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Research Article

Research on Rheological Properties by Desulfurized Rubber Powder/SBS Composite-Modified Asphalt and Road Performance of Its Mixture

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Desulfurized rubber powder and SBS were used as asphalt modifiers to study the rheological properties and performance of desulfurized rubber powder/SBS composite-modified asphalt (DR/SBSCMA). First, the basic performance indicators such as penetration, ductility, softening point, and viscosity were studied. Second, the high-temperature and low-temperature rheological properties of asphalt were evaluated by using a dynamic shear rheometer (DSR) and bending beam rheometer (BBR). Finally, their high-temperature stability, low-temperature crack resistance, and water stability under the gradation of AC-13 and SMA-13 were evaluated. The results show that DR/SBSCMA had great advantages in terms of ductility and softening point, especially the softening point, which reached 90°C. It also demonstrated excellent high-temperature performance and tensile strength, and penetration was slightly lower than that of SBS-modified asphalt. Moreover, after compound modification, high-temperature and low-temperature rheological properties were effectively improved, and DR/SBSCMA adequately met the requirements of PG82-34. In addition, DR/SBSCMA maintained excellent high-temperature stability in both AC-13 and SMA-13 mixtures, coupled with obvious improvements in rutting deformation. Meanwhile, its low-temperature cracking resistance is slightly lower than that of SBS-modified asphalt, but both adequately meet the specification requirements. Ultimately, the water stability of DR/SBSCMA is comparable to that of SBS-modified asphalt, with both reaching more than 90%, proving its excellent water stability.

1. Introduction

In recent years, with increasing traffic, ordinary asphalt pavement is prone to cracking, rutting, loosening, peeling, and other pavement diseases, affecting the quality and life of the pavement. As a means to improve the performance of conventional asphalt at high temperatures and low temperatures, polymer-modified asphalt has developed rapidly [1–3], of which SBS-modified asphalt is the most widely used. Under the stimulus of the circular economy and resource utilization policy, rubber asphalt has launched a new development. Compared with basic asphalt, high-temperature and low-temperature performances of SBS-modified asphalt are effectively improved. However, SBS-modified asphalt is expensive and deteriorates easily, which limits its application [4, 5]. Grinding scrap tires to obtain rubber powder for asphalt modification has become an important way to treat scrap tires in a harmless and resourceful way [6, 7]. However, when using rubberized asphalt, the compatibility and storage stability of rubber powder and asphalt are poor, and segregation occurs easily [8, 9], which limits its further development.

To solve the above difficulties and pain points, road researchers proposed measures such as rubber powder desulfurization and rubber powder/SBS blending and obtained preliminary results [10, 11]. Filippelli et al. [12] used ultrasonic waves to produce desulfurized rubber powder, and produced desulfurized rubber asphalt had better deformation resistance and fatigue life. Kabir et al. [13] used microbial devulcanization of rubber, and its surface energy was increased three times after devulcanization, which could increase rubber asphalt interaction and reduce segregation. Research by Presti et al. [14] found that the solubility of desulfurized rubber powder is high, the dosage can reach 30%, and the processing time can be shortened. Ibrahim et al. [15] used radiation to pretreat rubber powder and found that its high-temperature and low-temperature properties and antiaging properties were improved. Singh et al. [16] improved the surface activity of rubber crumb after desulfurization, which improves the compatibility of rubber crumb with asphalt and the storage stability of rubber asphalt [17]. Shatanawi et al. [18] found that the desulfurized rubber powder can be melted into asphalt, which enables modified asphalt to have better storage stability. Kim et al. [19, 20] used SBS, SIS, petroleum resin, and tire rubber powder to make composite-modified asphalt. The performance of composite-modified asphalt at high temperature and low temperature was effectively improved, and viscosity was dependent on the content of rubber powder and SIS. Behnood and Olek [21] studied the rheological properties of SBS rubber powder polyphosphoric acid (PPA) composite-modified asphalt, and its rheological properties at high temperatures were improved. Ameri et al. [22] found that adding rubber powder and SBS could improve the fatigue resistance of modified asphalt. Rasool et al. [23, 24] used a twin-screw extruder to desulfurize and degrade rubber powder to improve its dispersing effect on SBS-modified asphalt. The degree of desulfurization and degradation of rubber powder was found to affect its dispersibility and interaction with asphalt. It was then suggested that the components and materials between desulfurized rubber powder, asphalt, and SBS exchange and interact, and the desulfurized rubber powder showed an increase in compatibility with asphalt, thereby improving ductility, softening point, and aging resistance, while reducing viscosity of composite-modified asphalt, which is advantageous for construction workability. The SBS powder and desulfurized rubber powder were also determined to be crosslinked after aging, which further improved ductility and aging resistance. Ma et al. [25] developed modified asphalt with stable rubber powder and found that its storage stability was effectively improved, and after that, the modification mechanism was analyzed.

Desulfurized rubber asphalt is produced after rubber powder is desulfurized, and its storage stability is effectively improved. To a certain extent, the amount of rubber powder can be increased and the construction temperature reduced, but its viscosity and softening point index decrease significantly, which is not conducive to improving high-temperature performance. Rubber powder/SBS composite modification can greatly improve the pavement performance, and the content of SBS is reduced, reducing the cost of use, but the compatibility problem has not been effectively solved.

Based on this, this study extensively uses two solutions of rubber powder desulfurization and rubber powder/SBS compounding, with desulfurized rubber powder and SBS as asphalt modifier materials to produce composite-modified asphalt and to develop desulfurized rubber powder/SBS composite-modified asphalt. Then, research was conducted on the rheological properties of desulfurized rubber powder/SBS composite-modified asphalt and its mixture's performance. At the same time, compared to SBS-modified asphalt and rubber asphalt, which are commonly used in pavements, the advantages of composite-modified asphalt in terms of the rheological properties of asphalt and the pavement performance of mixtures are illustrated. Ultimately, the research results can effectively improve the overall performance of modified asphalt, improve the resource utilization of scrap tires in China, and greatly reduce the cost of asphalt pavement construction, which has important economic and environmental significance.

2. Materials and Methods

2.1. Materials

2.1.1. Asphalt

(1) Virgin Asphalt. In this study, base asphalt (SK $90^{\#}$) was used to prepare rubberized asphalt or SBS-modified asphalt, and the basic performance indicators are shown in Table 1.

(2) Modified asphalt. To compare and analyze the performance of asphalt and the pavement performance of the mixture in this paper, three kinds of modified asphalt commonly used in Shaanxi Province were selected as the control, namely, SBS-modified asphalt, rubber asphalt, and desulfurized rubber asphalt produced by an asphalt plant in Shaanxi Province. The performance indicators are shown in Table 2.

2.1.2. Desulfurized Rubber Powder. Desulfurized rubber powder is produced from rubber powder (Figure 1) after thermal-mechanical shear desulfurization, extrusion, and granulation by using a twin-screw extruder. The appearance and shape are shown in Figure 2, and black particles are uniform in particle size without agglomeration. The technical indicators are shown in Table 3.

