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Research Article

Preparation and Characterization of High Modulus Agent Modified Asphalt and Its High Modulus Mixture

Shi-Zhong Mi,[1] Yong-Xiang Li ,[2] and Hai-Wei Zhang[3]

[1] *School of Highway, Chang'an University, Xi'an, Shaanxi 710064, China*
[2] *College of Energy and Transportation Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China*
[3] *School of Civil Engineering and Architecture, Zhengzhou University of Aeronautics, Zhengzhou, Henan 450046, China*

Correspondence should be addressed to Yong-Xiang Li; lyxiang@imau.edu.cn

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Improving the high-temperature stability and water damage resistance of asphalt pavements has always been a priority. This study proposed a composite high modulus modifier with rock asphalt and nanopolymer as main materials (HRMA) to prepare the high modulus asphalt mixture for their excellent rutting resistance. Moreover, its modification effect and modification mechanism were studied. The effect of HRMA content on the rheological performance of asphalt was investigated using Brookfield rotational viscosity, dynamic shear rheometers (DSR), and bending beam rheometers (BBR). Their modification mechanisms were revealed by Fourier Transformation Infrared Spectroscopy (FTIR). Besides, the properties of the mixtures were studied in various laboratory tests and compared with the 90# asphalt mixture and SBS asphalt mixture. Some of these included the rutting test, the bending test, the Marshall immersion test, and the freeze-thaw indirect tension test. The results indicated that with the increase of HRMA content, the deformation resistance of the asphalt mixture under high-temperature conditions was significantly improved, and the temperature sensitivity was changed. However, the crack resistance of its asphalt mixtures under low temperature was reduced due to the lower ductility of HRMA-modified asphalt. The recommended HRMA content was 21.8% of the asphalt, combining performance and construction cost.

1. Introduction

The asphalt mixture is a viscoelastic material. Heavy traffic loads and extreme climates significantly influence the service performance of asphalt pavement. Cracking, rutting, surface loosening, flushing, and water damage are the main forms of pavement damage, which seriously affect the safety of road use [1–5]. High modulus modifiers have been introduced to improve the rutting of asphalt pavements under high summer temperature conditions due to their potential contribution to thermal and fatigue cracking of asphalt pavements [6, 7]. Research on high modulus modified asphalt mixes began earlier in foreign countries. The concept of high modulus asphalt mixture (HMAC) was first mentioned in the French high modulus asphalt concrete standard NFP98-140. HMAC is generally required to have a dynamic modulus excess of 14,000 MPa at 15°C and 10 Hz test conditions [8]. At present, high modulus modifiers are broadly divided into three categories: (1) hard asphalt, generally lower grade asphalt with higher viscosity; hard-grade paving asphalt binders refer to those neat asphalt binders with a penetration grade of 10–25 (0.1 mm) at 25°C and a softening point of 55–78°C; (2) natural asphalt, such as rock asphalt, Trinidad Lake, or Gilsonite-like materials with an 8–28 (0.1 mm) penetration at 25°C and a softening point of 55–80°C; (3) polymer high modulus modifiers, such as olefin high modulus modifiers.

Foreign research on high modulus asphalt mixture has been carried out for decades. It has been used in many practical projects with remarkable results [9, 10]. Des Croix [11] noted that the superior structural properties of high modulus materials allow for a 25–40% reduction in thickness. Zou et al. [12] found that the rutting resistance observed in the test section with HMAC was stronger than with

SBS modified asphalt mixtures. Hyun Jong Lee et al. [9] added SBS polymer to HMAC to significantly improve the moisture, rutting, and fatigue damage properties of the asphalt mixture. Moreno-Navarro et al. found that the addition of acrylic fibers to HMAC could improve the mechanical behavior at high and low temperatures, as well as under severe climates [13, 14]. The high modulus asphalt mix is a type of Hot Mix Asphalt (HMA) that has high stiffness at an intermediate temperature [15]. The traditional basic indicators such as penetration, softening point, and viscosity cannot reflect the technical characteristics of HMAC [16]. High-temperature rheological properties of HMAC should be evaluated with rheological methods. Zhao et al. [17] used dynamic shear rheometer (DSR) tests to conclude that the high-temperature stability of asphalt mastics with limestone filler was slightly better than that of asphalt mastics with calcareous sand filler. Geng et al. [18] pointed out that the rheological properties of asphalt binders exit correlated with the mixture's resistance to deformation. By using temperature sweep tests, HMACs were found to have a higher rutting factor ($G*/\sin\delta$) than base asphalt [19]. Numerous studies proved that the dynamic stability of asphalt mixtures is well correlated with the complex modulus, rutting coefficient, viscosity, and nonrecoverable creep flexibility of asphalt [20–22].

In conclusion, high modulus asphalt mixtures exhibit good rutting and fatigue resistance at high temperatures. However, related studies have observed drawbacks, including the complicated modifications process, poor low-temperature performance, cost, and undefined microscopic modification mechanisms. This paper uses a composite high modulus modifier as a new additive for asphalt pavement. The main components include natural rock asphalt, nanopolymer materials, and stabilizers. Natural rock asphalt and nanomaterial form an integrated organic unit to improve the high temperature and water stability of asphalt mixes. The effect of modifiers in terms of asphalt properties was analyzed using basic performance tests and rheological tests. The optimum admixture of HRMA was obtained. Transform infrared spectroscopy (FTIR) was used to investigate the microscopic modification mechanisms. High modulus mixes were studied and compared to matrix asphalt mixtures and SBS modified asphalt mixtures in terms of road performance. The obtained results provide a reference for applying high modulus mixtures to improve the durability of pavements. A flow chart of the research approach is shown in Figure 1.

2. Materials and Methods

2.1. Materials. This paper selected a composite high modulus agent HRMA (Figure 2) as the modifier. Its main components include natural rock asphalt, nanopolymer materials, and stabilizers. The basic properties of HRMA were presented in Table 1 according to JT/T 860.1–2013 [23] and JT/T 860.5–2014 [24]. HRMA is powdery and granular, and HRMA is in powder and granular form, so it requires storage in a moisture-proof condition. Tables 2 and 3 show the technical parameters of the basic binder (grade 90 pen) and the SBS modified binder, which were examined using Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering [25]. Continuous dense gradation asphalt mixture (AC-16) was adopted in this paper. The gradation AC-16 was known in Figure 3. The technical properties of virgin aggregate were tested according to JTG E42-2005 [26]. Table 4 presents the results.

2.2. Methods

2.2.1. Sample Preparation

(1) HRMA-Modified Asphalt. The percentages of HRMA (0.6%, 0.9%, 1.2%, 1.5%, and 1.8%, by weight of the aggregates) were selected in the range of the typical bitumen content for the target HRMA mixture. A previous experimental investigation by our group found that the modification effect of HRMA was not obvious when the proportion of HRMA (by weight of the aggregates) was less than 0.6%. However, a higher dosage than 1.8% will significantly increase the construction temperature of the mixture, and the cost will be higher as well. Therefore, the dosage of HRMA was compared and selected in the range of 0.6% to 1.8% under a comprehensive consideration. The modifier contents of the HRMA-modified asphalt were calculated to be 11.3%, 16.7%, 21.8%, 26.8%, and 31.6%, respectively. HRMA-modified asphalt was prepared by heating the 90# base binder to 135°C first and then manually premixing it with HRMA modifiers with a glass rod. A high-speed shear mixer was used to shear 1 h at 175°C with a speed of 3000 r/min to ensure sufficient mixture mixing.

(2) HRMA-Modified Asphalt Mixture. The HRMA asphalt mixture was prepared using a dry technique. HRMA was chosen as the optimal content of 21.8% of the asphalt mass, which comprised 1.2% of the mixture. In this paper, base asphalt mixes and SBS modified asphalt mixes were selected as the control group. The optimal asphalt content (by mass of aggregate) was 4.6% for HRAM modified asphalt mixture, 5.2% for 90# asphalt mixture, and 5.0% for SBS asphalt mixture based on the Marshall test.

