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Research Article

Analysis of the Influence of SBS Content and Structure on the Performance of SBS/CR Composite Modified Asphalt

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The performance of asphalt can be improved by adding styrene-butadiene-styrene (SBS) copolymer and crumb rubber (CR). This paper investigated the influence of the structure and content of styrene-butadiene-styrene (SBS) copolymer on the properties of SBS/CR modified asphalt (SBS/CRMA). These SBS/CRMA were prepared by mixing 90# matrix asphalt, 60 mesh CR powder, and SBS copolymers with two molecular structures, which were tested for penetration, softening point, ductility, and rheology. The complex modulus, phase angle, rutting factor, storage modulus, and dissipation modulus of SBS/CRMA were analyzed with the 64°C frequency sweep tests. The results revealed that the content and structure had significant impacts on the performances of SBS/CRMA, and the advantages of SBS polymer network structure in the modified asphalt system cannot be reflected when the amount of SBS was small. Meanwhile, the high-temperature stability, low-temperature tensile resistance, temperature sensitivity, and viscoelasticity of rubberized asphalt were further improved by adding a moderate amount of SBS copolymer. Furthermore, the properties of SBS/CRMA were better as the contents of SBS increased when the type of SBS doped was the same. The effect of modification improved by star-shaped SBS copolymer addition was more than that improved by linear SBS copolymer addition. As a conclusion, the content of 4 wt% star-shaped SBS and 20 wt% CR powder-modified 90# matrix asphalt has the best modification effect with the comparison of other groups.

1. Introduction

Nowadays, the demand for the performances of asphalt with the rapid development of road traffic construction is increasing. At the same time, the number of used tires is increasing with the increase in the number of motor vehicles [1]. As a nondecomposing material, the accumulation of scrap tires has a serious negative impact on the environment [2, 3]. Shredding waste tires to produce crumb rubber (CR) and then blending CR powder with petroleum asphalt can not only improve the performance of the asphalt but also solve the environmental pollution problem caused by the rubber [4].

After the asphalt is modified with CR powder, the swollen CR powder forms a stable network structure in the asphalt, which can increase the consistency of the asphalt and improve the rheology of the asphalt [5, 6]. In addition, the introduction of high molecular weight macromolecules into the matrix asphalt composed of low molecular weight small molecules can greatly improve the high-temperature deformation resistance of the asphalt [7]. In the application of rubber asphalt, the CR powder mesh can also be selected according to different types of asphalt pavements. Meng et al. [8] found that the low mesh CR powder was better for the low-speed driving region, and the high mesh CR powder was suitable for the high-speed driving region. However, there are still some problems with CR powder as asphalt modifier, such as the poor compatibility of CR powder, and asphalt leads to the unstable performance of rubber asphalt and the agglomeration of CR powder when the content is too high. In order to ensure that CR powder and asphalt can be mixed homogeneously, the amount of CR powder must be strictly controlled during the preparation of modified asphalt. Li et al. [9] proposed that the physical performances were optimal when the CR contents were 20–25 wt% for SK 90# matrix asphalt and 22–26 wt% for SK 70# matrix asphalt.

Therefore, there is a great need for additional modifiers to prepare composite modified asphalt to compensate for these limiting factors to enhance the high- and low-temperature performance, temperature sensitivity, and rheology of rubber asphalt [10].

There are many polymers used for asphalt modification. Among them, styrene-butadiene-styrene (SBS) copolymer is the preferred one with the superb properties of elasticity and strength which can improve the high-temperature and low-temperature performance of asphalt at the same time [11, 12]. Kök et al. [13] compared the performance of CR modified asphalt (CRMA) with SBS modified asphalt (SBSMA), and the results showed that CRMA can achieve the same performance as SBSMA when the dosage of CR reaches twice the dosage of SBS. The modified asphalt with the compound of SBS and rubber not only can improve the elasticity and high-temperature performance of asphalt but also has better comprehensive economic benefits due to the fact that the price of SBS is higher, while the price of CR powder is lower [14].

It can be seen from the above literature that the asphalt modified by SBS and CR powder has a superior research foundation, and some researchers have carried out related research on the composite modification of SBS and CR powder. Qian and Fan [7] blended 20 wt% CR powder with various amounts of SBS and two base asphalts to prepare SBS/CRMA; the performance test results of modified asphalt showed that the increase of SBS content can enhance the elastic properties of modified asphalt, thereby improving its rheology. Jiang et al. [15] evaluated the damping performance of SBS/CRMA, the results showed that SBS improved the integrity of the rubber asphalt system, and the cross-linking reaction of CR and SBS further enhanced the integrity of the modified asphalt system, thereby increasing the damping performance of asphalt. Li et al. [16] studied the thermal-oxidative aging of SBS/CRMA, and the results showed that, during the aging process of modified asphalt, SBS and CR modifiers played an antiaging effect, and SBS/CRMA had excellent antiaging properties. Qian et al. [17] studied the influence of CR powder particle size and SBS structure on the performance of SBS/CRMA, and it was found that larger CR particles were more advantageous in antirutting and antifatigue properties of asphalt, while smaller CR particles were more conducive to improve low-temperature cracking resistance and stability. Through the research mentioned above, it can be known that the complex structure of SBS has different degrees of influence on the modified performance of asphalt, and the influence of its content on the modified asphalt is also different. At the same time, the research of SBS/CRMA is practical and novel in a way, but the differences in SBS structure and dosage influencing the performance of SBS/CRMA have not been studied clearly yet. Therefore, in order to solve this problem, this article has conducted an in-depth study on SBS/CRMA with different structures and content of SBS modifiers. In this paper, various contents of SBS with two types of structure and CR powder were used to modify the matrix asphalt by mixing and high-speed shearing. The high-temperature stability, temperature sensitivity, viscoelasticity, and antideformation ability of all asphalt samples were studied by conventional (penetration, ductility, and softening) tests and dynamic shear rheological tests, and then the effects of the structure and content of SBS copolymers on SBS/CRMA were conducted by analyzing the test results.

2. Materials and Methods

2.1. Materials. In this study, the 90# base asphalt was supplied by the Maoming Branch of China Petroleum and Chemical Corporation. As per JTG F40-2004 of China, the basic properties of base asphalt are shown in Table 1. CR powder of 60-mesh size was purchased from Sichuan Huayi Rubber Factory. The SBS copolymer was selected as a modifier where the linear SBS was YH792 SBS produced by Yueyang Baling Petrochemical and the star-shaped SBS copolymer was SBS4402 SBS produced by Yanshan Petrochemical.

