

## Research Article

# Physical, Rheological, And Microsurface Characteristics of High-Viscosity Binder Modified with WMA Agents

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Received 13 December 2021; Revised 3 March 2022; Accepted 15 March 2022; Published 30 March 2022

Academic Editor: Yu Chen

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In order to investigate the feasibility of warm mix technology in high-viscosity asphalt mixes, in the current experiment, Shell 70 Grade A asphalt (base asphalt) was modified by AR-HVA (a high-viscosity modifier), and the high-viscosity modified asphalt was further incorporated with two surface-active warm mixes (Evotherm M1 and Retherm). The physical properties of the high-viscosity warm mix-modified asphalts were analyzed by dynamic and Brinell viscosity tests. The compatibility of the warm mixes with the high-viscosity modified and the base asphalt was analyzed by fluorescence microscopy. The modification mechanism of the high-viscosity warm mix-modified asphalts was revealed by Fourier-transform infrared spectroscopy. The high-viscosity modifier significantly reduced the penetration of the matrix asphalt and increased its softening point and 5°C ductility, whereas the two warm mixes increased the penetration and ductility of the high-viscosity modified asphalt and reduced its softening point. The surface-active warm mixes reduced the 60°C viscosity of the asphalt, and the viscosity reduction effect of M1 was better than that of Retherm. The high-viscosity modifier AR-HVA was well dispersed in the asphalt; however, its continuity was not good. The addition of the surface-active warm mixes effectively enhanced the continuity of the high-viscosity AR-HVA-modified asphalt. Infrared spectroscopy revealed little difference between the main components of the matrix asphalt and the high-viscosity asphalt. The addition of the surface-active warm mixes altered the amounts of four components in bitumen and increased its aromatic content.

## 1. Introduction

The top layer of drainage asphalt pavements contains a large amount of porous asphalt mixes. Asphalt pavement structures are designed to provide a drainage function that effectively discharges rainwater and ensures safe traffic flow. Moreover, asphalt pavement structures lead to improved road performance and noise reduction. In order to achieve effective drainage functionalities, the quantity of fine and coarse aggregates in porous asphalt mixes must be lowered and raised, respectively, resulting in a chain skeleton structure with a void ratio of around 20%; however, this structure has a high internal frictional resistance and low

cohesion. The bonding properties of asphalt must be improved to ensure the strength and road performance of asphalt pavement structures. Conventional modified bitumen cannot meet the requirements of practical drainage applications; hence, the employment of HVA (high-viscosity asphalt) is inevitable. HVA is generally applied to improve the long-term performance and durability of porous asphalt mixes. One of the most important properties of HVA is its dynamic viscosity at 60°C. The greater the value, the better the bonding performance of HVA; however, the viscosity of HVA at 135°C is significantly higher than those of other modified asphalt binders, and it causes problems in asphalt mix manufacturing and compaction construction. In

practical applications, HVA is heated to high temperatures to alleviate this issue. However, high temperatures accelerate the aging of asphalt and increase energy consumption and harmful emission during construction, limiting the application of HVA.

Warm mix asphalt (WMA) technology is considered a green road construction method. In this process, asphalt mixtures are compacted at a reduced temperature through the addition of warm mixes [1–3]. WMA can be divided into three main categories: foaming technology, organic additive-based technology, and chemical agents-based technology. Foaming technologies can be further subdivided into two categories: direct foaming method and indirect foaming method [4–7]. In the former case, water is injected through a specific tool, such as a manual nozzle, to create foam in asphalt binders, whereas in the indirect foaming method, finely crushed synthetic zeolite is directly added to asphalt mixes. As organic additives contain wax, they reduce the viscosity of asphalt binders [8–10]. However, the presence of wax lowers the road performance of warm mixes to some extent [11, 12]. Chemical agents improve the coating of aggregates without reducing the viscosity of warm mixes [13–15]. These agents also act on microscopic interactions between asphalt binders and aggregates by reducing surface tension and facilitate a smooth interaction between binders and aggregates, thus reducing the production temperature without changing the asphalt properties [16]. Therefore, chemical agents are promising candidates for warm mix technology.

For modified asphalt bitumen, several researchers have investigated the rheological and structural properties of bituminous materials at the nanoscale. Su et al. indicated that SBS has a significant effect on the molecular structure of bitumen, increasing the denseness and enhancing the activity of the branched chains of the bitumen components [17]. You et al. evaluated the thermal, transport and rheological properties of bitumen through laboratory experiments and molecular dynamics simulations, and the results of the study show good agreement between simulation and experiment [18]. For WMA Agents, the effects of warm mixes, such as RH, EC-120, and Sasobit, on the viscosity and rheological properties of high-viscosity asphalt have been explored [19–21]. However, how warm mixes affect the modification mechanism of high-viscosity asphalt at the microscopic scale is still not clear. Therefore, it is important to investigate the preparation process and modification mechanism of high-viscosity asphalt containing warm mixes.

In the present work, the preparation process, micro-mechanism, and physical properties of two different surface-active warm mix-modified high-viscosity asphalts were investigated.

## 2. Materials and Methods

**2.1. Materials.** Shell 70 Grade A matrix asphalt (70#) was used in this experiment, and its performance indicators are presented in Table 1. Second-generation high-viscosity AR-HVA modifier was supplied by Guolu Hi-Tech (Beijing,

TABLE 1: Physical properties of 70# asphalt.

Properties	Measured value	Specification
Penetration (25°C, 0.1 mm)	62.2	ASTM D5
Ductility (15°C, cm)	137.8	ASTM D113
Softening point (R&B, °C)	47.2	ASTM D36
Density (15°C, g·cm <sup>-3</sup> )	1.031	ASTM D70
Kinematic (135°C, mPa·s)	368.3	ASTM D4402
viscosity (175°C, mPa·s)	119.7	ASTM D4402
Absolute viscosity (60°C, Pa·s)	285	ASTM D4402

China) Engineering Research Institute Co. Evotherm M1 (M1) and Retherm were used as warming agents. (Figure 1) Second-generation surface-active warming agent M1 was procured from Mead Westvaco, and it was a dark yellow solution with a pH value of approximately 8.0, an amine value of 210 mg/g, and a solid content of 11%. Retherm is a domestic product. It is a liquid pale yellow surfactant with a variety of properties and consists of two groups: a lipophilic group of the carbon chain (tail) and a hydrophilic polar group.

**2.2. Sample Preparation.** In order to obtain bitumen with different modification requirements, different preparation methods were explored on the basis of previous studies [22]. Ultimately, this experiment used a high-speed shear method to prepare warm-mix modified high-viscosity bitumen. The preparation process of warm-mix HVA is shown in Figure 2. First, a stainless steel cup was placed in a shearer, which was placed in an oil bath at 180°C. Second, the 70# matrix asphalt was heated to about 180°C in an oven. The recommended dose (12%) of AR-HVA was added to the asphalt and stirred well with a glass rod for about 3 min to properly mix the modifier with the matrix asphalt. Next, the stainless steel cup was placed under high-speed shear. The speed of the shearer was first gradually increased to 3000 r/min for preshear for 3 min and was then set to 5000 r/min for continuous shear for 15 min. The temperature of the whole process was controlled between 180°C and 185°C. Special attention was paid to ensure that the asphalt was uniformly heated. After the shear process, modified bitumen was placed in the oven at 180°C for 40 min. Then, the two warm mixes were then incorporated into the as-developed high-viscosity asphalt according to the recommended dosing. The mixing process was first carried out for 2 min for preshear and then for 5 min for continuous shear. Last, the resultant sample was collected for testing.

