

Article

Laboratory Evaluation of Asphalt Binder and Asphalt Mixture Modified Using Styrene–Butadiene–Styrene/Rock Asphalt

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Abstract: This study investigates the performance enhancement of asphalt and its mixtures through modification with varying contents of styrene–butadiene–styrene (SBS) and rock asphalt (RA). A series of laboratory tests were conducted to comprehensively evaluate the effects of SBS and RA modification. The results demonstrated that SBS significantly improves elasticity, low-temperature ductility, and resistance to fatigue and rutting, while RA enhances high-temperature stability, water stability, and stripping resistance. The synergistic effects of SBS and RA were evident, with the 4% SBS/10% RA mixture achieving the best comprehensive performance, which was characterized by improved high-temperature stability, low-temperature performance, and durability. Conversely, 15% RA content was found to reduce low-temperature flexibility and fatigue performance. A radar chart-based evaluation further confirmed the optimal performance of the 4% SBS/10% RA combination. These findings provide valuable guidance for selecting appropriate SBS and RA proportions tailored to specific performance requirements in asphalt pavement applications.



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Keywords: asphalt; asphalt mixture; composed modification; SBS; rock asphalt; road performance

1. Introduction

With the rapid development of the transportation industry, the performance requirements for pavement materials have been increasing, particularly in terms of durability, rutting resistance, and low-temperature performance. Although conventional asphalt can meet road performance to some extent, its limitations have become increasingly apparent under the combined effects of rising traffic loads and environmental changes [1,2]. Consequently, the research and application of modified asphalt materials have become critical pathways for enhancing pavement quality and extending service life.

A variety of materials have been employed to modify asphalt for use in pavements, including natural asphalts (NA), styrene–butadiene–styrene (SBS), etc. NA is one of the potential substitutes for petroleum asphalt found in asphalt deposits, exhibiting varying levels of purity determined by the ratio of asphalt to other minerals. With the rising costs of asphalt products and energy, achieving a balance between low construction costs and high pavement performance has become increasingly important. As a result, the efficient

utilization of NA in road construction has attracted significant attention from the academic and engineering communities. Rock asphalt (RA) is a typical representative of NA. RA is a solid or semi-solid NA formed from crude oil through prolonged geological evaporation and oxidation infiltrating into rock formations. It primarily occurs in mineral deposits or rock strata, is tightly bonded with mineral substances, and typically contains a high proportion of minerals. Major sources of RA include Venezuela and Xinjiang, China. RA, as a kind of economic and environmental protection and high-potential natural asphalt modification material, has attracted wide focus and application due to its excellent aging resistance, stable physicochemical properties, and relatively low cost. Some studies by Lu et al. [3], Wang et al. [4], and Li et al. [5] have demonstrated that RA not only enhances the high-temperature performance of asphalt but also improves its durability and water damage resistance. However, RA-modified asphalt may exhibit limitations in low-temperature cracking resistance and flexibility. Based on this finding, a study conducted by Wang et al. investigated the effects of rubber powder and RA dosages on the viscoelastic and mechanical properties of asphalt, recommending optimal dosages of 20% rubber powder and 6% RA [6]. It has confirmed that compared to rubber-modified asphalt, composite-modified asphalt mixtures exhibit superior low-temperature, high-temperature, and moisture damage resistance properties, thereby expanding their application scenarios. Cai et al. proposed a composite-modified asphalt with SBS, RA, and nano-silica [7]. Compared with 5% SBS-modified asphalt, the composite-modified asphalt with three agents (3% SBS/6% RA/1% nano-silica) has better overall road performance and higher cost-effectiveness.

Currently, SBS is the most widely used asphalt modification material. SBS-modified asphalt is widely used in high-grade pavement due to its excellent rutting resistance, fatigue resistance, and low-temperature flexibility. However, SBS-modified asphalt faces challenges due to its high cost and the inherent incompatibility between SBS modifiers and base asphalt, leading to issues such as poor storage stability and susceptibility to aging and degradation. Based on this, researchers have conducted extensive research on composite-modified asphalt to explore more cost-effective modification methods, such as rubber powder [8–10], RA [11,12], biomass materials, nanomaterials, etc. Zhang et al. prepared a 20% desulfurization rubber/4% SBS composite-modified asphalt, demonstrating improved high- and low-temperature performance compared to SBS-modified asphalt [9]. Yang et al. adopted polyphosphoric acid (PPA), bio-asphalt (BA), and SBS to prepare composite-modified asphalt and found that BA had good performance characteristics when combined with SBS and PPA modifier, making it a promising alternative to petroleum asphalt [13]. Li et al. applied three types of modifiers (aluminate, stearic acid, and titanate) to modify the heavy calcium carbonate and mixed three different modified calcium carbonates with SBS, respectively [14]. The results demonstrated a significant improvement in the high-temperature viscoelastic properties of the composite-modified asphalt. Chen et al. proposed a composite-modified asphalt of waste polyurethane and SBS and determined optimal ratios of 4% SBS and 15% waste polyurethane based on comprehensive performance considerations [15]. Similarly, Shafabakhsh et al. proposed an SBS/nano-silica composite-modified asphalt and found that the incorporation of SBS/nano-silica can effectively improve the fatigue life of both asphalt binder and mixtures [16]. The recommended optimal dosages of SBS and nano-silica are 5% and 6%. Moreover, Chen et al. prepared composite-modified asphalt using SBS and three types of carbon nanomaterials (CNs) (carbon nanotubes, graphene nanosheets, and graphene oxide) and analyzed the modification mechanisms of CNs in asphalt [17]. The experiment confirmed that three types of CNs improved the mechanical properties and storage stability of SBS-modified asphalt through two modification pathways: chemical reaction and physical blending. Meng et al. proposed an SBS/waste steel slag/waste rubber composite-modified asphalt [18]. Compared

with SBS asphalt, the asphalt mastic prepared using composite-modified asphalt exhibits improved mechanical and high-temperature properties. Obviously, composite modification technology can effectively improve the performance of SBS asphalt and achieve good cost-effectiveness. Based on the abovementioned literature research results, it can be seen that the elastomer properties of SBS can significantly improve the low-temperature crack resistance and fatigue durability of asphalt, while the rigidity properties and excellent cost-effectiveness of RA can compensate for the limitations of SBS-modified asphalt, thereby achieving complementary and optimized performance. The composite modification not only contributes to improving the overall performance of asphalt in pavement applications but also reduces the usage of SBS, optimizing economic feasibility and providing more cost-effective solutions for practical engineering applications.

