

## Research Article

# Studying the Properties of SBS/Rice Husk Ash-Modified Asphalt Binder and Mixture

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Sustainable materials in the field of road pavement have become a research direction in recent years. In this study, the rice husk ash with small dosage of styrene-butadiene-styrene (SBS) was added as a bioadditive into the base asphalt to modify its properties. Different contents (0, 2, 5, 10, and 15%) of rice husk ash (RHA) and 1% of SBS were selected to prepare the modified asphalt. Penetration, softening point, ductility, rotational viscosity test, and temperature sweep test were conducted to investigate the properties of SBS/RHA-modified asphalt binder. Rutting test, moisture susceptibility, and low-temperature cracking were utilized to evaluate the performances of SBS/RHA-modified asphalt mixture. The results showed that the penetration decreased and the softening point and rotational viscosity enhanced while the ductility slightly decreased with the incorporation of rice husk ash. The SBS/RHA-modified asphalt mixture had better high-temperature performance than that of the virgin asphalt mixture but slightly lower moisture stability and low temperature performance. The tensile strength ratio of the virgin and modified asphalt mixture met the requirement of specification. The tensile strain of mixture SR15 was lower than the requirement for the asphalt mixtures on the basis of the specification. For the SBS/RHA-modified asphalt binder based on the comprehensive properties, the content of rice husk ash should not be higher than 15%.

## 1. Introduction

Rice is the basic source of food consumption in the world [1, 2]; every year, it is produced in large quantities worldwide. China is the largest producer of rice in the world, and the average yearly production of rice in China is about 200 million tons [3]. A by-product called rice husk ash (RHA) is generated by the rice milling. The average rice husk coefficient is about 0.18, which means that about 36 million tons of rice husk can be generated from the rice paddies [4]. The most prevalent way to deal with the rice husk in developing countries is to burn or dump in the field, which causes large concern of the environment pollution [2].

To solve the ecological problems produced by the by-product, waste materials such as rice husk improve the recycling of road materials [5, 6], and many researchers in the world focus on the target to utilize the byproduct as

recycle materials and the recycled pavements materials in the field of engineering [7–13]. Weiting et al. explored the structure of rice husk ash from nano- and microlevel, revealed the origin of high pozzolanic activity and specific surface area, and obtained the optimum combustion temperature for the highly reactive RHA [14]. The RHA was used to replace nano-SiO<sub>2</sub> to enhance the performance of recycled aggregate geopolymer concrete by Nuaklong et al. [15]. Rattanachu et al. grounded the husk ash to the size of no. 235 and utilized it to partially replace cement at 20~50% weight to cast binder and examined the chloride penetration depth and steel corrosion [16]. Hossain et al. used the rice husk ash as an alternative of silica sources to prepare the slip-casting slurry and investigated the properties of the foam samples such as density, porosity, thermal conductivity, and mechanical strength [17]. Holzschuh et al. incorporated the RHA in the molten aluminum and analyzed the chemical

compositions by density analysis, Charpy impact forces test, and Brinell hardness [18]. Zahedi et al. prepared the mortar with RHA and investigated the effect of rice husk ash on the chloride permeability, compressive strength, and capillary absorption of single and binary blended mortars [19]. Thanh and Ludwig evaluated the alkali silica reactivity of RHA in cement paste by the scanning electron microscope and X-ray spectroscopy [20].

In the field of asphalt pavement, rice husk ash was also incorporated as a kind of filler or additive to improve the properties of asphalt materials. Some studies were conducted by the researchers in this field [21–26]. Abdelmagid et al. added the RHA and crumb rubber powder (CRP) into the 60/80 penetration graded asphalt binder to prepare modified asphalt binder. They concluded that adding RHA and CRP affected the high-temperature performance of asphalt binder [3]. Zagvozda et al. summarized the utilization of bio-ash and provided a research view from various aspects for the study of bio-ash in road construction [27]. Ameli et al. evaluated the properties of mastics and stone matrix asphalt mixture with RHA and coal waste ash (CWA). They found that the replacement of RHA by conventional filler improved the Marshall stability of asphalt mixtures [28]. Arabani and Tahami et al. investigated the influences of RHA as a kind of asphalt modifier on the hot mix asphalt. The results presented that the rheological properties of asphalt were improved by the incorporation of RHA [29]. Mistry et al. used the RHA and fly ash as a replacement of hydrated lime as fillers in the asphalt mixture and tested the performances of asphalt mixture with RHA and fly ash. They found that RHA had greater affinity to the asphalt attributing the highest stiffening influence of the asphalt mastic droplets [30]. Ramadhansyah et al. ground the RHA to the fine particles with the size less than  $75\ \mu\text{m}$  and evaluated the performance of asphalt mixture with different contents of RHA by the Marshall test and density test. Based on the results, the RHA could be satisfactorily used as a kind of filler to increase the performance of asphalt mixture [25, 26, 31–33]. Tahami et al. utilized two kinds of biomass ashes, RHA and date seed ash, as filler to replace the conventional filler in the hot asphalt mixture and tested the mechanical performances of asphalt mixtures. The results showed that, compared to the control asphalt mixture, the asphalt mixture with RHA and date seed ash had higher stability and stiffness modulus [34].

From the previous researches on the RHA, it can be concluded that the RHA could be used as a kind of filler to improve the road materials and as a type of modifier to modify the base asphalt. However, most of the studies on RHA focused on the conventional properties of asphalt binder, and more systematic evaluation on the comprehensive performance on the modified asphalt binder and mixture is rarely found. In addition, most of the previous researches are international; the study based on the Chinese specification and for the application in China is also necessary because of the large quantities of rice husk generated in China. Thus, this research aims to evaluate the comprehensive performance of SBS/rice husk ash-modified asphalt binder and mixture based on the international

specification in the world and national specifications in China.

