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Rheological Properties of High-Viscosity Modified Asphalt Containing Warm-Mix Additives

Bei Chen[1]; Xin Yu[2]; Fuqiang Dong[3]; Wenxiu Wu[4]; Yuanzhe Zu[5]; and Shisong Ren[6]

Abstract: High-viscosity modified asphalt (HVMA) is the most commonly applied method in drainage asphalt pavements. However, some disadvantages of hot-mix HVMA, including high energy consumption and unavoidable environmental pollution, should be improved. Therefore, warm-mix additive (WMA) was introduced. In this paper, the effects of WMA on the rheological and microstructural properties of HVMA were studied to select optimum WMA conditions. WMAs mainly include foam warm mix (1%, 3%, and 5%), Sasobit (1%, 3%, and 5%), Evotherm (0.4%, 0.8%, and 1.2%), and the newly introduced warm additive glow brand (GLWBR) (0.4%, 0.8%, and 1.2%). Dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests were performed on HVMA after rheological processes. Also, microstructural properties were examined by Fourier transform infrared spectroscopy and scanning electron microscopy methods. Based on the obtained results, all WMAs reduced the viscosity (135°C) of HVMA and achieved warm mixing effects. However, absolute viscosity (60°C) was enhanced by Sasobit and GLWBR. In addition, GLWBR improved high-temperature rheological performance and had no significant effect on the low-temperature and aging performance of HVMA. These findings were further verified by morphological observations.
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Author keywords: High-viscosity modified asphalt (HVMA); Physical properties; Rheological properties; Aging performance; Morphological observation.

Introduction

Owing to its good permeability, noise reduction, anti-sliding and other characteristics, high-viscosity modified asphalt (HVMA) is extensively applied in urban road construction (Pasetto et al. 2017; Barrett and Shaw 2007; Takahashi 2013). Hot-mix HVMA, which is commonly used in production, construction, and maintenance processes, results in huge energy consumption and carbon emissions (Chen et al. 2021a). By contrast, the application of warm-mix additive (WMA) can reduce energy consumption and pollution gas emissions. At present, various types of WMA exist for asphalt, which could be classified into three categories: wax WMA (Sasobit), surface-active WMA (Evotherm), and foam warm mix (Xiao et al. 2015; Dinis-Almeida et al. 2016; Kataware and Singh 2018). These WMAs have been widely applied in asphalt pavement construction due to their advantages of realizing asphalt production, mixing, and compaction under low-temperature conditions. However, currently applied WMAs cannot follow rapid development in science and technology; therefore, new WMAs are still under continuous investigation and development. In fact, a new WMA has already been applied in asphalt pavement engineering (Xiao et al. 2012; Morea et al. 2012; Chen et al. 2021b; Behl and Chandra 2017; Antunes et al. 2017; Yu et al. 2017; Hurley et al. 2006). Hence, this field has far more potential for development.

Many studies have been performed on this topic, and a comprehensive analysis of previous works would reveal that, compared with hot-mix asphalt, the addition of WMAs affects the rheological and microstructural properties of asphalt (Rodríguez-Alloza et al. 2013; Zhao et al. 2012; Banerjee et al. 2012; Antunes et al. 2015; Yan et al. 2013). Mansoori and Modarres (2020) explored the effects of Sasobit and two chemical WMAs (Zycothm and PAWMA) on the warm mixing, rheological properties and microstructures of asphalt binders. The obtained results showed that three WMAs reduced the construction temperature of asphalt. Based on previous studies, Zheng et al. (2019) investigated the effects of relative humidity, EC-120, and Sasobit on the physical, rheological, and morphological properties of HVMAs. Their results showed that WMAs decreased viscosity (135°C) and significantly improved absolute viscosity (60°C). They also found that, even under different aging conditions, EC-120 could improve the rheological properties of the system regardless of the temperature. Wang et al. (2020) studied the effects of four asphalt binders on asphalt aging properties. Under the two aging conditions of rolling thin film oven test (RTFOT) and pressure aging vessel, Fourier transform infrared (FTIR) spectroscopy was applied to analyze the variations of carbonyl in asphalt and its results were used to predict the aging degree of asphalt. Xiao and Amirkhanian (2010) evaluated the performance (mix design method, elastic modulus, anti-stripping agents (ASAs) rutting, and water sensitivity) of warm mix asphalt and found the results of laboratory experiment were similar to that of a Fifield experiment, and

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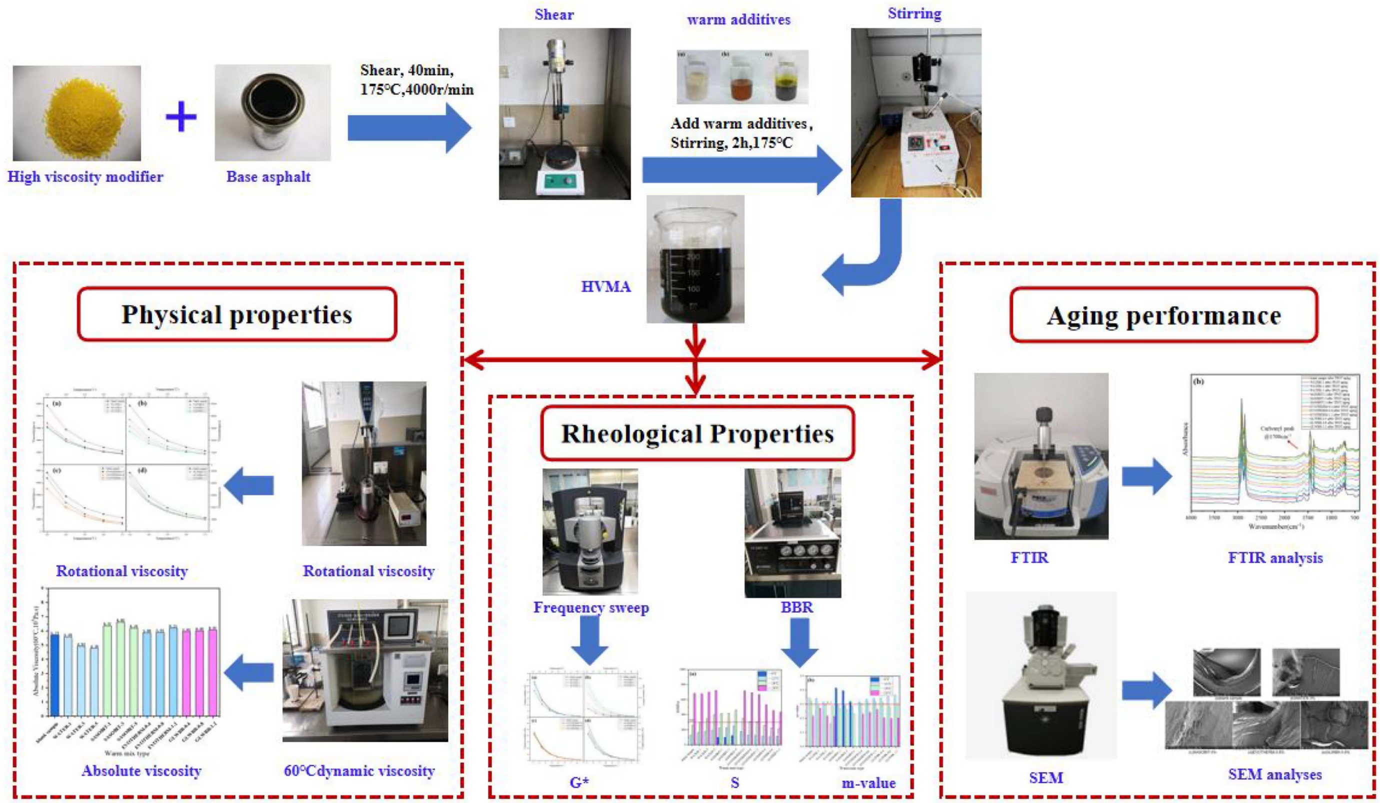

Fig. 1. Schematic overview of experimental techniques applied in this study.

adding foaming water did not decrease the water sensitivity of asphalt mixture.

Previous studies on WMAs mainly focused on the effects of WMAs on warm mixing as well as the physical and rheological properties of asphalt (Guo et al. 2017; Ragni et al. 2019; Sobhi et al. 2022). At present, further studies are still required to understand the influence of WMA on HVMA from two aspects: (1) the effects of different types of WMAs on HVMA, i.e., widely applied WMAs such as foam warm mix, Sasobit, and Evotherm, and the newly introduced WMA [glow brand (GLWBR)]; and (2) the effect of WMA on the rheological and microstructural properties of HVMA (Sol-Sánchez et al. 2018; Behnood 2020). Hence, investigation of the effects of foam warm mix, Sasobit, Evotherm, and the GLWBR on the rheological and microstructural properties of HVMA is of great potential and significance.

As mentioned earlier, this paper aimed to explored the effects of foam warm mix, Sasobit, Evotherm, and GLWBR on the rheological and microstructural properties of HVMA. This research was performed based on the following procedure. First, WMA effects on the basic properties, viscosity, and 60°C absolute viscosity of HVMA were investigated. Second, the effects of WMAs on the high-temperature rutting resistance, low-temperature crack resistance, and performance grade (PG) of HVMA were evaluated based on dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests. Third, RTFOT was applied to investigate the effects of different WMAs on asphalt aging properties. Correlations between the variations of carbonyl index value and aging indexes were also studied. Finally, morphology observations were performed using SEM to characterize the morphological variations of WMAs in HVMAs. Fig. 1 schematically illustrates the experimental techniques applied in this study.

