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Rheological and Chemical Characteristics of Rubberized Binders with Non-foaming Warm Mix Additives

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ABSTRACT

This study aims to investigate the rheological and chemical characteristics of asphalt rubber (AR) binders modified with four non-foaming warm mix asphalt (WMA) additives: Evotherm-DAT, Sasobit, conventional paraffin wax, and combined Evotherm-DAT and Sasobit. The main findings of this study include that: 1) all selected WMA additives are effective in enhancing AR's workability; 2) using combined Evotherm-DAT and Sasobit is not a viable option to reduce the construction temperature of AR mixture; 3) paraffin wax is a potential WMA additive for AR; and 4) WMA additives may affect the dissolution status of crumb rubber in base asphalt.

KEY WORDS: Crumb rubber, WMA, rheological properties, chemical analysis

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1 INTRODUCTION

Asphalt rubber (AR) is a blend of asphalt cement, reclaimed tire rubber and other additives, with a rubber content of no less than 15% by weight of the total blend [1, 2]. It has been verified that AR may bring various benefits to asphalt pavements, such as enhanced rutting resistance, alleviated road-tire noise, reduced long-term maintenance costs, and recycling of waste tires [3, 4]. However, AR faces the criticism of higher construction emissions due to the high mixing and compacting temperatures (170 ^{o}C-220 ^{o}C). Warm-mix asphalt (WMA) technology can help decrease the construction temperature of asphalt mixtures, including AR mixtures, allowing less energy consumption as well as better working condition during asphalt pavement construction [5]. Thus, it is a win-win combination to use AR and WMA together. Currently, there are over thirty commercial WMA additive products available in the market, which can be classified into two broad categories: foaming additives and non-foaming additives. Foaming additives provide better workability by causing volume expansion of asphalt binder while non-foaming additives achieve the goal by either decreasing the asphalt binder viscosity or acting as a surfactant at the asphalt-aggregate interface [6, 7].

Rheology refers to the deformation and flow properties of a material. The rheological properties of asphalt binder are directly related to asphalt pavement performance. Various studies have been conducted on the effects of crumb rubber and warm mix additives on the rheological properties of asphalt binders. It has been reported that the incorporation of crumb rubber increased the rutting factor ($G^*/\sin\delta$) and decreased the fatigue factor ($G^*\sin\delta$) of asphalt binder, leading to improved high- and intermediate-temperature performance [8]. Sasobit, a wax-type WMA additive, has been proven to improve the high-temperature performance of asphalt binder. However, controversial findings have been reported by the studies on its influence on the intermediate- and low-temperature performances [9-11]. Evotherm-DAT and Evotherm-3G, both of which are chemical additives, have been reported having different modification effects on different types of asphalt binder [12-14]. Although the major component of Sasobit is wax, normal paraffin wax is usually not considered an appropriate WMA additive for regular asphalt, because it may compromise the cracking resistance of asphalt mixture [10]. However, as crumb rubber can enhance the cracking resistance of asphalt mixture, the adverse effect of wax on low-temperature performance of asphalt binder may be compensated by crumb rubber when they are used together.

In literature, the individual effects of crumb rubber, Evotherm-DAT, Sasobit, and wax on asphalt binder and mixture have been extensively studied. However, the studies on their combined effects and their interaction mechanisms within warm AR binder are relatively limited. In consideration of this gap, this study aims to investigate the rheological properties and chemical compositions of AR binders with various types of non-foaming WMA additives, including Sasobit, Evotherm-DAT, paraffin wax, and combined Sasobit and Evotherm-DAT. To achieve this objective, the rheological properties, including penetration, viscosity, failure temperature, rutting factor, and fatigue factor, of the AR binders with various types of non-foaming WMA additives, were characterized. In addition, Fourier Transform Infrared Spectroscopy (FTIR) tests and Thermo-Gravimetric Analysis (TGA) were performed to investigate the interaction mechanism of crumb rubber, WMA additives and base asphalt.

2 EXPERIMENTAL DESIGN

2.1 Materials

In this study, asphalt with a penetration grade of 60/70 (Pen 60/70) commonly used in Hong Kong was selected as the base asphalt to produce AR. The AR binder was prepared by blending 18% of 40 mesh crumb rubber by the total weight of AR with the base asphalt at 176 ^{o}C and 4000 rpm/min for one hour using a high shear mixer.

As shown in Table 1, three types of non-foaming WMA additives were selected in this study, including Evotherm-DAT, Sasobit and 56$^{\#}$ paraffin. In addition to adding these additives individually to AR, Evotherm-DAT and Sasobit were also used together as a compound additive for AR, which finally resulted in the following four different Warm AR (WAR) binders: ARE (AR with 5wt% of Evotherm-DAT), ARS (AR with 3wt% of Sasobit), ARES (AR with 2.5wt% of Evotherm-DAT and 1.5wt% of Sasobit) and ARW (AR with 1.5wt% of 56# paraffin wax). The percentages of each WMA additive were determined based on the manufactures' recommendations and preliminary tests.

TABLE 1 Physical and Chemical Properties of Non-foaming WMA Additives

WMA Additive / Properties	Evotherm-DAT	Sasobit	56# Paraffin Wax
Ingredients	Fatty amine derivatives, Alkylamines	Solid saturated hydrocarbons	Solid saturated hydrocarbons
Physical state	Liquid	Solid	Solid
Color	Caramel	Milky-white	Light-white
Odor	Amine-like	None	None
Bulk density	>1.0 g/cm^3	0.622 g/cm^3	0.85 g/cm^3
PH value	9-10	N/A	N/A
Boiling point	150 ^{o}C-170 ^{o}C	N/A	N/A
Melting point	N/A	105 ^{o}C-110 ^{o}C	54 ^{o}C-58 ^{o}C
Solubility in water	Partially soluble	Insoluble	Insoluble
Appearance			

2.2 Testing Procedure

The experimental program of this study is shown in Fig. 1.

The 25 ^{o}C penetration and softening point tests were conducted in accordance with ASTM D5 and ASTM D36, respectively [15, 16]. The penetration test evaluates the consistency of the asphalt binders while the softening point test assesses the binder performance at high service temperature. A Brookfield rotational viscometer was used to measure the viscosities of the binders at three temperatures, i.e., 135 °C, 160 °C and

176°C, according to AASHTO T316 [17]. Three replicates were prepared for each type of binder in these tests.