2.1.3. SBS Modifiers. SBS modifiers have thermoplastic elastomer properties and are widely used in asphalt modification. An SBS 4303 modifier was selected in this paper, and the performance indicators are shown in Table 4.

2.1.4. Aggregate

(1) AC-13 aggregate. Coarse aggregates are diorite crushed stones from a company in Shaanxi, and the specifications are as follows: 9.5~16 mm, 4.75~9.5 mm, 2.36~4.75 mm. The test results of physical properties of coarse aggregates are shown in Table 5. Machine-made sand and mineral powder were processed by crushed limestone from a company in Shaanxi. The test results of physical properties are shown in Tables 6 and 7.

Table 1: The basic properties of SK 90# virgin asphalt.

Items		Value	Requirements
Penetration (25°C, 0.1 mm)		89	80~100
Penetration index		−0.6	−1.5~+1.0
Ductility (10°C, cm)		>100	≥20
Softening point (°C)		46.0	≥45
Viscosity (60°C, Pa·s)		162.9	≥160
Flash point (°C)		294.3	≥245
Solubility (%)		99.97	≥99.5
Density (15°C, g/cm^3)		1.032	Measured
Aged asphalt (TFOT)	Loss on heating (%)	−0.512	≤±0.8
	Penetration ratio (%)	59.9	≥57
	Ductility (10°C, cm)	9	≥8

Table 2: The performance technical indicators of three kinds of modified asphalt.

Items		Desulfurized rubber asphalt	Rubber asphalt		SBS-modified asphalt	
		Value	Value	Requirements	Value	Requirements
Penetration (25°C, 0.1 mm)		65	53	40~80	63	60~80
Ductility (5°C, cm)		12.6	8.5	≥8	32	≥30
Softening point (°C)		62	68	≥58	79	≥55
Density (15°C, g/cm^3)		—	1.047	Measured	1.030	Measured
Viscosity (135°C, Pa·s)		2.527	8.674	—	1.828	≤3.0
Viscosity (180°C, Pa·s)		0.790	2.142	1.5~4.0	—	—
Aged asphalt (TFOT)	Loss on heating (%)	−0.16	−0.182	≤±1.0	−0.229	≤±1.0
	Penetration ratio (%)	90	89	≥60	81	≥60
	Ductility (5°C, cm)	10.1	5.2	≥5	27.4	≥20

Figure 1: Rubber powder.

Figure 2: Desulfurized rubber powder.

Table 3: The technical indicators of desulfurized rubber powder.

Items	Value	Requirements
Heating loss (80°C) (%)	0.4	≤1.5
Ash (%)	7.2	≤8
Acetone extract (%)	16.4	≤20
Mooney viscosity ML 100°C (1 + 4)	35	≤45
Carbon black content (%)	28.3	≥18
Rubber hydrocarbon content (%)	48	≥40
Iron content (%)	0.028	≤0.03
Particle size (mm)	5	≤10

Table 4: The performance indicators of SBS 4303.

Items	Value
Melt index (g/10 min)	11.0
300% tensile stress (MPa)	2.5
Elongation at break (%)	590
Hardness (degree A)	80
Tear-off permanent deformation	12
Volatile	0.50
S/B (mass ratio)	30/70

(2) SMA-13 aggregate. Aggregates and ore powder were produced in a factory in Hainan Province. The specifications of ore materials are 10~15 mm, 5~10 mm, 3~5 mm, and 0~3 mm, respectively. The technical indicators of aggregates and ore powders are shown in Table 8.

Table 5: Coarse aggregate quality specification test results.

Items	9.5~16 mm	4.75~9.5 mm	2.36~4.75 mm	Requirements
Volume relative density	2.975	2.952	2.884	—
Apparent relative density	3.026	3.021	2.953	≥2.6
Water absorption (%)	0.57	0.77	0.81	≤2.0
Needle-like particle content (%)	6.1	8.1	—	≤12
Crushing value (%)	10.3	—	—	≤26
Particle content (<0.075 mm, %)	0.1	0.2	0.1	≤1.0
Los Angeles attrition (%)	10.2	—	—	≤28
Polished value (PSV)	43	≥38		
Soft stone content (%)	1.0	—	—	≤3
Firmness (%)	5.0	≤12		
Adhesion to asphalt (grade)	5	—	—	≥4

Table 6: Test results of physical properties of manufactured sand.

Items	Value	Requirements
Sand equivalent (%)	70	≥60
Methylene blue value (g/kg)	1.2	≤2.5
Angularity (s)	43	≥30
Robustness (>0.3 mm)	4.5	≤12
Apparent relative density	2.757	≥2.5

Table 7: Test results of physical properties of mineral powder.

Items	Value	Requirements
Apparent relative density	2.717	≥2.5
Hydrophilic coefficient	0.70	<1.0
Plasticity index (%)	3	<4
Moisture content (%)	0.1	≤1.0

Table 8: Test results of physical properties of SMA-13 aggregates.

Items	10~15 mm	5~10 mm	3~5 mm	0~3 mm	Mineral powder	Requirements
Apparent relative density	2.923	2.913	2.862	—	—	≥2.6
	—	—	—	2.818	2.756	≥2.5
Volume relative density	2.870	2.863	—	—	—	—
Water absorption (%)	0.63	0.60	—	—	—	≤2
Crushing value (%)			10.5			≤20
Wear value (%)			12.4			≤28

2.2. Test Methods

2.2.1. Evaluation Method of Asphalt Physical Properties. According to the previous research results of composite-modified asphalt under different formulations, the mixing ratio of composite-modified asphalt used in this paper was determined to be 25% desulfurized rubber powder + 2% SBS. We first add SBS and then add rubber powder, the preparation temperature is 175°C, and the shearing time is 50 min. Conventional indexes such as penetration, softening point, ductility, and Brookfield rotational viscosity of composite-modified asphalt were tested according to the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011).

2.2.2. Rheological Property Test. The high-temperature and low-temperature rheological properties of asphalt were evaluated by using a dynamic shear rheometer (DSR) and bending beam rheometer (BBR). The DSR strain control is 12%, the angular frequency is 10 rad/s, the temperature sweep range is 34~88°C, and the temperature range is 6°C. Parameters such as complex modulus G^*, phase angle δ, and rutting factor were tested. The BBR test temperature range was −6~−24°C, the temperature interval was 6°C, and the parameters such as stiffness modulus S and creep rate m were also tested.

