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Performance and Verification of High-Modulus Asphalt Modified by Styrene-Butadiene-Styrene Block Copolymer (SBS) and Rock Asphalt

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Abstract: High asphalt grade and poor high-temperature performance are the primary reasons for the permanent rutting deformation of asphalt pavement. However, the low grade of asphalt and the poor low-temperature performance and fatigue life of the mixture can easily lead to the low-temperature cracking of asphalt pavement. With the rapid increase in road traffic, volume, and traffic load, the performance requirements of road asphalt materials are becoming higher and higher. High-modulus asphalt has excellent temperature stability and good fatigue resistance. However, high-modulus asphalt is expensive, so its use can greatly increase the pavement cost, restricting its wide application in road engineering. It is necessary to find an economical way to produce modified asphalt to meet the current road requirements. The aim of this study is to investigate the effects of styrene-butadiene-styrene block copolymer (SBS) and rock asphalt on the road performance of modified high-modulus asphalt, in which the replacement level of SBS and rock asphalt below 8 wt.% are compared. Apart from the conventional performance measurements, such as softening point, penetration, ductility and viscosity, thermal storage stability and rheological properties are also measured. The test results show that the composite modification of SBS and North American rock asphalt can effectively improve the high-temperature resistance and reduce the temperature sensitivity of 50# matrix asphalt, but it has no obvious improvement on its low-temperature performance. The preferred ternary blending system containing 4~6 wt.% SBS and 6~8 wt.% rock asphalt was obtained by performance analysis. It was verified that the performances of high-modulus asphalt mixture with the ternary blending asphalt above all meet the requirements of high-modulus asphalt mixture performance index.

Keywords: high-modulus asphalt; SBS; rock asphalt; high- and low-temperature performance; creep performance; performance verification

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1. Introduction

The rapid growth of highway traffic volume, the continuous increase in super-heavy loads, and the complex and bad traffic environment lead to higher requirements for asphalt concrete pavement. According to statistics, more than 80% of the maintenance and repair of asphalt pavement is caused by the permanent deformation of pavement rutting [1]. Compared with other pavement performance issues, the rutting disease of asphalt pavement is the most harmful [2]. In order to improve the rutting resistance of asphalt concrete pavement, in the selection of raw materials, in addition to selecting the ore aggregate with hard stone, wear resistance, no impurities, no weathering and good particle shape, we should also select a high-performance asphalt with a high softening point, high consistency and good temperature stability, which can maintain sufficient viscosity under high-temperature conditions and ensure that the mixture has good low-temperature cracking resistance in a low-temperature environment.

In recent years, the application research direction of improving the high-temperature performance of asphalt mixture is mainly reflected in the selection of asphalt, such as

styrene-butadiene-styrene block copolymer (SBS) modified asphalt, natural rock asphalt-modified asphalt [3], low-grade hard asphalt [4–6], plus anti-rutting agent or high-modulus agent [7–11]. However, in engineering application, it is found that a single-modified asphalt, such as SBS-modified asphalt, cannot meet the increasing high-temperature performance requirements [12]. The asphalt modified with pure natural rock asphalt significantly improves the high-temperature performance, but reduces the low-temperature performance to almost the same extent [13]. Low-grade hard asphalt improves the high-temperature performance of the mixture, but also significantly reduces the low-temperature performance, and the low-temperature cracking of the pavement is serious [14,15]. The cost of adding high-modulus agent or anti-rutting agent is high, which increases the difficulty of mixing and the probability of inaccurate measurement. Therefore, considering both performance and cost factors, natural rock asphalt and SBS modifier were used to modify the matrix asphalt, so as to obtain a composite-modified asphalt with low price and high road performance, and apply it to the construction of expressway.

Rock asphalt is a kind of natural asphalt. It has the advantages of high nitrogen content, good durability and good compatibility with base asphalt. The preparation process and application process are simple. It is commonly used in the modification of asphalt and asphalt mixture. It can significantly improve the high-temperature stability and shear strength of asphalt pavement, reduce rutting deformation and prolong the service life of pavement. SBS polymer modifier can significantly improve the temperature sensitivity, stability, durability, adhesion and aging resistance of asphalt. It has been found [16–20] that the composite modification of asphalt with rock asphalt and SBS modifier can significantly improve the viscosity and softening point of asphalt binder, and improve the high-temperature stability and water stability of asphalt mixture. For example, Bulgis et al. [21] studied the influence of Buton rock asphalt particles on the compressive stress-strain behavior of asphalt mixture. The results showed that the compressive strength of the mixture mixed with butun rock asphalt is higher than that of the mixture without modifier, and the number of cracks is fewer. Suaryana [22] studied the performance of Buton rock asphalt in Stone Mastic Asphalt (SMA) pavement and the results showed that the addition of Buton rock asphalt can improve the road performance of SMA mixture. Li et al. [23] used dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests to study the rheological properties of asphalt modified by rock asphalt and found that the addition of rock asphalt can increase the strength of asphalt materials and reduce the low-temperature relaxation potential of asphalt mixture. Compared with the performance before and after long-term aging, rock asphalt can slow down the aging rate of asphalt mixture. Huang et al. [24] have systematically studied the high-temperature performance, water stability and fatigue resistance of rock asphalt-modified asphalt mixture by using sk70#, Zhonghai 70# asphalt as matrix asphalt and Qingchuan rock asphalt, North American rock asphalt and star rock asphalt as modifiers. The research shows that the high-temperature resistance, water stability and fatigue resistance of rock asphalt-modified asphalt mixtures have been improved to varying degrees. Li et al. [25] have compared and analyzed the road performance of matrix asphalt mixture, BRA rock asphalt mixture and SBS-modified asphalt mixture. The research shows that BRA rock asphalt can significantly improve the deformation resistance, water loss resistance, low-temperature crack resistance and fatigue resistance of asphalt mixtures. According to the above research and the application of rock asphalt, so far, compared with Qingchuan rock asphalt and Buton rock asphalt, the composite modification technology of North American rock asphalt and SBS has not been reported and has not been widely used. The research on North American rock asphalt is mostly in the indoor test stage. Therefore, according to the current situation, this paper studies and evaluates the road performance of rock asphalt and SBS composite modified asphalt. It provides a theoretical basis for the large-scale application of North American rock asphalt in highway construction.