This study aims to investigate the service performance of SBS/RA-modified asphalt binder and asphalt mixture. The effects of varying SBS and RA dosages on the performance of modified binders and asphalt mixtures are analyzed through extensive laboratory experiments. This research thoroughly examines the synergistic effects of SBS and RA, with a particular focus on evaluating the performance of modified asphalt in terms of rutting resistance, low-temperature performance, fatigue resistance, and other key properties. The objective is to optimize the design of asphalt pavement materials and promote the application of high-performance, cost-effective modified asphalt.

2. Experimental Programs

2.1. Materials

2.1.1. Asphalt

In this study, 70# petroleum asphalt produced in Maoming, Guangdong, was selected as the base binder, and its technical properties are summarized in Table 1. The technical properties satisfied the technical requirements of the Technical Specification for Construction of Highway Asphalt Pavement (JTG F40-2004) of China (JTG F40-2004) [19].

Table 1. Technical parameters of 70# petroleum asphalt.

Property		Value	Standard	Test Method [20]
Ductility (5 cm/min, 15 °C) (cm)		>100	≥100	T 0605-2011
Softening point (°C)		46.8	≤46	T 0606-2011
Penetration (25 °C, 100 g, 5 s) (0.1 mm)		63.9	60~80	T 0604-2011
Penetration index (PI)		−0.70	−1.5~+1.0	T 0604-2011
Density (15 °C, g/cm ³)		1.020	--	T 0603-2011
Wax content (%)		1.7	≤2.0	T 0615-2011
60 °C dynamic viscosity (Pa·s)		238	≥180	T 0620-2000
Solubility (%)		99.6	≥99.5	T 0607-2011
Flashpoint (°C)		273	≥260	T 0611-2011
Thin-film heating test (163 °C)	Mass loss (%)	−0.60	≤±0.8	T 0609-2011
	Residual penetration ratio (%)	62.2	≤61	T 0604-2011
	Residual ductility (10 °C) (cm)	9.1	≥8	T 0605-2011

2.1.2. SBS and RA

Linear SBS with a block ratio of 30:70, produced by Sinopec, was selected as the polymer matrix for preparing composite-modified asphalt. The RA used in this study was adopted Qingchuan RA from Sichuan, China. Their technical indicators are shown in Tables 2 and 3, respectively.

Table 2. Technical parameters of SBS.

Test Indices	Styrene Content (%)	Hardness (HA)	300% Stretching Strength (MPa)	Elongation (%)	Tensile Strength (MPa)
Value	35	79	2.50	750	26

Table 3. Technical parameters of RA.

Test Indices	Appearance	Density (15 °C, g/cm ³)	Ash Content (%)	Asphalt Content (%)	Water Content (%)	Flash Point (°C)
Value	Black	1.60	14.5	88.5	0.2	240

2.1.3. Aggregates and Filler

The coarse and fine aggregates are limestone aggregates with particle size ranges of 0–5 mm, 5–10 mm, and 10–15 mm. The mineral filler used in this study is limestone mineral powder. The technical properties of all materials complied with the technical requirement specified in Chinese Standard JTG F40-2004 [19].

2.2. SBS/RA-Modified Asphalt Preparation

In order to ensure a thorough and uniform mixing of the modified material with the base asphalt, the modified asphalt was prepared using a high-speed shearing mixer. The preparation process of SBS/RA composite-modified asphalt is illustrated in Figure 1. First, 70# asphalt was placed in an oven and heated at 165 °C. Then, SBS of predetermined quality was added to the 70# asphalt. Secondly, shearing and mixing were conducted at a rotational speed of 5000 rad/min for 60 min to ensure that the SBS was uniformly distributed throughout the asphalt. Thirdly, RA of predetermined quality was added to the SBS-modified asphalt, followed by shearing for 30 min. Finally, the modified asphalt with uniform shear was put into a 165 °C oven for 30 min. It should be noted that regular stirring prevents segregation during the development process. The proportion schemes of SBS and RA for different modified asphalt formulations are listed in Table 4.

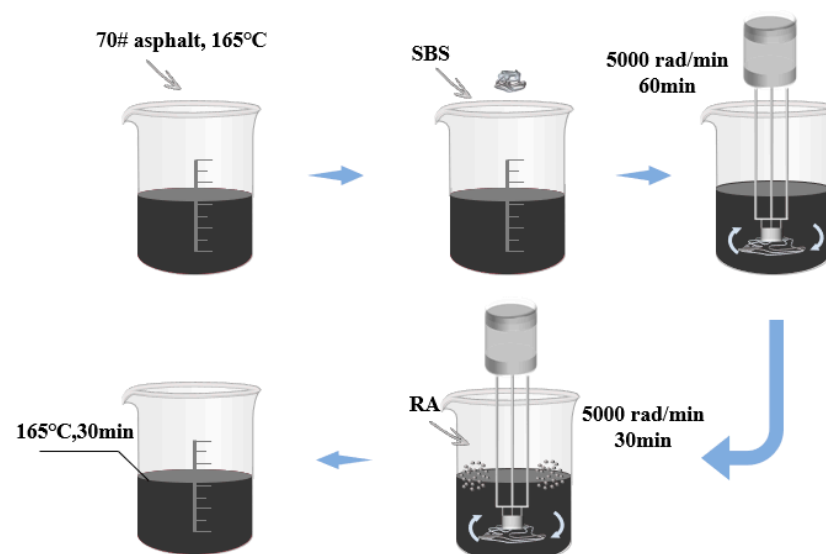
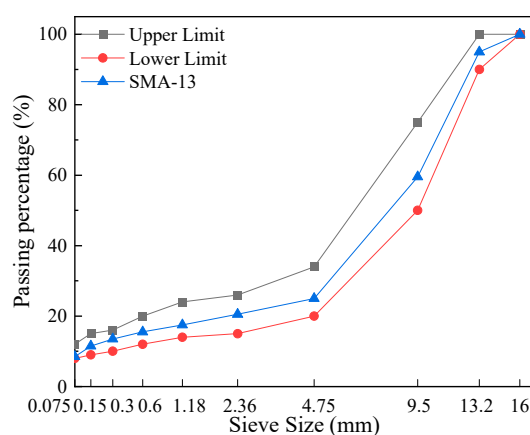
**Figure 1.** Preparation process of SBS/RA-modified asphalt.

Table 4. Proportion schemes of SBS/RA-modified asphalt.

Group ID	2S5R	2S10R	2S15R	3S5R	3S10R	3S15R	4S5R	4S10R	4S15R
SBS content	2%	2%	2%	3%	3%	3%	4%	4%	4%
RA content	5%	10%	15%	5%	10%	15%	5%	10%	15%

2.3. Mixes Design

The mineral gradation of stone mastic asphalt (SMA) mixtures used in this study is presented in Figure 2. Referencing Appendix C of Chinese Standard JTG F40-2004 [19], the mix design of SMA-13 mixtures was carried out using the volumetric design method of Marshall specimens. The mix design results for nine SMA-13 mixtures are provided in Table 5, including key properties such as the optimal asphalt content (OAC), asphalt voids filled with asphalt (VFA), voids in mineral aggregate (VMA), air voids (VA), and theoretical maximum specific gravity.