2.2. Preparation of Samples. Firstly, the base asphalt was heated until it flowed fully in the vessel. As the temperature rose to 175°C, 20 wt% CR powder (by weight of base asphalt) was gradually added to the base asphalt and stirred at 1200 rpm for 20 minutes. Then, shearing was continued at a speed of 2500 rpm for 20 minutes when the temperature dropped to 170°C, after which rubberized asphalt (CRMA) was obtained. Secondly, keeping the temperature as a constant, amounts of SBS (1 wt%, 2 wt%, 3 wt%, and 4 wt% by the mass of the base asphalt) and furfural extraction oil (8 wt% by the mass of the base asphalt) were added slowly to the CRMA. Then, the asphalt blends were stirred at 1200 rpm for 30 minutes, and shearing was continued at 5000 rpm for 40 minutes. Finally, the blends were stirred for 1 hour at 170°C and 1000 rpm to obtain SBS/CR powder composite modified asphalt (SBS/CRMA). The sample preparation process is shown in Figure 1. Next, the modified asphalt mixed with 1 wt%, 2 wt%, 3 wt%, or 4 wt% star-shaped SBS was coded as SSA1, SSA2, SSA3, and SSA4, respectively; similarly, the modified asphalt mixed with 1 wt %, 2 wt%, 3 wt%, or 4 wt% linear SBS was coded as LSA1, LSA2, LSA3, and LSA4, respectively.

2.3. Test Methods. In this paper, the test content mainly includes penetration, softening point, ductility, and dynamic shear rheology (DSR) test. The experimental instruments used to test asphalt performance indexes mainly include DF-6 asphalt penetration meter, DF-10 softening point meter, SY-1.5D asphalt extensometer, and MCR102 dynamic shear rheometer (as shown in Figure 2). Penetration, softening point, and ductility are the basic performance parameters of road asphalt, which are widely applied to evaluate the high- and low-temperature performance and temperature sensitivity of asphalt. Measurements of penetration (15°C, 25°C, 30°C, 100–g, 5–s, and 0.1 mm), softening point (Ring-and-Ball method), and ductility (5°C) were conducted in accordance with the standard JTG E20-2011.

DSR test was utilized to characterize the rheological properties of asphalt as a viscoelastic material [18].

Table 1: Basic performances of neat asphalt.

Item	Unit	Standard values	Values
Penetration (25°C, 100 g, 5 s)	0.1 mm	80~100	84
Penetration index	—	−1.5~1.0	−1.02
Softening point	°C	≥45	46.0
Dynamic viscosity (60°C)	Pa·s	≥160	178
Ductility (10°C)	cm	≥20	>100
Ductility (15°C)	cm	≥100	>100
RTFOT residue			
Quality change	%	−0.8~0.8	−0.112
Residual penetration ratio	%	≥57	62.4
Residual ductility (10°C)	cm	≥8	11.9

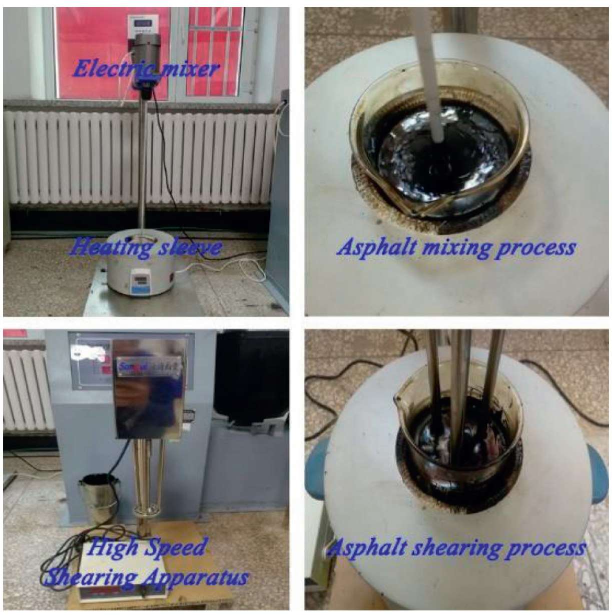

Figure 1: Mixing and shearing of modified asphalt.

Figure 2: Dynamic shear rheometer (DSR).

Table 2: Penetration test results of asphalt binder.

Asphalt type	Penetration (0.1 mm) 15°C	25°C	30°C	Regression equation	R^2	PI
CRMA	16.83	36.37	51.67	$\lg P = 0.0326T + 0.7391$	0.999	1.41
SSA1	28.80	55.23	76.90	$\lg P = 0.0284T + 1.0329$	0.999	2.40
SSA2	28.00	52.03	71.60	$\lg P = 0.0271T + 1.0394$	0.999	2.74
SSA3	27.67	49.47	67.33	$\lg P = 0.0257T + 1.0557$	0.999	3.13
SSA4	25.37	45.60	59.13	$\lg P = 0.0246T + 1.0367$	0.998	3.45
LSA1	25.50	54.87	76.47	$\lg P = 0.0298T + 0.9920$	0.999	2.05
LSA2	26.60	51.07	67.60	$\lg P = 0.0274T + 1.0160$	0.998	2.66
LSA3	26.37	48.17	65.73	$\lg P = 0.0264T + 1.0243$	0.999	2.93
LSA4	22.13	42.40	55.90	$\lg P = 0.0253T + 0.9910$	0.999	3.25

According to related researches and comprehensive consideration of the AASHTO asphalt evaluation system, 64°C was adopted as the frequency sweep test temperature in this paper [19–21]. In this paper, the frequency sweep tests were carried out with a diameter of 25 mm and a gap of 1 mm at 64°C, and the frequency domain was 0.1–100 rad/s. Moreover, the resin molds with a diameter of 25 mm and a thickness of 2 mm were used to prepare binder samples. The modified asphalt was poured into the mold after heating to a flow state and then waited until the samples cooled down for the preparation of DSR tests. Through the DSR test, the complex shear modulus (G^*) and phase angle (δ) can be directly obtained, and the rutting factor ($G^*/\sin\delta$), storage modulus ($G^* \cdot \cos\delta$), and dissipation modulus ($G^* \cdot \sin\delta$) can also be obtained by calculating these two parameters.

