Available online at http://www.ijprt.org.tw/

Chinese Society of Pavement Engineering

International Journal of Pavement Research and Technology 11 (2018) 774-788

http://www.ijprt.org.tw/

Multiple Stress Creep Recovery (MSCR) characterization of polymer modified asphalt binder containing wax additives

Ahmed Wajahat Ali [a], Hyun Hwan Kim [a], Mithil Mazumder [a], Moon-Sup Lee [b,*], Soon-Jae Lee [a]

[a] Texas State University, San Marcos, TX 78666, USA
[b] Korea Institute of Civil Engineering and Building Technology, 10223 South Korea

Received 10 January 2018; received in revised form 17 March 2018; accepted 7 May 2018

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, $G^*/\sin\delta$, $G^*\sin\delta$ 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 $G^*\sin\delta$ values) was observed at the binders with LEADCAP; (3) by adding the wax additives, the percentage increase of rutting resistance ($G^*/\sin\delta$) 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.

Keywords: MSCR; Polymer modified asphalt; Wax additives

1. Introduction

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 [17]. This phenomenon accelerates the deterioration process in the asphalt pavement and expedite the distress mechanism which reduces the pavement 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. Asphalt binders, due to their viscoelastic properties, is an important material used in road paving which affect the pavement performance. But, due to the high stresses exerted on the asphalt surface, most of the road system experience distress and deterioration before it can achieve the design service life [12]. 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 increasing number of traffic volume. The use of polymer modified asphalt (PMA) in the pavement exhibits greater resistance to rutting and

* Corresponding author.
E-mail addresses: a_a757@txstate.edu (A.W. Ali), k_h82@txstate.edu (H.H. Kim), m_m624@txstate.edu (M. Mazumder), truepath@kict.re.kr (M.-S. Lee), SL31@txstate.edu (S.-J. Lee).
Peer review under responsibility of Chinese Society of Pavement Engineering.

https://doi.org/10.1016/j.ijprt.2018.05.001
1996-6814/© 2018 Chinese Society of Pavement Engineering.

thermal cracking and decreased fatigue damage, stripping and temperature susceptibility [14].

According to Chamoun [4], 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). 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. With the decreased production temperatures 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 might lead to an increased 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. According to Edwards et al. [5], 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 aging 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.

Generally, the rutting resistance of asphalt binder was evaluated through $G^*/\sin\delta$ measured by traditional DSR test based on PG system. However, there are several researches which reported low relation between $G^*/\sin\delta$ and real field [2–3,6–8,16–17,19]. To overcome the issues mentioned in these researches, FHWA introduced Superpave plus testing protocol for better characterization of these materials. Multiple Stress Creep Recovery (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 $G^*/\sin\delta$. 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. 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. Also, two wax warm additives, LEADCAP and Sasobit, are used.

2. Experimental design

2.1. Polymer modified asphalt (PMA) binder

To improve the performance of the pavement, it is valuable to modify the asphalt binder by adding polymers with it. Therefore, different types of polymers are being used to achieve performance of 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 modified binder were used. PG 64-22 binder was modified with three different modifiers to study the rheological properties and stress-dependent behavior of modified asphalt binders. Table 1 shows the details of the modified binders used in the study. CRM and SBS modified asphalt binders are relatively common materials in pavement industry. However, SIS modified asphalt binder is not generally used, compared to CRM and SBS. According to Raghu et al. [13], the addition of SIS polymers in asphalt binder increases the toughness, elongation and impact strength. Also, it reduces the yield stress. It was reported that the use of SIS has the potential to improve the mechanical and dispersion as compared to the unmodified state.

For this experiment, 600 g of SIS, CRM and SBS modified asphalt binder was heated in oven for 1 h at 365°F, for 2 h at 365°F and for 2 h at 365°F respectively. 5% of SIS (5% of 600 g = 30 gm was added in the oven-heated sample and mixed at 365°F for 60 min by an open blade mixer at a blending speed of 700 rpm. 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 600 g = 60 g) was added in the oven-heated sample and put on the mixer for 30 min 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. In reference to WMA technologies involving additives, the dosage of each product should be selected according to manufacturer recommendations. Usually,

Table 1
Identification and content of binders.

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

the dosage rate has significant effect on the performance of asphalt binder. The tests were performed for binders in original state (without additives), and after the addition of wax additives (Fig. 1).

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

2.2. Wax additives

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 [18].

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 reduces 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 expedites the wax-based additive to exhibit a high potential for cracking [18]. Sasobit forms a lattice structure in the binder after crystallization, which is the basis of the structural stability of the binder containing Sasobit [9]. Fig. 2 shows LEADCAP and Sasobit used in this study.

2.3. Production of warm PMA binders

Two types of warm asphalt additives; Sasobit and LEADCAP, are used each with a ratio by weight of binder.