**Figure 2.** SMA-13 mix gradation.**Table 5.** Mix design results.

Group ID	OAC (%)	VA (%)	VMA (%)	VFA (%)	Theoretical Maximum Specific Gravity
2S5R	6.09	3.3	17.1	79.0	2.548
2S10R	6.18	3.6	18.4	81.5	2.552
2S15R	6.24	3.6	17.3	79.6	2.547
3S5R	6.15	3.9	18.1	80.6	2.550
3S10R	6.26	3.8	17.0	79.3	2.552
3S15R	6.31	3.5	17.6	79.9	2.555
4S5R	6.25	3.4	17.9	80.1	2.552
4S10R	6.35	3.7	17.4	78.7	2.560
4S15R	6.43	3.1	17.4	81.0	2.565

3. Engineering Performance

3.1. Experimental Framework

The performance evaluation was conducted on three aspects. Firstly, a series of laboratory tests were performed to assess the physical properties of asphalt binders with different amounts of SBS/RA. Secondly, the research concerned the improvement of SBS/RA on the road performances of the SMA-13 mixture. Finally, the optimal ratio of SBS/RA was recommended based on the principle of achieving the optimal comprehensive performance for both asphalt and asphalt mixtures. The experimental flowchart is shown in Figure 3.

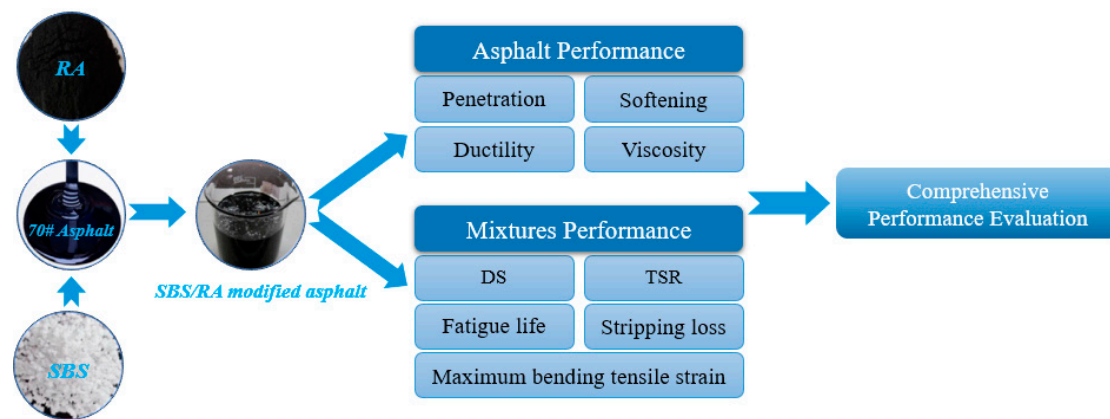


Figure 3. Experimental framework.

3.2. Asphalt Performance Evaluation

3.2.1. Ordinary Physical Test

Penetration, softening point, and ductility are the three most commonly used indicators for evaluating asphalt performance in China. Thus, in order to comprehensively assess the impact of SBS and RA ratios on the physical properties of 70# asphalt, penetration, softening point, and ductility tests were conducted. These performance tests were performed in accordance with sections T0604-2011, T0605-2011, and T0606-2011 of the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011) of China (JTG E20-2011) [20].

3.2.2. Rotational Viscosity Test

Rotational viscosity reflects the pumpability of asphalt, as well as the mixing and compaction temperatures required for asphalt mixtures. The viscosity of the asphalt binder was measured at 135 °C using an NDJ-5S Brookfield viscometer (Ruipu Company, Hebi, China). The test procedure was conducted in accordance with section T0625-2011 of Chinese Standard JTG E20-2011 [20].

3.3. Asphalt Mixture Performance Evaluation

3.3.1. Wheel Tracking Test

According to Chinese Standard JTG F40-2004 [19], the high-temperature performance of asphalt mixtures is assessed using the wheel tracking test, with dynamic stability (DS) serving as the evaluation index. A wheel tracking test was conducted following section T0719 of the Chinese Standard JTG E20-2011 to evaluate the rutting resistance of the SMA-13 mixture reinforced with SBS/RA [20]. The test utilized a 300 mm × 300 mm × 50 mm rutting specimen and was performed at a temperature of 60 °C under a loading pressure of 0.7 MPa for a duration of 60 min. The DS value is calculated using Equation (1).

$$DS = \frac{(t_2 - t_1) \times 42}{d_2 - d_1} \times C_1 \times C_2 \quad (1)$$

Here, t_1 and t_2 are taken as 45 min and 60 min; d_1 and d_2 correspond to the deformations at t_1 and t_2 , respectively; and C_1 and C_2 are the experiment coefficients, both set to 1.0.

3.3.2. Three-Point Bending Beam Test

The resistance to low-temperature cracking in asphalt mixtures is vital for ensuring their long-term durability [21]. In accordance with the Chinese Standard JTG F40-2004 [19], the three-point bending beam test was employed to evaluate the low-temperature per-

formance of SMA-13 mixtures. As specified in Section T0715 of Chinese Standard JTG E20-2011 [20], the test utilized prism specimens measuring 250 mm × 30 mm × 35 mm, which were extracted from rutting specimens. The testing was conducted at −10 °C with a loading rate of 50 mm/min. The maximum bending tensile strain (MBS) served as a key evaluation parameter and was calculated using Equation (2).

$$\varepsilon_B = \frac{6hd}{L^2} \quad (2)$$

Here, L and h denote the specimen span and the width of the middle section of the specimen, respectively, while d denotes the mid-span deflection at the point of specimen failure.

3.3.3. Freeze–Thaw Splitting Test

Asphalt mixtures are susceptible to the effects of rainfall and air moisture during service, leading to a reduction in the adhesion between the asphalt binder and the aggregates. Repeated freeze–thaw cycles cause water to expand and contract within the pavement structure, leading to the formation of voids and cracks in the mixture, thereby accelerating the deterioration of asphalt mixture properties. Therefore, the freeze–thaw splitting test was employed to assess the impact of SBS/RA on the water stability of SMA-13 mixtures. According to Section T0729-2000 of Chinese Standard JTG E20-2011 [20], $\varnothing 101.6 \times H63.5$ mm specimens were compacted 50 times using the Marshall compaction instrument (Changji Company, Shanghai, China). The test was conducted at 25 °C with a loading rate of 50 mm/min. The tensile strength ratio (TSR) was used as the key indicator to evaluate freeze–thaw cycle performance, with the TSR calculated based on Equation (3).

$$\text{TSR} = \frac{R_2}{R_1} \times 100\% \quad (3)$$

Here, R_1 and R_2 represent the average splitting strength measured before and after the freeze–thaw cycle process, respectively.