3. Results and Discussion

3.1. Penetration. Penetration is one of the important indicators of asphalt, which is used to indicate the hardness and consistency of asphalt. The penetration test results of each kind of asphalt binder are listed in Table 2. In the table, the penetrations of 15°C, 25°C, and 30°C were treated by semilogarithm and linearly fitted with the temperature. The obtained linear regression correlation coefficients (R^2) are all greater than 0.997, indicating that the fitting results are accurate. The penetration index (PI) was calculated according to the fitting result as in the two following equations:

$$\lg P = AT + K, \tag{1}$$

$$\mathrm{PI} = \frac{20 - 500A}{1 + 50A}, \tag{2}$$

where $\lg P$ is the logarithm of the penetration value measured under different temperature conditions; T is the test temperature (°C); K is the constant term of the regression equation; A is the regression equation coefficient; and PI is the penetration index.

The penetration values of all asphalt samples at 25°C are plotted in Figure 3. It can be seen from the figure that, compared to the CRMA, the penetration of the asphalt was significantly improved after adding SBS to the CRMA. But, comparing the penetration of SBS/CRMA, it can be found

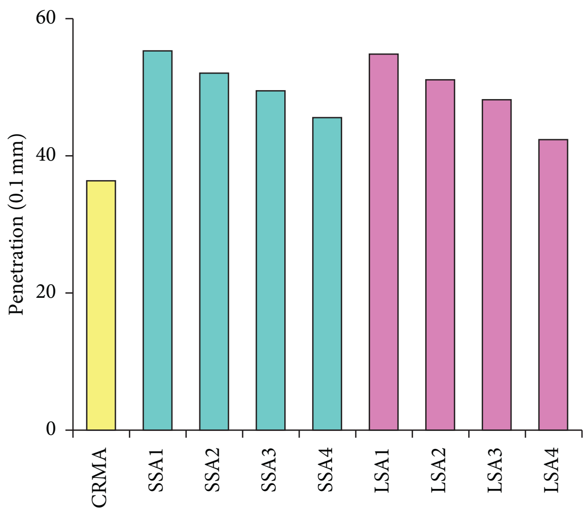

FIGURE 3: Penetration for each asphalt binder.

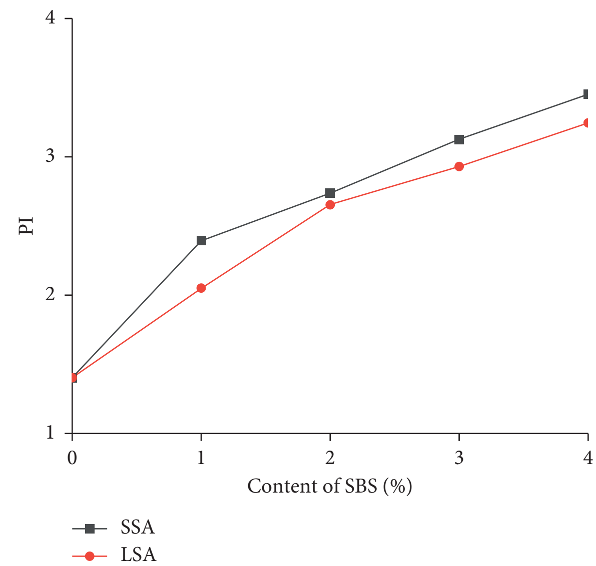

FIGURE 4: Variation of penetration index (PI) with the SBS contents for modified asphalts.

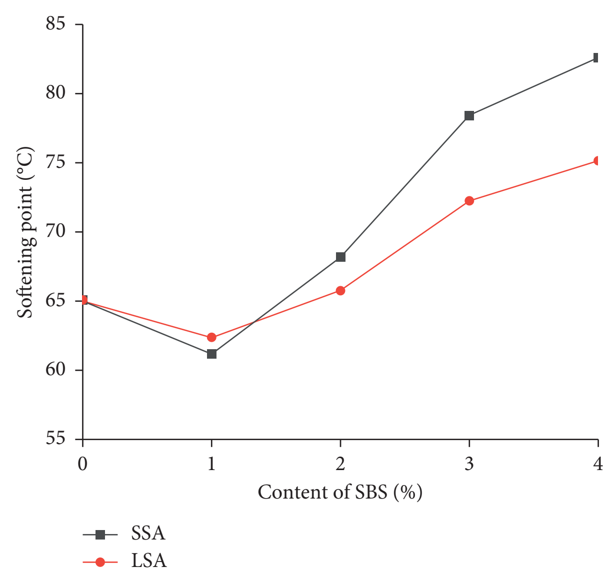

FIGURE 5: Variation of softening point with the SBS contents for modified asphalts.

that the penetration of SBS/CRMA shows a downward trend with the increase of the amount of SBS. The reason is that SBS is evenly dispersed under the action of high-speed shearing, forming an interconnected network structure. As the content of SBS increases, the viscosity of the asphalt increases and the permeability decreases. In addition, the permeability of SSA was higher than that of LSA when the content of SBS is the same, and the difference in permeability increases with the increase of SBS content.

The variations in PI of modified asphalts with the increase of SBS content for modified asphalts are shown in Figure 4. In the figure, all asphalt samples were divided into two groups of LSA and SSA according to the different types of SBS, which were added into matrix asphalt. The PI of CRMA was the point where the SBS content was 0 wt%. It can be seen in Figure 3 that the PI of SSA and LSA increases with the increase of the amount of modifier. The PI of the two modified asphalts increases significantly when the content of SBS is 0-1 wt%, indicating that the addition of SBS can reduce the temperature sensitivity of the asphalt. Moreover, the penetration index of SSA is generally higher than that of LSA, and this shows that the temperature sensitivity of modified asphalt mixed with star-shaped SBS is lower than that of modified asphalt mixed with linear SBS.

3.2. Softening Point. The softening point can reflect the high temperature stability and viscosity of asphalt. The relationship between the softening point of SBS/CRMA and the SBS content is shown in Figure 5. The softening points of the two modified asphalts show a downward trend when the SBS content is 0 wt%-1 wt%. The main reason is that the SBS copolymer and the asphalt cannot be completely miscible. The compatibility of the two is essentially a physical blend; that is, the SBS is fully sheared and stirred evenly in the asphalt with the help of a high-speed shearing machine. Therefore, the SBS is more fully sheared and broken into smaller particles to be dispersed in the asphalt when the blending amount of SBS is 1 wt%. The further reduction in the particle size of SBS leads to a lower softening point of SSA1 and LSA1 than CRMA.