## 2. Objectives

The overall objective of this study was to study the properties of polystyrene-butadiene-styrene (SBS) and RHA-modified asphalt binder and mixture. More specific objectives were as follows:

- (1) To investigate the effect of the addition of SBS/RHA on the rheological properties of the asphalt binder
- (2) To evaluate the high-temperature and low-temperature performance and moisture susceptibility of SBS/RHA-modified asphalt mixture

## 3. Materials and Methods

### 3.1. Materials and Sample Preparation

**3.1.1. Virgin Asphalt Binder.** The asphalt 70# (that is divided based on the penetration grade) was selected as the virgin asphalt. The technical indicators of the virgin asphalt binder based on the specification [35] are shown in Table 1.

**3.1.2. Polystyrene-Butadiene-Styrene.** The polystyrene-butadiene-styrene (SBS) was 1301-1 linear structure. The relative molecular weight was larger than 10000, the density at  $25^\circ\text{C}$  was  $0.8\sim 1.0\ \text{g}\cdot\text{cm}^{-3}$ , and the viscosity at  $160^\circ\text{C}$  was  $500\sim 10,000\ \text{Pa}\cdot\text{s}$ .

**3.1.3. Aggregate and Filler.** The aggregate was limestone and the filler was also made from limestone. The technical properties based on the specification [36] are shown in Tables 2 and 3, respectively.

**3.1.4. Preparation of Rice Husk Ash.** In this study, the RHA was obtained from the rich rice husk by combustion in a muffle furnace. The detailed procedure [1] is as follows. The rice husk was placed in the muffle furnace for incineration at  $700^\circ\text{C}$  for 2 hours. After the incineration, the RHA was taken directly from the furnace and scattered in the tray to be cooled at room temperature. The cooled RHA was wet-grinded in a vertical square ball mill for 15 minutes and the high active rice husk ash was obtained. The RHA used in this study was then sieved by the  $0.075\ \text{mm}$  aperture-sized sieve. The specific surface area was  $0.61\ \text{m}^2/\text{g}$ , and the active silica content was 88.3%.

**3.1.5. Preparation of SBS/RHA-Modified Asphalt.** The preparation of SBS/RHA-modified asphalt and the parameters for the preparation were determined based on the previous studies [1, 37], and it was divided into two parts: the SBS-modified asphalt preparation and SBS/RHA-modified asphalt preparation.

To make a better compatibility, the virgin asphalt was heated to  $180^\circ\text{C}$ , and the SBS was added into the flowable virgin asphalt and mixed by a high-speed shear mixer with a

TABLE 1: Technical indicators of virgin asphalt 70#.

Technical indicators	Test results	Technical requirements	Specification
Penetration/0.1 mm	70.3	60~80	T0604-2011
Softening point/ $^{\circ}$ C	48.2	$\geq 46$	T0606-2011
Ductility at 10 $^{\circ}$ C/cm	25.5	$\geq 20$	T0605-2011
Viscosity at 60 $^{\circ}$ C/Pa·s	198	$\geq 180$	T0620-2011
Viscosity at 135 $^{\circ}$ C/Pa·s	2.821	—	T0620-2011

TABLE 2: Technical indicators of coarse aggregates.

Technical indicators	Test results of coarse aggregate			Requirement
	10~20 (mm)	5~10 (mm)	3~5 (mm)	
Apparent relative density	2.624	2.657	2.688	—
Water absorption (%)	0.9	0.9	0.4	$\leq 2.0$
<0.075 mm content (%)	0.2	0.2	0.2	<1.0
Elongated content (%)	6.2	6.3	3.6	$\leq 18$
Crushing value (%)	22.1	—	—	$\leq 28$

TABLE 3: Technical indicators of fine aggregate and filler.

Technical indices	Test results	Requirement
Fine aggregate		
Apparent relative density	2.621	$\geq 2.5$
Sand equivalent/%	70	$\geq 60$
<0.075 mm content/%	8.5	$\leq 10$
Filler		
Apparent relative density	2.603	$\geq 2.5$
Hydrophilic coefficient	0.7	<1
Water content/%	0.33	$\leq 1$
<0.6 mm/%	100	100
<0.15 mm/%	94.6	90~100
<0.075 mm/%	79.2	75~100

rotation speed of 3000 rpm at 180 $^{\circ}$ C for 15 minutes. Then, the prepared high active rice husk ash was added into the SBS-modified asphalt, and they were mixed at 150 $^{\circ}$ C for 10 minutes by the shear mixer with a rotational speed of 5000 rpm. The mixed asphalt binder was placed in the oven at 135 $^{\circ}$ C for 1 hr. Given the price of SBS, low concentration, 1% of total binder by weight, was selected in this study. The contents of rice husk ash were 0%, 2%, 5%, 10%, and 15% of the total binder by weight; the SBS/RHA-modified asphalt binder was denoted as SR0, SR2, SR5, SR10, and SR15, respectively.

**3.1.6. Gradation for the Asphalt Mixture and Optimum Asphalt Content.** To prepare the asphalt mixture and evaluate the comprehensive performance of the asphalt mixture, AC-16 was selected and the gradation of aggregate is shown in Figure 1. According to Technical Specifications for Construction of Highway Asphalt Pavements in China (JTG F40-2004) [36, 38], combined with practical engineering experience, the optimum asphalt content was determined by the Marshall test and as 4.4% [39].

### 3.2. Test Methods

**3.2.1. Binder Test Methods.** The asphalt binder tests include the conventional binder tests, rotational viscosity test, and temperature sweep test. The conventional tests, penetration, softening point, and ductility were conducted according to the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011) [35]. The asphalt binder was unaged and rolling thin film oven (RTFO) aged based on the different tests. The rotational viscosity test was conducted using the Brookfield rotational viscometer, the test temperatures were 90, 135, 150, and 175 $^{\circ}$ C, and the rotational speeds were 10, 20, and 50 r/min.

