22 +S	SBS	SBS +L	SBS +S	CRM	CRM+L	CRM+S	SIS	SIS +L	SIS +S
PG 64-22	-	N	S	N	N	S	S	S	S	S	S	S
PG 64-22+L		-	S	N	N	S	S	S	S	S	S	N
PG 64-22+S			-	S	S	N	S	S	S	S	S	S
SBS				-	N	S	S	S	S	S	S	S
SBS+L					-	S	S	S	S	N	S	N
SBS+S						-	S	S	S	S	S	S
CRM							-	N	N	S	N	S
CRM+L								-	N	S	N	S
CRM+S									-	S	N	S
SIS										-	S	N
SIS+L											-	S
SIS+S												-

S: significant N: non-significant

The statistical significance of the change in the stiffness value as a function of binder type and wax additive was analyzed and the results are shown in Table 5-2. The data show that there was a statistically significant difference in the stiffness values depending on the binder types at -12°C. In general, the addition of wax additive resulted in a significant change of stiffness values, within each binder type.

5.3. Dynamic Shear Rheometer test

5.3.1. Original binder

G*/sin δ, for original (unaged binder), was measured using Dynamic Shear Rheometer at 64°C, as accordance to AASHTO T 315. Figure 5-4 shows the G*/sin δ, conducted on the PG 64-22 (unaged) binder and polymer modified binders. According to Asphalt Institute (2003), the binders are less susceptible to permanent deformation or rutting at high pavement temperature, if higher G*/sin δ values are observed from DSR test. In general, PMA binders have the higher G*/sin δ value as compared to PG 64-22 binder. The addition of wax additives into the binders caused an increase in the G*/sin δ value. Figure 5-4 also shows the percentage difference of G*/sin δ for

PMA binders with wax additives. It is found that the wax additives have positive effect on the rutting resistance at high-temperature. This might be due to the presence of wax crystals in the binders which increases the complex modulus of the binders. The addition of Sasobit and LEADCAP with unmodified PG 64-22 binder increased the G*/sin δ value of the binder up to 47% and 40%, respectively. The addition of LEADCAP and Sasobit with SBS modified binder increased the G*/sin δ value to approximately 21% and 47%, respectively, as compared to the control SBS binder. Similar trends were observed for CRM and SIS binders.

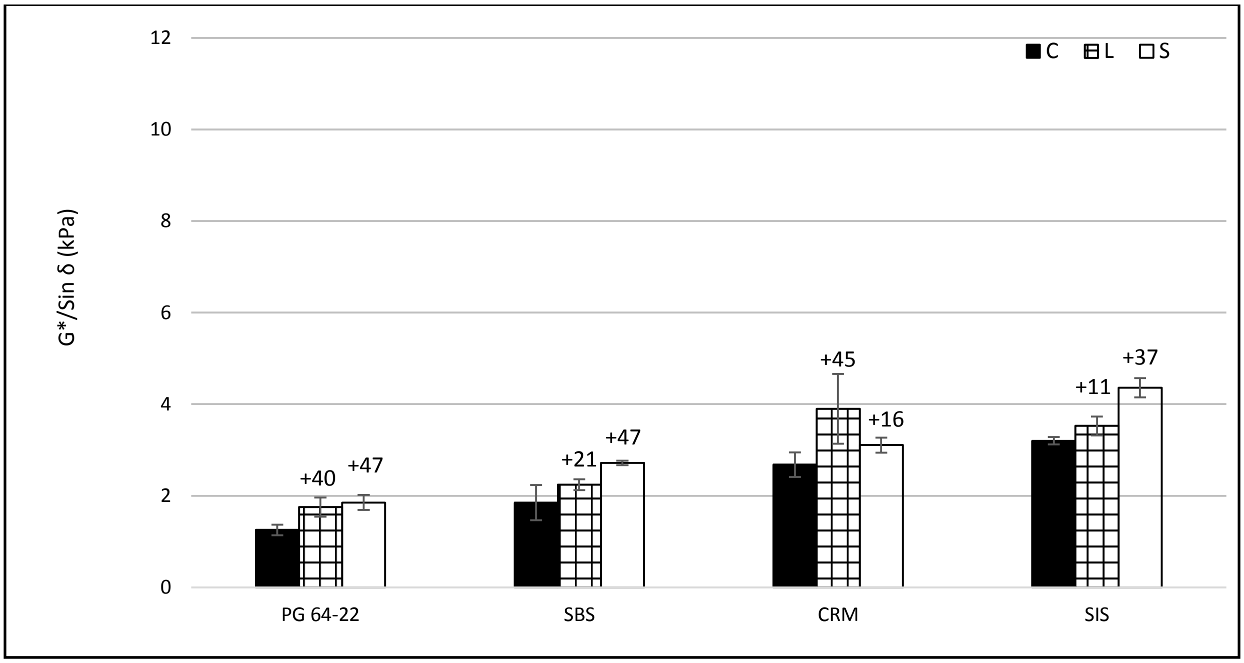


Figure 5-4. G*/sin δ of the binders with wax additives at 64°C (No aging)

Table 5-3. Results of statistical analysis of the G*/sin δ value as a function of the binder and wax additives at 64°C (No aging)

G*/sin δ	PG 64-22	PG 64-22 +L	PG 64-22 +S	SBS	SBS +L	SBS +S	CRM	CRM+L	CRM+S	SIS	SIS +L	SIS +S
PG 64-22	-	N	N	S	S	S	S	S	S	S	S	S
PG 64-22+L		-	N	S	S	S	S	S	S	S	S	S
PG 64-22+S			-	S	S	S	S	S	S	S	S	S
SBS				-	N	N	S	S	S	S	S	S
SBS+L					-	N	S	S	S	S	S	S
SBS+S						-	S	S	S	S	S	S
CRM							-	S	N	N	S	S
CRM+L								-	N	N	N	N
CRM+S									-	N	N	S
SIS										-	N	S
SIS+L											-	S
SIS+S												-

S: significant N: non-significant

The statistical results of the change in the G*/sin δ values for un-aged binder at 64°C are shown in Table 5-3. The results indicated that the binder types have a significant effect on the G*/sin δ values. In general, within each binder type, the difference between two wax additives was found to be statistically insignificant.

