

Article

Fineness-Dependent Rheology and Chemothermal Modification Mechanism of RHB-SBS Composite-Modified Asphalt

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Abstract

This study investigates the synergistic and fineness-dependent modification of base asphalt using rice husk biochar (RHB) and styrene–butadiene–styrene (SBS), aiming to achieve the efficient utilization of agro-waste resources while markedly improving the high-temperature performance and durability of green pavement materials and sustainable transportation infrastructure. Through conventional performance tests, rheological measurements, and microstructural analyses, the performance behavior of RHB-SBS composite-modified asphalt and the interaction mechanisms between the modifiers were systematically examined. The results indicate that the fineness of RHB has a significant effect on the performance of the composite-modified asphalt, with 300 mesh identified as the optimal particle size that provides the best balance between high-temperature stiffness, low-temperature ductility, and storage stability. When the RHB fineness is fixed at 300 mesh, increasing the RHB content from 0 to 16 wt% markedly enhances the high-temperature performance of the composite asphalt, while its low-temperature performance slightly decreases. Scanning electron microscopy (SEM) analysis reveals that the porous structure and large specific surface area of RHB enable it to form a stable spatial network within the asphalt matrix, thereby improving high-temperature stability. Fourier-transform infrared spectroscopy (FTIR) results show that the incorporation of RHB alters the chemical structure of the asphalt and increases the degree of crosslinking, while thermogravimetry–differential scanning calorimetry (TG-DSC) analysis further confirms that the thermal stability of the composite-modified asphalt is significantly enhanced.

Keywords: rice husk biochar; SBS; composite-modified asphalt; rheological properties; microscopic mechanism



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1. Introduction

As a core material for highway pavements, conventional base asphalt exhibits strong temperature sensitivity: it softens easily at high temperatures, leading to rutting, while becoming brittle at low temperatures, developing cracks, which seriously compromise

pavement service life and traffic safety [1,2]. To address these issues, modified asphalt technologies have emerged as a key research focus. Among them, styrene–butadiene–styrene (SBS)-modified asphalt has become the mainstream choice for high-grade highway construction owing to its outstanding properties across a broad temperature spectrum [3,4]. Systematic research on SBS-modified asphalt has been conducted both domestically and internationally. Mechanistically, Shi [5] found through component analysis that physical blending of SBS with base asphalt forms an elastic network structure, which Cui [6] further confirmed arises from the swelling interaction between SBS and the light fractions of asphalt, fundamentally improving asphalt performance. In terms of performance optimization, Zhang [7] demonstrated that increasing the SBS content within an appropriate range enhances high-temperature stability and reduces temperature sensitivity, while Özdemir [8] further verified its advantages in rutting and crack resistance. However, SBS-modified asphalt has notable limitations: it involves high production costs and faces issues such as poor storage stability and high energy consumption during construction, which restrict its large-scale application [3,9]. Therefore, identifying strategies that improve the performance of SBS-modified asphalt while effectively reducing its cost has become a critical challenge requiring urgent attention.

Biochar, a solid carbon material derived from biomass through oxygen-limited pyrolysis, has gained considerable interest in recent years owing to its remarkable thermal stability, chemical reactivity, and porous structure [10–12]. Current research on biochar exhibits a multi-directional expansion trend. In terms of preparation, Zhao [13] demonstrated that pyrolysis temperature and heating rate significantly influence the microstructure of biochar, with high-temperature pyrolysis producing materials with larger specific surface areas and more complex pore structures, thereby enhancing their modification effects. Regarding performance applications, studies by Xie [14] and Ma [15] indicate that incorporating biochar into asphalt can improve high-temperature stability, rutting resistance, and reduce temperature sensitivity. Zhou [16,17] further revealed that biochar can adsorb the light fractions of asphalt, thereby reducing the formation of aging products and delaying the aging process. From an environmental perspective, related studies [18,19] confirmed that biochar can reduce volatile organic compound (VOC) emissions by approximately 30% during asphalt construction. Nevertheless, research on biochar-modified asphalt remains in its early stages. Systematic investigations are still needed to clarify the differences in modification effects among biochars derived from different raw materials, their long-term aging performance, and the underlying micro-mechanisms.

Rice husk biochar (RHB), an important category of biochar, is produced from the low-cost agricultural waste rice husks through oxygen-limited pyrolysis and has recently demonstrated unique potential for asphalt modification. Existing studies have primarily focused on its performance enhancement and environmental benefits. Wang [20] applied RHB to asphalt mixtures, effectively improving pavement performance while achieving emission reduction goals through carbon sequestration. Yi [21] systematically evaluated the feasibility of using rice husk biochar as a partial replacement for SBS in asphalt modification. The results indicated that an appropriate dosage of rice husk biochar markedly enhances the high-temperature stability of asphalt.

Furthermore, the intrinsic characteristics of RHB support its effectiveness in modification. Heo [22] and Tsai [23] reported that RHB maintains a high yield even at carbonization temperatures above 600 °C. Gunn and Lu [24,25] confirmed that its small particle size (5–10 µm), large specific surface area (50–60 m²/g), and approximately 40% content of amorphous silica facilitate effective adsorption of asphalt components and strengthen interfacial bonding, providing a physicochemical foundation for optimizing asphalt performance.

Based on the above research background, this study focuses on the performance of RHB-SBS composite-modified asphalt, aiming to address key issues that remain insufficiently explored in existing modification technologies. Table 1 summarizes recent studies on biochar-modified asphalt. It can be observed that, although considerable research efforts have been devoted to investigating the effects of different biochar contents, systematic studies on the influence of biochar particle size are still lacking. Existing literature has primarily concentrated on identifying the optimal biochar dosage in modified asphalt systems, while insufficient attention has been paid to biochar particle size (mesh number), a critical parameter that directly affects specific surface area, dispersion behavior, and interfacial interaction efficiency. As a result, the role and underlying mechanisms of particle size in biochar-SBS composite modification systems have not yet been systematically elucidated. In view of this research gap, this study builds upon previous work that established the appropriate content of RHB in SBS-modified asphalt systems [21]. From the perspective of the coupled regulation of dosage and fineness, the effects of RHB content and mesh size on the rheological properties of RHB-SBS composite-modified asphalt are systematically analyzed. Particular emphasis is placed on the performance transition characteristics induced by particle size variation and their potential mechanistic thresholds, and a reasonable range of parameter combinations is consequently determined. Furthermore, scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and thermogravimetric-differential scanning calorimetry (TG-DSC) are employed to further investigate the interaction characteristics between RHB and SBS within the asphalt matrix and to elucidate the synergistic enhancement effects and their underlying mechanisms during the composite modification process. This study provides a theoretical basis for understanding the modification mechanism and engineering application of RHB-SBS composite-modified asphalt, promotes the high-value utilization of agricultural waste, and contributes to the development of green and low-carbon road materials in support of the dual-carbon strategy.

Table 1. Comparison of biochar-modified asphalt.

Researcher	Asphalt Binder	Biochar Type	Research Focus
Feng Ma [15]	70 # base asphalt	straw-based biochar (150 mesh)	Investigated the effects of biochar content (0–15%) as an asphalt modifier on the high-temperature performance of asphalt
Xiule Chen [26]	90 # base asphalt	corn straw biochar (50 mesh)	Examined the influence of biochar content (1–3%) on the high-temperature stability of asphalt and the road performance of asphalt mixtures
Clara Celauro [27]	50/70 penetration-grade bitumen	commercial biochar (pyrolysis of birch and beech wood)	Evaluated the effects of biochar content (0–10%) on the properties of biochar-modified asphalt before and after short-term aging
Youqiu Yi [21]	70 # base asphalt	RHB	Our previous work established the feasibility of RHB-SBS composite modification and identified appropriate dosage ranges.
This study	70 # (A-grade) road petroleum asphalt	RHB	This work advances RHB-SBS composite-modified asphalt by introducing biochar fineness (mesh size) as a key design variable, and by systematically mapping the coupled effects of dosage and fineness on performance, supported by microstructural and thermal evidence, including storage-stability evaluation

2. Materials and Methods

2.1. Materials

The base asphalt employed in this research was a 70# (A-grade) petroleum-based road material, and its key performance characteristics are shown in Table 2. The RHB produced by pyrolysis carbonization under oxygen-free conditions at 600–800 °C, followed by physical activation and sieving into particle sizes of 100, 200, 300, and 400 mesh. The elemental analysis results are presented in Table 3. The SBS modifier used was type YH-791, with its leading performance indicators listed in Table 4. The stabilizer adopted was commercial-grade sulfur, and its detailed technical specifications are presented in Table 5.