### 2.3. Physical Property Test

**2.3.1. Physical Properties Test.** In order to analyze the physical properties of warm-mix HVA, penetration (ASTM D5), softening point (ASTM D36), ductility (ASTM D113), kinematic viscosity (ASTM D4402), and Absolute viscosity (60°C) (ASTM D4402) measurement tests were performed.

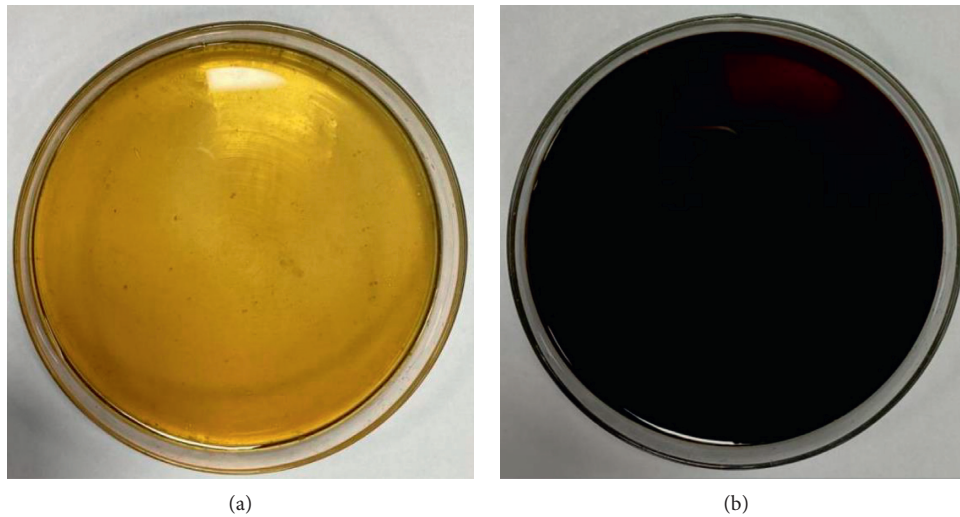


FIGURE 1: WMA agents. (a) Evotherm M1 (b) Retherm.

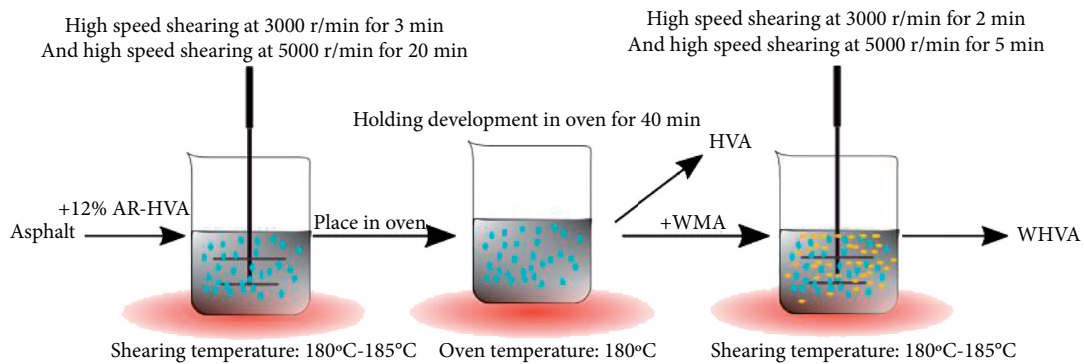


FIGURE 2: Preparation process of warm-mix HVA.

**2.3.2. Rheological Test.** The high temperature rheological properties of warm mix high-viscosity asphalt were explored by applying the Discovery HR-2 rheometer. In this paper, a strain control mode was used with a strain setting of 10%, a parallel plate fixture diameter of 8 mm was selected, the test oscillation frequency was 10.0 rad/s, and the test temperature range was 52–82°C. The rutting factor  $G^*/\sin\delta$  was used to characterise the resistance of the asphalt to permanent deformation, thus reflecting the high temperature performance of the asphalt. The phase angle  $\delta$  is used to characterise the ratio of elastic to viscous components in the asphalt binder and it is used to reflect the synchronisation of stress and strain. The creep behaviour of high-viscosity bitumen at low temperatures was characterised by applying a bending beam rheometer (BBR) to attain creep stiffness  $S$  and the rate of change  $m$  of the stiffness with time.

**2.3.3. Microsurface Characteristics.** In this paper, we use fluorescence microscopy (Suntech SOPTOP CX40 series) to observe the microstructure of warm mix high viscous

asphalt, so as to investigate the compatibility of high viscous agent, warm mix agent and asphalt. And we analyze the modification mechanism of warm mix high viscous asphalt binder with the help of FTIR infrared spectrometer (TENSOR).

### 3. Results and Discussion

**3.1. Penetration, Softening Point, and Ductility.** The penetration, softening point, and ductility of the high-viscosity warm mix-modified asphalts and the original asphalt are compared in Figure 3.

It is clear from Figure 3(a) that the penetration of the base asphalt was reduced with the inclusion of AR-HVA, which produced a three-dimensional network of molecular chains in the base asphalt, thus increasing its viscosity. In comparison to AR-HVA, the surface-active warm mixes caused a small increase in the needle penetration, indicating that they significantly reduced the viscosity of the high-viscosity asphalt at room temperature. These findings are consistent with the well-accepted statement [23, 24]. Retherm had a better viscosity reduction effect than M1 on the high-viscosity asphalt at