Material and Methods

Materials

Asphalt

As presented in Table 1, HVMA samples were SK-based asphalt produced by Korea Asphalt Plant, with a permeability of 60/80.

High-Viscosity Modifier

The high-viscosity modifier applied in this work was prepared in the laboratory. Fig. 2 shows an image of the high-viscosity modifier and Table 2 summarizes basic performance test results.

Warm-Mix Additives

WMAs mainly include wax WMA, surface-active WMA, and foam warm mix. Foam warm mix is a WMA where the foaming process only requires the addition of water (Dong et al. 2018). The WMAs applied in this research were Sasobit, Evotherm, and GLWBR. Fig. 3 shows images of these WMAs. Sasobit is a wax WMA, Evotherm is a surface-active WMA, and GLWBR is a new type of

Table 1. Properties of base asphalt

Parameter	Results	Standard in China (JTG E20-2011)
Penetration (0.1 mm)	68	T0604
Softening point (°C)	47.8	T0606
Ductility (15°C) (cm)	>100	T0605
Dynamic viscosity at 60°C (Pa · s)	167.5	T0620
Density (15°C) (g/cm^{-3})	1.047	T0603
Flash point (°C)	345	T0611

surface-active WMA that is classified as a chemical WMA and its warm mixing effect is expected to be similar to that of Evotherm. The difference between GLWBR and traditional WMAs is that its manufacturing cost is low and its performance is stable.

Proposed Preparation Method of Warm-Mix HVMA

Proposed Preparation Method for Foamed Warm-Mix HVMA

First, a FM300-DIGITAL shear machine was used to prepare the HVMA. At 175°C, 8% high-viscosity modifier was added to base asphalt and the shear machine was run at 4,000 rpm for 40 min. Specifically, HVMA was prepared by stirring for 2 h. Second, a FCF-1 reactor was used to prepare foam-mixed HVMA. During the experiments, the foaming water contents were 1%, 3%, and 5% of the quantity of HVMA (Dong et al. 2018). Foam HVMA was prepared using a reaction kettle as follows. HVMA and water were added to the reaction kettle simultaneously. The reaction kettle temperature was set at 175°C, the pressure was adjusted to 0.8 MPa, and the stirring time was set at 5 min. The stirring conditions in the reactor were controlled to ensure that water remained in the liquid state even at high temperatures and under high pressures. If liquid water was fully mixed with asphalt, it would be beneficial to the generation of uniform bubbles in the foamed asphalt.

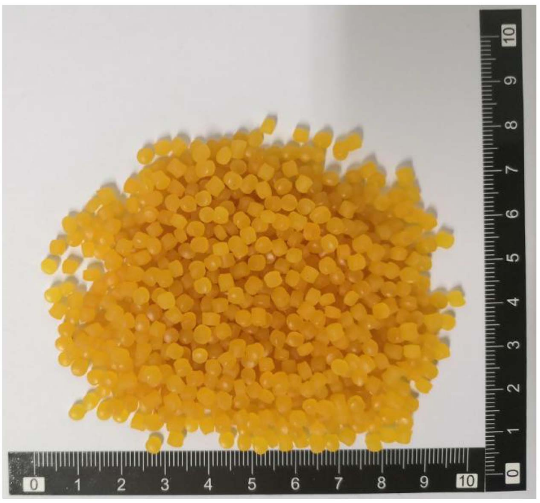

Fig. 2. Appearance of high-viscosity modifier.

Table 2. Properties of high-viscosity modifier

Test item	Test results	Standard results	Test method
Exterior	Yellow particles	Granular	Visual inspection
Melt index (g/10 min)	8	≥2.0	Melt
Individual particle quality (g)	0.12	≤0.5	Weighing
Dry mix dispersibility	No residue	No residue	Dry mix

Preparation of Warm-Mix HVMA with WMA

The HVMA was prepared according to the same method. At 175°C, three types of WMA were added to the HVMA and mixed with a stirrer for 1 h to prepare different types of warm-mix HVMA. Based on the recommended amount of WMA in the literature, the dosages of Sasobit and Evotherm were determined to be 1%, 3%, and 5% and 0.4%, 0.8%, and 1.2%, respectively. The GLWBR dosage was recommended by the manufacturer to be 0.4%, 0.8%, and 1.2% (Jamshidi et al. 2013; Podolsky et al. 2016; Ferrotti et al. 2017). For convenience, the four developed warm-mix HVMAs were called WATER, Sasobit, Evotherm, and GLWBR, respectively. HVMA without WMA treatment was applied as a blank sample.

Physical Properties Test

Basic Performance Test

According to the required specifications of ASTM and AASHTO modified asphalt, the basic properties of warm-mix HVMA, including penetration, softening point, and 5°C ductility, were explored [JTG E20-2011 (Ministry of Transport of the People's Republic of China 2011)]. The temperature sensitivity of asphalt could be determined by the penetration index (PI). Higher PI indexes indicated lower sensitivity. Asphalt has a gel structure at PI values greater than or equal to 2 and a sol-gel structure at PI indexes of less than 2. The PI index can be deduced according to the following equation (Jin et al. 2020):

$$PI = \frac{1952 - 500\log(P25) - 20Sp}{50\log(P25) - Sp - 120} \tag{1}$$

where Sp = softening point; and $P25$ = penetration at 25°C.

(a) (b) (c)

Fig. 3. Images of the tested WMAs: (a) Sasobit; (b) Evotherm; and (c) GLWBR.

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Rotational Viscosity and Absolute Viscosity Test at 60°C

According to ASTM D4402 specifications, warm-mix HVMA viscosity was measured by rotating viscosity equipment within a temperature range of 135°C–175°C. Also, experimental research helpful to explore WMA effect on HVMA viscosity. SYD-0620B asphalt absolute viscosity tester was used for the analysis of the 60°C absolute viscosity of the warm-mix HVMA (Zhang and Hu 2015).

Rheological Properties Test

Temperature Scanning Test

A temperature scanning test is more sensitive in the evaluation of the high-temperature performance of HVMA than conventional test methods such as softening point and ductility. Based on ASTM D 7175 (ASTM 2015), the rheological properties of HVMA were investigated by TA-AR1500 DSR. More specifically, experimental temperatures were 46°C, 52°C, 58°C, 64°C, 70°C, 76°C, and 82°C. The measured high-temperature rheological properties of HVMA included complex modulus G^* and phase angle δ.

BBR Test

To explore the effects of different WMAs on the low-temperature performance of HVMA, the warm-mixed HVMA was first subjected to the RTFOT (short-term aging) treatment, and then the low-temperature performance of the sample was tested by TE-BBR SD equipment produced by Cannon Instrument. The creep stiffness (S) and creep rate (m-value) of warm-mix HVMA were measured according to ASTM D6648 and AASHTO T313 standards (Jiang et al. 2017). Test temperatures were −6°C, −12°C, −18°C, and −24°C. The PG of the warm-mix HVMA was determined based on the high- and low-temperature rheological properties of warm-mix HVMAs.

Aging Performance Test

Aging Procedures

Based on ASTM D1754 and ASTM D6521 standards [ASTM D1754 (ASTM 2009); ASTM D6521 (ASTM 2008)], RTFOT was applied for the simulation of short-term thermal oxidation aging of HVMA. In addition, the aging sensitivity of warm-mix HVMA was defined by the variation range of the physical or rheological properties of material before and after aging (Zhang et al. 2018), which is given in detail in Table 3 (Wang et al. 2020).

FTIR Test

It is well known that the main reason asphalt ages in high-temperature environments is thermal oxidation. The number of carbonyl (C=0) functional groups of asphalt changes during thermal oxidation (Mouillet et al. 2008). Therefore, asphalt aging degree can be determined by evaluating the change in carbonyl levels in warm-mix HVMA before and after aging. During experiments, a carbonyl index (CI) was determined by the carbonyl number, which was defined by the following equation (Zhang et al. 2018; Wang et al. 2020; Hu et al. 2020):

$$CI = \frac{A_{C=O}}{\sum A} \tag{2}$$

where $A_{C=O}$ is the area of carbonyl function group (C=O) absorption peak at 1,700 cm^{-1}; and $\sum A$ is the sum of the absorption peak area calculated as $\sum A = A_{1,700\,cm-1} + A_{1,600\,cm-1} + A_{1,460\,cm-1} + A_{1,376\,cm-1} + A_{1,030\,cm-1} + A_{864\,cm-1} + A_{814\,cm-1} + A_{743\,cm-1} + A_{724\,cm-1}$. A greater change ($\Delta$CI) in CI before and after sample aging resulted in higher warm-mix HVMA aging degree.

In this study, warm-mix HVMA was placed on a FTIR test bench, compacted, and fixed with a metal layer. Asphalt samples were scanned 32 times in a wavenumber range of 400 to 4,000 cm^{-1}. Spectral analyses were carried out using a computer program developed in Matlab software.

