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Research on the Influence of Different Warm-Mix Modifiers on Pavement Performance of Bitumen and Its Mixture

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Abstract: Recently, bitumen pavements have been widely used for road paving. Various scholars have used modified bitumen in road paving to improve pavement performance, thus increasing the service life. In this study, Sasobit, XT-W3, and Evotherm were selected as warm-mix modified bitumen and various investigations including conventional performance, Brookfield rotational viscosity, dynamic shear rheology, Marshall stability, high-temperature rutting, water stability, low-temperature beam bending, fatigue, and compaction performance tests of modified bitumen mixtures were conducted to evaluate the pavement performance of modified bitumen and its mixtures. The effect of different warm-mix modifiers on high-temperature performance, temperature sensitivity, low-temperature performance, and water stability were compared and analyzed. The results indicated that incorporating Sasobit, XT-W3, and Evotherm modifiers enhanced the compressive properties, high-temperature rutting resistance, water stability, and fatigue resistance of the bitumen mixtures, whereas the Evotherm modifier reduced the deformation resistance of the bitumen mixtures. XT-W3 and Evotherm modifiers can effectively improve low-temperature cracking resistance, but Sasobit modifiers have a negative impact.

Keywords: warm-mix modified bitumen; Sasobit; Evotherm; XT-W3; bitumen mixture; energy saving and emission reduction

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1. Introduction

With rapid economic development the transportation industry is gradually evolving and road engineering in China has made significant progress. In road engineering, pavement can be divided into bitumen concrete and cement concrete pavements. Bitumen pavements are widely used on all levels of road surfaces in China because of their advantages, such as comfortable driving and pronounced noise reduction. However, with increasing traffic volume and traffic load bitumen pavements are subjected to a highly complex environment during the service phase and often some unavoidable problems occur, such as cracks, rutting, pits, and loosening, which can reduce their actual service life [1]. Therefore, in recent years, various scholars have applied modified bitumen to the paving of roads to improve the road performance, thus increasing their service life [2]. However, the traditional hot-mix bitumen mixture requires significant energy during construction owing to the high mixing and rolling temperatures and it generates substantial pollution of waste gases and dust, which impacts environmental management. In this context, a warm-mix bitumen technology has been developed and is widely used in all pavement construction projects. The mixing temperature of warm-mix bitumen mixture is lower than that of hot-mix bitumen mixture by approximately 20–40 °C, which can significantly reduce energy consumption while meeting the road performance requirements of bitumen mixture. It can also reduce polluting gases and dust emissions, significantly improving

the construction environment. Thus, it is a typical energy-saving and emission-reducing construction technology [3,4]. Currently, the commonly used warm-mix bitumen mixture technologies are divided into three categories: foaming technology, chemical additives, and organic additives [4–8]. The warm-mix modifiers selected for this paper include XT-W3, Evotherm, and Sasobit.