The temperature sweep tests of the SBS-modified asphalt binder with 2%, 5%, 10%, and 15% content of rice husk ash were conducted. The SBS/RHA-modified asphalt was unaged and RTFO aged. This test was carried out through the DHR-1. For the unaged asphalt binder, the controlled strain was 12% while it was 10% for the RTFO-aged asphalt binder. The diameter of sample fixture for the unaged and RTFO-aged asphalt binder was 25 mm, and the spacing between the upper sample fixture and lower fixture was 1 mm. For temperature sweep in this study, the test temperatures were 52, 58, 64, 70, 76, and 82 $^{\circ}$ C; the test frequency was 10 rad/s (i.e., 1.59 Hz). The complex modulus  $G^*$ , phase angle  $\delta$ , and the rutting factors  $G^*/\sin \delta$  of the SBS/RHA-modified asphalt binder were obtained and analyzed.

**3.2.2. Mixture Test Methods.** The high-temperature performance of asphalt mixture in this study was evaluated by the rutting test. The slab samples were placed in the chamber for rolling using a wheel. The temperature was 60 $^{\circ}$ C. The detailed process was conducted based on Standard Test Methods of Bitumen and Bituminous Mixture for Highway Engineering (JTG E20-2011) [35].

The low-temperature performance of asphalt mixture in this study was investigated by the low-temperature bending beam test. The size of the bending beam was

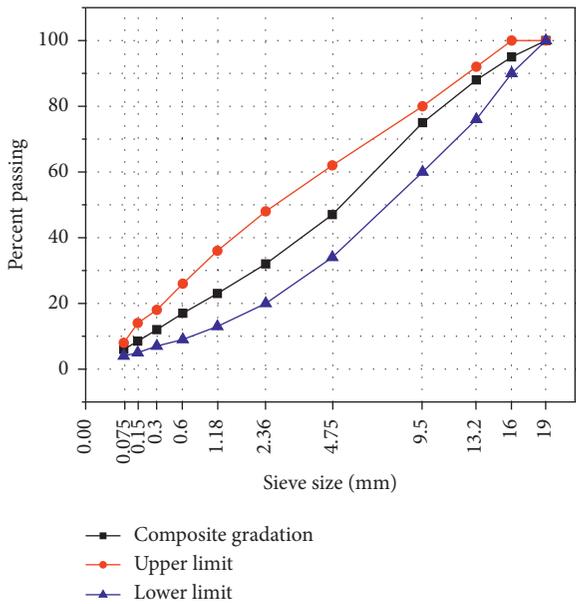


FIGURE 1: The gradation of AC-16 in this study.

250 mm × 30 mm × 35 mm. The test temperature was  $-10^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ . The maximum bending tensile strain, flexural tensile strength, and bending stiffness modulus were determined to evaluate the low temperature crack resistance of asphalt mixture.

The moisture susceptibility of the mixture in this study was conducted by the freezing-thaw splitting test. The detailed process followed the Standard Test Methods of Bitumen and Bituminous Mixture for Highway Engineering (JTG E20-2011) [35].

## 4. Results and Discussion

### 4.1. Properties of SBS/Rice Husk Ash-Modified Asphalt Binder

**4.1.1. Conventional Binder Test.** The conventional tests, penetration, softening point, ductility, and mass loss were conducted based on the specification called Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011) [35]. For the penetration, softening point, ductility tests, the asphalt binder used in these tests were the unaged and RTFO-aged binder.

The penetration test measures the consistency of paving asphalt binder. The penetration results of the asphalt binders are shown in Figure 2. For the unaged asphalt binders, it can be found that the addition of SBS/RHA decreased the penetration value of the virgin asphalt binder. This indicated that the modified asphalt binder had harder consistency than the virgin asphalt binder did. Meanwhile, when the content of rice husk ash increased from zero to 5%, the penetration decreased slightly, and when the content was 10% and 15%, the penetration decreased more. For instance, the penetration of asphalt binder SR0 was 70.3 (0.1 mm), the penetrations of SR5 and SR15 were 68.2 (0.1 mm) and 58.6 (0.1 mm), respectively, and the decreases of SR5 and SR15 were 2.9% and 16.6% compared to SR0. For the RTFO-aged,

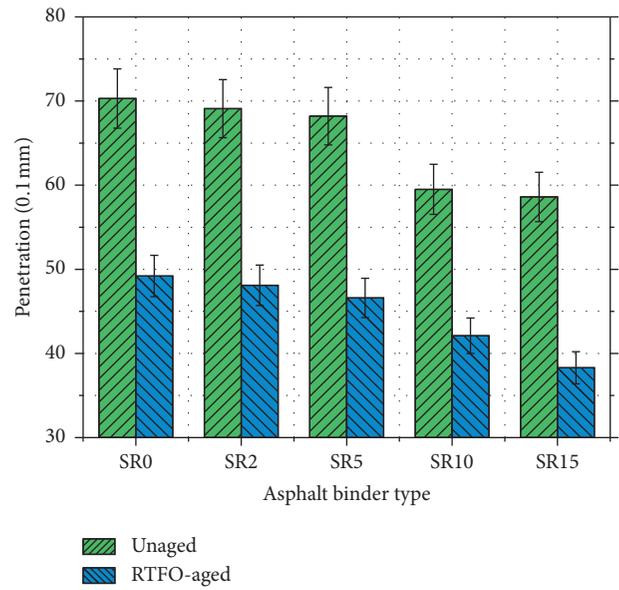


FIGURE 2: Penetration.

they showed the same law when the SBS/RHA was added into the virgin binder. These may be caused by the dispersion of rice husk ash in the asphalt binder and the physical miscibility between the rice husk ash and asphalt binder [1].

The temperature determined by the softening point shows the phase change for the asphalt binder. Figure 3 shows the softening point of the unaged and RTFO-aged virgin asphalt binder and SBS/RHA-modified asphalt binders. For the unaged and RTFO-aged asphalt binders, the incorporation of SBS/RHA enhanced the softening point of the virgin asphalt binder. For example, compared to SR0, the softening point of SBS/RHA-modified asphalt binders SR2, SR5, SR10, and SR15 and increased 4.7%, 6.0%, 8.3% and 9.3%, respectively. This meant that the ability of the modified asphalt binder to the deformation at the condition of high temperature was improved. This was consistent with the findings based on the penetration test.

