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Research Article

Composition and Performance Evaluation of SBS/SBR Modified Emulsified Asphalt for Tack Coat on Airport Pavement

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Asphalt concrete pavement is gradually being adopted in cement concrete pavement repair and paving due to its short construction period and low vibration to aircraft. However, the performance of the interlayer binder is the critical factor affecting the paving effect. For the preparation of interlayer high-performance emulsified asphalt suitable for airport pavement, the type and dosage of modifier and emulsifier were taken as factors and levels for the orthogonal test. Combined with the evaporation residue, softening point, penetration, ductility, and Engla viscosity indexes, the range analysis was carried out to determine the optimal dosage of modifier and emulsifier. Furthermore, the dynamic shear rheology test (DSR), fluorescence microscope test, TG-DSC test, and shear and tensile tests were used to evaluate the technical properties of SBS/SBR modified emulsified asphalt. These results showed that the best blending mass ratio of SBS/SBR modified emulsified asphalt is 1.5% SBS + 3% SBR + 1% emulsifier. Temperature sweep at 48°C, compared with SBS/SBR modified emulsified asphalt, the complex shear modulus (G^*) of SBS/SBR modified emulsified asphalt increased by 71% and 75%, while the rutting factor($G^*/\sin\delta$) increased by 83% and 86%, respectively, which indicates that its shear deformation resistance and rutting resistance have been significantly improved. The Han curve indicates that the SBS/SBR modifier has excellent compatibility with asphalt and can maintain a stable state at a lower frequency. Before demulsification, SBS/SBR modifier and emulsified asphalt formed a stable spatial network structure. After demulsification, the continuous phase and the dispersed phase were more closely integrated, so that the emulsified asphalt exhibited better bonding performance. At different temperatures, by increasing the spraying volume, the shear and tensile strength of SBS/SBR modified emulsified asphalt increased first and then decreased. At 25°C, the maximum shear and tensile strengths are 0.86 MPa and 0.65 MPa. This study demonstrated that SBS/SBR modified emulsified asphalt formed a stable spatial network structure, giving it excellent technical properties, and can be widely used for tack coat on airport pavement.

1. Introduction

Airport pavement mainly uses cement concrete pavement in China, accounting for more than 90% of the total [1]. The concrete pavement built in China in the 1980s and 1990s has entered the late-use stage. Coupled with the rapid growth of air traffic in China and the proportion of sizeable heavy-duty wide-body aircraft in recent years, some of the runway structures built in the early days have been seriously damaged, and their service performance has plummeted. The pavement of the old airport is in urgent need of structural reinforcement or functional restoration without stopping aircraft navigation, so the white-to-black asphalt overlay technology that meets the nonstop requirement has become a standard renovation measure [2–4]. However, in actual engineering, the interlayer bonding problem of asphalt overlays is severe and common [5–7]. If the interlayer bonding is poor, the integrity of the pavement structure will be destroyed, and the bearing capacity of the pavement will be weakened [8, 9]. In addition, airport pavement disease also needs to be solved urgently in the newly built airport due to the poor high-temperature and low-temperature performance and bonding performance of the asphalt interlayer bonding material. According to the "14th Five-Year Plan for Civil Aviation Development" requirements, the number of civil airports in China will reach 770 by 2025, of which 270 are expected to be civil transport airports [10]. At present, ordinary emulsified asphalt is commonly used as an interlayer material. However, due to its poor high-temperature and low-temperature performance, poor fatigue resistance, and poor bonding effect, it cannot meet the requirements of interlayer mechanical performance [11, 12].

Based on this, many scholars have researched the technical performance of modified emulsified asphalt based on SBS and SBR. Hou [13] conducted an experimental study on an SBS modified emulsified asphalt suitable for alpine regions, and it was found that 6% SBS dosage could achieve better road performance. Lee [14] used a nonionic emulsifier (Span 60) and cationic emulsifiers (ID, DDA) to emulsify SBR and SBS modified asphalt. It was concluded that ID and DDA emulsifiers were essential in improving the adhesion and compressive strength of SBR and SBS modified emulsified asphalt. Wei [15] and Geng et al. [16] prepared SBS modified emulsified asphalt and tested its performance index. The results showed that SBS has superior high-temperature, bonding, and durability performance, but its emulsification process was complex and lacked storage stability. Sun et al. [17] studied the effect of SBS and SBR modifiers on asphalt cohesion. With the increase in SBS/(SBS + SBR) ratio, the cohesive force of asphalt decreases, it was concluded that the SBR modifier has more advantages in improving cohesion. Zhang et al. [18] and Abedini et al. [19] used SBR modified emulsified asphalt as sticky oil and evaluated its fundamental performance indexes. The prepared SBR modified emulsified asphalt has better ductility, shear resistance, and low-temperature performance than ordinary emulsified asphalt; however, its high-temperature and bonding performance are poor.

Given this, there is a need to improve the comprehensive performance of emulsified asphalt further. Studies have shown that the softening point, elastic recovery value, and bonding performance of SBS/SBR modified emulsified asphalt have been improved compared with SBS modified emulsified asphalt [20–22]. However, the current research on the microscopic morphology, action mechanism, high-temperature, low-temperature, and bonding performance of SBS/SBR modified emulsified asphalt still needs further improvement. In this study, based on the existing research of SBS modified emulsified asphalt, SBS/SBR modified emulsified asphalt was prepared using SBR, solubilizer, and emulsifier, combined with a series of physical properties tests. Finally, the physical properties, rheological properties, microscopic mechanism, and shear and tensile properties of the prepared SBS/SBR modified emulsified asphalt are analyzed with base emulsified asphalt, SBS modified emulsified asphalt, and SBR modified emulsified asphalt. It provides a reference for expanding the engineering application of emulsified asphalt in airport pavement overlay and new airport engineering.

2. Materials

2.1. Raw Materials. Co., Ltd. (Guangdong Province, China), and its primary properties were tested according to the standard test methods in the Specification of Asphalt and Asphalt Mixtures for Highway Engineering (JTG E20-2011) [23]. Its main performance is listed in Table 1. The modifier adopts the YH-792 (SBS 1401) linear SBS modifier produced by Sinopec Baling Petrochemical Company. SBR styrene-butadiene latex is produced by Jinan Shanhai Chemical Technology Co., Ltd.. The emulsifier was from Beijing Ward Road Chemical Co., Ltd.. Auxiliary agents used VOD-7677 cationic fast-breaking emulsifier, calcium chloride ($CaCl_2$), polyvinyl alcohol (PVA), and hydrochloric acid (HCl). Tables 2–5 lists the fundamental performance indexes of the material, and tap water is used for the test water. All the indicators meet the technical indicators required by the test.

2.2. Preparation Method of SBS/SBR Modified Emulsified Asphalt. The preparation of SBS/SBR modified emulsified asphalt adopts the first mixing method inside and outside [24–26]. The preparation process is shown in Figure 1, including the following steps: (1) added rubber oil and SBS to AH-70 base asphalt and mechanically stirred for 10 minutes at 165°C. (2) The mixture was sheared at a high speed of 4500r/min for 30 minutes; a small amount of stabilizer was added and sheared for 5 minutes to make SBS modified asphalt. (3) Added polyvinyl alcohol, calcium chloride, and emulsifier to 70°C water and stirred evenly, adjusted pH value to 2, and prepared the soap solution. (4) Poured the 70°C soap solution into a fully preheated colloid mill and circulated for the 30 s, added 165°C SBS modified asphalt, and circulated for 3 minutes; the mixture turned into a brown liquid and prepared the SBS modified emulsified asphalt. (5) Poured the SBR latex into the SBS modified emulsified asphalt at 30°C and stirred mechanically for 30 minutes.

3. Experiment Methods

3.1. Orthogonal Test. Three materials, linear SBS modifier, SBR latex modifier, and fast-cracking cationic emulsifier, were selected for the experiment. Based on the results of previous researchers [24, 27, 28], three levels of each factor were formulated, as shown in Table 6, using a L_9 (3^4) orthogonal table, and the test protocol is shown in Table 7. Properties tests on the prepared emulsified asphalt were carried out by the "Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering" (JTG E20-2011) [23]. The properties test mainly used the evaporation residue. The penetration, the softening point, the ductility, and the Engla viscosity as the evaluation indexes of the base emulsified asphalt, SBS and SBR modified emulsified asphalt, and SBS/SBR modified asphalt [26]. Combined with the test results, the variation of the comprehensive indexes under different levels of factors was studied by extreme

Table 1: Base asphalt technical performance index.

Items	Technical indexes	Results	Standard
Penetration (25°C, 100 g, 5 s)/0.1 mm	60~80	67	T 0604-2011
Penetration index (PI)	−1.5~+1.0	−1.31	T 0604-2011
Softening point (°C)	≥46	48.0	T 0606-2011
60°C dynamic viscosity (Pa·s)	≥180	208	T 0620-2000
10°C ductility (cm)	≥50	52.5	T 0605-2011
15°C ductility (cm)	≥100	>100	T 0605-2011

Table 2: Performance of polymer SBS.