5.3.2. RTFO aged binder

Figure 5-5 shows the G*/sin δ, conducted on the PG 64-22 binder and polymer modified binders. SBS modified binders generally resulted in the higher G*/sin δ as compared to the control binders irrespective of aging state. The addition of wax additives into the binders caused an increase in the G*/sin δ value. In general, the percentage improvement of rutting resistance was observed to be much higher for PG 64-22 binder than SBS, CRM and SIS modified binders each containing wax additives.

The addition of LEADCAP and Sasobit with unmodified PG 64-22 binder increased the G*/sin δ value of the binder up to 46% and 47%, respectively, as compared to the binder without wax additives. For CRM binder, the addition of LEADCAP and Sasobit with the binder caused an increase in the parameter value to approximately 22% and 29%, respectively, as compared to the control CRM binder. This trend was observed for all the binders.

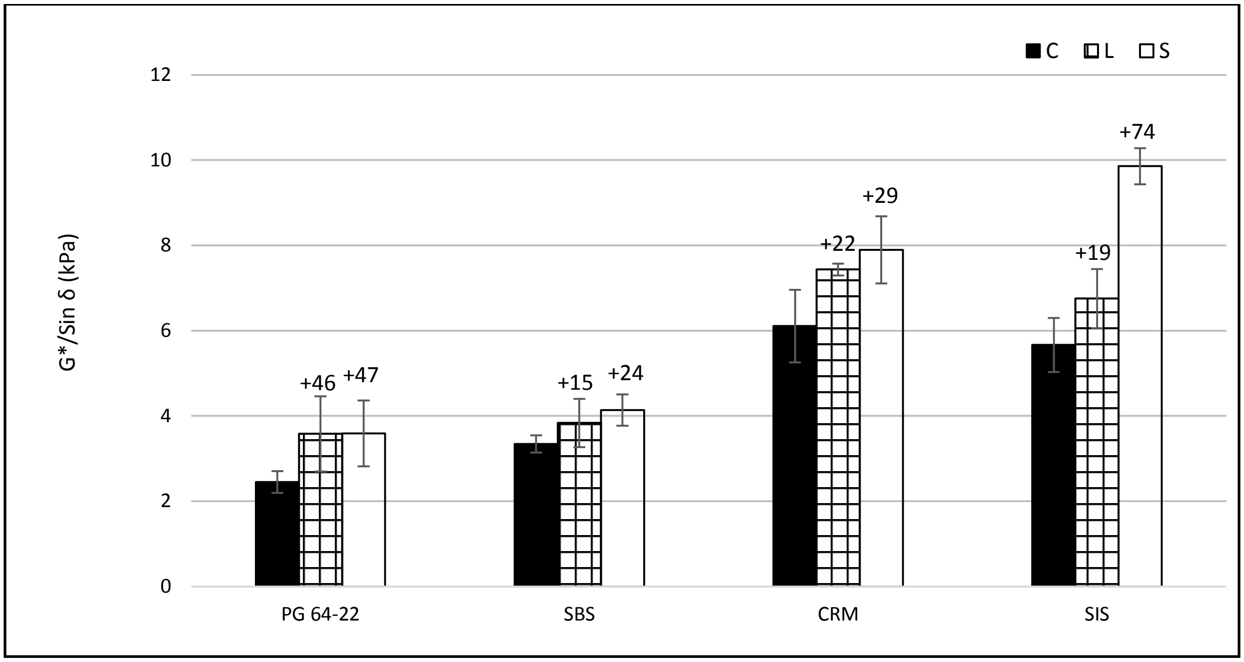


Figure 5-5. G*/sin δ of the binders with wax additives at 64°C (after RTFO)

Table 5-4. Results of statistical analysis of the G*/sin δ value as a function of the binder and wax additives at 64°C (RTFO aging)

G*/sin δ	PG 64-22	PG 64-22 +L	PG 64-22 +S	SBS	SBS +L	SBS +S	CRM	CRM+L	CRM+S	SIS	SIS +L	SIS +S
PG 64-22	-	N	N	S	S	S	S	S	S	S	S	S
PG 64-22+L		-	N	S	S	S	S	S	S	S	S	S
PG 64-22+S			-	S	S	S	S	S	S	S	S	S
SBS				-	N	S	S	S	S	S	S	S
SBS+L					-	N	S	S	S	S	S	S
SBS+S						-	S	S	S	S	S	S
CRM							-	N	S	N	N	S
CRM+L								-	N	S	N	S
CRM+S									-	S	N	S
SIS										-	N	S
SIS+L											-	S
SIS+S												-

S: significant N: non-significant

The statistical significance of the change in the G*/sin δ value as a function of the binder types and wax additive, after RTFO aging, was examined and the results are shown in Table 5-4. The binder types showed a statistically significant difference in the G*/sin δ values. Generally, the type of wax additive (LEADCAP or Sasobit), within each binder type, resulted in an insignificant difference in G*/sin δ (after RTFO aging).

5.3.3. RTFO+PAV aged binder

G*sin δ was measured using Dynamic Shear Rheometer at 25°C for RTFO+PAV aged binder, according to AASHTO T 315, for long-term aged state. Figure 5-6 shows the G*sin δ, conducted on the RTFO+PAV binders. In Superpave binder specification, the product of the complex shear modulus (G*) and the sine of the phase angle (δ) is used to control the fatigue cracking of asphalt pavement. According to Asphalt Institute (2003), the lower value of G*sin δ is the desired attribute for the resistance of fatigue cracking.