The ductility of the unaged and RTFO-aged virgin asphalt binder and SBS/RHA-modified asphalt binders is described in Figure 4. It was shown that the ductility of the unaged modified asphalt binder slightly decreased with the content of RHA from 2% to 10% and dramatically decreased when the content of RHA was 15%. The decrease of ductility of SR5 and SR15 were 1.6% and 22.4% compared to the virgin asphalt binder SR0. For the RTFO-aged asphalt binder, they showed the same law with the incorporation of SBS/RHA. In addition, the residual ductility ratios of SR0, SR2, SR5, SR10, and SR15 were 32.2%, 32.4%, 31.8%, 31.9%, 29.3%, respectively. This indicated that the RTFO-aging almost had no influence on the base asphalt binder with the addition of rice husk ash. In addition, the criteria of ductility at  $10^{\circ}\text{C}$  for the unaged and RTFO-aged are at least 10 cm and 4 cm, and the ductility of SBS/RHA-modified asphalt binders could meet the criteria.

Figure 5 illustrates the mass loss of the SBS/RHA-modified asphalt binders through RTFO-aging. The mass loss of SR0, SR2, SR5, SR10, and SR15 was  $-0.276\%$ ,

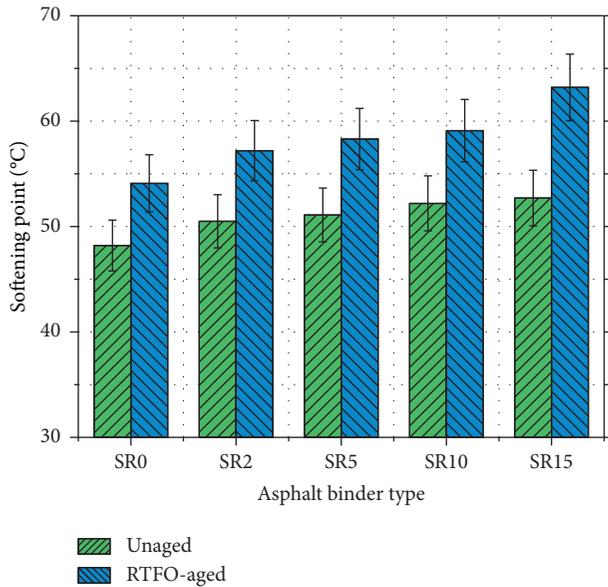


FIGURE 3: Softening point.

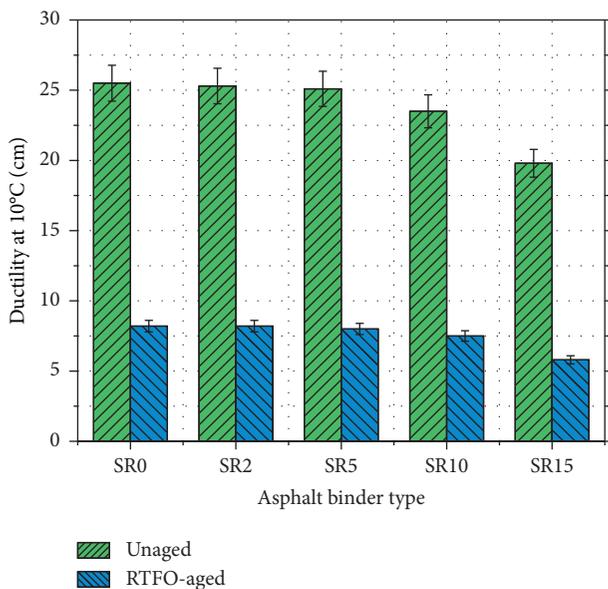


FIGURE 4: Ductility.

-0.276%, -0.302%, -0.309%, and -0.321%, respectively. Though the mass loss value had a trend of increasing with the addition of rice husk ash, the mass loss of all the modified asphalt binders met the value requirement of the specification, which is no more than -0.8%.

**4.1.2. Rotational Viscosity Test.** Asphalt binder has viscosity. Viscosity refers to the ability of asphalt to resist deformation under the action of external forces. A characteristic reflects the internal flow of asphalt to hinder its relative flow. The asphalt viscosity of SR0 and the SBS/RHA-modified asphalt binder at different

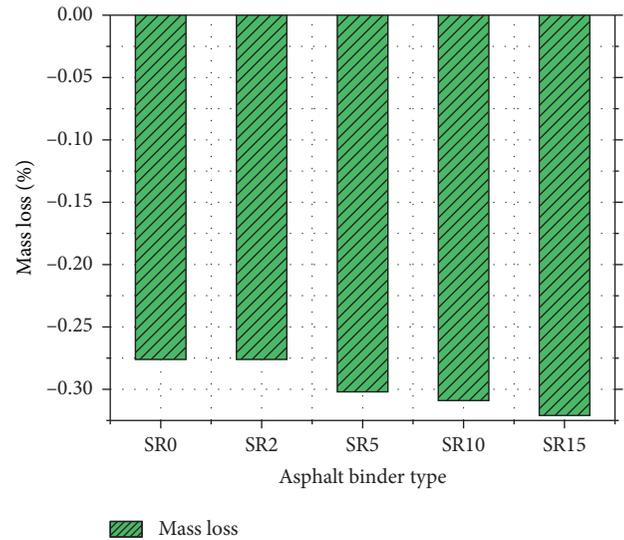


FIGURE 5: Mass loss.

rotational speeds (10, 20, and 50 rpm) and different temperatures (135, 150, and 175°C) are presented in Figure 6.

Figures 6(a)–6(c) show that the viscosities of all the modified asphalt binders at 135°C were less than 3.00 Pa·s, which is required based on the specification. The viscosities of asphalt binders decreased with the increase of the test temperature, and the decreasing value of the viscosity between 150°C and 175°C was higher than that between 135°C and 150°C. For example, at 20 rpm, the change of viscosity between 150°C and 175°C was 0.220 Pa·s, while the change of viscosity between 135°C and 150°C was 0.298 Pa·s. Meanwhile, the incorporation of SBS/RHA increased the viscosity of the base asphalt binder, and the viscosity increased with the increase of the RHA content no matter what the rotational speeds were. This indicated that the addition of RHA hardened the virgin asphalt binder. Take the viscosity with the rotational speed of 20 rpm at 135°C as an example; the increasing of viscosity of SR2, SR5, SR10, and SR15 were 1.1%, 3.9%, 7.4%, and 20.8%, respectively.