2. Materials and Experimental

2.1. Raw Materials

The 50 mesh North American rock asphalt powder and SBS modifier are used to modify 50# matrix asphalt for the preparation of high-modulus asphalt in this paper. The selected raw materials are tested according to Chinese standards JTG E20-2011 [26] and SH/T 1610-2011 [27]. The test results meet the basic road requirements of The Technical Specifications for Construction of Highway Asphalt Pavements (JTG F40-2004) [28] as shown in Tables 1–3.

Table 1. The basic index of 50# matrix asphalt.

Test Project	Test Values	Threshold Values
Softening point/°C	49.6	45~60
Penetration/mm	45.3	40~60
Ductility (10 °C)/cm	15.2	≥15
135 Brookfield viscosity/Pa.s	0.5	<3.0
RTFOT ductility (15 °C)/cm	10.1	≥10

Table 2. The basic index of SBS modifier.

Test Project	Structure	Volatile/%	Styrene Content/%	Molecular Weight/10,000	Melt Mass Flow Rate (MFR)/ (g/10 min)	Tensile Strength/MPa	300% Constant Elongation Stress/MPa	Elong-ation at Break/%	Yellow Index	Else
Test values	Linear type	0.4	40	15	0.09	21.4	3.1	736	0.6	Unsaturated

Table 3. The basic index of North American rock asphalt powder.

Test Project	Color	Density/g.cm^{-3}	Softening Temperature/°C	Asphalt Content (Combustion Method)/%	Water Content/%	Ash Content/%
Test values	Black-brown	1.18	175	86.6	0.8	8

2.2. Preparation of High-Modulus Asphalt

The preparation of high-modulus modified asphalt is mainly divided into two steps. The first step is the preparation of SBS-modified asphalt. 2%, 4% and 6% of SBS modifier are added to 1000 g of 50# matrix asphalt by external mixing methods to complete the preliminary modification of base asphalt. The second step is the preparation of composite modified high-modulus asphalt. 4%, 6% and 8% dosages of 50-mesh North American rock asphalt powder were added to the SBS-modified asphalt by external admixture methods for compound modification to complete the preparation of high-modulus asphalt. The modifier blending scheme was given in Table 4. Here, the reference group MA0 denotes the 50# matrix asphalt. S02, S04 and S06 denote the SBS-modified asphalt using 2%, 4% and 6% of SBS modifier, respectively. S2R4, S2R6 and S2R8 denote the composite-modified high-modulus asphalt using 4%, 6% and 8% of 50-mesh North American rock asphalt on the basis of 2% SBS-modified asphalt. S4R4, S4R6 and S4R8 denote the composite-modified high-modulus asphalt using 4%, 6% and 8% of 50-mesh North American rock asphalt on the basis of 4% SBS-modified asphalt. S6R4, S6R6 and S6R8 denote the composite-modified high-modulus asphalt using 4%, 6% and 8% of 50-mesh North American rock asphalt on the basis of 6% SBS-modified asphalt.

Table 4. The modifier blending scheme.

Sample	SBS Modifier/%	Rock Asphalt Powder/%
MA0	0	0
S02	2	0
S04	4	0
S06	6	0
S2R4	2	4
S2R6	2	6
S2R8	2	8
S4R4	4	4
S4R6	4	6
S4R8	4	8
S6R4	6	4
S6R6	6	6
S6R8	6	8

2.3. Mixture Design

EME-20 is selected for asphalt mixture gradation. According to the aggregate screening results, the composite gradation of the mixture is designed as shown in Table 5, and the grading curve is shown in Figure 1. The optimum asphalt aggregate ratio of the designed mixture is 4.8%.

Table 5. Synthetic Gradation Design of High-Modulus Asphalt Mixture.

Seive Size (mm)	31.5	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Upper limit	100	100	100	-	-	82.0	64.0	43.0	-	-	-	-	8.0
Lower limit	100	100	90.0	-	-	66.0	41.0	28.0	-	-	-	-	6.0
Design median	100	100	95.0	-	-	74.0	52.5	35.5	-	-	-	-	7.0
Synthetic grading	100	100	93.8	88.5	82.1	71.4	46.6	32.4	26.2	17.6	13.0	8.4	6.3

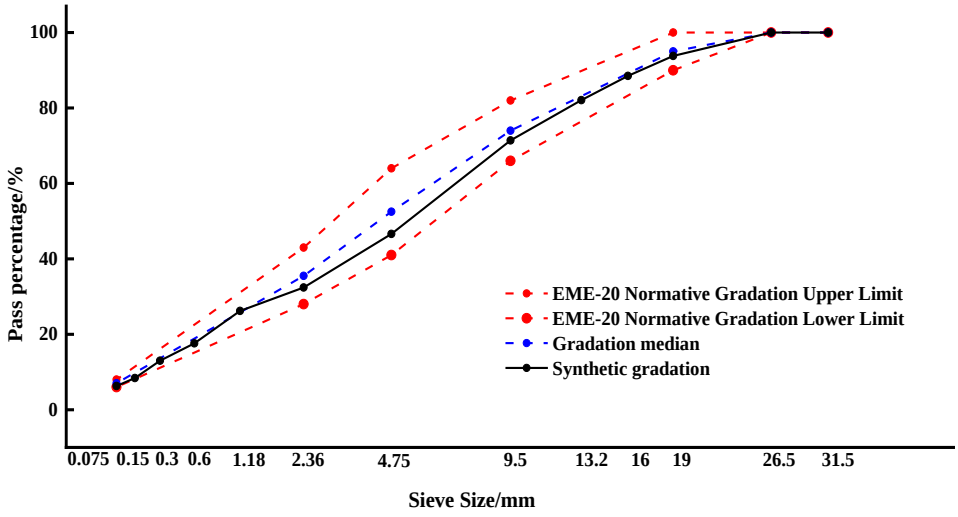


Figure 1. Synthetic gradation curves of high-modulus asphalt mixtures.

2.4. Test Methods

2.4.1. Softening Point, Penetration, Ductility and Viscosity Tests

Softening point refers to the temperature measured when the asphalt specimen is softened and sagged by heat, which represents the temperature stability of asphalt. The

test was carried out according to the test specification (JTG E20-2011) [26]. The asphalt sample in the metal ring of prescribed size was placed in 5 °C water or 32.5 °C glycerol, and heated at a rate of 5 ± 0.5 °C/min until the steel ball sank to the prescribed distance (25.4 mm). The temperature was recorded and expressed in °C.