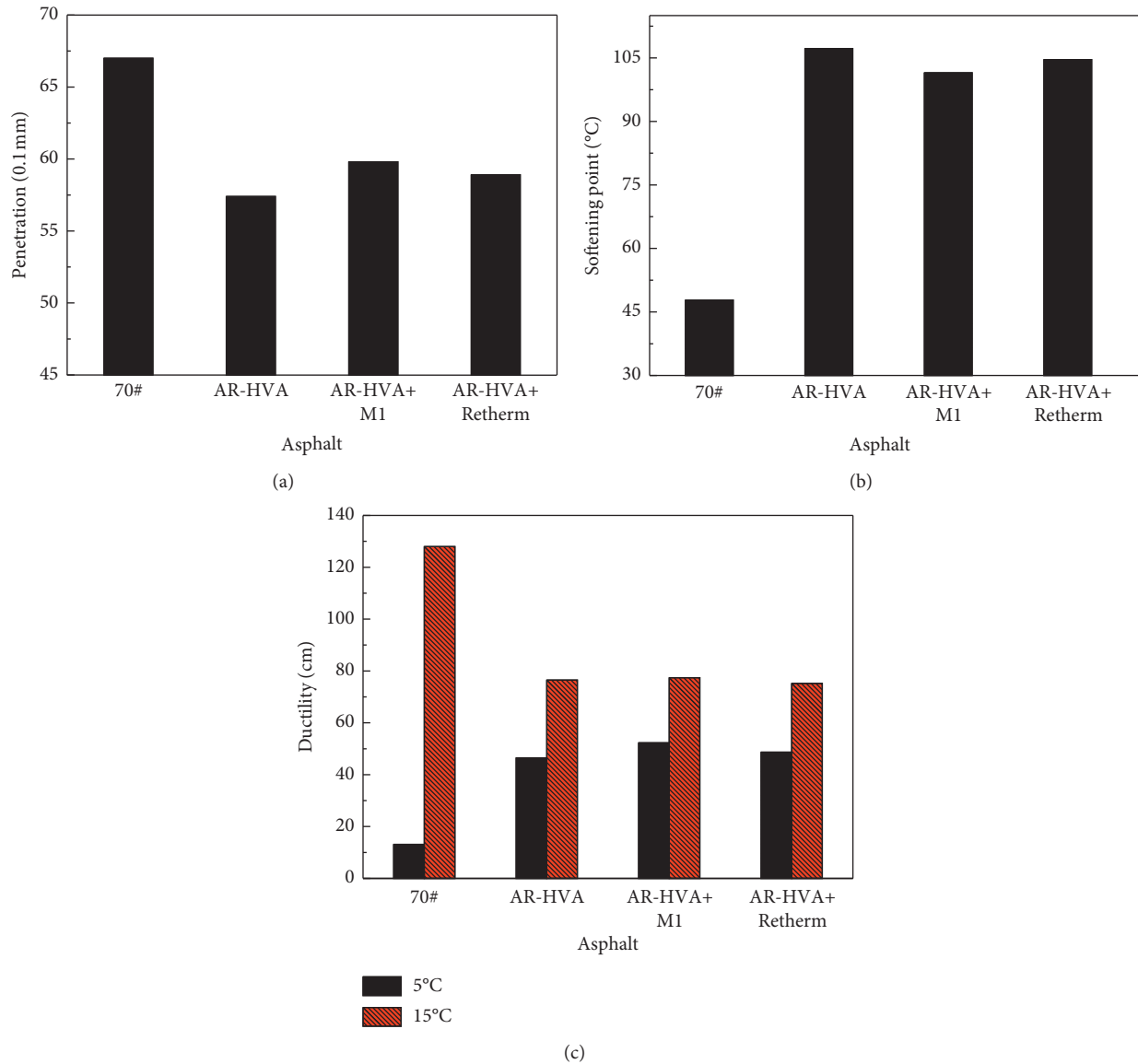


FIGURE 3: Penetration, softening point, and ductility test results of different asphalts. (a) Penetration. (b) Softening point. (c) Ductility.

room temperature. It is noticeable from Figure 3(b) that the high-viscosity modifier significantly increased the softening point of bitumen to around 107°C, improving the high-temperature stability of bitumen. The addition of the warm mixes slightly decreased the softening point of bitumen. Retherm had a better viscosity reduction effect than M1. Figure 3(c) shows that the 5°C ductility of the matrix asphalt increased significantly after the incorporation of AR-HVA, indicating that AR-HVA significantly improved the low-temperature deformation ability of the base asphalt. The surface-active warm mixes improved the ductility and low temperature performance of the high-viscosity asphalt. Moreover, M1 had a better 5°C ductility enhancement effect than Retherm. The asphalt ductility at 15°C was significantly higher than that at 5°C, and the high-viscosity asphalt had a problem of uneven dispersion after the addition of the high-viscosity modifier. Hence, at 5°C, the asphalt became brittle and its stretching length was shorter.

### 3.2. Viscosity

**3.2.1. Absolute Viscosity.** The absolute viscosity tests of the base asphalt, the high-viscosity AR-HVA-modified asphalt, the high-viscosity AR-HVA + M1-modified asphalt, and the high-viscosity AR-HVA + Retherm-modified asphalt were carried out by using an STD-0620A asphalt dynamic viscosity tester based on the vacuum decompression capillary method, and the obtained results are shown in Figure 4.

It is clear that the AR-HVA modifier greatly improved the 60°C viscosity of the matrix asphalt. The viscosity of the 70# matrix asphalt was low (around 0.2 kPa s); however, after the addition of AR-HVA, the 60°C dynamic viscosity of the high-viscosity asphalt reached around 180 kPa s (increased by three orders of magnitude). This is consistent with the findings in the literature [25, 26]. Moreover, the surface-active warm mixes reduced the low-temperature viscosity of the asphalt, and M1 had a more pronounced viscosity

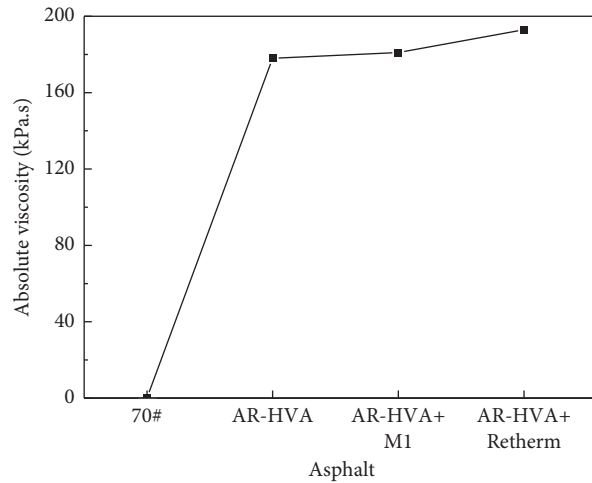


FIGURE 4: Absolute viscosity of different asphalts.

TABLE 2: Fitting equations for the viscosity-temperature curves of different asphalts.

Asphalt species	Fitting equation	$R^2$	Mixing temperature/ $^{\circ}\text{C}$	Compaction temperature/ $^{\circ}\text{C}$
70#	$y = 145453e^{-0.042x}$	0.9915	161	149
AR-HVA	$y = 260524e^{-0.041x}$	0.9984	179	167
AR-HVA + M1	$y = 354934e^{-0.044x}$	0.9958	178	166
AR-HVA + retherm	$y = 374804e^{-0.044x}$	0.9977	177	165

$y$  is viscosity;  $x$  is temperature;  $e$  is natural logarithm.

reduction effect than Retherm. This is contrary to the findings of Zheng et al. that warm mixes increased the absolute viscosity at  $60^{\circ}\text{C}$  [21]. The main reason for this result could be the inconsistency in the type of WMA agents.

**3.2.2. Brookfield Rotational Viscosity.** Brookfield rotational viscosity tests are used to determine the shear stress and shear strain of Newtonian or non-Newtonian fluids. Brookfield rotational viscosity tests are generally adopted to determine the high temperature ( $>80^{\circ}\text{C}$ ) viscosity of asphalt. Construction temperatures have a significant impact on the quality of asphalt pavements. Construction processes at too high temperatures consume high energy, cost more, and accelerate the aging of asphalt, whereas construction processes at too low temperatures lead to inadequate mixing of warming mixes, affect the compaction of asphalt, and reduce the properties of asphalt pavements [27–29]. According to the ASTM D 6925 standard, the mixing and compaction temperatures of asphalt pavement mixtures are determined by the corresponding temperatures at the viscosity values of  $0.17 \pm 0.02 \text{ Pa}\cdot\text{s}$  and  $0.28 \pm 0.03 \text{ Pa}\cdot\text{s}$ , respectively. In this work, the apparent viscosity values of the base asphalt, AR-HVA, AR-HVA + M1, and AR-HVA + Retherm were measured at  $120\text{--}180^{\circ}\text{C}$  to analyze the viscosity variation of the warm mix-modified asphalts and provide a reference for temperature selection for warm mix-modified asphalt pavement construction. The obtained results are presented in Table 2, and the viscosity-temperature curves of different asphalts are shown in Figure 5.

It is observable from Figure 5 that the apparent viscosity of the asphalt decreased with the rise of temperature. The rate of viscosity decrease was faster at lower temperatures,

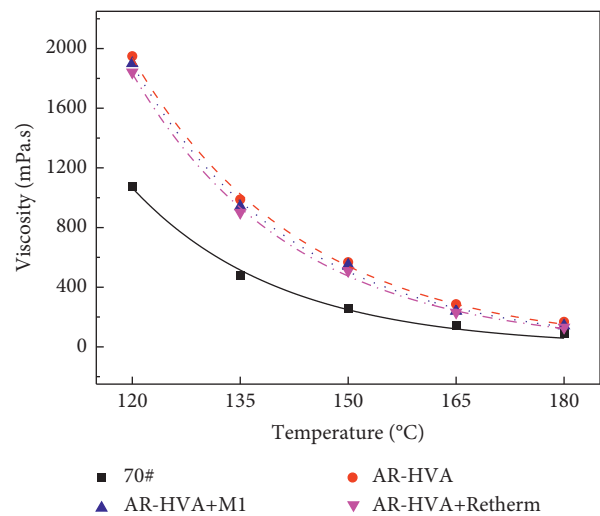


FIGURE 5: Viscosity-temperature curves of different asphalts.

and the decrease in viscosity slowed down significantly after the temperature reached  $165^{\circ}\text{C}$ . The surface viscosity of the asphalt increased significantly after the incorporation of AR-HVA. In comparison to the surface-active warm mixes, AR-HVA had a better viscosity enhancement effect. The apparent viscosity of the two warm mixes decreased slightly as compared to that of high-viscosity bitumen, proving that the surface-active warm mixes achieved warm mixing without reducing the viscosity of bitumen.