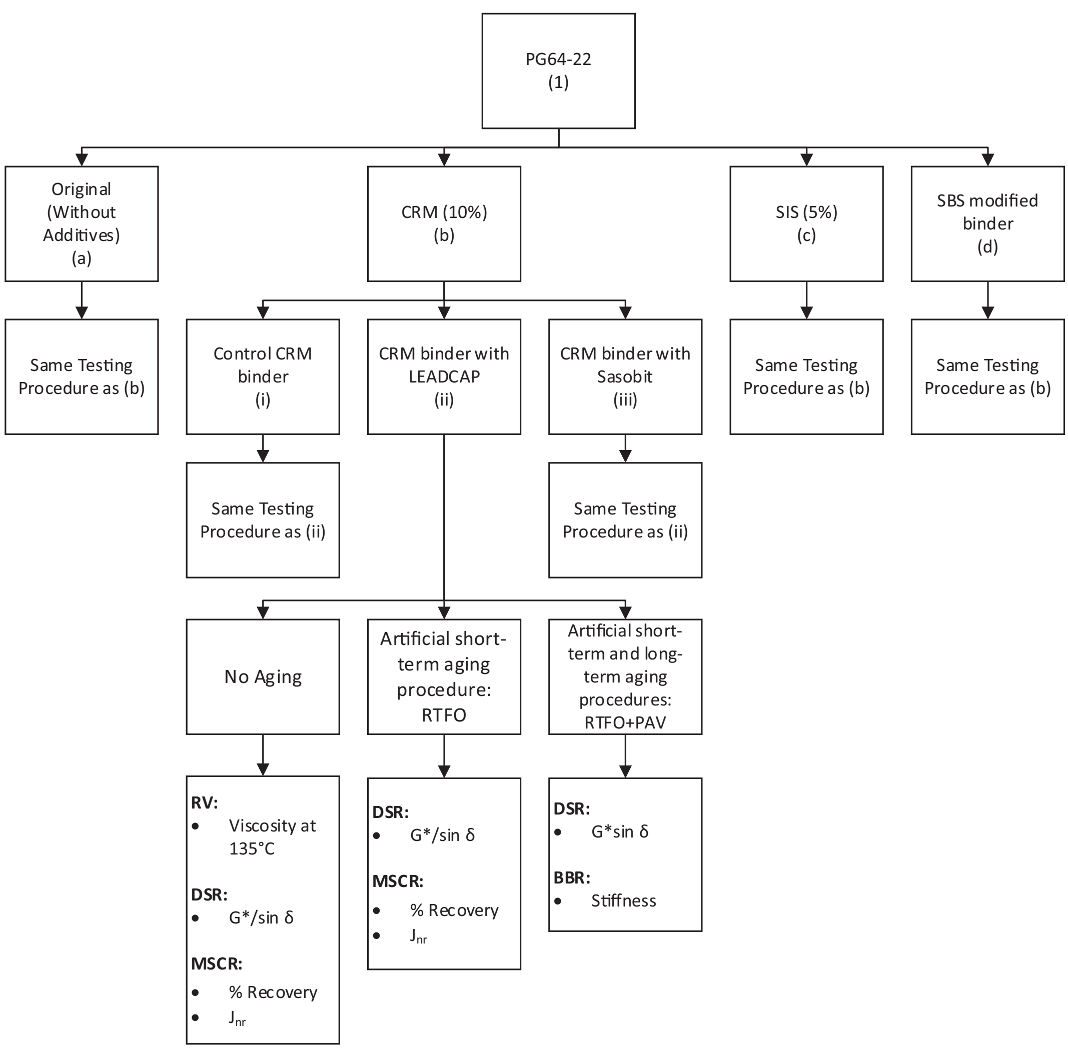


Fig. 1. Flow chart of experimental design procedures.

Table 2
Properties of base asphalt binder.

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

(a) (b)

Fig. 2. Wax additives; (a) LEADCAP and (b) Sasobit.

These additives were added in the quantity of 1.5 percent (1.5 g) 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 min in order to get a consistent mixing. Table 3 describes the binder types used in this study and their arrangements as mixed with wax warm additives.

Table 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

2.4. Multiple Stress Creep Recovery (MSCR) tests

MSCR test is conducted using the DSR 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 no-aged, and rolling thin film oven (RTFO) aged samples at high PG temperatures. As shown in Fig. 3, the binder is subjected to creeploading and unloading cycle of 1 s and 9 s 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.

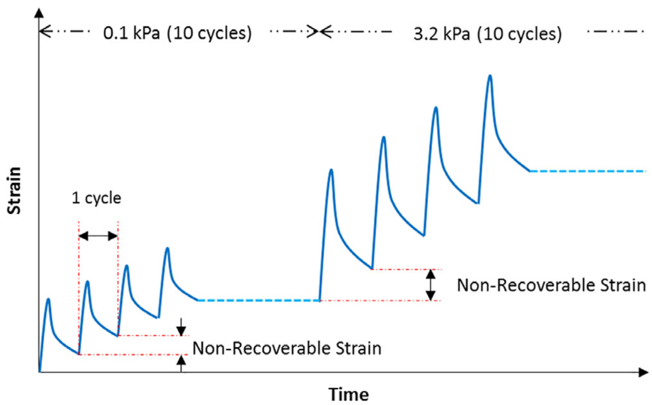


Fig. 3. Typical MSCR test results with 10 cycles of creep and recovery at stress levels of 0.1 and 3.2 kPa [19].

2.5. Superpave asphalt binder tests

The Superpave asphalt binder tests are conducted to quantify the asphalt's performance at three states of its life: in its original state, after mixing and construction, and after in-service aging [Asphalt Institute, 2003]. In this research, the properties of virgin CRM binders containing LTA warm CRM binder were evaluated using selected Superpave binder test procedures including the viscosity test (AASHTO T 316), the bending beam rheometer (BBR) test (AASHTO T 313), and the dynamic shear rheometer (DSR) test ([1]: with the plate gap adjusted to 2 mm).