Table 3. Calculation methods of aging indexes

Aging indexes	Calculation methods
Softening point increment (SPI)	$SPI = \lvert \text{Softening point}_{aged} - \text{Softening point}_{unaged} \rvert$
Viscosity aging index (VAI)	$VAI = \lvert (\text{Viscosity}_{aged} - \text{Viscosity}_{unaged}) \rvert \times 100/\text{Viscosity}_{unaged}$
Complex modulus aging index (CAI)	$CAI = G^*_{aged}/G^*_{unaged}$
Phase angle aging index (PAI)	$PAI = \delta_{aged}/\delta_{unaged}$

Morphology Observation

To examine and visualize the compatibility and distribution of WMA in HVMA, scanning electron microscopy (SEM) (FEI Scios 2 HiVac) was used to obtain microscopic images of the cross sections of HVMA at 200× magnification. Since the asphalt material is not conductive, it needs to be sprayed before testing. First, a sample with a small amount of HVMA was placed on a conductive adhesive and sprayed with gold. Then the samples were placed in a sample chamber. Finally, the microstructural characteristics of the samples were observed by SEM.

Results and Discussion

Physical Properties Analysis

Basic Properties Analysis

Fig. 4 shows the effect of WMAs on the basic performance of HVMA. As can be seen from Fig. 4(a), WATER penetration degree was significantly greater than that of the blank sample. When the foaming water content was increased, penetration gradually increased. Since the aim of bubble formation in the foaming process was to soften the HVMA, penetration was increased. The penetration of the other three WMAs, especially Sasobit, was lower than that of the blank sample. The order of the penetration degree of these three WMAs on the HVMA was Sasobit > GLWBR > Evotherm. Sasobit reduced the penetration of HVMA because the wax crystals of Sasobit were dispersed in the asphalt, forming a network of peak structures, which could make the HVMA harder (Qin et al. 2014). Evotherm and GLWBR had little effect on HVMA penetration because the surface-active WMA mainly acted under specific conditions between asphalt and aggregate; meanwhile, they had no obvious effects on asphalt performance (Cao and Ji 2011). As seen in Fig. 4(b), compared with the blank sample, Sasobit increased the HVMA softening point, and the remaining three WMAs had little effect (Sanchez-Alonso et al. 2011). According to Fig. 4(c), all four WMAs, especially Sasobit, were able to reduce the low-temperature cracking resistance of HVMA. At the same time, an increase in WMA content was not conducive to the low-temperature resistance of HVMA. As was observed in Fig. 4(d), compared with the blank sample, a dramatic increase was seen in the PI value of WATER, whereas that of Sasobit markedly decreased and those of Evotherm and GLWBR did not change significantly. Also, the WMA

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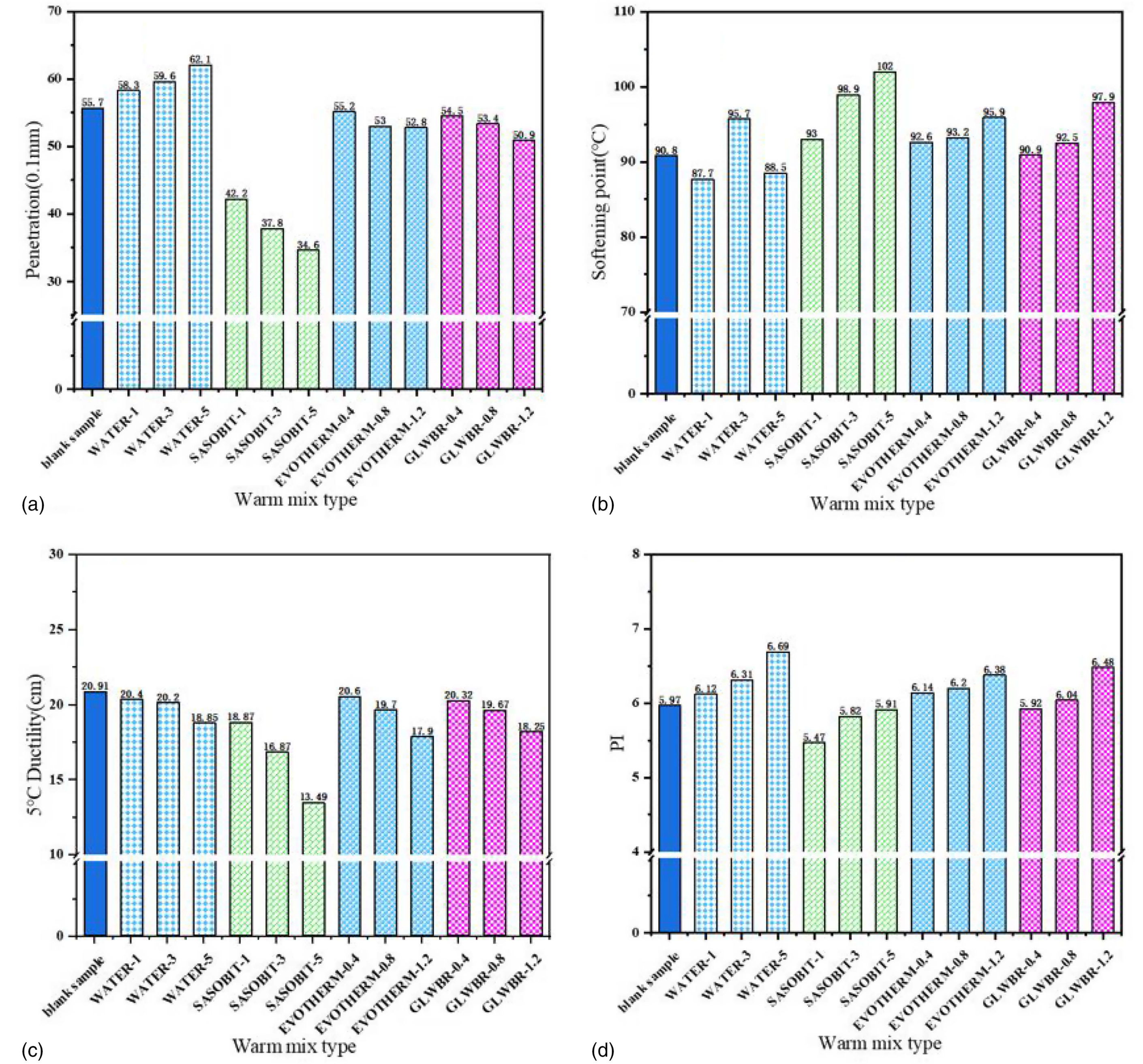

Fig. 4. Conventional properties of warm-mix HVMA: (a) penetration (0.1 mm); (b) softening point; (c) 5°C ductility; and (d) penetration index.

dosage affected the PI value of the warm-mix HVMA. An increase in the PI value of WATER increased the temperature sensitivity of the foam warm-mix HVMA due to the presence of residual water in the warm-mix HVMA. The PI value of Sasobit decreased, which indicated that Sasobit reduced the temperature sensitivity of the HVMA, perhaps due to the fact that the wax in Sasobit absorbed a fraction of heat (Yu et al. 2016). However, the PI values of Evotherm and GLWBR were not changed significantly, which may be due to the mechanism of surface active WMA.

Rotational Viscosity and Absolute Viscosity in 60°C Analysis
To investigate the viscosity reduction effect of WMA on HVMA, the viscosity changes in the warm-mix HVMA at different temperatures were evaluated based on rotational viscosity and absolute viscosity at 60°C.

Variations in the viscosity of warm-mix HVMA with temperature is shown in Fig. 5. As expected, test results showed that four kinds of WMAs could significantly decrease HVMA viscosity. Moreover, the increase in WMA content significantly reduced HVMA viscosity. Comparing the four WMAs, WATER and Sasobit had the most obvious viscosity reduction effects. Among them, foam warm mix presented the highest viscosity reduction, 37.6%, for the HVMA. This was because the water phase state in the foaming process was changed from liquid to gas, which led to a sharp increase in the asphalt volume with a significant decrease in viscosity. Sasobit of the HVMA viscosity dropped to 44%, which was due to the melting of organic wax in Sasobit at high temperature, which improves the fluidity of HVMA (Liu et al. 2011). The viscosity reduction effects of Evotherm and GLWBR on HVMA were not obvious because they were surface-active WMAs,