The preparation process of the HRMA-modified asphalt mixture was as follows: firstly, the aggregate heated to 180°C was poured into the mixing pot preheated to 185°C and mixed for 30 s. The HRMA modifiers were then added and dry mixed with the aggregate for another 180 s. Again, the insulated asphalt was poured into the mixing pot and wet mixed for the 90 s. After that, the heated mineral powder was added and mixed for another 90 s. Finally, the HRMA-modified asphalt mixture was obtained.

2.2.2. Modified Asphalt Performance Testing

(1) Physical Properties. The measurement of temperature sensitivity and three indexes of the HRMA-modified asphalt were determined. The aging resistance of HRMA-modified asphalt was analyzed and evaluated using the film oven test

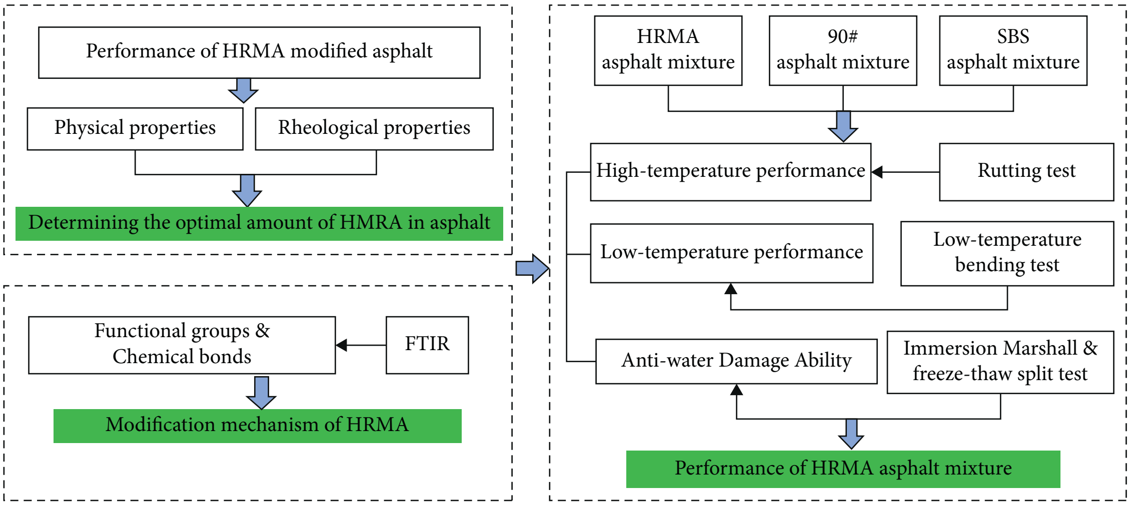


Figure 1: Research method flow chart.

Figure 2: HRMA modifier.

Table 1: Properties of high modulus agent HRMA.

Indicators	Unit	Test results	Standard
Appearance	—	Dark brown powder	—
Density	g/cm^3	1.4	JT/T 860.1
Flash point	°C	307	JT/T 860.1
Water content	%	0.82	JT/T 860.1
Natural rock bitumen content	%	51	JT/T 860.5

(RTFOT). All of the tests were implemented in accordance with JTG E20-2011 [26].

(2) Rheological Properties. As shown in Figure 4, Brookfield rotational viscometer (RV) was used to measure the viscosity of the asphalt binders at high temperatures according to AASHTO T316 [27]. Rotor and speed were selected according to the type of asphalt. The viscosity results measured at different temperatures were used to estimate the range of mixing and compaction temperatures for different asphalt binders.

A dynamic shear rheometer (DSR) was employed to evaluate the viscoelastic properties of pre-and-post aging HRMA-modified asphalt binders at high and medium temperatures in accordance with AASHTO T315 [28]. For unaged and RTFO aged HRMA-modified asphalt binders, an 25 mm parallel plate with a gap of 1 mm was conducted. The temperature sweep tests from 46 to 70°C were performed with an interval of 6°C. The loading frequency was 10 rad/s. For PAV aged HRMA-modified asphalt binders, an 8 mm parallel plate with a gap of 2 mm was used. The temperature ranges were 19–28°C with an interval of 3°C. The loading frequency was 10 rad/s. Complex modulus ($G*$), phase angle (δ), rutting factor ($G*/\sin\ \delta$), and fatigue factor ($G* \cdot\ \sin\ \delta$) were determined from testing data.

The BBR test of unaged and RTFO aged HRMA-modified asphalt binders was conducted, according to AASHTO T313 [29]. The size of the specimen was 125 mm × 125 mm × 6.25 mm, and the test temperature was −12°C, −18°C, and −24°C. Three replicates for each binder were tested in this study. The creep stiffness (S) and the creep recovery (m) at $t = 60$ s were used for the test results.

(3) Microcosmic Structure. As shown in Figure 5, Transform Infrared Spectroscopy (FTIR) was used to identify the structure of the HRMA-modified asphalt with potassium bromide. The infrared absorption spectrum of the sample was taken with a spectrophotometer (Nicolet6700) in the wavenumber range of 400–4000 cm^{-1} with a resolution of 4 cm^{-1}.

2.2.3. HRMA Asphalt Mixture Performance Testing.

The high-temperature performance, low-temperature crack resistance, and antimoisture damage capacity were selected to evaluate the road performance of different mixtures (90# asphalt mixture, SBS asphalt mixture, and HRMA asphalt mixture).

(1) High-Temperature Performance. The high-temperature performance of different mixes (90# asphalt mixture, SBS asphalt mixture, and HRMA asphalt mixture) was studied by making specimens with dimensions of 300 mm (width) × 300 mm (length) × 50 mm (height) and measuring the

Table 2: Technical indexes of pen # 90 asphalt binder.

Indicators	Unit	Standard index	Test values	Standard
Penetration (25°C, 100 g, 5 s)	0.1	80–100	82.9	T0604
Softening point	°C	≥43	46.3	T0606
Ductility (5 cm/min, 15°C)	cm	≥100	167.3	T0605
Dynamic viscosity (60°C)	Pa·s	≥140	162	T0620
Relative density (15°C)	g/cm^3	—	1.034	T0603
After the thin-film oven test (TFOT)				
Loss on heating	%Wt	≤±0.8	−0.48	T0609
Retained penetration after TFOT	%	≥57	76	
Retained ductility after TFOT	Cm	≥8	10	

Table 3: Technical indexes of SBS asphalt.

Indicators	Unit	Standard index	Test values	Standard
Penetration (25°C, 100g, 5s)	0.1	60–80	71.7	T0604
Softening point	°C	≥55	72	T0606
Ductility (5 cm/min, 15°C)	Cm	≥30	39	T0605
After the thin-film oven test (TFOT)				
Loss on heating	%Wt.	≤±1.0	−0.019	T0609
Retained penetration after TFOT	%	≥60	84	
Retained ductility after TFOT	Cm	≥20	32	

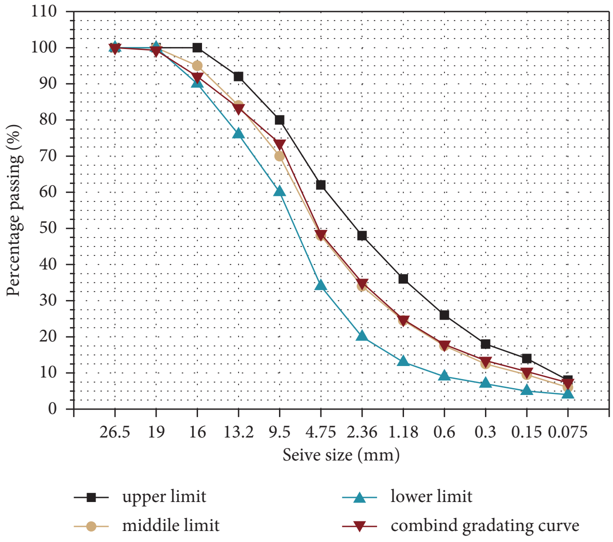


Figure 3: Gradation of the AC-16.

dynamic stability at 60°C with a rutting instrument according to the method specified in JTG E20-2011 T 0719 [26], as shown in Figure 6.