The modification of asphalt binder with SBS polymers exhibited the higher G*sin δ value as compared to unmodified PG 64-22 binder. It shows that SBS does not play a significant role in improving the resistance for fatigue cracking. In general, SBS binder containing Sasobit showed higher G*sin δ value compared to the control SBS binder, meaning that Sasobit results in the SBS binder being less resistant to fatigue cracking at intermediate temperature (Kim et al., 2010). The addition of LEADCAP into the binders made a trend in reducing the G*sin δ value and positively effecting the cracking resistance at intermediate temperature. It was found that the addition of LEADCAP into PG 64-22, SBS, CRM, and SIS modified binders reduced the G*sin δ by 11%, 27%, 21% and 43%, respectively. The trend shown in Figure 5-6 describes that the binder containing Sasobit shows the highest value and the binder containing LEADCAP has the lowest value.

According to the Superpave specifications, the maximum requirement for G*sin δ is 5,000 kPa. As shown in Figure 5-6, all the values are under 5,000 kPa and satisfied the maximum requirement set by Superpave. It is predicted that the CRM binders have higher resistance on fatigue cracking at intermediate temperature compared to the unmodified PG 64-22 and other polymer modified binders (SBS and SIS).

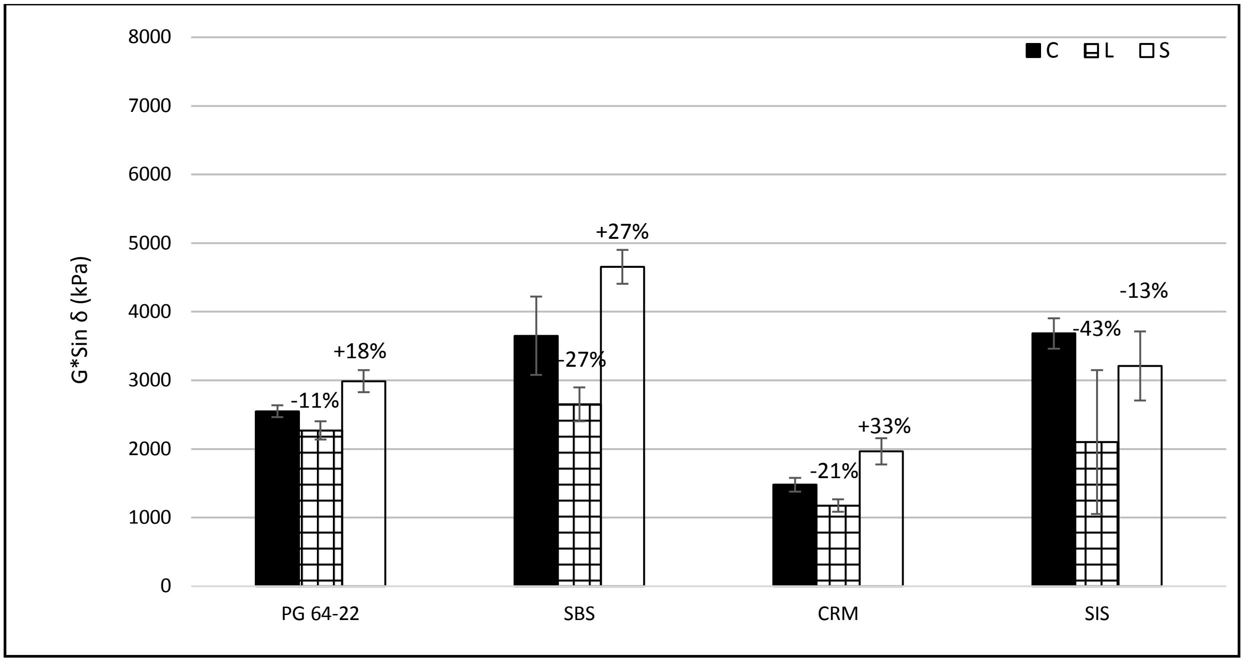


Figure 5-6. G*sin δ of the binders with wax additives at 25°C (after RTFO+PAV)

Table 5-5. Results of statistical analysis of the G*sin δ value as a function of the binder and wax additives at 25°C (RTFO + PAV aging)

G*sin δ	PG 64-22	PG 64-22 +L	PG 64-22 +S	SBS	SBS +L	SBS +S	CRM	CRM+L	CRM+S	SIS	SIS +L	SIS +S
PG 64-22	-	N	N	S	N	S	S	S	N	S	N	N
PG 64-22+L		-	S	S	N	S	S	S	N	S	N	S
PG 64-22+S			-	N	N	S	S	S	S	S	S	N
SBS				-	S	S	S	S	S	N	S	N
SBS+L					-	S	S	S	S	S	N	N
SBS+S						-	S	S	S	S	S	S
CRM							-	N	N	S	N	S
CRM+L								-	S	S	S	S
CRM+S									-	S	N	S
SIS										-	S	N
SIS+L											-	S
SIS+S												-