It is evident from Table 2 that the mixing and compaction temperatures of the high-viscosity asphalt and the high-viscosity warm mix-modified asphalt increased by

approximately 20°C as compared to those of the matrix asphalt. Moreover, the difference between the mixing and compaction temperatures of the high-viscosity modified asphalt and the high-viscosity warm mix-modified asphalts was within 2°C, indicating that the mixing and compaction temperatures of the high-viscosity warm mix-asphalts determined by this method are not applicable in actual engineering projects. These findings are consistent with the literature that the isoviscous method of determining mixing and compaction temperatures is applicable to base bitumen and is not as applicable to modified bitumen [30].

### 3.3. Rheological Properties of High-Viscosity Warm Mix-Modified Asphalts

**3.3.1. High Temperature Rheological Performance Test.** As is shown in Figure 6, the complex modulus and rutting factor of the high-viscosity asphalt and the high-viscosity warm mix-modified asphalts decreased sharply, and the phase angle increased gradually with the rise of temperature. The complex modulus and rutting factor of several asphalts gradually approached each other at the final temperature of 82°C, indicating that the rise in temperature weakened the deformation resistance of the high-viscosity asphalt and the high-viscosity warm mix-modified asphalts [26, 31].

Moreover, at the same temperature, the incorporation of the high-viscosity modifier (AR-HVA) significantly increased the  $G^*$  and  $G^*/\sin\delta$  of the base asphalt by nearly an order of magnitude, implying that AR-HVA greatly improved the deformation resistance of the high-viscosity asphalt. The addition of a surface-active warm mix to the high-viscosity modifier also increased the  $G^*$  and  $G^*/\sin\delta$  of the base asphalt, indicating that the surface-active warm mix further enhanced the deformation resistance of the high-viscosity asphalt. The deformation resistance enhancement effect of M1 was greater than that of Retherm. As ionic functional groups of the lipophilic surfactants underwent a directional arrangement in the molten matrix asphalt solution, the distance between mutually exclusive molecules of the asphalt increased, improving the high-temperature rheological properties of the high-viscosity asphalt [26, 31].

It is noticeable from Figure 6(b) that the phase angle of different asphalts increased with the rise of temperature, indicating that the rise in temperature weakened the deformation resistance of bitumen. As the temperature of warm mix asphalt bonds increased, their viscoelastic composition changed, causing a sharp increase in the viscous component and a gradual decrease in the elastic component of the asphalt. The phase angle of the matrix asphalt was greater than that of the high-viscosity AR-HVA-modified asphalt, indicating that the addition of the high-viscosity modifier reduced the viscous component of the asphalt and increased the elastic component. The high-viscosity AR-HVA + M1-modified asphalt and the high-viscosity AR-HVA + Retherm-modified asphalt both had a lower phase angle than the high-viscosity AR-HVA-modified asphalt, implying that the warm mixes further reduced the viscous component of the high-viscosity asphalt [19, 32].

From Figure 6(c), it can also be found that the rutting factor of 70# asphalt is greater than 1 MPa at 64°C and less than 1 MPa at 70°C, therefore, the high temperature grading temperature of 70# asphalt is 64°C. The rutting factor for all three modified bitumen types is greater than 1 MPa at 82°C, therefore the high temperature classification temperature for AR-HVA, AR-HVA + M1 and AR-HVA + Retherm is 82°C.

**3.3.2. Bending Beam Recession Test.** The SHRP program proposes the Bending Beam Recession (BBR) test to evaluate the low temperature cracking resistance of asphalt binders, which has a high degree of accuracy and it is a low temperature test method for determining asphalt performance classification [33, 34]. Therefore, this paper tests the low temperature cracking resistance of warm mix high-viscosity asphalt by means of the BBR test. The test results are shown in Table 3.

The modulus of stiffness  $S$  is an important indicator of the rheological properties of asphalt, indicating the ability of asphalt to resist deformation; the creep rate  $m$  reflects the sensitivity of asphalt stiffness over time and the ability of stress relaxation. The decrease in  $S$  value as well as the increase in  $m$  correspond to an increase in the low temperature cracking resistance of the asphalt pavement. Table 3 shows that the addition of AR-HVA high-viscosity modifier causes a significant decrease in creep stiffness  $S$ . The incorporation of two surface-active warm mixes further reduces the creep stiffness  $S$  of high-viscosity asphalt, and the effect of the warm mix Retherm is more obvious. This indicates that the addition of a high-viscosity agent improves the low temperature deformation resistance of the asphalt and that the addition of a surface-active warm mix enhances this effect, while it can be seen that the warm mix Retherm is more effective. From Table 3 it can also be found that the creep rate  $m$ s of AR-HVA high-viscosity modified bitumen increased significantly compared to the matrix bitumen, while AR-HVA + M1 and AR-HVA + Retherm warm mix high-viscosity bitumen showed a small decrease in  $m$ s compared to the high-viscosity bitumen, but both decreases were small and within the 10% range. This indicates that AR-HVA significantly increases the low temperature stress relaxation capacity of asphalt and that surface-active warm mixes have a small weakening effect on the low temperature stress relaxation capacity of high-viscosity modified asphalt. In general, both high adhesive modifier and surfactant temperature mixer can increase the low-temperature crack resistance of asphalt [35, 36].

On the other hand, the  $S$  value of 70# asphalt at  $-24^\circ\text{C}$  is greater than 300 MPa and the  $m$ -value is less than 0.3, while at  $-18^\circ\text{C}$  the  $S$  value is less than 300 MPa and the  $m$ -value is greater than 0.3, therefore the low temperature grading temperature for this 70# asphalt is  $-18^\circ\text{C}$ .  $S$  values of the other three modified bitumen types is less than 300 MPa and  $m$  value is greater than 0.3 at  $-24^\circ\text{C}$ . Therefore, the low temperature classification temperature for AR-HVA, AR-HVA + M1 and AR-HVA + Retherm is  $-24^\circ\text{C}$ .

In summary, the PG grades of 70# asphalt is PG 64–18, and the PG grades of AR-HVA, AR-HVA + M1 and AR-HVA + Retherm is PG 82–36.