3.3.4. Cantabro Test

Insufficient asphalt content or poor adhesion can cause surface aggregates to detach under traffic loading conditions, resulting in severe distresses like potholes. According to Section T0733 of the Standard JTG E20-2011 [20], the Cantabro test was employed to assess the anti-stripping performance of SBS/RA composite-modified SMA-13 samples. The test was conducted using Marshall specimens with dimensions of $\varnothing 101.6 \times H63.5$ mm at 20 °C. The evaluation indicator was stripping loss, ΔS , which was calculated using Equation (4).

$$\Delta S = \frac{S_0 - S_1}{S_0} \quad (4)$$

Here, S_0 and S_1 denote the mass of the test samples before and after the test, respectively.

3.3.5. Four-Point Bending Fatigue Test

The fatigue performance of asphalt mixtures reflects their ability to resist damage under repeated loading, which is crucial for the durability and service life of asphalt pavements. In accordance with Section T0739 of the standard JTG E20-2011 [20], a four-point bending fatigue test was conducted using trabecular specimens with dimensions of 380 mm in length, 50 mm in thickness, and 63.5 mm in width. The test conditions were as follows: a test temperature of 15 °C, a test strain of 600 $\mu\epsilon$, and a loading frequency of 10 Hz. The specimens were subjected to repeated loading in a continuous partial sine wave

mode under constant strain control. The test continued until the stiffness modulus of the specimen decreased to 50% of its initial value, at which point the loading was terminated.

3.4. Comprehensive Performance Evaluation

SBS and RA play distinct roles in improving the performance of asphalt mixtures, and their combined use can enhance and optimize the overall properties of the mixtures. However, excessive RA content can result in an overly high elastic modulus of both the asphalt binder and the mixture, which negatively impacts low-temperature performance. Similarly, an excessively high SBS content may raise concerns about the storage stability of the modified asphalt. Therefore, it is essential to focus on the influence of SBS and RA content on the performance of both the asphalt binder and the asphalt mixture. The radar chart method is a widely employed method for comprehensive evaluation, providing a multidimensional assessment of an object, with the results being both intuitive and clear [22]. In this study, the radar chart method was employed to evaluate the performance of various types of SBS/RA composite-modified asphalts and mixtures.

(1) Standardization

In order to ensure the comparability between different variables, the mean standardization method is used to process the test data dimensionless. The calculation formula is given in Equation (5).

$$b_{ij} = \frac{a_{ij} - \frac{1}{k} \sum_{i=1}^k a_{ij}}{\sqrt{\frac{\sum_{i=1}^k (a_{ij} - \frac{1}{k} \sum_{i=1}^k a_{ij})^2}{k}}} \quad (5)$$

Here, i and j denote the serial numbers of the evaluated objects and the evaluation indices, respectively, and a_{ij} and b_{ij} refer to the experimental and standardized values, respectively.

(2) Mapping

Upon completion of normalization, the data should be represented in the radar chart in accordance with Equation (6). Meanwhile, the area A and perimeter L of the radar chart are calculated using Equation (7).

$$r_{ij} = \frac{2}{\pi} \arctan(b_{ij}) + 1 \quad (6)$$

$$\begin{cases} A_i = \frac{\pi}{k} \sum_{j=1}^k r_{ij}^2 \\ L_i = \frac{2\pi}{k} \sum_{j=1}^k r_{ij} \end{cases} \quad (7)$$

Here, r_{ij} is the converted value, and k is the total number of evaluation indices.

(3) Ranking

Furthermore, the scores, f , of different SMA-13 mixtures are calculated using Equation (8) to assess the overall performance.

$$f_i = \sqrt{\frac{A_i}{\max A_i} \times \frac{L_i}{2\sqrt{\pi A_i}}} \quad (8)$$

4. Results and Discussion

4.1. Asphalt Performance

4.1.1. Penetration and Softening Point

The penetration and softening point characterize the consistency and high-temperature stability of asphalt binder, respectively. The penetration and softening point results of asphalt binder modified using SBS/RA are shown in Figure 4. As the content of SBS or RA increases, the penetration value gradually decreases, indicating an enhancement in asphalt hardness and a significant improvement in resistance to high-temperature deformation. Similarly, the softening point increases with higher SBS or RA contents, demonstrating a notable enhancement in the high-temperature stability of the asphalt. Compared to the 70# asphalt, the sample containing 4% SBS and 15% RA exhibited the most substantial performance improvement, with an 87% increase in the softening point and a 61% reduction in penetration. In contrast, the 2% SBS/5% RA sample showed the smallest performance enhancement, with a 65% increase in softening point and a 41% decrease in penetration. As an elastomeric modifier, SBS primarily enhances the elasticity and rutting resistance of asphalt, while RA, as a natural rock asphalt, effectively thickens and hardens the asphalt binder [23,24]. Additionally, compared to the 70# asphalt, for samples with RA contents of 5%, 10%, and 15%, each 1% increase in SBS content resulted in an average reduction in penetration by 12.6%, 13.8%, and 15.3%, respectively, and an average increase in the softening point by 19.2%, 20.8%, and 21.8%, respectively. These findings highlight the synergistic effect of RA and SBS in improving asphalt consistency and thermal stability.

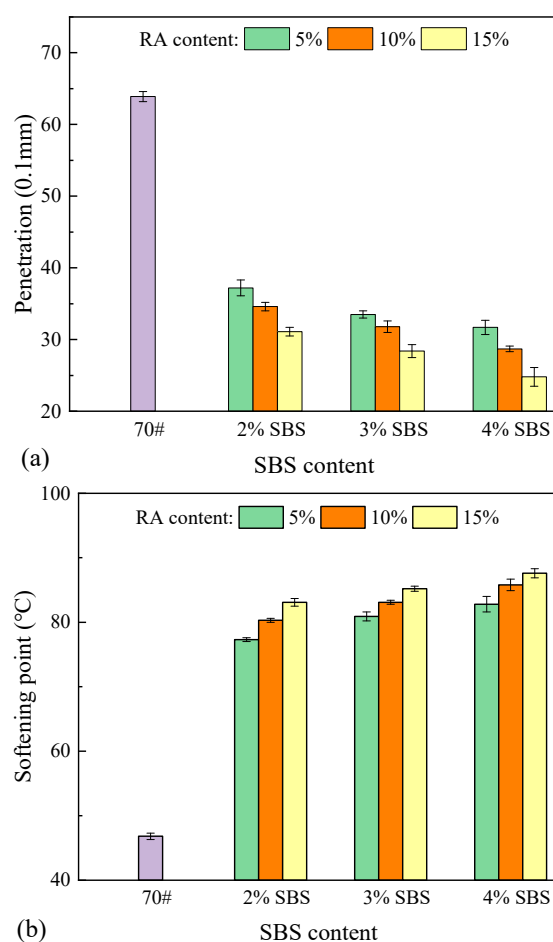


Figure 4. Results of penetration and softening point: (a) Penetration; (b) Softening point.