An 8.5 g binder sample of the binders was tested with a number 27 spindle in the rotational viscometer at 135 °C. In the DSR test, the binders (Original, RTFO residual, and RTFO + PAV residual) were tested at a frequency of 10 rad per second, which is equal to approximately 1.59 Hz. The low temperature stiffness of recycled warm CRM asphalt binders was measured at −12 °C using the BBR test equipment. The BBR test was conducted using each asphalt beam (125 × 6.35 × 12.7 mm), and creep stiffness of the binders were measured at a loading time of 60 s.

2.6. Statistical analysis method

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 ($\alpha = 0.05$) 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.

3. Results and discussions

3.1. Viscosity at 135 °C

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 Fig. 4. The test was conducted using Rotational Viscometer at 135 °C in 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 easily seen, 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 [11]; Kantipong et al., 2007; Kim, 2007; Hurley and Prowell, 2005; Edwards et al., 2010; Kim et al., 2011, 2012; Jamshidi et al., 2012, 2013; Susana et al., 2008; [7–8,10,15]. 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. Fig. 4 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. 3000 cP), except for SBS modified binder without wax additives, which is slightly higher than the maximum requirement.

The statistical results of the change in the viscosity as a function of binder type and wax additive are shown in Table 4. It can be seen that the binder types have a significant effect on the viscosity value at 135 °C. There was a

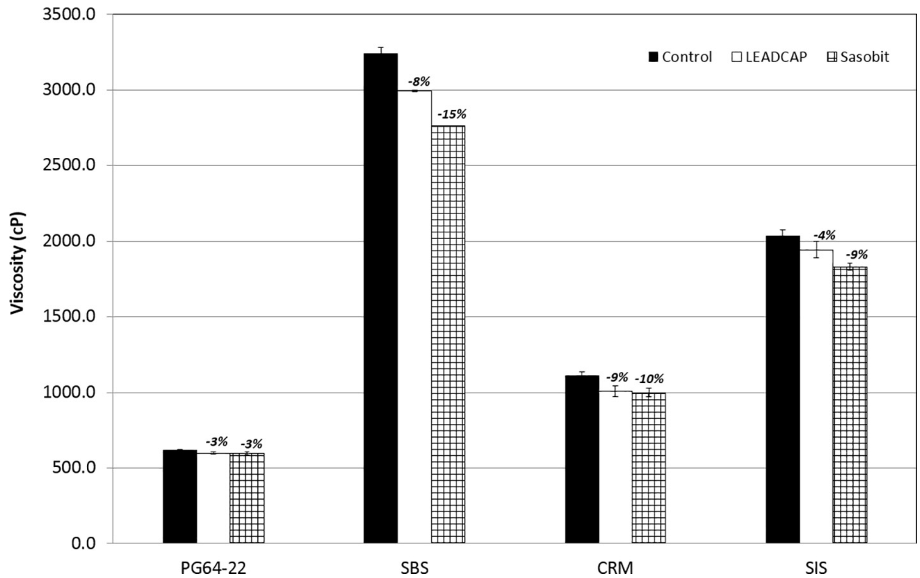


Fig. 4. Viscosity of recycled CRM binders at 135 °C.

Table 4
Statistical analysis results of the viscosity value as a function of binder type and wax additives ($\alpha = 0.05$).

Viscosity	PG 64-22			SBS			CRM			SIS		
	C	L	S	C	L	S	C	L	S	C	L	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												–

C: Control, L: LEADCAP, S: Sasobit.
N: non-significant, S: significant.

statistically significant difference in the viscosity of these binders due to the addition of wax additives.

3.2. Low temperature cracking property

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. For creep stiffness, Superpave asphalt binder specification contains a maximum requirement of 300 MPa of measured stiffness. Fig. 5 demonstrate the differences in stiffness 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.

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. 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.

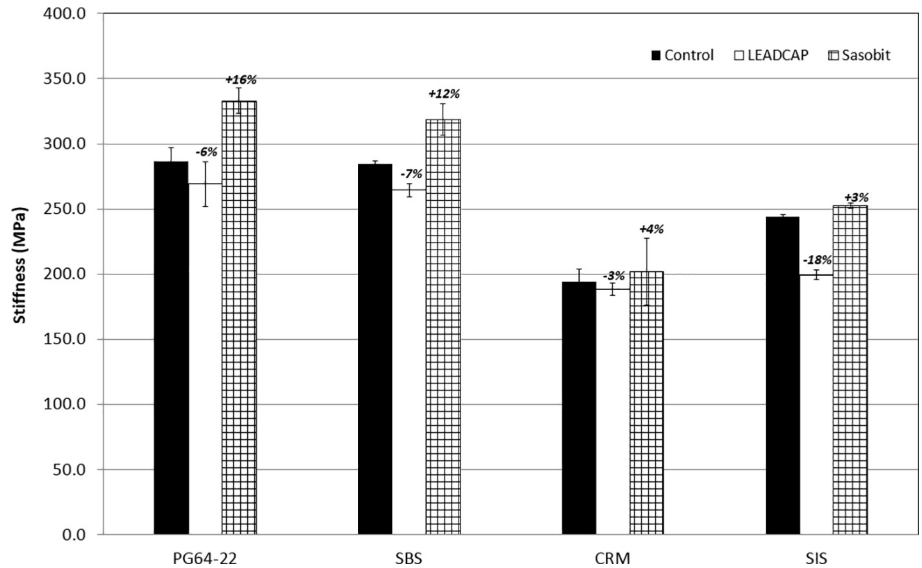


Fig. 5. Stiffness of the binders with wax additives at -12 °C (after RTFO + PAV).