(2) Low-Temperature Performance. The low-temperature performance of different mixtures was carried out with MTS universal material testing machine according to JTG E20-2011 T0715 [26]. The samples with a size of 250 mm (width) × 30 mm (length) × 35 mm (height) were cut from the track plate, as presented in Figure 7.

(3) Antiwater Damage Ability. The immersion Marshall and freeze-thaw split tests were used to evaluate the water stability of different mixtures, referring to JTG E20-2011 T 0729 and T 0709 [26]. The immersion Marshall test was used to simulate the damage to the pavement by strong precipitation factors. The asphalt mixture specimens were maintained in water immersion at 60°C for 48 h. The water stability of the asphalt mixture was evaluated by calculating the stability ratio of the asphalt mixture before and after water immersion. The freeze-thaw split test was used to simulate the damage to the asphalt mixture by water and temperature. The tensile strength ratio of frozen and melted was calculated after the test.

3. Results and Discussion

3.1. Performance of HRMA-Modified Asphalt

3.1.1. Physical Properties. The content of the modifier has a significant influence on the performance of modified asphalt. In order to study the basic performance of HRMA-modified asphalt, the influence on modified asphalt performance was studied by a different dosage of HRMA agent through laboratory tests (penetration grade, softening point, ductility, and RTFOT tests). The test results have shown in Figure 8.

The penetration grade of the modified asphalt was gradually decreasing with the increase of the compound high modulus modifier HRMA. Compared with 90# asphalt, the penetration grade of modified asphalt with 11.3%, 16.7%, 21.6%, 26.8%, and 31.6% HRMA was decreased by 35.1%, 48.1%, 48.4%, 67.4%, and 73.1%, respectively. The results showed that the addition of HRMA improved the deformation resistance of asphalt. The same trend as the penetration grade was shown. The penetration index (PI) value increased from −1.392 to −0.354 as the modifier HRMA additive increased from 0% to 31.6%. The experimental results showed that the composite high modulus modifier

Table 4: Properties of mineral filler, coarse, and fine aggregate.

Indicators		Units	Specification limits	Test results	Standard
Coarse aggregate	Crushed stone value	%	≤26	14.1	T0316
	Loss Angeles abrasion loss	%	≤28	16.5	T0317
	Soundness	%	≤12	3	T0314
	Apparent relative density	g/cm^3	-	2.780	T0304
	Adhesion with asphalt binder (grade)	—	≥4	5	T0616
Fine aggregate	Apparent relative density	g/cm^3	-	2.732	T0328
	Sand equivalent	%	≥60	80	T0304
	Mud content	%	≤3	2.1	T0333
Mineral filler	Apparent density	g/cm^3	≥2.5	2.697	T0334
	Water content	%	≤1.0	0.3	T0103
	Hydrophilic coefficient	%	≤1.0	0.75	T0353
	Appearance		No agglomerates	No agglomerates	—
	Plasticity index		<4	3.6	T0354

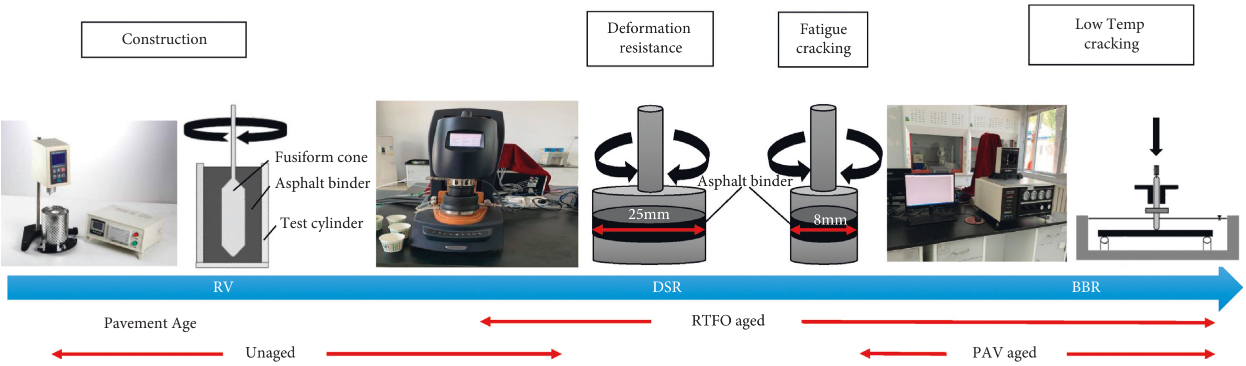


Figure 4: The rheological experiment.

(a) (b)

Figure 5: Fourier transform infrared spectrometer characterization: (a) the equipment and (b) test sample.

HRMA can reduce the temperature sensitivity of asphalt. Sol-gel properties of the asphalt were altered by the dispersion and swelling development of the particles of HRMA, thus making the asphalt sensitive to temperature changes. The softening point of modified asphalt increased gradually with the content of the high modulus modifier HRMA, and the equivalent softening point T800 has the same trend as the softening point. With an increase in HRMA content, the ductility of the asphalt has a smaller decline at first and then decreased rapidly with the amount of modifier exceeding 21.8%. This phenomenon was because the HRMA modifier was enriched with rock asphalt, which contains a large number of mineral components that cause stress concentration in the specimen when stretched in tensile tests.

As shown in Figure 9, the mass loss of the asphalt increased at first and then decreased with an increase in HRMA content. The content of rock asphalt in the modified asphalt increased when the modifier content reached 11.3%, and the matrix asphalt content decreased comparatively. The excellent antiaging and antioxidation properties of rock

Figure 6: Asphalt mixture rutting test.

asphalt can protect the matrix asphalt to a certain extent and reduce the mass loss of HRMA-modified asphalt.

In summary, the high-temperature performance of the matrix asphalt was significantly enhanced, the thermal sensitivity was improved, and the aging resistance capacity and stability were strengthened. In contrast, the low-temperature performance was slightly reduced after introducing the HRMA modifier.

3.1.2. Rheological Properties

(1) Brookfield Rotational Viscosity. The viscosity changes for different asphalt binders plotted against HRMA content for a temperature range of 100°C –175°C were presented in Figure 10. HRMA content significantly impacted viscosity at lower temperatures and higher concentrations. Specifically, the increase in HRMA content was found to enhance the viscosity of the modified asphalt at the same test temperature. The viscosity of modified asphalt containing 11.3%, 16.7%, 21.6%, 26.8%, and 31.6% HRMA was 0.79 times, 1.07 times, 2.52 times, 4.32 times, and 5.74 times that of 90# asphalt at 135°C, respectively. Moreover, the viscosity results measured at different temperatures were used to estimate the range of mixing and compaction temperatures for different asphalt binders. The required mixing and compaction temperature of the asphalt material increased, due to the increased asphalt viscosity with the HRMA content. The viscosity requirement of JTG F40 2004 specification for SBS modified bitumen at 135°C was <3 Pa˙s. However, the viscosity of HRMA-modified asphalt exceeded 3 Pa˙s at 135°C when the content of HRMA was greater than 21.8%, which indicated that the excessive amount of HRMA modifier had a negative impact on the working performance of asphalt. The difficulty of paving and compaction would increase. Moreover, the consumption of fuel consumption would enhance.