Recently, various scholars have studied the addition of warm-mix modifiers to virgin bitumen, which can reduce the construction temperature and energy consumption, protect the environment, and improve bitumen performance. Gao et al. found that Sasobit can reduce bitumen penetration, increase the softening point and rutting factor, and improve the deformation resistance of bitumen [9]. Farshad et al. found that Sasobit reduced the mixing temperature of rubber bitumen and improved the water stability, fatigue resistance, and rutting resistance of rubber bitumen [10]. Aniket and Dharamveer showed that Sasobit reduced the bitumen viscosity and improved its fatigue resistance [11]. Using Brookfield rotational viscosity, dynamic shear rheology, and bending beam rheology tests, Khalid et al. found that Sasobit modifiers can improve the high-temperature stability of bitumen mixtures; however, they harm low-temperature crack resistance [12]. Ashok and Choudhary studied the rheological properties of Sasobit-modified bitumen and found that increasing the Sasobit admixture can improve the elastic properties and permanent deformation resistance of bitumen [13]. Liang studied the effects of different doses of Sasobit, EC120, and Evotherm on porous and highly viscous bitumen pavements, and using dynamic shear rheology and low-temperature small beam-bending tests, they determined that the warm-mix additive improved the high-temperature stability of the bitumen mixture and negatively affected the low-temperature cracking resistance [14]. Shi studied the effect of Sasobit on the rheology and conventional properties of high-viscosity bitumen using dynamic mechanical analysis (DMA), which showed that Sasobit modifiers have an excellent viscosity reduction effect and can increase the softening point and rutting factor and reduce the penetration and ductility indicating that Sasobit can significantly improve high-temperature rutting performance; however, the low-temperature cracking resistance is reduced [15]. Luo studied two surface-active warm mixes, Evotherm M1 and Retherm, and found that warm mixes could improve the penetration and ductility of bitumen and reduce the softening point and bitumen viscosity [16]. Ji studied the effects of different warm mixes on the properties of bitumen and found that the high- and low-temperature performance of the surfactant Evotherm was more balanced, while the adhesion and anti-aging properties were better [17]. Lakshmi used warm-mix bitumen technology to reduce the mixing and compaction temperatures of bitumen; however, the addition of a warm-mix modifier also affected the rheological response of bitumen during pavement use [18]. Song conducted a temperature scan test on bitumen mixed with Evotherm warm mix using a dynamic shear rheometer and analyzed the complex shear modulus, phase angle, and rutting factor of the modified bitumen. They found that when the temperature was between 28–52 °C, Evotherm could improve the rutting resistance of bitumen, while at temperatures higher than 52 °C, the effect of Evotherm diminished. Moreover, Evotherm could improve the elastic recovery properties of bitumen [19]. Yu showed that adding Evotherm during the preparation of rubber bitumen could save energy and reduce emissions [20]. Subsequently, further studies revealed that the Sasobit modifier could improve the rutting resistance of bitumen and Evotherm could improve the fatigue resistance of bitumen [21]. Julaganti investigated the effects of Sasobit and Evotherm on bitumen properties using the tensile strength ratio (TSR) and retained Marshall stability (RMS) tests. Evotherm-modified bitumen mixes exhibited higher TSR and RMS values than Sasobit [22].

As mentioned above, the modification of bitumen and its mixtures differs among the modifiers of different warm-mix technologies. Therefore, in this study, three warm-mix modifiers, XT-W3 for foaming technology, Evotherm for chemical additives, and Sasobit for organic additives, were separately studied for comparative analysis to investigate their effect on the road performance of bitumen and its mixtures. Virgin bitumen and SBS-modified bitumen and their mixtures were analyzed and studied as control groups.

2. Materials and Testing Program

2.1. Materials

The test materials included 70# virgin bitumen, white diameter 2–5 mm granular Sasobit modifier provided by Chongqing Pengfang Transportation Technology Co. (Chongqing, China), XT-W3 powder modifier provided by Changzhou Xintuo Pavement Modifier Co., Ltd. (Changzhou, China) containing 20% of crystalline water, which produces a foaming reaction to lubricate when mixed, and Evotherm modifier provided by Shanghai Longfu Material Technology Co. (Shanghai, China). The performance indices of 70# virgin bitumen and the three modifiers selected in this study are shown in Tables 1–5.

Table 1. Properties of virgin bitumen.

Property		Units	Testing Value	Technical Requirements
Penetration (100 g, 5 s)	15 °C	0.1 mm	24.2	-
	25 °C	0.1 mm	68	60~80
	30 °C	0.1 mm	104.6	-
Penetration Index(PI)		-	−0.4	−1.5~1.0
T800		°C	50.5	-
T1.2		°C	−15.7	-
Ductility	15 °C	mm	1451	-
	5 °C	mm	133.5	-
Softening Point		°C	49.8	≥45

Table 2. Properties of Sasobit.

Property	Melting Point/°C	Flashing Point/°C	Viscosity at 135 °C /(Pa·s)	Viscosity at 150 °C/(Pa·s)	Penetration at 25 °C /0.1 mm	Penetration at 60 °C /0.1 mm
Testing Value	100	290	5.47×10^{-3}	3.26×10^{-3}	1	8

Table 3. Properties of XT-W3.