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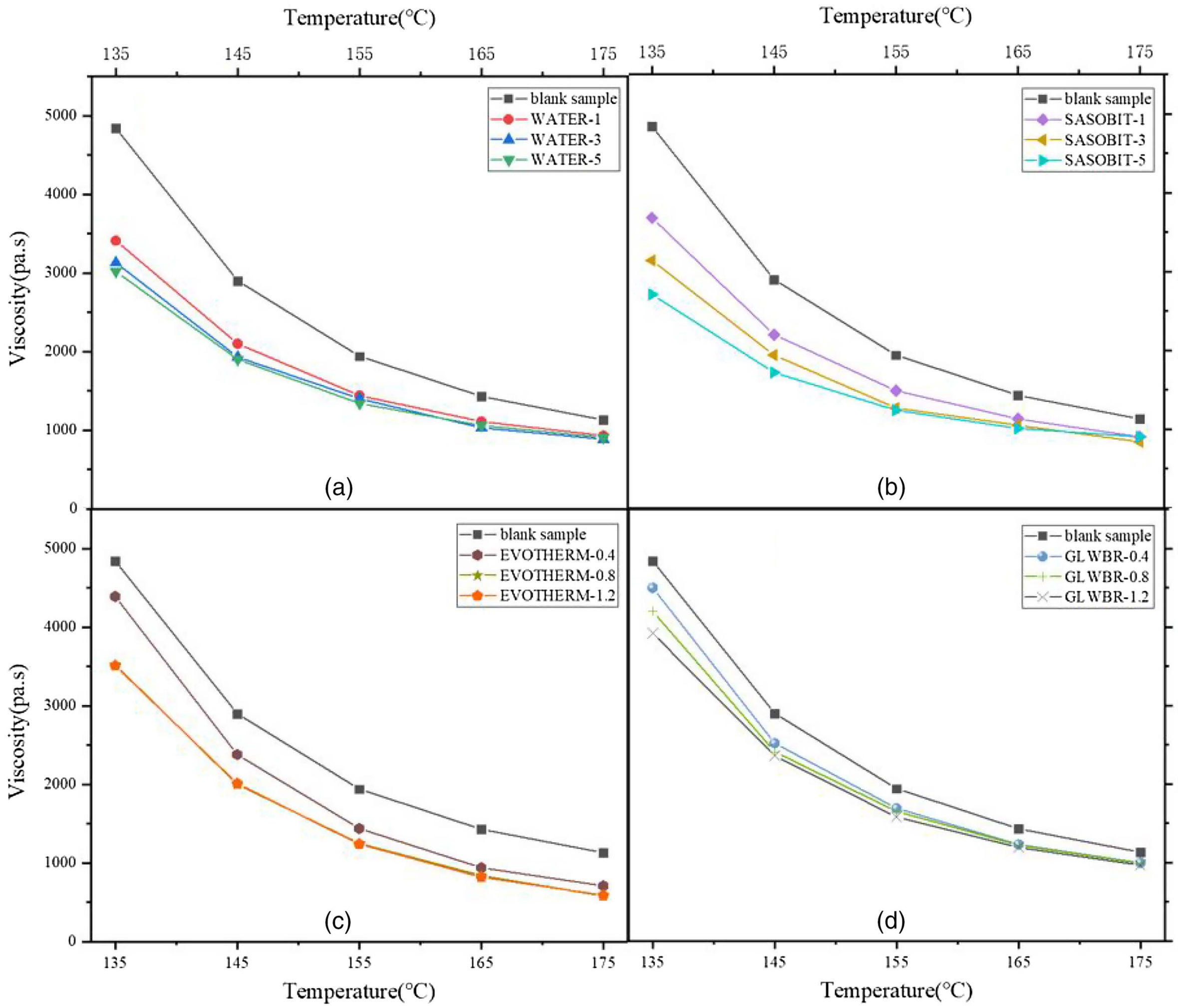

Fig. 5. Effect of warm-mix HVMA on viscosity: (a) water; (b) Sasobit; (c) Evotherm; and (d) GLWBR.

greatly influencing the contact relationship between asphalt and aggregate and improving the adhesion ability of asphalt to aggregate. However, they had little effect on asphalt viscosity (Wan 2020).

Absolute viscosity at 60°C is an important HVMA index that reflects the friction among asphalt molecules. The absolute viscosity at 60°C directly affected the deformation resistance and rutting resistance of the asphalt mixture. The results of the absolute viscosity tests for warm-mix HVMA at 60°C are shown in Fig. 6. Compared with the blank sample, the absolute viscosity of the foam warm-mix HVMA was significantly decreased. Increasing the water content more notably decreased the absolute viscosity. The reason for this was that the water added to the foam warm mix acted as a lubricant among the asphalt molecules, and when the molecular weight gain of the water was increased, friction among the asphalt molecules tended to decrease. The addition of Sasobit, Evotherm, and GLWBR increased the absolute viscosity of the warm-mix HVMA, regardless of their dosage. The addition of Sasobit first increased and then decreased the absolute viscosity of the HVMA because it is a wax WMA and its melting temperature is 90°C to 110°C (Silva et al. 2010). At 60°C, Sasobit acted as a physical stabilizer in HVMA. When the Sasobit content exceeded 3%, excessive wax crystals had a negative impact on the absolute viscosity of the asphalt (Kim et al. 2011). The addition of Evotherm and GLWBR increased the absolute viscosity of the HVMA, but this

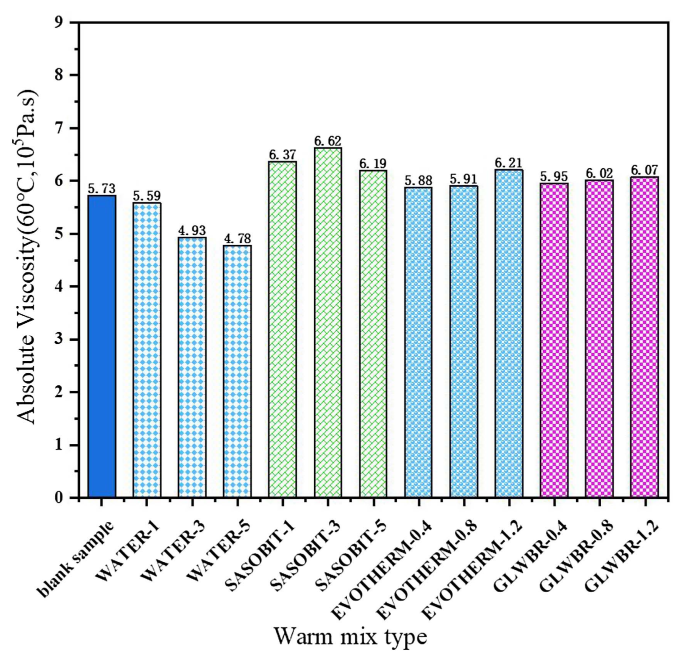

Fig. 6. Effect of warm-mix HVMA on absolute viscosity (60°C).

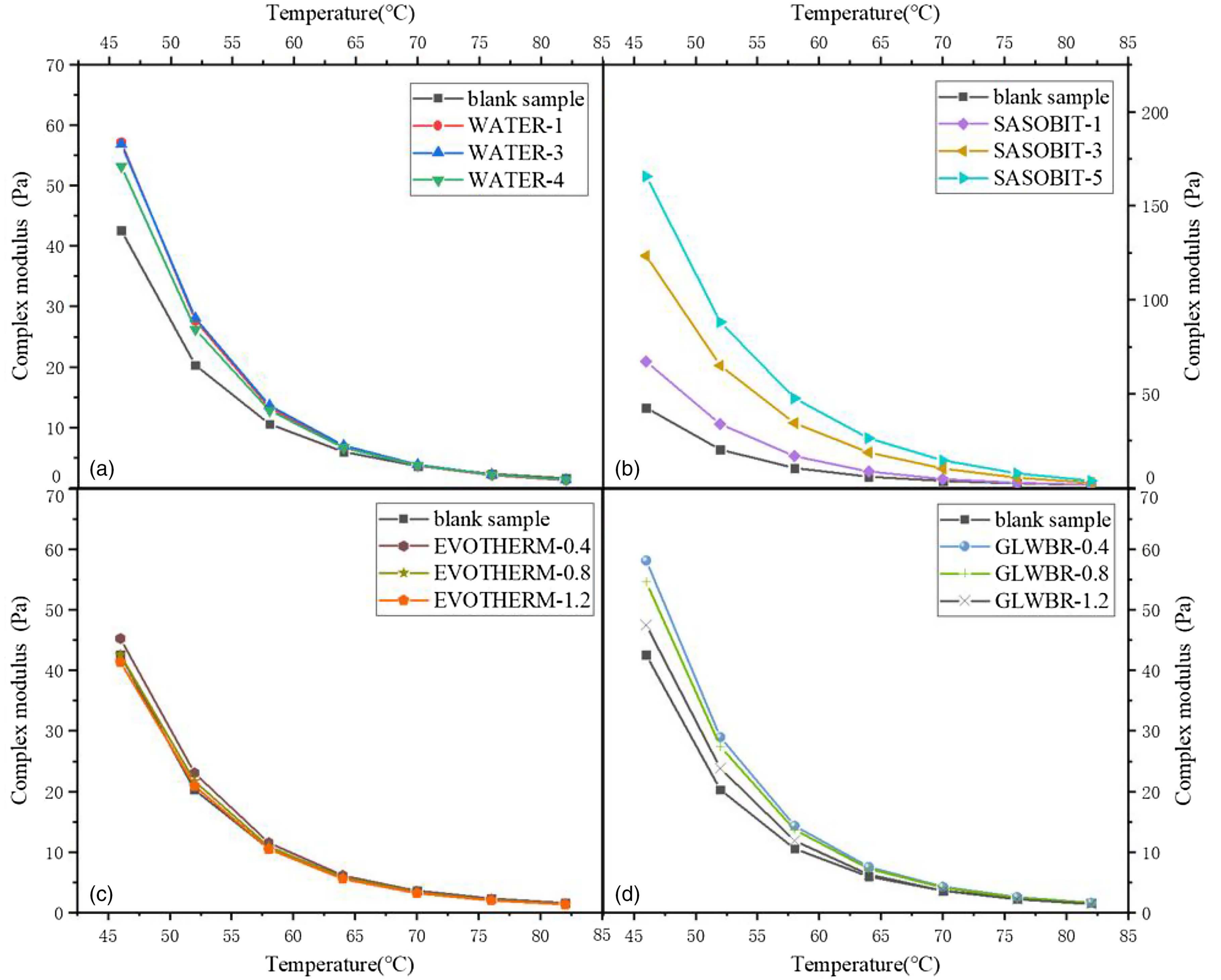

Fig. 7. Variation of complex modulus (G^*) with temperature (10 rad/s, 42°C–82°C): (a) water; (b) Sasobit; (c) Evotherm; and (d) GLWBR.

increase was not very obvious. This was because Evotherm and GLWBR are surface-active WMAs. Under high-temperature conditions, a large number of surfactant micelles in the WMA make contact with the hot asphalt, and the water molecules outside the micelles evaporate and change their conditions accordingly, so that the lipophilic group makes contact with the asphalt, thereby improving the absolute viscosity of the HVMA. However, the dosage of WMA was so small and the improvement effect was not obvious.