S: significant N: non-significant

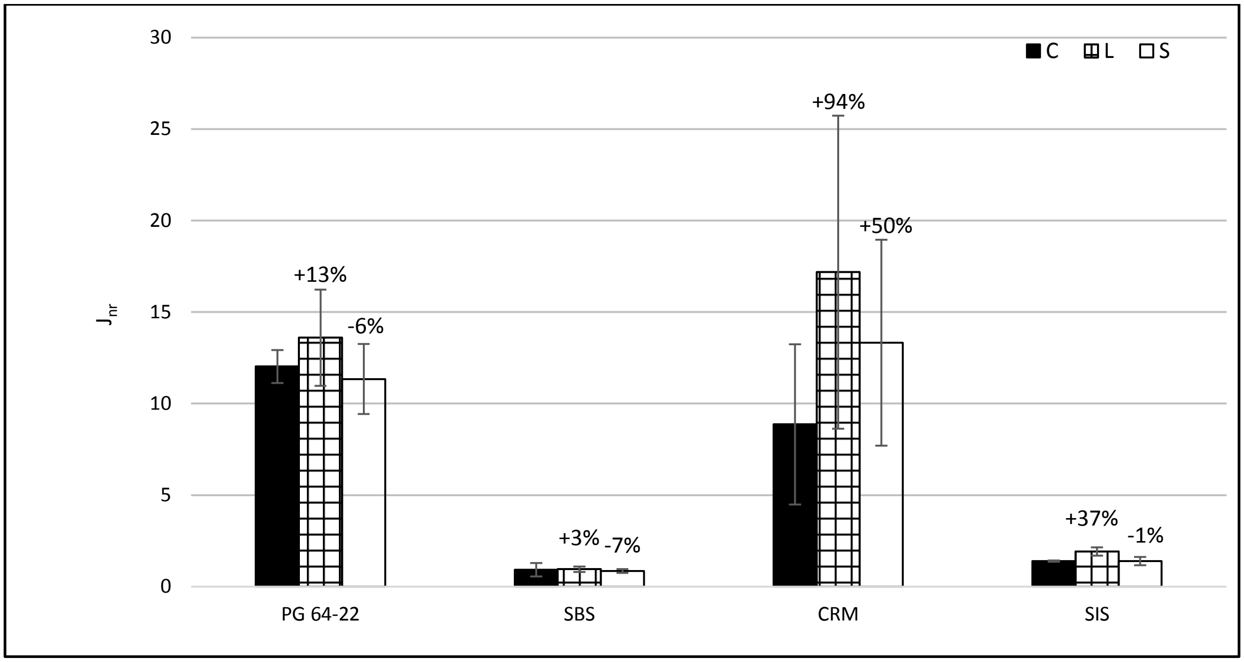
The statistical results of the change in the G*sin δ value are shown in Table 5-5. The results showed that the binder types have a significant effect on the G*sin δ values. It was found that there was a statistically significant difference in the G*sin δ values of these binders due to the addition of wax additives. In general, within each binder type, the difference between LEADCAP and Sasobit was found to be statistically significant.

5.4. Multiple Stress Creep Recovery test

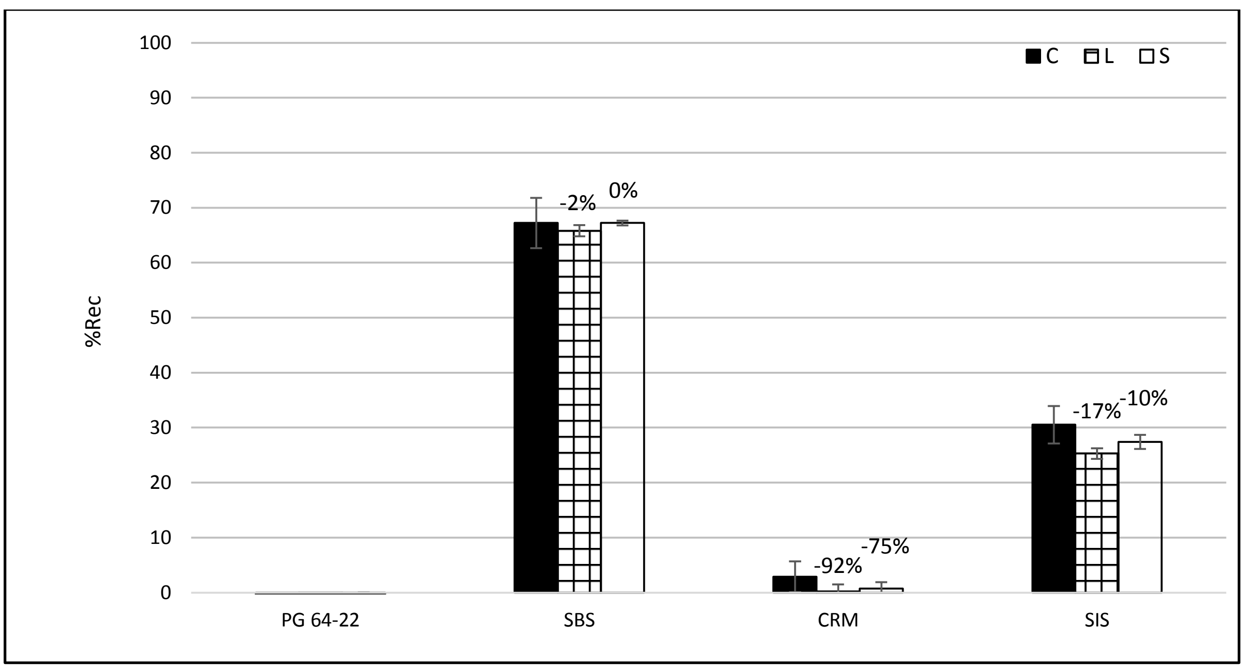
5.4.1. Original Binder

MSCR test was conducted on the original (un-aged) binder, according to AASHTO TP 70. Figure 5-7 shows the variation of creep compliance at 3.2 kPa stress level, the percent difference of creep compliance and percent recovery of the un-aged binders with and without wax additives at 64°C. MSCR test and specification represents a technical advancement over the current PG specification that will allow for better characterization of the high-temperature performance related properties of an asphalt binder (Asphalt Institute, 2010). The non-recoverable creep compliance J_{nr} addresses the high-temperature rutting for both neat and modified binders. % Recovery provides an indication of the delayed elastic response of the asphalt binder. A high delayed elastic response is an indication that the asphalt binder has a significant elastic component at the test temperature.

The modification of asphalt binder affects the creep and recovery parameters significantly, as shown in Figure 5-7. It shows that the addition of LEADCAP with binders increased the J_{nr} value, and reduced the %Rec value. While, the addition of Sasobit with binders reduced the J_{nr} and %Rec value. SBS modified binder showed the lowest J_{nr} value and highest %Rec value as compared to the other binders. It means that SBS modified binder showed comparatively higher recovery rate, after 1 second of creep load. Generally, the addition of LEADCAP and Sasobit increased the %J_{nr} value, as shown in Figure 5-7(c). CRM binder showed a similar trend for rutting resistance as PG 64-22 binder. It illustrates that the MSCR test does not show improved results of rutting resistance for CRM binder.