Penetration is one of the main quality control indexes of asphalt. The relative hardness and consistency of asphalt and its ability to resist shear failure can be characterized. The test was carried out according to the test specification (JTG E20-2011) [26]. A 100 g standard cone was sunk vertically into a bitumen sample insulated at 25 °C for 5 s, and the depth was recorded in 1/10 mm units.

Ductility is an important index to evaluate the plasticity of asphalt. The test was carried out according to the test specification (JTG E20-2011) [26]. The asphalt was poured into a standard specimen, and the specimen was drawn to fracture at a speed of 50 mm/min under the corresponding test temperature (5 °C, 10 °C, 15 °C or 25 °C). The length at this time was recorded and expressed as cm.

Viscosity is an index to characterize the viscosity of asphalt, the main basis for the classification of modern asphalt, and a main control index for the production and construction of asphalt mixture. There are many viscosity indicators, and 135 °C kinematic viscosity is selected to study in this paper. The kinematic viscosity at 135 °C is often measured by a capillary viscosity meter according to the test specification (JTG E20-2011) [26].

2.4.2. Segregation Softening Point Test

Segregation softening point test is usually used to evaluate the thermal storage stability of SBS-modified asphalt according to Chinese standard JTG E20-2011 [26]. The separation tube containing about 50 g of asphalt was sealed and put in an oven at 163 ± 5 °C for 48 ± 1 h, and then was moved to the freezer for at least 4 h. After the asphalt is solidified, it is taken out and divided into three equal parts, and the upper and lower softening points are measured according to the softening point test method (T0606), and the difference is taken. When the value is less than 2.5 °C, it is considered that the SBS-modified asphalt segregation is qualified.

2.4.3. Dynamic Shear Rheometer (DSR)

The dynamic shear rheometer (DSR) is usually used to evaluate the high-temperature stability of asphalt binder. According to Chinese standard JTG E20-2011 [26], a fully automatic dynamic shear rheometer was used to determine the dynamic shear modulus and phase angle of asphalt. The instrument applies periodic sinusoidal shear stress to asphalt samples through the axis of rotation. The asphalt sample is placed between two 25 mm plates, one plate is fixed, the other plate is rotated around the central axis at a speed of 10 rad/s. It goes through the A-B-A-C-A cycle. When the stress (strain) is applied to the sample, DSR can calculate the strain (stress) response generated by the sample, and the complex shear modulus can be calculated from the stress and the corresponding strain.

2.4.4. Bending Beam Rheometer (BBR)

Bending Beam Rheometer (BBR) is usually used to evaluate the low-temperature performance of asphalt materials. According to Chinese standard JTG E20-2011 [26], a fully automatic bending beam rheological tester was used to measure the flexural creep stiffness modulus S and creep rate m. The bending beam rheometer applies loads to asphalt samples through load sensors and records deflection changes over time. The instrument can automatically collect the creep stiffness modulus S of sample at 8 s, 15 s, 30 s, 60 s, 120 s and 240 s, and calculate the value of creep rate m when the test is carried out at the test temperature. The asphalt should be kept warm in absolute ethanol at a constant temperature before the start of the test. Taking into account the low-temperature climate in cold regions, the test temperature is selected as −12 °C and −18 °C.The S and m values with the load acting time of 60 s are taken in the test.

2.4.5. Pneumatic Rheological Rebound Test

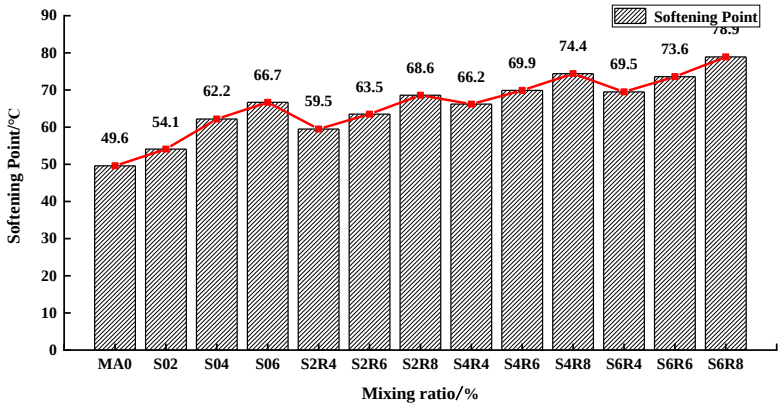
The maximum creep deformation when loaded and the ability to recover from deformation when unloaded are unique properties of each thermoplastic material. The LTI-210 asphalt quality rapid testing equipment can quickly evaluate the mechanical response and road performance of asphalt materials at a certain temperature. It mainly uses nitrogen-loading technology to load asphalt specimens at 25 °C in a circular area for a period of time. The laser measurement system of the equipment measures and records the deformation (displacement) of the loading center. After the loading is finished, the deformation of asphalt materials begins to recover. The creep and creep recovery ability of asphalt under single stress or multiple stress conditions can be measured.

3. Results and Discussions

3.1. Penetration, Softening Point, Ductility and Viscosity Index

The basic performance indicators of modified asphalt with different contents are analyzed. Figure 2 exhibits the effect of SBS and rock asphalt on the softening point, penetration, ductility, and viscosity of high-modulus asphalt. The additions of 2%, 4% and 6% SBS modifier cause obvious increases in softening point of approximately 9.07%~34.5% higher than that of MA0, and achieve penetrations 13.7%~25.9% lower than that of MA0. It indicates that the high-temperature performance is significantly improved by the addition of SBS modifier. As for ductility and viscosity, continuous increases occur with the increase in SBS modifier content. However, when the SBS content reaches 6%, the viscosity index exceeds the requirement of index $\leq$3 Pa·s in technical code for construction of asphalt pavement JTG F40-2004 [28]. If the viscosity of modified asphalt is too large, it may increase the difficulty of the process of transportation and mixing, which is not conducive to the transportation and construction of asphalt mixture.

The addition of rock asphalt improves the softening point and viscosity and decreases the penetration and ductility. In comparing the results of the binary blend containing SBS modifier, the ternary blends containing both SBS and rock asphalt show better performance. Considering S2R4 as an example, increases of approximately 10% and 22.2% in softening point and viscosity and decreases of 4.9% and 14.2% in penetration and ductility are achieved compared to those of S02. It indicates that the addition of rock asphalt further improves the high- and low-temperature performance of the composite-modified asphalt. Moreover, the higher the dosage of rock asphalt, the better the improvement effect.