(2) DSR Test. The composite shear modulus ($G*$), phase angle (δ), rutting factor ($G*/\sin\delta$), and fatigue factor ($G*\cdot\sin\delta$) were determined to compare the rheological characteristics of various binders. The results were shown in Figure 10, and temperatures significantly affected HRMA-modified asphalt. The shear modulus, rutting factor, and fatigue factor of all asphalt specimens tended to decrease with increasing temperature. Moreover, the rutting factor $G*/\sin\delta$ and complex shear modulus $G*$ increased gradually with the increase of HRMA content at the same test temperature, indicating that HRMA-modified asphalt has better deformation resistance. In contrast, the phase angle δ exhibited an inverse correlation with temperature, suggesting increased flexibility. The rock asphalt of HRMA has a high shear modulus and viscosity, thus significantly enhancing the high-temperature performance of the modified asphalt binder. However, the rate of change slowed down when the temperature exceeded 55°C.

Furthermore, it appeared that aging has a positive effect on providing better resistance to permanent deformation. The complex shear modulus $G*$ of HRMA-modified asphalt with 11.3% 16.7%, 21.8%, 26.8%, and 31.6% was 2.64 times, 4 times, 6.27 times, 10.09 times, and 16.81 times that of matrix asphalt, according to Figure 11(a). After RTFO aging, the complex shear modulus $G*$ was 3.25, 5.1, 12.75, 15.75, and 39.15 times higher than the matrix asphalt, respectively. Figure 11(c) shows that the rutting factor of unaged asphalt with 11.3%, 16.7%, 21.8%, 26.8%, and 31.6% HRMA was 2.64 times, 4 times, 6.36 times, 10.27 times, and 17.36 times than that of unaged matrix asphalt, respectively. The rutting factor of RFTO-aged binders has a higher slope compared to unaged binders. As shown in Figure 11(b), the phase angle slope consistently reflected a similar effect of HRMA on this parameter.

The fatigue factor was usually used as an indicator to evaluate the fatigue performance of asphalt materials. The relationship between temperature and fatigue factor was shown in Figure 11(d), with temperature as the horizontal coordinate and $G*\cdot\sin\delta$ as the vertical coordinate. Fatigue factor ($G*\cdot\sin\delta$) from the DSR test increased with HRMA content for all tested binders. However, the fatigue resistance of modified asphalt with HMAB content over 21.8% was found unable to meet the specification requirements with $G*\cdot\sin\delta$ less than 5000 kPa. At that point, the asphalt binder exhibited excessive hardness and occurred fatigue cracking easily. Therefore, the negative impact on the fatigue resistance of asphalt with an excessive amount of HRMA modifier cannot be ignored.

(3) BBR Test Result. Low-Temperature can harden and brittle the asphalt, making asphalt pavements more prone to cracking due to temperature shrinkage. The SHRP in the USA proved that the direct contribution of asphalt properties to the low-temperature cracking damage of asphalt mixtures is 80% [30]. As a result, determining the low-temperature rheological characteristics of asphalt has given insight into the low-temperature crack resistance of the mixtures. The BBR test was conducted on unaged and RTFO aged asphalts, with the results demonstrated in Figure 12.

At the same temperature, the creep stiffness modulus S of HRMA-modified asphalt rose as the HRMA concentration increased (Figure 12(a)). S of RTFO aged HRMA asphalt was greater than that of unaged HRMA asphalt when loaded for 60 seconds at −12°C. Both unaged and RTFO aged HRMA asphalt exceeded the AASHTO M320 standard of 300 MPa for S-value [31]. BBR test reflects that aging influenced the

(a) (b)

Figure 7: Asphalt mixture low-temperature bending test: (a) the equipment and (b) test sample.

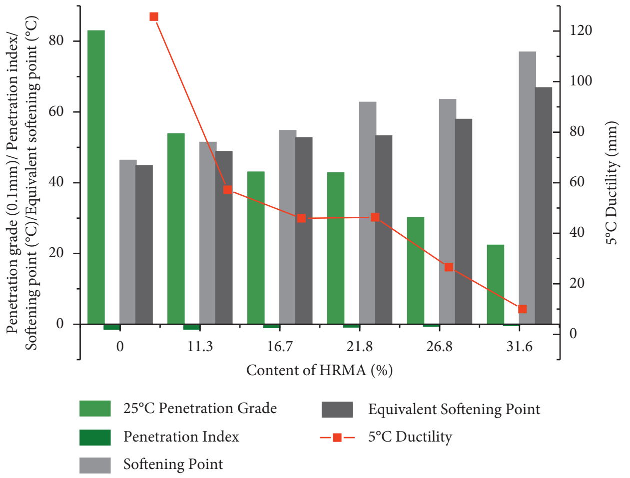


Figure 8: Variation of basic properties of modified asphalt with HRMA content.

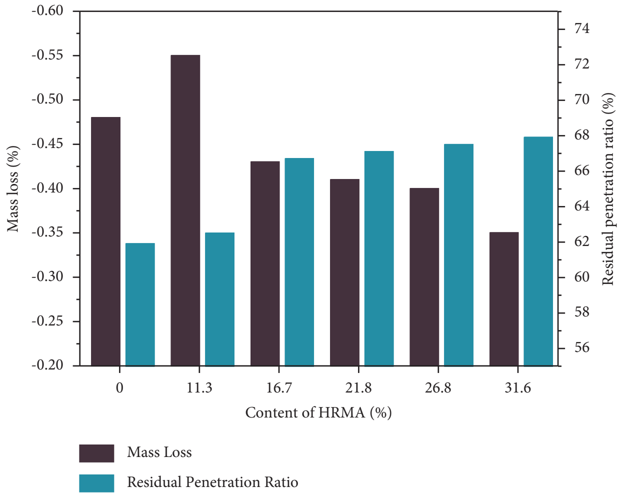


Figure 9: Variation of RTFO aged modified asphalt with HRMA content.