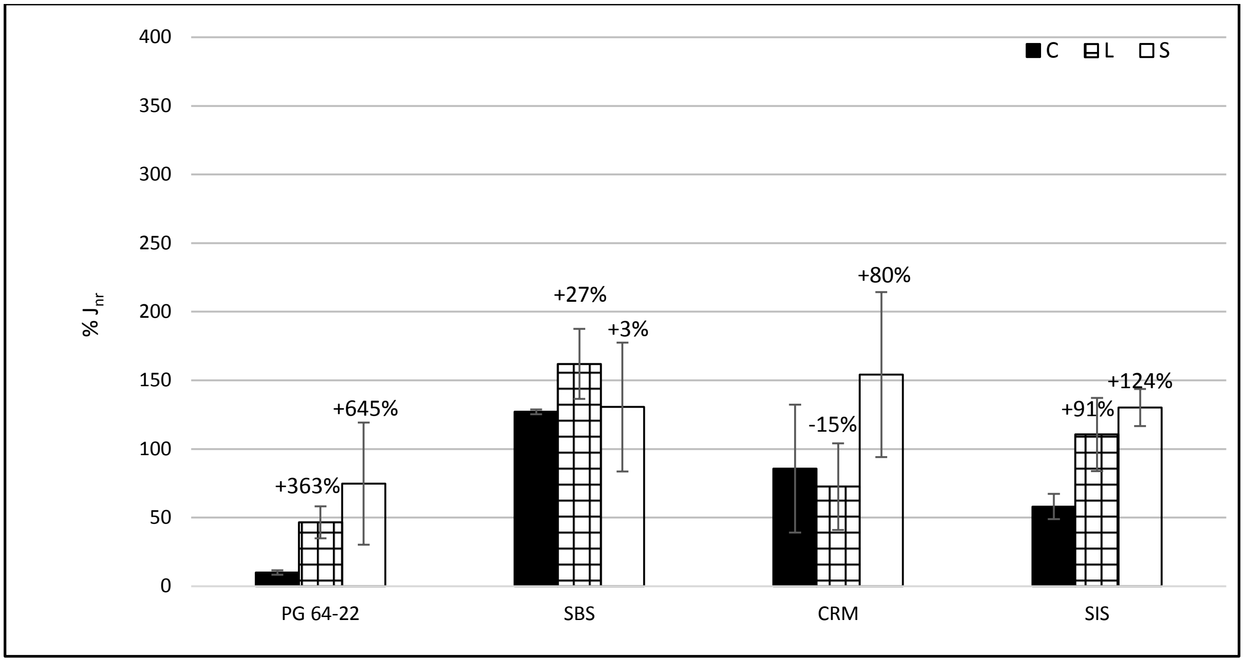


(a)



(b)

Figure 5-7. Variations in creep compliance, percent recovery and percent difference in creep compliance of the binder with wax additives at 64°C (No Aging); (a) J_{nr}, (b) %Rec and (c) % J_{nr}



(c)

Figure 5-7. (Continued.)

Table 5-6. Results of statistical analysis of the creep compliance, percent recovery and percent difference in creep compliance values as a function of the binder and wax additives (No aging) at 64°C (a) J_{nr} (b) %Rec and (c) %J_{nr}

(a)

J_{nr}	PG 64-22	PG 64-22 +L	PG 64-22 +S	SBS	SBS +L	SBS +S	CRM	CRM+L	CRM+S	SIS	SIS +L	SIS +S
PG 64-22	-	N	N	S	S	S	N	S	N	S	S	S
PG 64-22+L		-	N	S	S	S	S	S	N	S	S	S
PG 64-22+S			-	S	S	S	N	S	N	S	S	S
SBS				-	N	N	S	S	S	N	N	N
SBS+L					-	N	S	S	S	N	N	N
SBS+S						-	S	S	S	N	N	N
CRM							-	S	N	S	S	S
CRM+L								-	S	S	S	S
CRM+S									-	S	S	S
SIS										-	N	N
SIS+L											-	N
SIS+S												-

(b)

%Rec	PG 64-22	PG 64-22 +L	PG 64-22 +S	SBS	SBS +L	SBS +S	CRM	CRM+L	CRM+S	SIS	SIS +L	SIS +S
PG 64-22	-	N	N	S	S	S	N	N	N	S	S	S
PG 64-22+L		-	N	S	S	S	N	N	N	S	S	S
PG 64-22+S			-	S	S	S	N	N	N	S	S	S
SBS				-	N	N	S	S	S	S	S	S
SBS+L					-	N	S	S	S	S	S	S
SBS+S						-	S	S	S	S	S	S
CRM							-	N	N	S	S	S
CRM+L								-	N	S	S	S
CRM+S									-	S	S	S
SIS										-	N	N
SIS+L											-	N
SIS+S												-

(c)

%Jnr	PG 64-22	PG 64-22+L	PG 64-22+S	SBS	SBS+L	SBS+S	CRM	CRM+L	CRM+S	SIS	SIS+L	SIS+S
PG 64-22	-	N	N	S	S	S	S	S	S	N	S	S
PG 64-22+L		-	N	S	S	S	N	N	S	N	N	S
PG 64-22+S			-	S	S	N	N	N	S	N	N	S
SBS				-	N	N	N	N	N	N	N	N
SBS+L					-	N	S	S	N	S	N	N
SBS+S						-	N	N	N	N	N	N
CRM							-	N	N	N	N	N
CRM+L								-	N	N	N	N
CRM+S									-	S	N	N
SIS										-	N	S
SIS+L											-	N
SIS+S												-

S: significant N: non-significant

The statistical significance of the change in creep and recovery value for un-aged binder as a function of wax additive and the binder types was analyzed and results are shown in Table 5-6. Table 5-6(a) indicates that there was a significant difference in the J_{nr} values depending on the binder types. It was found that there was a statistically insignificant difference in the J_{nr} values of the binders due to the addition of wax additives. In general, within each binder type, the difference between two wax additives was also found to be statistically insignificant. The similar trends were found for %Rec and %J_{nr}, as shown in Table 5-6(b) and (c), respectively.