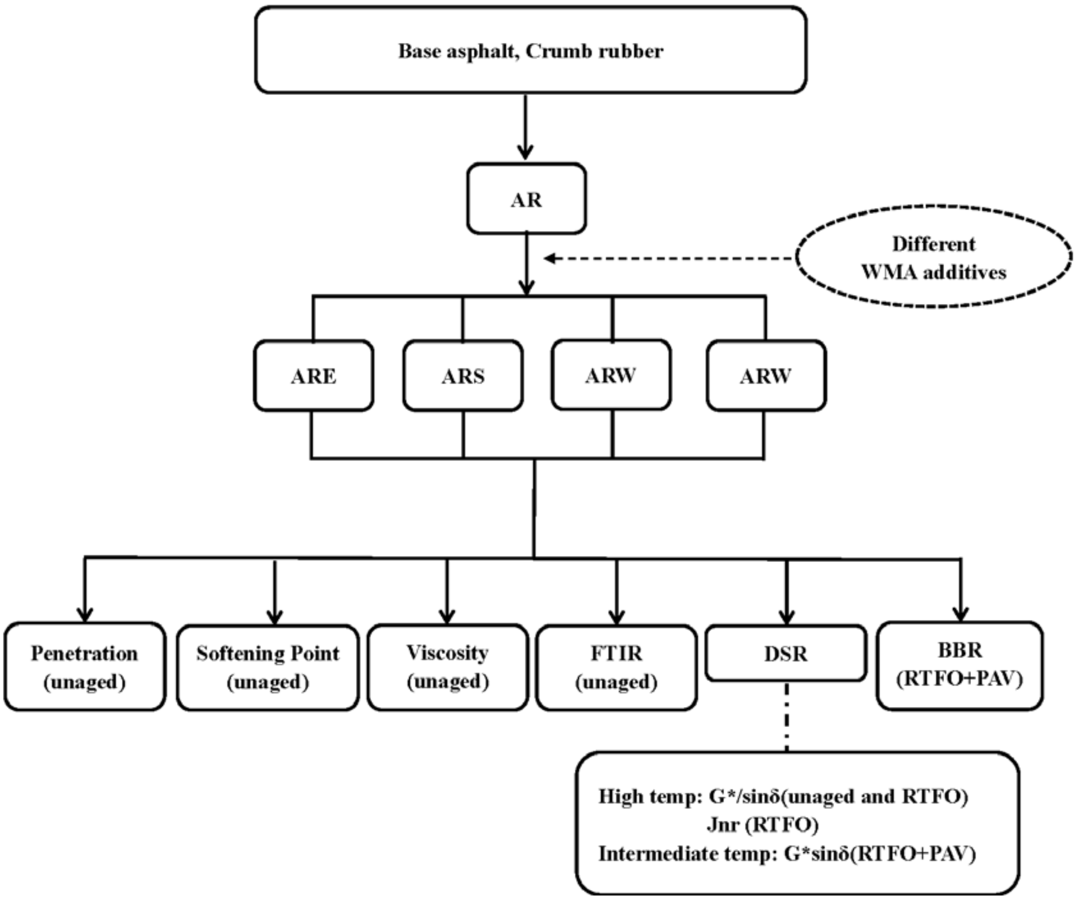


FIGURE 1 Experimental program

The high-temperature performance of the binder was characterized by two properties: the rutting factor (both unaged and rolling thin film oven (RTFO) aged samples) and the non-recoverable creep compliance (only RTFO aged samples). 2 mm gap and 25 mm-diameter plate were used in all tests. The rutting factor test started at 64 ^{o}C, and the testing temperature was raised automatically to next PG temperature if the measured rutting factor was larger than the values specified in AASHTO M320, i.e., 1.0 kPa for unaged binder and 2.2 kPa for RTFO binder. The non-recoverable creep compliance was determined by the multiple stress creep recover (MSCR) test according to ASTM D7405 [18, 19]. In each cycle of this test, a creep load was applied for 1s followed by 9s recovery at 64 °C. Each specimen was subjected to ten cycles with a creep stress of 0.1 kPa, followed by ten cycles with a creep stress of 3.2 kPa. Two replicates were prepared and tested for each type of binder.

The fatigue factors of the Pressure Aging Vessel (PAV) aged binders were measured to evaluate their intermediate-temperature performance. The fatigue factor tests were started at 25 ^{o}C with a decrement of 3 ^{o}C until the fatigue factor was larger than 5000kPa [20]. 2 mm gap and 8 mm-diameter plate were used, and two replicates were prepared and tested for each binder as well.

The BBR tests were conducted to evaluate the low-temperature performance of the binders according to AASHTO T313 [21]. PAV aged samples were tested in a temperature fluid bath with a constant load (980±50 mN). The critical parameters obtained from the BBR tests included the creep stiffness and m-value. Three replicates were prepared and tested for each type of binder.

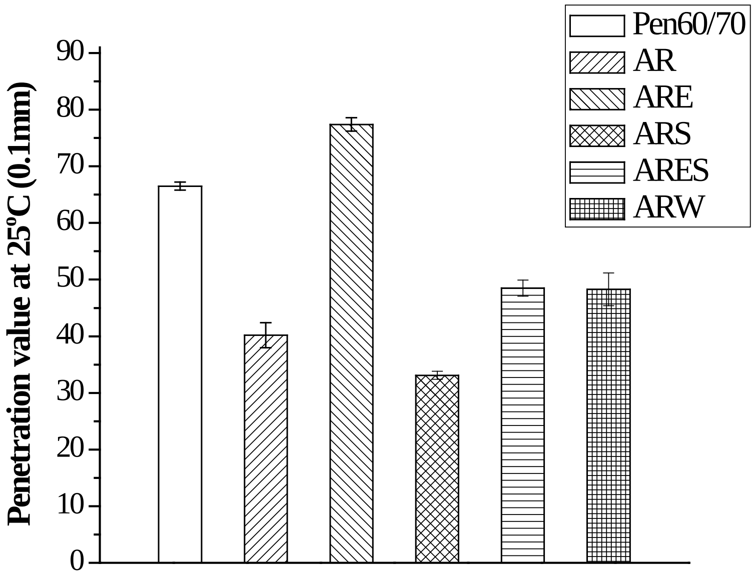
The FTIR tests were conducted to characterize the chemical bonds of the binders [9, 22]. The binder sample was pressed to prepare pellets (0.5 to 1 mm thick), which were then placed in a transmission holder and scanned by the infrared. Three replicates were prepared and tested for each type of binder.