Property	Technical Requirements	Testing Value
Appearance	White powder solid	White powder solid
Heap Weight (g/mL)	0.40–0.48	0.46
Grain Size (μm)	2–4	3
Crystalline Water Content (%/wt)	≥18	19.8

Table 4. Properties of Evotherm.

Property	Testing Value	Lower Limit	Upper Limit
Amine Value	176	165	185
Solid Content (%)	74	67	-
PH	8.9	6.5	11

Table 5. Properties of SBS.

Property	Testing Value	Units
Oil Content	0.71	%
Total Ash	0.23	≤%
Volatility	1.08	≤%
S/B Ratio	30/70	-
Tensile Strength	18.0	≥MPa

2.2. Testing Program

2.2.1. Conventional Performance Tests

As a temperature-sensitive material, penetration is one of the leading performance indicators and can accurately reflect the degree of hardness, consistency, and relative viscosity of bitumen. In this study, the penetration values of modified bitumen were measured at 15 °C, 25 °C, and 35 °C.

The concept of softening point is primarily used to determine the high-temperature stability of bitumen in China. In this study, the softening point test of modified bitumen was performed using the ring and ball method.

The ductility of bitumen is its ability to resist plastic deformation by external tensile forces. Under low-temperature conditions, greater ductility indicates that the bitumen is more resistant to cracking at low temperatures. This study determined the ductility of modified bitumen at 5 °C and 15 °C.

The aging test of modified bitumen was performed by the rotating film oven test, and the aging resistance of modified bitumen was investigated by the penetration ratio before and after aging.

2.2.2. Brookfield Rotational Viscosity Test

Brookfield rotational viscosity at two different temperatures, 120 °C and 135 °C, was measured and compared with virgin bitumen and SBS-modified asphalt bitumen for analysis in this study to evaluate the effects of Sasobit, XT-W3, and Evotherm modifiers on bitumen viscosity.

2.2.3. Dynamic Shear Rheological Test

In this study, a dynamic shear rheology test was performed to evaluate the high-temperature stability of the modified bitumen. During the test, a strain control mode with 12% strain and 10 rad/s frequency was used to apply external forces to the test specimens in the temperature range of 52–82 °C. The rutting factor, $G^*/\sin\delta$, of the modified bitumen was determined.

2.2.4. Marshall Stability Test

The maximum load of Marshall specimens damaged by loading a vertical force using the stability instrument is called stability and the flow value is the vertical deformation of the specimen at the maximum damage load. A Marshall stability test was conducted using an automatic Marshall compaction instrument to prepare specimens for the AC−13 C bitumen mixture.

2.2.5. High-Temperature Rutting Test

The rutting test characterizes the high-temperature stability of a bitumen mixture. According to the "Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering" (JTG E20–2011) [23], an AC−13 C type bitumen mixture was rutted using the wheel rolling method of 300 mm × 300 mm × 50 mm. The test conditions were a temperature of 60 °C ± 1 °C, heat preservation in a constant-temperature room for at least 5 h, and a test wheel and specimen pressure of 0.7 ± 0.05 MPa.

2.2.6. Water Stability Test

Water damage is one of the primary diseases of bitumen pavement. The preparation of 101.6 mm ± 0.2 mm diameter, 63.5 mm ± 1.3 mm height test specimens using a soak Marshall test and freeze-thaw splitting test, respectively, the effect of Sasobit, XT-W3 and Evotherm modifiers on the water stability performance of bitumen mixtures was evaluated using residual stability MS_0 and freeze-thaw splitting strength ratio TSR.

2.2.7. Low-Temperature Crack Resistance Test

In this study, a rectangular beam of 250 mm ± 2.0 mm in length, 30 mm ± 2.0 mm in width, and 35 mm ± 2.0 mm in height was constructed and the bitumen mixture low-temperature small beam bending test was used to evaluate the low-temperature crack resistance of the bitumen mixture, bending tensile strength RB, bending tensile strain ε_B, and bending stiffness modulus S_B.