Meanwhile, the softening point of LSA is higher than that of SSA when the amount of SBS is small. From the perspective of SBS structure, it is because linear SBS has better compatibility with asphalt, and linear SBS is easier to form a stable system than star-shaped SBS when the amount of SBS is lower. As the content of SBS continues to increase, the softening point of SBS/CRMA shows an overall upward trend, and the softening point of SSA is higher. It can be concluded that the star-shaped SBS can form a stronger network structure with the asphalt, which helps to stabilize the asphalt in the high-temperature flow state, so the effect of improving the high-temperature stability of the asphalt is more significant.

3.3. Ductility. Ductility is an important index to characterize the plasticity of asphalt, where temperature has a great influence on it [22, 23]. In this paper, the ductility of 5°C was used to evaluate the low-temperature crack resistance of asphalt under external force. Figure 6 shows the relationship between the ductility of SBS/CRMA and the amount of SBS. It can be found that the ductility of asphalt binders increases when the amount of SBS increases whatever the type of SBS was chosen. Meanwhile, LSA outperforms SSA in the ductility. The reason is that SBS and CR powder adsorb the surrounding asphalt to form a cross-linked network, which increases the intermolecular force, thereby effectively offsetting and dispersing the stress and improving the ductility of the asphalt.

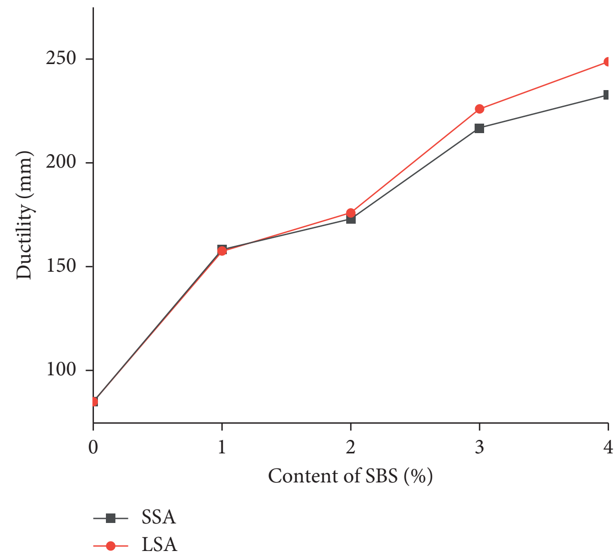

Figure 6: Variation of ductility with the SBS contents for modified asphalts.

3.4. Frequency Sweep Test. In this paper, the high-temperature rheological properties of modified asphalt were evaluated by analyzing the results of DSR frequency sweep test. The temperature condition of the test was 64°C, and the frequency domain was 0.1–100 rad/s. Through this test, the complex shear modulus (G^*) and the phase angle (δ) of all asphalt binders can be directly obtained. Between them, G^* measures the overall ability to resist deformation under dynamic shear loading, and the variation curves of G^* in the frequency domain of 0.1–100 rad/s are shown in Figure 7. From the longitudinal comparison in the figure, it can be found that the complex modulus of LSA1 and SSA1 is lower than that of CRMA. This is mainly due to the SBS content at a low stage that affects the softening point of asphalt binders negatively, and the results of these two asphalt samples are softer than CRMA at 64°C. The lower softening point of LSA1 and SSA1 indicates that the cohesion between internal components was weaker than CRMA; thus, as for LSA1 and SSA1, the ability to resist external deformation was weaker then. As the SBS content continues to increase, the G^* value of the asphalt binder increases, indicating that a certain amount of SBS can effectively improve the antideformation ability of the asphalt.

δ is the ratio of the elastic component to the viscous component in the asphalt. The greater δ, the more the viscous component in the asphalt, that is, the more the unrecoverable part of the deformation and the easier the asphalt will be deformed [24]. The variation curves of δ in the frequency range of 1–10 rad/s for each asphalt sample are shown in Figure 8. The loading frequency of 10 rad/s is equivalent to the simulated high-speed driving speed of 60 km/h. It can be found in Figure 8 that as the loading frequency increases, δ of all asphalt samples shows a downward trend, indicating that, under the action of high-speed vehicle load, each asphalt binder has more elastic components and stronger resistance to permanent deformation.

Meanwhile, δ of the LSA and SSA asphalt samples gradually decreased with the increase of the SBS content. The main reason for this change is that the increase of the SBS content increases the elastic component of the modified asphalt, and δ decreases accordingly. Furthermore, the phase angle of SSA is smaller than the phase angle of LSA when the SBS content is the same. This is mainly due to the internal cross-linking of the star-shaped SBS to form a dense three-dimensional network structure with greater strength, which is more effective to improve the elasticity of the modified asphalt. From comprehensive analysis of Figures 7 and 8, SSA4 shows the maximum complex modulus value and the minimum phase angle value among all asphalt samples, indicating that its antideformation ability and antirutting ability are the best.

The rutting factor ($G^*/\sin\delta$) is an important index to evaluate the high-temperature performance of asphalt, and the larger the rutting factor, the stronger the resistance of asphalt to rutting [25, 26]. The change curves of $G^*/\sin\delta$ with frequency for all asphalt samples are shown in Figure 9. In the figure, it can be seen that the change trend of $G^*/\sin\delta$ is similar to that of G^*. By intragroup comparison of the change curves of LSA and SSA, it can be found that $G^*/\sin\delta$ of LSA and SSA increased with the increase of the content of SBS in the range of 0.1–100 rad/s. The $G^*/\sin\delta$ curves of LSA1 and SSA1 in the figure are slightly lower than CRMA, indicating that $G^*/\sin\delta$ of asphalt binders have not been improved when the SBS content was 1 wt%. This result should be attributed to the fact that when the SBS content is low, the new phase composed of a small amount of SBS and CR powder prevented the degradation and dispersion of the CR powder in the asphalt, reducing the effect of CR on improving the elasticity of modified asphalt. Therefore, although SBS can increase the stiffness of asphalt, the increase of asphalt stiffness caused by SBS cannot make up for the decrease of rubber asphalt elasticity when the SBS content is low. When the SBS content exceeds 2 wt%, the $G^*/\sin\delta$ curves of LSA and SSA are higher than CRMA, indicating