Table 2. Performance characteristics of base asphalt.

Technical Index	Unit	Specification Requirement	Test Result
Penetration at 25 °C (25 °C, 100 g, 5 s)	0.1 mm	60~80	69.1
Softening point	°C	≥46	51.2
Ductility at 10 °C	cm	≥20	80
Ductility at 15 °C	cm	≥100	>100
Density at 15 °C	g/cm ³	Measured data	1.040
Dynamic viscosity at 60 °C	Pa·s	≥180	193.1
Mass change	%	≤±0.8	−0.026
After RTFOT			
Penetration ratio at 25 °C	%	≥61	62
Residual ductility at 10 °C	(cm)	≥6	6

Table 3. Elemental analysis of RHB.

Sample	Elemental Composition (%)				
	N	C	H	S	O
RHB	0.897	55.346	1.261	0.121	42.375

Table 4. Technical specifications of SBS.

Grade	Block Ratio	Specified Extensional Stress (MPa)	Tensile Strength (MPa)	Elongation at Break (%)
YH-791	30/70	≥2.50	≥18.00	≥815

Table 5. Technical specifications of stabilizer.

Technical Index	Unit	Test Result
Appearance	—	Pale yellow powder
Density	g/cm ³	2.07
Melting point	°C	118
Flash point	°C	250
Ash content	%	0.003
Solubility	—	Insoluble

2.2. Sample Preparation

The composite-modified asphalt was prepared using a laboratory high-speed shear emulsifying machine (FLUKO, FM 30-D, sourced from Nanjing, China). The base asphalt was initially heated in an oven at 150 °C until entirely melted to ensure a uniform fluid state, and a certain mass was weighed for later use. Subsequently, SBS was incorporated into the base asphalt and then processed by high-speed shearing at 6000 r/min for 1 h at 180 °C to ensure thorough dispersion and preliminary mixing with the asphalt. Then,

an appropriate amount of sulfur powder was incorporated and sheared for an additional 10 min. Afterward, under the same temperature and shearing conditions, pretreated RHB was incorporated into the mixture and sheared for 45 min to promote compatibility and uniform distribution of RHB with SBS and the asphalt. Finally, upon cooling the mixture to an appropriate temperature and gently stirring it with a glass rod to eliminate entrapped air, the RHB-SBS composite-modified asphalt was ultimately obtained.

2.3. Test Methods

Based on previous work [21], the dosages of RHB and SBS were controlled at 15% and 4% of the asphalt mass, respectively, enabling a systematic examination of how variations in RHB fineness (mesh size) influence the fundamental characteristics exhibited by the resulting RHB-SBS composite-modified asphalt. Subsequently, the optimal RHB fineness was selected, and under a constant SBS content of 4%, the RHB content was varied at 0%, 10%, 12%, 14%, 16%, and 18% by asphalt mass. Conventional and rheological evaluations were performed to comprehensively assess how RHB content affects the properties of the composite-modified asphalt. (When the RHB content reached 18%, the ductility at 5 °C failed to meet the specification requirements; therefore, the 18% content group was excluded from the rheological performance analysis.) Finally, the collaborative modification behavior between RHB and SBS was examined at the microscopic scale to clarify their impacts on the microstructure and compositional evolution of asphalt.

2.3.1. Methods for Conventional Performance Tests

According to the test methods and technical requirements specified in the Test Specifications for Asphalt and Asphalt Mixtures in Highway Engineering, a series of conventional performance evaluations was conducted on the prepared RHB-SBS composite-modified asphalt. All tests were conducted using three parallel specimens. The specific tests included: penetration measured at 25 °C under a 100 g load for 5 s; a softening point test to assess high-temperature deformation resistance; a ductility test at 5 °C to characterize low-temperature extensibility; apparent viscosity determined using a Brookfield rotational viscometer to evaluate workability and construction performance; and a 48-h thermal storage stability test to examine the material's susceptibility to segregation.

2.3.2. Methods for Temperature Sweep Test

Using an MCR702 rheometer (Anton Paar, Graz, Austria) in accordance with the relevant AASHTO specifications, the viscoelastic properties of the RHB-SBS composite-modified asphalt were evaluated using unaged samples. A parallel-plate geometry with a diameter of 25 mm and a 1 mm gap was employed, and temperature scanning was conducted under strain-controlled mode. The applied strain was set to 12%, with a loading frequency of 10 rad/s. The temperature range for testing extended from 58 °C to 88 °C, with increments of 6 °C. Three replicate specimens were tested for each condition. At each temperature level, the complex shear modulus (G^*) and phase angle (δ) of the composite-modified asphalt were recorded, and the reported values represent the average of the three replicates, based on which the rutting factor was subsequently calculated.

2.3.3. Methods for MSCR Test

The creep-recovery behavior of the unaged RHB-SBS composite-modified asphalt was characterized using an MCR702 rheometer (Anton Paar, Graz, Austria) in accordance with the relevant AASHTO standards. A parallel-plate assembly with a diameter of 25 mm and a thickness of 1 mm was employed. To assess the material's high-temperature deformation and recovery characteristics under different loading conditions, two stress levels (0.1 kPa and 3.2 kPa) were applied, and tests were conducted separately at 64 °C, 70 °C, and 76 °C.

The creep-recovery procedure consisted of a cyclic mode comprising 1 s of loading followed by 9 s of unloading, with ten cycles performed under each test condition. Three replicate specimens were tested for each condition, and the values of the non-recoverable creep compliance (J_{nr}) and creep recovery percentage (R) were reported as the average of the three replicates. The creep-recovery behavior was further quantified using the percentage difference of non-recoverable creep compliance ($J_{nr-diff}$) and the difference in creep recovery percentage (R_{diff}), calculated according to Equations (1)–(4).

$$J_{nr}(\tau) = \sum_{n=1}^{10} \left(\frac{\gamma_r^n - \gamma_0^n}{\tau} \right) \times 100\% \quad (1)$$

$$R(\tau) = \sum_{n=1}^{10} \left(\frac{\gamma_c^n - \gamma_r^n}{\gamma_c^n - \gamma_0^n} \right) \times 100\% \quad (2)$$

$$J_{nr-diff} = \left(\frac{J_{nr}(3.2 \text{ kPa}) - J_{nr}(0.1 \text{ kPa})}{J_{nr}(0.1 \text{ kPa})} \right) \times 100\% \quad (3)$$

$$R_{diff} = \frac{R(0.1 \text{ kPa}) - R(3.2 \text{ kPa})}{R(0.1 \text{ kPa})} \times 100\% \quad (4)$$

where: n : number of loading cycles; γ_r^n : final recovered strain in the n th cycle; γ_0^n : initial strain in the n th cycle; γ_c^n : final strain in the n th cycle; τ : test stress level.

2.3.4. Methods for BBR Test

A bending rheometer (CANNON Instrument Company, State College, PA, USA) was used to apply a constant load to beam specimens prepared from unaged asphalt, with dimensions of 120 mm $\times$ 12.5 mm $\times$ 6.25 mm at -6°C and -12°C , and the resulting creep deformation as a function of time was recorded. Three replicate beam specimens were tested at each temperature. The bending creep stiffness (S) and creep rate (m) were calculated according to Equations (5) and (6), and the reported values represent the average of the three replicates.

$$S(t) = \frac{PL^3}{4bh^3\delta(t)} \quad (5)$$

$$m = \frac{d\log[S(t)]}{d\log(t)} \quad (6)$$

where: $S(t)$: creep stiffness; P : applied load on the specimen; L , b , h : length, width, and height of the beam, respectively; $\delta(t)$: deflection of the beam.

2.3.5. Methods for SEM Test

Scanning electron microscopy (SEM) was utilized to characterize the component distribution and microstructural features of the RHB and RHB-SBS composite-modified asphalt samples. The instrument employed was a Helios 5 CX electron microscope (Thermo Fisher Scientific, Brno, Czech Republic).