2.2.8. Fatigue Test

The fatigue resistance of a bitumen mixture refers to the ability of the mixture to resist repeated loading under the influence of specific loads and climatic conditions. The fatigue resistance of modified bitumen mixtures was studied using a three-point beam bending fatigue test. The prepared specimen size was prismatic 40 mm × 40 mm × 250 mm, temperature 15 °C ± 1 °C, stress 0.3, 0.4, 0.5, and 0.6 four levels, three points for continuous sinusoidal load, frequency 10 Hz, with regression parameters *n* and K as the evaluation index.

2.2.9. Compaction Performance Tests

The Marshall compaction method was employed to prepare Marshall specimens using AC−13 mineral grading. The compaction degree, gross bulk density, and other volume parameters of bitumen mixtures were analyzed by changing the compaction temperature and number of compactions. Subsequently, the compaction performances of different bitumen mixtures were evaluated.

2.3. Preparation of Modified Bitumen

First, the virgin bitumen was heated in an oven at 135 °C until completely melted. Then Sasobit, XT-W3, Evotherm, and SBS modifiers were weighed and poured into the virgin bitumen in batches, stirred while pouring, and sheared at 155 °C for 30 min using a high-speed shear with a speed of 5000 r/min to produce the modified bitumen. According to the research results of domestic and foreign scholars, the amounts of Sasobit-modified bitumen selected in this study were 2%, 3%, and 4%; XT-W3-modified bitumen was 3%, 5%, and 8%; Evotherm modified bitumen was 0.4%, 0.6%, and 0.8%; and SBS-modified bitumen was 4%.

2.4. Modified Bitumen Mix Ratio Design

In this study, a continuous dense-graded AC−13 C bitumen mixture was selected for pavement performance. The grade of mineral material was adopted as the median value of the grade in the Implementation Manual of Technical Specification for Highway Bitumen Pavement Construction (JTG F40–2004) [24]. The Marshall specimen was prepared by the compaction method in the "Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering" (JTG E20–2011) [23]; the asphalt content was 11.3% and the target void ratio of the specimen was 4.0%. The test results indicated that the optimum petroleum ratios of virgin bitumen, Sasobit-modified bitumen, XT-W3-modified bitumen, Evotherm-modified bitumen, and SBS-modified bitumen mixtures were 4.9%, 4.8%, 4.8%, 4.8%, and 4.9%, respectively.

3. Results and Analysis

3.1. Results and Analysis of Basic Performance Test of Modified Bitumen

3.1.1. Penetration Test

The results are shown in Figure 1.