4.1.2. Ductility and Viscosity

Ductility and viscosity reflect the low-temperature performance and workability of asphalt binder, respectively. Figure 5 shows the influence of SBS and RA content on the ductility and 135 °C viscosity of asphalt binder. As illustrated in Figure 5a, the 5 °C ductility showed a downward trend, with an increase in RA content at the same SBS content, indicating that the addition of RA reduced the low-temperature ductility of asphalt and deteriorated its low-temperature performance. At the same RA content, an increase in SBS content significantly enhanced the 5 °C ductility, suggesting that SBS effectively improved the elasticity of asphalt and enhanced its resistance to cracking at low temperatures. The elastic improvement of SBS plays a compensatory role, while the rigidity of RA may weaken the ductility at low temperatures. Benefiting from the synergistic effect and complementary advantages of RA and SBS [11,23], the low-temperature ductility of all types of composite-modified asphalts showed significant improvement in comparison with 70# asphalt, with the 4% SBS/5% RA sample exhibiting the best performance.

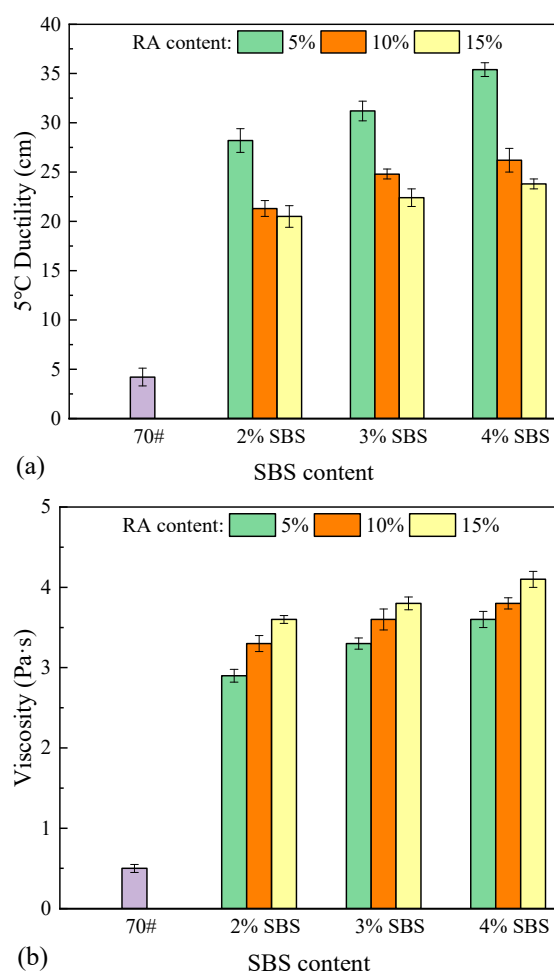


Figure 5. Results of ductility and viscosity: (a) Ductility; (b) Viscosity.

As shown in Figure 5b, at the same SBS content, the 135 °C viscosity increased with higher RA content. This can be attributed to the presence of high molecular components in RA. The total proportion of asphaltene and resin contents in RA are significantly higher than those in base asphalt [5,25,26]. The polarity of modified asphalt micelles is enhanced, and the colloidal structure gradually changes from sol-gel type to sol-gel type and gel type, which increases the viscosity of asphalt. Similarly, at the same RA content, the viscosity increased with the increase in SBS content. This is due to the swelling of SBS particles in asphalt, which increases the viscosity of the system [27]. Compared with

70# asphalt, SBS/RA significantly increased the viscosity of asphalt and reduced the workability. Therefore, an appropriate balance in the proportions of RA and SBS must be carefully considered to achieve an optimal compromise between improved performance and adequate workability during construction.

4.2. Asphalt Mixture Performance

4.2.1. Effect of SBS/RA on High-Temperature Rutting Resistance

Asphalt mixtures are prone to shear flow deformation and rutting under the combined effects of high temperature and traffic loading. Figure 6 illustrates the effect of SBS/RA content on the rutting resistance of SMA-13 mixtures. Similar to the trend observed in SBS/RA-modified asphalt, the DS value of SBS/RA composite-modified SMA-13 samples increased with increasing SBS/RA content, with the SMA-13 mixture containing 4% SBS and 15% RA demonstrating the best high-temperature performance. Furthermore, when the RA content was 5%, 10%, or 15%, each 1% increase in SBS resulted in average DS increases of 26.1%, 24.4%, and 14.4%, respectively. When the SBS content was 2%, 3%, or 4%, each 5% increase in RA resulted in average DS increases of 25.7%, 20.8%, and 14.1%, respectively. Clearly, both SBS and RA significantly enhanced DS, with SBS demonstrating a more pronounced effect on improving high-temperature performance compared to RA. SBS disperses within the asphalt under high-shear conditions and forms a continuous three-dimensional network structure through physical crosslinking, thereby enhancing the mixture's deformation resistance [27,28]. At the same time, the incorporation of RA into the asphalt mixture increases the proportion of asphaltenes and resins, which are key components responsible for the stiffness and rigidity of the binder [5,25,26,29]. The incorporation of RA into the asphalt mixture increases the proportion of asphaltenes and resins, which are key components responsible for the stiffness and rigidity of the binder. As these components are known to enhance the binder's resistance to deformation, their increased presence leads to a higher modulus, thereby improving the overall stiffness of the asphalt mixture. This contributes to the enhanced mechanical performance of the modified asphalt, particularly in terms of its resistance to rutting and deformation under load.