2.3.6. Methods for FTIR Test

Using a SYD-0672 infrared spectrometer (Shanghai Changji Geological Instrument Co., Ltd., Shanghai, China) operated in ATR mode (resolution: 4 cm^{-1} ; wavenumber range: $4000\text{--}500 \text{ cm}^{-1}$), Fourier-Transform Infrared Spectroscopy (FTIR) was employed to characterize the chemical structure of the RHB-SBS composite-modified asphalt by identifying changes in the absorption peaks associated with key functional groups and their constituent components.

2.3.7. Methods for TG-DSC Test

To thoroughly assess the mass variation and thermal responses of asphalt during heating, TG-DSC characterization was conducted using a NETZSCH comprehensive thermal analyzer (NETZSCH-Gerätebau GmbH, Selb, Bavaria, Germany). All measurements were carried out in a nitrogen environment, and the specimens were heated from ambient temperature to 800 °C at a uniform rate of 10 °C/min.

3. Results and Discussion

3.1. Conventional Performance Tests

3.1.1. Effect of RHB Mesh Size on the Properties of RHB-SBS Composite Modified Asphalt

As presented in Table 6, the RHB-SBS composite-modified asphalt shows an initial decrease followed by an increase in penetration as the RHB mesh size increases, reaching its minimum value ($42.1 \times 0.1 \text{ mm}^2$) at 300 mesh. This indicates that the particle size of RHB significantly influences the hardness and consistency of the asphalt. At lower mesh sizes, the RHB particles exhibited poor dispersibility, weak interfacial bonding, and a loose structure. When the mesh size was increased to 300, both dispersibility and interfacial bonding improved, leading to a denser microstructure. However, at 400 mesh, the excessively large specific surface area may have led to overly strong interfacial interactions or the adsorption of light components, thereby disrupting matrix uniformity and increasing penetration again.

Table 6. Effect of RHB mesh size on the properties of composite-modified asphalt.

Mesh Size	100 Mesh	200 Mesh	300 Mesh	400 Mesh	Method (JTG E20)	Technical Requirements
Penetration at 25 °C (0.1 mm)	46.2	44.6	42.1	43.9	T0604	40~60
Softening point (°C)	68.8	72.6	75.0	76.3	T0606	≥60
Ductility at 5 °C (cm)	17.5	20.8	25.4	23.6	T0605	≥20
Brookfield viscosity at 135 °C (Pa·s)	2.68	2.75	2.73	2.70	T0625	≤3
Softening point Difference after 48 h (°C)	2.1	1.6	1.3	1.2	T0661	≤2.5

The softening point increased continuously with the RHB mesh size, reaching a maximum of 76.3 °C, although the growth rate slowed between 300 and 400 mesh. Higher mesh RHB, with its larger specific surface area [28,29], strengthened the interfacial bonding with the asphalt matrix and possibly interacted synergistically with SBS to form a more homogeneous and stable network structure, thus enhancing high-temperature stability.

The ductility first increased and subsequently declined as the RHB mesh size increased, reaching a peak value of 25.4 cm at 300 mesh and slightly decreasing to 23.6 cm at 400 mesh. Low-mesh samples exhibited wide and irregular fracture surfaces with visible particle features, and fractures mainly occurred around the RHB particles. As the mesh size increased, improved dispersion and interfacial bonding enhanced ductility. However, at 400 mesh, possible particle agglomeration reduced dispersibility, leading to a decline in ductility.

At a 15% RHB content, the effect of RHB mesh size on viscosity was relatively limited, with the highest Brookfield viscosity at 135 °C observed for the 200–300 mesh range. This was attributed to optimal particle dispersion and interfacial bonding within this range, resulting in superior structural performance. Beyond 300 mesh, particle agglomeration may have disrupted the SBS network, leading to a reduction in viscosity.

The softening point difference after 48 h decreased gradually with increasing RHB mesh size, indicating that storage stability improved with finer particles. High-mesh RHB

had a larger specific surface area and stronger interactions with SBS and the asphalt matrix, thereby helping suppress phase separation. The softening point difference decreased notably between 100 and 300 mesh but leveled off between 300 and 400 mesh, likely due to saturation in dispersion and improved stability.

This optimum mesh size is consistent with the SEM observations in Section 3.5, where the 300-mesh RHB particles exhibit a more continuous and well-dispersed micro-network compared with coarser (100–200 mesh) or ultra-fine (400 mesh) particles. Such a uniform microstructure facilitates more effective interaction with the SBS-asphalt matrix, thereby contributing to improved high-temperature and storage stability.

In summary, considering both overall performance and construction feasibility, 300-mesh RHB was selected as the optimal parameter for preparing RHB-SBS composite-modified asphalt, achieving a balance between performance enhancement and economic feasibility.

3.1.2. Effect of RHB Content on the Properties of RHB-SBS Composite-Modified Asphalt

As illustrated in Table 7, increasing the RHB content results in a decrease in the penetration of the RHB-SBS composite-modified asphalt, suggesting a marked improvement in asphalt hardness. This is attributed to the strong adsorption capacity of RHB, which absorbs the light components of asphalt, restricts the fluidity of the matrix, and leads to a denser and more stable structure [30]. At low RHB contents, the change in penetration was minor, suggesting that the hardening effect was not yet prominent. However, when the content reached 14–16%, penetration decreased sharply, indicating that a higher RHB dosage substantially strengthened the asphalt skeleton effect and increased hardness.

Table 7. Effect of RHB content on the properties of composite-modified asphalt.

RHB Content	0%	10%	12%	14%	16%	18%	Method (JTG E20)	Technical Requirements
Penetration at 25 °C (0.1 mm)	55.0	46.3	45.0	42.2	40.1	37.5	T0604	40~60
Softening point (°C)	68.0	74.5	75.4	76.0	76.7	78.5	T0606	≥60
Ductility at 5 °C (cm)	32.0	24.2	23.5	22.8	20.3	17.6	T0605	≥20
Brookfield Viscosity at 135 °C (Pa·s)	2.0	2.58	2.70	2.79	2.82	2.85	T0625	≤3

At the same time, increasing the RHB content markedly raised the softening point of the composite-modified asphalt, demonstrating that RHB incorporation positively contributes to improving the high-temperature performance of asphalt. This enhancement stems from the reinforcing effect of RHB as a biochar material, which enhances the internal framework of the asphalt matrix and limits the movement of molecular chains, thereby improving its thermal resistance.

However, with higher RHB content, the composite-modified asphalt dropped significantly in ductility, with a particularly sharp decline at 5 °C. This reduction in ductility may be associated with excessive RHB particles increasing the brittleness of the matrix and facilitating internal crack propagation, indicating that the incorporation of RHB partially reduces the low-temperature flexibility of the asphalt.

Moreover, variations in RHB content markedly influenced the Brookfield viscosity of the composite asphalt, exhibiting a steady upward tendency. This behavior can be attributed to the role of RHB as a solid particulate filler, which strengthens interactions among asphalt molecules, limits their mobility, and increases flow resistance, ultimately resulting in higher viscosity.

From an engineering design perspective, the RHB content can be divided into two practical modification zones. A dosage of 10–12 wt% may be regarded as a “moderate-

modification range”, in which the viscosity remains relatively manageable during construction and the reduction in low-temperature flexibility is limited. In contrast, higher dosages (14–16 wt%) constitute a “high-rutting-resistance range”, offering markedly enhanced high-temperature stiffness and MSCR performance. However, this comes at the cost of reduced low-temperature ductility, making high-dosage binders more suitable for heavy-duty pavements or hot-climate regions rather than cold climates.

3.2. Temperature Sweep Test

As shown in Figure 1, the G^* values of all samples decrease with increasing temperature, indicating that the shear resistance of the material gradually weakens—a typical viscoelastic behavior of asphalt binders [31]. Compared with SBS-modified asphalt, the RHB-SBS composite-modified asphalt exhibits consistently higher G^* across all temperatures. For instance, at 58 °C, the G^* values of the composites containing 10%, 12%, 14%, and 16% RHB are 12.8%, 18.4%, 21.6%, and 23.2% higher, respectively, than those of the SBS-modified asphalt. Such improvement results from the high specific surface area and strong filling capability of RHB, which facilitates the development of a multi-scale reinforcing network in the asphalt matrix and ultimately enhances the material’s rigidity and structural stability. Moreover, the micropores and surface functional groups of RHB may interact physically or chemically with asphalt molecules, further enhancing the cohesive strength of the material.