In the Superpave asphalt binder specification, the original asphalt rutting factor $G^*/\sin\delta$ is required to be no less than 1.00 kPa. The corresponding rutting factor critical temperature can be obtained by fitting the rutting factor change curve, which corresponds to the temperature when the rutting factor is 1.00 kPa. The rutting factor is further improved, and $G^*/(\sin\delta)^9$ is used as the improved rutting factor [26]. The critical temperature was determined by exponential regression, and then, high-temperature rheological properties were evaluated. In this paper, formulas (1)

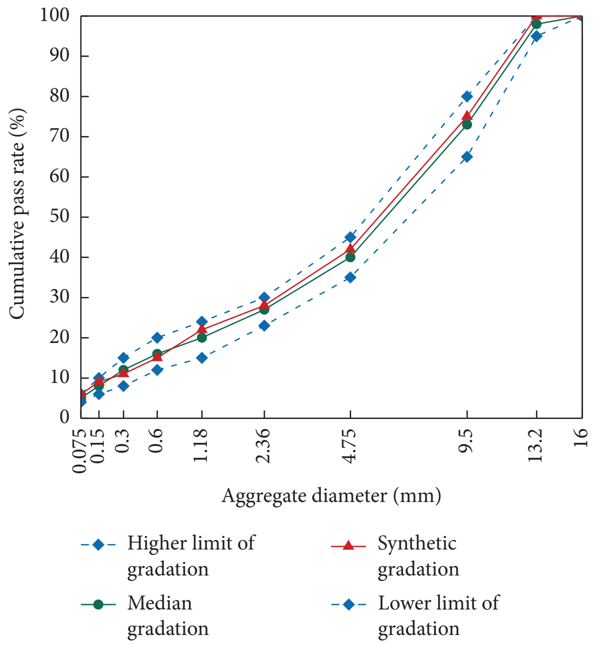

Figure 3: Synthetic gradation diagram of AC-13 asphalt mixture.

and (2) were used to perform exponential regression fitting on the rutting factor $G*/\sin\delta$ and the improved rutting factor $G*/(\sin\delta)^9$, as well as to further obtain the critical temperature, and determine its PG classification.

$$y = \exp(a + b * x + c * x\hat{2}), \quad (1)$$

$$y = d * \exp(e * x), \quad (2)$$

where a–e are regression coefficients.

2.2.3. Mixture Mix Ratio Design and Pavement Performance Test

(1) Mix ratio design. According to the grading requirements of AC-13 and SMA-13 asphalt mixture in the Technical Specifications for Construction of Highway Asphalt Pavement (JTG F40-2004), the design of mineral material gradation was carried out. The synthetic gradation diagram of the mixture is shown in Figures 3 and 4.

The optimum asphalt dosage of desulfurized rubber powder/SBS composite-modified asphalt in AC-13 mixture grading was determined to be 4.7%. According to the same method, the optimum amounts of rubber asphalt, desulfurized rubber asphalt, and SBS-modified asphalt were determined to be 6.0%, 5.7%, and 4.8%, respectively. In the gradation of SMA-13 asphalt mixture, the optimum asphalt dosage of desulfurized rubber powder/SBS composite-modified asphalt and SBS-modified asphalt was 6.0%. The optimum asphalt dosage was then applied to the road asphalt pavement mixture, and after that, test pieces were moulded for performance testing.

(2) Pavement performance test. According to the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011), the rutting test, low-temperature trabecular bending test, immersion Marshall test, and freeze-thaw splitting test were used to evaluate high-temperature stability, low-temperature cracking resistance, and water stability of asphalt mixture, respectively.

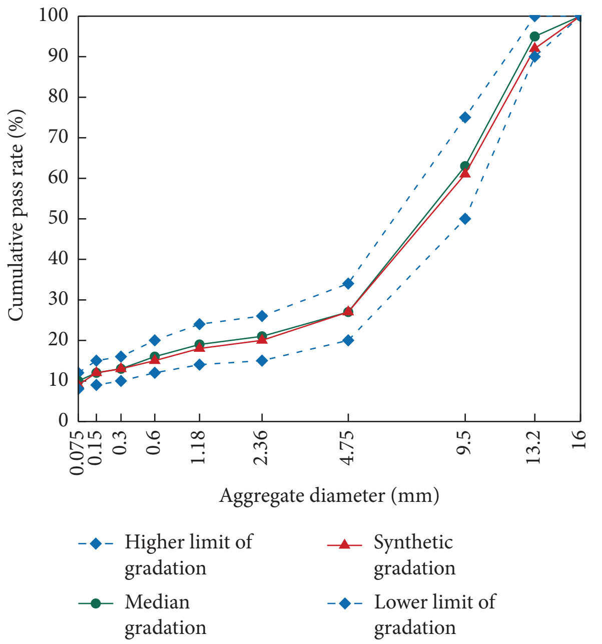

Figure 4: Synthetic gradation diagram of SMA-13 asphalt mixture.

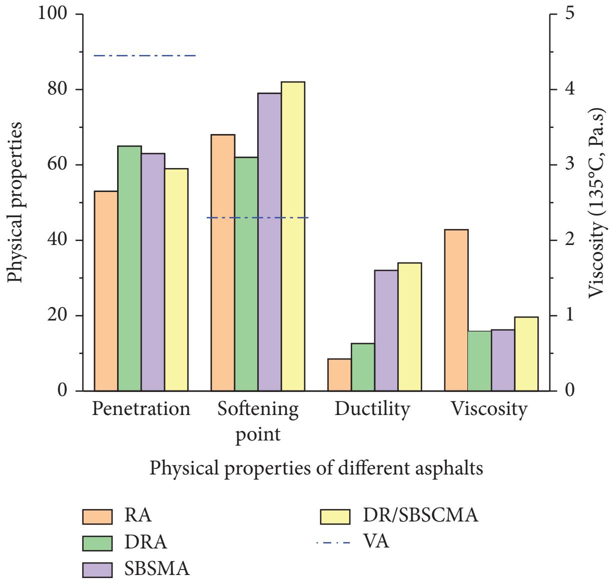

Figure 5: Test results of different basic performance indexes of asphalt.

3. Results and Analysis

3.1. Basic Performance Analysis. Penetration, ductility, softening point, and viscosity of virgin asphalt (VA), rubber asphalt (RA), desulfurized rubber asphalt (DRA), SBS-modified asphalt (SBSMA), and desulfurized rubber powder/SBS composite-modified asphalt (DR/SBSCMA) were tested. The test results are shown in Figure 5. In the follow-up research, each type of asphalt is represented by the corresponding letter code.

From Figure 5, it can be seen that the four types of modified asphalt have some improvement over the conventional performance of virgin asphalt and that the penetration, softening point, ductility, and viscosity of DR/SBSCMA could all meet the performance requirements of composite-modified asphalt in the specification. It is superior to SBSMA, RA, and DRA in ductility and softening point, especially the softening point, which reached whopping 90°C, indicating that DR/SBSCMA has excellent high-temperature performance and tensile strength. It also proves the stability of the crosslinked lattice structure, which is formed by rubber powder and SBS is higher than that of the a single modified asphalt system. The penetration of DR/SBSCMA is slightly lower than that of SBSMA and DRA but higher than that of RA. This is due to swelling and dispersion of rubber powder particles, which absorb a large amount of light oil, and composite-modified asphalt becomes hard to some extent, resulting in a decrease in penetration. With rubber-modified asphalt, the viscosity at 180°C is crucial to ensure that construction can be carried out smoothly. The viscosity of DR/SBSCMA is slightly higher than that of SBSMA and DRA but much lower than that of RA, indicating that composite-modified asphalt can fully meet construction requirements and does not affect construction workability.