5.4.2. RTFO aged binder

MSCR test was also conducted on the RTFO aged binder, according to AASHTO TP 70. Figure 5-8 shows the variation of creep compliance at 3.2 kPa stress level, the percent difference of creep compliance and percent recovery of the RTFO aged binders with and without wax additives at 64°C.

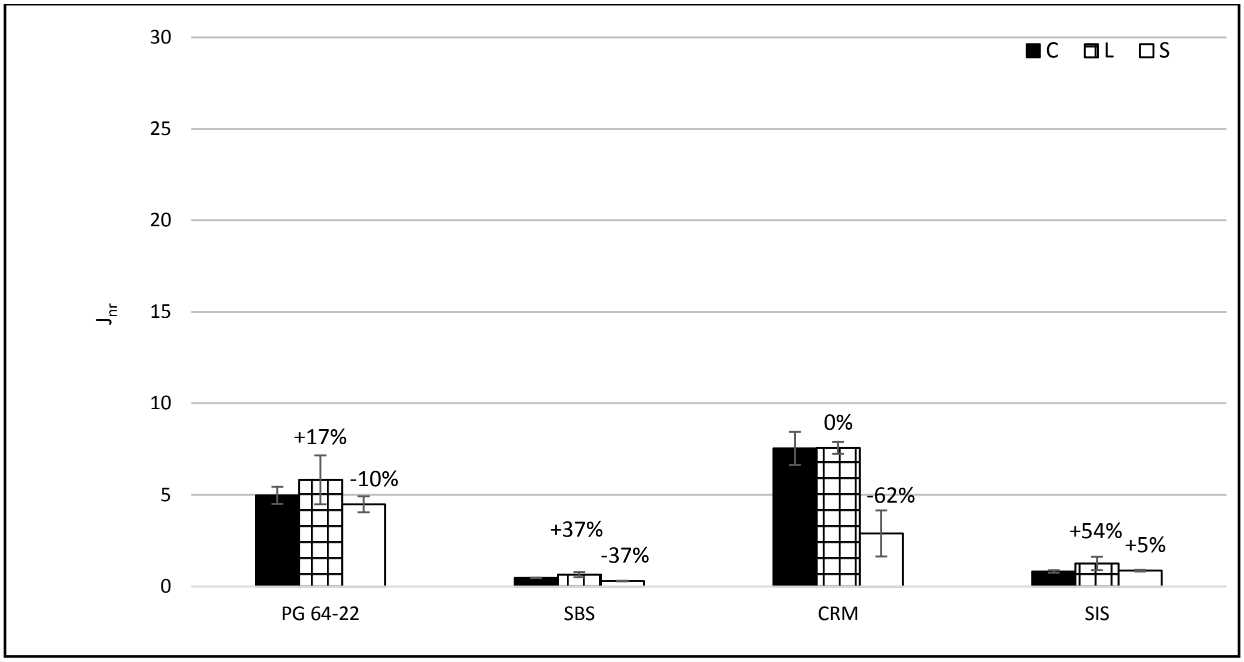
Table 5-7. Minimum % Recovery from MSCR test for J_{nr} value range (AASHTO TP 70)

Minimum % Recovery for Measured J_{nr} values	
J_{nr} at 3.2 kPa	Minimum % Recovery
2.0 – 1.01	30%
1.0 – 0.51	35%
0.50 – 0.251	45%
0.25 – 0.125	50%

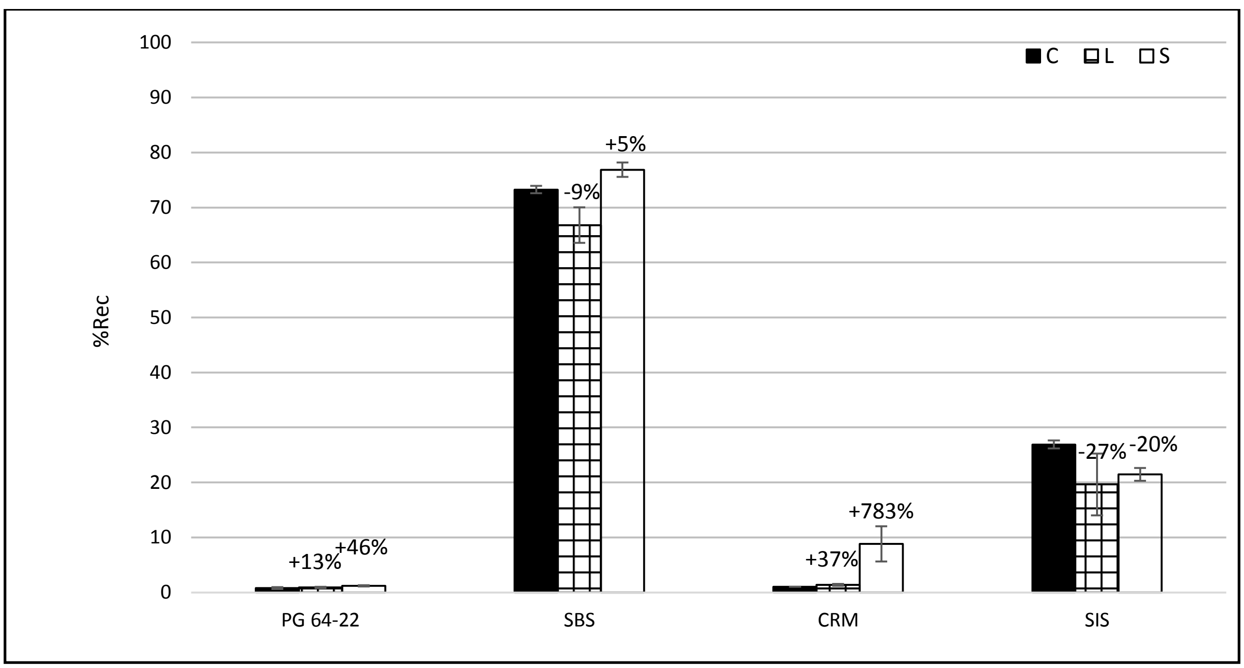
AASHTO TP 70 test procedure for MSCR indicates the minimum requirement for percent recovery for non-recoverable creep compliance at 3.2 kPa stress level for RTFO aged binder. SBS modified binder satisfied the minimum requirement of 35%. The unmodified PG 64-22 binder and