The TGA tests were performed to characterize the components of crumb rubber after it interacted with base asphalt and WMA additives. Crumb rubber was extracted from the WAR using the method adopted by many other researchers [23, 24]. In this method, the WAR binder was first dissolved in trichloroethylene (TCE) and then filtered through a 200# (75 um) sieve. The solid remaining on the 200# sieve was further washed by TCE to obtain crumb rubber without asphalt components. In the TGA test, the extracted crumb rubber was heated to over 600 ^{o}C with a rate of 20 ^{o}C/min. Three replicates were prepared and tested for each type of binder.

3 RESULTS AND DISCUSSION

3.1 Penetration and Softening Point

The results of the penetration and softening point tests are shown in Fig. 2. It can be seen that in general, the binders with higher penetration values had relatively lower softening points. As expected, crumb rubber significantly reduced the penetration and increased the softening point of Pen 60/70. The incorporation of Sasobit stiffened the AR binder while Evotherm-DAT softened it. When Sasobit and Evotherm-DAT were added together (ARES), the effects of Sasobit and Evotherm-DAT seemed to be counteracted by each other. The two wax-type additives, Sasobit and paraffin wax, showed different effects on the penetration and softening point of AR.



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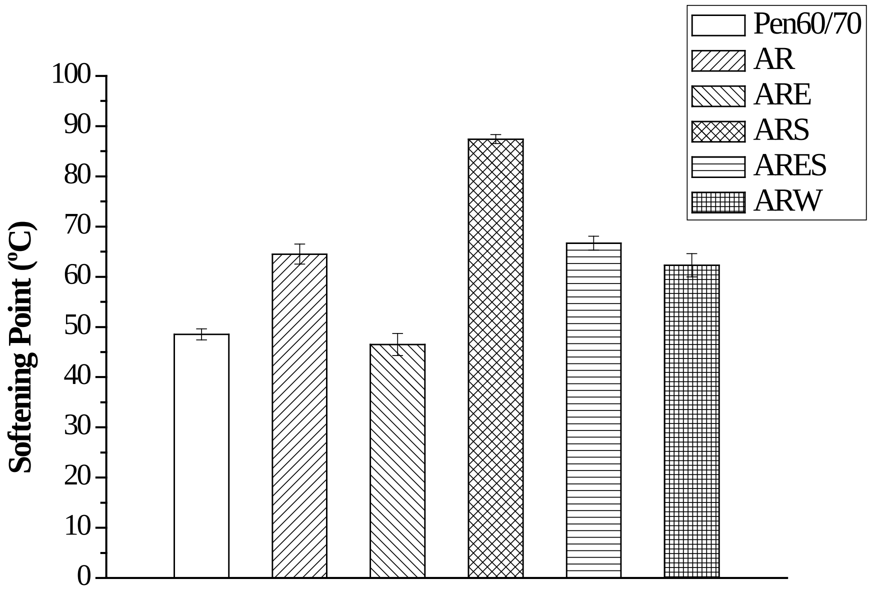


(b)

FIGURE 2 Test results: (a) Penetration at 25 °C; (b) Softening point

3.2 Brookfield Viscosity

The Brookfield viscosity test has been commonly used to assess the workability and determine the suitable mixing and compacting temperatures of asphalt binders. In this study, the viscosity tests were conducted at three temperatures, 135 °C, 160 °C and 176 °C. Fig. 3 presents the test results of all binders. It can be seen that the viscosities of all binders except for ARE decreased with the increasing of test temperature. The unexpected results of ARE may be ascribed to the evaporation of Evotherm-DAT emulsion at a high test temperature (over 160 °C). This result also indicated that when Evotherm-DAT is used, the mixing temperature should not be higher than 160 °C. As expected, all WMA additives were effective in reducing the viscosities of AR within a temperature range of 135 °C to 176 °C. However, the viscosities of all WARs at 135 °C are still greater than that of Pen 60/70. ARW and ARES showed similar viscosities, which are slightly higher than those of ARS.