3.2. Research on Rheological Properties

3.2.1. Dynamic Shear Rheological Test. The American SHRP program proposes to use the DSR test to evaluate the high-temperature stability of asphalt, test the complex shear modulus $G*$ and phase angle δ, and calculate the rutting factor $G*/\sin\delta$. In this paper, the temperature sweep was used, and the $G*$ and δ test results of the five types of asphalt at a test temperature of 34~88°C are shown in Figures 6 and 7.

From Figure 6, it can be seen that the complex shear modulus $G*$ of some asphalt gradually decreases with increasing temperature. Compared to virgin asphalt, the removal of modified asphalt is somewhat slower. In the temperature range, $G*$ of asphalt ranking from large to small goes as follows: DR/SBSCMA, SBSMA, RA, DRA, and VA, indicating that composite-modified asphalt has higher rigidity and greater resistance to deformation under load. Modifiers such as rubber powder and SBS have good resilience and strength, and their incorporation improves the viscoelastic properties of asphalt and improves the asphalt system's ability to resist deformation. Compared with the single modification, the compound modification shows greater improvement in asphalt viscoelasticity.

It can be seen from Figure 7 that the phase angle of virgin asphalt gradually increases with increasing temperature and gradually tends to 90°, thereby losing elastic deformability and entering a viscous flow state. Unlike virgin asphalt, the phase angles of four types of modified asphalt became significantly smaller at the same temperature, indicating that the addition of the modifier improved the elastic properties of the asphalt system, and showed a trend of first decreasing and then increasing with an increase in temperature. In the lower temperature range, the change in the phase angle was relatively gentle. At this time, the phase angle trend was VA > DRA > RA > DR/SBSCMA > SBSMA; when temperature exceeded 70°C, SBSMA, RA, and DRA had similar growth trends, while DR/SBSCMA was still growing slowly, and the phase angle trend at this stage was VA > RA > DRA > SBSMA > DR/SBSCMA. In the test

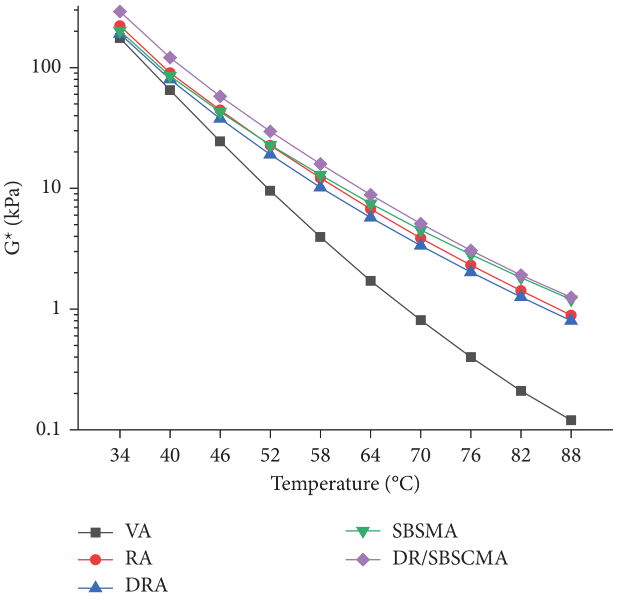

Figure 6: Relationship between complex shear modulus and temperature.

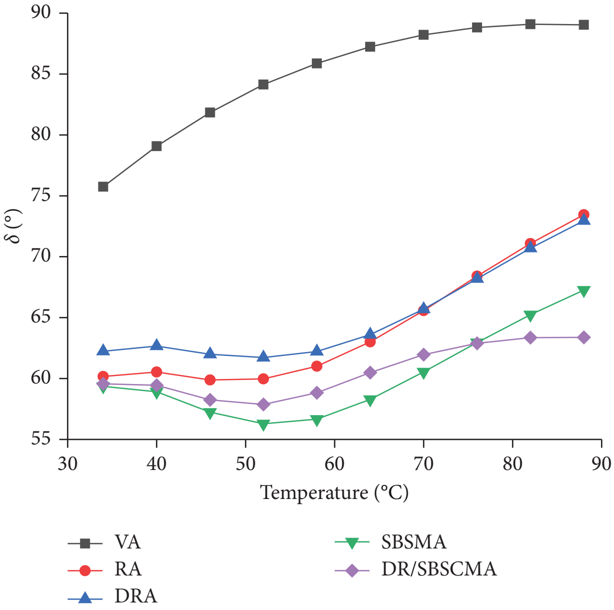

Figure 7: Relationship between the phase angle and temperature.

temperature range, high-temperature performance of DR/SBSCMA and SBSMA was better and temperature sensitivity was reduced.

The rutting factor $G*/\sin\delta$ is calculated, and the results are shown in Figure 8.

It can be seen from Figure 8 that the rutting factor gradually decreased exponentially with increasing temperature, and the rutting factor, also called high-temperature stiffness, characterizes the resistance of asphalt to rutting at high temperature. It can be intuitively seen that in the temperature range of 30–50°C, the rutting resistance of the five types of asphalt is DR/SBSCMA > RA > SBSMA > DRA > VA. When it exceeds 50°C, asphalt rutting resistance is DR/SBSCMA > SBSMA > RA > DRA > VA, with DR/SBSCMA having the strongest high temperature performance, followed by SBSMA and RA. As the temperature rises, the performance difference of four types of modified asphalt gradually decreased, and it was also shown that the improvement in high-temperature performance by the composite modification method was better than that in the single modification.

The rutting factor $G*/\sin\delta$ and the improved rutting factor $G*/(\sin\delta)^9$ were further fitted by exponential regression, respectively. The regression curves are shown in Figures 9 and 10, and it can be seen that equations (1) and (2) achieved good fitting results. On this basis, the corresponding critical temperatures of the rutting factor and the improved rutting factor were obtained, respectively, as shown in Table 9.

It can be seen from Table 9 that the difference between the critical temperature of the rutting factor determined by the regression fitting of equations (1) and (2) is not large. Overall, the fitting results of the critical temperature of formula (2) were slightly lower than those of formula (1), and the difference was basically within 3°C. DR/SBSCMA had the highest critical temperature, the strongest antirutting ability, and met the requirements of high temperature classification PG-82, followed by SBSMA, RA, and DRA, which all had the same trend as the softening point index.

The critical temperature of the improved rutting factor is higher than that of the rutting factor, indicating that the improved rutting factor is more sensitive to the phase angle, and the improved rutting factor can be selected when analyzing the difference in the high-temperature performance of modified asphalt. If high-temperature performance requirements are more stringent or the results are more conservative, the rutting factor can be selected and fitted with (2).