Rheological Properties

High-Temperature Performance

Fig. 7 shows the rheological properties of warm-mix HVMA at different temperatures. In Fig. 7(a), compared with the blank sample, the complex shear modulus (G^*) of the foam warm-mix HVMA has increased, mainly due to the migration or evaporation of water during the foaming process, which leads to the separation of light and heavy components of the asphalt and the volatilization of light components, so that the asphalt is aged and its viscoelasticity is improved. As shown in Fig. 7(b), the addition of Sasobit significantly improved the G^* value of the HVMA. This was mainly because the wax crystals in the Sasobit formed a lattice structure below the melting point. Since Sasobit was dispersed in the HVMA, it improved the elastic properties of the HVMA (Zheng et al. 2019). Figs. 7(c and d) shows the test results of the addition of Evotherm and GLWBR as surface-active WMAs to HVMA. Both the aforementioned WMAs had little effect on the G^* of the HVMA, and mainly because of the warm-mix mechanism of the surface-active WMA, in this process a large number of surface micelles make contact with the hot asphalt, and the water molecules in the periphery of the micelles evaporate and dissipate rapidly, so a warm mixing effect is achieved and the asphalt's viscoelasticity is not affected.

Variations in the phase angle δ of the warm-mix HVMA are shown in Fig. 8. Compared with the blank sample, WATER, Evotherm, and GLWBR increased the δ of the HVMA, indicating that these three WMAs improved the HVMA viscosity. Evotherm and GLWBR improved the HVMA viscosity because of the generation of surface micelles. The addition of less than 3% Sasobit to the HVMA improved δ, indicating that a small amount of Sasobit increases HVMA viscosity. This was because the Sasobit dispersed in the asphalt crystalline structure, providing physical stability. Sasobit amounts exceeding 3% reduced the δ of the HVMA,

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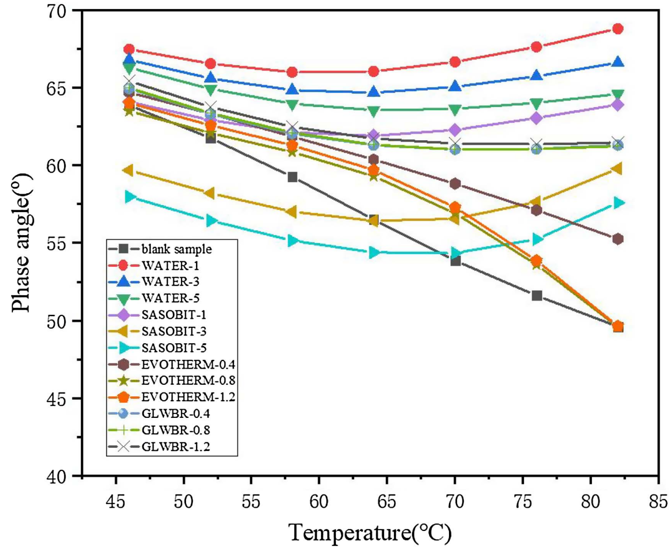


Fig. 8. Variations of phase angle (δ) with temperature (10 rad/s, 42°C–120°C).

indicating that excessive unreacted Sasobit could have an adverse effect on viscosity. This conclusion was consistent with the result obtained when the absolute viscosity was at 60°C (Zheng et al. 2019).

BBR Analysis

Low-temperature cracks in asphalt pavement are a major problem (Sun et al. 2018). In this study, the low-temperature performance index of warm-mix HVMA was investigated by BBR tests: creep stiffness (S) and creep rate (m-value) were evaluated to explore the low-temperature characteristics of warm-mix HVMA.

The variations of creep stiffness (S) and creep rate (m-value) of warm-mix HVMA at different temperatures (−6°C, −12°C, −18°C, and −24°C) are shown in Fig. 9. Compared with the blank sample, the S value of Sasobit was increased and its m-value decreased, whereas those of the other three WMAs did not show obvious changes. An increase in the WATER and Sasobit contents was not conducive to low-temperature crack resistance of HVMA; in contrast, Evotherm and GLWBR showed opposite results. This showed that Sasobit was not conducive to the low-temperature performance of HVMA, and the other three WMAs had no obvious effects. This was mainly caused by the different warm mixing mechanisms of WMAs (Qin et al. 2014; Yu et al. 2017). Therefore, a comprehensive analysis had to be performed on the effects of four WMAs at high and low temperatures. Sasobit greatly influenced the high- and low-temperature performance of HVMA, while the other three WMAs had no obvious effect on the high- and low-temperature performance of HVMA.

PG Analysis

A PG test is commonly used to evaluate the performance of HVMA. PG can not only reveal the effects of high and low temperatures and different construction stages on asphalt but also characterize asphalt diseases, i.e., high-temperature rut resistance and low-temperature cracking (Li 2018; Hajj et al. 2012). Based on DSR and BBR test results, this study followed the requirements of the modified asphalt PG classification method in the US strategy highway research program (SHRP) specification ($G^*/\sin\delta \geq 1.0$ kPa for unaged asphalt, $G^*/\sin\delta \geq 2.2$ kPa for aged asphalt, $S \leq 300$ MPa, and m-value ≥ 0.3) (Zhang et al. 2019). The determination

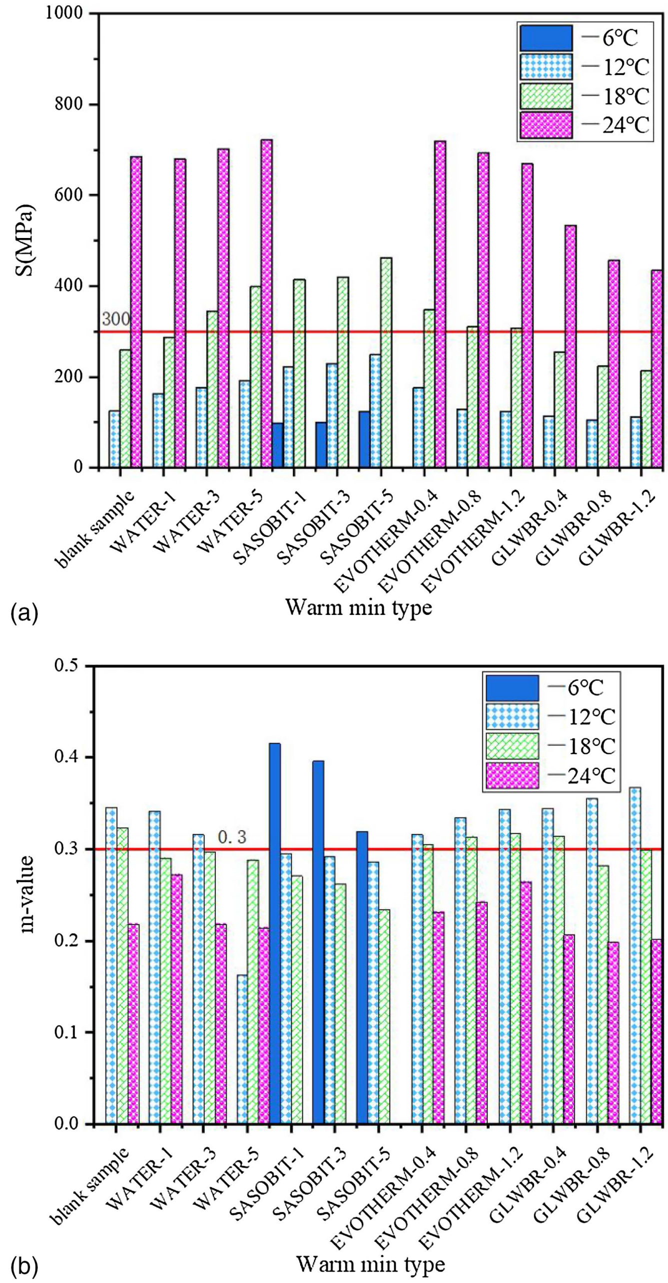


Fig. 9. Variations of creep stiffness (S) and creep rate (m-value) with HWMA: (a) S; and (b) m-value.

of continuous PG results from warm-mix HVMA, as shown in Table 4. Compared with the blank sample, the warm-mix HVMA in high- and low-temperature PG tests, respectively, showed lower and higher continuous gradations, indicating that WMA reduced rutting to a certain extent and retained low-temperature resistance of asphalt, of which the Sasobit performance was the most prominent. The three WMAs of WATER, Evotherm, and GLWBR had little effect on the PG grade of the HVMA.