Table 5
Statistical analysis results of the stiffness value as a function of the binder type and wax additives after RTFO + PAV at −12 °C.

Stiffness	PG 64-22			SBS			CRM			SIS		
	C	L	S	C	L	S	C	L	S	C	L	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												–

C: Control, L: LEADCAP, S: Sasobit.
N: non-significant, S: significant.

3.3. Dynamic Shear Rheometer (DSR) test

3.3.1. Original binder

$G^*/\sin\delta$, for original (unaged binder), was measured using Dynamic Shear Rheometer (DSR) at 64 °C, as accordance to [1]. Fig. 6 shows the $G^*/\sin\delta$, 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 $G^*/\sin\delta$ values are observed from DSR test. In general, PMA binders have the higher $G^*/\sin\delta$ value as compared to PG 64-22 binder. The addition of wax additives into the binders caused an increase in the $G^*/\sin\delta$ value. Fig. 6 also shows the percentage difference of $G^*/\sin\delta$ 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 $G^*/\sin\delta$ value of the binder up to 47% and 40%, respectively. The addition of LEADCAP and Sasobit with SBS modified binder increased the $G^*/\sin\delta$ value to approximately 21% and 47%, respectively, as compared to the control SBS binder. Similar trends were observed for CRM and SIS binders.

The statistical results of the change in the $G^*/\sin\delta$ values for un-aged binder at 64 °C are shown in Table 6. The results indicated that the binder types have a significant effect on the $G^*/\sin\delta$ values. In general, within each binder type, the difference between two wax additives was found to be statistically insignificant.

3.3.2. RTFO binder

Fig. 7 shows the $G^*/\sin\delta$, conducted on the PG 64-22 binder and polymer modified binders. SBS modified

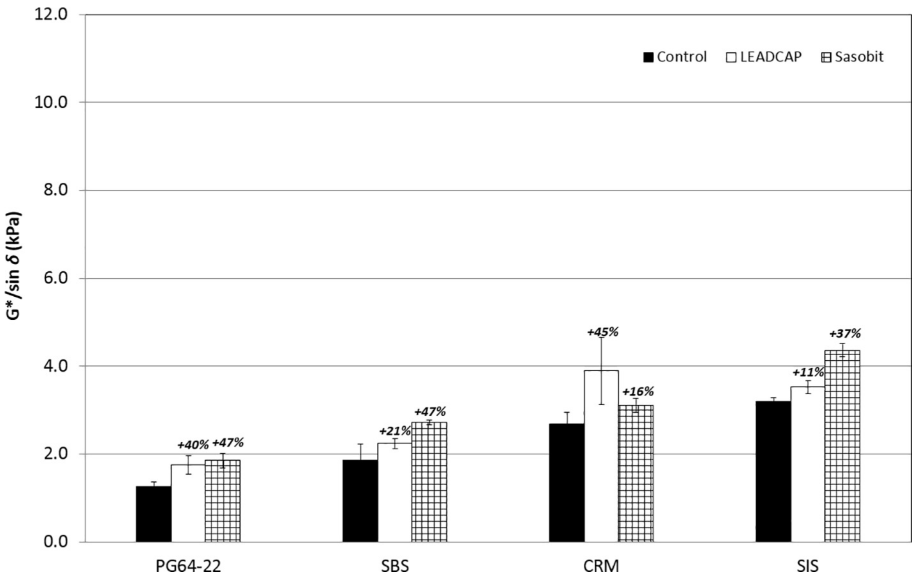


Fig. 6. $G^*/\sin\delta$ of the binders with wax additives at 64 °C (No aging).

Table 6
Statistical analysis results of the $G^*/\sin\delta$ value as a function of the binder type and wax additives at 64 °C (No aging).

Stiffness	PG 64-22			SBS			CRM			SIS		
	C	L	S	C	L	S	C	L	S	C	L	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												–

C: Control, L: LEADCAP, S: Sasobit.
N: non-significant, S: significant.

binders generally resulted in the higher $G^*/\sin\delta$ as compared to the control binders irrespective of aging state. The addition of wax additives into the binders caused an increase in the $G^*/\sin\delta$ 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 $G^*/\sin\delta$ 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.

The statistical significance of the change in the $G^*/\sin\delta$ value as a function of the binder types and wax additive, after RTFO aging, was examined and the results are shown in Table 7. The binder types showed a statistically significant difference in the $G^*/\sin\delta$ values. Generally, the type of wax additive (LEADCAP or Sasobit), within each binder type, resulted in an insignificant difference in $G^*/\sin\delta$ (after RTFO aging).

3.3.3. RTFO + PAV aged binder

$G^*\sin\delta$ was measured using Dynamic Shear Rheometer at 25 °C for RTFO + PAV aged binder, according to [1], for long-term aged state. Fig. 8 shows the $G^*\sin\delta$, 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 $G^*\sin\delta$ is the desired attribute for the resistance of fatigue cracking.