3.2.2. Bending Beam Rheometer Test. The creep stiffness modulus S represents the ability of asphalt to resist permanent deformation under low temperature load, and the creep rate m is the rate of change of the stiffness modulus. SHRP stipulates that $S \leq 300.0$ MPa, $m \geq 0.300$, if stiffness is too high, asphalt is brittle and prone to cracks; the thermal stress of asphalt accumulates during the process of temperature reduction, and stiffness changes. The faster the change, the stronger the relaxation stress. Therefore, a high m value and low S value can effectively reduce low-temperature cracking, and both are indispensable.

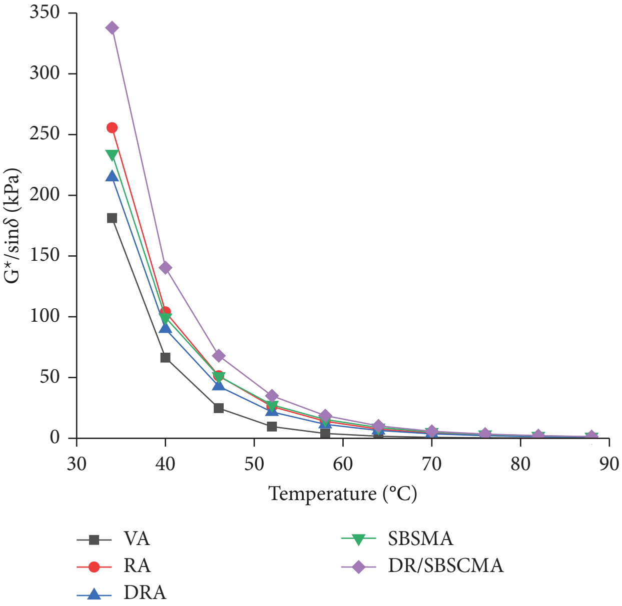

Figure 8: Test results of the rutting factor.

The creep stiffness modulus and creep rate test results are shown in Figures 11 and 12.

It can be seen from Figure 11 that in the temperature range of −12~−24°C, except for virgin asphalt, the creep stiffness modulus of four types of modified asphalt all meets the requirements of the specification (less than 300 MPa). Meanwhile, with the decrease in temperature, the stiffness modulus shows a gradual upward trend, and the increase range is quite different. DR/SBSCMA and SBSMA have the same growth trend. When temperature is higher than −18°C, the growth rate of the stiffness modulus is relatively slow, and after temperature is lower than −18°C, the amplitude increases greatly. DRA and RA are completely opposite and gradually tend to be flat when temperature is lower than −18°C. After compound modification, DR/SBSCMA did not show obvious rubber-like asphalt properties in terms of low-temperature rheological properties, which further indicated that there was more than physical swelling reaction between desulfurized rubber powder, SBS, and asphalt.

It can be seen from Figure 12 that with the decrease of temperature, the creep rate gradually decreases. At −18°C, several types of asphalt meet specification requirements. At −24°C, only DRA and DR/SBSCMA meet specification requirements. The creep rate from large to small is DRA > DR/SBSCMA > RA > SBSMA > VA. The addition of the rubber powder modifier significantly improved the elasticity of the asphalt system, enabling it to respond quickly and relax the stress in the face of thermal stress concentration, thereby reducing the possibility of cracking.

Based on the test results of the creep stiffness modulus and creep rate, low-temperature rheological properties from best to worst are DRA > DR/SBSCMA > RA > SBSMA > VA.

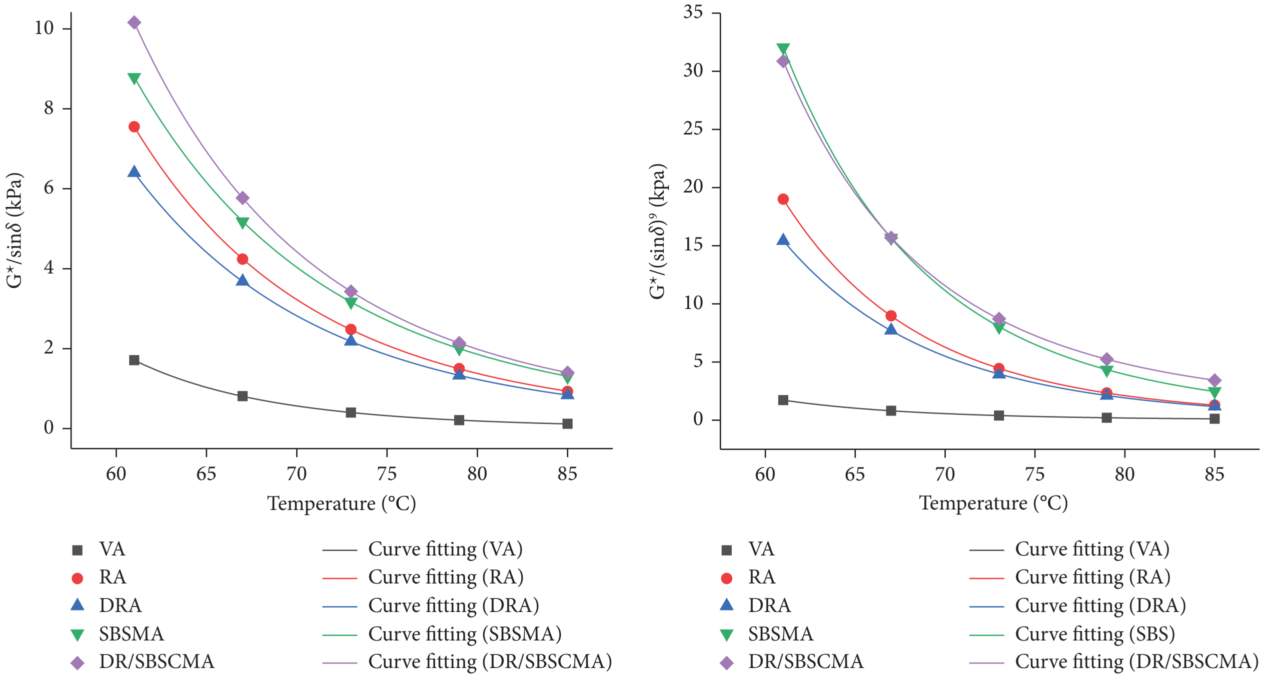

Figure 9: Equation (1) fitting regression curve.