Polymer structure	S/B (quality ratio)	Tensile strength (MPa)	300% constant stress (MPa)	Elongation (%)	Tensile permanent deformation (%)
Linear	30/70	15.0	2.0	700	30

Table 3: Performance of SBR latex.

Solids dosage (%)	Viscosity (MPa·s)	pH value	Proportion (25°C)
50 ± 2	50~300	6–10	0.97

Table 4: Performance of VOD-7677 cationic fast-splitting emulsifier.

Dosage of active ingredients (%)	Scent	Solubility	Appearance
65 ± 1	Nontoxic, slightly aromatic odor	Soluble in hot water and some organic solvents	Pale yellow liquid

Table 5: Performance parameters of additives.

Name	Polyvinyl alcohol PVA	Calcium chloride	Hydrochloric acid
Chemical formula	$[C_2H_4O]n$	$CaCl_2$	HCl
Uses	Organic compounds	Inorganic compounds	pH conditioner
Appearance	Solid white powder	Solid white powder	Liquid
Features	Easily deliquescent	Easily deliquescent	Volatile

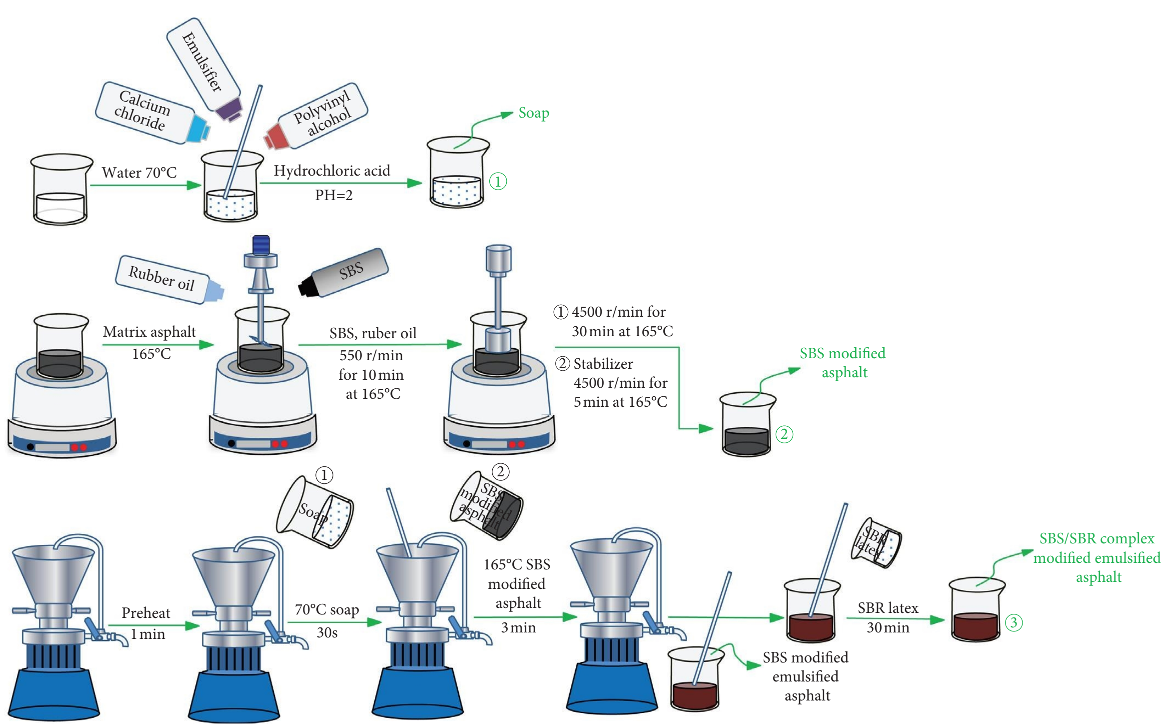


Figure 1: Preparation process of SBS/SBR modified emulsified asphalt.

difference analysis, and the optimal dosage of modifier and emulsifier was determined [29].

3.2. Dynamic Shear Rheometer (DSR) Test. Three kinds of emulsified asphalt, namely base emulsified asphalt, 1.5% SBS modified emulsified asphalt, and 3% SBR modified emulsified asphalt, were selected as comparative experiments. Strain sweep, temperature sweep, and frequency sweep were carried out on the evaporation residue of emulsified asphalt with a dynamic shear rheometer (DSR-MCR102) from Anton Paar Company in Austria. From the complex shear modulus (G^*), phase angle (δ), and rutting factor ($G^*/\sin\delta$) to characterize the rheological properties of the emulsified asphalt [30]. The set parameters are shown in Table 8.

3.3. Fluorescence Microscopy Test. The TSM-400C fluorescence microscope is from Shanghai (Suzhou) Instrument Co., Ltd. The TSM-400C fluorescence microscope was used to analyze the microscopic morphology of the modified emulsified asphalt through the fluorescence microscope structure diagram to study the dispersion of SBS and SBR modifiers in the emulsified asphalt [31, 32].

3.4. TG-DSC Test. The thermal stability properties of emulsified asphalt were evaluated by studying the thermal weight loss, thermodynamic parameters, and material components of emulsified asphalt using TG-DSC test analysis [33, 34]. Setting the temperature rise rate at 10°C/min, sample size 5–10 g, temperature control from room temperature to 800°C, and nitrogen rate of 20 ml/min.

3.5. Shear and Tensile Tests. The PLD-100 microcomputer-controlled electro-hydraulic servo fatigue testing machine is from Xi'an Lichuang Material Testing Technology Co., Ltd. The shear and tensile properties tests were carried out with a fatigue testing machine to evaluate the interlayer mechanical properties of the modified emulsified asphalt [35–37]. The shear test adopted a 45° oblique shear method; the loading rate of the shear and tensile tests is 10 mm/min. The composite concrete specimen of "asphalt concrete + modified emulsified asphalt + cement concrete" was made with self-made SBS/SBR modified emulsified asphalt; the size was 300 mm × 300 mm × 100 mm, as shown in Figure 2. The composite concrete slab was then drilled, as shown in Figure 3, and finally fixed on the fatigue testing machine with a self-made shear and tensile jig. Shear and tensile tests were carried out under different spraying volumes (0.5 kg/m^2, 0.7 kg/m^2, 0.9 kg/m^2, and 1.1 kg/m^2) and different temperatures (25°C, 45°C, and 60°C).

4. Results and Discussion

4.1. Orthogonal Test. The orthogonal test results of SBS/SBR modified emulsified asphalt are shown in Figure 4. The range analysis of the orthogonal test results was carried out to examine the significance of the influence of the dosage of the SBS modifier, SBR modifier, and emulsifier on the evaluation indexes of the modified emulsified asphalt. The results are shown in Table 9. It can be seen from Table 9 that the evaporation residue, softening point, penetration, and Engla viscosity of SBS/SBR modified emulsified asphalt are most significantly affected by the dosage of SBS followed by the amount of emulsifier. However, the effect of emulsifier dosage on the 5°C ductility is the most significant, followed by SBS dosage. Compared with 6% SBS latex modified asphalt [13], the 5°C ductility of SBS/SBR modified emulsified asphalt increases by 26%. SBR dosage has a minor effect on the five indexes. For the changing trend of the comprehensive index, as shown in Figure 5, the primary performance is that with the increase of the modifier dosage, the comprehensive index first increases and then decreases; with the increase of emulsifier dosage, the comprehensive index shows an upward trend. Therefore, the order of the influence degree of the three factors is SBS modifier > emulsifier > SBR modifier, and the optimal group of SBS/SBR modified emulsified asphalt is $A_2B_2C_3$, that is, 1.5% SBS + 3% SBR + 1% emulsifier.

Table 6: Test factors and levels.

Level	Influencing factors		
	SBS (A)%	SBR (B)%	Emulsifier (C)%
1	1.0	3.0	0.6
2	1.5	4.0	0.8
3	2.0	5.0	1.0

4.2. Dynamic Shear Rheometer (DSR) Test

4.2.1. Strain Sweep. To ensure the accuracy of the test results, it is necessary to determine the viscoelastic range of the emulsified asphalt by strain sweep [38]. The strain sweep results of the four emulsified asphalts are shown in Figure 6. When the strain is controlled within 30%, the four emulsified asphalts can be guaranteed to be within the linear viscoelasticity range. The linear viscoelasticity will gradually fail after exceeding the strain. The strain sweep results show that with the increase of shear strain, the four emulsified asphalts show the same law, which is mainly represented by the increase of δ and the decrease of G^* of emulsified asphalt. Compared with the other three kinds of emulsified asphalt, the change rate of δ and G^* of SBS/SBR modified emulsified asphalt is more significant. When the shear strain is 0.01, compared with the SBS modified emulsified asphalt and the SBR modified emulsified asphalt, the δ of the SBS/SBR modified emulsified asphalt decreases by 15% and 13%, the G^* increases by 129%, and 110%. It shows that the elastic components of SBS/SBR modified emulsified asphalt increase significantly, which significantly improves the strain sensitivity and shear deformation resistance of emulsified asphalt.