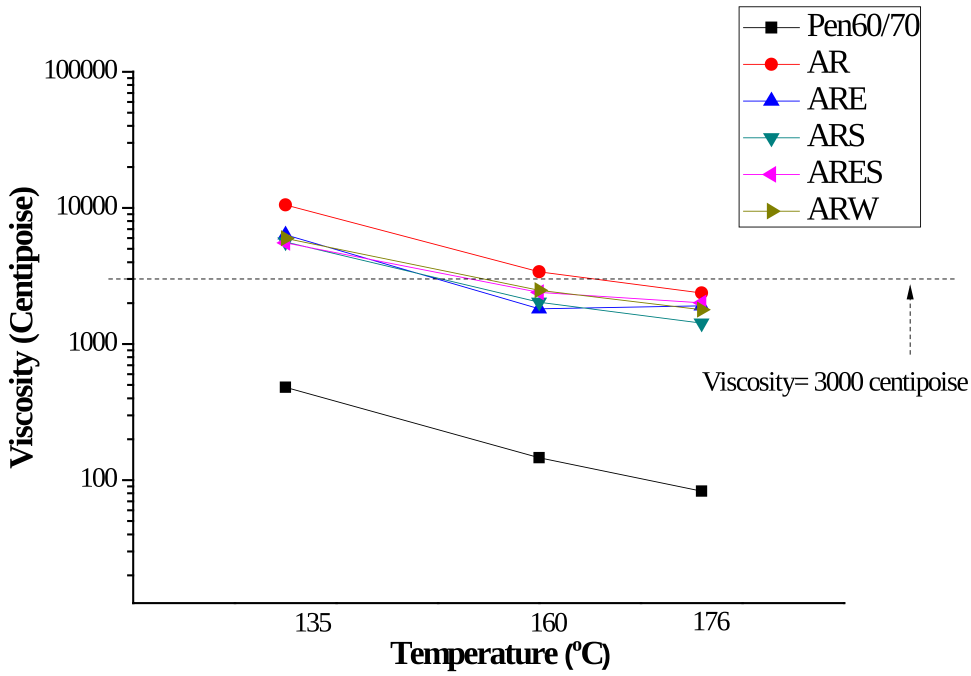
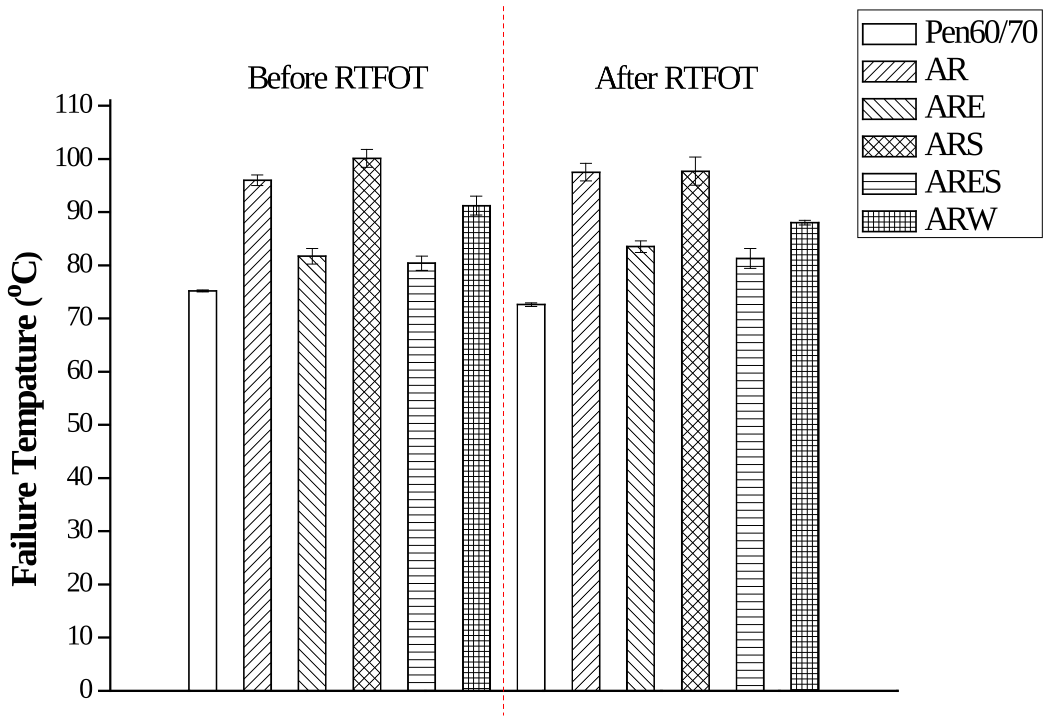


FIGURE 3 Brookfield viscosity test results

3.3 Failure Temperature and Rutting Factor

Failure temperature refers to the critical temperature when $G^*/\sin\delta$ equals to 1.0 kPa for raw binder and 2.2 kPa for RTFO aged binder. Fig. 4 illustrates the failure temperature test results, which show no significant difference between the binders before and after RTFO. AR had a much higher failure temperature than Pen 60/70, indicating better rutting resistance. Besides, the influence of WMA additives on AR varied remarkably. Fig. 4b and Fig. 4c show the rutting factors of unaged samples and RTFO samples, respectively. It can be seen that ARS is the only binder that had a higher $G^*/\sin\delta$ value than AR. In other words, only Sasobit helped to further increase the failure temperature of AR. The addition of paraffin wax had slightly negative effect on the high-temperature performance. Although both Sasobit and paraffin wax are wax-type additives, they showed different effects. The possible reason is that the wax in Sasobit has much longer carbon chain than normal paraffin wax. AR with Evotherm-DAT had only one grade higher failure temperature than the base asphalt, which may be attributed to the liquid nature of Evotherm-DAT emulsion. Finally, it is surprising that ARES had the lowest failure temperature among all WARs. Whether this negative effect is caused by any chemical reaction between Evotherm-DAT and Sasobit still requires further investigation.



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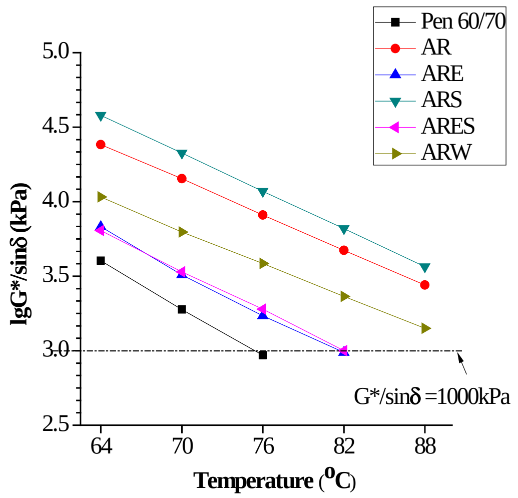

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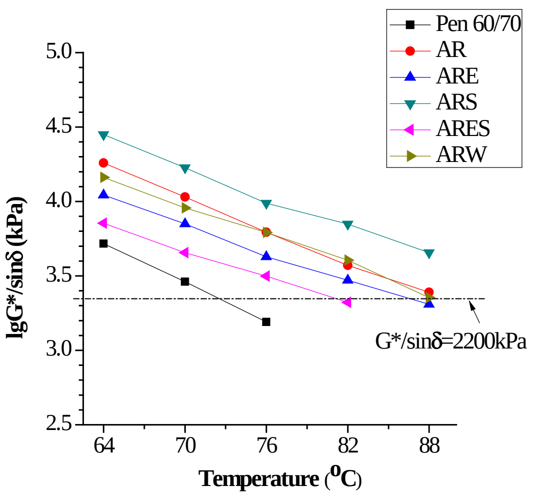


(c)

FIGURE 4 High-temperature performances: (a) failure temperature; (b) rutting factors for unaged samples; (c) rutting factors for RTFO samples

Fig. 5a and Fig. 5b present the relationships between phase angle and temperature for unaged and RTFO aged binders, respectively. Phase angle (δ) is defined as the time lag between strain and stress under the traffic loading. A larger phase angle indicates that the asphalt binder is more viscous. As the test results show, the RTFO aged binders had smaller phase angles compared to the unaged binders, because short-term aging makes asphalt binders less viscous. Compared to AR, all warm AR binders had higher phase angles except for ARS. Among all WARs, ARE had the largest phase angle, followed by ARES, ARW and ARS.