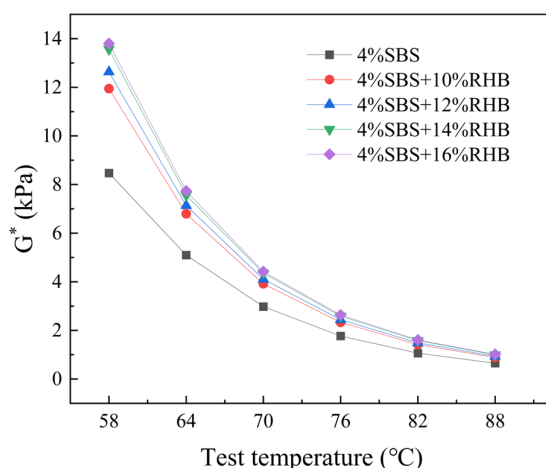


Figure 1. Variation curve of G^* with temperature.

Further analysis indicates that when the RHB content exceeds 14%, the rate of performance improvement diminishes. This may be attributed to the uneven dispersion or agglomeration of RHB at higher dosages, leading to its reinforcing effect approaching saturation. In addition, the influence of temperature varies significantly among different samples. The G^* reduction of the composite-modified asphalt containing 16% RHB is notably lower than that of SBS-modified asphalt, indicating that adding RHB lowers the temperature susceptibility of the composite system and improves its high-temperature stability, which is of great significance for mitigating rutting under high summer temperatures [32].

Figure 2 presents the temperature-dependent evolution of δ for the SBS composite-modified asphalt containing different RHB contents within the range of 58 °C to 88 °C. As temperature increases, the δ of all samples gradually rises, indicating that the viscous component of the material becomes increasingly dominant, the energy storage capacity decreases, and the elastic performance diminishes. Specifically, the δ of SBS-modified asphalt increases from 65.3° at 58 °C to 69.4° at 88 °C, representing a 6.3% increase. In

contrast, the δ of the RHB-SBS composite-modified asphalt stays below that of the SBS-modified asphalt across the entire temperature range and continues to decline as the RHB content increases. This phenomenon suggests that incorporating RHB enhances the elastic component and energy storage capacity of asphalt to some extent, allowing the material to maintain structural stability more effectively under high-temperature conditions. Notably, with the increase in RHB content from 10% to 16%, the rate at which δ decreases begins to level off, indicating that the modification effect of RHB may approach saturation at higher dosages, potentially due to uneven particle dispersion or agglomeration. Overall, incorporating RHB markedly enhances the high-temperature elastic performance of SBS-modified asphalt, resulting in superior structural stability and resistance to permanent deformation. In particular, at 16% RHB content, the δ of the samples remains around 65° within the $70\text{--}88^\circ\text{C}$ temperature range, approximately 7.8% lower than that of the base asphalt (70°), demonstrating excellent high-temperature performance.

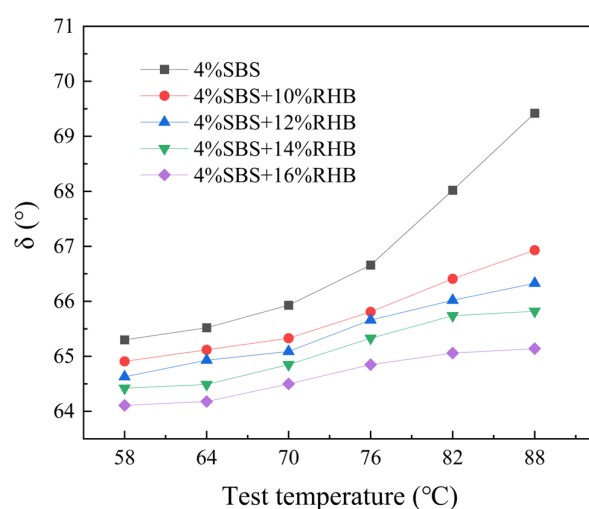


Figure 2. Variation in δ with temperature.

In the Superpave design specification, the rutting factor, calculated from G^* and δ , is an important indicator for evaluating the asphalt's resistance to rutting deformation [33]. Under the maximum pavement design temperature, a higher rutting factor indicates a stronger ability of the asphalt to resist high-temperature shear deformation and permanent deformation [34]. Therefore, this parameter serves as a key indicator for evaluating the rutting resistance of asphalt binders. Based on the experimental data, Figure 3 presents the temperature-dependent trend curves of the rutting factor for the RHB-SBS composite-modified asphalt.

As illustrated in the figure, with an increase in temperature, the rutting factor of all asphalt samples exhibits a significant decreasing trend, indicating a marked reduction in the material's resistance to rutting under high-temperature conditions. Upon the incorporation of RHB, the rutting factor of the RHB-SBS composite-modified asphalt is significantly higher than that of the SBS-modified asphalt at all temperatures. Additionally, as the RHB content increases, the rutting factor shows a gradual improvement. This suggests that RHB can effectively enhance the high-temperature rutting resistance of asphalt. However, when the RHB content reaches a higher level, the improvement trend gradually slows down, displaying a nonlinear characteristic. This may be attributed to the uneven dispersion or agglomeration of RHB at higher dosages, which limits the further enhancement of its modification effect. These findings align with the conclusions drawn from Figures 1 and 2, which suggest that the enhancing effect of RHB tends to saturate at higher dosages and does not continue to exhibit a linear increase. Furthermore, as shown in the figure, the

composite-modified asphalt containing 16% RHB (300 mesh) demonstrates approximately a 50% higher rutting factor at 70 °C compared to the SBS-modified asphalt. Compared to previous studies that focused primarily on the RHB content [21], the rutting factor increased by about 15% at 70 °C with a 10% RHB dosage in this study. The rutting factor at the optimal dosage in the present study has shown further improvement, especially with a 20% increase at 70 °C, when compared to the best dosage in previous research. This highlights the significant influence of RHB mesh size on the performance of asphalt.

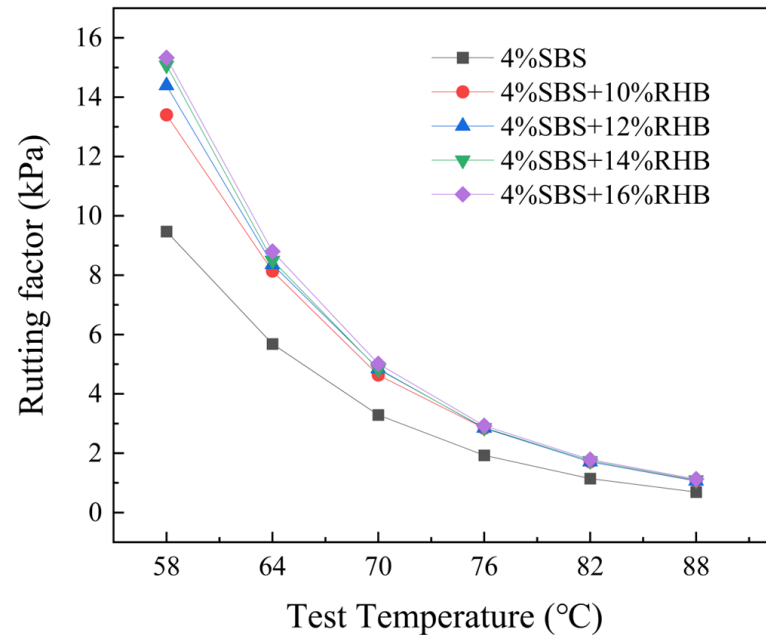


Figure 3. Variation in rutting factor with temperature.

3.3. MSCR Test

MSCR testing was performed on several types of modified asphalt under the prescribed loading temperatures. The test results are shown in Figures 4–6.

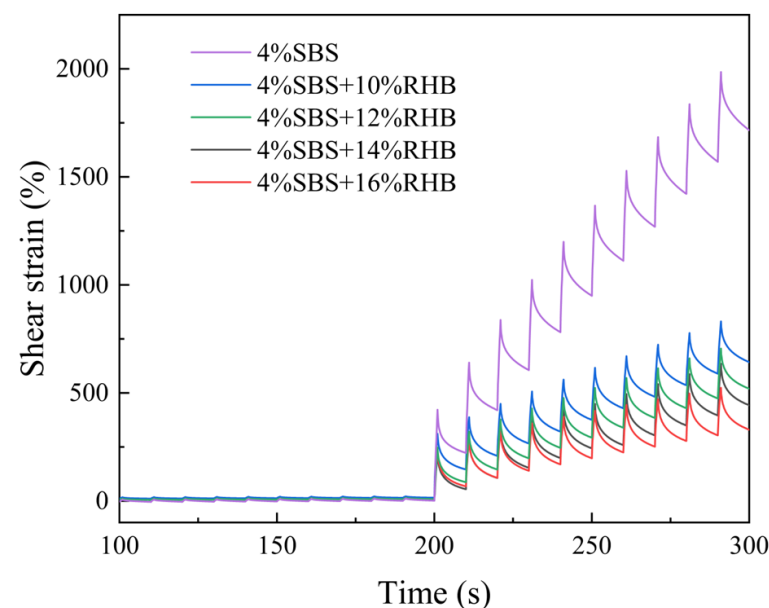


Figure 4. Accumulated shear strain curve at 64 °C.