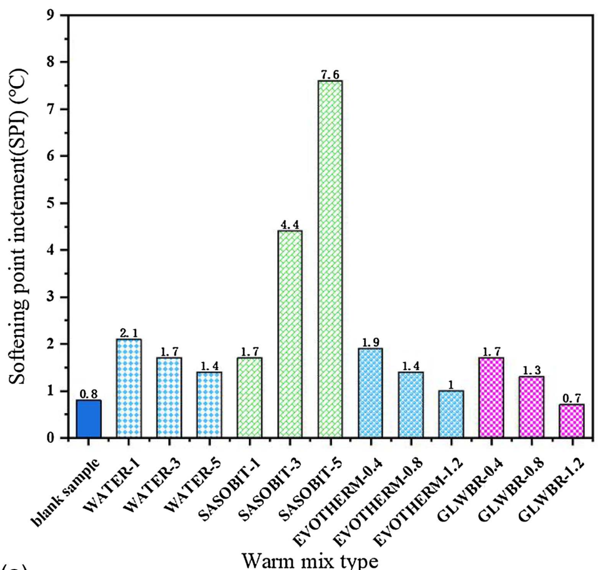
Antiaging Property Analysis

Evaluation of Physical Aging Indexes

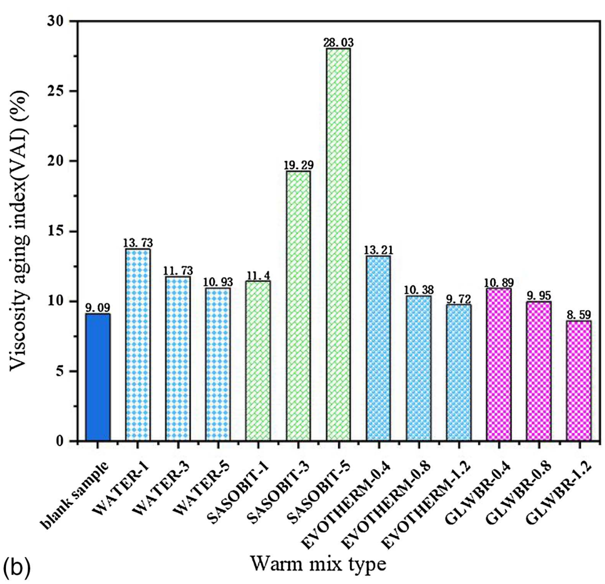
Changes in the physical aging indexes [softening point increment (SPI) and viscosity aging index (VAI)] of HVMA after RTFOT

Table 4. PG grading of warm-mix HVMA

Sample	Critical temperature ($G^*/\sin\delta \geq 1.0$ kPa for original HVMA, °C)	Critical temperature ($G^*/\sin\delta \geq 2.2$ kPa for RTFOT residue, °C)	High continuous grading temperature	Critical temperature ($S \leq 300$ MPa)	Critical temperature (m-value ≥ 0.3)	Low continuous grading temperature	Continuous grade
Blank sample	86.4	86.6	86.4	−26.9	−28.7	−26.9	86.4–26.9
WATER-1	83.0	83.7	83.0	−26.2	−25.5	−25.5	83.0–25.2
WATER-3	83.3	85.1	83.3	−25.5	−27.5	−25.5	83.3–25.5
WATER-5	83.6	85.2	83.6	−24.7	−25.0	−24.7	83.6–24.7
SASOBIT-1	84.1	85.0	84.1	−23.9	−23.2	−23.2	84.1–23.2
SASOBIT-3	84.4	84.8	84.4	−24.0	−23.5	−23.5	84.4–23.5
SASOBIT-5	84.5	85.3	84.5	−22.8	−22.1	−22.1	84.5–22.1
EVOTHERM-0.4	85.2	84.7	84.7	−25.0	−25.8	−25.0	84.7–25.0
EVOTHERM-0.8	86.1	85.0	85.0	−25.6	−27.0	−25.6	85.0–25.6
EVOTHERM-1.2	86.0	84.0	84.0	−26.3	−27.9	−26.3	84.0–26.3
GLWBR-0.4	84.7	85.1	84.7	−28.0	−27.0	−27.0	84.7–27.0
GLWBR-0.8	84.6	85.9	84.6	−29.3	−26.4	−26.4	84.6–26.4
GLWBR-1.2	84.2	86.9	84.2	−29.3	−27.3	−27.3	84.2–27.3



(a)



(b)

Fig. 10. SPI and VAI of different warm-mix HVMAs after RTFOT: (a) SPI; and (b) VAI.

aging are shown in Fig. 10. After RTFOT aging, the effect of WMAs on the aging of HVMA was different. The order of the influence degree of WMAs on HVMA was Sasobit > WATER > GLWBR > EVOTHERM. In particular, Sasobit had the greatest influence on HVMA aging. It is well known that there are two main processes in the thermal oxidative aging of asphalt: the volatilization of light components under thermal oxidation and the transformation of light components into heavy components under the influence of thermal oxidation (Wu et al. 2007). The influence of WMA on HVMA aging degree was mainly caused by the influence of the chemical composition of WMA on HVMA. Sasobit increased the heat absorption rate of HVMA due to the presence of wax crystals, and light components in asphalt were more likely to volatilize, exerting a significant effect on HVMA aging (Zheng et al. 2019).WATER affected HVMA aging due to the existence of residual water after foaming, the accelerated disturbance of warm-mix HVMA, and the accelerated volatilization of light components in asphalt, but this effect was not obvious (Dong et al. 2018). In the thermal oxidation processes of GLWBR and EVOTHERM, water molecules outside the surfactant micelles were absorbed and evaporated, and the internal lipophilic group made contact with asphalt. In this way, along with the influence of thermal oxidation, the light components of asphalt were transformed into recombination components, and HVMA aging was intensified. However, due to the low amounts of WMAs, their influence on HVMA aging was not very obvious, as was seen in Fig. 10 (Wan 2020).

Evaluation of Rheological Aging Indices

Variations in the complex modulus aging index (CAI) and phase angle aging index (PAI) of warm-mix HVMA after RTFOT aging are shown in Fig. 11. After RTFOT aging, the warm-mix HVMA showed a higher CAI and a lower PAI in the temperature range of 46°C–82°C. This result indicated that WMA had affected the short-term thermal-oxidative aging performance of the HVMA. Considering the variations of CAI and PAI, 1.2% GLWBR and 1.2% Evotherm had the weakest effects on the short-term thermal aging resistance of the HVMA, followed by 0.8% GLWBR and 5% WATER. The WMA effect on HVMA aging was described in the section "Evaluation of Physical Aging Indexes." Comprehensive analysis revealed that GLWBR and Evotherm are two kinds of surface-active WMAs on HVMA aging degree is not obvious. Taking into consideration the viscosity reduction effect of a warm mix and the construction cost of WMAs, WATER was superior to

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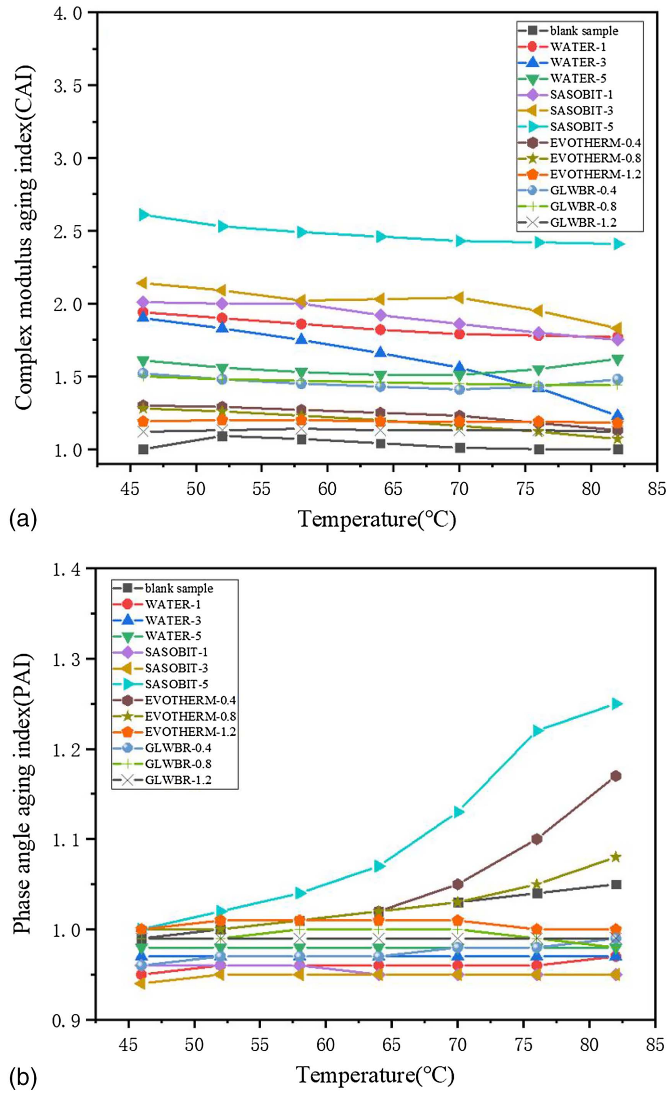

Fig. 11. CAI and PAI of different warm-mix HVMAs after RTFOT: (a) CAI; and (b) PAI.