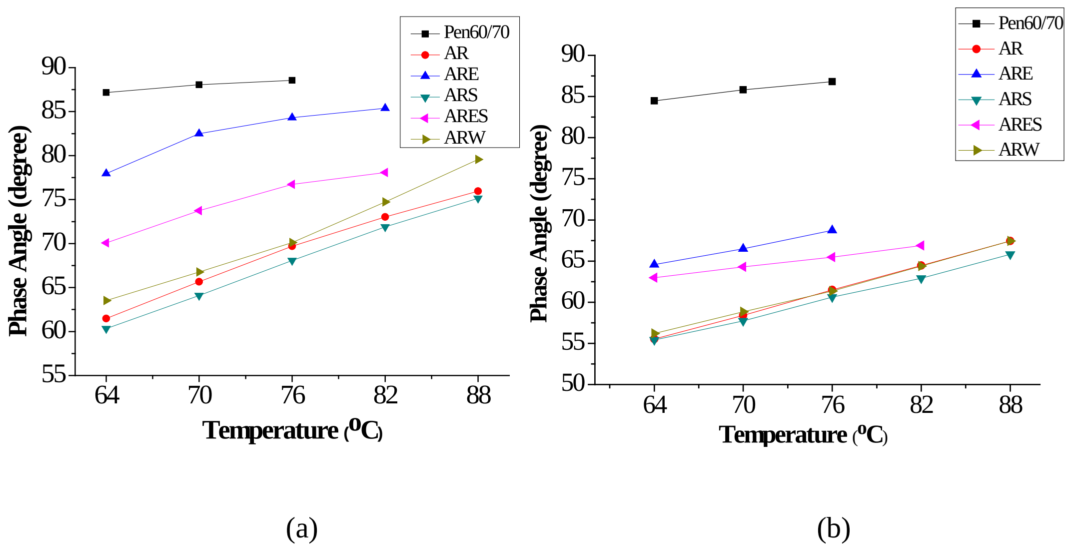


FIGURE 5 Phase angles: (a) unaged samples; (b) RTFO aged samples

3.4 Frequency Sweep Tests

Fig. 6 presents the frequency sweep test results. The tests were performed under stresses which were proportional to frequencies. According to Xiao et al. [9], the frequency sweep tests at various frequencies can help identify the linear viscoelastic response of asphalt binders. It is expected that the increased frequency should result in increase of complex shear modulus and reduction of phase angle. From Fig. 6, it can be seen that this tendency fits well for Pen 60/70, ARE and ARES. However, for AR, ARS, and ARW, this trend is not very clear. Among various WAR binders, ARS and ARW had significantly larger complex shear modulus and smaller phase angle than ARE and ARES at various frequencies, indicating their better rutting resistance.

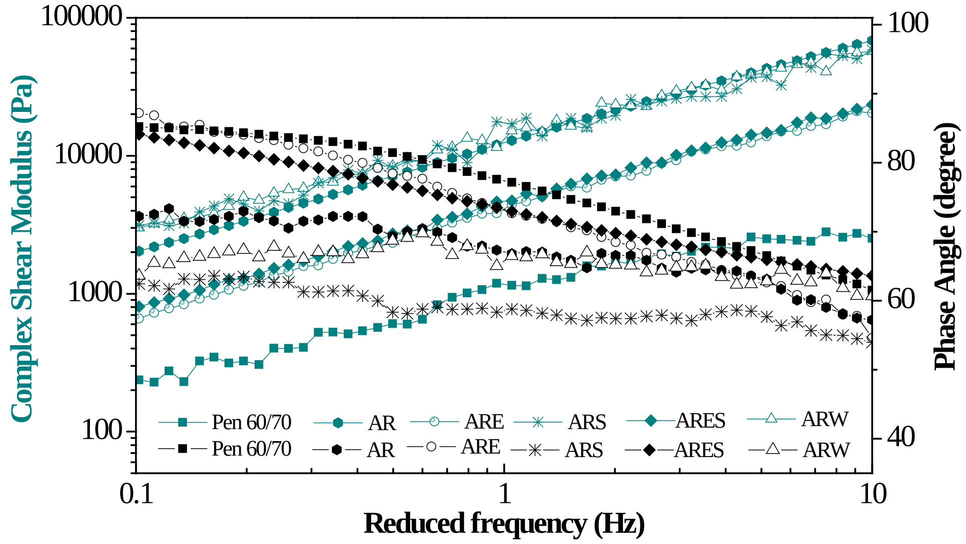


FIGURE 6 Frequency sweep results

3.5 Multiple Stress Creep Recover (MSCR) Tests

Aiming at evaluating the linear and non-linear behaviors of asphalt binders, the multiple stress creep recovery (MSCR) tests were conducted. The MSCR test determines the percentage recovery and non-recoverable creep compliance of asphalt binders. It also helps assess the elastic response and the change in elastic response at two different stress levels (0.1 kPa and 3.2 kPa) subjected to ten cycles of creep stress and recovery [18, 25]. Fig. 7 presents an example of creep and recovery cycles in the MSCR test. The acceptable non-recoverable creep compliance at 3.2 kPa and percent differences for various traffic levels specified in AASHTO MP19-10 are provided in Table 2.

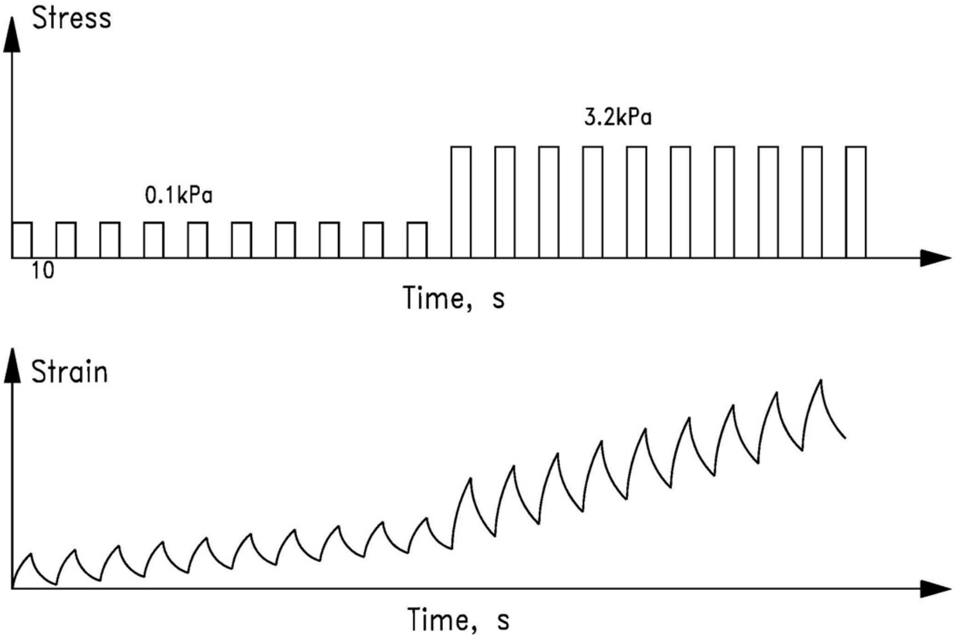


FIGURE 7 Description of MSCR test

TABLE 2 Requirements for Non-recoverable Creep Compliance [18, 26]