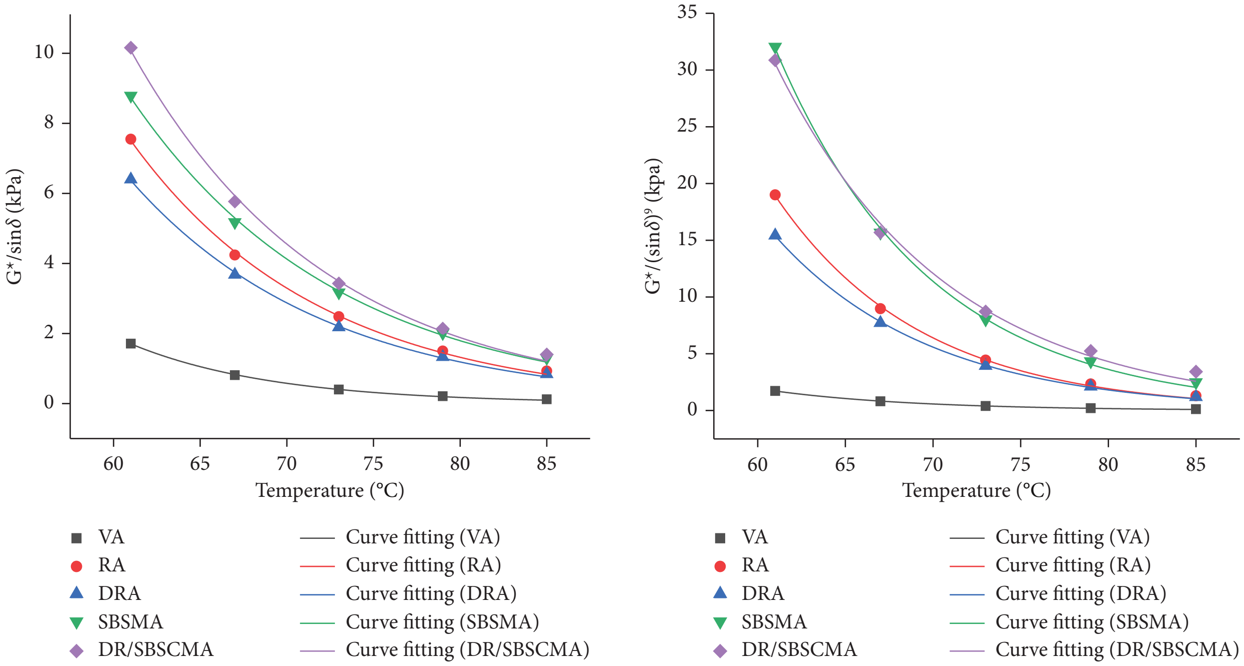

Figure 10: Equation (2) fitting regression curve.

Combined with the dynamic shear rheological test, PG grades were carried out, and DR/SBSCMA was PG82-34, DRA was PG76-34, SBSMA was PG82-28, RA was PG82-28, and VA was PG64-22.

3.3. Research on the Pavement Performance of Mixture

3.3.1. High-Temperature Stability. The high-temperature stability of asphalt mixture is mainly reflected in the ability of the pavement to resist rutting when the pavement is subjected to traffic loads during the high-temperature process in summer. The rutting test results are shown in Figure 13.

From Figure 13 it can be seen that the dynamic rut stability of four modified asphalt mixes far exceeds the requirements of more than 3000 or 5000 times/mm in the specification. Moreover, DR/SBSCMA had excellent high temperature stability for both AC-13 and SMA-13 compounds, as they both improved to varying degrees compared

Table 9: Test results of critical temperature.

Type	$G*/\sin\delta$ critical temperature (°C)		$G*/(\sin\delta)^9$ critical temperature (°C)	
	Equation (1)	Equation (2)	Equation (1)	Equation (2)
VA	65.25	65.43	65.30	65.49
RA	84.12	83.05	87.81	85.43
DRA	82.67	81.95	86.71	85.29
SBSMA	89.06	87.02	95.99	91.25
DR/SBSCMA	90.29	87.17	111.44	94.19

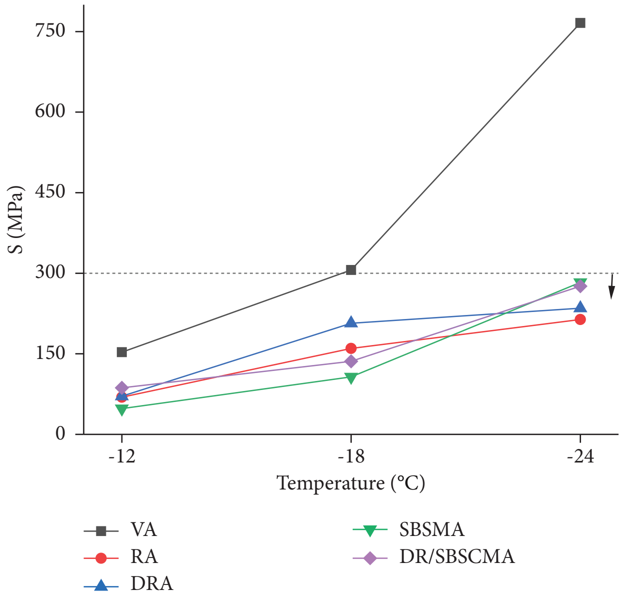

Figure 11: Creep stiffness modulus test results.

to other types of modified asphalt, and rut deformation was also effectively improved, indicating that the composite modification of desulfurized rubber powder and SBS can effectively improve mixtures' resistance to high temperature and load capacity. When continuously rated to AC-13, the dynamic stability of composite-modified asphalt was 24.3%, 7.0%, and 5.0% higher than that of RA, DRA, and SBSMA, respectively. With SMA-13 discontinuous grading, the dynamic stability of composite-modified asphalt mixture reaches 8664 times/mm, which is 5.2% higher than that of SBS-modified asphalt mixture. This shows that composite-modified asphalt has a more obvious effect on improving high-temperature stability in batch sorting and has more performance advantages. At the same time, it can be noted that under the same type of asphalt, the dynamic stability of the SMA-13 compound is significantly higher than that of the AC-13 compound. This is because the gradation composition of the SMA-13 mixture is different, and the aggregate contains coarse aggregates. During the moulding process, aggregates are embedded into a skeletal structure and pores are filled with mastic, which consists of fine aggregates, mineral powder, and asphalt. This special structure has stronger integrity and more strength, showing that SMA-13 connection has better high-temperature stability. In addition, because of high viscosity properties of composite-modified asphalt, there is no need to add lignin fibers into the composite-modified asphalt SMA mixture. When fibers are added, they affect mixing difficulty of mixture and increase production costs.

3.3.2. Low-Temperature Crack Resistance. The low-temperature cracking of asphalt pavements is prone to occur in areas with large temperature difference, and temperature drops, the volume shrinkage of mixture is limited, and temperature stress is generated. The results of the trabecular bending test are shown in Figure 14.

It can be seen from Figure 14 that the elongations at break of four types of modified asphalt in the mixed bending tests AC-13 and SMA-13 all meet the technical requirements. In the AC-13 mixture, rubber asphalt has the highest elongation at break, followed by DR/SBSCMA and SBSMA, and DRA has the lowest elongation at break, indicating that rubber asphalt has the best low-temperature crack resistance. On the other hand, in the SMA-13 mix, the low-temperature crack resistance of SBS-modified asphalt has more performance advantages than that of composite-modified asphalt. For the same type of asphalt, the crack resistance of the SMA-13 compound proved to be better than that of the AC-13 mixture.