CRM binder, at 3.2 kPa, show the J_{nr} value of greater than 2 kPa^{-1}. According to the specifications, for J_{nr} values greater than 2 kPa^{-1}, there is no minimum requirement of %Rec.

The modification of asphalt binder affects the creep and recovery parameters significantly as shown in Figure 5-8. As shown in Figure 5-8(a) and (b), the addition of LEADCAP with binders increased the J_{nr} value. While, the addition of Sasobit with binders reduced the J_{nr} value. SBS modified binder showed the highest %Rec value as compared to other binders. The modification of asphalt binders resulted in an increase in the %J_{nr} value, when added with LEADCAP and Sasobit, and is shown in Figure 5-8(c).

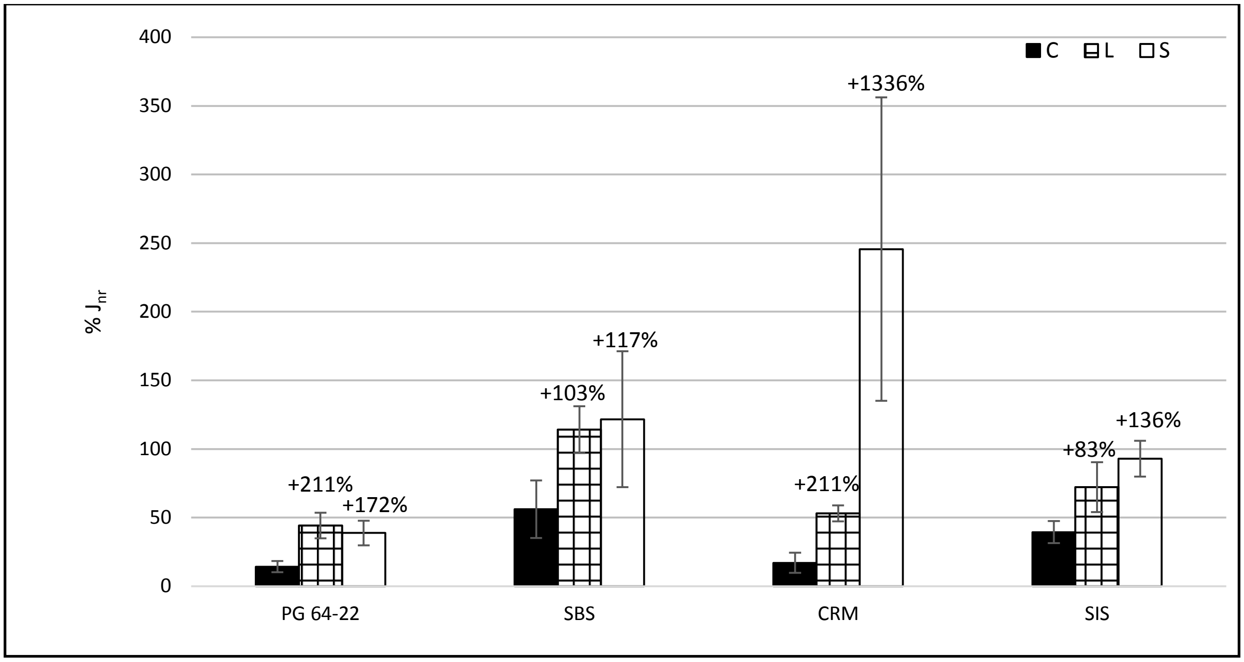


(a)



(b)

Figure 5-8. Variations in creep compliance, percent recovery and percent differences in creep compliance of the binder with wax additives at 64°C (after RTFO); (a) J_{nr}, (b) %Rec and (c) % J_{nr}



(c)

Figure 5-8. (Continued.)

Table 5-8. Results of statistical analysis of the creep compliance, percent recovery and percent difference in creep compliance values as a function of the binder and wax additives (RTFO aging) at 64°C (a) J_{nr} (b) %Rec and (c) $\%J_{nr}$

(a)

J_{nr}	PG 64-22	PG 64-22 +L	PG 64-22 +S	SBS	SBS +L	SBS +S	CRM	CRM+L	CRM+S	SIS	SIS +L	SIS +S
PG 64-22	-	N	N	S	S	S	S	S	S	S	S	S
PG 64-22+L		-	S	S	S	S	S	S	S	S	S	S
PG 64-22+S			-	S	S	S	S	S	S	S	S	S
SBS				-	N	N	S	S	S	N	N	N
SBS+L					-	N	S	S	S	N	N	N
SBS+S						-	S	S	S	N	N	N
CRM							-	N	S	S	S	S
CRM+L								-	S	S	S	S
CRM+S									-	S	S	S
SIS										-	N	N
SIS+L											-	N
SIS+S												-

(b)