Figure 7 presents the viscosity of SR0 and the SBS/RHA-modified asphalt binder at different rotational speeds at 90°C. Figure 7 indicates that the viscosity of different asphalt binders at 90°C also increased with the increase of the content of rice husk ash. Meanwhile, the increased rotational speed contributed to the decrease of the viscosity. This illustrated that all the SBS/RHA-modified asphalt binder showed the characteristic of a non-Newtonian fluid, which was consistent with the previous study.

**4.1.3. Temperature Sweep Test.** To investigate the viscoelastic properties and evaluate the antirutting performance of the asphalt binder, the temperature sweep test was conducted by DSR.

The phase angles of the unaged and RTFO-aged virgin asphalt binder and SBS/RHA-modified asphalt binders are presented in Figure 8. Phase angle reflects the viscoelastic

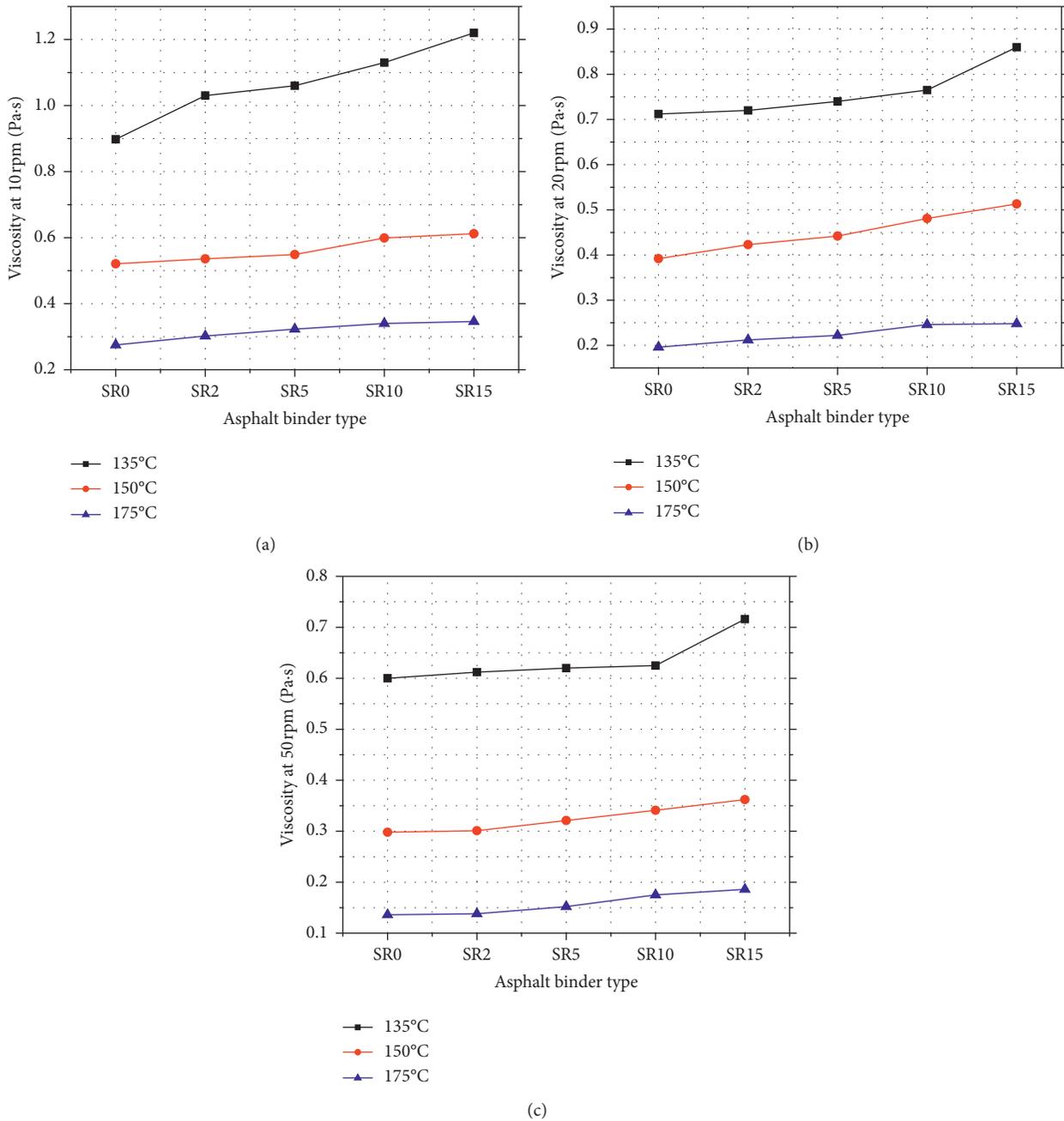


FIGURE 6: The viscosity of different asphalt binders at different rotational speeds: (a) at 10 rpm; (b) at 20 rpm; (c) at 50 rpm.

properties of asphalt binder, and the higher the phase angle, the lower elastic portion. As shown in Figure 8(a), for the unaged asphalt binder, the phase angle enhanced with the increase of the test temperature. This meant that higher temperature led to lower elastic portion in the asphalt binder. Meanwhile, the RHA also contributed to the decrease of the phase angle. When the temperature was 64°C, the phase angles of SR2, SR5, SR10, and SR15 were 84.88°, 84.36°, 84.15°, and 83.36°, which decreased 0.8%, 1.5%, 1.7%, and 2.6%, respectively. It can be found from Figure 8(b) that, for the RTFO-aged asphalt binder, the change of phase angle with the change of temperature and the content of rice husk

ash presented the similar trend. In Figures 8(a) and 8(b), the phase angle of SR15 was the lowest, which meant that the 15% content of rice husk ash made the asphalt binder harder than other modified asphalt binders in this study.