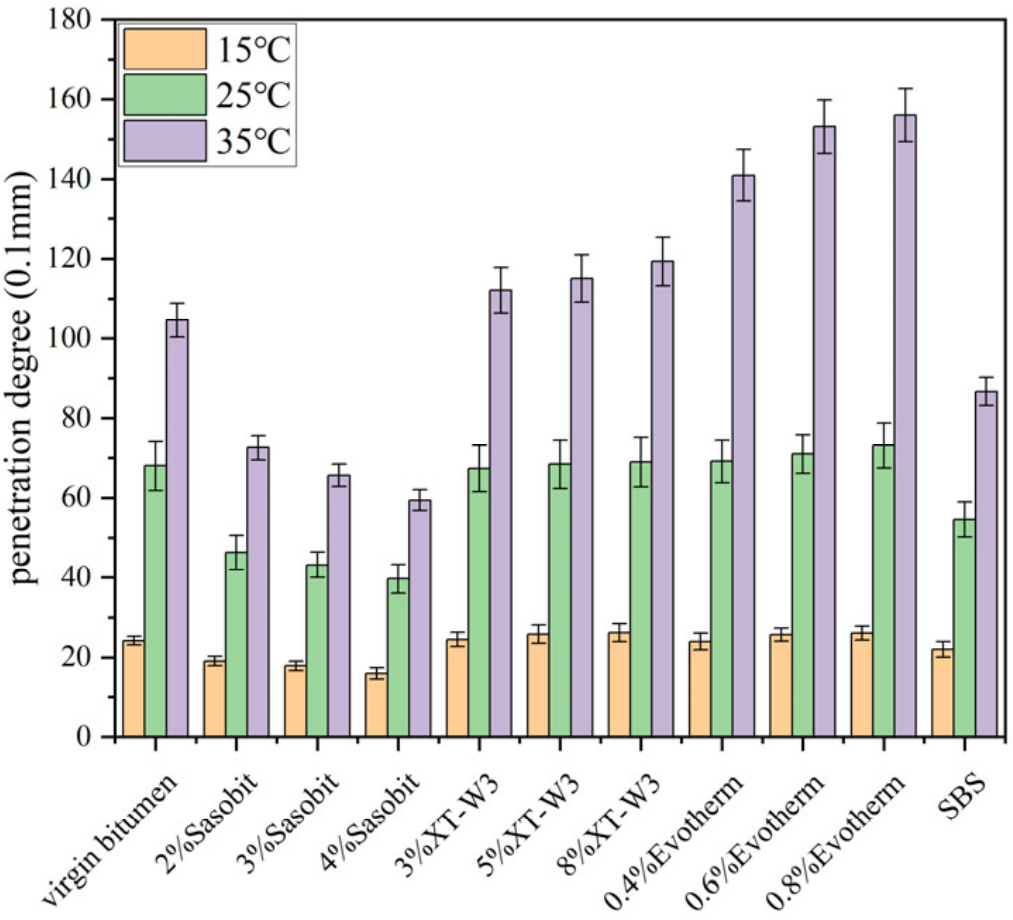


Figure 1. Penetration test results.

Figure 1 shows that after mixing with the Sasobit modifier, the penetration value decreases with the increase in admixture and decreases compared with the base bitumen, indicating that the Sasobit modifier can improve the hardness of bitumen and enhance its resistance to deformation. After mixing with the XT-W3 and Evotherm modifiers, the penetration of modified bitumen increases with the increase in admixture, indicating that the XT-W3 and Evotherm modifiers soften the bitumen as a whole, and its resistance to deformation becomes relatively poor. Under certain admixtures, the penetration of Sasobit-modified bitumen was lower than that of SBS-modified bitumen, and the penetration of XT-W3-modified and Evotherm-modified bitumens was higher than that of SBS-modified bitumen. This shows that the deformation resistance of Sasobit-modified bitumen is better than that of SBS-modified bitumen under a proper admixture, whereas XT-W3-modified and Evotherm-modified bitumens are worse than SBS-modified bitumen.

3.1.2. Softening Point Test

The results are shown in Figure 2.