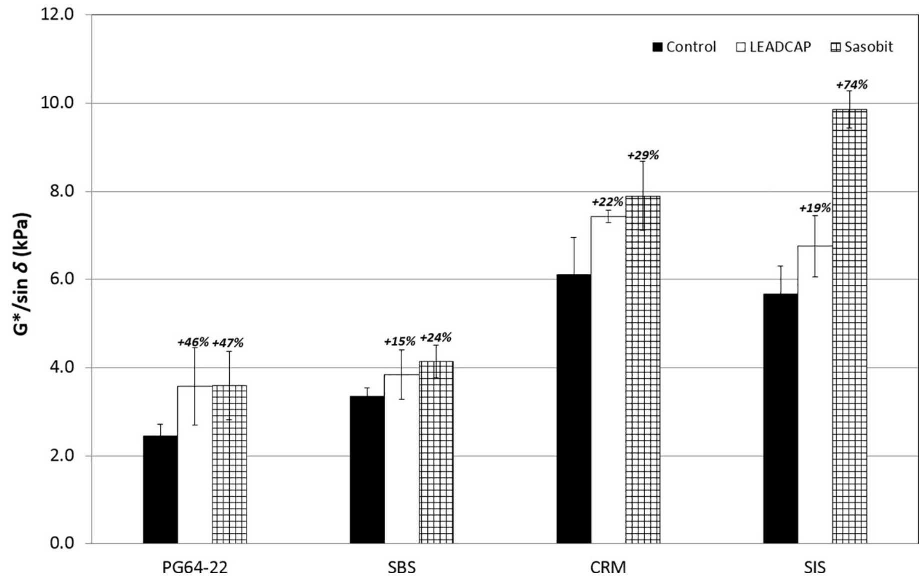


Fig. 7. $G^*/\sin\delta$ of the binders with wax additives at 64 °C (after RTFO).

Table 7
Statistical analysis results of the G*/sin δ value as a function of the binder type and wax additives at 64 °C (RTFO aging).

Stiffness	PG 64-22			SBS			CRM			SIS		
	C	L	S	C	L	S	C	L	S	C	L	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												–

C: Control, L: LEADCAP, S: Sasobit.
N: non-significant, S: significant.

The modification of asphalt binder with SBS polymers exhibited the higher $G^*\sin\delta$ 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 $G^*\sin\delta$ value compared to the control SBS binder, meaning that Sasobit results in the SBS binder being less resistant to fatigue cracking at intermediate temperature [10]. The addition of LEADCAP into the binders made a trend in reducing the $G^*\sin\delta$ 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 $G^*\sin\delta$ by 11%, 27%, 21% and 43%, respectively. The trend shown in Fig. 8 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 $G^*\sin\delta$ is 5000 kPa. As shown in Fig. 8, all the values are under 5000 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).

The statistical results of the change in the $G^*\sin\delta$ value are shown in Table 8. The results showed that the binder types have a significant effect on the $G^*\sin\delta$ values. It was found that there was a statistically significant difference in the $G^*\sin\delta$ 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.

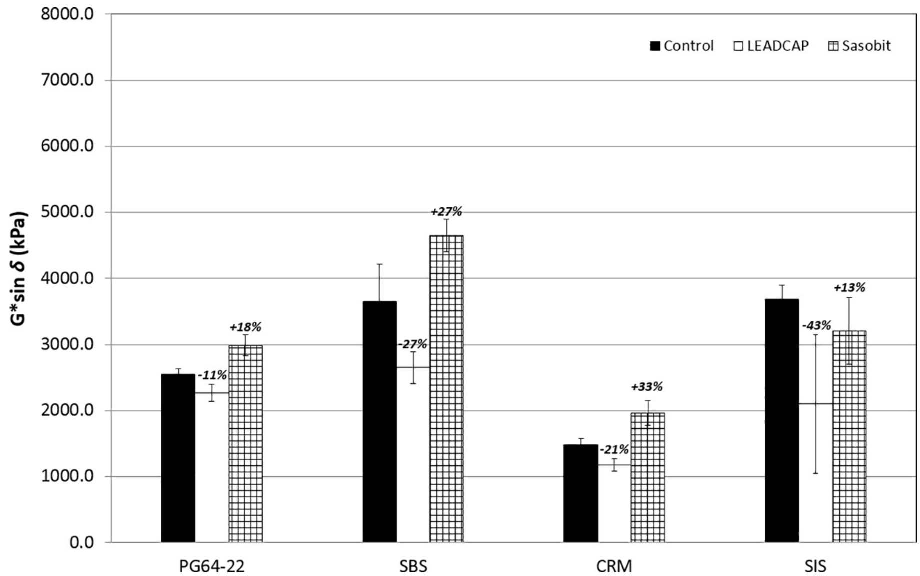


Fig. 8. $G^{*}\sin\delta$ of the binders with wax additives at 25 °C (after RTFO + PAV).

Table 8
Statistical analysis results of the $G^{*}/\sin\delta$ value as a function of the binder type and wax additives at 25 °C (RTFO + PAV aging).

Stiffness	PG 64-22			SBS			CRM			SIS		
	C	L	S	C	L	S	C	L	S	C	L	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												–

C: Control, L: LEADCAP, S: Sasobit.
N: non-significant, S: significant.

3.4. Multiple Stress Creep Recovery (MSCR) test

3.4.1. Original binder

MSCR tests were conducted on the original (un-aged) binder, according to AASHTO TP 70. Fig. 9 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 Fig. 9. 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 s of creep load. Generally, the addition of LEADCAP and Sasobit increased the % J_{nr} value, as shown in Fig. 9 (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.