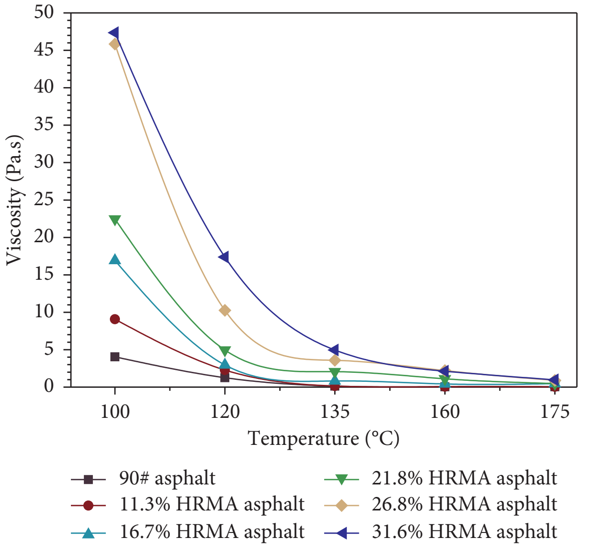


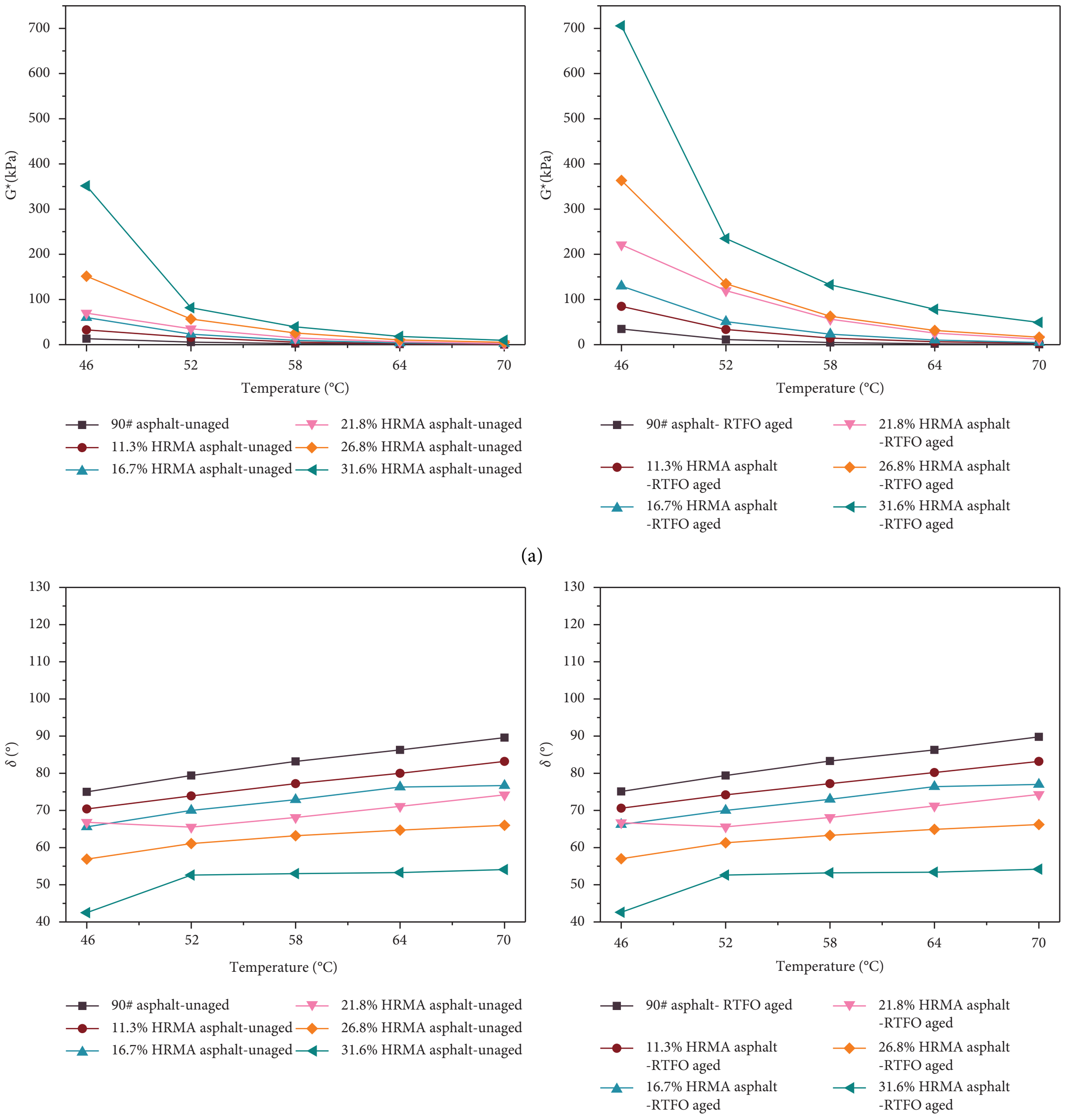
Figure 10: The viscosity of asphalt binders versus temperature under different HRMA content.

stiffness modulus and low-temperature flexibility while decreasing the low-temperature crack resistance. The creep rate m-value of asphalt decreased with HRMA content for the same temperature, as shown in Figure 11(b). Given the response of binder at different HRMA content, it was clear that the increasing content of HRMA modifier has a negative effect on the low-temperature crack resistance of asphalt. This phenomenon was because HRMA was rich in rock asphalt, which increased the viscosity of the base asphalt and reduced its fluidity.

Comprehensive considering the modified asphalt high-temperature stability, fatigue resistance, and low-temperature crack resistance, the optimum amount of the compound high modulus modifier HRMA was 21.8%.

3.1.3. Modification Mechanism of HRMA-Modified Asphalt.

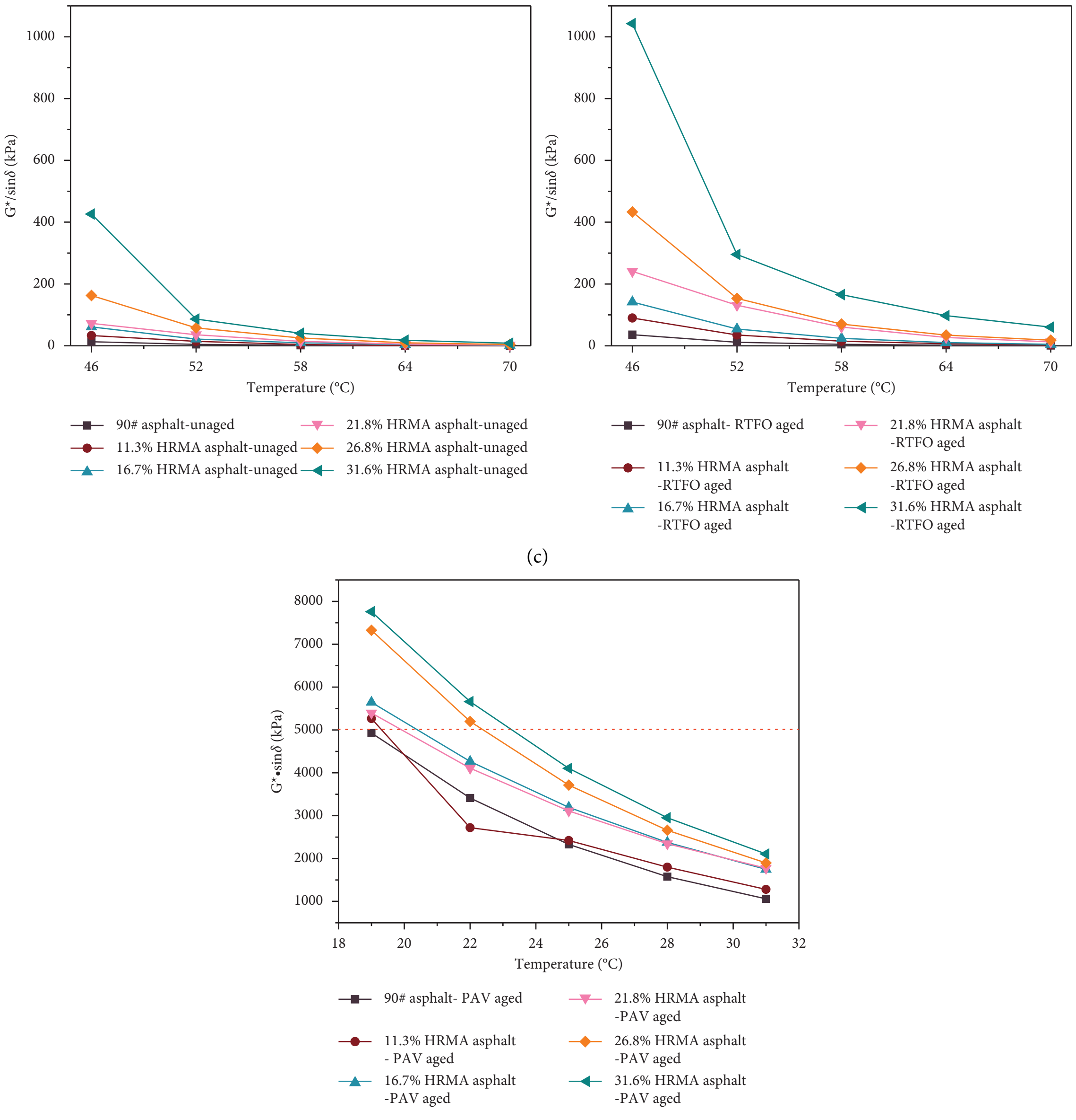
Evaluating the effect of the introduction of HRMA modifier on the molecular structure of the matrix asphalt and



(a)

(b)

Figure 11: Continued.