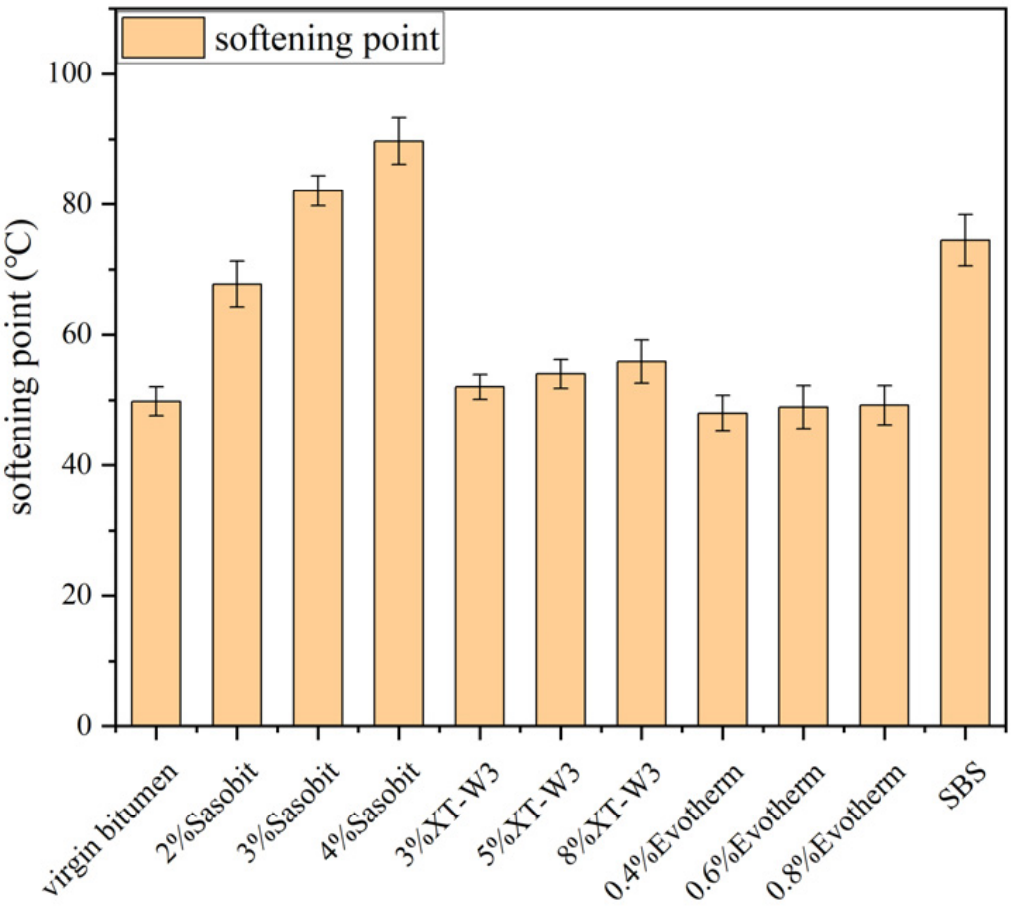


Figure 2. Softening point test results.

Figure 2 shows that the softening point of bitumen increased to different degrees when Sasobit and XT-W3 modifiers were incorporated. Sasobit increased by 36.1%, 65.1%, and 80.1%, respectively; XT-W3 increased by 2.2 °C, 4.2 °C, and 6.1 °C, respectively, while the incorporation of Evotherm modifier decreased by 0.6 °C, 0.9 °C, and 1.8 °C. This shows that the Sasobit modifier can improve the high-temperature stability of the bitumen material as well as its high-temperature deformation resistance; after mixing with the XT-W3 modifier, the improvement in the softening point of bitumen is not significant; after mixing with the Evotherm modifier, the softening point is reduced, and overall, the bitumen becomes softer. When the Sasobit dose was greater than 3%, its softening point was higher than that of the SBS-modified bitumen, while the softening points of the XT-W3 and Evotherm-modified bitumens were consistently lower than those of the SBS-modified bitumen, indicating that under a specific Sasobit dose, the high-temperature performance of the modified bitumen was better than that of the SBS-modified bitumen, while the high-temperature stability of XT-W3 and Evotherm-modified bitumens were lower than that of the SBS-modified bitumen.

3.1.3. Ductility Test

The results are shown in Figure 3.