The rutting factor is an index to evaluate the antirutting performance of the asphalt binder; higher rutting factor illustrates better antirutting performance. Figure 9 displays the rutting factors of the unaged and RTFO-aged virgin and SBS/RHA-modified asphalt binders. It can be found from Figure 9(a) that the rutting factor decreased with the increase of the temperature, and the decreasing trend became slow when the test temperature was higher than 64°C. This

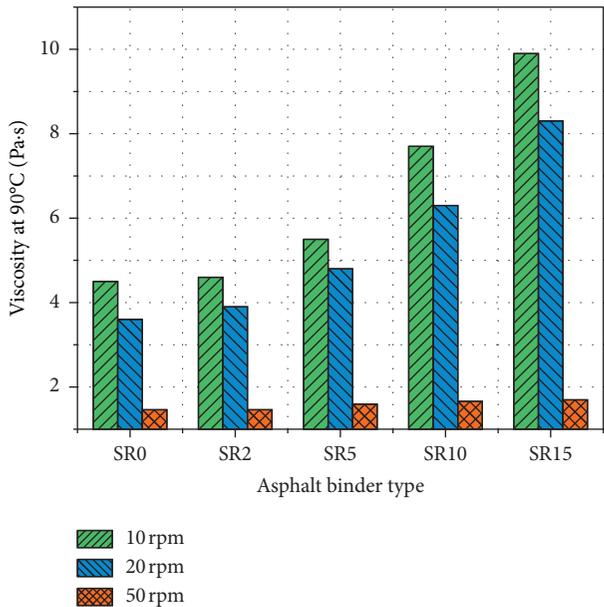


FIGURE 7: The viscosity of different asphalt binders with different rotational speeds at 90°C.

indicated that the ability of asphalt binder to resist the rutting was dramatically decreased from 52°C to 64°C and reduced slower when the temperature was higher than 64°C. Meanwhile, the rutting factor slightly improved with the addition of RHA and SBS. The more the content of rice husk ash, the higher the rutting factor. For instance, when the temperature was 64°C, the rutting factors of SR10 and SR15 were 2.671 kPa and 3.453 kPa and increased to 12.9% and 46.0% compared to the SR0. Figure 9(b) shows that the change of rutting factor of RTFO-aged asphalt binder modified by SBS/RHA with the change of the temperature and rice husk ash content had the similar rule compared with the unaged modified asphalt binder. This indicated that the addition of SBS/RHA enhanced the high-temperature performance of base asphalt binder.

To further analyze the effect of the test temperature on the rutting factor of SBS/RHA-modified asphalt, a single-factor analysis of variance was conducted. The results are shown in Table 4. From the table, the significance level of the unaged and RTFO-aged asphalt binder modified by SBS/RHA was below 0.05. It showed that the test temperature could significantly affect the high-temperature rutting factor of SBS/RHA-modified asphalt binder. The value of F for the RTFO-aged asphalt binder was higher than the unaged, so the test temperature had a greater influence on the rutting factor of SBS/RHA-modified asphalt binder.

## 4.2. Performances of the SBS/Rice Husk Ash-Modified Asphalt Mixture

**4.2.1. High-Temperature Performance.** Rutting test measures the rutting depth formed on the surface of the test sample under the repeated action of the test wheel. Thus, the dynamic stability (DS) and rutting depth at 60 minutes were

utilized to evaluate the high temperature performance of asphalt mixture.

Figure 10 illustrates the dynamic stability and rutting depth at 60 minutes of the virgin and SBS/RHA-modified asphalt mixtures. It can be found that the dynamic stabilities of all the SBS/RHA could meet the minimum criteria for the summer-hot zone, which is 2400 times/mm. The incorporation of SBS/RHA enhanced the dynamic stability and decreased the rutting depth at 60 minutes. For mixture SR2, the dynamic stability was 2659.6 times/mm, which increased 4.3% compared to the mixture SR0. When the content of RHA increased from 5% to 15%, the dynamic stability increased dramatically compared to the mixture SR0. For instance, the increase of dynamic stability of mixture SR10 and SR15 was 24.23% and 34.84% compared with the virgin asphalt mixture SR0, respectively. The rutting depth at 60 minutes showed the same rule with the incorporation of RHA. This indicated that the incorporation of rice husk ash could enhance the resistance of asphalt mixtures; the modified asphalt mixture had high temperature performance.

**4.2.2. Low-Temperature Crack Resistance.** The maximum tensile strain and tensile strength were tested and calculated in this study to evaluate the low-temperature performance crack resistance.

The maximum tensile strain and tensile strength of the virgin and SBS/RHA-modified asphalt mixtures are described in Figure 11. The SBS/RHA-modified asphalt mixture had lower maximum tensile strain and tensile strength than the virgin asphalt mixture since the downward trend of the two curves presented with the increase of rice husk ash, which indicated that the low temperature performance slightly decreased with the addition of SBS/RHA. Meanwhile, when the content of RHA was higher than 2%, the maximum tensile strain decreased more than that of the virgin asphalt mixture. The results obtained from the low temperature bending beam test was consistent with the results obtained from the ductility test at 10°C. However, the tensile strain of mixture SR15 was 1948.33  $\mu\epsilon$ , which was lower than the requirement (not less than 2000  $\mu\epsilon$ ) for the asphalt mixtures based on the specification. Thus, the content of rice husk ash should be not higher than 15%.

**4.2.3. Moisture Susceptibility.** Moisture susceptibility of asphalt mixture is the ability to resist the peeling and loosening of asphalt film due to water erosion.