(c)

(d)

FIGURE 11: High-temperature rheological properties of different asphalt binders versus temperature: (a) complex shear modulus, (b) phase angle, (c) rutting factor, and (d) fatigue factor.

exploring the modification mechanism of HRMA-modified asphalt, FTIR experiments were conducted. FTIR test analyzes the functional group characteristics of substances based on the different absorption peaks to different wavelengths of infrared radiation [32]. The absorption of the absorption peak corresponding to the molecular structure of the substance, further, confirmed the types of groups in the substance and the combination of other groups. The results were shown in Figure 13.

As shown in Figure 13(a), HRMA exhibited strong peaks at 2920–2848 cm^{-1}, assigned to -CH2 stretching vibration of the carbon-hydrogen bond. The C = C (benzene skeleton vibration) in the aromatic ring produced the absorption peak at 1551 cm^{-1}. The broad absorption peak at 1024 cm^{-1} corresponded to the vibration pattern of the S = O bonded compound. The peak at 466 cm^{-1} was generated by the symmetric stretching vibration of the Si–O bond in HRMA.

As shown in Figure 13(b), with the increase in HRNA content, there was no significant change in the chemical bonding in HRMA-modified bitumen with the increase of HRNA content. However, the intensity of the absorption peak increased accordingly. The absence of new functional groups suggested that the modification mechanism of HRMA is a physical fusion. The weak absorption peaks at 2358 and 2341 cm^{-1} were attributed to the associated vibrations of CO_2 in air, which were interfering peaks. The carbon-hydrogen bonding vibration peaks of the CH_2 group between 2920 and 2848 cm^{-1}, C = C bonding vibration peaks in the aromatic ring at 1551 cm^{-1}, and carbon-oxygen bonding vibration peaks in the aromatic ring at

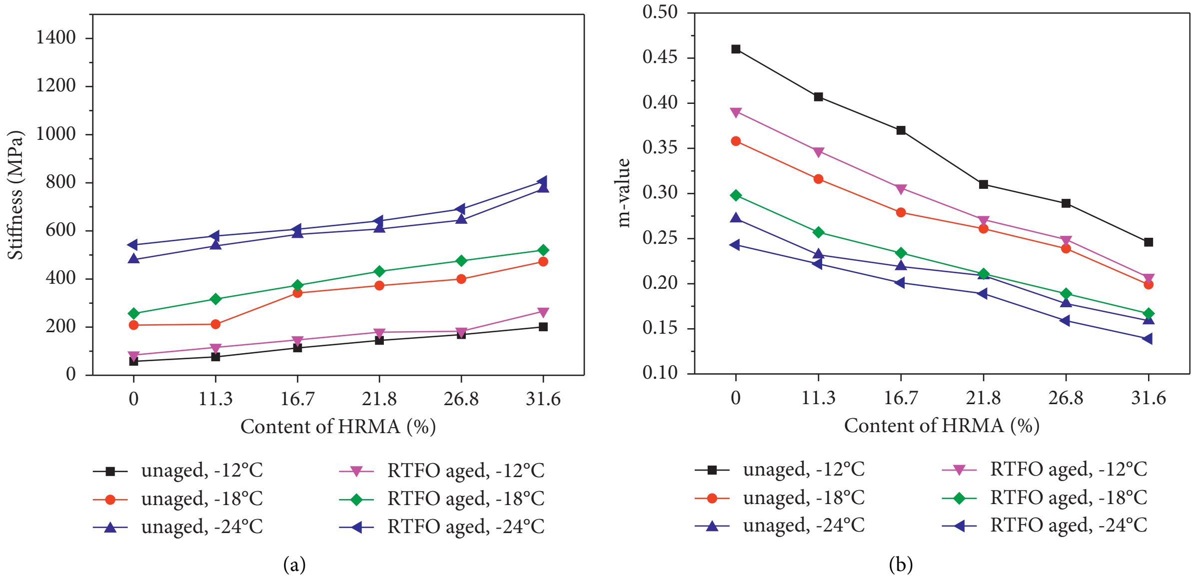


Figure 12: Low-temperature rheological properties of different asphalt binders versus HRMA content: (a) stiffness and (b) *m*-value.

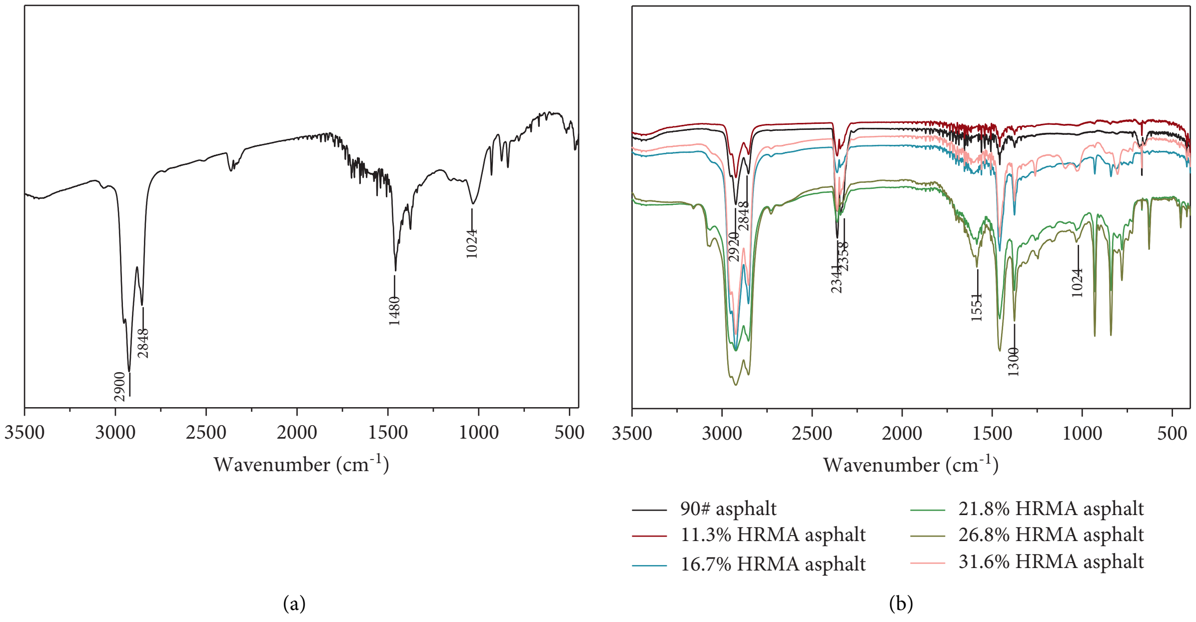


Figure 13: FTIR spectra: (a) HRMA; (b) modified asphalt with different content of HRMA.

1300–1000 cm^{-1} were significantly enhanced with the increase of HRMA. These spectral band changes were attributed to the natural rock asphalt component in the HRMA modifier, which can be fully integrated with the matrix asphalt. The infrared spectrum of the matrix asphalt showed no obvious absorption peak at 1024 cm^{-1}. With the increase of HRMA, the infrared spectrum of the HRMA-modified asphalt showed the characteristic peak of sulfoxide group $S=O$ at 1024 cm^{-1}. These polar groups ($S=O$, $C=O$) enhanced the intermolecular forces and increased the viscosity of the asphalt. It was expressed as a reduction in the needle penetration and an increase in the softening point of the modified asphalt; i.e., the high-temperature properties of the modified asphalt were improved.