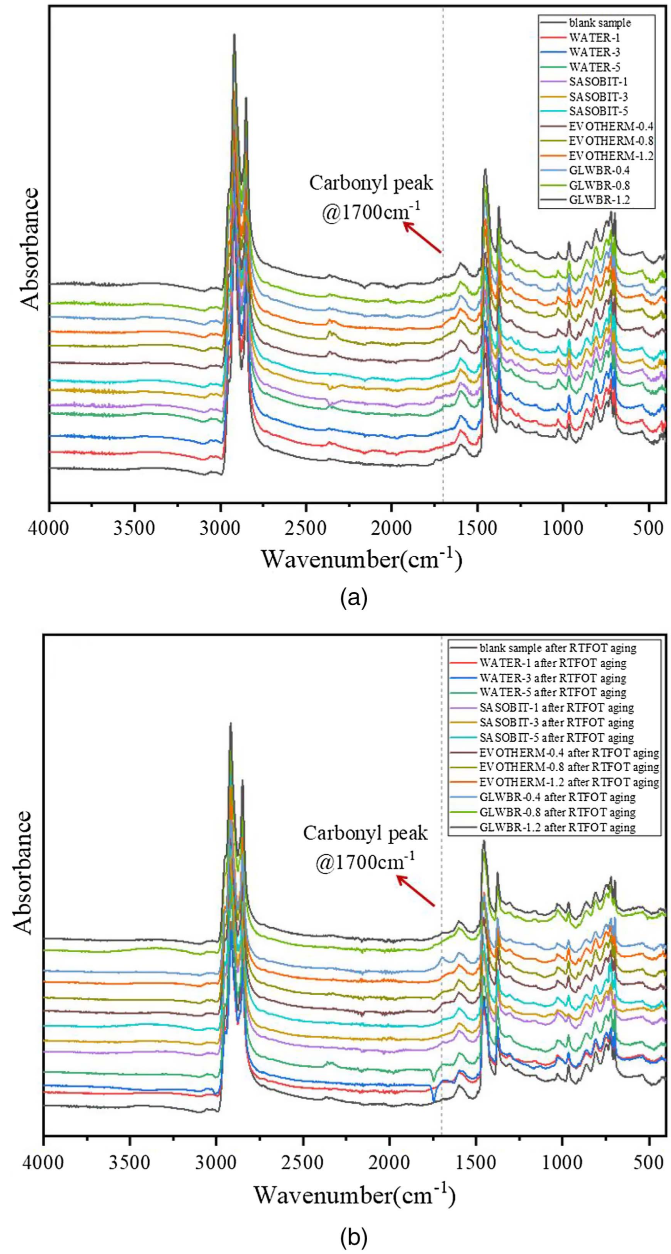

Fig. 12. FTIR spectra of binders before and after aging: (a) unaged; and (b) aging.

surface-active WMAs in reducing HVMA viscosity and construction cost. Therefore, WATER was recommended for reducing HVMA viscosity.

FTIR Analysis

Based on the comprehensive analysis of physical and rheological aging indexes, FTIR analyses of HVMA before and after aging were carried out and blank samples were considered as a comparison group. Fig. 12 shows warm-mix HVMA spectra before and after RTFOT aging. The corresponding CI is summarized in Table 5. As shown in Fig. 12, carbonyl functional groups appeared in an absorption band at around 1,700 cm^{-1}. After RTFOT aging, the peak area of the carbonyl group was increased. To quantitatively explore the aging degree of warm-mix HVMA, the difference in CI before and after sample aging was considered. According to Table 5, the CI value of the warm-mix HVMA after RTFOT aging was significantly increased, which further proved that WMA affected the short-term thermo-oxidative aging degree of HVMA. Compared with the blank sample, after RTFOT aging, the ΔCI values of the Sasobit warm-mix HVMA were 0.0071, 0.0102, and 0.0118, respectively, which were significantly greater than those of blank sample. This showed that Sasobit had the greatest effect on HVMA aging, which was consistent with the results of physical and rheological aging indexes. Similarly, the ΔCI values of WATER, GLWBR, and Evotherm were increased, but the changes were not obvious (Zhang et al. 2018).

Correlation Analysis

It is commonly accepted that a change in carbonyl content can characterize the asphalt oxidation degree (Morian et al. 2015). Therefore, the ΔCI index could be used to characterize the asphalt aging index. In this study, correlations among the ΔCI index after RTFOT aging and physical and rheological aging indexes (SPI, VAI, CAI at 55°C, PAI at 55°C) were analyzed by gray relational analysis (Zhao et al. 2015). The analysis results are shown in Fig. 13 and Table 6. It is seen from Fig. 13 that asphalt aging indexes (SPI, VAI, CAI at 55°C) were closely related to ΔCI with R^2 values of 0.75, 0.78, and 0.88, respectively. However, the results of this study showed a weak correlation between the asphalt aging index (PAI at 55°C) and ΔCI.

Table 5. CI of binders before and after aging

Sample	Index	Unaged	RTFOT aging
Blank sample	CI	0.0509	0.0521
	ΔCI	—	0.0012
WATER-1	CI	0.0523	0.0592
	ΔCI	—	0.0069
WATER-3	CI	0.0462	0.0521
	ΔCI	—	0.0059
WATER-5	CI	0.0491	0.0527
	ΔCI	—	0.0036
SASOBIT-1	CI	0.0468	0.0539
	ΔCI	—	0.0071
SASOBIT-3	CI	0.0541	0.0643
	ΔCI	—	0.0102
SASOBIT-5	CI	0.0463	0.0581
	ΔCI	—	0.0118
EVOTHERM-0.4	CI	0.0487	0.0534
	ΔCI	—	0.0047
EVOTHERM-0.8	CI	0.0533	0.0561
	ΔCI	—	0.0028
EVOTHERM-1.2	CI	0.0494	0.0510
	ΔCI	—	0.0016
GLWBR-0.4	CI	0.0506	0.0545
	ΔCI	—	0.0040
GLWBR-0.8	CI	0.0486	0.0506
	ΔCI	—	0.0020
GLWBR-1.2	CI	0.0526	0.0536
	ΔCI	—	0.0011

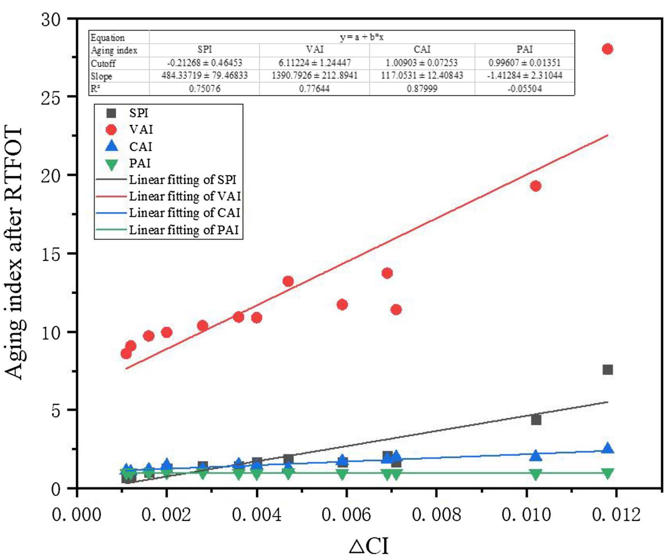

Fig. 13. Correlation analysis of ΔCI with overall results of physical and rheological tests.

Therefore, it was concluded that, despite the different correlations between the ΔCI values of different warm-mix HVMAs and physical and rheological aging indexes, the ΔCI also had very close correlations with aging indexes (SPI, VAI, CAI). Therefore, the aging degree of warm-mix HVMA could be predicted by the aging indexes (SPI, VAI, CAI).

Table 6. Data sets for correlation analysis

Sample name	ΔCI	SPI	VAI	CAI	PAI
Blank sample	0.0012	0.8	9.09	1.01	1.03
WATER-1	0.0069	2.1	13.73	1.79	0.96
WATER-3	0.0059	1.7	11.73	1.56	0.97
WATER-5	0.0036	1.4	10.93	1.51	0.98
SASOBIT-1	0.0071	1.7	11.40	1.86	0.95
SASOBIT-3	0.0102	4.4	19.29	2.04	0.95
SASOBIT-5	0.0118	7.6	28.03	2.43	1.13
EVOTHERM-0.4	0.0047	1.9	13.21	1.23	1.05
EVOTHERM-0.8	0.0028	1.4	10.38	1.16	1.03
EVOTHERM-1.2	0.0016	1	9.72	1.19	1.01
GLWBR-0.4	0.0040	1.7	10.89	1.41	0.98
GLWBR-0.8	0.0020	1.3	9.95	1.45	1.00
GLWBR-1.2	0.0011	0.7	8.59	1.13	0.99

SEM Analyses

SEM images of HVMA at 200× magnification are presented in Figs. 14 and 15. Fig. 14 shows that the surface morphology of the investigated samples were compacted with a homogeneous integral structure.

To reveal the warm mixing mechanism of WMAs in asphalt, the microscopic morphologies of the samples were observed at 200× magnification. Fig. 14(a) shows that the asphalt section had a relatively flat and homogeneous structure. The micropore in Fig. 14(b) was caused by residual water in the foam warm mix process, resulting in the appearance of micropores in the material. With the addition of Sasobit, compared to Fig. 14(a), an obvious morphological change was observed in Fig. 14(c) where wax-based Sasobit particles were uniformly dispersed and embedded in the binder with clear boundaries, indicating that Sasobit separately crystallized in the binder. As shown in Figs. 14(d and e), by the addition of Evotherm and GLWBR, the asphalt surface became rough. However, the Evotherm and GLWBR used in this study could not be observed in these images. Since the two types of WMA were oily liquids, the WMAs had to be dispersed in asphalt in the form of physical blending. On the other hand, since asphalt is nonconductive, it needed to be treated with gold spraying before testing.