4.2.2. Temperature Sweep. The temperature sweep results are shown in Figure 7. The results show that with the increase in temperature, the four emulsified asphalts show the same law, which is mainly represented by the decrease of G^*

Table 7: The factors and levels of different experimental groups in the orthogonal test.

Test number	Influencing factors			
	SBS (A) (%)	SBR (B) (%)	Emulsifier (C) (%)	Error column (D)
1	1.0	2.0	0.6	1
2	1.0	3.0	0.8	2
3	1.0	4.0	1.0	3
4	1.5	2.0	0.8	3
5	1.5	3.0	1.0	1
6	1.5	4.0	0.6	2
7	2.0	2.0	1.0	2
8	2.0	3.0	0.6	3
9	2.0	4.0	0.8	1

Table 8: Rheological parameter settings.

Test type	Test temperature (°C)	Load setting	Loading frequency (Hz)
Strain sweep	60	Strain control (0.1%–100%)	1.59
Temperature sweep	40~80	Strain control (12%)	1.59
Frequency sweep	40, 48, 56, 64, 72	Strain control (12%)	1–100

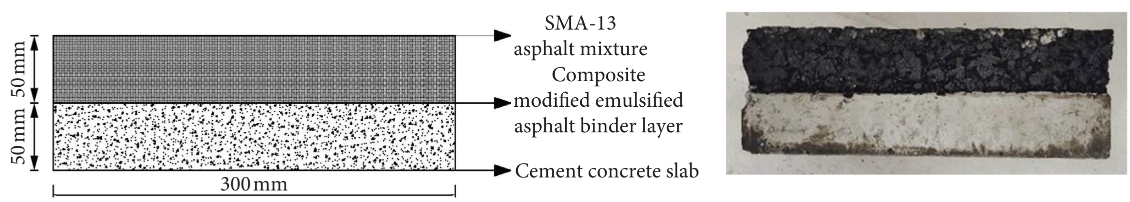


Figure 2: Composite concrete slab model and object. (a) Composite concrete slab model. (b) Composite concrete slab.

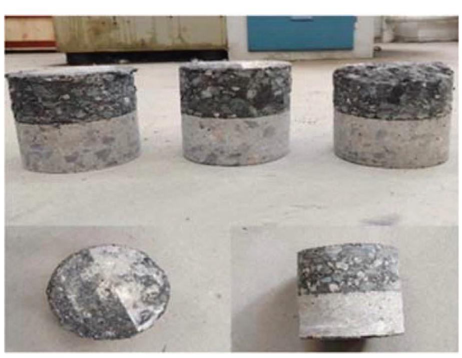


Figure 3: Drill core samples.

and $G^*/\sin\delta$ and the increase of δ. It shows that with the increase in temperature, the elastic component of emulsified asphalt decreases, which is close to a viscous fluid, weakening the ability of emulsified asphalt to resist shear deformation and recover deformation. At 48°C, compared with SBS and SBR modified emulsified asphalt, the G^* of SBS/SBR modified emulsified asphalt increased by 71% and 75%, and the $G^*/\sin\delta$ increased by 83% and 86%, δ decreased by 13%, and 15%. At 40°C–70°C, the G^* of SBS/SBR modified emulsified asphalt is close to that of waterborne epoxy resin (WER) emulsified asphalt, but the δ is significantly lower than that of WER emulsified asphalt [39]. The continuous phase of asphalt is closely integrated with SBS/SBR, forming a stable spatial network structure in the emulsified asphalt. The above results showed that the high-temperature performance and the ability to resist deformation of SBS/SBR modified emulsified asphalt are significantly improved.

4.2.3. Frequency Sweep. For viscoelastic materials, the mechanical response is greatly affected by the loading frequency. The slower the loading speed, the more pronounced the viscous characteristics, and the faster the loading, the more pronounced the elastic characteristics. The simulation of the taxiing state of the aircraft on the airport pavement can be performed by frequency sweeping to achieve [40]. The frequency sweep results of the four emulsified asphalts at different temperatures are shown in Figures 8 and 9.

The frequency sweep results show that with the increase of frequency, the G^* and $G^*/\sin\delta$ of each emulsified asphalt increase, and the emulsified asphalt's shear deformation and rutting resistance are enhanced. It shows that when the aircraft is taxiing at high speed, the time that the aircraft load acts on the emulsified asphalt decreases, which reduces the shear deformation of the emulsified asphalt. At the same temperature and the same frequency, compared with the other three emulsified asphalts, the G^* and $G^*/\sin\delta$ of the SBS/SBR modified emulsified asphalt increased significantly; at low frequency, the growth rate of G^* and $G^*/\sin\delta$ is faster. When the temperature is 72°C and the frequency is

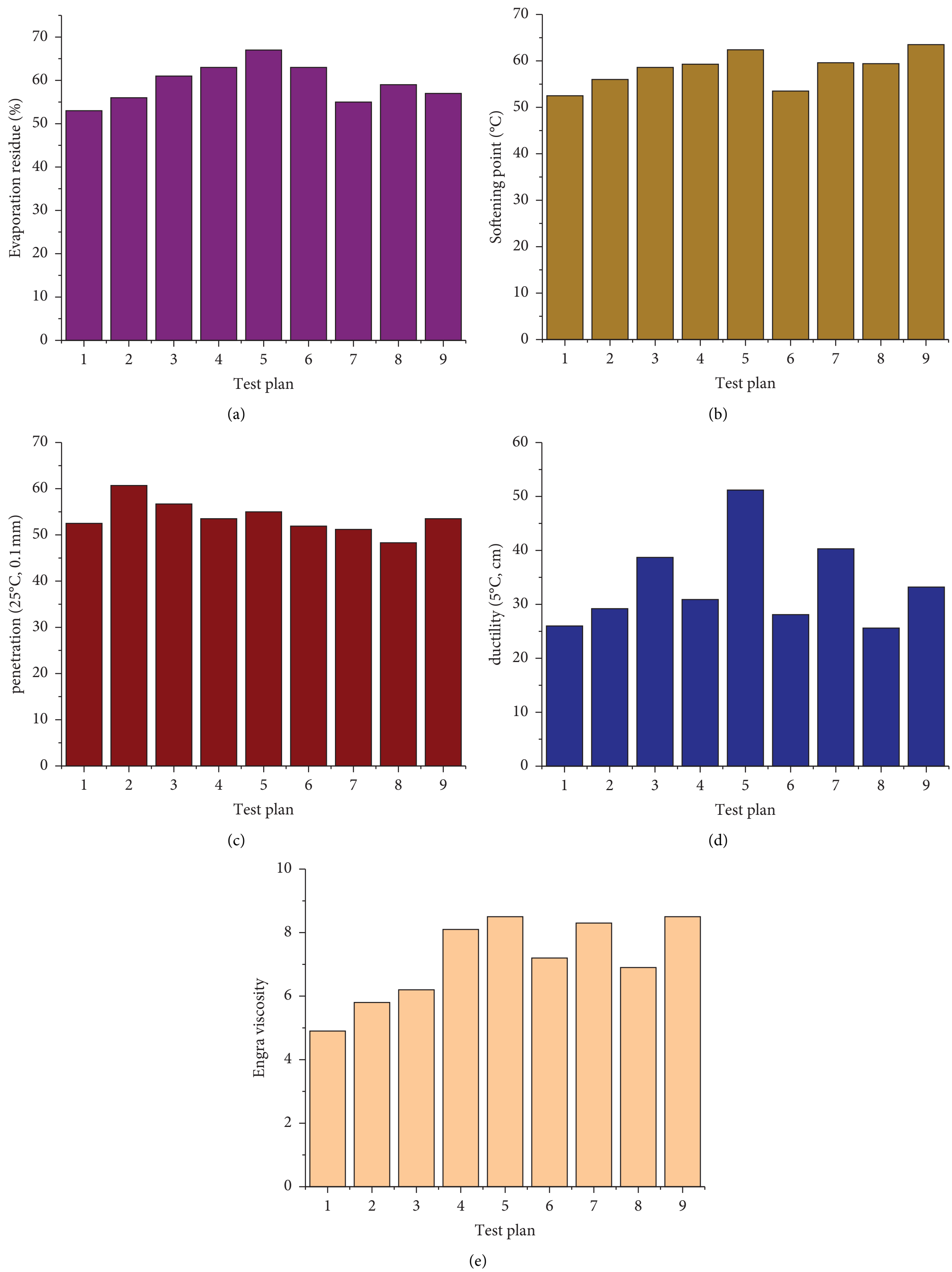


Figure 4: Orthogonal test results. (a) Evaporation residue. (b) Softening point. (c) Penetration (25°C). (d) Ductility (5 cm/min, 5°C). (e) Engla viscosity.