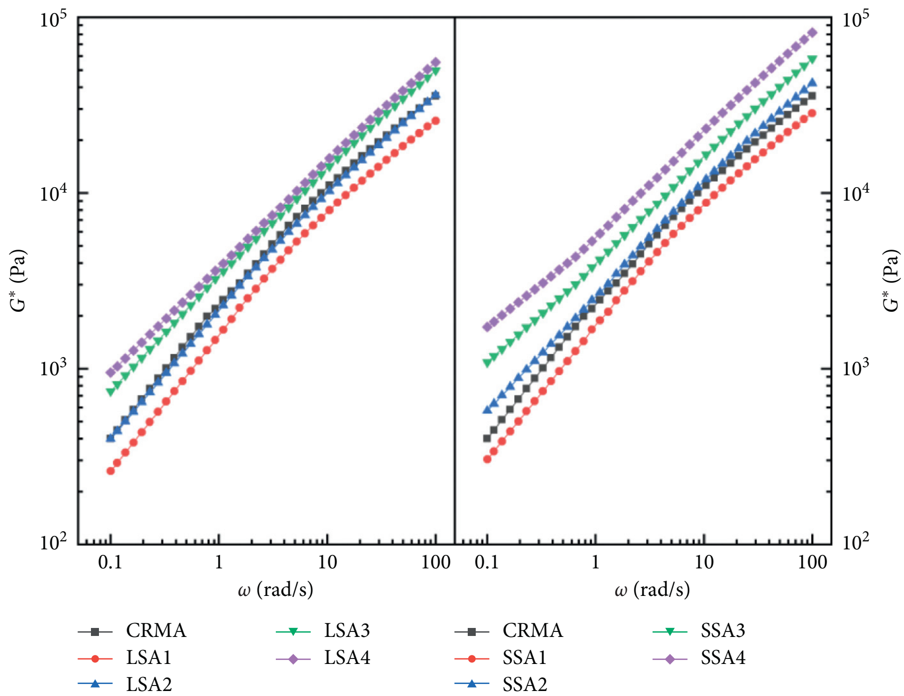

Figure 7: Variation of G^* with the SBS contents for modified asphalts.

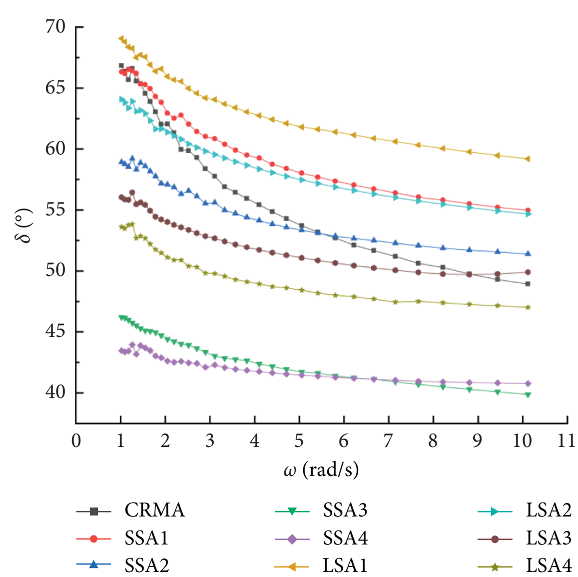

Figure 8: Variation of δ with the SBS contents for modified asphalts.

that only when the SBS content reaches a certain value can the beneficial modification effect on asphalt be achieved.

Comparing the two sets of asphalt samples of LSA and SSA, it can be found that $G^*/\sin\,\delta$ of SSA at the same SBS content is higher. Mainly because the star-shaped SBS structure is similar to the polymer cross-linked structure and has greater rigidity, after being dispersed in the asphalt, the modification effect of the asphalt is more obvious. SSA4 has highest $G^*/\sin\,\delta$ among all asphalt samples, indicating that it has the best high-temperature performance and antirutting ability. It can be concluded that the 4 wt% content of star-shaped SBS has the best effect on CRMA modification in this study.

In order to analyze the elastic and viscous behavior of asphalt at different frequencies, G^* was further divided into storage modulus ($G' = G^* \times \cos\,\delta$) and loss modulus ($G'' = G^* \times \sin\,\delta$), as shown in Figure 10, where G' characterized the elastic component in asphalt, and G'' characterized the viscous component in asphalt.

As shown in Figures 11 and 12, in the frequency domain of 0.1–100 rad/s, G' and G'' show an upward trend as the frequency increases. It can be found in Figure 11 that the G'

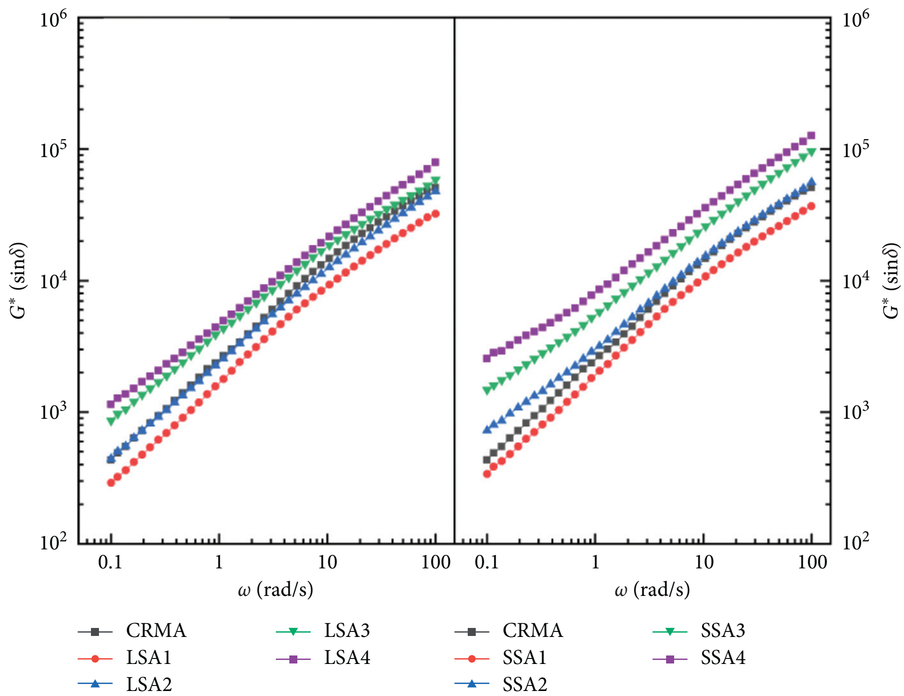

FIGURE 9: Variation of $G^*/\sin\,\delta$ with the SBS contents for modified asphalts.