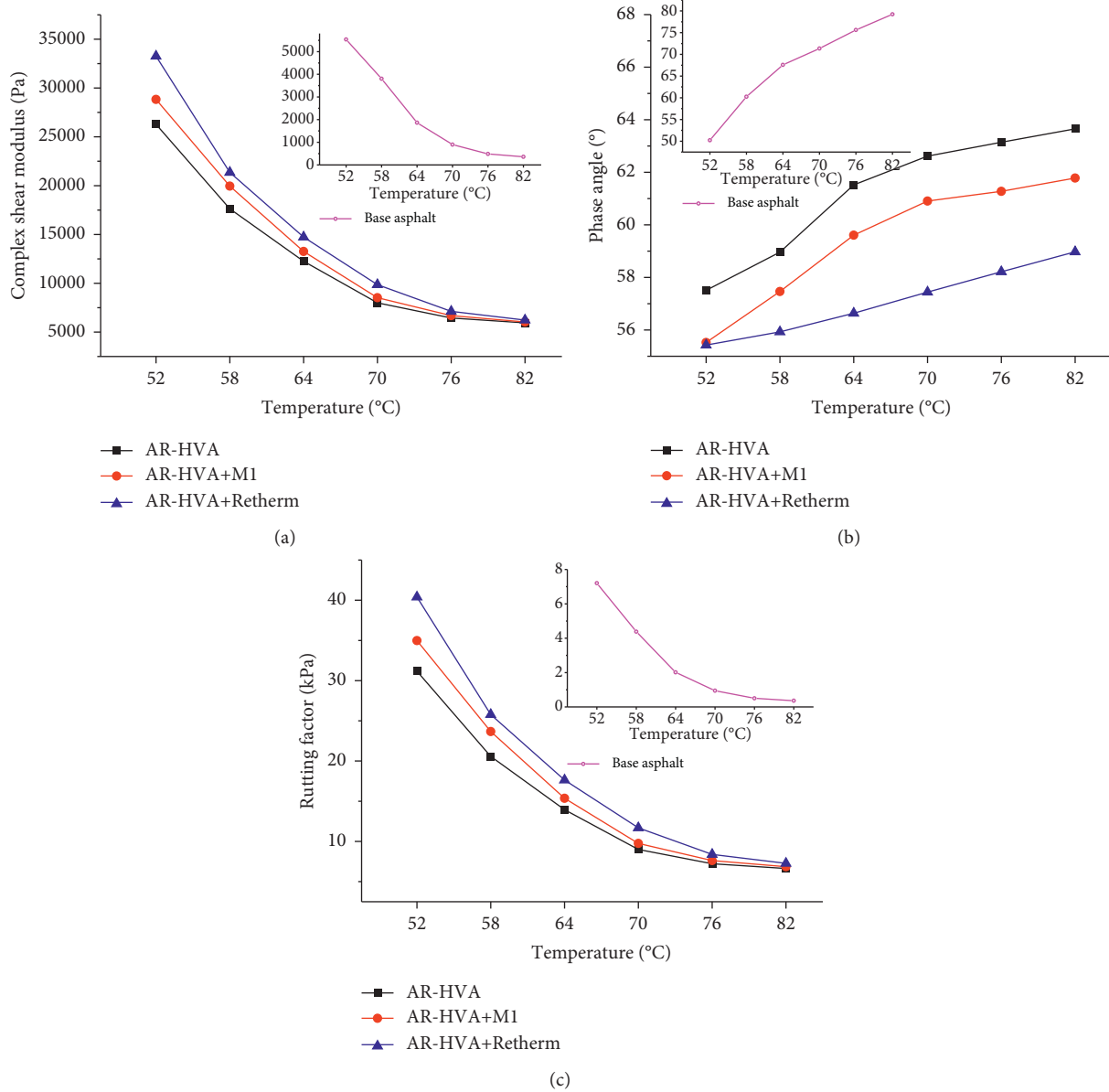


FIGURE 6: High-temperature rheological performance test results of asphalt. (a) Complex modulus ( $G^*$ ) variation with temperature. (b) Phase angle variation with temperature. (c) Rutting factor variation with temperature.

TABLE 3: Results of creep test of bending beam recession.

Asphalt species	Temperature (°C)					
	-12		-18		-24	
	S/MPa	m	S/MPa	m	S/MPa	m
70#	89.6	0.396	121.5	0.311	324	0.235
AR-HVA	74.5	0.441	104.3	0.365	268	0.321
AR-HVA + M1	68.6	0.435	96.04	0.353	254	0.313
AR-HVA + Retherm	38	0.417	53.2	0.341	239	0.308

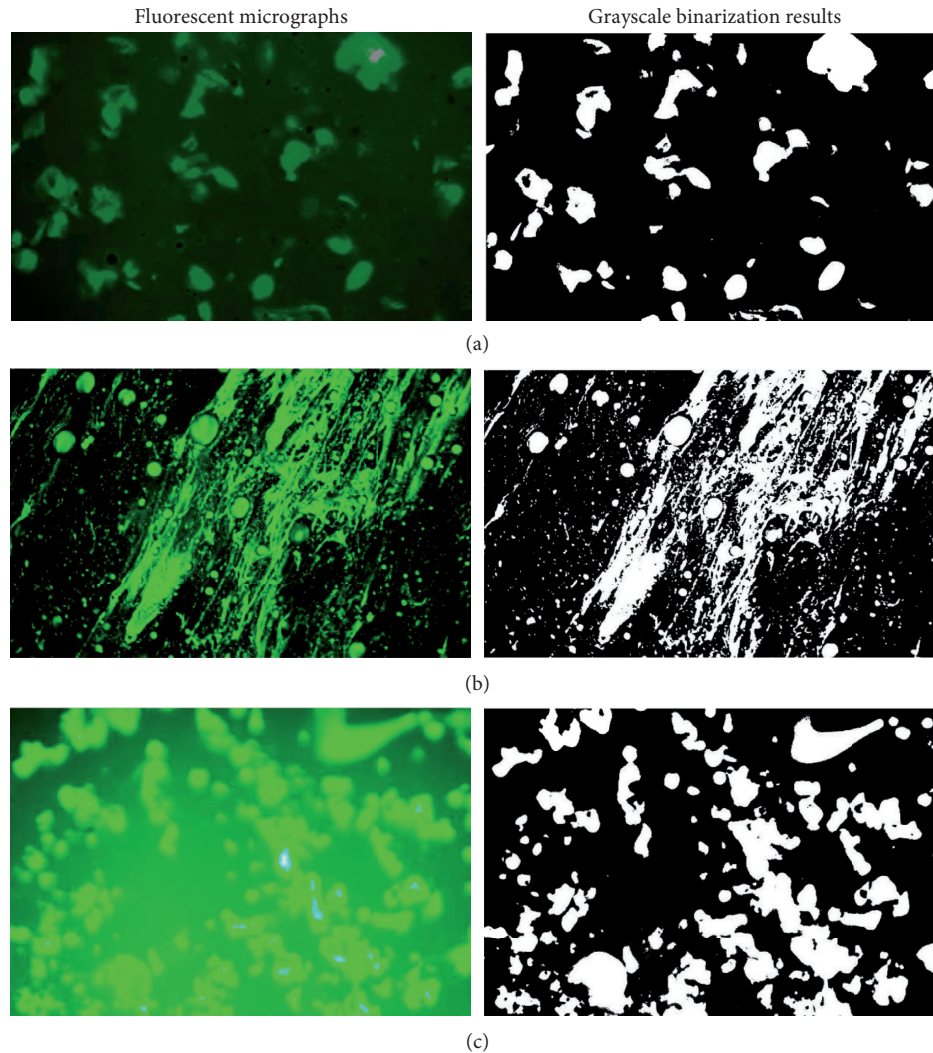


FIGURE 7: Fluorescence micrographs of different asphalts. (a) AR-HVA, (b) AR-HVA + M1, (c) AR-HVA + Retherm.

### 3.4. Modification Mechanism Analysis of High-Viscosity Warm Mix-Modified Asphalts

**3.4.1. Fluorescence Microscopy.** Fluorescence microscopy does not change the physical and chemical states of asphalt and visually reflects the form, size, and distribution of modifiers in the asphalt matrix. Asphalt appears black in computer-generated images, whereas modifiers appear fluorescent yellow-green [28]; thus, fluorescence microscopy can be used to reflect the compatibility of high-viscosity agents with warm mixes and asphalt by observing the distribution of black and fluorescent yellow-green particles. Asphalt specimens for fluorescence microscopy are generally prepared by freeze forming, test mold forming, and hot-drop cover-glass forming [37–39].