Traffic Level	Max Jnr 3.2 (k/Pa)	Max Jnr diff (%)
Standard traffic "S" grade	< 4	< 0.75
Heavy traffic "H" grade	< 2	< 0.75
Very heavy traffic "V" grade	< 1	< 0.75
Extremely heavy traffic "E" grade	< 0.5	< 0.75

Table 3 summarizes the MSCR test results. It can be seen that all AR binders exceeded the maximum allowable J_{nr} difference, i.e., 75%. Similar results have also been reported by other researchers [26]. This is mainly due to the extremely low J_{nr}

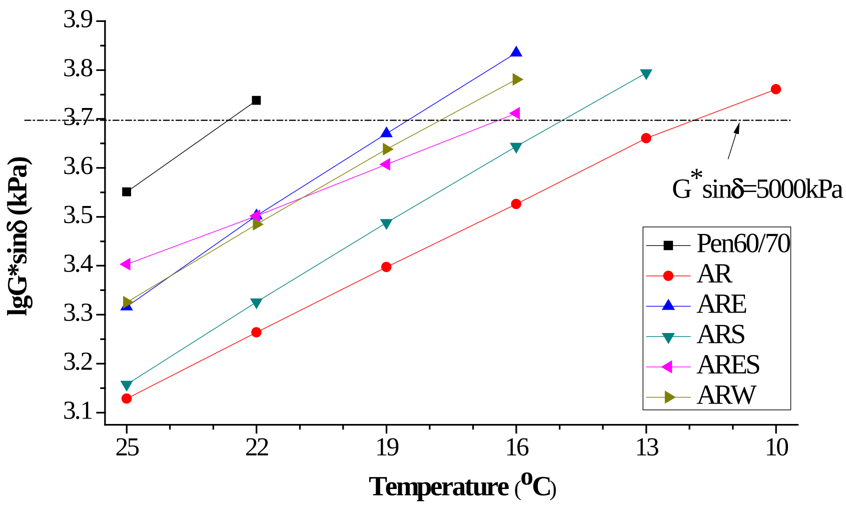
values at 0.1 kPa. Although the maximum J_{nr} difference cannot meet the requirement of AASHTO MP19-10, the low J_{nr} 0.1 and J_{nr} 3.2 results of AR binders still proved that they have adequate resistance to permanent deformation at high service temperature. AR and ARS met the requirements for the highest traffic level “E”, while ARW met the requirement of the second highest level “V”. ARE and ARES only met the qualification of level “H”. With respect to the influence of various WMA additives, only Sasobit showed positive effect on the rutting resistance property, which is consistent with the rutting factor test results.

TABLE 3 MSCR results

Binder Type	J_{nr}			%Recovery		Traffic Level
	0.1k/Pa	3.2k/Pa	J_{nr} %Diff	0.1k/Pa	3.2k/Pa	
Pen60/70	3.172	3.473	9.42	5.41	2.07	S
AR	0.151	0.288	91.7	71.8	54.2	E
ARE	0.311	1.360	339	70.0	34.1	H
ARS	0.051	0.020	285	86.7	58.3	E
ARES	0.387	1.362	252	70.2	36.3	H
ARW	0.204	0.528	159	75.2	45.5	V

3.6 Fatigue Factor

The fatigue factor, $G^*\sin\delta$, is used to describe the fatigue properties of the binder. As aforementioned, the long term aged samples by RTFO and PAV were tested. It is specified that the $G^*\sin\delta$ should be less than 5 MPa to pass a performance grade test at a specific temperature [20]. Fig. 8a shows the relationship between the logarithms of $G^*\sin\delta$ and temperatures. Fig. 8b presents the failure temperature of each binder corresponding to a 5.0 MPa fatigue factor. As can be seen from Fig. 8, the logarithms of the $G^*\sin\delta$ of all binders decrease proportionally with the temperature. The threshold temperatures of all binders are less than 25 °C. All WMA additives negatively affected the fatigue properties of AR. Among various WARs, ARS showed the best fatigue resistance. The threshold temperatures of ARES, ARW and ARE are 5.5 °C, 6.9 °C and 8.3 °C higher than that of AR, respectively. However, all WARs showed better fatigue resistance than Pen 60/70.



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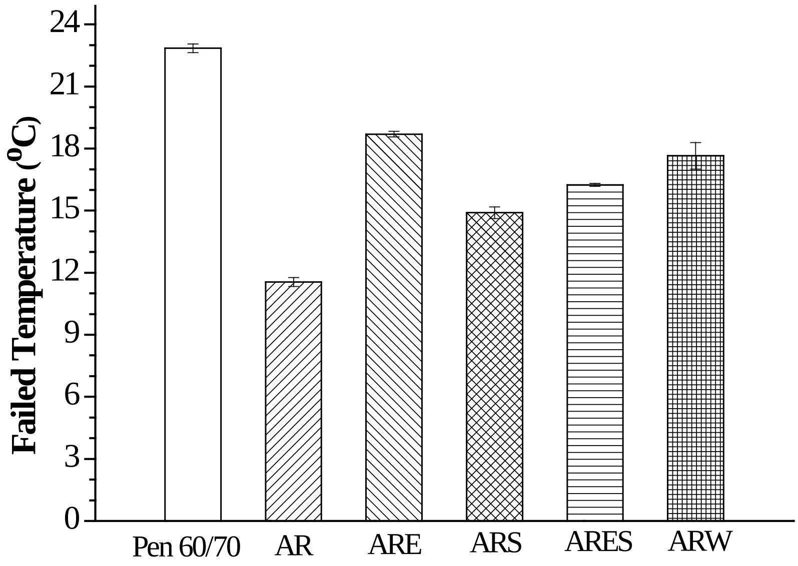