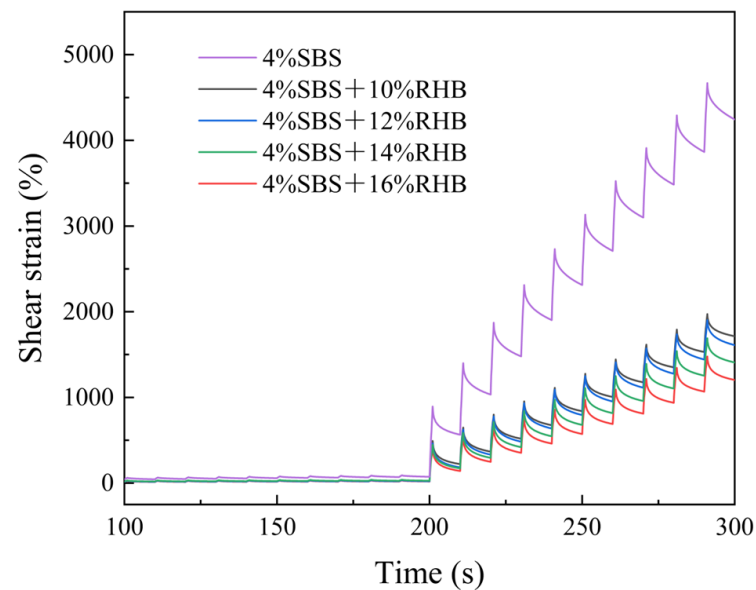


Figure 5. Accumulated shear strain curve at 70 °C.

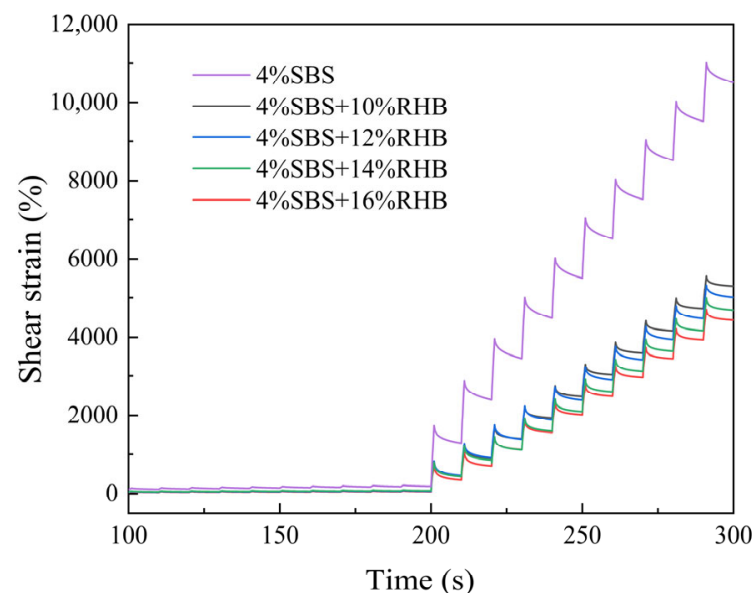


Figure 6. Accumulated shear strain curve at 76 °C.

The cumulative shear strain curve is used to characterize the cumulative characteristics of shear strain and creep recovery in asphalt under loading cycles over time [35]. The flatter the curve, the higher the material's stiffness, the lower the creep rate, the stronger the recovery ability, and the better the resistance to plastic deformation [36]. Analysis of Figures 4–6 shows that the incorporation of RHB significantly reduces the cumulative shear strain of the composite-modified asphalt, improving its high-temperature rutting resistance. Previous studies on RHB-SBS composite-modified asphalt did not conduct MSCR tests. In this study, the MSCR test further verified that the addition of RHB effectively improves the high-temperature performance of the RHB-SBS composite-modified asphalt, providing important theoretical and practical guidance for engineering applications.

To more intuitively and specifically analyze the elastic recovery and deformation resistance of the composite-modified asphalt at different temperatures, the calculated results for various indicators are presented in Figure 7.

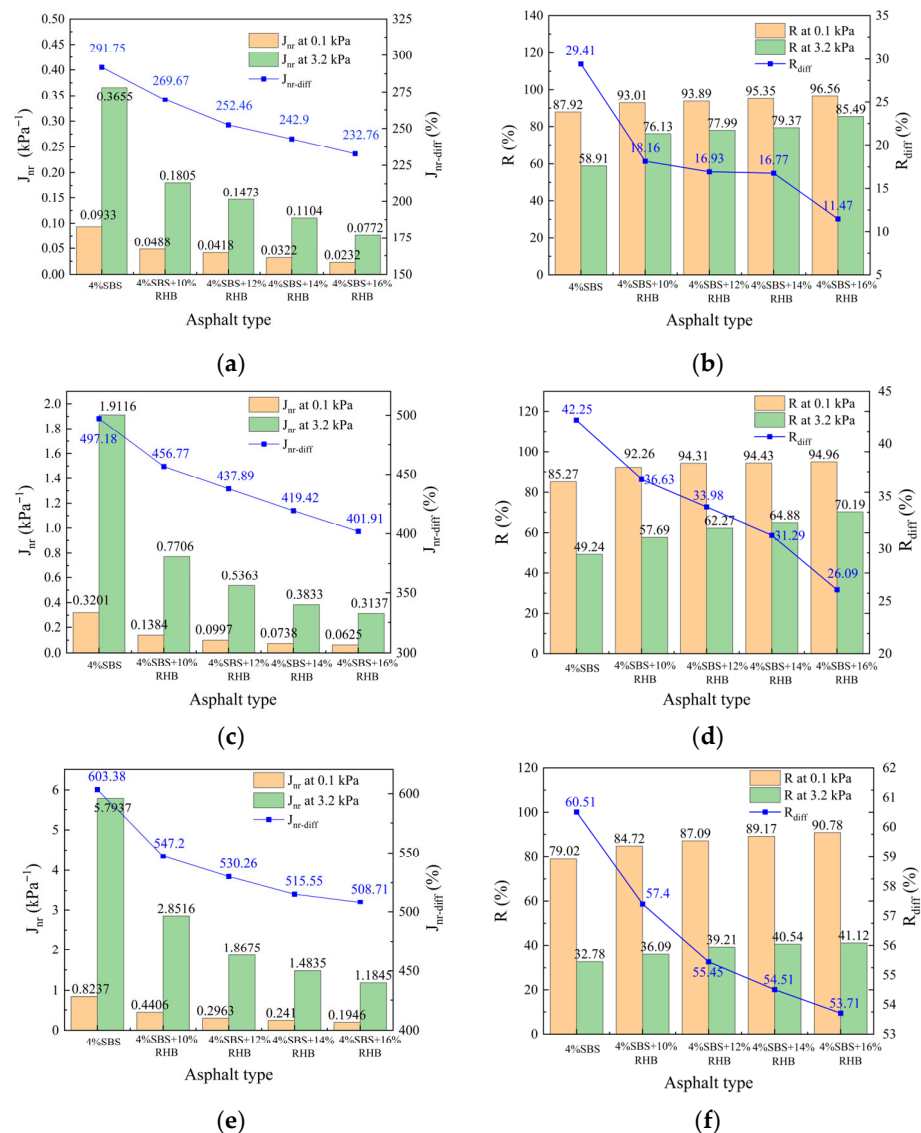


Figure 7. MSCR test results of RHB-SBS composite-modified asphalt. (a) J_{nr} of the composite-modified asphalt at 64 °C; (b) R of the composite-modified asphalt at 64 °C; (c) J_{nr} of the composite-modified asphalt at 70 °C; (d) R of the composite-modified asphalt at 70 °C; (e) J_{nr} of the composite-modified asphalt at 76 °C; (f) R of the composite-modified asphalt at 76 °C.