In this experiment, high-viscosity asphalt and high-viscosity warm mix-modified asphalt specimens were prepared separately by hot-drop cover-glass forming. First, a high-viscosity warm mix-modified asphalt specimen was heated to about 190°C so that it remained in a fluid state. Slides and coverslips were then placed in a high-temperature

oven for about 5 min. A glass rod was dipped into the flowing high-viscosity warm mix-modified asphalt, and a drop of the solution was placed on a slide without applying pressure. It was ensured that the asphalt specimen surface was flat and no air bubbles were generated in the asphalt. The as-prepared high-viscosity warm mix-modified asphalt specimens were selected for fluorescence irradiation data collection at 100 times magnification. MATLAB image processing software was used to process the collected fluorescent microscopic images of the high-viscosity warm mix-modified bitumen and to analyze the effect of the area occupied by fluorescence on the microstructure of the modified bitumen, and the corresponding results are shown in Figure 7.

It is noticeable that the high-viscosity modifier AR-HVA was well dispersed in the asphalt; however, its continuity was poor, and tiny particles existed in the asphalt. Molecular chain segments of AR-HVA became dispersed and thawed in the asphalt and were free to stretch; thus, AR-HVA had a solubilizing and plasticizing effect [40]. The addition of M1 effectively enhanced the continuity of the high-viscosity AR-



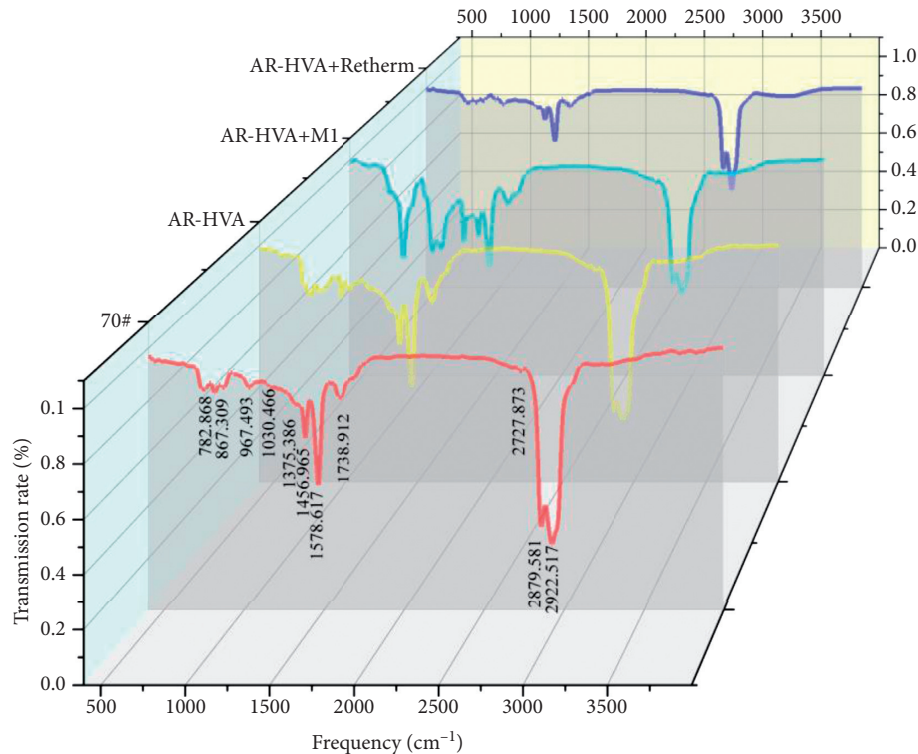


FIGURE 8: FTIR spectra of different asphalts.

HVA-modified asphalt. The addition of Retherm also improved the continuity of the high-viscosity AR-HVA-modified asphalt; however, its enhancement effect was weaker than that of M1. The area occupied by fluorescence was quantified by gray-scale binarization in MATLAB. It was found that AR-HVA, AR-HVA + M1, and AR-HVA + M1 accounted for 12.1063%, 28.434%, and 27.655% of the collected fluorescence micrographs, respectively. These results indicate that the addition of the warm mixes increased the fluorescence area; hence, a higher percentage of the modifier was present in the fluorescence micrographs, resulting in increased continuity of AR-HVA.

**3.4.2. Infrared Spectroscopy.** Infrared absorption spectroscopy can be used to characterise functional groups in organic compounds and speculate chemical reactions. Microscopic changes in bitumen can be identified by infrared spectroscopy [41–43]. In this experiment, the modification mechanism of the high-viscosity asphalt and the high-viscosity warm mix-modified asphalts was analyzed by FTIR at the microscopic scale, and the obtained results are shown in Figure 8.

The sharp absorption peaks at  $2922.517\text{ cm}^{-1}$  and  $2879.581\text{ cm}^{-1}$  appeared due to the symmetric and asymmetric stretching vibrations of methylene ( $\text{CH}_2$ ), respectively. In both peaks, matrix bitumen and AR-HVA-modified bitumen were more intense than the two surface-active warm mixes, indicating that the addition of the warm mixes attenuated the intensity of absorption peaks; hence, the total amount of  $\text{CH}_2$  was reduced. The weak absorption peak near  $2727\text{ cm}^{-1}$  indicates the presence of a small

amount of aliphatic aldehyde compounds in the matrix and high-viscosity bitumen. The peak at  $1738.912\text{ cm}^{-1}$  appeared due to the stretching vibration of the ketone carbonyl group, and different asphalts had a weak absorption peak at this point. It indicates that both AR-HVA and the two surface-active warm mixes did not contain keto carbonyl and also did not alter the keto carbonyl content of bitumen. The peaks at  $1578.617\text{ cm}^{-1}$ ,  $1456.965\text{ cm}^{-1}$ , and  $1375.966\text{ cm}^{-1}$  represent the telescopic vibration frequencies of the centrosymmetric junction of  $\text{C}=\text{C}$  olefins. At these frequencies, AR-HVA had a higher peak intensity than the matrix asphalt, whereas the two warm mixes attenuated the peak, indicating that the addition of AR-HVA to the matrix asphalt introduced centrosymmetric knotted  $\text{C}=\text{C}$  olefins, whereas the two warm mixes depleted these centrosymmetric knotted  $\text{C}=\text{C}$  olefins. Moreover, two weak absorption peaks appeared at  $1456.965\text{ cm}^{-1}$  and  $1375.966\text{ cm}^{-1}$ . Further, two more absorption peaks with a wider shape were detected at  $1030.466\text{ cm}^{-1}$  and  $967.493\text{ cm}^{-1}$ . The absorption peaks of the matrix asphalt and the high-viscosity asphalt were weaker than those of the high-viscosity warm mix-modified asphalts. Moreover, the warm mixes contained sulfite ( $\text{S}=\text{O}$ ). At the weak multi-peak spectral band at  $867.309\text{ cm}^{-1}$ , a substitution reaction of CH aromatics on the benzene ring occurred. It is clear that the absorption peaks of the high-viscosity warm mix-modified asphalts were stronger than those of the high-viscosity asphalt and the matrix asphalt, and it can be attributed to the introduction of a large number of CH aromatics to the warm mixes. The peak at  $782.868\text{ cm}^{-1}$  appeared due to the vibration of  $\text{CH}_2$ . At this point, both the matrix asphalt and the high-viscosity asphalt had a weak absorption peak. The high-viscosity

warm mix-modified asphalts did not manifest this peak, indicating that the warm mixes consumed the  $\text{CH}_2$  in the asphalt. The matrix asphalt and the high-viscosity asphalt consisted of a large number of long-chain alkanes, unsaturated hydrocarbons, aromatic rings, benzene ring aromatic hydrocarbons, and a small amount of ketone carbonyl aliphatic aldehyde compounds.