Without considering aggregate forces, there are a large number of rubber powder particles due to the special system structure of rubber asphalt. When loaded, the load is mainly concentrated on rubber powder particles, because rubber powder has its own elastic properties, and it can absorb and consume external energy, so it can store a large amount of elastic strain energy, thereby improving the low-temperature crack resistance of rubber asphalt. Since the modified material for composite-modified asphalt and desulfurized rubber asphalt is mainly desulfurized rubber powder, desulfurized rubber powder is easier to swell and decompose into asphalt, different from ordinary rubber powder. The reaction in asphalt is more complete and forms a more stable overall structure with asphalt. At the same time, desulfurized rubber asphalt and composite-modified asphalt are manufactured by the shearing method, considering that different manufacturing methods have a certain influence on it, there are fewer and smaller rubber powder particles in asphalt. Meanwhile, rubber asphalt is produced by agitation methods, and the incompatibility of rubber powder and asphalt leads to a large number of large rubber powder particles in asphalt, which has a positive effect on low-temperature cracking resistance.

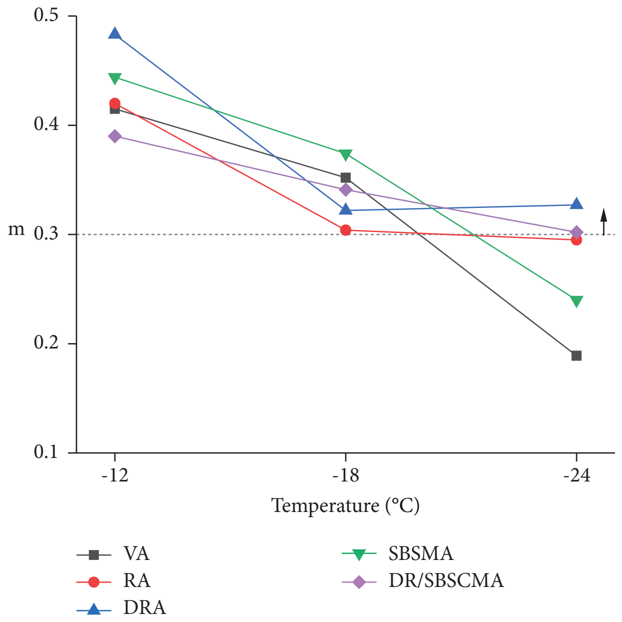

Figure 12: Creep rate test results.

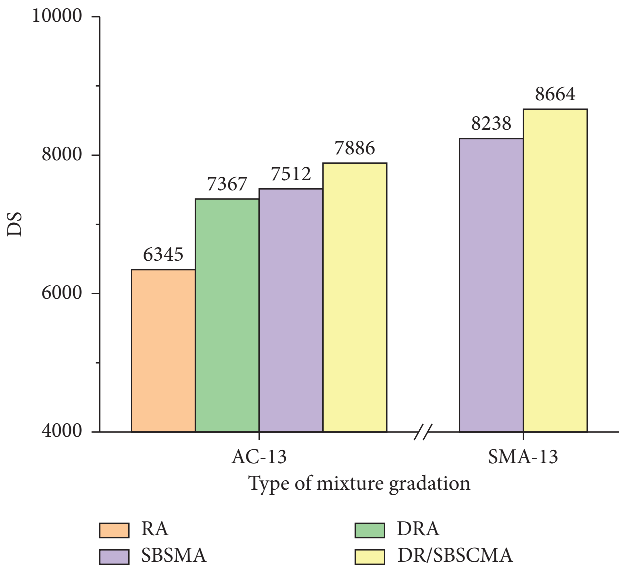

Figure 13: Results of the mixture rutting test.

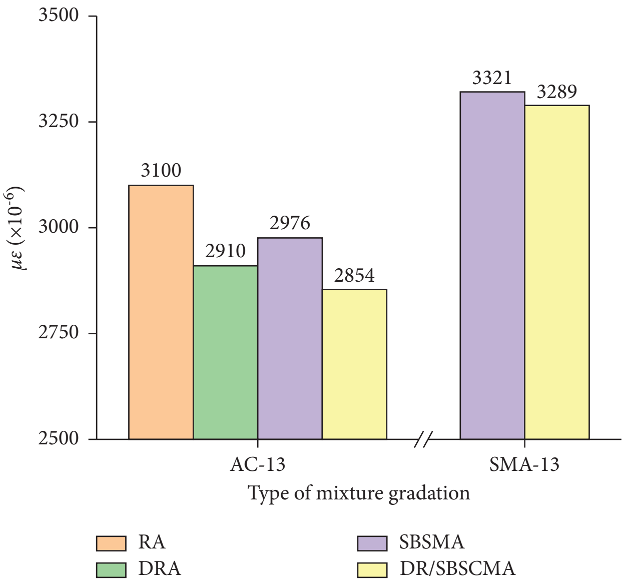

Figure 14: Results of the bending test of mixture.

In the low-temperature flexural test, rubber-modified asphalt has higher fracture stress than SBS-modified asphalt, indicating that the addition of the rubber-based modifier has a positive effect on stress absorption and is used in the asphalt pavement with high cold crack resistance requirements. When planning, it is recommended that rubber-modified asphalt be used. In addition, rubber asphalt has a better effect on reducing road noise.

3.3.3. Water Stability. Water damage usually means that under the action of rainwater and seasonal freeze-thaw cycles, road surface water enters the interior of the pavement structure through cracks or the dynamic water pressure of the load. Under the action of water and load, the adhesion between asphalt and aggregate is gradually weakened. Then, they are separated from each other and damaged. The results of immersion Marshall and freeze-thaw split tests are shown in Figure 15.

From Figure 15, it can be seen that the residual stability ratios in water immersion from large to small are DR/SBSCMA > SBSMA > DRA > RA. The residual stability of four types of modified asphalts meets the specification requirements. In AC-13 and SMA-13 mixtures, the residual stability of the composite-modified asphalt mixture exceeded 95%, and especially, in the AC-13 mixture, the residual stability of composite-modified asphalt reached 98%. This shows that it has excellent water damage resistance and that the compound modification of desulfurized rubber powder and SBS can improve the water stability of the compound. The strength of the mix depends on the cohesiveness of asphalt and the internal friction between minerals. The addition of desulfurized rubber powder and SBS increases the viscosity of asphalt, which improves the interfacial strength between asphalt and aggregates, effectively reducing oil scale detachment, and further improves adhesion and resistance to water damage, ultimately improving the water stability of the mixture.

The improvement of compound-modified asphalt by desulfurized rubber powder and SBS contrasts with other related research on rubber-asphalt mixtures. Usually, water stability is affected by the addition of rubber powder. This is because ordinary rubber powder cannot completely react with asphalt and there are a large number of incompletely dissolved rubber powder particles. As a stress concentration point, it is easy to generate stress concentration and damage. On the other hand, the addition of rubber powder to absorb the light oil and part of paraffin in asphalt increases asphaltic acid and acid anhydride in asphalt, which is beneficial for the adhesion of stone and asphalt. The two effects have a mutually weakening and strengthening effect on water stability.