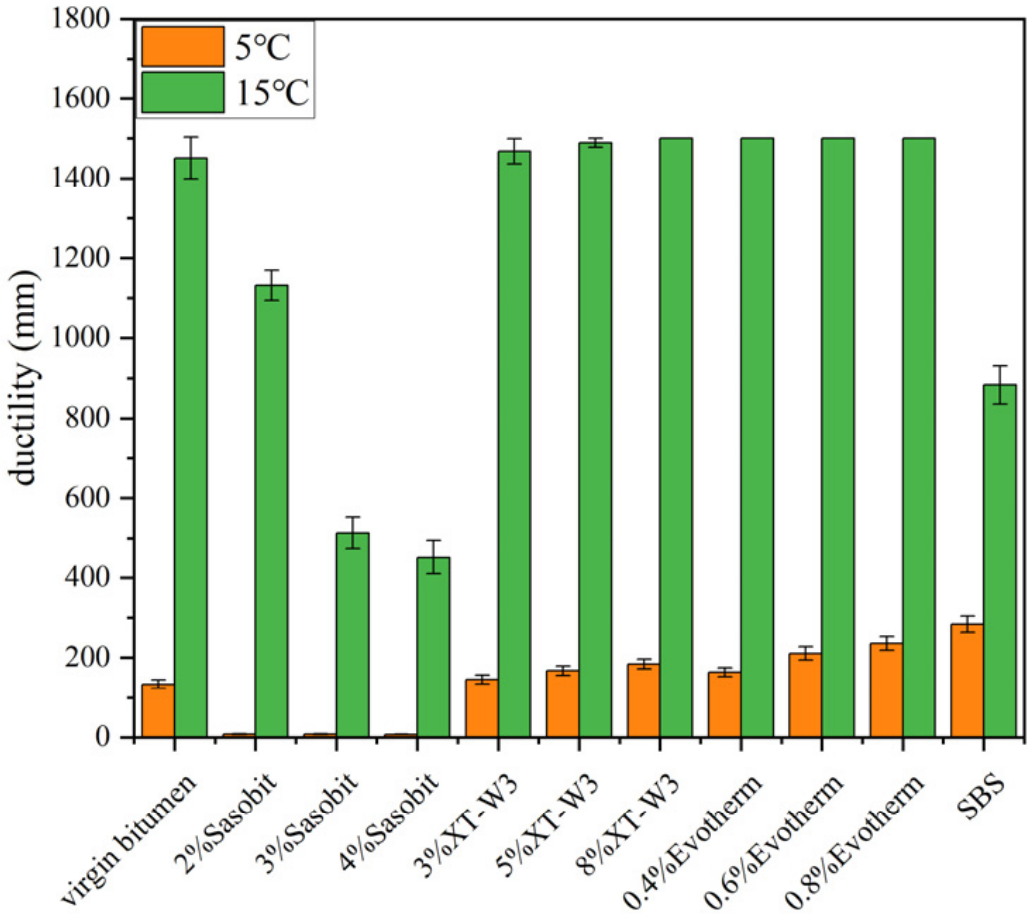


Figure 3. Ductility test results.

Figure 3 shows that after incorporating the Sasobit modifier, the modified bitumen exhibited brittle breakage at the test temperatures of 5 °C and 15 °C; the bitumen ductility was inversely proportional to the amount of modifier incorporated. The test results indicate that the Sasobit modifier deteriorates the low-temperature ductility of the bitumen and harms its low-temperature performance. After mixing with the XT-W3 and Evotherm modifiers, the bitumen ductility increased to some extent at different test temperatures, indicating that these two modifiers improved on the low-temperature ductility of bitumen. Meanwhile, when the test temperature was 15 °C, according to the amount of Sasobit modifier, the modified bitumen ductility value was first higher than the SBS-modified bitumen. With the increase in the amount of modified bitumen, and lower than the SBS-modified bitumen, this phenomenon indicates that to a certain extent the Sasobit-modified bitumen low-temperature ductility is better than the SBS-modified bitumen and XT-W3-modified and Evotherm-modified bitumen are better than the SBS-modified bitumen in low-temperature ductility.

3.1.4. Aging Test

The results are shown in Figure 4.