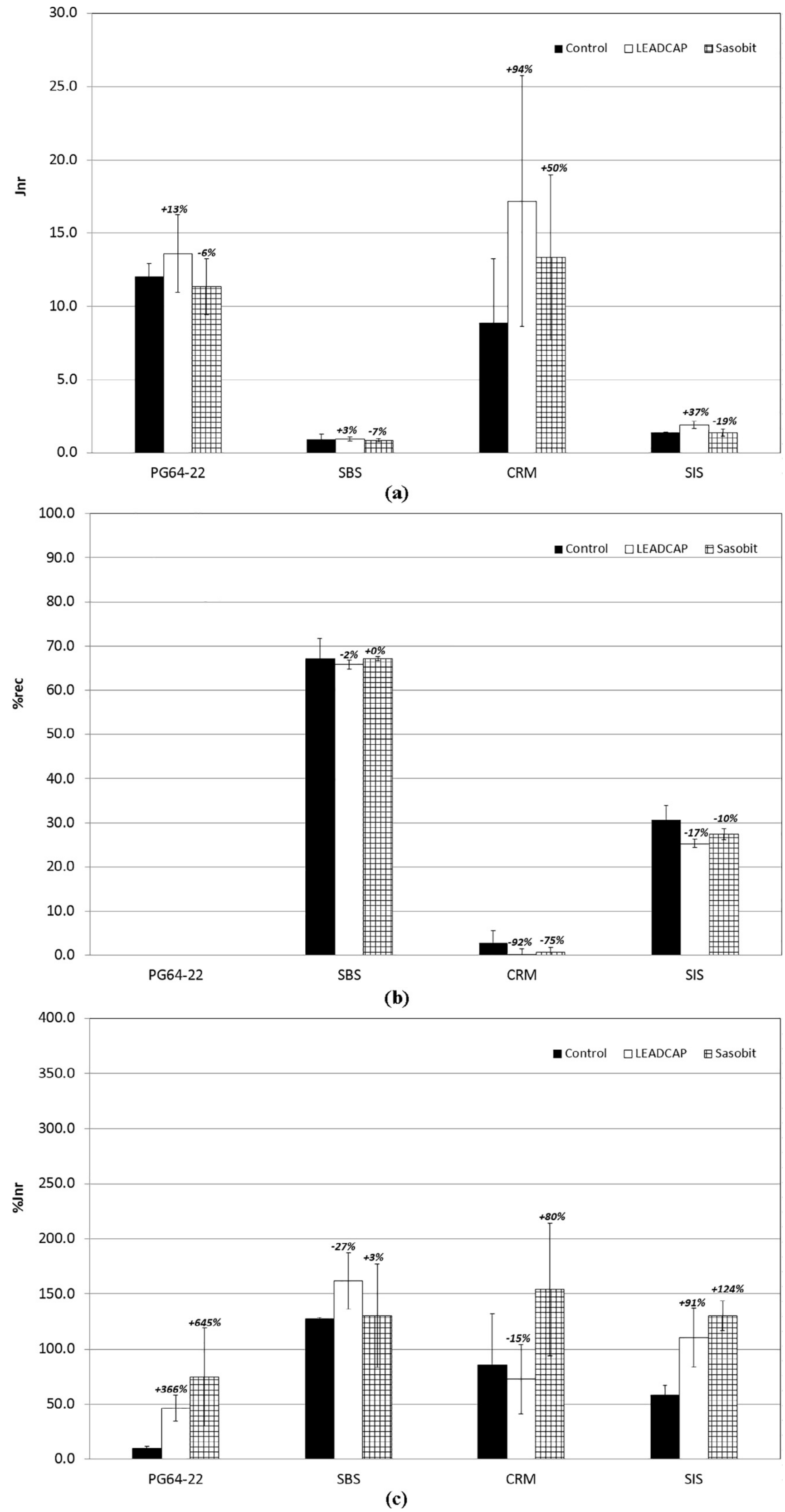


Fig. 9. Variations in creep compliance, percent recovery and percent difference in creep compliance of the binder with wax additives at 64 °C (No Aging); (a) J_{nr}, (b) % Rec and (c) % J_{nr}.

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 9. Table 9(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

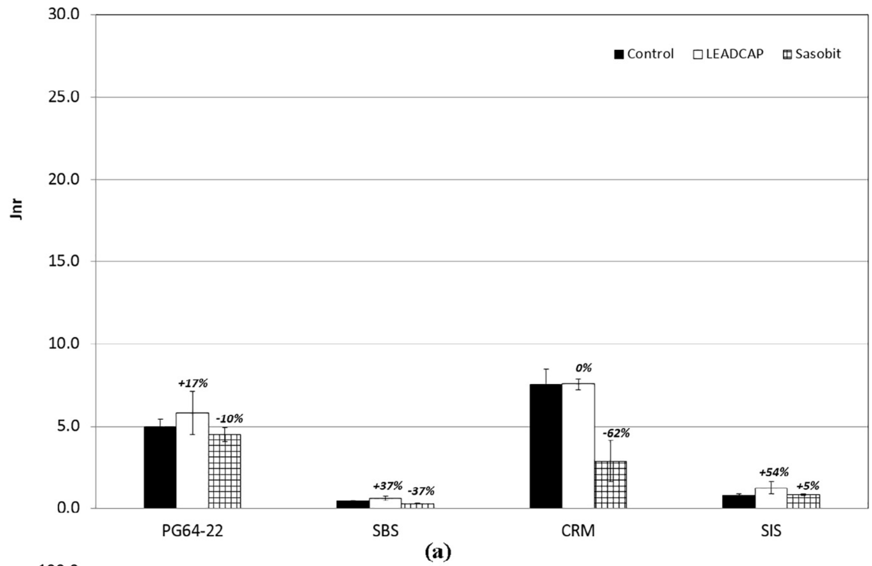
Table 10
Minimum % Recovery from MSCR test for Jnr value range (AASHTO TP 70).