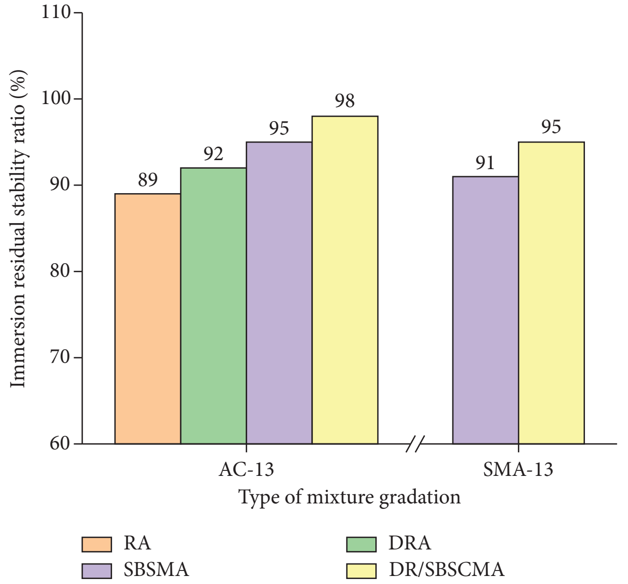

Figure 15: Marshall test results of mixture immersion in water.

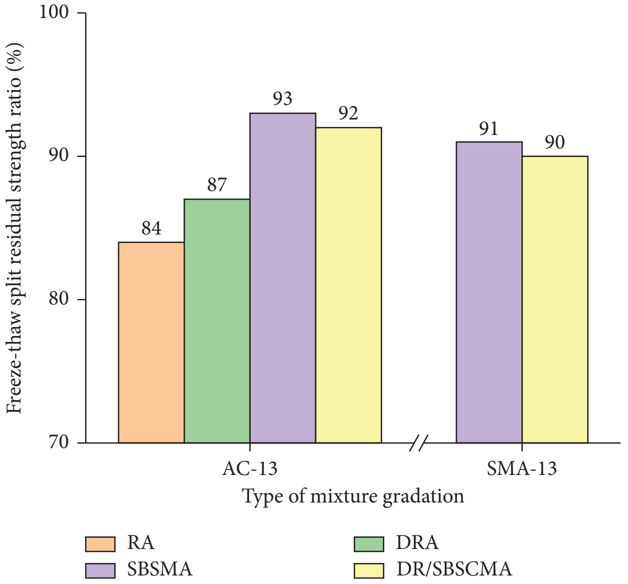

Figure 16: Results of the freeze-thaw splitting test of mixture.

The composite-modified asphalt in this study is different from conventional rubber asphalt. The modification process is no longer simple physical swelling but a compatible and stable modification of the coexistence of physical mixing and chemical reaction, forming a more stable three-dimensional network structure, and there is not a large amount of undissolved rubber powder particles. Under the compatible and stable system, mutual flow between molecules is impeded, viscosity increases, cohesion is increased, aggregate encapsulation is stronger, and cohesion is improved, and it has a greater positive effect on water stability.

The freeze-thaw splitting test results are shown in Figure 16.

It can be seen from Figure 16 that the residual strength ratio of freeze-thaw splitting is SBSMA > DR/SBSCMA > DRA > RA. In the AC-13 and SMA-13 mixtures, the residual strength ratio of the composite-modified asphalt mixture reached more than 90%, which was slightly lower than that of SBS-modified asphalt. The reason for the above results may be that rubber powder particles made asphalt hard at low temperature and viscoelastic properties decreased, thus affecting its water stability.

On the other hand, considering that the curing temperature of the specimens in the immersion Marshall test and the freeze-thaw split test were 60°C and −18°C, respectively, combined with the properties of composite-modified asphalt and SBS-modified asphalt. Composite-modified asphalt had stronger adhesion at a temperature of 60°C; SBS-modified asphalt had stronger rheological and low-temperature properties at −18°C, which are reflected in Sections 3.1 and 3.2. Thus, the different performance trends of composite-modified asphalt and SBS-modified asphalt in the two tests appeared.

Under the same asphalt conditions, the residual stability ratio and the strength ratio of AC-13 mixture are larger than those of SMA-13 mixture, indicating that AC-13 mixture has stronger resistance to water damage, which is closely related to gradation. AC-13 is a continuous dense gradation, which contains more fine aggregates, the flatness and the depth of the surface structure are small, and it is not easy for the surface water to enter the interior of the mixture structure, which reduces the impact of water damage on it. The SMA-13 mixture contains more coarse aggregates, has larger structural depth, and is more likely to accumulate and store water. Under the action of load, small molecular water easily enters the structure and affects water stability.

Based on the above analysis, composite-modified asphalt has water stability equivalent to that of SBS and even surpassed SBS-modified asphalt in the water immersion Marshall test, indicating that the composite modification improved the water damage resistance of the asphalt mixture to a certain extent, and the improvement was more obvious in the AC-13 mixture.

4. Conclusions

In this paper, the rheological properties of desulfurized rubber powder/SBS composite-modified asphalt and the properties of its mixture were studied. The main conclusions are as follows:

(1) DR/SBSCMA is superior to SBSMA, RA, and DRA in terms of ductility and softening point, especially the softening point which reached 90°C, with excellent high temperature performance and tensile strength. In addition, the penetration ofDR/SBSCMA is slightly lower than that of SBSMA, and the viscosity ofDR/SBSCMA is slightly higher than that of SBSMA and DRA but much lower than that of RA.

(2) DR/SBSCMA has higher stiffness and greater deformation resistance under load and has the strongest high-temperature performance, followed by SBSMA and RA. With the increase in temperature, the performance difference of four types of modified

asphalt gradually narrows, showing that the improvement of rheological properties by composite modification is better than that of a single modifier. Low-temperature rheological properties were as follows: DRA > DR/SBSCMA > RA > SBSMA > VA. The comprehensive high- temperature and low-temperature rheological tests were carried out for PG classification, and DR/SBSCMA was found to be PG82-34, DRA was PG76-34, SBSMA was PG82-28, RA was PG82-28, and VA was PG64-22.

(3) DR/SBSCMA maintains excellent high-temperature stability in both AC-13 and SMA-13 mixtures, which is improved to varying degrees compared with other modified asphalt, and rutting deformation is also effectively improved. It has the advantage of high-temperature performance in intermittent grading. The low-temperature cracking resistance of DR/SBSCMA is slightly lower than that of SBS-modified asphalt, but both meet the requirements of the specification. The water stability of DR/SBSCMA is comparable to that of SBS-modified asphalt, reaching more than 90%, which is better than that of RA and DRA, thereby proving its excellent water stability.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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