(**a**) Softening point

Figure 2. *Cont.*

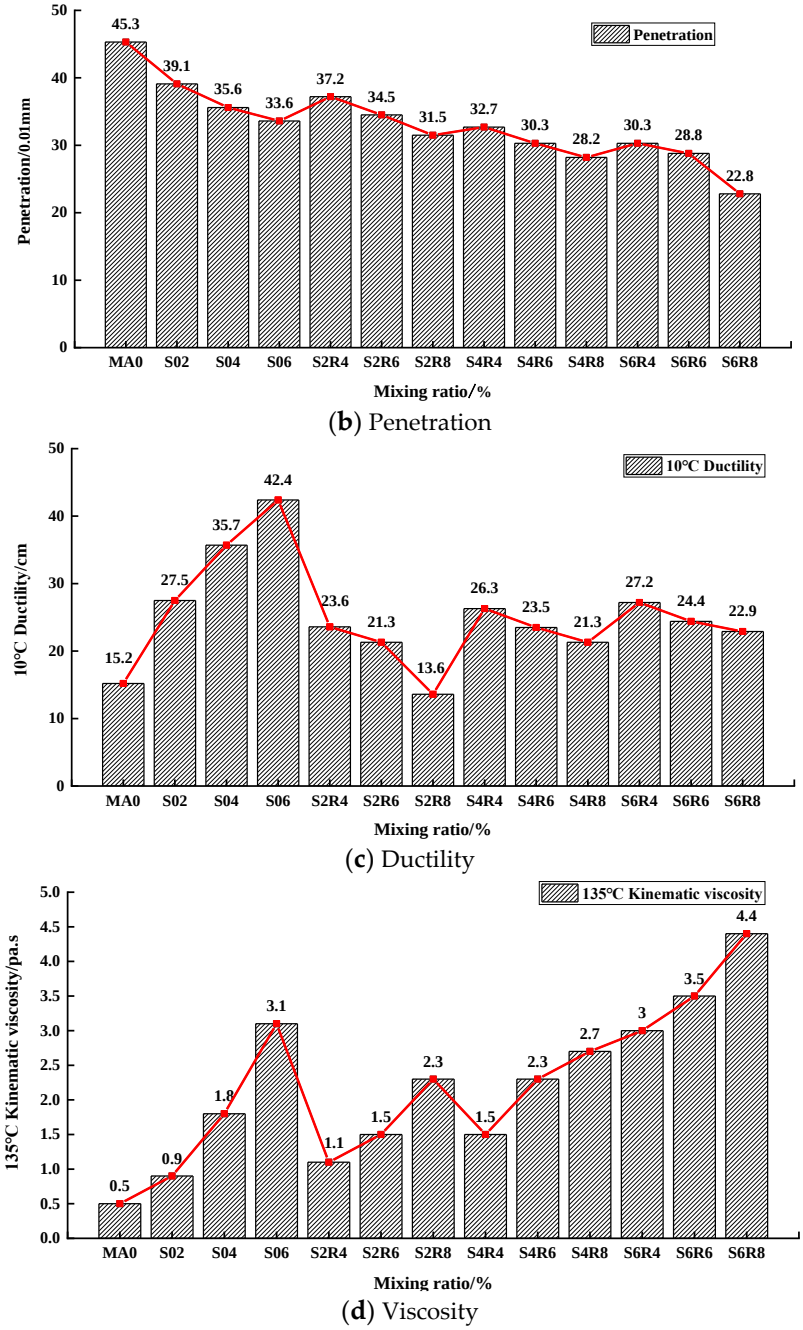


Figure 2. The change law of soft point, penetration, ductility and viscosity for modified asphalt.

3.2. Thermal Storage Stability of Asphalt

Thermal storage stability is an important indicator to ensure that modified asphalt does not segregate or lose its excellent performance during storage and transportation. The thermal stability of the prepared composite-modified asphalt was analyzed as shown in Figure 3. Results show that the softening point difference of 50# matrix asphalt between top and bottom is 0 °C, and there is no segregation. The inclusion of SBS increases the difference of the softening point; the higher the content of SBS, the greater the difference in softening point. When the SBS modifier content is 4% and 6%, the softening point difference exceeds the specified value ≤2.5 °C index in the construction technical specification JTG F40-2004 [28], resulting in segregation.

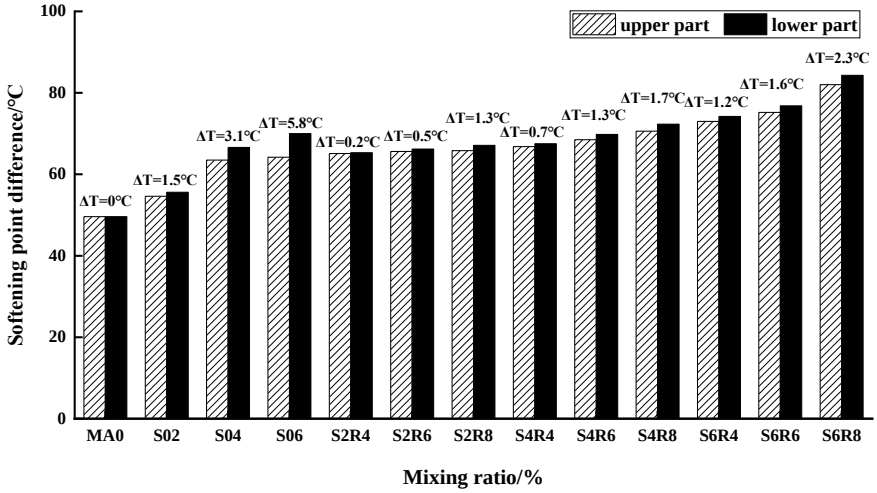


Figure 3. The difference in change of softening point for modified asphalt.

However, when rock asphalt is used, the asphalt segregation condition is improved and the softening point difference is gradually reduced compared to the SBS series. Taking the rock asphalt content of 8 wt.% as an example, the S- and R-containing ternary composite-modified asphalt achieve differences of softening point 13.3%~60.3% lower than those of the SBS series, which indicates that the ternary blending system containing SBS and rock asphalt behaves well in improving the thermal storage stability, better than the effect of SBS modifier alone. When the content of SBS modifier is fixed, the softening point difference of composite-modified asphalt increases with the increase in rock asphalt content.