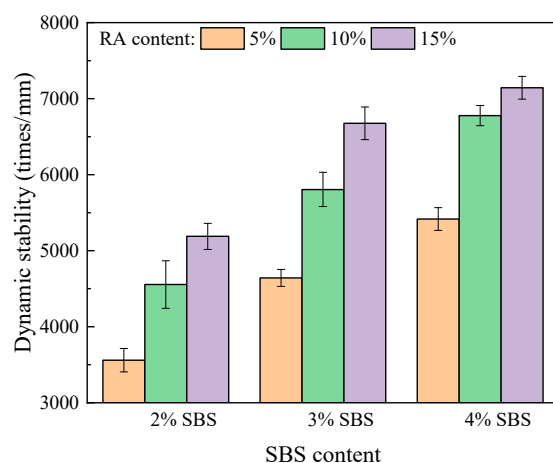


Figure 6. Results of wheel tracking test.

4.2.2. Effect of SBS/RA on Low-Temperature Cracking Resistance

The $-10\text{ }^{\circ}\text{C}$ bending test results of SMA-13 mixtures reinforced with different contents of SBS/RA are shown in Figure 7. When the RA content is set at 5%, 10%, and 15%, the MBS values of the SMA-13 mixture increase by 15.5%, 17.4%, and 20.7%, respectively, as the SBS content rises from 2% to 4%. Conversely, when the SBS content is set at 2%, 3%, and 4%, the MBS values decrease by 15%, 10.2%, and 11.2%, respectively, with the RA content increasing

from 5% to 15%. These findings clearly indicate that the addition of SBS enhances the low-temperature performance of the SMA-13 mixture, while RA exhibits a detrimental effect. The improvement achieved through SBS can be attributed to the polybutadiene blocks, which retain excellent flexibility at low temperatures, thereby significantly enhancing the low-temperature ductility and crack resistance of asphalt and its mixtures. Moreover, SBS swells and forms a uniform composite structure with the asphalt matrix, effectively mitigating internal stress concentration caused by low-temperature shrinkage through stress dispersion [30,31]. However, the high rigidity of RA causes its modification effect to primarily enhance the hardness of asphalt and the rigidity of the mixture [32]. As a result, the mixture's low-temperature flexibility is weakened, making it more susceptible to cracking under low-temperature conditions.

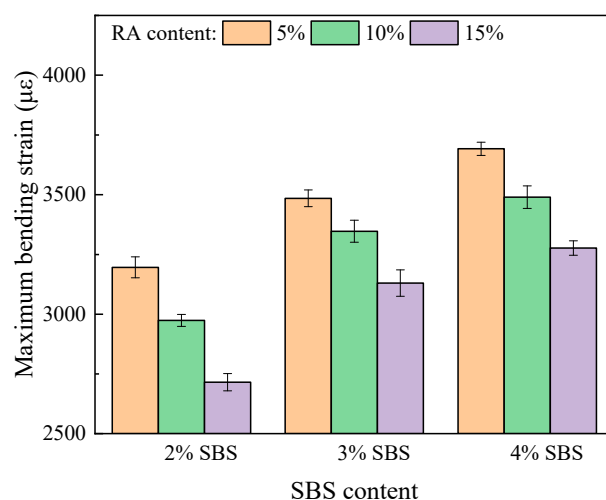


Figure 7. Results of three-point bending beam test.

4.2.3. Effect of SBS/RA on Freeze–Thaw Cycle Resistance

Figure 8 displays the TSR results of different SMA-13 samples. As can be seen, when the SBS content is set as 3%, the TSR value of the SMA-13 mixture increases with the addition of RA. For SBS contents of 2% and 4%, the TSR value follows a parabolic trend as the RA content increases. Similarly, when the RA content remains constant, the TSR value exhibits a parabolic relationship with increasing SBS content, peaking at 3% SBS. Among all design mixes, the 3% SBS/15% RA-modified SMA-13 mix demonstrates the best freeze–thaw resistance. In conclusion, the appropriate proportion of RA and SBS is beneficial to improving the water stability of the mixture. The addition of SBS improves the toughness and adhesion of asphalt, further enhancing the crack resistance of the mixture in the freeze–thaw environment [31,33]. The RA used in this study is Qingchuan RA. The nitrogen element in Qingchuan RA exists in the form of functional groups, which gives Qingchuan RA the advantages of strong wettability and strong resistance to free radical oxidation [7,34]. Nitrogen-containing compounds, such as amines and pyridines, influence the surface chemistry of asphalt by interacting with both the binder and aggregates. These compounds increase the binder's polarity, improving its ability to wet polar aggregates like quartz and limestone, thereby enhancing adhesion. Additionally, nitrogen groups act as antioxidants, reducing the binder's susceptibility to oxidative aging and helping maintain asphalt's long-term durability. The unique composition significantly improves the adhesion and anti-stripping properties of the aggregate. These properties can improve the adsorption of asphalt to the aggregate surface, thereby enhancing the water stability of the asphalt mixture.

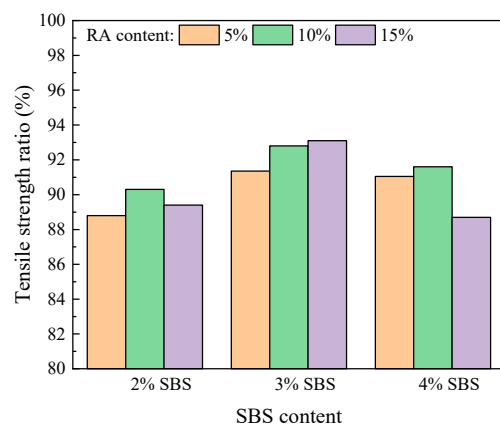


Figure 8. Results of freeze–thaw splitting test.

4.2.4. Effects of SBS/RA on Stripping Resistance

Figure 9 displays the Cantabro test results of different SMA-13 mixes. When the SBS content was 2%, the mass loss rate decreased by approximately 1.9% as the RA content increased from 5% to 15%. At SBS contents of 3% and 4%, 10% RA exhibited the best performance in enhancing the anti-dispersion properties. RA enhances the stiffness of the mixture and stabilizes the skeletal structure, thereby reducing material loss caused by external impacts. However, the high content of RA may lead to the brittleness of the mixture, which limits the further improvement of the stripping resistance [4,25]. At the same dosage of RA, the mass loss rate of SMA-13 samples followed a V-shaped trend with increasing SBS content. The effectiveness of SBS in improving stripping resistance was observed in the order of 3% > 4% > 2%. Notably, 3% SBS effectively enhanced the anti-dispersion performance of the mixture, while excessive SBS content might lead to excessive internal stress concentration, thereby increasing the mass loss rate [33]. The optimal combination of 3% SBS and 10% RA achieves a favorable balance among elasticity, rigidity, and bonding performance, significantly reducing the mass loss rate of the asphalt mixture.