The absorption peaks of the high-viscosity warm-mix modified asphalts at  $2922.517\text{ cm}^{-1}$  and  $2879.581\text{ cm}^{-1}$  weakened as compared to those of the matrix bitumen and the high-viscosity bitumen, indicating that the total amount of  $\text{CH}_2$  was reduced. The warm mixes weakened the peak intensity at  $1578.617\text{ cm}^{-1}$ ,  $1456.965\text{ cm}^{-1}$ , and  $1375.966\text{ cm}^{-1}$  by reducing the amount of centrosymmetric  $\text{C}=\text{C}$  olefins and enhanced the peak intensity at  $1030.466\text{ cm}^{-1}$  and  $967.493\text{ cm}^{-1}$  by increasing the amount of  $\text{S}=\text{O}$ . The warm mixes enhanced the absorption peak intensity at  $867.309\text{ cm}^{-1}$  and increased the  $\text{CH}$  content. The warm mixes decreased the absorption peak intensity at  $782.868\text{ cm}^{-1}$  and reduced the amount of  $\text{CH}_2$ . Therefore, the addition of the surface-active warm mixes altered the contents of four components in bitumen and increased its aromatic content. And it furthered improve the thermo-mechanical properties [44].

#### 4. Conclusion

The preparation process of high-viscosity warm mix-modified asphalt binders was optimized, and a feasible method for the stable preparation of high-viscosity warm mix-modified asphalt binders was proposed. The as-prepared high-viscosity warm mix-modified asphalt binders were subjected to conventional experimental analyses and microscopic tests. The main findings of this work are as follows.

The high-viscosity modifier significantly reduced the penetration of the base asphalt and increased its softening point and  $5^\circ\text{C}$  ductility. The two warm mixes (M1 and Retherm) increased the penetration and ductility of the high-viscosity modified asphalt and decreased its softening point by a small degree.

The high-viscosity modifier AR-HVA increased the  $60^\circ\text{C}$  dynamic viscosity of the base asphalt by three orders of magnitude, whereas the addition of a surface-active warm mixer reduced the  $60^\circ\text{C}$  dynamic viscosity of the asphalt by a small degree. The mixing and compaction temperatures of the high-viscosity AR-HVA-modified asphalt increased by approximately  $20^\circ\text{C}$  as compared to those of the base asphalt; however, the warm mixes had no significant effect on the mixing and compaction temperatures of the asphalt.

The high-viscosity modifier significantly increased the  $G^*$  and  $G^*/\sin\delta$  of the asphalt and enhanced its deformation resistance. The surface-active warm mixes further increased the deformation resistance of high-viscosity bitumen, and the deformation resistance enhancement effect of M1 was better than that of Retherm. The phase angle of matrix bitumen was greater than that of high-viscosity AR-HVA-modified bitumen. The addition of the high-viscosity modifier reduced the viscous component of bitumen and

increased the elastic component, and the PG grades of 70# asphalt is PG 64–18, and the PG grades of AR-HVA, AR-HVA + M1 and AR-HVA + Retherm is PG 82–36.

Fluorescence microscopy revealed that AR-HVA was well dispersed in bitumen; however, the continuity of AR-HVA + M1 and AR-HVA + Retherm was relatively poor. Infrared spectra indicated little difference between the main components of the matrix asphalt and the high-viscosity asphalt. The addition of the surface-active warm mixes altered the amounts of four components in bitumen and its aromatic content.

#### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

#### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

#### Acknowledgments

This study was supported by the Key Scientific and Technological Project of Transportation Industry “Research and Demonstration on Key Technologies of Resonance Crushed Asphalt Overlay of Old Cement Concrete Pavement in Guangxi” (project no. 2020-MS1-005) and the Key Scientific and Technological Project of the Transportation Industry in Guangxi “Study on Preparation and Application Technology of a Fast Hardening, Micro Expansion and High Crack Resistance Curing Material” and “Research and Demonstration on Key Technologies of High Performance and Low Cost Plant Mix Hot Regeneration in Guangxi.” The authors thank LetPub (<https://www.letpub.com>) for its linguistic assistance during the preparation of this manuscript.

#### References

- [1] Z. Gao, H. Fu, Q. Chen, and Y. Cao, “Rheological properties and viscosity reduction mechanism of SBS warm-mix modified asphalt,” *Petroleum Science and Technology*, vol. 38, no. 6, pp. 556–564, 2020.
- [2] P. Georgiou and A. Loizos, “Characterization of sustainable asphalt mixtures containing high reclaimed asphalt and steel slag,” *Materials*, vol. 14, 2021.
- [3] P. Guo, Y. Feng, W. Wei, L. He, and B. Tang, “Adhesion of warm-mix recycled asphalt aggregate mixtures based on surface free energy theory,” *Journal of Materials in Civil Engineering*, vol. 31, 2019.
- [4] M. Iwanski and J. Mrugala, *Moisture and Frost Resistance of Asphalt concrete with Foamed Bitumen Modified with Synthetic Wax, 3rd International Conference on Transportation Infrastructure (ICTI)*, pp. 131–137, Univ Pisa, Pisa, ITALY, 2014.
- [5] A. Kavussi and L. Hashemian, “Laboratory evaluation of moisture damage and rutting potential of WMA foam mixes,” *International Journal of Pavement Engineering*, vol. 13, no. 5, pp. 415–423, 2012.