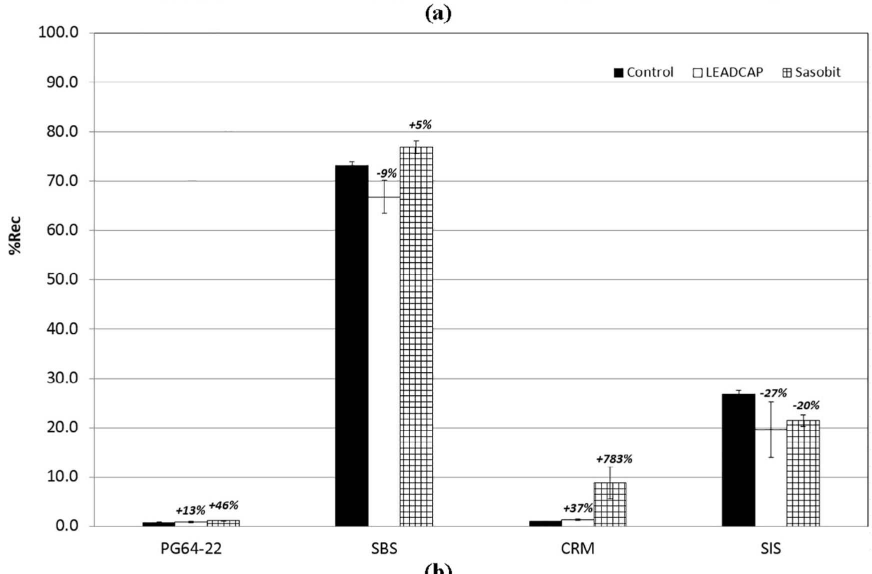
Minimum % Recovery for Measured J_{nr} values	
J_{nr} at 3.2 kPa	Minimum % Recovery
2.0–1.01	30%
1.0–0.51	35%
0.50–0.251	45%
0.25–0.125	50%

Table 9
Statistical analysis results 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) $\%J_{nr}$.

J_{nr}	PG 64-22			SBS			CRM			SIS		
	C	L	S	C	L	S	C	L	S	C	L	S
(a)												
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												–
	PG 64-22			SBS			CRM			SIS		
% Rec	C	L	S	C	L	S	C	L	S	C	L	S
(b)												
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												–
	PG 64-22			SBS			CRM			SIS		
% J_{nr}	C	L	S	C	L	S	C	L	S	C	L	S
(c)												
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												–

C: Control, L: LEADCAP, S: Sasobit.
N: non-significant, S: significant.





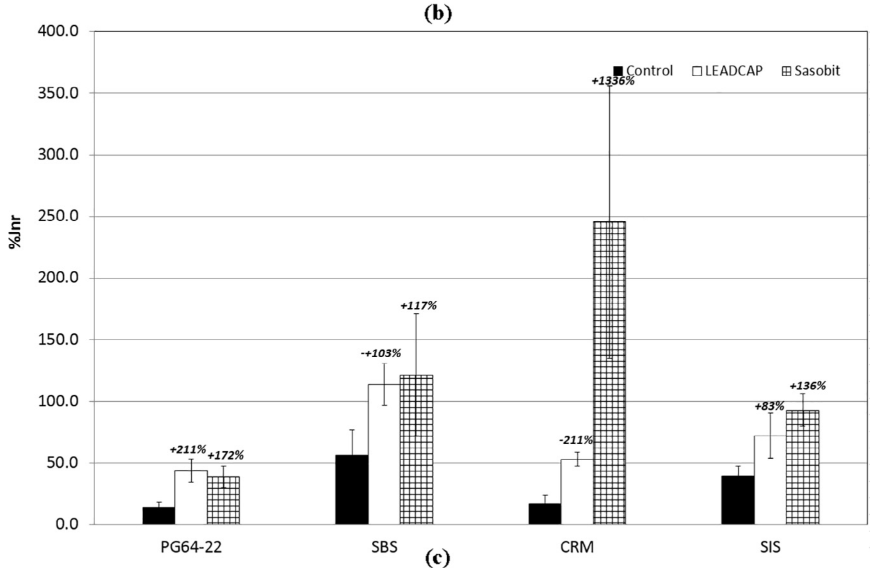


Fig. 10. Variations in creep compliance, percent recovery and percent difference in creep compliance of the binder with wax additives at 64 °C (after RTFO); (a) J_{nr}, (b) % Rec and (c) % J_{nr}.

trends were found for % Rec and % J_{nr}, as shown in Table 9(b) and (c), respectively (Table 10).

3.4.2. RTFO aged binder

MSCR test was also conducted on the RTFO aged binder, according to AASHTO TP 70. Fig. 10 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.

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 % Recovery.

Table 11
Statistical analysis results of the creep compliance, percent recovery and percent difference in creep compliance values as a function of the binder and wax additives (after RTFO) at 64 °C: (a) J_{nr} (b) % Rec and (c) % J_{nr}.