J_{nr} is a key indicator used to measure the resistance of asphalt materials to permanent deformation under stress [37]. A higher J_{nr} value indicates greater material ductility. As shown in Figure 7a,c,e, with increasing temperature or load level, the J_{nr} value of the RHB-SBS composite-modified asphalt increases significantly, which aligns with the typical behavior of asphalt under high-temperature and heavy-load conditions, where permanent deformation tends to increase. It is important to emphasize that the incorporation of RHB significantly reduces the J_{nr} value: at 76 °C, the addition of 16% RHB results in a reduction in J_{nr} of 76.4% and 81.2% under different stresses. This indicates that RHB effectively improves the material's stiffness, significantly enhancing its high-temperature deformation resistance. The reduction in J_{nr} is especially evident in the high-temperature range of 70–76 °C, where the material's resistance to deformation is notably improved.

Meanwhile, R reveals the material's elastic recovery performance [38]. The results show that with increasing temperature or load, the R value gradually decreases, indicating that high temperatures and high stresses weaken the elastic recovery ability. However, the incorporation of RHB significantly increases the R value of the composite-modified asphalt,

especially under a high stress of 3.2 kPa. At a 16% RHB dosage, the R value increases by 45.1%, 42.5%, and 24.4% at 64 °C, 70 °C, and 76 °C, respectively. This change not only suggests that RHB enhances the material's elastic recovery performance but also implies a synergistic enhancement effect between RHB and SBS, potentially forming a more stable composite system through the interaction of RHB with the elastic network of SBS.

$J_{nr-diff}$ and R_{diff} are important indicators for evaluating the stress sensitivity of asphalt materials. Lower values indicate reduced sensitivity to stress variations [38]. Low stress sensitivity means asphalt can maintain relatively stable performance across different stress levels, effectively mitigating the long-term deformation risk to pavement structures. With increasing temperature, both $J_{nr-diff}$ and R_{diff} values show a continuous upward trend, indicating that asphalt pavements are more prone to damage under complex loading conditions at high temperatures. Moreover, as the RHB content increases, $J_{nr-diff}$ and R_{diff} exhibit a significant decreasing trend. When the RHB content reaches 16%, compared with SBS-modified asphalt, $J_{nr-diff}$ decreases by 20.2%, 19.2%, and 15.7% at the three tested temperatures, while R_{diff} decreases by 61.0%, 38.3%, and 11.2%, respectively. These results indicate that increasing RHB content can significantly enhance asphalt's resistance to stress sensitivity and improve its high-temperature stability.

3.4. BBR Test

As shown in Figures 8 and 9, with decreasing test temperature, the S of different asphalt binders gradually increases, while the m correspondingly decreases. This trend indicates that under low-temperature conditions, the flowability of asphalt binders is significantly reduced, their stress relaxation ability gradually weakens, and the materials exhibit pronounced stiffening and embrittlement characteristics. Further analysis reveals that although the incorporation of RHB leads to an increase in S and a decrease in m compared with the base asphalt, according to the Superpave low-temperature performance criteria for asphalt binders ($S \leq 300$ MPa and $m \geq 0.300$), the BBR test results demonstrate that all parameters still satisfy the specification limits when the biochar content is 16%.

These results indicate that the addition of RHB increases the internal viscosity of the asphalt binder, thereby intensifying the stiffening and embrittlement tendency of the modified asphalt under low-temperature conditions. Under external loading, the biochar-modified composite asphalt is more prone to fracture than the unmodified base asphalt, resulting in a certain degradation in low-temperature performance. Nevertheless, the overall performance remains within the allowable specification limits, indicating that the modified asphalt with a 16% biochar content still exhibits an engineering-acceptable low-temperature performance.

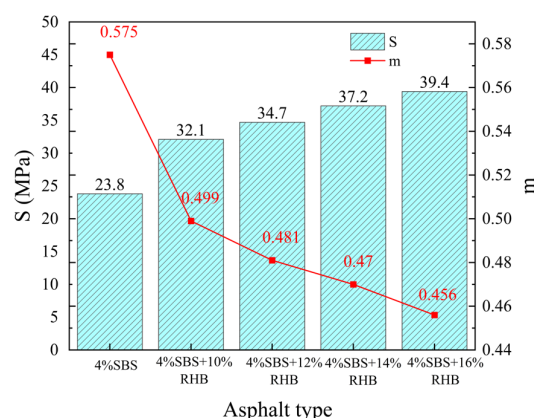


Figure 8. BBR testing outcomes of composite-modified asphalt at -6 °C.

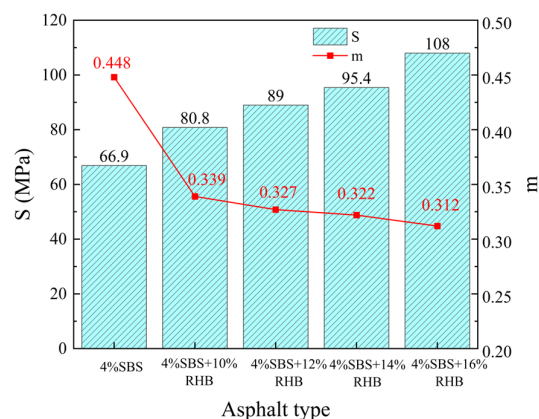


Figure 9. BBR testing outcomes of composite-modified asphalt at $-12\text{ }^{\circ}\text{C}$.

3.5. SEM Test

Figure 10 shows two typical morphologies of RHB observed under SEM. In Figure 10a, the ground RHB fracture surface exhibits a rough texture with numerous irregularly distributed pores of varying sizes. This highly porous surface morphology provides RHB with a large specific surface area, which significantly enhances its physical adsorption and interfacial interaction with asphalt components, ultimately leading to better dispersibility and compatibility in the asphalt matrix. In Figure 10b, a distinct tubular structure can be observed, which may result from partially unbroken vascular tissues of the rice husk. These vascular cells are typically tubular and interconnected, forming continuous transport channels throughout the plant body. Such a tubular structure not only improves filling when incorporated into the asphalt matrix but also facilitates the formation of an interlocked, crosslinked skeleton, further enhancing the structural stability and mechanical performance of the modified asphalt. A comparison of the two morphologies reveals that the RHB surfaces are covered with numerous irregular protruding particles that tend to cluster together. Based on relevant studies, these irregular particles are likely aggregates of SiO_2 , which may further influence the performance of RHB in asphalt modification [39,40].

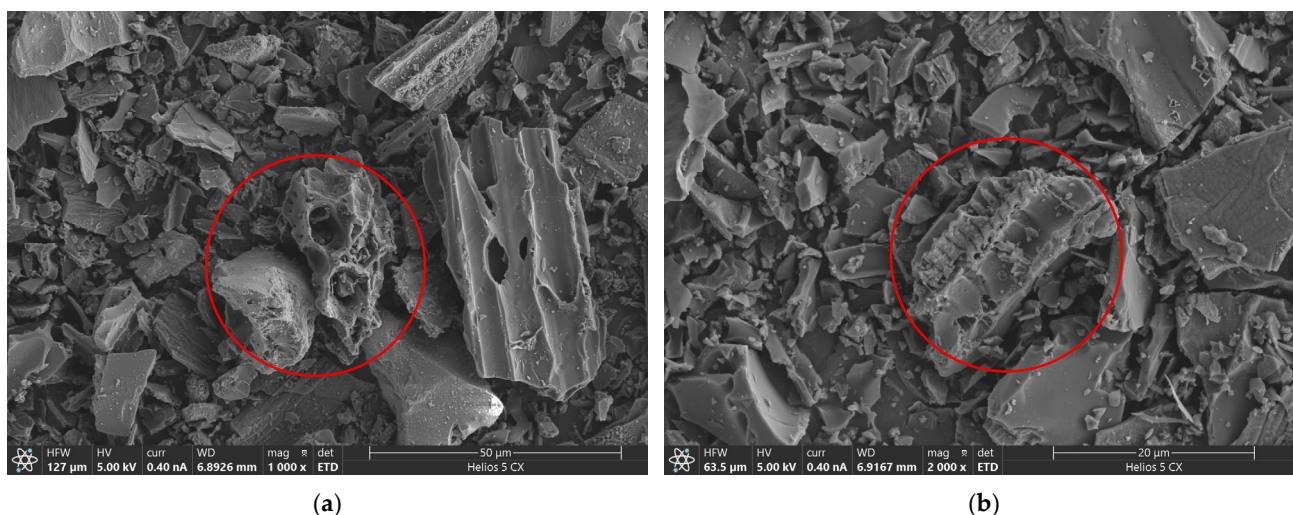


Figure 10. SEM images of RHB. (a) RHB Structure I; (b) RHB Structure.