- [6] Z. You, D. Porter, X. Yang, and H. Yin, "Preliminary laboratory evaluation of methanol foamed warm mix asphalt binders and mixtures," *Journal of Materials in Civil Engineering*, vol. 29, 2017.
- [7] W. Wei, B. Zheng, C. Han, X. Niu, J. Xu, and J. Yan, "Evaluation method of resistance to water damage for foamed warm-mixed asphalt mixture based on surface free energy theory," *Advances in Civil Engineering Materials*, vol. 7, pp. 193–206, 2018.
- [8] N. M. Asmael, M. Y. Fattah, and A. J. Kadhim, "Exploring the effect of warm additives on fatigue cracking of asphalt mixtures," *Journal of Applied Science and Engineering*, vol. 23, pp. 197–205, 2020.
- [9] A. J. Kadhim, M. Y. Fattah, and N. M. Asmael, "Evaluation of the moisture damage of warm asphalt mixtures," *Innovative Infrastructure Solutions*, vol. 5, 2020.
- [10] A. M. Rodriguez-Alloza and J. Gallego, "Volumetric characteristics and compactability of asphalt rubber mixtures with organic warm mix asphalt additives," *Materiales De Construcción*, vol. 67, 2017.
- [11] M. Sukhija and N. Saboo, "A comprehensive review of warm mix asphalt mixtures-laboratory to field," *Construction and Building Materials*, vol. 274, 2021.
- [12] H. Wang, X. Liu, P. Apostolidis, and T. Scarpas, "Review of warm mix rubberized asphalt concrete: towards a sustainable paving technology," *Journal of Cleaner Production*, vol. 177, pp. 302–314, 2018.
- [13] R. Ghabchi, S. Rani, M. Zaman, and S. A. Ali, "Effect of WMA additive on properties of PPA-modified asphalt binders containing anti-stripping agent," *International Journal of Pavement Engineering*, vol. 22, no. 4, pp. 418–431, 2021.
- [14] H. F. Haghshenas, Y.-R. Kim, M. D. Morton, T. Smith, M. Khedmati, and D. F. Haghshenas, "Effect of softening additives on the moisture susceptibility of recycled bituminous materials using chemical-mechanical-imaging methods," *Journal of Materials in Civil Engineering*, vol. 30, 2018.
- [15] J. Yu, C. Xiong, X. Zhang, Z. Ge, and G. An, "Assessing moisture sensitivity of rubberized warm mix asphalt mixtures using the surface free energy method and dynamic water pressure tester," *Journal of Testing and Evaluation*, vol. 46, pp. 580–592, 2018.
- [16] S. R. Omranian, M. O. Hamzah, G. S. Mounik, K. P. Reddy, Y. M. Kapadia, and S. Y. Teh, *Laboratory Investigation on Warm Mix Asphalt Incorporating Organo-Silane Additive*, International Conference on Sustainable Energy and Green Technology, SEGTECH, Bangkok, THAILAND, 2019.
- [17] M. Su, J. Zhou, J. Lu, W. Chen, and H. Zhang, "Using molecular dynamics and experiments to investigate the morphology and micro-structure of SBS modified asphalt binder," *Materials Today Communications*, vol. 30, 2022.
- [18] L. You, T. Spyriouni, Q. Dai, Z. You, and A. Khanal, "Experimental and molecular dynamics simulation study on thermal, transport, and rheological properties of asphalt," *Construction and Building Materials*, vol. 265, 2020.
- [19] J. Shi, W. Fan, Y. Lin, P. Zhao, and J. Ouyang, "Effects of surfactant warm-mix additives on the rheological properties of high-viscosity asphalt," *Advances in Materials Science and Engineering*, vol. 2020, Article ID 6506938, 11 pages, 2020.
- [20] F. Yazdipanah, M. Ameri, M. Shahri, N. Hasheminejad, and H. F. Haghshenas, "Laboratory investigation and statistical analysis of the rutting and fatigue resistance of asphalt mixtures containing crumb-rubber and wax-based warm mix asphalt additive," *Construction and Building Materials*, vol. 309, 2021.
- [21] X. Zheng, S. M. Easa, T. Ji, Z. Jiang, and A. O. Abd El Halim, "Influence of warm-mix additives on physical, rheological, and morphological properties of high-viscosity asphalt," *Journal of Materials in Civil Engineering*, vol. 31, 2019.
- [22] J. Yu, X. Luo, S. Wu, X. Zeng, and P. Cong, "Preparation and properties of Flame-retarded SBS modified asphalt," *China Journal of Highway and Transport*, vol. 20, pp. 35–39, 2007.
- [23] S. F. Chen, S. Y. Zhu, X. T. Qin, and Z. Z. Li, "Material design and property of high viscosity asphalt used in pervious asphalt pavement," *Advanced Materials Research*, vol. 753-755, pp. 495–499, 2013.
- [24] X. Hu, H. Wang, and H. Wang, "The Performance of Nanometer CaCO<sub>3</sub> High-Viscosity Compound Modified Asphalt," *DEStech Transactions on Engineering and Technology Research*, pp. 210–218, 2016.
- [25] J. Hu, T. Ma, Y. Zhu, X. Huang, J. Xu, and L. Chen, "High-viscosity modified asphalt mixtures for double-layer porous asphalt pavement: design optimization and evaluation metrics," *Construction and Building Materials*, vol. 271, 2021.
- [26] P. Kong, G. Xu, X. Chen, X. Shi, and J. Zhou, "Effect of different high viscosity modifiers on rheological properties of high viscosity asphalt," *Frontiers of Structural and Civil Engineering*, vol. 15, no. 6, pp. 1390–1399, 2021.
- [27] H. Wang, X. Li, J. Xiao, Z. You, X. Yang, and M. Irfan, "High-temperature performance and workability of crumb rubber-modified warm-mix asphalt," *Journal of Testing and Evaluation*, vol. 48, pp. 2946–2962, 2020.
- [28] M. Wang, L. Liu, and H. Wu, "Correlation between phase microstructure and macroscopic performance of SBS modified bitumen," *Journal of Building Materials*, vol. 19, pp. 119–123, 2016.
- [29] J. Xie, W. Huang, B. Hu, Z. Xiao, H. M. Z. Hassan, and K. Wu, "Study on the road performance of foamed warm-mixed reclaimed semi-flexible asphalt pavement," *Material, Materials*, vol. 14, 2021.
- [30] A. Almusawi, B. Sengoz, and A. Topal, "Investigation of mixing and compaction temperatures of modified hot asphalt and warm mix asphalt," *Periodica Polytechnica: Civil Engineering*, vol. 65, pp. 72–83, 2021.
- [31] H. C. Zhang, J. Wu, Y. Luo, and Z. Qin, "High-temperature properties of composite modified light-colored synthetic asphalt binders," *Materials Research Express*, vol. 8, 2021.
- [32] H. K. Veeraiah and S. S. Nagabhushanarao, "Effect of optimized short-term aging temperature on rheological properties of rubberized binders containing warm mix additives," *Construction and Building Materials*, vol. 261, 2020.
- [33] Z. A. Zeng, B. S. Underwood, and C. Castorena, "Low-temperature performance grade characterisation of asphalt binder using the dynamic shear rheometer," *International Journal of Pavement Engineering*, vol. 23, no. 3, pp. 811–823, 2022.
- [34] A. Mohseni and H. Azari, "Quick Asphalt Binder Low-Temperature PG Determination Using DSR," in *Proceedings of the ASCE International Conference on Transportation and Development (ASCE ICTD)*, pp. 271–283, Seattle, WA, USA, May 2020.
- [35] M. Stienss and C. Szydowski, "Influence of selected warm mix asphalt additives on cracking susceptibility of asphalt mixtures," *Materials*, vol. 13, 2020.
- [36] E. Sedaghat, R. Taherian, S. A. Hosseini, and S. M. Mousavi, "Rheological properties of bitumen containing nanoclay and organic warm-mix asphalt additives," *Construction and Building Materials*, vol. 243, 2020.

- [37] C. Fang, X. Liu, R. Yu, P. Liu, and W. Lei, "Preparation and properties of asphalt modified with a composite composed of waste package poly(vinyl chloride) and organic montmorillonite," *Journal of Materials Science & Technology*, vol. 30, no. 12, pp. 1304–1310, 2014.
- [38] J. Wei, Y. Li, F. Dong, H. Feng, and Y. Zhang, "Study on the amorphous poly alpha olefin (APAO) modified asphalt binders," *Construction and Building Materials*, vol. 66, pp. 105–112, 2014.
- [39] B. Zhang, M. Xi, D. Zhang, H. Zhang, and B. Zhang, "The effect of styrene-butadiene-rubber/montmorillonite modification on the characteristics and properties of asphalt," *Construction and Building Materials*, vol. 23, no. 10, pp. 3112–3117, 2009.
- [40] Z. N. Tian, Z. Q. Zhang, K. W. Zhang, S. L. Huang, and Y. F. Luo, "Preparation and properties of high viscosity and elasticity asphalt by styrene-butadiene-styrene/polyurethane prepolymer composite modification," *Journal of Applied Polymer Science*, vol. 137, 2020.
- [41] M. Lin, P. Li, T. Nian, Y. Mao, and X. Kang, "Performance evaluation and modification mechanism analysis of the synthesized rubber asphalt," *Advances in Civil Engineering Materials*, vol. 8, pp. 497–510, 2019.
- [42] X. F. Wang, "Study of rubber asphalt modification mechanism," *Advanced Materials Research*, vol. 194-196, pp. 844–847, 2011.
- [43] X. Yang, A. Shen, Y. Guo, and Z. Lyu, "Effect of process parameters on the high temperature performance and reaction mechanism of CRMA," *Petroleum Science and Technology*, vol. 36, no. 19, pp. 1537–1543, 2018.
- [44] S. Sobhi, S. Hesami, M. Poursoltani, P. Ayar, and R. S. Mullapudi, "Coupled effects of gilsonite and Sasobit on binder properties: rheological and chemical analysis," *Journal of Materials in Civil Engineering*, vol. 34, 2022.