(b)

FIGURE 8 Fatigue test results: (a) fatigue factor versus temperature and (b) failure temperature

3.7 BBR Tests

The BBR tests were conducted to evaluate the low-temperature performance of the binders. According to the AASHTO specification [21], the stiffness value should be less than 300 while the m-value should be larger than 0.3 for a specific temperature grade. As the BBR test results in Table 4 indicate, all test binders meet and only meet the requirement at -12 ^{o}C. It was also found that the incorporation of crumb rubber significantly reduced the creep stiffness of Pen 60/70. Evotherm-DAT seemed to have no significant effect on the binder stiffness, while Sasobit and paraffin wax had negative effect. It has been commonly believed that the asphalt binder with higher wax content is easier to deflect or creep at low-temperatures. However, the BBR test results at -12 °C indicated that such adverse effect of wax could be compensated by the positive effect of crumb rubber, as the stiffness' of ARS and ARW are both smaller than that of Pen 60/70.

TABLE 4 BBR Test Results

Binder	-12 °C		-18 °C		-24 °C	
	Stiffness	m-value	Stiffness	m-value	Stiffness	m-value
Pen 60/70	201	0.318	317	0.245	522	0.152
AR	109	0.346	213	0.283	406	0.188
ARE	117	0.323	181	0.269	439	0.201
ARS	133	0.301	293	0.256	516	0.176
ARES	107	0.379	204	0.271	412	0.191
ARW	154	0.308	347	0.243	666	0.152

3.8 Statistical Analysis

To statistically investigate the effects of different WMA additives on the fatigue factor, rutting factor and stiffness of AR, the Bonferroni's post ANOVA test at the 5% significance level was conducted [27]. In Table 5, Numbers 0, 1, 2, 3, and 4 represent AR, ARE, ARS, ARES, and ARW, respectively. Binder pair 0-1 represents the comparison was conducted between AR and ARE, and so on. Letter Y indicates that the difference is statistically significant while letter N indicates that the difference is statistically insignificant. From Table 5, it can be seen that statistically there is no significant difference between AR and ARS in all properties, indicating that Sasobit has insignificant effect on AR properties. Comparing AR and ARS, significant difference in low-temperature stiffness can be observed, but their differences in rutting and fatigue factors are not significant. When Evotherm-DAT was used, there was no significant difference between ARE and ARES in all properties, and both showed statistically lower rutting and fatigue resistances compared to AR. Table 6 summarizes the effects of various WMA additives on AR’s performance. It can be seen that all WMA additives were effective in improving the workability of AR, but their effects on the mechanical properties of AR varied.

TABLE 5 Statistical Significance Analysis on the Effects of WMA Additives

Properties of Binder	Comparison Binder Pairs (0-AR, 1-ARE, 2-ARS, 3-ARES, 4-ARW)									
	0-1	0-2	0-3	0-4	1-2	1-3	1-4	2-3	2-4	3-4
$G^*/\sin\delta$ at 64 ^oC	Y	N	Y	N	Y	N	Y	Y	N	Y
$G^*/\sin\delta$ at 76 ^oC	Y	N	Y	N	Y	N	Y	Y	N	Y
$G^*\sin\delta$ at 25 ^oC	Y	N	Y	Y	Y	N	Y	N	Y	N
$G^*\sin\delta$ at 22 ^oC	Y	N	Y	Y	Y	N	Y	N	Y	N
Stiffness at -12 ^oC	N	N	N	Y	N	N	N	N	N	N

*Note: Y-significant difference; N-no significant difference (α = 0.05)

TABLE 6 Summary of WMA Additives’ Effects on Rheological Properties of AR

Performance	Evotherm-DAT (5wt %)	Sasobit (3wt %)	Evotherm-DAT (2.5wt %) + Sasobit (1.5wt %)	56# Paraffin Wax (1.5wt %)
Workability	Significantly enhanced			
Rutting Resistance	Significantly deteriorated	Slightly enhanced	Significantly deteriorated	Slightly deteriorated
Fatigue Resistance	Significantly deteriorated	Deteriorated	Significantly deteriorated	Deteriorated
Low Temperature Cracking Resistance	Insignificant effect	Slightly deteriorated	Insignificant effect	Deteriorated

3.9 FTIR Tests

The effects of crumb rubber and WMA additives on the chemical compositions of asphalt binder were evaluated through the FTIR tests. Fig. 9 illustrates the FTIR spectrums of six different binders. In these FTIR spectrums, the major bands around 2,918 and 2,850 cm^{-1} are caused by the stretching vibrations of Alkyl C-H and Aliphatic C-H, respectively, while those at 1600, and 1012 cm^{-1} are due to the stretching of C=C and C-O, respectively [9, 12, 22, 28]. Since all test binders, including Pen 60/70, had typical absorption peaks at similar wavenumbers, no major chemical reactions were detected due to the addition of crumb rubber and WMA additives.