3.3. Analysis on Rheological Properties of Asphalt

3.3.1. High-Temperature Rheological Properties

The research shows that the dynamic shear rheometer (DSR) can be used to characterize the viscoelastic characteristics of asphalt under medium- and high-temperature conditions [29], and the rutting factor G*/sinδ was taken as an index for evaluating and controlling the high-temperature rutting resistance of asphalt materials. The research shows that the dynamic shear rheometer (DSR) can be used to evaluate the viscoelastic characteristics of asphalt under medium- and high- temperature conditions [29], and the rutting factor G*/sinδ is taken as an index for evaluating and controlling the high-temperature rutting resistance of asphalt materials. The effects of SBS and rock asphalt on the high-temperature rheological properties of modified asphalt are exhibited in Figure 4. It can be seen in Figure 4 that the rutting factor G*/sinδ of all series of modified asphalt decreases with the increase in temperature. The effects of SBS and rock asphalt on the rutting factor of modified asphalt are exhibited in Figure 4. The effects of SBS and rock asphalt on the high-temperature rheological properties of all series of modified asphalt decreases are exhibited in Figure 4. The rutting factor G*/sinδ rheological properties of all series of modified asphalt are exhibited in Figure 4. It can be seen in Figure 4 that the rutting factors G*/sinδ of all series of modified asphalt decrease with the increase in temperature. The smaller the asphalt rutting factor, the greater the loss of shear flexibility of asphalt [17], the fewer elastic components contained in asphalt, and the worse the rutting resistance of asphalt. With the incorporation of SBS modifier, the rutting resistance is improved, with larger rutting factor values than that of MA0. The combination of SBS and rock asphalt produces better effects than that of SBS alone in the rutting resistance improvement. When 4%~6% of SBS is added, the high-temperature grade of modified asphalt can reach 75~85 °C, which is about 10~20 °C higher than that of MA0. There is no obvious change in the high-temperature grade of ternary blending modified asphalt containing SBS and rock asphalt, but significant increases by approximately 1~3 times are achieved in rutting factor values compared to those of asphalt containing SBS alone.

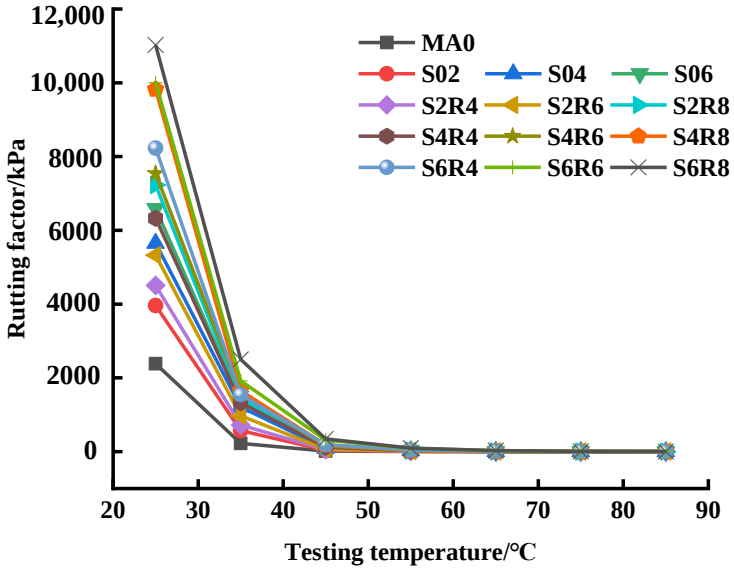


Figure 4. The change of rutting factor with temperature.

3.3.2. Low-Temperature Rheological Properties

The bending creep stiffness modulus *S* and creep rate *m* are usually used to evaluate the low-temperature crack resistance of asphalt. The larger the stiffness modulus *S* value of asphalt material, the more obvious the brittleness of asphalt, the easier the pavement is to crack and damage. The smaller the *m* value of the asphalt creep rate, the greater the stiffness of the material when the temperature decreases, the greater the tensile force in the material, and the greater the possibility of low-temperature cracking.

The effects of SBS and rock asphalt on the low-temperature rheological properties of modified asphalt are exhibited in Figures 5 and 6. It can be seen that with the inclusion of SBS, the stiffness modulus of modified asphalt gradually decreases and the creep rate continuously increases at −12 °C and −18 °C. When SBS is added in 50# matrix asphalt, decreases of 8.2%~27.6% and 5.0%~13.9% in stiffness modulus at −12 °C and −18 °C, respectively, are achieved, and increases of 0.9%~15.9% and 9.58%~32.5% in creep rate at −12 °C and −18 °C, respectively, are obtained. This indicates that the addition of SBS modifier reduces the tensile force of 50# matrix asphalt at low-temperature conditions and effectively improves the low-temperature cracking of asphalt. However, for the ternary blending asphalt system containing SBS and rock asphalt, the values of stiffness modulus *S* increase obviously and the values of creep rate *m* decrease compared to the binary blend containing SBS alone. The addition of rock asphalt increases the brittleness of ternary blending composite-modified asphalt, reduces the relaxation stress, and increases the possibility of low-temperature cracking of asphalt.

According to the Superpave specification of SHRP [30], the creep stiffness modulus *S* should be less than 300 MPa, and the creep rate *m* should be greater than 0.300. It can be seen in Figure 5 that at −12 °C, the *S* of MA0 is less than 300 MPa and the *m* is less than 0.300. When the SBS is added, the *S* and *m* of SBS- all meet the requirements at −12 °C. When the dosage of SBS reaches 4% and 6%, the *S* and *m* of SBS meet the requirements at −18 °C. when rock asphalt is added to the modified asphalt by SBS, the *S* and *m* of all the ternary blending series do not meet the requirements at −18 °C. At −12 °C, the *S* and *m* of the ternary blending system containing 4~6 wt.% SBS and 6~8 wt.% rock asphalt can meet the requirements. This shows that although the addition of rock asphalt weakens the low-temperature cracking resistance of composite modified asphalt, it still has advantages compared to 50# matrix asphalt.