Figure 12 shows the splitting strength before and after freeze-thaw and tensile strength ratio (TSR) of the virgin asphalt mixture and SBS/RHA-modified asphalt mixtures. The splitting strength before freeze-thaw of the SBS/RHA-modified asphalt mixture slightly increased with the increase of rice husk ash content. The splitting strength of mixture SR15 after freeze-thaw decreased significantly, and this may be caused by the fact that the content of 15% rice husk ash increased the stiffness of the asphalt binder more than other contents. The tensile strength ratio slightly decreased with the incorporation of rice husk ash, which illustrated that the

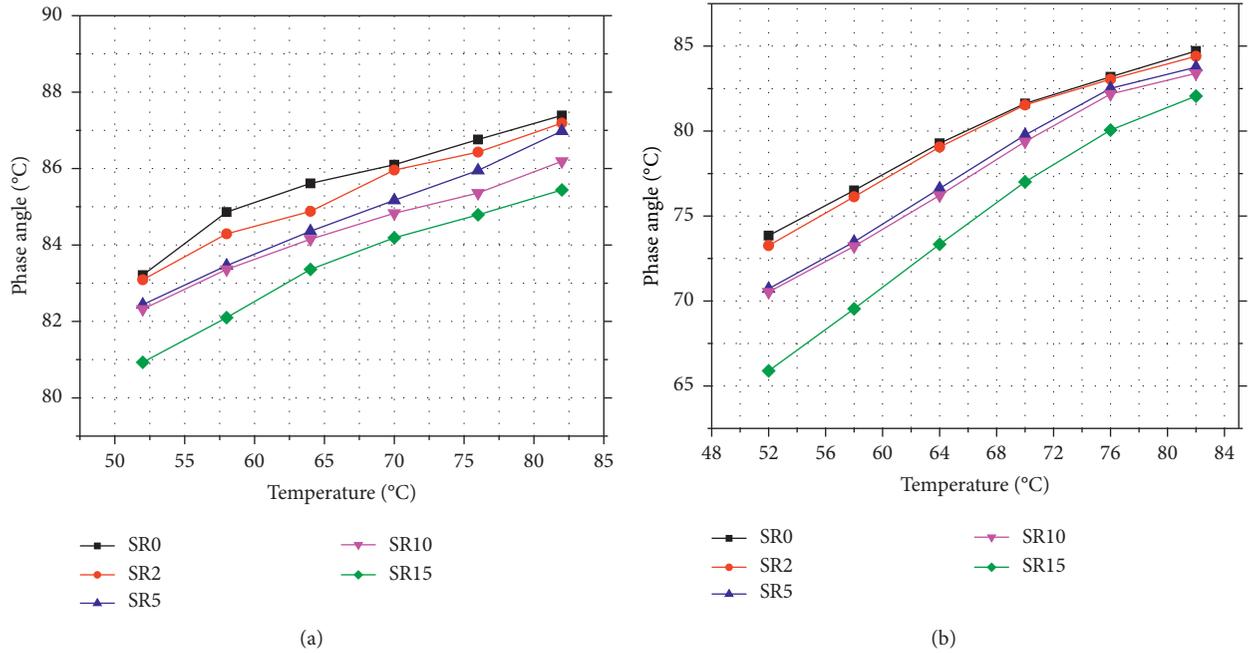


FIGURE 8: Phase angle of different asphalt binder type: (a) the unaged; (b) the RTFO-aged.

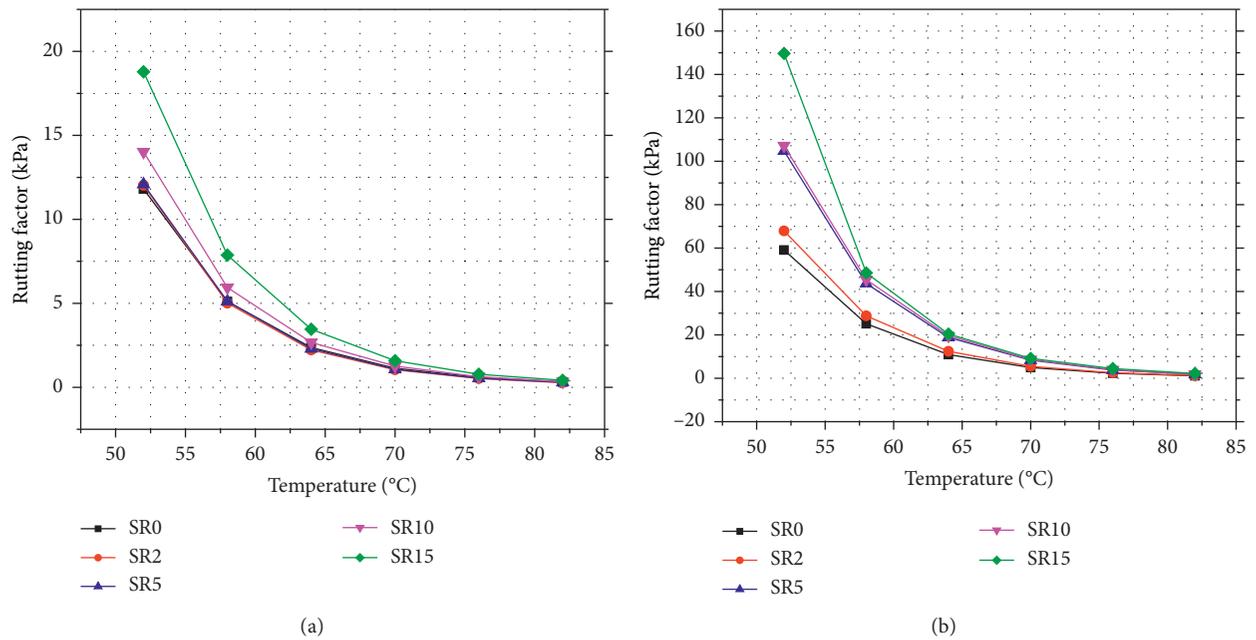


FIGURE 9: Rutting factor of different asphalt binder type: (a) the unaged; (b) the RTFO-aged.

TABLE 4: Single factor analysis of variance of rutting factor under different temperatures.