Table 9: Analysis of the range results of the orthogonal test.

Index		A	B	C	Empty column
Evaporation residue (%)	k1	56.67	57.00	58.33	59.00
	k2	64.33	60.67	58.67	58.00
	k3	57.00	60.33	61.00	61.00
	Range (R)	7.67	3.67	2.67	3.00
	Factors in priority			A > B > C	
	Preferred solution			$A_2B_2C_3$	
Softening point (°C)	k1	55.70	57.13	55.13	59.47
	k2	58.40	59.27	59.60	56.37
	k3	60.83	58.53	60.20	59.10
	Range (R)	5.13	2.13	5.070	3.10
	Factors in priority			A > C > B	
	Preferred solution			$A_3B_2C_3$	
Penetration (cm)	k1	56.63	52.40	50.90	53.67
	k2	53.47	54.67	55.90	54.60
	k3	51.00	54.03	54.30	52.83
	Range (R)	5.63	2.27	5.00	1.77
	Factors in priority			A > C > B	
	Preferred solution			$A_1B_2C_2$	
5°C ductility (cm)	k1	31.30	32.40	26.57	36.80
	k2	36.73	35.33	31.10	32.53
	k3	33.03	33.33	43.40	31.73
	Range (R)	5.43	2.93	16.83	5.067
	Factors in priority			C > A > B	
	Preferred solution			$A_2B_2C_3$	
Engla viscosity	k1	5.63	7.10	6.33	7.30
	k2	7.93	7.07	7.47	7.10
	k3	7.90	7.30	7.67	7.07
	Range (R)	2.30	0.23	1.33	0.23
	Factors in priority			A > C > B	
	Preferred solution			$A_2B_3C_3$	

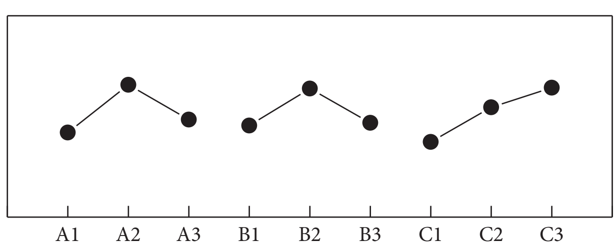


Figure 5: Trend figure of the comprehensive index.

0.1–3.54 Hz, the SBS modified emulsified asphalt, SBR modified emulsified asphalt, and SBS/SBR modified emulsified asphalt compared with the base emulsified asphalt, the logarithm of G^* increased by 54%, 53%, and 205%, and the logarithm of $G^*/\sin\delta$ increased by 58%, 55%, and 223%. Liu [41] prepared WER/SBS modified emulsified asphalt through indoor tests and measured the G^* through frequency sweep. At 48°C, the G^* of SBS/SBR modified emulsified asphalt is increased by 39% compared with WER/SBR modified emulsified asphalt. It shows that SBS/SBR modified emulsified asphalt can significantly improve aircraft's antishear deformation and antirutting performance in low-speed taxiing areas under high-temperature conditions.

4.2.4. Phase Structure Analysis. Han studied the relationship between $\lg G'$ and $\lg G''$ using a molecular model of the viscoelasticity of homogeneous polymers, the Han curve. The Han curve can examine the compatibility between the blend systems. The closer the slope of the Han curve is to 2, the closer the mixture is to a homogeneous polymer. In the frequency sweep data at a temperature of 64°C, the loss modulus G'' and storage modulus G' of four emulsified asphalts were extracted, and the logarithms were taken for analysis, as shown in Figure 10. A linear fit to the curve in Figure 10 yields the results in Table 10. It can be seen from Figure 10 and Table 10 that the fitting R_2 of the Han curve of the four emulsified asphalts under the frequency sweep is all above 0.99, and the fitting accuracy is high.

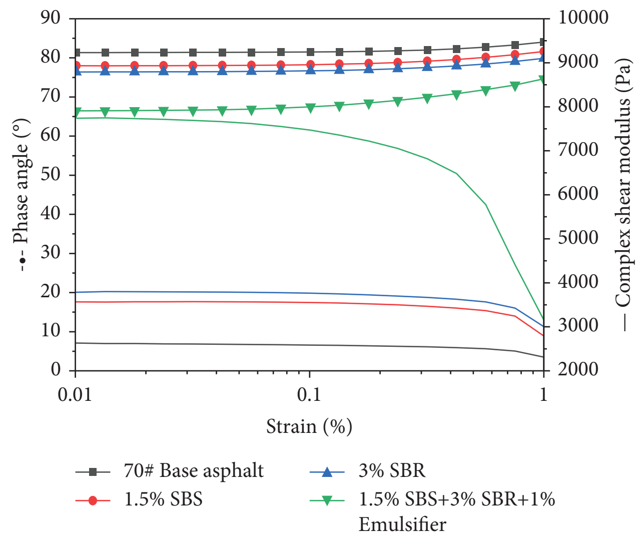


Figure 6: Variation of complex shear modulus and phase angle with shear strain for four types of emulsified asphalt.

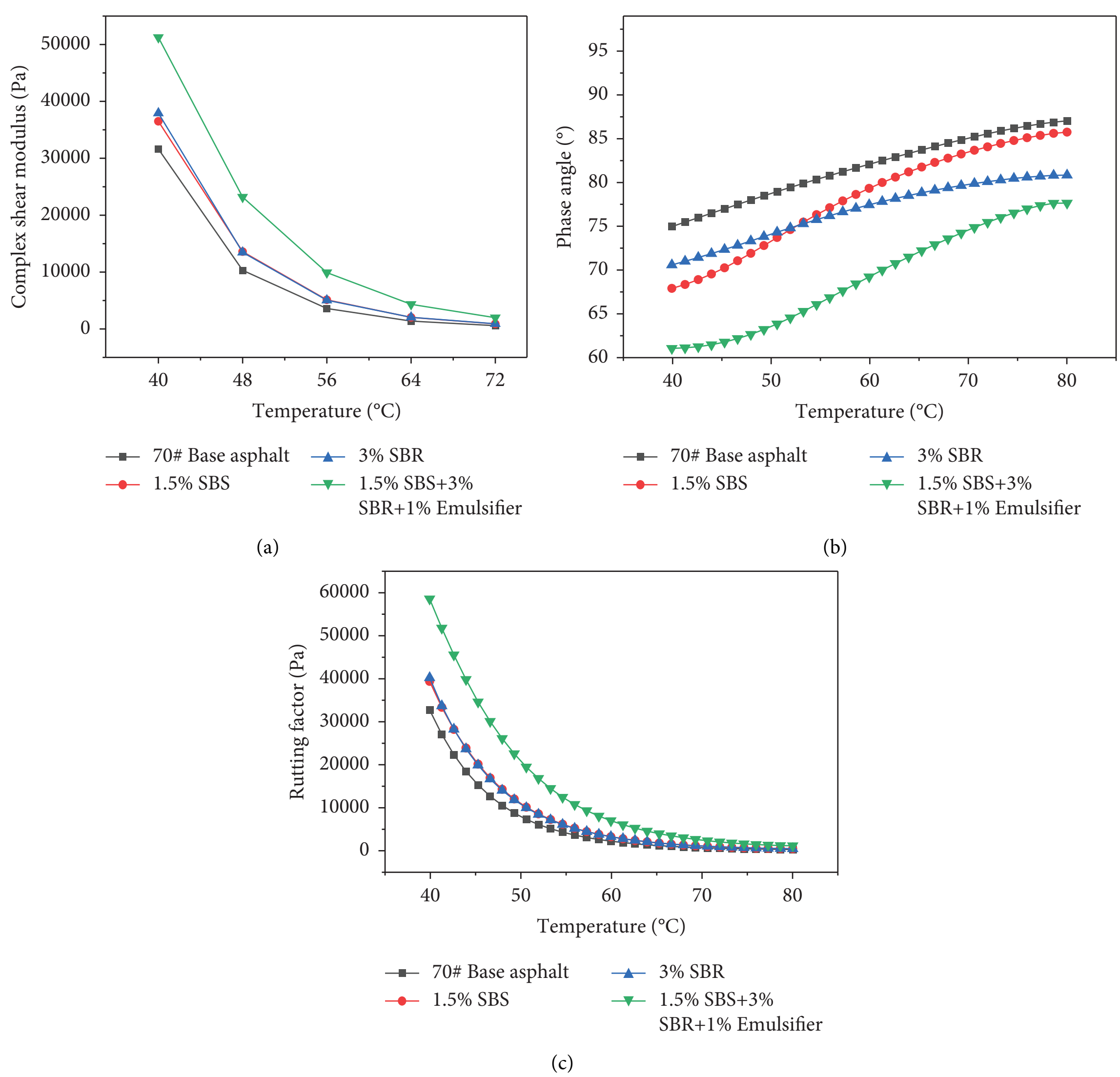


Figure 7: DSR temperature sweep results for four types of emulsified asphalt. (a) Variation of complex shear modulus with temperature for four types of emulsified asphalt. (b) Variation of phase angle with temperature for four types of emulsified asphalt. (c) Variation of rutting factor with temperature for four types of emulsified asphalt.