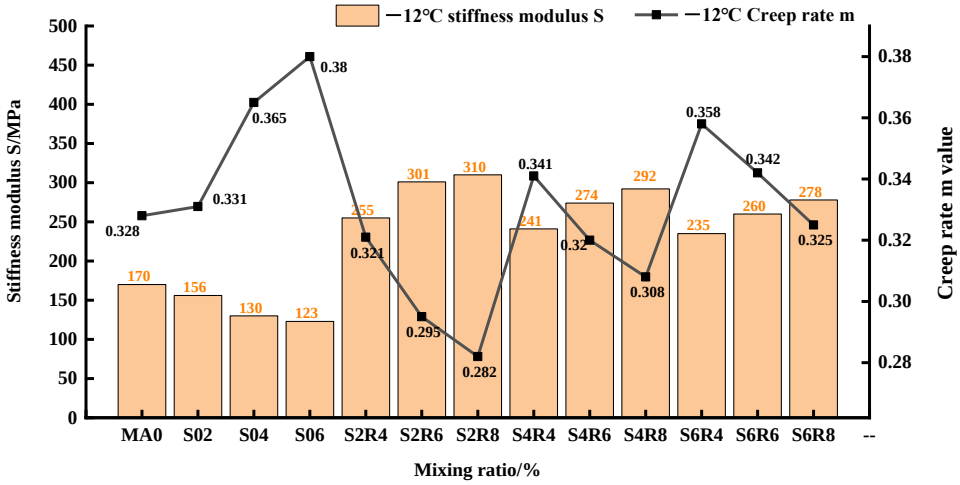


Figure 5. The results of stiffness modulus and creep rate for modified asphalts under −12 °C.

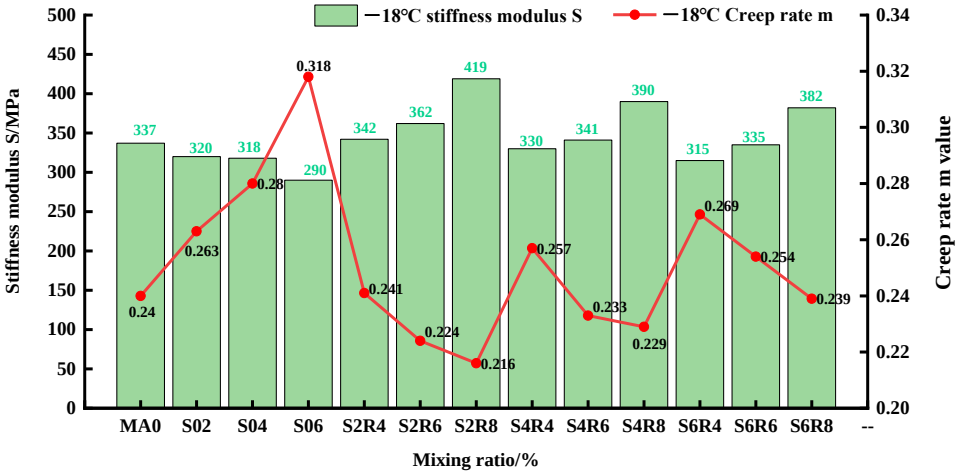


Figure 6. The results of stiffness modulus and creep rate for modified asphalts under −18 °C.

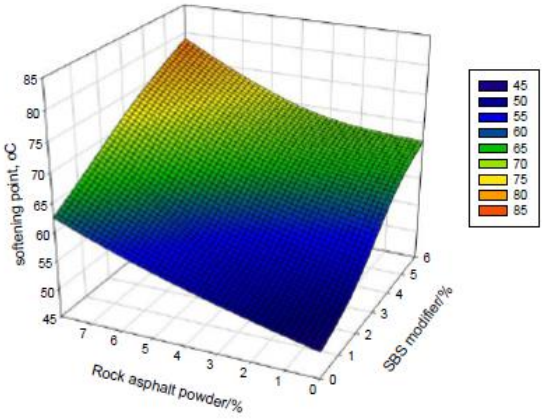
3.3.3. Pneumatic Rheological Rebound Performance

The pneumatic asphalt rheological rebound test is carried out using the detection equipment of lti-210 asphalt quality control system to quickly measure the creep and creep recovery capacity of asphalt under the same temperature (25 °C) and stress (9.75 Pa·S). The PG classification, maximum creep deformation and elastic recovery rate of asphalt binder are exhibited in Table 4, Figures 6 and 7. It can be seen from the results that 43.6%~57.9% decreases in the maximum creep deformation and 55.5%~198.5% increases in the creep recovery rate are achieved when 2%~6% SBS modifier is added to 50# matrix asphalt. This shows that the stiffness and modulus of the SBS-modified asphalt are larger, the asphalt is harder, and the viscoelastic performance of the asphalt is better compared to those of MA0.

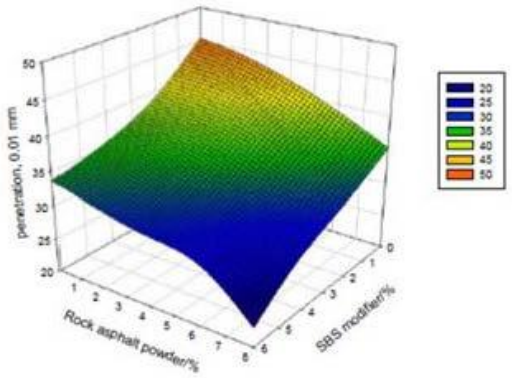
As shown in Table 4 and Figure 6, the lowest maximum creep deformation and the highest deformation recovery rate of modifier asphalt are obtained with SBS and rock asphalt additions. The addition of SBS at 6% and rock asphalt at 8% leads to a reduction of 87.5% in maximum deformation and an increase of 32.5% in deformation recovery rate, respectively, compared to those of S06. As more rock asphalt is added, the maximum creep deformation is decreased and the deformation recovery rate is increased. The incorporation of rock asphalt can sufficiently improve the pneumatic rheological rebound performance of modified asphalt containing SBS.