Asphalt aged	Item	Sum of squares	df	Mean square	F	Sig.
The unaged	Between groups	298.021	5	59.396	48989.897	0.002
	Within groups	0.013	12	0.001	—	—
	Total	298.034	17	—	—	—
The RTFO-aged	Between groups	23971.324	5	4895.795	109924.857	0
	Within groups	0.42	12	0.039	—	—
	Total	23971.764	17	—	—	—

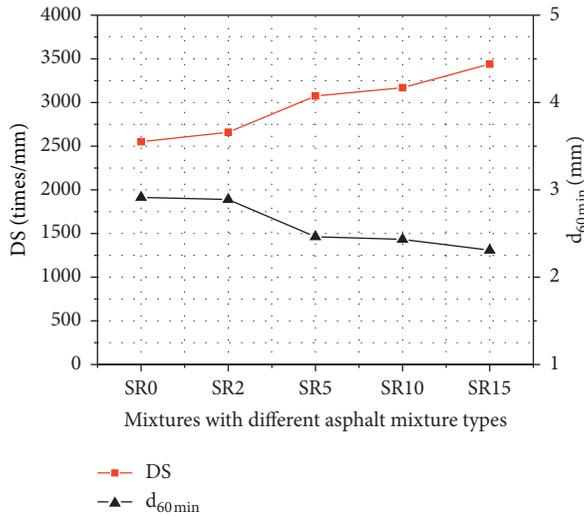


FIGURE 10: Dynamic stability and rutting depth of different asphalt mixtures.

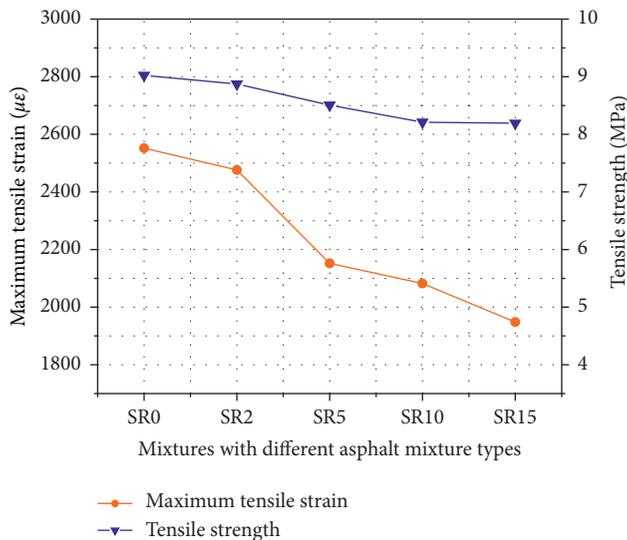


FIGURE 11: Maximum tensile strain and tensile strength of different asphalt mixtures.

moisture stability slightly decreased. However, the tensile strength ratio of the virgin asphalt mixture and modified asphalt mixture met the requirement of specification, which should not be less than 75%.

### 5. Conclusions

This research investigated the properties of SBS/RHA-modified asphalt binder by the conventional binder test, rotational viscosity test, and temperature sweep test and evaluated the performances of SBS/RHA-modified asphalt mixture by the rutting, moisture susceptibility, and low-temperature cracking. The main conclusions were obtained as follows.

- (1) The addition of SBS/RHA decreased the penetration value and the ductility of the virgin asphalt binder

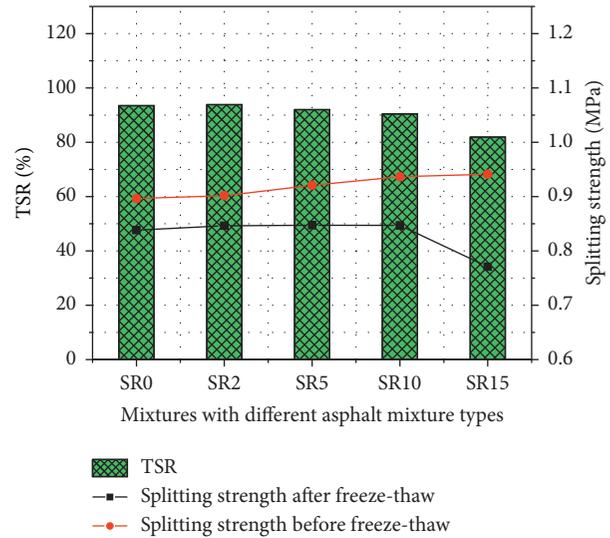


FIGURE 12: Freeze-thaw splitting test results of different asphalt mixtures.

and enhanced the softening point of the base asphalt binder. When the content of rice husk ash increased from 0 to 5%, the penetration slightly decreased, and when the content was 10% and 15%, the penetration decreased more. The ductility of the unaged modified asphalt binder slightly decreased with the content of RHA from 2% to 10% and dramatically decreased when the content of RHA was 15%. The mass loss of all the modified asphalt binders could meet the value requirement of the specification.

- (2) The viscosity of asphalt binders decreased with the increase of the test temperature. The incorporation of SBS/RHA increased the viscosity of the base asphalt binder, and the viscosity increased with the increase of the rice husk ash content. All the SBS/RHA-modified asphalt binders showed the characteristic of a non-Newtonian fluid.
- (3) For the original and RTFO-aged SBS/RHA-modified asphalt binders, the phase angle enhanced with the increase of the test temperature, and the RHA contributed to the decrease of the phase angle. The rutting factor decreased with the increase of the temperature, and the decreasing trend became slow when the test temperature was higher than 64°C. The rutting factor slightly improved with the addition of rice husk ash and SBS.
- (4) The incorporation of SBS/RHA enhanced the dynamic stability and decreased the rutting depth at 60 minutes, which meant the high temperature performance of the mixture improved with the incorporation of SBS/RHA. The addition of SBS/RHA slightly decreased the moisture stability and low temperature performance. The tensile strain of mixture SR15 was lower than the requirement for the asphalt mixtures based on the specification. The tensile strength ratio (TSR) of the virgin and

modified asphalt mixture could meet the requirement of specification. For the SBS/RHA-modified asphalt binder based on the comprehensive properties, the content of rice husk ash should not be higher than 15%.

## Data Availability

The data used to support the findings of this study have not been made available because the data are a part of an ongoing study (National Key Research and Development Program of China, grant no. 2018YFB1600200).

## Conflicts of Interest

The authors declare no conflicts of interest.

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