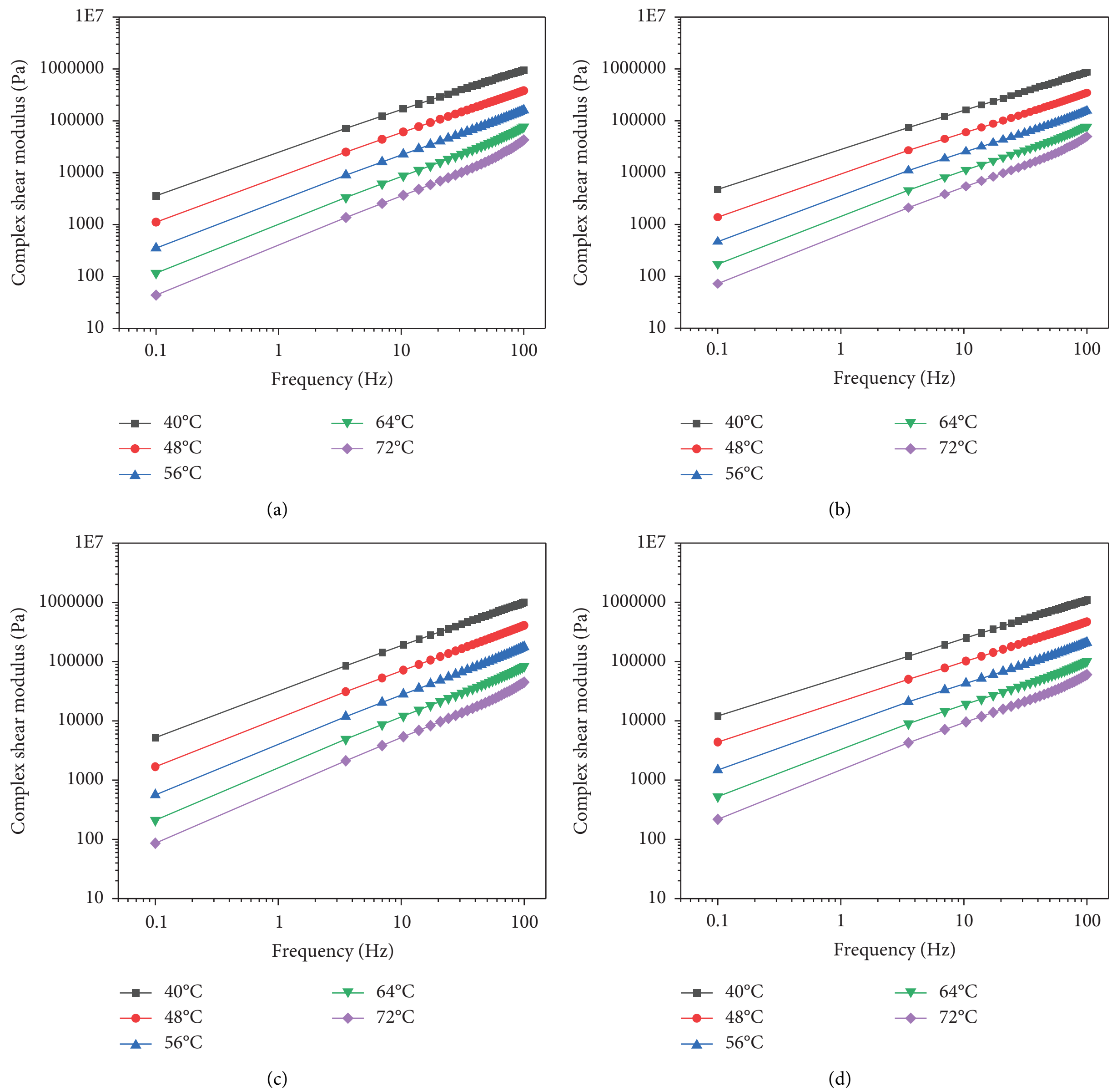


FIGURE 8: Variation of complex shear modulus with frequency for four types of emulsified asphalt. (a) Base emulsified asphalt. (b) 1.5% SBS modified emulsified asphalt. (c) 3% SBR modified emulsified asphalt. (d) SBS/SBR modified emulsified asphalt.

Compared with the base emulsified asphalt, the SBR modified emulsified asphalt slope is slightly lower because the SBR latex is easier to precipitate in the emulsified asphalt, resulting in agglomeration, which has a specific impact on the continuity of the emulsified asphalt. Compared with the base emulsified asphalt, the slope of SBS/SBR modified emulsified asphalt increases, indicating that SBS/SBR has better compatibility with emulsified asphalt. The swelling effect of SBS makes SBS/SBR modified emulsified asphalt form a relatively stable spatial network structure, which can still maintain a stable state at lower frequencies.

4.3. Fluorescence Microscopy Test. The micromorphological changes of SBS modified emulsified asphalt, SBR modified emulsified asphalt, and SBS/SBR modified emulsified asphalt were analyzed, and the test results are shown in Figure 11. From Figures 11(a) and 11(b), it can be seen that the particle size of the SBS modifier at 400 times is significantly larger than that of the SBR modifier, and both SBS and SBR latex are uniformly dispersed in the emulsified asphalt. From the comparison of Figures 11(c) and 11(d), the dispersion of the modifier of the modified emulsified asphalt becomes uneven after the evaporation residue, and the particle size is not uniform. It starts to become unstable, and the continuous phase of asphalt and the dispersed phase of modifier are unevenly distributed, making SBS and SBR modifier agglomerate in emulsified asphalt, resulting in poor compatibility. It can be seen from Figures 11(e) and 11(f) that before the SBS/SBR modified emulsified asphalt is demulsified, SBS/SBR and emulsified asphalt are uniformly fused to form a stable spatial network structure. The stable spatial network