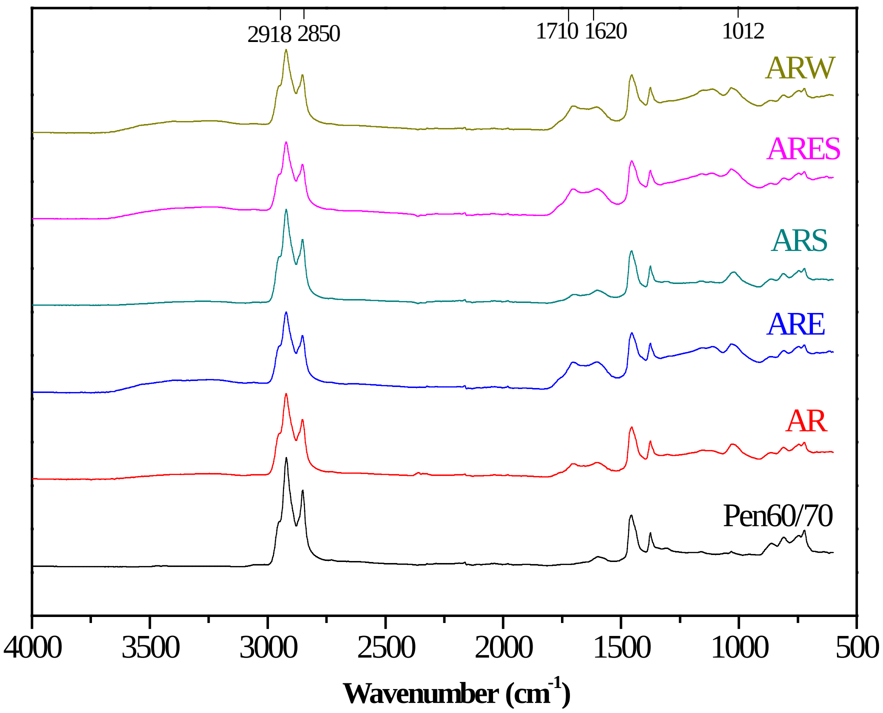

FIGURE 9 FTIR test results

However, the magnitudes of the peaks at approximately 2918 cm^{-1}, 2850 cm^{-1}, 1650 cm^{-1} and 1012 cm^{-1} of each binder are different. An obvious peak at 1012cm^{-1} can be observed for all binders except for Pen 60/70. This is possibly due to the loss of light components of asphalt binder after crumb rubber was added. Among various WAR binders, ARS and ARW have larger peak areas around 2900 cm^{-1} than the others, which might be caused by the long hydrocarbon chains in wax [29]. In addition, since the water and surfactant in Evotherm-DAT had negative effect on the C-H bonds [12], the peaks at 2918 cm^{-1} and 2850 cm^{-1} for ARE are not so obvious as those for the other binders. Some difference can also be noticed at 1620 cm^{-1} to 1700cm^{-1}. At these two wavenumbers, clear peaks showed up in the spectra of ARE, ARES, and ARW. These peaks were possibly caused by the water, lipids or fatty acid esters components in wax and surfactant [22, 30].

3.10 TGA Tests

Crumb rubber (CR) from waste tires is a complex vulcanized rubber mainly containing oily components, natural rubber (NR), synthetic rubber (SR), and fillers. Previous studies have demonstrated that these four components have different decomposition temperatures [23, 31, 32]. Therefore, the volatilisation temperature can be used to separate different components. According to Ghavibazoo and Abdelrahman [24], the decomposition temperature ranges of the oily components, NR and SR, and fillers are 25 ^oC to 300 ^oC, 300 ^oC to 500 ^oC, and above 500 ^oC, respectively.

Fig. 10 shows the TGA test results of the crumb rubbers extracted from four WARs. It can be seen that the crumb rubber from ARW seems to have more oily components than the others, which may be attributed to the penetration of some oily components from paraffin wax into the crumb rubber during the mixing process. On the other hand, ARE, ARES and ARS have almost no oily components. The filler contents of crumb rubbers for ARS, ARE and ARES are about 46wt%, 34wt% and 38wt%, respectively, indicating that their amounts of NR and SR in the extracted crumb rubbers are approximately 54wt%, 66wt% and 62wt%, respectively. Thus, a better dissolution of crumb rubber was achieved in AR binder with Sasobit, which is probably one of the reasons for the better performance of ARS.

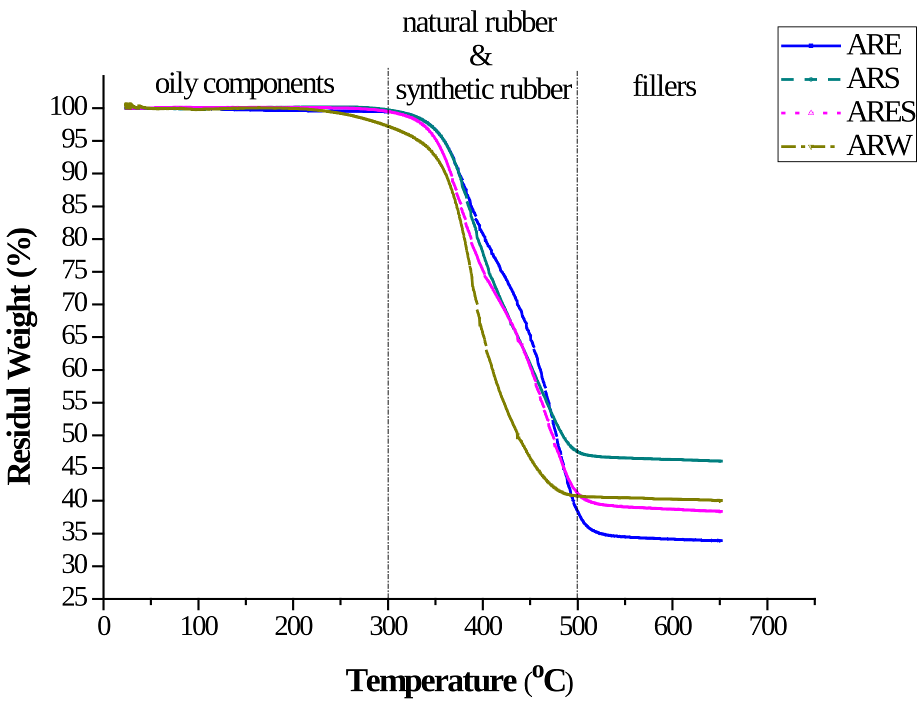

FIGURE 10 TGA test results

4 CONCLUSIONS

In this study, a series of conventional rheological tests as well as two chemical analysis tests were conducted on AR binders to characterize the effects of four non-foaming WMA additives on AR. The main conclusions of this study are summarized as the following:

1. All non-foaming WMA additives evaluated in this study are effective in improving the workability of AR binder, allowing for lower mixing and compacting temperatures of AR mixture.
2. Sasobit enhances the high-temperature performance of AR binder, but has slightly negative effects on its fatigue and cracking resistance.
3. Evotherm-DAT decreases the rutting resistance of AR, but has no significant effect on its low-temperature performance. Besides, the use of Evotherm-DAT in AR binder leads to lower fatigue resistance.
4. The use of combined WMA additives, i.e., 1.5wt% Sasobit and 2.5wt% Evotherm-DAT, compromises the rutting, fatigue and cracking resistance of AR. Thus, it is not considered as a viable option to reduce the construction temperature of AR mixtures in practice.
5. The incorporation of paraffin wax had minor negative effects on the rheological properties of AR at different temperature ranges. However, it is

still considered as a potential WMA additive for AR binders, since its adverse effect on low- temperature performance of asphalt can be compensated by crumb rubber.

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