In comparing the results of PG grading analysis in Table 6 by S04 and S4R6, Rock asphalt has a better effect in improving the high- and low-temperature grade of modified asphalt than SBS does. The high- and low-temperature grades of S04 are 76 °C and −28 °C,

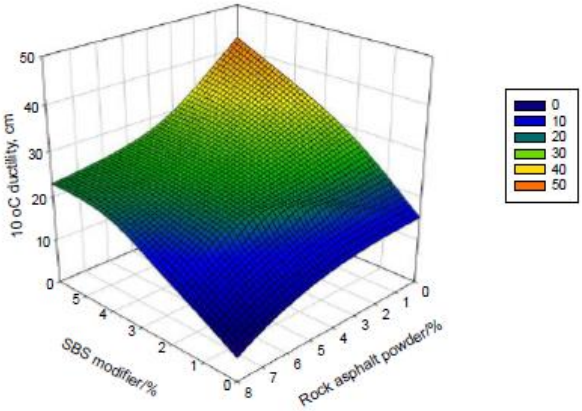
respectively, 1 level higher than those of MA0. In addition, with the incorporation of rock asphalt at 6%, the high-temperature classification of asphalt is improved by 2 grades, while the low-temperature grade has no change compared to those of MA0. It is concluded that the presence of rock asphalt improves the high-temperature stability and viscoelastic properties of composite-modified asphalt, but has no obvious improvement on its low-temperature performance. Although the low-temperature performance is attenuated, it can still maintain the original level with addition of rock asphalt.