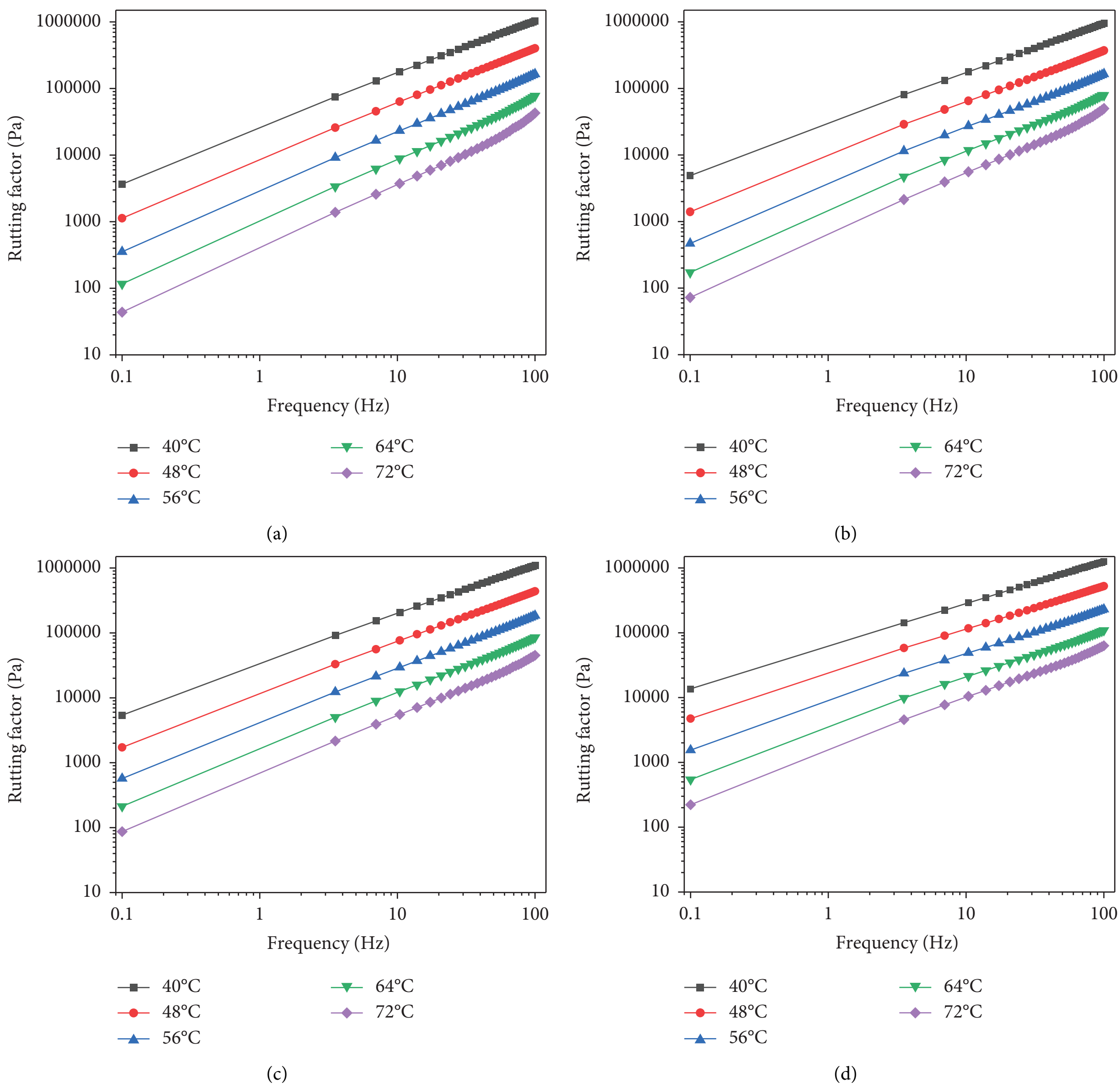


FIGURE 9: Variation of rutting factor with frequency for four types of emulsified asphalt. (a) Base emulsified asphalt. (b) 1.5% SBS modified emulsified asphalt. (c) 3% SBR modified emulsified asphalt. (d) SBS/SBR modified emulsified asphalt.

structure improves the high-temperature rutting resistance of SBS/SBR modified emulsified asphalt. This conclusion is consistent with Liu's research results on WER/SBR modified emulsified asphalt [42]. His study concluded that the cross-linked three-dimensional network structure formed by the WER/SBR modified emulsified asphalt could improve high-temperature stability. After demulsification, the interaction between asphalt molecules is also significantly enhanced, which improves the cohesion and makes the SBS/SBR modified emulsified asphalt show better bonding performance.

4.4. TG-DSC Test. The thermogravimetric analysis test results are shown in Figure 12: From the analysis of the TG curve, it can be seen that the SBS/SBR modified emulsified asphalt has three stages of mass-loss. At 0–200°C, the quality of the four kinds of emulsified asphalt is not lost, proving that the emulsified asphalt can be used in the actual production process from the microscopic.

The first stage of mass-loss is between 200°C and 350°C. The mass-loss in this stage is mainly due to the volatilization of lighter components in the bitumen, such as saturated and aromatic hydrocarbons, the thermal decomposition of modifiers and emulsifiers, and the release of small molecules formed in the thermal polycondensation reaction. At this stage, the temperature of the mass-loss point of SBS/SBR modified emulsified asphalt decreased by 82°C and 67°C compared with that of SBS and SBR modified emulsified asphalt, which was due to the thermal decomposition of the modifier and emulsifier. At 350°C–550°C, it is the second stage of mass-loss, and the mass-loss is as high as 53%. This

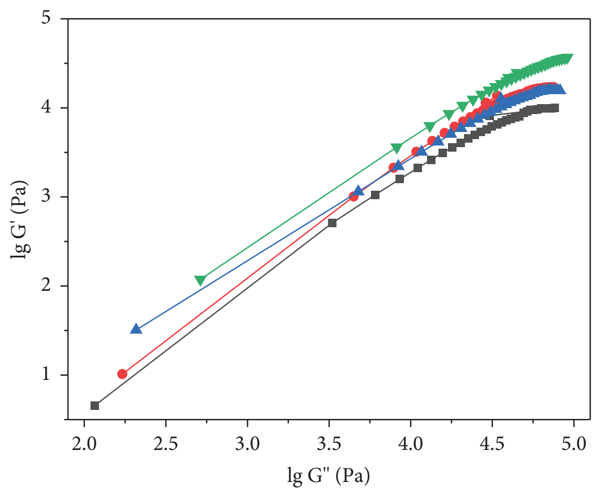


FIGURE 10: Han curves of four emulsified asphalts under frequency sweep.

TABLE 10: Fitting parameters of four emulsified asphalt Han curves under frequency sweep.

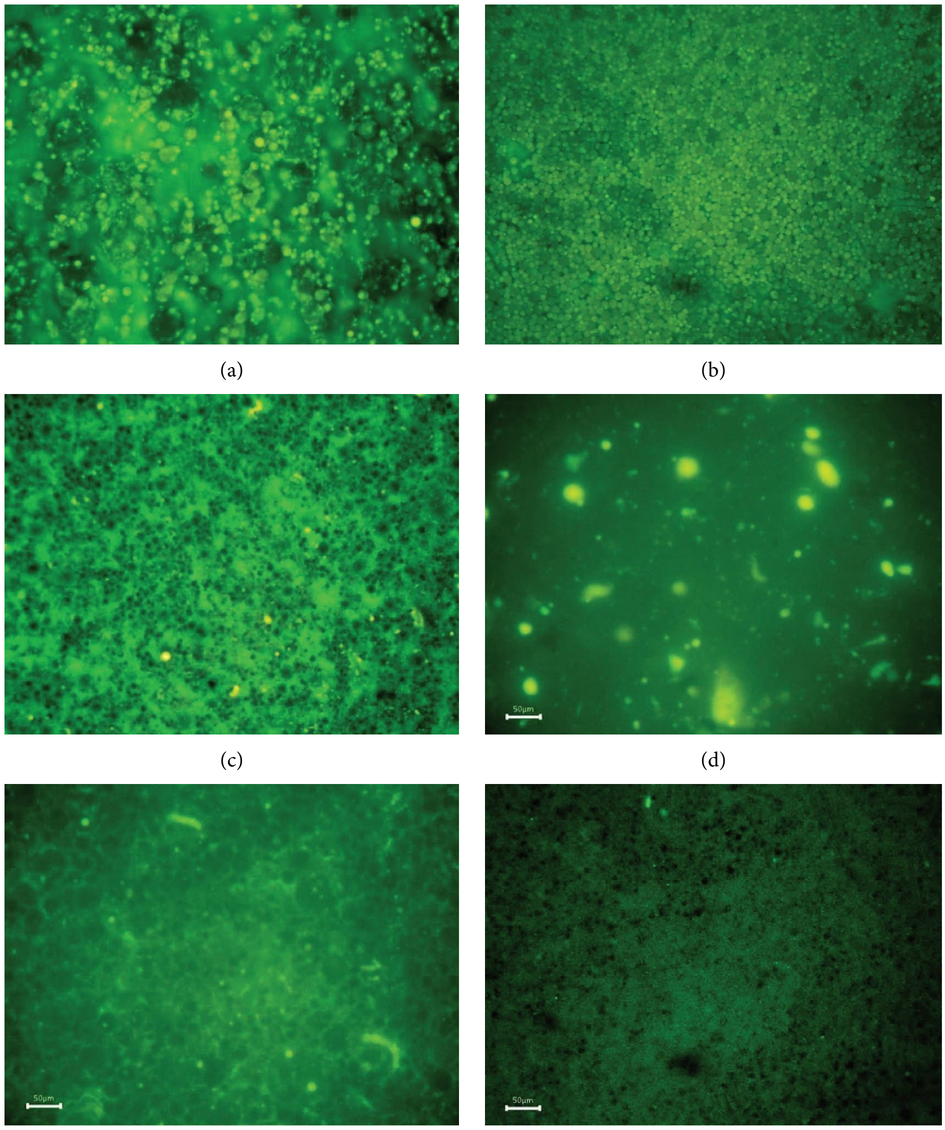
Asphalt type	Slope (k)	R^2
Base emulsified asphalt	1.150	0.997
1.5% SBS modified emulsified asphalt	1.192	0.997
3% SBR modified emulsified asphalt	1.132	0.998
1.5% SBS + 3% SBR modified emulsified asphalt + 1% emulsifier	1.183	0.998

stage is the main stage of the mass-loss of emulsified asphalt. Liu [42] measured the mass-loss of WER/SBR modified emulsified asphalt through the DSC test and found that the main stage of mass-loss occurred at 300°C–420°C, and the decomposition peak of WER/SBR modified emulsified asphalt appeared at about 50°C. SBS/SBR modified emulsified asphalt has a higher mass-loss temperature and a higher decomposition temperature than WER/SBS modified emulsified asphalt, indicating that SBS/SBR modified emulsified asphalt has excellent high-temperature stability at this stage. From the analysis of the DTG curve, the peak mass-loss rate of SBS/SBR modified emulsified asphalt appears at 432.31°C, which may be caused by the four components of the asphalt, the modifier, and the emulsifier all reaching the peak of the mass-loss rate. However, the temperature is lower when the peak occurs, and minor compositional changes. The SBS/SBR modified emulsified asphalt has outstanding thermal stability. The mass-loss in the third stage starts between 550°C and 800°C, and the mass-loss is mainly due to the further volatilization of asphaltenes and colloids and the carbonization of residues.