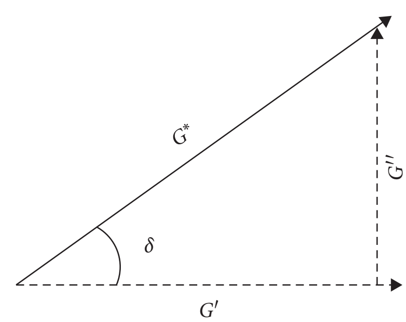

FIGURE 10: Modulus parameter relationship.

values of LSA1 and SSA1 are lower than CRMA when the SBS content is 1 wt%, and there is an intersection point between LSA2 and CRMA, which indicates that the elastic component of CRMA gradually becomes higher than the elastic component of LSA2 with the frequency increases. Moreover, the G' value of the two modified asphalts continued to rise with the further increase of the SBS content, and the SSA increase was more significant, of which the G' value of SSA4 was one order of magnitude higher than that of SSA1. The G' value of SSA under the same SBS content is higher than that of LSA, indicating that the addition of star-shaped SBS has a better effect on improving the elastic properties of asphalt [27].

Comparing the G'' change curves of the two groups of asphalt binders in Figure 12, it can be found that, in the same frequency domain [28], the growth of G'' is not obvious with the increase of the SBS content. Among them, the G'' curves of LSA3 and LSA4 are almost the same. Similar to the G' curve, the G'' value of SSA under the same SBS content is higher than that of LSA, indicating that the star-shaped SBS has a more obvious improvement effect on asphalt viscosity. Overall, the viscoelasticity of asphalt can be enhanced by adding SBS modifiers, and the degree of enhancement is inseparable from the content and structure of SBS.

Moreover, comparing the values of G' and G'' in the test frequency range, it can be found that, in the low-frequency range, the rheological behavior of modified asphalt is dominated by viscous components. Then, the G' value of each asphalt binder is higher than the G'' value after the frequency increases, and the elastic deformation is greater than the irreversible deformation in the modified asphalt. In addition to being affected by frequency changes, G' and G'' of LSA and SSA all increase with the increase of SBS content. Among them, the growth of G' can reach an order of magnitude, which is significantly higher than the growth of G''. This result reveals that the addition of SBS modifiers to CRMA mainly enhanced the elastic ability of asphalt to improve the rheological properties of asphalt.

3.5. Three-Parameter Solid Model. Since a single elastic element or viscous element cannot satisfy the description of the mechanical behavior of a viscoelastic material, the elastic element and the viscous element are usually combined to characterize the mechanical behavior of the viscoelastic material. The model composed of the Kelvin model and a spring in series is called a three-parameter solid model, in which the Kelvin model is composed of a spring and a dashpot in parallel, as shown in Figure 13 [29].

The three-parameter solid model of viscoelastic materials gives the constitutive equation as follows:

$$\sigma(t) * \left(E_0 + E\right) + \eta\dot{\sigma}(t) = EE_0\varepsilon(t) + E_0\eta\dot{\varepsilon}(t). \quad (3)$$

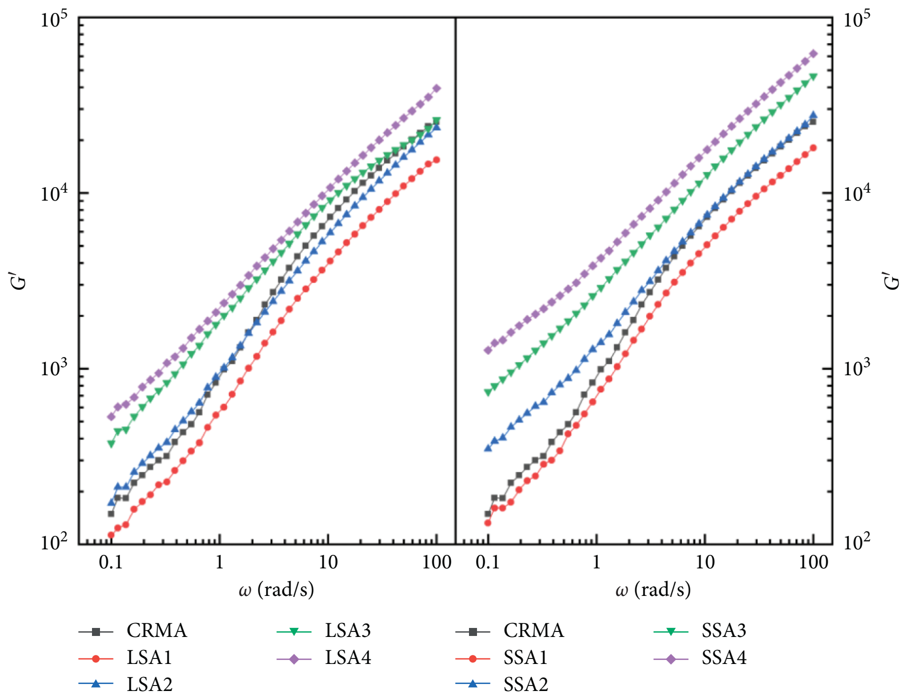

Figure 11: Variation of G' with the SBS contents for modified asphalts.