%Rec	PG 64-22	PG 64-22 +L	PG 64-22 +S	SBS	SBS +L	SBS +S	CRM	CRM+L	CRM+S	SIS	SIS +L	SIS +S
PG 64-22	-	N	N	S	S	S	N	N	S	S	S	S
PG 64-22+L		-	N	S	S	S	N	N	S	S	S	S
PG 64-22+S			-	S	S	S	N	N	S	S	S	S
SBS				-	S	N	S	S	S	S	S	S
SBS+L					-	S	S	S	S	S	S	S
SBS+S						-	S	S	S	S	S	S
CRM							-	S	S	S	S	S
CRM+L								-	N	S	S	S
CRM+S									-	S	S	S
SIS										-	S	S
SIS+L											-	N
SIS+S												-

(c)

$\%J_{nr}$	PG 64-22	PG 64-22 +L	PG 64-22 +S	SBS	SBS +L	SBS +S	CRM	CRM+L	CRM+S	SIS	SIS +L	SIS +S
PG 64-22	-	N	N	N	S	S	N	N	S	N	N	S
PG 64-22+L		-	N	N	S	S	N	N	S	N	N	N
PG 64-22+S			-	N	S	S	N	N	S	N	N	N
SBS				-	N	S	N	N	S	N	N	N
SBS+L					-	N	S	N	S	S	N	N
SBS+S						-	S	S	S	S	N	N
CRM							-	N	S	N	N	S
CRM+L								-	S	N	N	N
CRM+S									-	S	S	S
SIS										-	N	N
SIS+L											-	N
SIS+S												-

S: significant N: non-significant

The statistical results of the change in creep and recovery value for RTFO aging at 64°C are shown in Table 5-8. The results showed that binder types have a significant effect in the J_{nr}, %Rec and %J_{nr} value. However, within each binder type, the addition of wax additives resulted in statistically insignificant difference. In general, the difference between LEADCAP and Sasobit, within each binder types, was found to be statistically insignificant. Table 5-8(b) shows the statistical results for %Rec. In general, there was a statistically significant difference in the %Rec values of the binders due to the addition of wax additives. Table 5-8(c) indicates the statistical results for %J_{nr}. The results showed an insignificant difference in %J_{nr} values of the binder types and the wax types. Generally, the percent difference between the creep compliance at 3.2 kPa and 0.1 kPa seems to be an insufficient criterion for the modified binders with wax additives.

6. SUMMARY AND CONCLUSIONS

To characterize the performance properties of PG 64-22 and PMA binders with wax additives, binders were produced using two wax additives, LEADCAP and Sasobit, and artificially aged using PAV and RTFO procedures in the laboratory. A series of Superpave binder tests were performed using the rotational viscometer, the BBR, and the DSR to determine the performance properties of the binders. The performance properties investigated through Superpave binder tests include viscosity, stiffness, rutting (G*/sin δ), and fatigue cracking (G*sin δ). MSCR test was conducted to evaluate the rutting resistance properties and to characterize both the recovery and non-recovery compliances of the asphalt binder. Table 6-1 demonstrates the comprehensive and summarized data for this study. Ultimately, the following conclusions can be inferred from the test results, for the materials used in this study.

Table 6-1. Summary of data

Binders	Viscosity at 135°C (cP)	Stiffness at -12°C (MPa)	G*/sin δ at 64°C (kPa)		G*sin δ at 25°C (kPa)	J_{nr} at 64°C (kPa^{-1})		%Rec at 64°C (%)	
			Original	RTFO		Original	RTFO	Original	RTFO
PG 64-22	619	287	1.3	2.5	2550	12.0	4.9	0	0.8
PG 64-22+L	600	269	1.8	3.6	2270	13.6	5.8	0	0.9
PG 64-22+S	599	333	1.9	3.6	2987	11.3	4.4	0	1.2
SBS	3242	285	1.9	3.3	3650	0.9	0.5	67.2	73.3
SBS+L	2994	265	2.2	3.9	2650	0.9	0.6	65.8	66.8
SBS+S	2762	319	2.7	4.1	4653	0.8	0.3	67.2	76.9
CRM	1112	194	2.7	6.1	1480	8.8	7.5	2.9	1
CRM+L	1008	189	3.9	7.4	1175	17.2	7.5	0.2	1.4
CRM+S	1000	202	3.1	7.9	1965	13.3	2.9	0.7	8.8
SIS	2035	244	3.2	5.6	3683	1.4	0.8	30.5	26.9
SIS+L	1944	199.5	4.2	6.7	2100	1.9	1.3	25.3	19.6
SIS+S	1830	252.5	4.9	9.9	3210	1.4	0.9	27.4	21.5

1) The addition of LEADCAP and Sasobit in PG 64-22 and PMA binders (SBS, CRM and SIS) significantly reduced the viscosity at 135°C, which shows that the wax additives can reduce the production and paving temperature of the binder. This trend was quite similar for all the binders studied.
2) According to the BBR test results, the addition of LEADCAP into the binder caused to produce the binder with lower stiffness values. All the binders showed the similar trend in the stiffness value. However, the binders with Sasobit were found to have significantly higher stiffness value which shows possibly a lower resistance on low temperature cracking.
3) From the DSR test, all the binder mixed with wax additives were observed to be effective on increasing rutting resistance. It was found that the additives mixed with PG 64-22 and PMA binders play a significant role in the resistance for permanent deformation of asphalt pavement. Irrespective of aging state, PG 64-22 containing additives have the higher percentage improvement in rutting resistance than PMA binders with additives.
4) According to the DSR test at intermediate temperature (25°C), it appeared that the use of LEADCAP was useful to improve the resistance to fatigue cracking by significantly reducing the $G^*\sin\delta$ values.
5) It was observed that MSCR test is viable to quantify the rutting resistance depending on the polymer modification, especially for SBS modified binder.
6) In general, the addition of wax additives did not show a significant difference in J_{nr}, %Rec and $\%J_{nr}$ values, within each binder type.

7) It is suggested that MSCR test method is not applicable to measure the rutting performance of CRM binders. It may be inappropriate due to the bigger particle size and the higher amount of rubber modifiers.

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