From the DSC curve analysis, it can be seen that at 334.05°C, the heat flow curve of the SBS/SBR modified emulsified asphalt has a prominent endothermic peak due to the heat absorbed when the modifier, emulsifier, and asphalt impurities decompose. At 554.54°C, the integral area of the decomposition peak of the heat flow curve of the SBS/SBR modified emulsified asphalt is the largest. Moreover, the absorbed heat is the most, indicating that the high-temperature performance of the SBS/SBR modified emulsified asphalt is outstanding.

4.5. Shear and Tensile Tests. It can be seen from Figures 13 and 14 that at the same temperature, with the increase of spraying volume, the shear strength and tensile strength of the modified emulsified asphalt have the same law; both increase first and then decrease. At 25°C, the maximum shear and tensile strengths are 0.86 MPa and 0.65 MPa. The spraying volume of 0.85 kg/m^2 increased by 28%, 13% and 12% compared with the shear strength at 0.54 kg/m^2, 0.67 kg/m^2 and 1.03 kg/m^2, respectively. Compared with the tensile strength of 0.56 kg/m^2, 0.69 kg/m^2 and 1.06 kg/m^2, the spraying volume of 0.86 kg/m^2 increased by 40%, 13% and 10%, respectively. At 60°C, compared with WER emulsified asphalt, the shear strength of SBS/SBR modified emulsified asphalt is increased by 40%, and the tensile strength has no significant difference [39].

In Figures 15 and 16, the logarithmic shear strength and tensile strength have strong correlations with temperature, and the correlation coefficients are 0.995 and 0.971, respectively. It can be seen from Figures 17, and 18 that compared with the commercially available SBR modified emulsified asphalt for sticky layers, the prepared SBS/SBR modified emulsified asphalt has better shear resistance and tensile resistance.



(a) (b) (c) (d) (e) (f)

Figure 11: Microstructure of various modified emulsified asphalts under the fluorescence microscope. (a) 1.5% SBS modified emulsified asphalt (×400). (b) 3% SBR modified emulsified asphalt (×400). (c) SBS/SBR modified emulsified asphalt (×100). (d) SBS/SBR modified emulsified asphalt evaporation residue (×400). (e) SBS/SBR modified emulsified asphalt before demulsification (×400). (f) SBS/SBR modified emulsified asphalt after demulsification (×400).

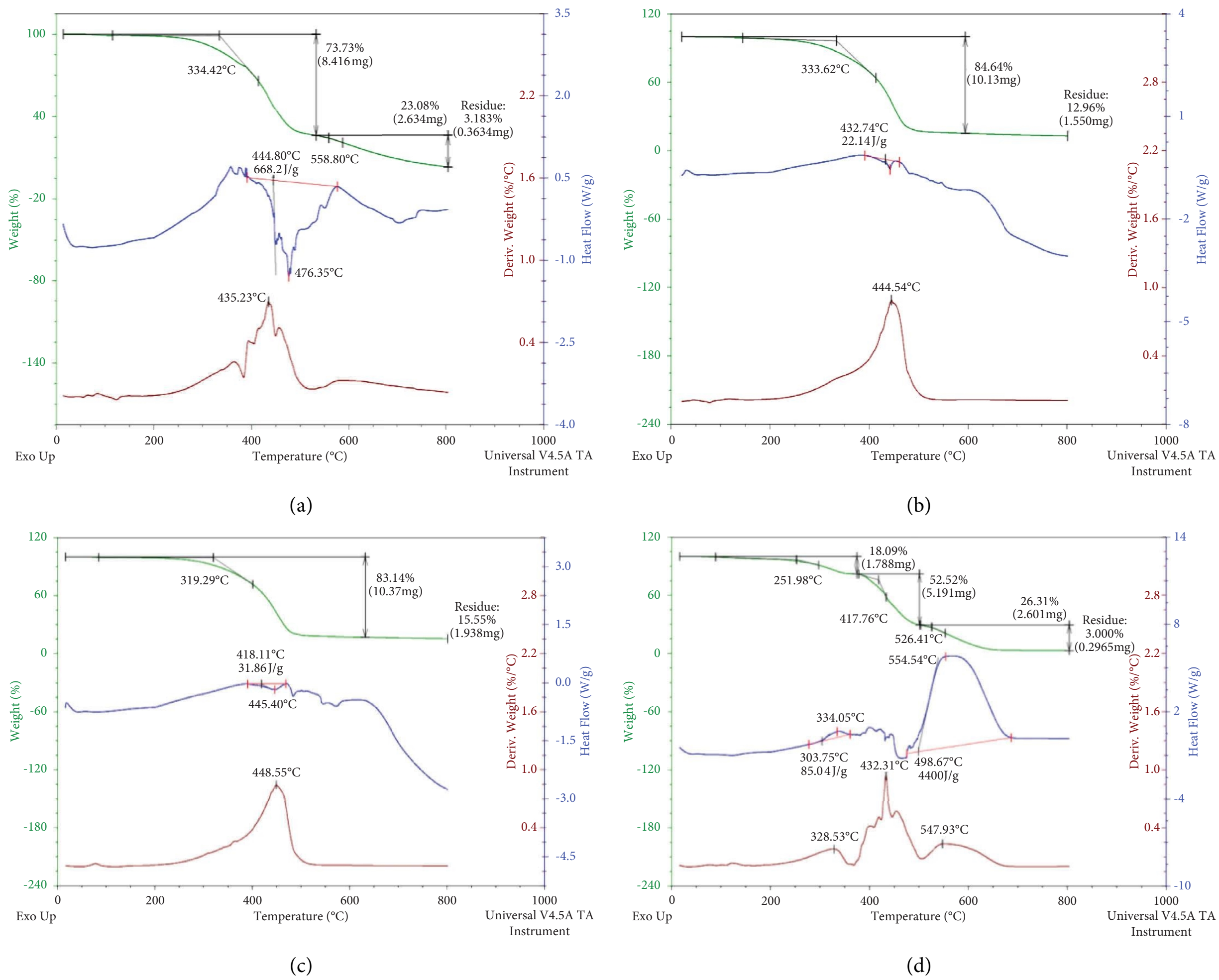


FIGURE 12: TG-DSC curve. (a) Base emulsified asphalt. (b) 1.5% SBS modified emulsified asphalt. (c) 3% SBR modified emulsified asphalt. (d) SBS/SBR modified emulsified asphalt.

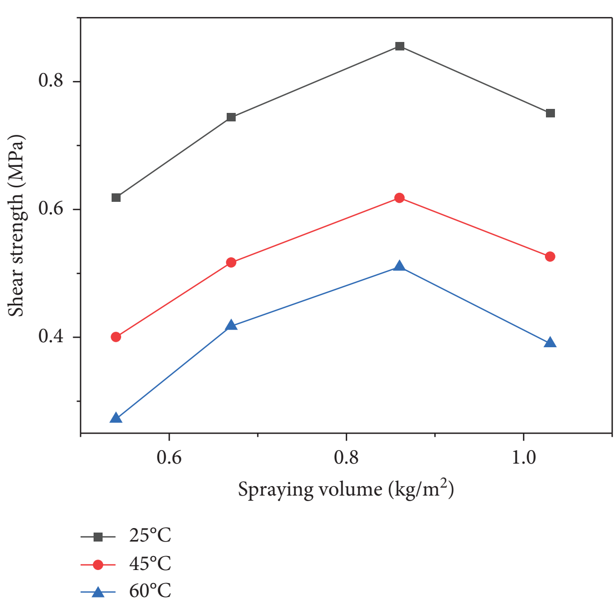


FIGURE 13: Variation of shear strength with temperature.