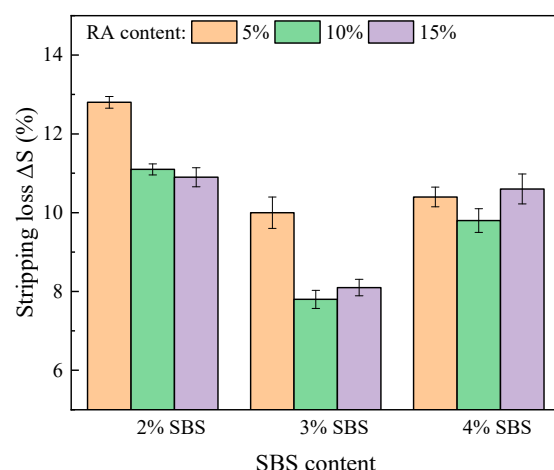


Figure 9. Results of Cantabro test.

4.2.5. Effects of SBS/RA on Fatigue Resistance

Figure 10 illustrates the influence of SBS and RA content on the fatigue performance of asphalt mixtures. As shown in Figure 10a, at a constant SBS content, the initial stiffness modulus demonstrated an upward trend with increasing RA content. Similarly, at a constant RA content, the initial stiffness modulus increased with higher SBS content. The observed increase in initial stiffness modulus indicated an enhancement in the mixture's

resistance to deformation under load. However, excessive stiffness could reduce the mixture's fatigue resistance under repeated loading conditions. Figure 10b illustrates that with constant RA content, the fatigue life varies as SBS content increases. Specifically, when the SBS content increases from 2% to 4%, the fatigue life of the mixture containing 5% RA increases by approximately 9.7%, the mixture with 10% RA shows an increase of about 8.3%, and the mixture with 15% RA demonstrates an increase of around 6.5%. The molecular structure of SBS, which is composed of styrene and butadiene, plays a crucial role in this behavior. The styrene component contributes rigidity, while the butadiene component provides elasticity [31,35]. Consequently, the addition of SBS enhances the elastic recovery properties of asphalt and the corresponding mixture. Under external loading, the increased elasticity allows the asphalt mixture to effectively absorb and disperse stress, thereby mitigating the formation of microcracks and reducing fatigue damage. At a fixed SBS content, the fatigue life exhibited a fluctuating trend with increasing RA content. With increasing RA content, the fatigue life curve of 2% SBS specimens decreased, while that of 3% SBS specimens increased, and the curve for 4% SBS specimens exhibited a parabolic pattern. The results suggested that the rigidity enhancement effect of RA positively influenced the stiffness modulus. However, excessive RA content may increase the brittleness of the mixture, thereby adversely impacting its fatigue life [32,36]. Among the tested mixtures, the SMA-13 mixture modified with 3% SBS and 15% RA exhibited the best fatigue performance.

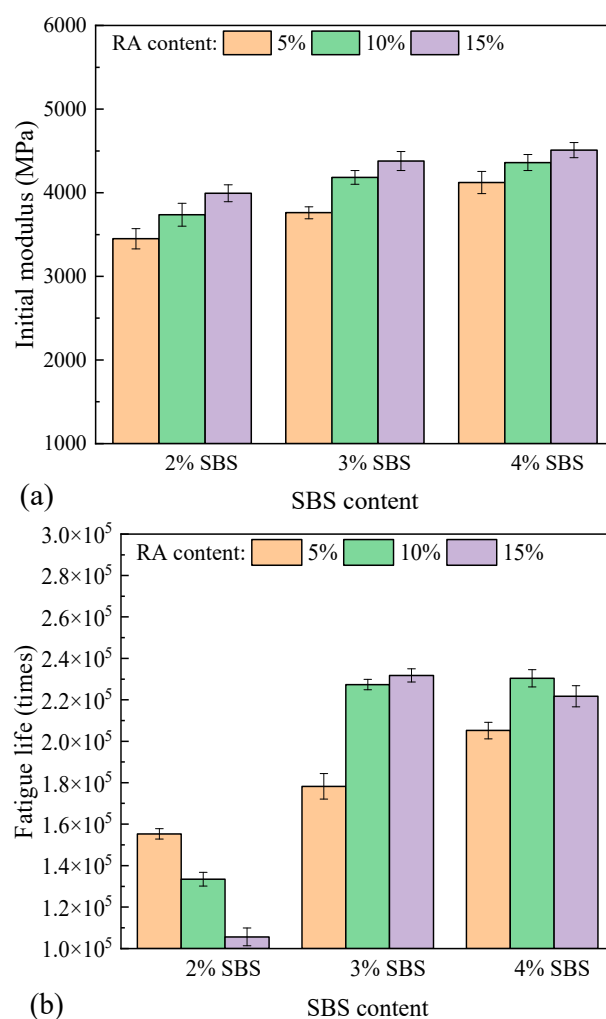


Figure 10. Results of four-point bending fatigue test: (a) Initial modulus; (b) Fatigue life.

4.3. Comprehensive Performance

Based on the results of the laboratory tests, different SBS/RA design mixes exhibit varying effects on enhancing the service performance of asphalt and its mixtures. To comprehensively evaluate the service performance, the radar chart method is employed in this study. A total of nine tests involving 10 performance indicators are considered. For asphalt indicators, the softening point, ductility, and viscosity are selected as they effectively represent the high-temperature performance, low-temperature performance, and workability of the asphalt, respectively. The penetration index, which is primarily used for asphalt grade classification, is excluded from this comprehensive assessment. For asphalt mixture indicators, DS, MBS, TSR, ΔS , and fatigue life are chosen as they effectively reflect the high-temperature resistance, low-temperature performance, water stability, and durability of asphalt mixtures. The initial stiffness modulus is excluded as an evaluation indicator in this study. Notably, all indicators are considered such that higher values correspond to better performance in the radar chart evaluation method. Thus, viscosity and stripping loss (ΔS) require conversion. According to the SHRP specification, the 135 °C viscosity of asphalt should not exceed 3 Pa·s [37]. During the analysis, the viscosity values are converted using Equation (9), while the stripping loss (ΔS) is converted using Equation (10).

$$V_1 = \left| \frac{3 - V_0}{3} \right| \quad (9)$$

$$\Delta S_1 = 1 - \Delta S_0 \quad (10)$$

Here, V_0 and V_1 represent the viscosity test value and the converted value, respectively, and ΔS_0 and ΔS_1 refer to the experimental value and the converted value of stripping loss, respectively.

Table 6 provides the r_{ij} values calculated using Equations (5) and (6). Using the data from Table 6, the radar chart shown in Figure 11 is plotted. Figure 11 provides an intuitive visualization of the effects of varying SBS and RA contents on the road performance of SMA-13 mixtures.

Table 6. r_{ij} results for nine types of SMA-13 mixture.