SEM images of the RHB-SBS composite-modified asphalt prepared using various RHB mesh sizes at the optimal dosage are shown in Figure 11.

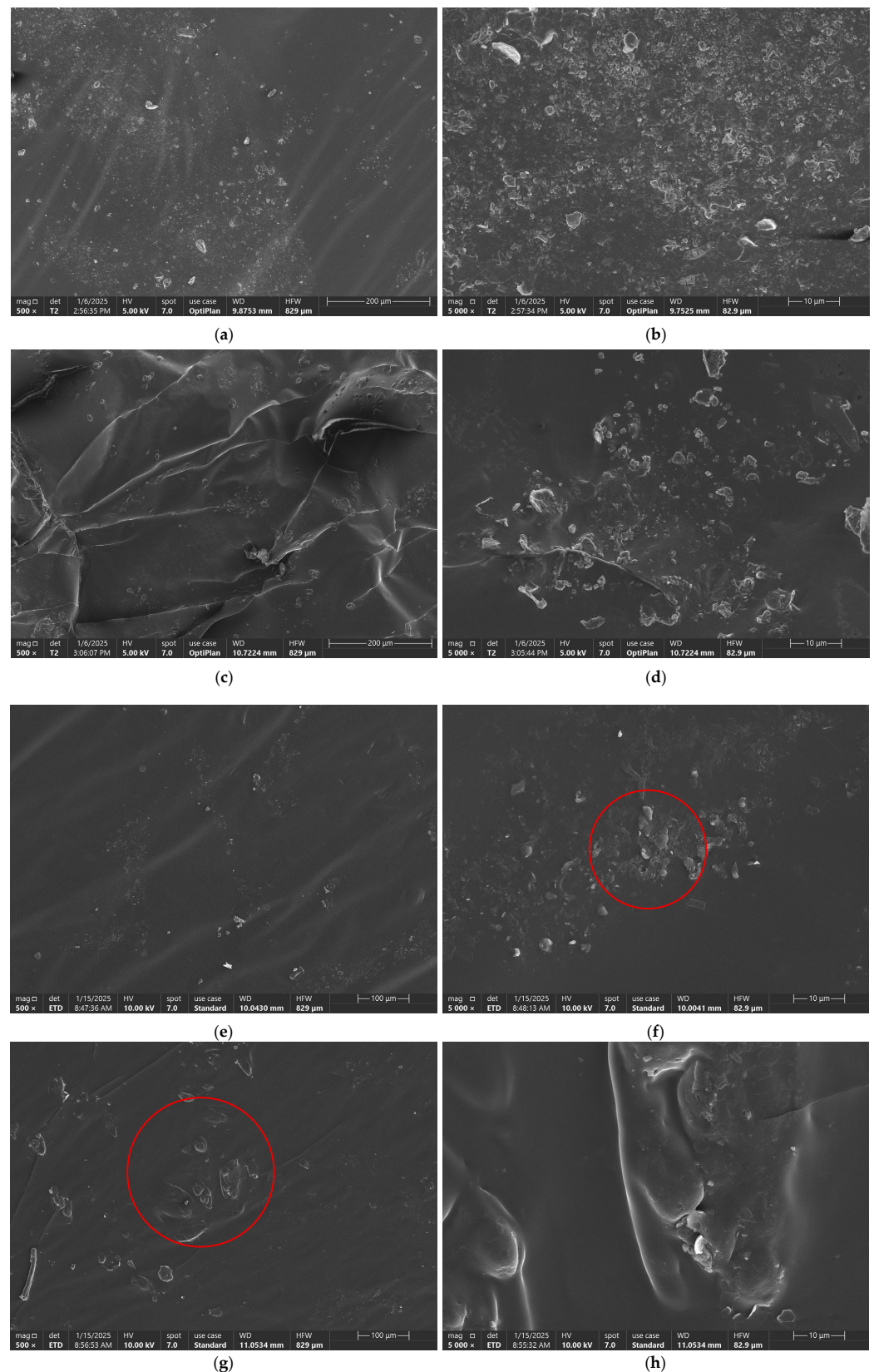


Figure 11. SEM images of RHB-SBS composite-modified asphalt with different mesh sizes. (a) 100 Mesh, 500× Magnification; (b) 100 Mesh, 5000× Magnification; (c) 200 Mesh, 500× Magnification; (d) 200 Mesh, 5000× Magnification; (e) 300 Mesh, 500× Magnification; (f) 300 Mesh, 5000× Magnification; (g) 400 Mesh, 500× Magnification; (h) 400 Mesh, 5000× Magnification.

Figure 11a,c,e,g display the microstructures of the RHB-SBS composite-modified asphalt produced using various RHB mesh sizes at $500\times$ magnification. By comparing these images, it can be observed that when the mesh size of RHB is relatively small, the particles exhibit poor dispersion within the asphalt matrix, with obvious particle aggregation and limited interfacial bonding with the matrix. This non-uniform dispersion results in a relatively loose microstructure, which may cause local stress concentration and adversely affect the material's homogeneity and overall performance. When the mesh size increases to 400 mesh (as shown in Figure 11g, although the particles become finer, particle agglomeration still occurs, leading to reduced dispersion in the asphalt matrix. This aggregation not only weakens the uniform distribution of the modifier but also causes performance instability in certain regions. Therefore, an appropriate degree of RHB fineness is crucial to ensure balanced performance in the composite-modified asphalt.

3.6. FTIR Test

As shown in Figure 12, the FTIR spectra of the three asphalt samples exhibit only slight variations, and their main absorption peak positions remain essentially unchanged. Strong peaks at 2920 cm^{-1} and 2850 cm^{-1} arise from hydrocarbon absorptions near 3000 cm^{-1} , particularly the pronounced stretching vibrations of $-\text{CH}_2-$ groups. Therefore, these peaks originate from the stretching vibrations of $-\text{CH}_2-$ groups. Additionally, a notable absorption peak near 1600 cm^{-1} may be mainly associated with the skeletal vibration of conjugated $\text{C}=\text{C}$ double bonds and possibly overlapping contributions from other functional groups. The peak at 1455 cm^{-1} is mainly associated with coupled vibrations between methylene ($-\text{CH}_2-$) and methyl ($-\text{CH}_3-$) groups, while the peak around 1375 cm^{-1} corresponds to the bending vibrations of $\text{C}-\text{H}$ bonds in methyl groups. In the fingerprint region, multiple peaks correspond to skeletal vibrations of benzene rings. For example, the peak at 1030 cm^{-1} may result from a combination of in-plane bending vibrations of $\text{C}-\text{H}$ bonds and stretching vibrations of $\text{C}-\text{O}$ bonds, whereas the peak near 750 cm^{-1} reflects the out-of-plane bending vibrations of $\text{C}-\text{H}$ bonds at the disubstituted positions on the benzene ring.

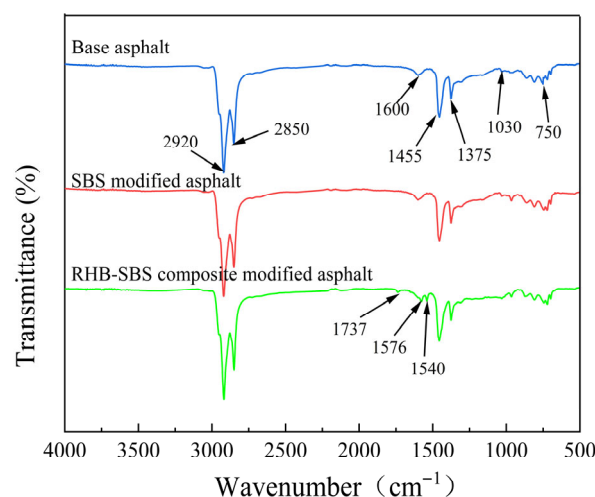


Figure 12. FTIR spectra of different asphalt samples.