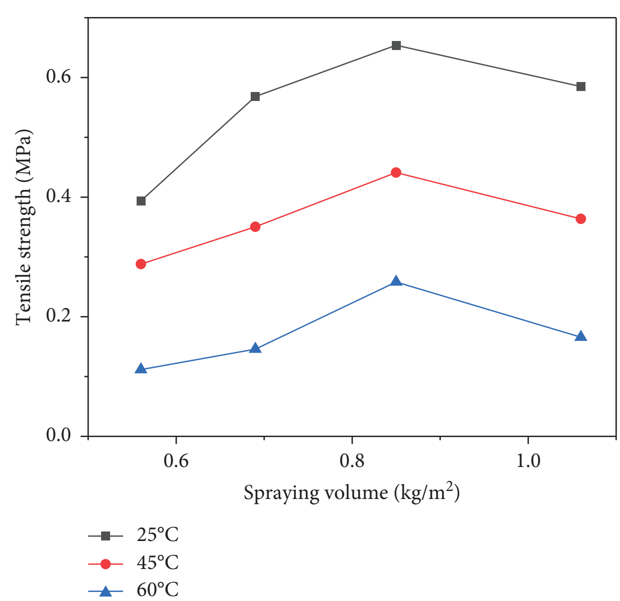


FIGURE 14: Variation of tensile strength with temperature.

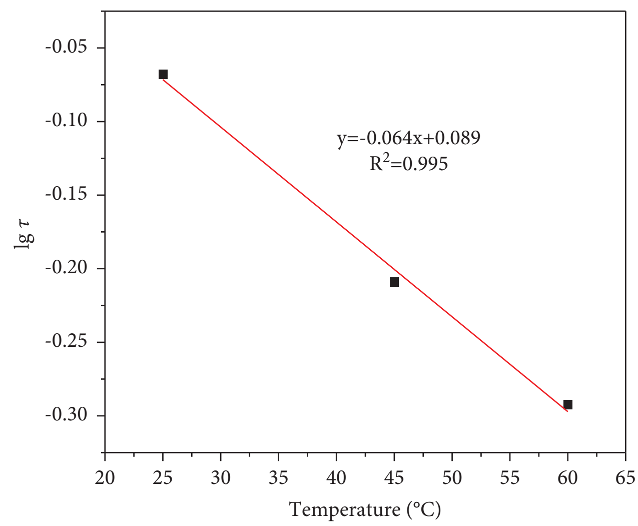


FIGURE 15: Variation of the logarithm of shear strength with temperature.

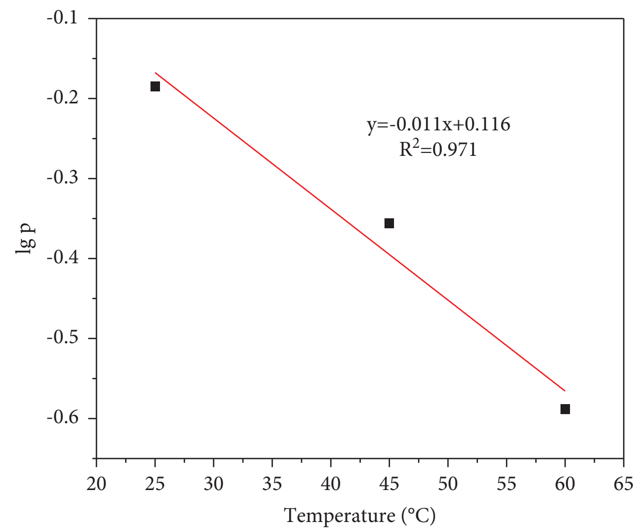


FIGURE 16: Variation of the logarithm of tensile strength with temperature.

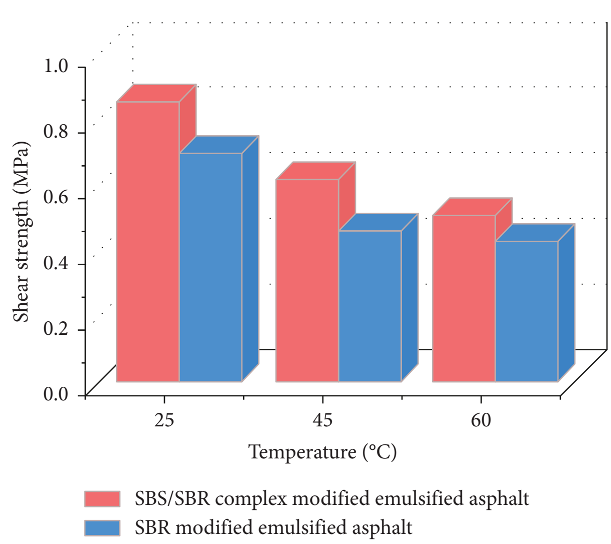


FIGURE 17: Variation of shear strength of different modified emulsified asphalt with temperature.

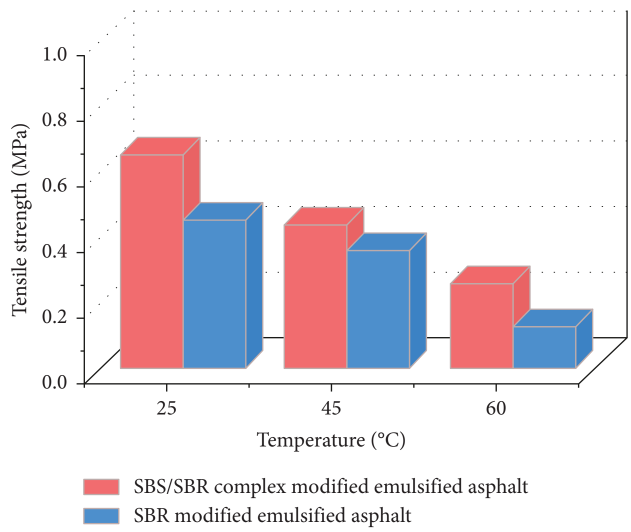


Figure 18: Variation of tensile strength of different modified emulsified asphalt with temperature.

5. Conclusion

Using the orthogonal test method and combining five kinds of physical performance indexes, we determined the best SBS/SBR modified emulsified asphalt combination. The rheological performance, microscopic mechanism, and mechanical performance of emulsified asphalt were evaluated and analyzed by laboratory tests. The main conclusions are as follows:

(1) The SBS/SBR modified emulsified asphalt was prepared by the orthogonal test plan. Then the range analysis was carried out in combination with the evaporation residue, softening point, penetration, ductility, and Engla viscosity indexes. The result shows that the influence degree of each factor was SBS modifier > Emulsifier > SBR modifier; The optimum dosage of SBS/SBR modified emulsified asphalt is 1.5% SBS + 3.0% SBR + 1.0% emulsifier.

(2) When the strain is controlled within 30%, each emulsified asphalt can be guaranteed to be within the linear viscoelasticity range. Temperature sweep at 48°C, compared with SBS and SBR modified emulsified asphalt, the G^* of SBS/SBR modified emulsified asphalt increased by 71% and 75%, $G^*/\sin\delta$ increased by 83% and 86%, and δ decreased by 13% and 15%, indicating that its shear deformation resistance, rutting resistance, and recovery deformation ability are significantly improved. At a temperature of 72°C and a frequency of 0.1–3.54 Hz, the G^* logarithm of SBS modified emulsified asphalt, SBR modified emulsified asphalt, and SBS/SBR modified emulsified asphalt increased by 54%, 53%, and 205% compared with the base emulsified asphalt. The logarithm of $G^*/\sin\delta$ increased by 58%, 55%, and 223% compared with the base emulsified asphalt. The result shows that the SBS/SBR modified emulsified asphalt can significantly improve the shear deformation and rutting resistance under high-temperature conditions.

(3) Han curve indicates that the SBS/SBR modifier has excellent compatibility with asphalt and can maintain a stable state at a lower frequency. SBS/SBR is compatible with emulsified asphalt and can be uniformly dispersed in emulsified asphalt. Before demulsification of SBS/SBR modified emulsified asphalt, SBS/SBR and emulsified asphalt are uniformly fused to form a stable spatial network structure. After demulsification, SBS/SBR and emulsified asphalt are more closely fused. The interaction between asphalt molecules is significantly enhanced; the cohesion is improved so that the asphalt can exert its better bonding performance.

(4) Compared with SBS and SBR modified emulsified asphalts, the temperature of the mass-loss point of SBS/SBR modified emulsified asphalt decreased by 82°C and 67°C. When the mass-loss rate peaks, the temperature is low, the peak value is small, and the number of component changes is small. At 200°C–500°C, the maximum thermal weight loss of SBS/SBR modified emulsified asphalt decreases. At 554.54°C, the integrated area of the decomposition peak of the heat flow curve of the SBS/SBR modified emulsified asphalt is the largest, and the heat absorption is the largest. It shows that the SBS/SBR modified emulsified asphalt has outstanding thermal stability.

(5) At different temperatures, with the increase of spraying volume, the shear and tensile strength of SBS/SBR modified emulsified asphalt showed the same law, which first increased and then decreased. At 25°C, the maximum shear and tensile strengths are 0.86 MPa and 0.65 MPa. Compared with the commercially available SBR modified emulsified asphalt for the adhesive layer, the prepared SBS/SBR modified emulsified asphalt has better shear and tensile resistance.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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