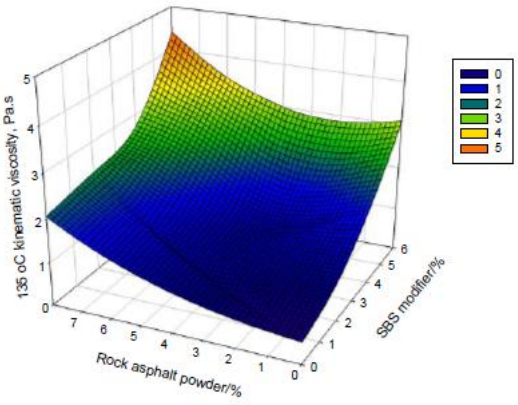
(**a**) Softening point



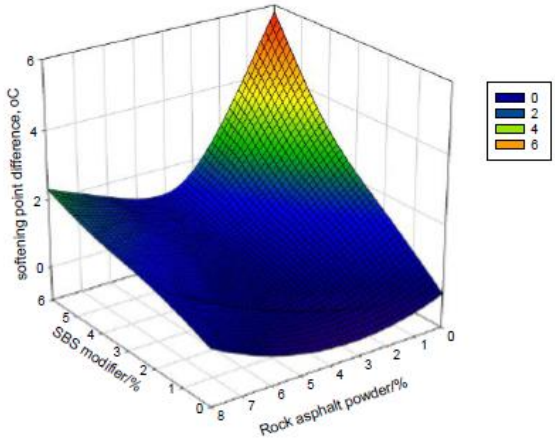
(**b**) Penetration



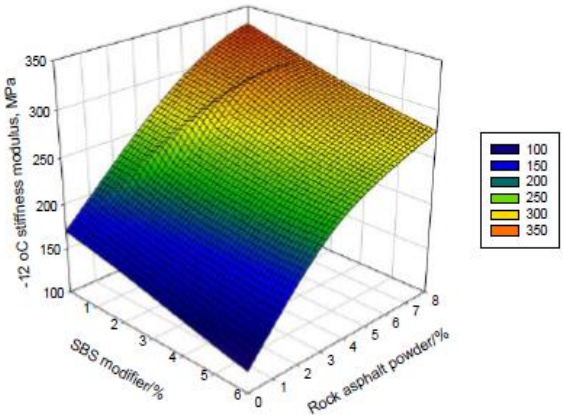
(**c**) Ductility



(**d**) Viscosity

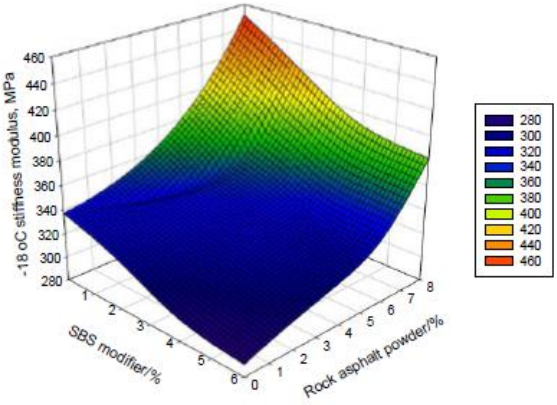


(**e**) Softening point difference

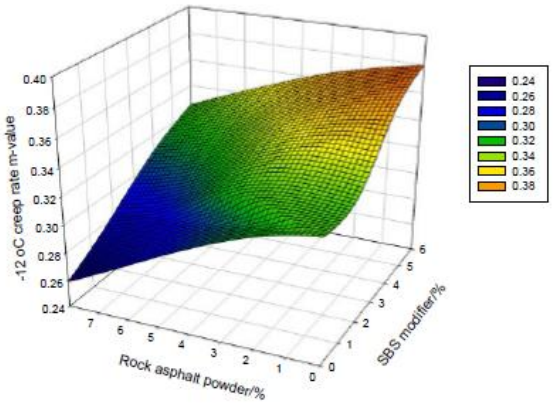


(**f**) −12 °C stiffness modulus

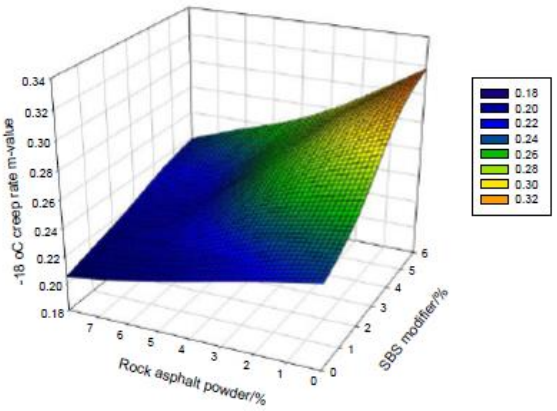
Figure 7. *Cont.*



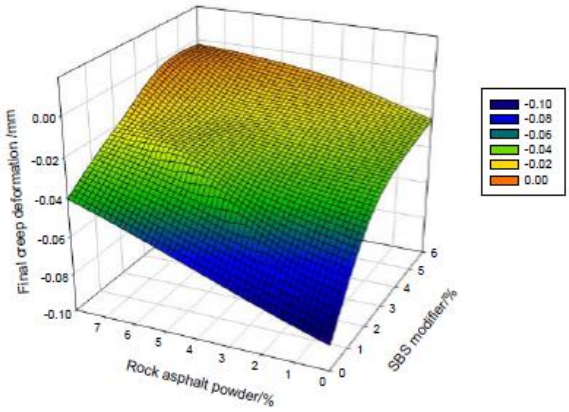
(**g**) −18 °C stiffness modulus



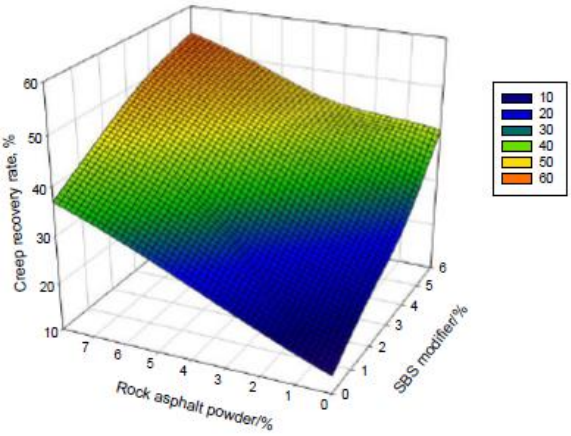
(**h**) −12 °C creep rate



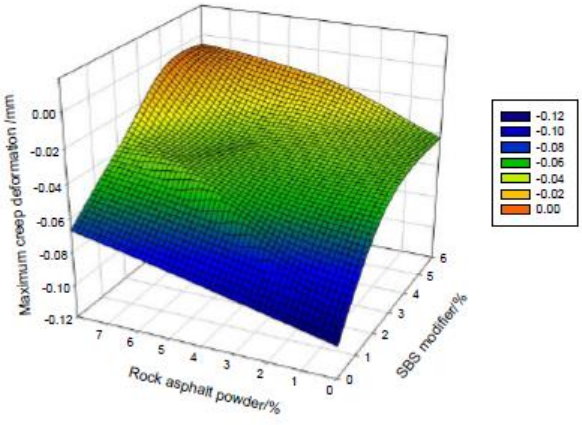
(**i**) −18 °C creep rate



(**j**) Final creep deformation



(**k**) Creep recovery rate



(**l**) Maximum creep deformation

Figure 7. The multivariate analysis results.

3.3.4. Multivariate Analysis

In order to better analyze the effect of the content of rock asphalt and SBS on high-modulus modified asphalt, multivariate analysis was carried out. The analysis results are shown in Figure 7. It gives SBS modifier and Rock asphalt powder component effects. It can be seen that the effect of composite modification of SBS and North American rock asphalt is better than SBS or rock asphalt alone in the performance improvement on the matrix asphalt. According to the performance characteristic of the modified asphalt by multivariate analysis, the ternary blending system containing 4~6 wt.% SBS and 6~8 wt.%

rock asphalt is preferred. When the content of SBS modifier is 4%~6% and the content of rock asphalt is not less than 6%, the performance indicators of modified asphalt meet the requirements of DB 37/T 3564-2019 and EN14023 specifications for high-modulus asphalt.

Table 6. The creep deformation and recovery rate of different asphalt samples.

Samples	Final Creep Deformation/mm	Creep Recovery Rate/%	Maximum Creep Deformation/mm	PG
MA0	−0.0868	13.7	−0.1006	PG 70-22
S02	−0.0446	21.3	−0.0567	PG 70-22
S04	−0.0304	28.3	−0.0424	PG 76-28
S06	−0.0252	40.9	−0.0426	PG 76-28
S2R4	−0.0319	32.4	−0.0472	PG 76-22
S2R6	−0.0237	39.8	−0.0394	PG 76-16
S2R8	−0.0216	44.2	−0.0387	PG 76-16
S4R4	−0.0221	41.9	−0.0380	PG 76-22
S4R6	−0.0193	46.6	−0.0361	PG 82-22
S4R8	−0.0043	50.5	−0.0087	PG 82-22
S6R4	−0.0087	44.8	−0.0158	PG 82-22
S6R6	−0.0049	49.9	−0.0098	PG 82-22
S6R8	−0.0027	54.2	−0.0059	PG 82-22

3.4. Performance Verification of Composite Modified Asphalt Mixture

To further verify the performance of the preferred modified high-modulus asphalt, the performances of the high-modulus asphalt mixture with asphalt S4R6, S4R8, S6R6 and S6R8 are evaluated. According to JTG E20-2011 [26] and GB/T 36143-2018 [31], the high-temperature, low-temperature, water stability, modulus and fatigue performance indicators of composite-modified asphalt mixture are verified. The results indicate that the performance indicators of the mixture meet the requirements of GB/T 36143-2018 [31]. The test results are shown in Table 7.

Table 7. Test results of compound-modified asphalt mixtures.

Technical Index	Requirements	Test Results				
		MA0	S4R6	S4R8	S6R6	S6R8
Void ratio/%	≤4	3.46	3.52	3.50	3.55	3.45
Freeze-thaw splitting tensile strength/%	≥80	79.8	86.5	88.5	88.4	87.6
60 °C dynamic stability times/mm	≥4000	3150	4117	4345	4200	4375
Dynamic modulus (45 ± 0.5 °C, 10 ± 0.1 Hz)/MPa	≥4000	3250	4010	4080	4040	4150
Fatigue life (15 ± 0.5 °C, 10 ± 0.1 Hz, 230 με)/cycles	$\geq 10^6$	865,245	2,424,220	2,362,530	2,260,360	2,116,500
Low-temperature bending test failure strain (−10 ± 0.5 °C)/με	≥2000	1864.56	2510.60	2493.98	2385.16	2149.32

4. Conclusions

Based on the limited testing results, the following conclusion can be drawn.

(1) The composite modification of SBS and North American rock asphalt can effectively improve the high-temperature resistance and reduce the temperature sensitivity of 50# matrix asphalt, but it has no obvious improvement on the low-temperature performance. It is found that the reasonable content of SBS and rock asphalt can better reflect the thermal storage stability of composite-modified asphalt. The preferred ternary blending system containing 4~6 wt.% SBS and 6~8 wt.% rock asphalt is obtained by performance analysis.

(2) When the content of SBS modifier is 4%~6% and the content of rock asphalt is not less than 6%, the performance indicators of modified asphalt meet the requirements of DB

37/T 3564-2019 and EN14023 specifications for high-modulus asphalt. The test results meet the requirements of GB/T 36143-2018 specification for high-modulus asphalt mixtures.

(3) This study shows that the 50# matrix asphalt can be enhanced in its traditional performance, thermal storage stability and rheological properties using common modifiers. Moreover, the ternary blending system containing SBS and rock asphalt can achieve good performance, indicating their potential to reduce construction costs in road engineering.

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