3.2. Performance of HRMA Asphalt Mixture

3.2.1. High-Temperature Performance. Rutting is the most common type of structural deformation in asphalt pavements. As a result, rutting is a critical factor in determining the high-temperature stability of the asphalt mixture. The optimal amount of HRMA was 21.8% of the mass of asphalt, which comprised 1.2% of the mixture, according to the experimental results in Section 3.1. As shown in Figure 14, its

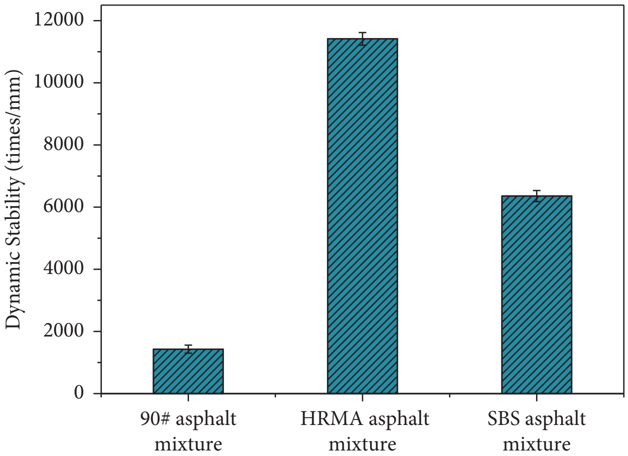


Figure 14: Dynamic stability of asphalt mixture.

Table 5: Low-temperature performance of asphalt mixture.

Mixture type	Flexural tensile strength (MPa)	Flexural tensile strain ($\mu\varepsilon$)	Stiffness modulus (MPa)
90# asphalt mixture	9.46	2608	3608
HRMA asphalt mixture	9.86	2477A	3961
SBS asphalt mixture	9.04	3381	2661

properties were compared to those of the 90# asphalt mixture and the SBS asphalt mixture. The high modulus modifier HRMA can significantly improve the rutting resistance of asphalt mixes. The dynamic stability of the HRMA asphalt mixture met the requirement of ≥6000 times/mm according to (DB 23/T2600-2020) specification [33], and the high-temperature antirutting performance was excellent. Moreover, the dynamic stability of the HRMA asphalt mixture was 7.95 times and 1.79 times higher than that of the 90# asphalt mixture and SBS asphalt mixture, respectively. This phenomenon was due to the compound high modulus modifier HRMA enriched with natural rock asphalt. Natural rock asphalt has the characteristics of a high softening point and high nitrogen content. Its addition improved the softening point and cohesion of the matrix asphalt. Therefore, the high-temperature performance of the asphalt mixture was improved.

3.2.2. Low-Temperature Performance. The test results for the three types of combinations (90# asphalt mixture, SBS asphalt mixture, and HRMA asphalt mixture) were presented in Table 5. The composite high modulus modifier HRMA has no significant effect on the flexural tensile strength of the asphalt mixture but has a certain reduction on the flexural strain of the asphalt mixture. The highest maximum flexural tensile strain was found in the SBS mixture, followed by the 90# mixture and the lowest in the HRMA mixture. The low-temperature stiffness modulus of the asphalt mixture was related to the transverse crack of the pavement. The smaller the modulus, the more the resistance to low-temperature cracking of the asphalt mixture. The strength modulus of HRMA asphalt mixture was 3961 MPa, which was 1.1 and 1.5 times of 90# asphalt mixture and SBS asphalt mixture, respectively. The results revealed that the HRMA modifier has a negative impact on the low-temperature crack resistance of the asphalt mixture. The rock bitumen enriched in HRMA causes this negative effect by dispersing it in the mixture as a powder, which enhanced the rigidity of the mixture while at the same time damaging the low-temperature properties of the mixture.

3.2.3. Antiwater Damage Ability. Water damage is one of the main diseases of asphalt mixture pavement. The immersion Marshall test is employed to simulate the damage to the pavement caused by heavy precipitation effects. The freeze-thaw indirect tension test simulates damage to asphalt pavements under the action of static water and temperature cycling. The immersion Marshall test and the freeze-thaw indirect tension test are provided to assess the water damage resistance of asphalt mixes. As shown in Figure 15(a), the introduction of HRMA significantly improved the residual stability of the asphalt mixes, which were 27.3% and 13.7% higher than those of the matrix asphalt mixes and SBS modified asphalt mixes, respectively. Both the Marshall modulus and residual Marshall modulus of the HRMA asphalt mixture were higher than the matrix asphalt mixture and SBS modified asphalt mixture. Consistent with the water immersion Marshall test results, the Freeze-thaw Splitting test also reached similar conclusions. Figure 15(b) showed that the HRMA mixture was the best, with 95.7%, followed by the 90# and SBS mixtures with 75.9% and 84.2%, respectively. This result was that the HRMA modifier has a high modulus. Its dispersion and dissolution in the asphalt relieved the stresses produced by water freezing on the mixtures. Therefore, improving the resistance of the mixtures to water damage was achieved.

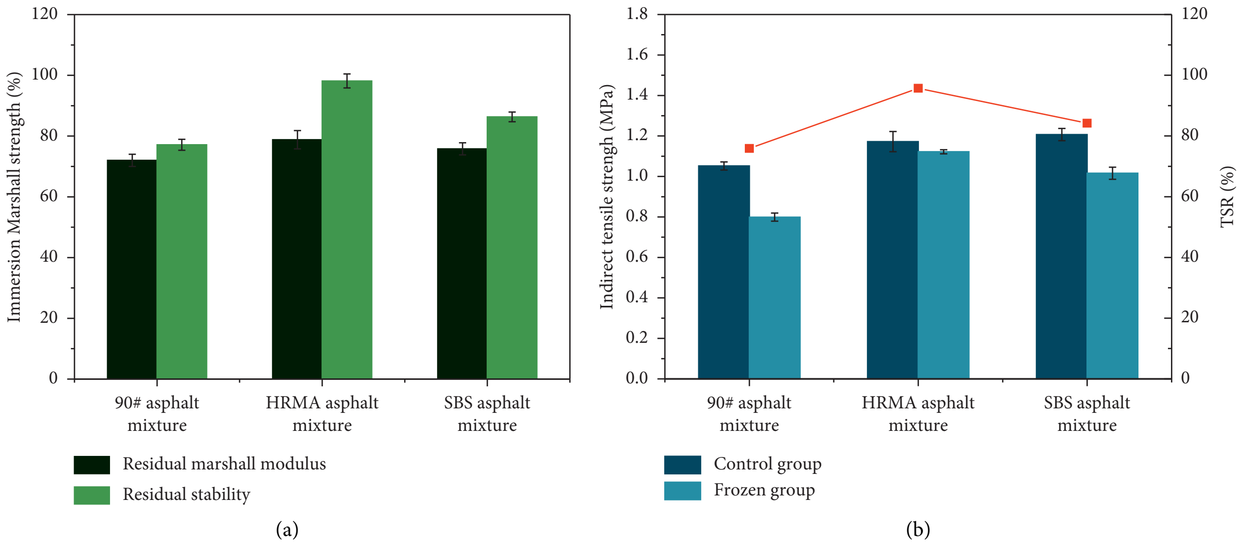


Figure 15: Antiwater damage ability of asphalt mixtures: (a) immersion Marshall test; (b) freeze-thaw splitting test.

The experimental results indicated that the HRMA-modified asphalt mixes have excellent resistance to water damage. HRMA mixes could meet the performance requirements when the pavement is under frost and heavy precipitation conditions.

4. Conclusion

(1) Asphalt physical tests showed that the high-temperature performance of the matrix asphalt was significantly enhanced, the thermal sensitivity was improved, and the aging resistance capacity and stability were strengthened after introducing the HRMA modifier.

(2) The viscosity, rutting factor, complex shear modulus, and creep stiffness modulus S all increased with the HRMA content. Combining performance (high temperature, low temperature, and fatigue resistance) and construction cost, HRMA content of 21.8% (1.2% of the mixture) was recommended.

(3) Polar functional groups in the HRMA modifier existed in asphaltene with stable chemical properties. The reaction between HRMA and matrix asphalt was a physical fusion reaction, and no new functional groups were generated. HRMA modifier improved the intermolecular force of the matrix asphalt and increased the viscosity of the asphalt.