Fig. 15 shows SEM images of HVMA after RTFOT aging where the asphalt surface became rough. In addition to Sasobit, by the aging of RTFOT, the damage marks of the HVMA under external forces were deepened in the remaining three WMAs. This was mainly because the WMAs could strengthen the viscoelasticity of the HVMA, making the HVMA difficult to deform at high temperatures. After RTFOT aging, it was observed [Fig. 15(c)] that the number of dispersed wax particles increased in the asphalt. In addition, wax crystal particles partially clustered and the boundaries between the wax crystal particles and HVMA remained clear. This was mainly attributed to the fact that wax-based Sasobit particles had recrystallized and agglomerated in the binder during the RTFOT aging process, which formed an improved elastic network by the interconnection of Sasobit crystal particles. This morphological change may provide a reasonable explanation for the preceding physical and rheological performance of asphalt binder after short-term aging.

Conclusions

The aim of this research was to investigate the effects of WMAs on the rheological and morphological properties of HVMA. The optimum WMA was first determined based on physical properties to control WMA and HVMA with WMA (foam warm mix and

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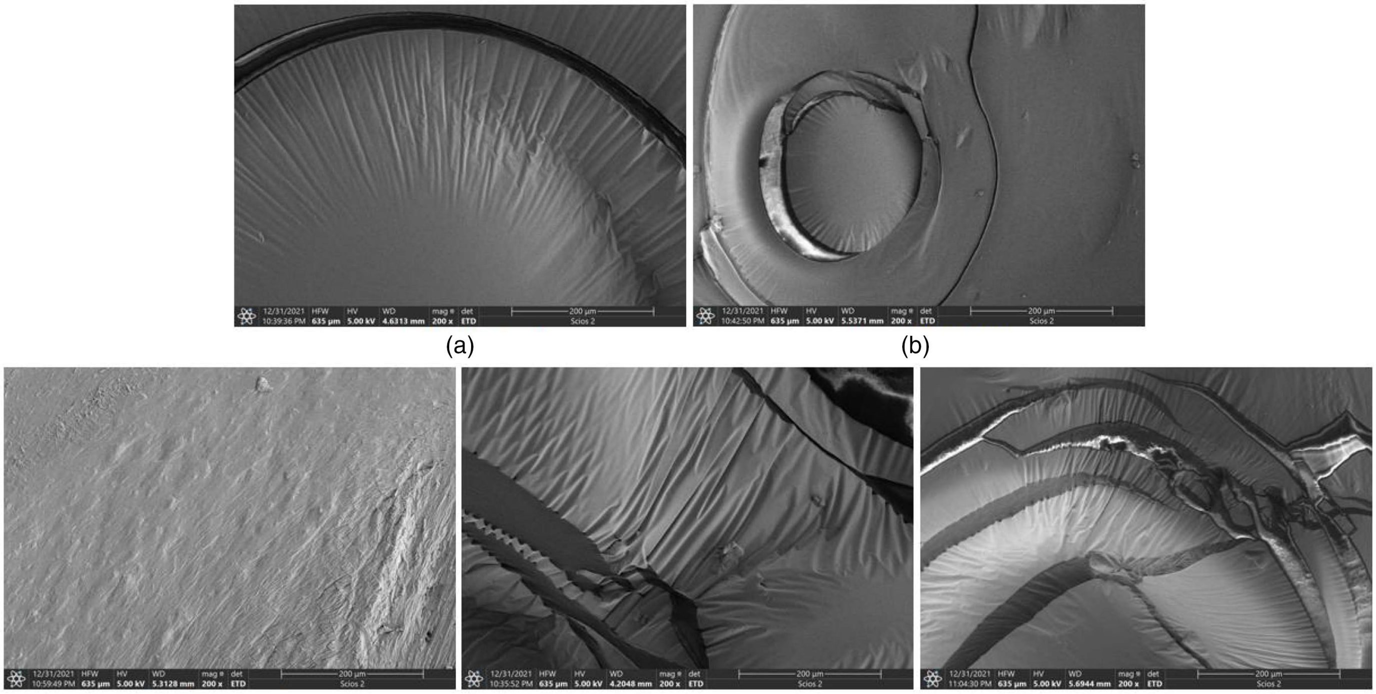

Fig. 14. Morphology of HVMA under SEM: (a) blank sample; (b) WATER-3%; (c) SASOBIT-3%; (d) EVOTHERM-0.8%; and (e) GLWBR-0.8%.

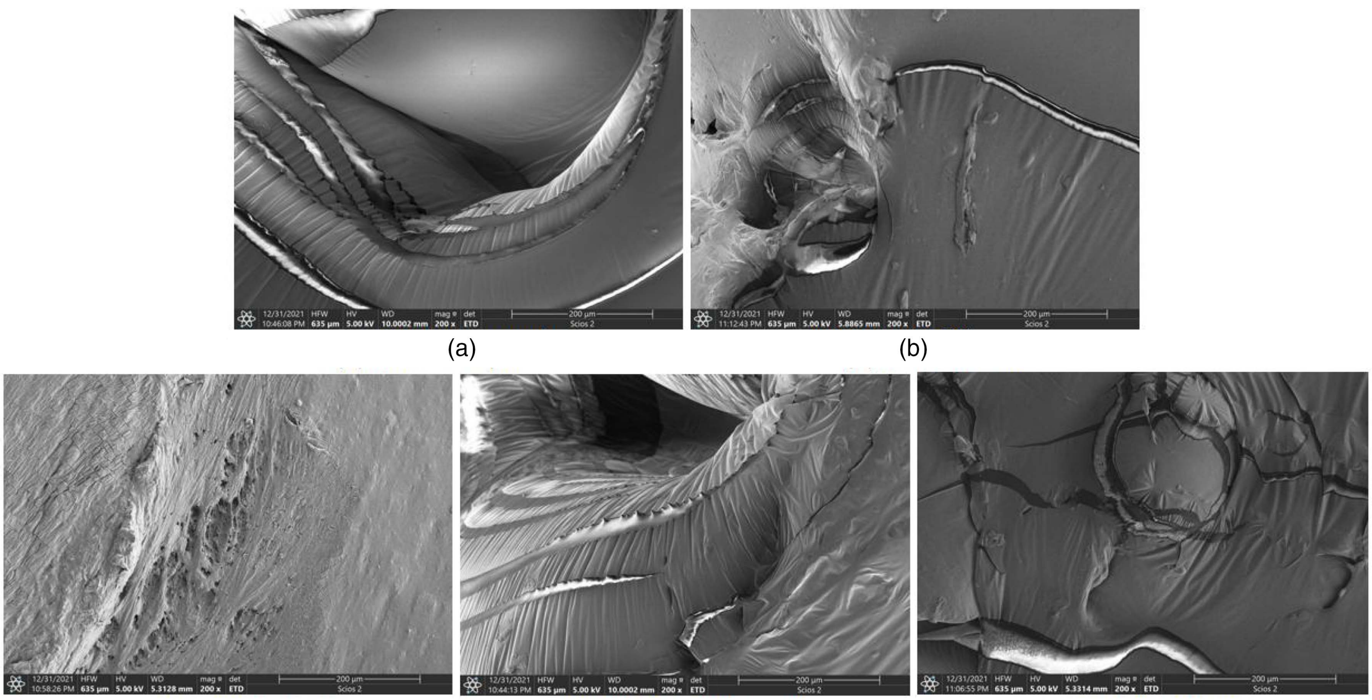

Fig. 15. Morphology of HVMA after aging under SEM: (a) blank sample; (b) WATER-3%; (c) SASOBIT-3%; (d) EVOTHERM-0.8%; and (e) GLWBR-0.8%.

Sasobit with 1%, 3%, and 5%, Evotherm and GLWBR with 0.4%, 0.8%, and 1.2%) and then applied to conduct rheological and morphological evaluations. Based on the findings of this study, the following conclusions were drawn:

1. WMAs, especially Sasobit, WATER, and GLWBR, reduced HVMA viscosity and achieved a warm mixing effect.
2. Sasobit exerted a strong influence on high-temperature rheological properties, indicating a positive correlation trend, low-temperature cracking resistance, and the PG of HVMA, whereas foam warm mix, GLWBR, and Evotherm surface-active WMAs had no obvious effects on the physical and rheological properties or PG of HVMA.

3. After RTFOT aging, the physical and rheological aging indexes of the Sasobit warm-mix HVMA were weaker than those of the blank sample. Although the remaining three WMAs affected the aging performance of the asphalt, their effects were not strong. This finding was demonstrated by morphological observations. Based on FTIR test results, the effect of WMA on the aging performance of HVMA was further demonstrated by the ΔCI difference.
4. Aging indexes (SPI, VAI, CAI) could be applied to predict the aging degree of warm-mix HVMAs after short-term thermal oxidative aging.
5. Compared with EVOTHERM, GLWBR has a better warm mixing effect on HVMA. GLWBR can improve the antirutting performance of HVMA and improve the low-temperature performance S and *m*-value of HVMA. In addition, GLWBR had almost no effect on the aging of HVMA. GLWBR could serve as a new WMA in HVMA construction engineering.

Data Availability Statement

Some or all data, models, and code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

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