By comparing the base asphalt with the SBS-modified asphalt, it can be seen that the FTIR spectral features of SBS-modified asphalt largely represent a direct superposition of the base asphalt spectrum, without the appearance of new characteristic absorption peaks. This indicates that the interaction between SBS and asphalt is primarily a physical mixing process, with no significant changes in chemical structure. Therefore, it can be inferred that the modification of asphalt by SBS involves almost no chemical reactions and

is mainly achieved through physical blending, enhancing asphalt performance via physical interactions.

By comparison, in the RHB-SBS composite-modified asphalt, the characteristic absorption peak at 1600 cm^{-1} , originally corresponding to the C=C stretching vibration of aromatic rings, disappears. This may be attributed to the adsorption of some aromatic compounds by RHB, which alters the chemical structure of asphalt and suppresses the original aromatic ring vibrations. New absorption peaks appear at 1737 cm^{-1} , 1576 cm^{-1} , and 1540 cm^{-1} . Specifically, the peak at 1737 cm^{-1} is typically associated with C=O stretching vibrations, suggesting that trace nitrogen in RHB may react with nitrogen-containing compounds in asphalt during modification, forming amide structures. The peak at 1576 cm^{-1} is generally related to aromatic C=C stretching vibrations or conjugated double-bond vibrations in aromatic compounds. The addition of RHB may lead to the formation of new aromatic structures or nitrogen-containing compounds, or to alterations in the electronic environment of existing aromatic rings, thereby producing this new absorption peak. The peak at 1540 cm^{-1} indicates that the incorporation of RHB may induce new chemical reactions, particularly involving nitrogen-containing groups, resulting in N-H bending vibrations in this spectral region.

By comparison, in the RHB-SBS composite-modified asphalt, the characteristic absorption peak at 1600 cm^{-1} , originally corresponding to the C=C stretching vibration of aromatic rings, becomes less pronounced or disappears, which may be attributed to the adsorption of aromatic compounds by RHB or to spectral overlap effects, thereby suppressing the apparent aromatic ring vibrations. New absorption peaks appear at 1737 cm^{-1} , 1576 cm^{-1} , and 1540 cm^{-1} . Specifically, the peak at 1737 cm^{-1} is typically associated with C=O stretching vibrations, which may indicate changes in oxygen-containing functional groups in the composite system; however, FTIR analysis alone cannot conclusively confirm the formation of amide structures or nitrogen-related chemical reactions. The peak at 1576 cm^{-1} is generally related to aromatic C=C stretching vibrations or conjugated double-bond vibrations in aromatic compounds. The addition of RHB may alter the distribution or electronic environment of aromatic structures, thereby producing this absorption peak. The peak at 1540 cm^{-1} may be associated with aromatic skeletal vibrations or N-H bending vibrations; however, this assignment should be interpreted with caution, since such spectral changes may be attributed to physical adsorption effects introduced by RHB or to spectral overlap.

In summary, incorporating RHB into the composite-modified asphalt may influence the interactions between SBS and the asphalt matrix, primarily through physical adsorption and interfacial interactions, with possible contributions from weak chemical interactions rather than confirmed covalent cross-linking, thereby potentially enhancing the structural stability and performance of the composite-modified asphalt.

3.7. TG-DSC Test

As shown in Figure 13, the TG curves of the three asphalt samples exhibit three distinct stages. In the first stage, at temperatures below $350\text{ }^{\circ}\text{C}$, the residual mass percentage changes only slightly with increasing temperature. This corresponds to the gentle endothermic region in the DSC curves shown in Figure 14, indicating that the low-volatility components in the asphalt have not yet undergone significant decomposition or reaction. In the second stage, the sample mass decreases rapidly, as most of the organic components in the modified asphalt reach or exceed their flash points within this temperature range, undergoing intense thermal decomposition or combustion, resulting in a significant increase in the mass loss rate. In the third stage, the mass loss rate gradually slows down, indicating

that the major combustible components in the asphalt have been largely consumed, and the remaining material mainly consists of stable residues from thermal decomposition.

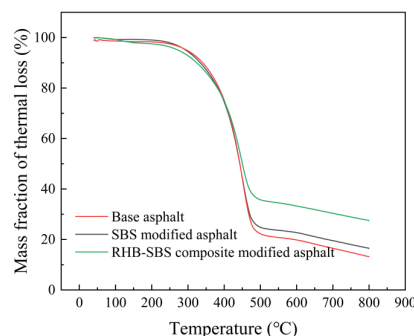


Figure 13. TG Curve.

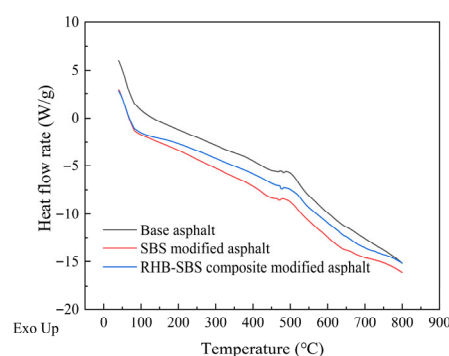


Figure 14. DSC Curve.

At the end of the test, the residual mass percentages were measured as 13.17% for base asphalt, 16.51% for SBS-modified asphalt, and 27.51% for RHB-SBS composite-modified asphalt. These results indicate that the RHB-SBS composite-modified asphalt exhibits superior thermal stability at high temperatures compared to the other two types of asphalt. This improvement is likely due to the incorporation of RHB, which enhances the asphalt's resistance to thermal aging and improves its overall thermal stability.

4. Conclusions and Perspectives

4.1. Conclusions

To advance the utilization of sustainable agroforestry waste in pavement materials, this study introduced RHB into an SBS-modified asphalt system. Through systematic laboratory testing, both the basic and rheological characteristics of the resulting RHB-SBS composite-modified asphalt were thoroughly assessed, and the role of RHB in the composite modification process was clarified from a microstructural standpoint. The primary findings are summarized below:

(1) The experimental results indicate that the particle size of RHB has a significant impact on the performance of the composite-modified asphalt. Specifically, 300-mesh RHB can significantly enhance the overall performance of the asphalt, making it the recommended particle size for preparing RHB-SBS composite-modified asphalt.

(2) With increasing RHB content, the hardness and high-temperature deformation resistance of the composite-modified asphalt are significantly enhanced. However, this is accompanied by a decrease in ductility and an increase in stiffness modulus, indicating a certain tendency toward low-temperature embrittlement. The synergistic effect of SBS can partially compensate for the loss of low-temperature performance. When the

RHB content is 16%, the composite-modified asphalt achieves the maximum improvement in high-temperature stability while still satisfying the specified low-temperature performance requirements.

(3) Microscopic analysis indicates that the porous structure and larger specific surface area of RHB contribute to the formation of a stable physical network structure with the asphalt matrix, thereby enhancing high-temperature stability. Infrared spectroscopy and thermogravimetric analysis further show that the incorporation of RHB improves the structural stability and thermal stability of the SBS-modified asphalt system. However, the existing experimental results primarily support its physical enhancement and structural synergy effects, with the related chemical interactions still needing further quantitative characterization.

4.2. Perspectives

Future research may be conducted in the following aspects. First, at the engineering application level, the mixing temperature, mixing time, and energy consumption of RHB-SBS composite-modified asphalt with different RHB contents should be systematically evaluated. In addition, its long-term storage stability and compatibility with existing production and transportation processes need to be quantitatively assessed. Test-section studies are further required to verify its compatibility with conventional asphalt mixing plants, and mixture design should be optimized to achieve a reasonable balance between high- and low-temperature performance as well as construction workability. Particular attention should be paid to its applicability in warm and hot regions under heavy traffic conditions, especially its effectiveness in mitigating high-temperature rutting. Moreover, the feasibility of this material as a binder-layer material warrants further investigation, while its comprehensive engineering applicability still requires validation through mixture design optimization and field testing.

At both the performance and mechanistic levels, further studies are needed to investigate the long-term aging behavior, fatigue performance, and in-service field performance of the binder and corresponding asphalt mixtures. In addition, advanced characterization techniques such as X-ray photoelectron spectroscopy (XPS) and nuclear magnetic resonance (NMR) should be employed to gain deeper insight into the role of RHB in the composite modification system. Furthermore, the potential application of RHB in functional asphalt, such as electrically conductive or self-sensing asphalt materials, is also worth exploring, although systematic experimental validation is still required.

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research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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