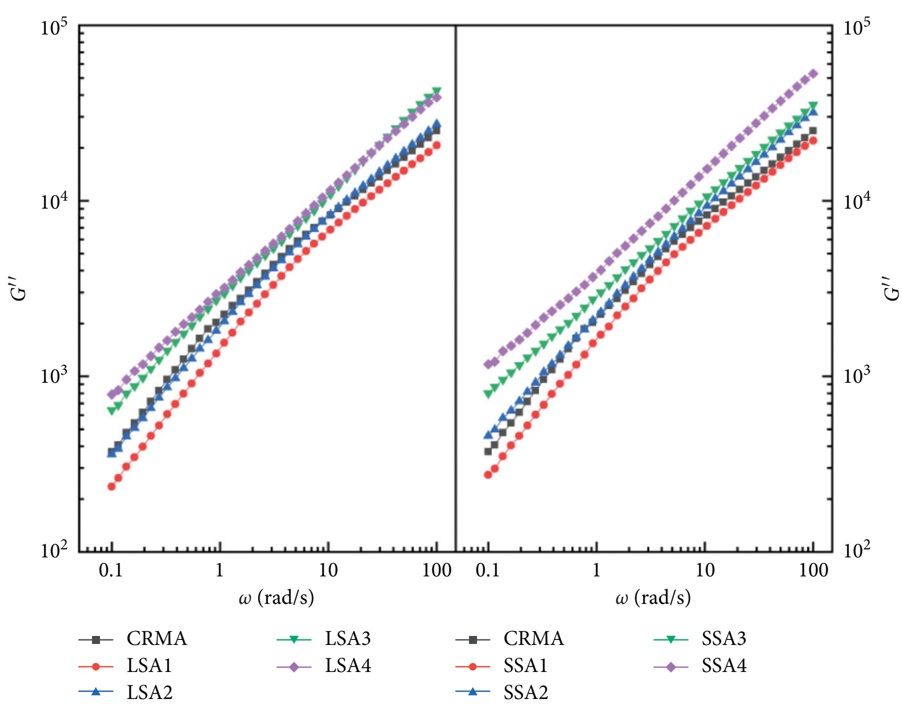

Figure 12: Variation of G'' with the SBS contents for modified asphalts.

The three-parameter solid complex modulus formula gives the constitutive equation as follows:

$$G^*(i\omega) = \frac{EE_0(E+E_0) + E_0\eta^2\omega^2}{(E+E_0)^2 + \eta^2\omega^2} + \frac{E_0^2\eta\omega}{(E+E_0)^2+\eta^2\omega^2} i, \quad (4)$$

where E (Pa) and E_0 (Pa) are unknown modulus parameters, η (Pa · s) is the unknown viscosity parameter, and ω (rad/s) is the angular frequency.

According to the complex modulus expression $G^* = G' + G''i$, the storage modulus and loss modulus are given by the two following equations:

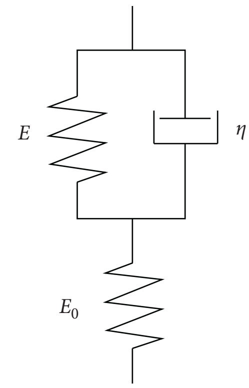

FIGURE 13: Three-parameter solid model.

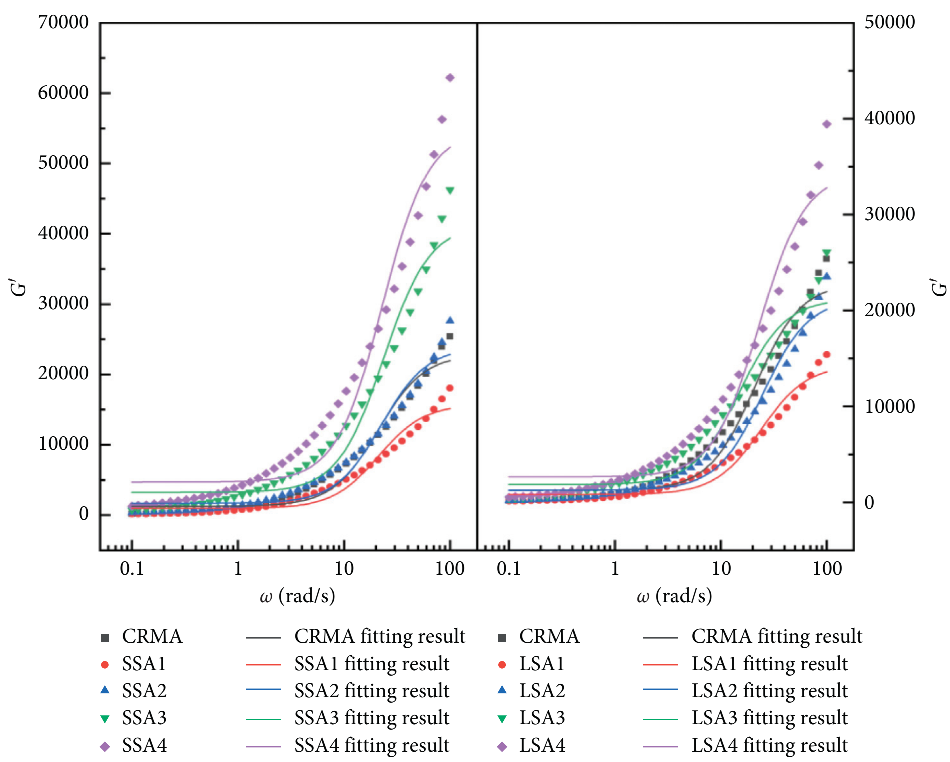

FIGURE 14: Storage modulus fitting curve.

$$G'(\omega) = \frac{EE_0(E+E_0) + E_0\eta^2\omega^2}{(E+E_0)^2 + \eta^2\omega^2}, \tag{5}$$

$$G''(\omega) = \frac{E_0^2\eta\omega}{(E+E_0)^2 + \eta^2\omega^2}. \tag{6}$$

According to equation (5), the storage modulus results in the test frequency range are nonlinearly fitted, and the fitting results are shown in Figure 14. It can be seen from Figure 14 that the trend of the fitted curves is basically consistent with the trend of the experimental data. Therefore, this paper mainly uses a three-parameter solid constitutive model to obtain E_0, E, and η parameter values and characterizes the influence of SBS structure and content changes on the mechanical properties of modified asphalt through the changing trend of each parameter [30, 31].

The parameter values of E_0, E, and η in equation (5) are obtained by nonlinear fitting, and the fitting results are shown in Table 3.

According to the correlation coefficient R^2 in Table 3, it can be found that the three-parameter solid model has a better fit for the storage modulus in the frequency range of 0.1–100 rad/s at 64°C. The variation curves of the fitting parameters E_0, E, and η of SSA and LSA with SBS content are depicted in Figure 15.

Table 3: Storage modulus fitting parameter results.