J_{nr}	PG 64-22			SBS			CRM			SIS		
	C	L	S	C	L	S	C	L	S	C	L	S
(a)												
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												–
% Rec	PG 64-22			SBS			CRM			SIS		
	C	L	S	C	L	S	C	L	S	C	L	S
(b)												
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												–
% J_{nr}	PG 64-22			SBS			CRM			SIS		
	C	L	S	C	L	S	C	L	S	C	L	S
(c)												
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												–

C: Control, L: LEADCAP, S: Sasobit.
N: non-significant, S: significant.

The modification of asphalt binder affects the creep and recovery parameters significantly as shown in Fig. 10. As shown in Fig. 10(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 Fig. 10(c).

The statistical results of the change in creep and recovery value for RTFO aging at 64 °C are shown in Table 11. 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 11 (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 11(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.

4. Summary and conclusions

To characterize the performance properties of PG 64-22 and PMA binders with wax additives, PMA 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 ($G^*/\sin\delta$), and fatigue cracking ($G^*\sin\delta$). MSCR test was conducted to evaluate the rutting resistance properties and to characterize both the recovery and non-recovery compliances of the asphalt binder. Ultimately, following conclusions can be inferred from the test results, for the materials used in this study.

Acknowledgements

This research was supported by the Research Grant from KICT through the Korea Agency for Infrastructure Technology Advancement funded by the Ministry of Land, Infrastructure and Transport of the Korean government (Project No: 17TBIP-C125188-01).

References

[1] AASHTO, T. 315-10, Determining the rheological properties of asphalt binder using a Dynamic Shear Rheometer (DSR), AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and, 2 (2011).
[2] A. Behnood, Rheological Properties of Asphalt Binders: An Analysis of the Multiple Stress Creep Recovery Test (Doctoral dissertation), Purdue University, 2016.
[3] A. Behnood, A. Shah, R.S. McDaniel, M. Beeson, J. Olek, High-temperature properties of asphalt binders: comparison of multiple stress creep recovery and performance grading systems, Transp. Res. Rec.: J. Transp. Res. Board 2574 (2016) 131–143.
[4] Z. Chamoun, Evaluation of Warm Mix Asphalt Additives for Use in Modified Asphalt Mixtures (Doctoral dissertation), University of Nevada, Reno, 2013.
[5] Y. Edwards, Y. Tasdemir, U. Isacsson, Rheological effects of commercial waxes and phosphoric acid in bitumen 160/220 – low temperature performance, Fuel (2006) 989–997.
[6] H. Soenen, T. Blomberg, T. Pellinen, O. Laukkanen, The multiple stress creep recovery test: a detailed analysis of repeatability and reproducibility, Road Mater. Pavement 14 (2013) 2–11.
[7] A.V. Kataware, D. Singh, Evaluating effectiveness of WMA additives for SBS modified binder based on viscosity, Superpave PG, rutting and fatigue performance, Constr. Build. Mater. 146 (2017) 436–444.
[8] A.V. Kataware, D. Singh, A study on rutting susceptibility of asphalt binders at high stresses using MSCR test, Innovative Infrastruct. Solutions 2 (1) (2017) 4.
[9] H.H. Kim, S.J. Lee, Evaluation of rubber influence on cracking resistance of crumb rubber modified binders with wax additives, Can. J. Civ. Eng. 43 (4) (2016) 326–333.
[10] H. Kim, S.J. Lee, S.N. Amirkhanian, Effects of warm mix asphalt additives on performance properties of polymer modified asphalt binders, Can. J. Civ. Eng. 37 (1) (2010) 17–24.
[11] H. Kim, K.D. Jeong, M.S. Lee, S.J. Lee, Performance properties of CRM binders with wax warm additives, Constr. Build. Mater. 66 (2014) 356–360.
[12] C. Nicholls, Asphalt Surfacing, E and FN Spon, London, 1998, pp. 68–79.
[13] P. Raghu, C.K. Nere, R.N. Jagtap, Effect of styrene–isoprene–styrene, styrene–butadiene–styrene, and styrene–butadiene–rubber on the mechanical, thermal, rheological, and morphological properties of polypropylene/polystyrene blends, J. Appl. Polym. Sci. 88 (2) (2003) 266–277.
[14] M.A. Shafii, M.A. Rahman, J. Ahmad, Polymer modified asphalt emulsion, 2011.
[15] D. Singh, A.V. Kataware, Comparison of different rheological parameters for rutting susceptibility of SBS+ WMA modified binders, Innovative Infrastruct. Solutions 1 (1) (2016) 28.
[16] H. Soenen, T. Blomberg, T. Pellinen, O.V. Laukkanen, The multiple stress creep-recovery test: a detailed analysis of repeatability and reproducibility, Road Mater. Pavement Des. 14 (sup1) (2013) 2–11.
[17] N. Tabatabaee, H. Tabatabaee, Multiple stress creep and recovery and time sweep fatigue tests: Crumb rubber modified binder and mixture performance, Transp. Res. Rec.: J. Transp. Res. Board 2180 (2010) 67–74.
[18] S. Yang, J. Lee, S. Hwang, S. Kwon, C. Baek, Development of warm-mix asphalt additive and evaluation of performance, Transp. Res. Rec.: J. Transp. Res. Board 2294 (2012) 89–97.
[19] J. Zhang, L.F. Walubita, A.N. Faruk, P. Karki, G.S. Simate, Use of the MSCR test to characterize the asphalt binder properties relative to HMA rutting performance–A laboratory study, Constr. Build. Mater. 94 (2015) 218–227.