Group ID	Softening Point	Ductility	Viscosity	DS	MBS	TSR	ΔS	Fatigue Life
2S5R	0.3081	1.2856	0.3470	0.3193	0.8644	0.4162	0.3347	0.5979
3S5R	0.6201	1.5391	0.5134	0.5645	1.4379	1.2277	1.0889	0.8665
4S5R	0.9784	1.7099	1.0487	0.9393	1.6381	1.1075	0.9204	1.2399
2S10R	0.5394	0.4958	0.5134	0.5344	0.4957	0.8021	0.8790	0.4356
3S10R	1.0432	0.8410	1.0487	1.1664	1.2006	1.5868	1.6453	1.4653
4S10R	1.4952	1.0306	1.4165	1.5505	1.4446	1.3109	1.1701	1.4886
2S15R	1.0432	0.4459	1.0487	0.9235	0.3025	0.5294	0.4628	0.3149
3S15R	1.4222	0.5803	1.4165	1.4954	0.7290	1.6286	1.6063	1.4992
4S15R	1.6438	0.7194	1.6775	1.5889	1.0474	0.4013	0.8387	1.4176

Furthermore, the final comprehensive scores presented in Table 7 were calculated using Equations (7) and (8). The ranking of the f values is as follows: 4S10R > 3S15R > 3S10R > 4S5R > 4S15R > 3S5R > 2S15R > 2S5R > 2S10R. The results indicate that the comprehensive performance of the SMA-13 mixture modified with 4% SBS/10% RA is the best, while the mixture with 2% SBS/10% RA exhibits the poorest performance. SBS and RA each contribute to improving different aspects of the road performance of the SMA-13 mixtures. These findings provide valuable insights for selecting the optimal combination of SBS and RA based on specific performance priorities for different application scenarios.

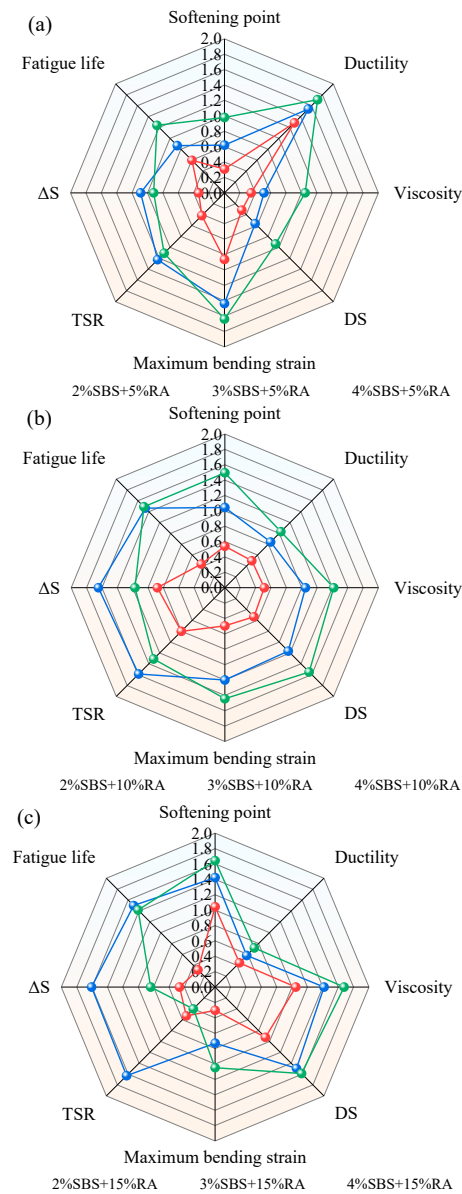


Figure 11. Radar chart for nine types of SMA-13 mixture: (a) 5%RA; (b) 10%RA; (c) 15%RA.

Table 7. Scoring results based on radar chart method.

Group ID	2S5R	3S5R	4S5R	2S10R	3S10R	4S10R	2S15R	3S15R	4S15R
<i>L</i> value	1.3194	3.4742	4.7743	1.1536	5.1324	5.9293	1.5413	5.7388	4.9203
<i>A</i> value	3.5133	6.1718	7.5259	3.6879	7.8519	8.5664	3.9826	8.1505	7.3314
<i>f</i> value	0.4382	0.7398	0.8845	0.4341	0.9199	0.9962	0.4850	0.9638	0.8796
Ranking	8	6	4	9	3	1	7	2	5

5. Conclusions

This study investigates the performance enhancement of asphalt and its mixtures modified with different combinations of SBS and RA. Through a series of laboratory tests, the effects of SBS and RA contents on the performance of both asphalt binders and asphalt mixtures were evaluated. The findings highlight the following key conclusions:

(1) The incorporation of SBS and RA significantly enhances the high-temperature stability and consistency of asphalt binders. As the contents of SBS and RA increase, both the softening point and viscosity exhibit marked improvements, while penetration values decrease. However, RA negatively impacts the low-temperature ductility of asphalt,

whereas SBS enhances elasticity and crack resistance at low temperatures. The synergistic interaction between SBS and RA facilitates an optimized balance of service performance.

(2) The combined modification of SBS and RA markedly improves the rutting resistance of SMA-13 mixtures. The mixture containing 4% SBS and 15% RA demonstrates the best high-temperature performance, with SBS exerting a dominant influence on enhancing deformation resistance.

(3) The incorporation of SBS improves the low-temperature performance of SMA-13 mixtures, whereas RA shows a detrimental effect by increasing rigidity and reducing flexibility. These findings suggest that optimizing SBS content while controlling RA content is crucial to achieving superior low-temperature cracking resistance.

(4) The optimal combination of 3% SBS and 15% RA demonstrates the best freeze–thaw resistance, while the combination of 3% SBS and 10% RA achieves the most favorable balance between elasticity and rigidity, resulting in superior stripping resistance. This highlights the importance of tailoring SBS and RA contents to achieve specific performance enhancements in asphalt mixtures.

(5) SBS enhances the fatigue life of SMA-13 mixtures by improving the elastic recovery properties of the asphalt. However, excessive RA content reduces fatigue performance due to increased brittleness. The mixture modified with 3% SBS and 15% RA demonstrates the best fatigue performance.

(6) A comprehensive evaluation using the radar chart method reveals that the 4% SBS/10% RA-modified SMA-13 mixture achieves the best overall performance across various indicators, while the 2% SBS/10% RA mixture exhibits the lowest performance.

In conclusion, this study provides valuable insights into the optimal combinations of SBS and RA for enhancing the performance of SMA-13 mixtures. The findings underscore the importance of a balanced approach to SBS and RA content to achieve optimal road performance of asphalt pavements under diverse environmental and traffic conditions.

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