Asphalt type	E (Pa)	E_0 (Pa)	η (Pa·s)	R^2
CRMA	1333.071	22885.376	1154.752	0.968
SSA1	1007.848	15781.925	796.865	0.966
SSA2	1807.533	23904.749	1147.557	0.966
SSA3	3515.963	41394.054	1898.089	0.965
SSA4	5150.446	54793.403	2613.331	0.963
LSA1	875.173	14338.687	634.908	0.968
LSA2	1364.140	21280.397	909.758	0.968
LSA3	2020.156	21208.892	1541.044	0.962
LSA4	2870.786	34399.861	1614.797	0.963

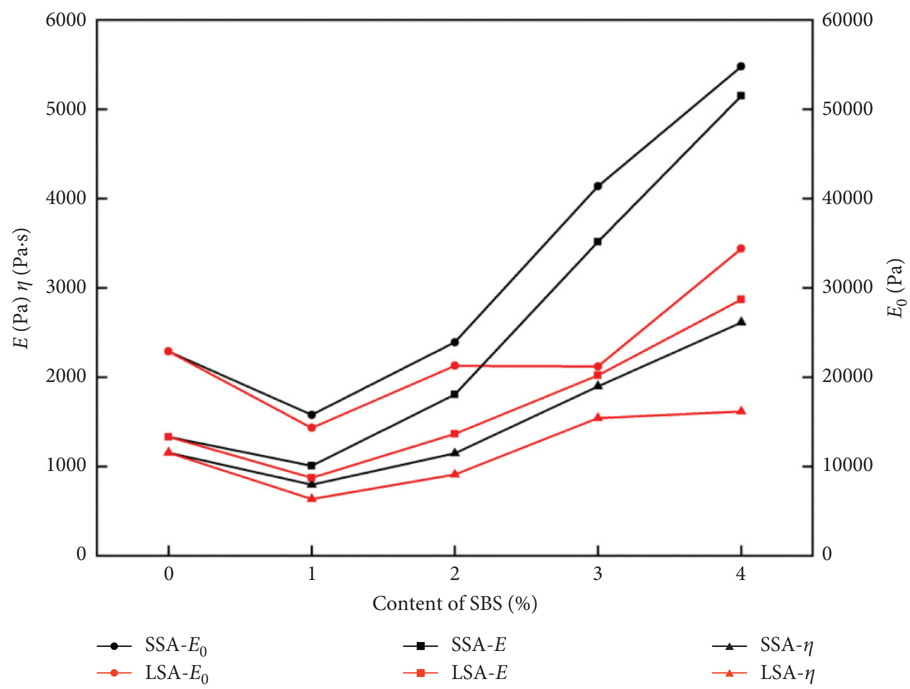

Figure 15: Variation of E, E_0, and η with the SBS contents.

The parameters in the three-parameter solid model have relatively clear mechanical meanings. E and η, respectively, represent the elastic part and the viscous part of delayed deformation, and E_0 represents the instantaneous deformation part. It can be seen from Figure 15 that, with the increase of SBS content, the change curves of E, E_0, and η all show an upward trend, indicating that the instantaneous deformation of modified asphalt decreases with the increase of SBS content. The parameters increase of the modified asphalt with star-shaped SBS is higher than that with linear SBS, and E_0 does not change significantly when the content of SBS in the modified asphalt with linear SBS increases from 2 wt% to 3 wt%.

4. Conclusions

In this study, two types of SBS were selected to modify CRMA, and the high-temperature performance, temperature sensitivity, low-temperature tensile performance, and rheological performance of SBS/CRMA of different SBS structures and SBS content were systematically studied. Analysis of the test results can draw the following conclusions:

(1) Compared with the performance indicators of CRMA, after adding SBS, the ductility at 5°C and the penetration at 25°C of LSA and SSA were increased, and the softening point first decreased and then increased. With the increase of SBS content, the ductility and softening point of SBS/CRMA at 5°C show an upward trend, while the penetration degree shows a downward trend. The star-shaped SBS modified asphalt has a higher softening point and better temperature sensitivity, while the linear SBS modified asphalt has higher ductility at 5°C and better low-temperature tensile property.

(2) The addition of SBS copolymers can increase the complex modulus G^*, rutting factor $G^*/\sin\delta$, storage modulus G', and dissipation modulus G'' of CRMA and reduce the phase angle δ. Among the

four SBS contents of 1 wt%, 2 wt%, 3 wt%, and 4 wt%, the higher the SBS content, the stronger the rutting resistance and deformation resistance of LSA and SSA. Furthermore, SBS mainly improves the rheological properties of asphalt by enhancing the elasticity of asphalt, and the proportion of elastic components in asphalt is the highest when the SBS content is 4 wt%.

(3) The antideformation ability of asphalt binders is affected by the loading frequency. The higher the loading frequency in the frequency range of 0.1–100 rad/s, the more elastic components in the asphalt, and the more deformable parts it can recover. Besides, in the frequency domain of 1–10 rad/s, the higher the loading frequency, the smaller δ of the modified asphalt. According to the angular frequency of 10 rad/s to characterize the vehicle speed of 60 km/h, it can be concluded that the viscous components in the asphalt are smaller under a load of high-speed vehicles, and it is less prone to permanent deformation.

(4) Compared with linear SBS, star-shaped SBS improves the performances of asphalt binders more significantly. The star-shaped SBS has high rigidity and can form a denser and more stable cross-linked network with CR powder in the asphalt, which has a greater degree of improvement in the viscoelasticity, rutting resistance, high-temperature stability, and temperature sensitivity of the asphalt. The linear SBS has better flexibility and has advantages in optimizing the low-temperature tensile properties of the asphalt binders.

CR powder modified asphalt can meet the requirements of road construction for asphalt's high-temperature performance, temperature sensitivity, and antideformation ability. However, due to the limited improvement of CR powder on the viscoelasticity of asphalt and the fact that it is easy to agglomerate when the content is too high, considering the preparation cost and modifier performance, SBS polymer can be added to prepare composite modified asphalt to make up for the deficiencies of the above limiting factors. In this paper, through the analysis of the test results of each asphalt binder with different types and different dosages of SBS, it is concluded that it is recommended that 4 wt% star-shaped SBS be added when the CR powder content is 20 wt%. Under this dosage, SBS/CRMA has the best modification effect, and the performance of modified asphalt is the best.

Data Availability

The experimental data used to support the findings of this study are included within the article.

Conflicts of Interest

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

Acknowledgments

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