(4) HRMA-modified asphalt mixes showed excellent high-temperature stability and antiwater damage ability compared to SBS and matrix asphalt mixtures. However, low-temperature crack resistance has a certain degree of decline. Therefore, HRMA-modified asphalt mixtures were recommended for high-temperature and rainy areas.

Data Availability

All data included in this study are available upon reasonable request to the corresponding author.

Conflicts of Interest

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

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References

[1] Q. Chen, S. Wang, C. Wang, F. Wang, H. Fu, and X. Yang, “Modified waterborne epoxy as a cold pavement binder: preparation and long-term working properties,” *Journal of Materials in Civil Engineering*, vol. 33, no. 5, Article ID 4021079, 2021.

[2] Q. Chen, Y. Lu, C. Wang, B. Han, and H. Fu, “Effect of raw material composition on the working performance of waterborne epoxy resin for road,” *International Journal of Pavement Engineering*, vol. 10, pp. 1–12, 2020.

[3] C. Wang, S. Wang, Z. Gao, and Z. Song, “Effect evaluation of road piezoelectric micro-energy collection-storage system based on laboratory and on-site tests,” *Applied Energy*, vol. 287, Article ID 116581, 2021.

[4] M. Zhang, P. Hao, G. Men, N. Liu, and G. Yuan, “Research on the compatibility of waterproof layer materials and asphalt mixture for steel bridge deck,” *Construction and Building Materials*, vol. 269, Article ID 121346, 2021.

[5] A. H. Norhidayah, M. Z. H. Mahmud, and P. J. Ramadhansyah, “Air void characterisation in porous asphalt using x-ray computed tomography,” *Advanced Materials Research*, vol. 911, pp. 443–448, 2014.

[6] C. Wang, X. Zhou, H. Yuan, H. Chen, L. Zhou, and Y. Fu, “Preparation and performance of UHMWP modified asphalt

and its high modulus mixture," *Construction and Building Materials*, vol. 294, Article ID 123629, 2021.

[7] N. Abdul Hassan, G. D. Airey, N. I. Md Yusoff et al., "Microstructural characterisation of dry mixed rubberised asphalt mixtures," *Construction and Building Materials*, vol. 82, pp. 173–183, 2015.

[8] Association Francaise de Normalisation (Afnor), *NF EN 13108-1: Bituminous Mixtures e Material Specifications-Part 1: Asphalt Concrete*, Association Francaise de Normalisation, Paris, France, 2007.

[9] H. J. Lee, J. H. Lee, and H. M. Park, "Performance evaluation of high modulus asphalt mixtures for long life asphalt pavements," *Construction and Building Materials*, vol. 21, no. 5, pp. 1079–1087, 2007.

[10] X. Xu, G. Lu, J. Yang, and X. Liu, "Mechanism and rheological properties of high modulus asphalt," *Advances in Materials Science and Engineering*, vol. 2020, Article ID 8795429, 13 pages, 2020.

[11] P. Des Croix and L. Planque, *Experience with Optimised Hard Grade Bitumens in High Modulus Asphalt Mixes*, pp. 158–172, Eurasphalt & Eurobitume Congress, Vienna, Austria, 3rd edition, 2004.

[12] X. Zou, A. Sha, W. Jiang, and X. Huang, "Modification mechanism of high modulus asphalt binders and mixtures performance evaluation," *Construction and Building Materials*, vol. 90, pp. 53–58, 2015.

[13] F. Moreno-Navarro, M. Sol-Sánchez, E. Tomas-Fortun, and M. C. Rubio-Gamez, "High-modulus asphalt mixtures modified with acrylic fibers for their use in pavements under severe climate conditions," *Journal of Cold Regions Engineering*, vol. 30, no. 4, Article ID 4016003, 2016.

[14] F. Moreno-Navarro, M. Sol-Sánchez, M. C. Rubio-Gámez, and M. Segarra-Martinez, "The use of additives for the improvement of the mechanical behavior of high modulus asphalt mixes," *Construction and Building Materials*, vol. 70, pp. 65–70, 2014.

[15] Y. Chen, H. Wang, S. Xu, and Z. You, "High modulus asphalt concrete: a state-of-the-art review," *Construction and Building Materials*, vol. 237, Article ID 117653, 2020.

[16] X. G. Xue, N. L. Li, H. X. Chen, and Z. Q. Zhang, "Reliability evaluation on the high-temperature performance index of modified bitumen with polymer," *Highways & Transportation in Inner Mongolia*, vol. 1, pp. 6–8, 2004.

[17] Z. G. Zhao, S. P. Wu, Q. Liu et al., "Characteristics of calcareous sand filler and its influence on physical and rheological properties of asphalt mastic," *Construction and Building Materials*, vol. 301, Article ID 124112, 2021.

[18] H. Geng, C. S. Clopotel, and H. U. Bahia, "Effects of high modulus asphalt binders on performance of typical asphalt pavement structures," *Construction and Building Materials*, vol. 44, pp. 207–213, 2013.

[19] M. Liang, Y. Hu, X. Kong, W. Fan, and H. Luo, "Effects of SBS configuration on performance of high modulus bitumen based on dynamic mechanical analysis," *Kemija u Industriji*, vol. 65, no. 7-8, pp. 379–384, 2016.

[20] S. Ren, X. Xie, Y. Wang et al., "Molecular characterization of a Class I Newcastle disease virus strain isolated from a pigeon in China," *Journal of Building Materials*, vol. 45, no. 4, pp. 408–417, 2016.

[21] Y. Chen, R. Gao, H. Wang, W. Zheng, and Z. You, "Rheological behavior of high modulus asphalt binder and its indication for fracture performances," *Construction and Building Materials*, vol. 306, no. 11, Article ID 124835, 2021.

[22] Y. Fang, Z. Zhang, S. Wang, and N. Li, "High temperature rheological properties of high modulus asphalt cement (HMAC) and its definition criteria," *Construction and Building Materials*, vol. 238, Article ID 117657, 2020.

[23] Ministry of Transport, *Modifier for Asphalt Mixture Part1: Anti-Rutting Additive (JT/T 860.1)*China Communication Press, Beijing, China, 2013.

[24] Ministry of Transport, *Modifier for Asphalt Mixture Part 5: Natural Asphalt (JT/T 860.5)*China Communication Press, Beijing, China, 2014.

[25] Research Institute of Highway Ministry of Transport, *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20)*China Communication Press, Beijing, China, 2011.

[26] Ministry of Transport, *Test Methods of Aggregate for Highway Engineering (JTG E42-2005)*China Communication Press, Beijing, China, 2005.

[27] AASHTO, "Viscosity determination of asphalt binder using rotational viscometer," *American Association of State Highway and Transportation Officials*, AASHTO provisional standards, Washington, D. C, USA, 2017.

[28] AASHTO, "Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)," *American Association of State Highway and Transportation Officials*, AASHTO provisional standards, Washington, D. C, USA, 2016.

[29] AASHTO, *Standard Test Methods for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)*, American Association of State Highway and Transportation Officials, Washington, D.C, USA, 2008.

[30] Asphalt Institute, *Performance Graded Asphalt Binder Specifications and Testing Superpave Series No.1 (SP–1)*, pp. 36–48, Asphalt Institute, Lexington, Kentucky, 1994.

[31] Aashto, *MP1., Standard Specification for Performance Graded Asphalt Binder*, Standard by American Association of State and Highway Transportation Officials, Washington, D. C, USA, 1995.

[32] M. Zhang, P. Hao, S. Dong, Y. Li, and G. Yuan, "Asphalt binder micro-characterization and testing approaches: a review," *Measurement*, vol. 151, Article ID 107255, 2020.

[33] Department of Transportation of Heilongjiang Province, *Technical Specifications for Construction of High Modulus Asphalt Mixture Pavements (DB23/T 2600-2020)*Heilongjiang Provincial Administration for Market Regulation Press, Harbin, China, 2004.