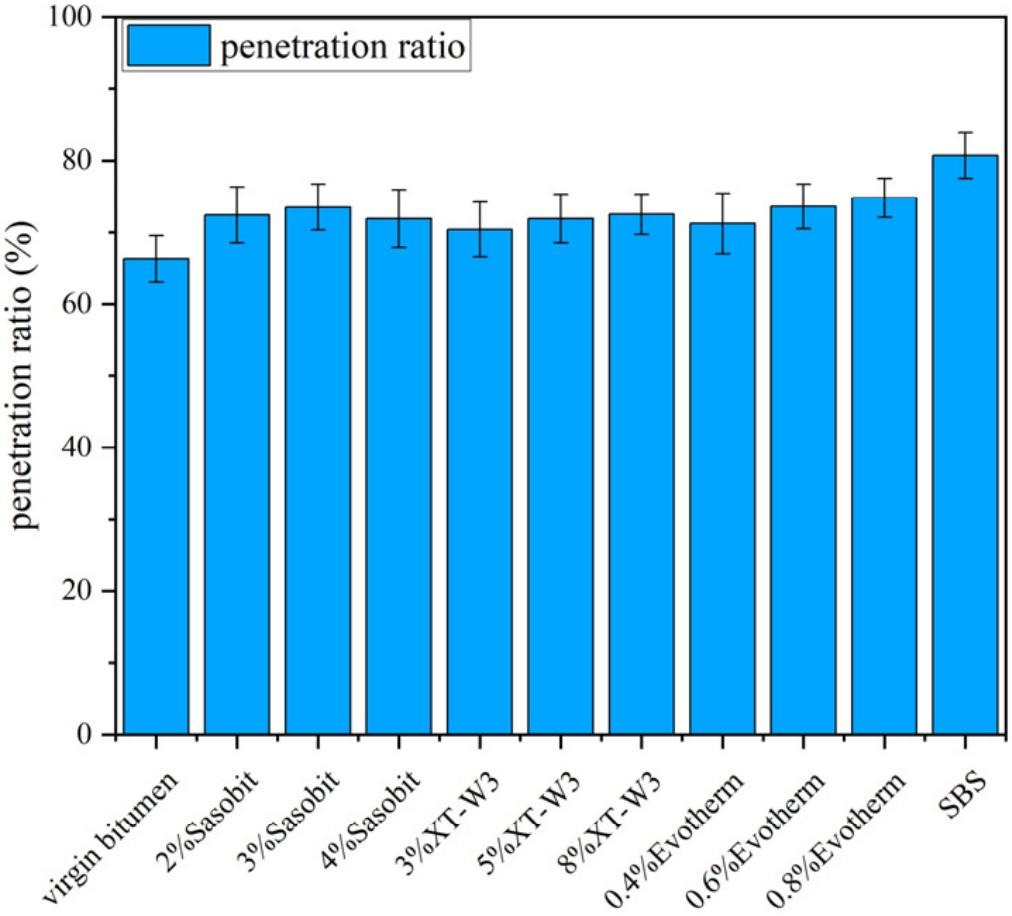


Figure 4. Penetration ratio of bitumen before and after aging.

Figure 4 shows that the penetration ratio of Sasobit-modified bitumen increased and then decreased with the increase in Sasobit dosing; however, the values were higher than that of the virgin bitumen, indicating that the Sasobit modifier can effectively improve the anti-aging performance of bitumen with optimal dosing. The penetration ratios of the XT-W3-modified and Evotherm-modified bitumens were higher than those of the virgin bitumen, indicating that in terms of aging resistance, the two modifiers showed certain advantages. However, the penetration ratio of SBS-modified bitumen is the largest among several bitumens after aging, which indicates that SBS-modified bitumen has the best anti-aging performance.

3.2. Results and Analysis of Superpave Evaluation Index of Modified Bitumen

3.2.1. Brookfield Rotational Viscosity Test

The results are shown in Figure 5.

Figure 5 shows that the Brookfield rotational viscosity of the Sasobit−modified, XT-W3−modified, and Evotherm−modified bitumens decreased compared to that of the virgin bitumen at the same test temperature, and all of them decreased with the increase in admixture. Compared with the viscosity of the virgin bitumen, the viscosities of the Sasobit−modified bitumen decreased by 21.4%, 28.5%, and 32.3%, respectively; those of XT-W3−modified bitumen decreased by 9.1%, 12.3%, and 13.7%, respectively; and those of Evotherm−modified bitumen decreased by 15.8%, 25.5%, and 30.0%, respectively. The test results show that incorporating modifiers can effectively reduce the high−temperature viscosity of virgin bitumen and improve its construction and ease. Three modifiers were compared to the Sasobit−modified bitumen to improve the viscosity of the most pronounced effect. According to the test results, SBS−modified bitumen has the largest rotational viscosity among several types of bitumen, indicating that it produces less defor-

mation under an external load, is more closely combined with bitumen, and shows stronger rutting resistance; however, its construction is also more challenging by comparison.

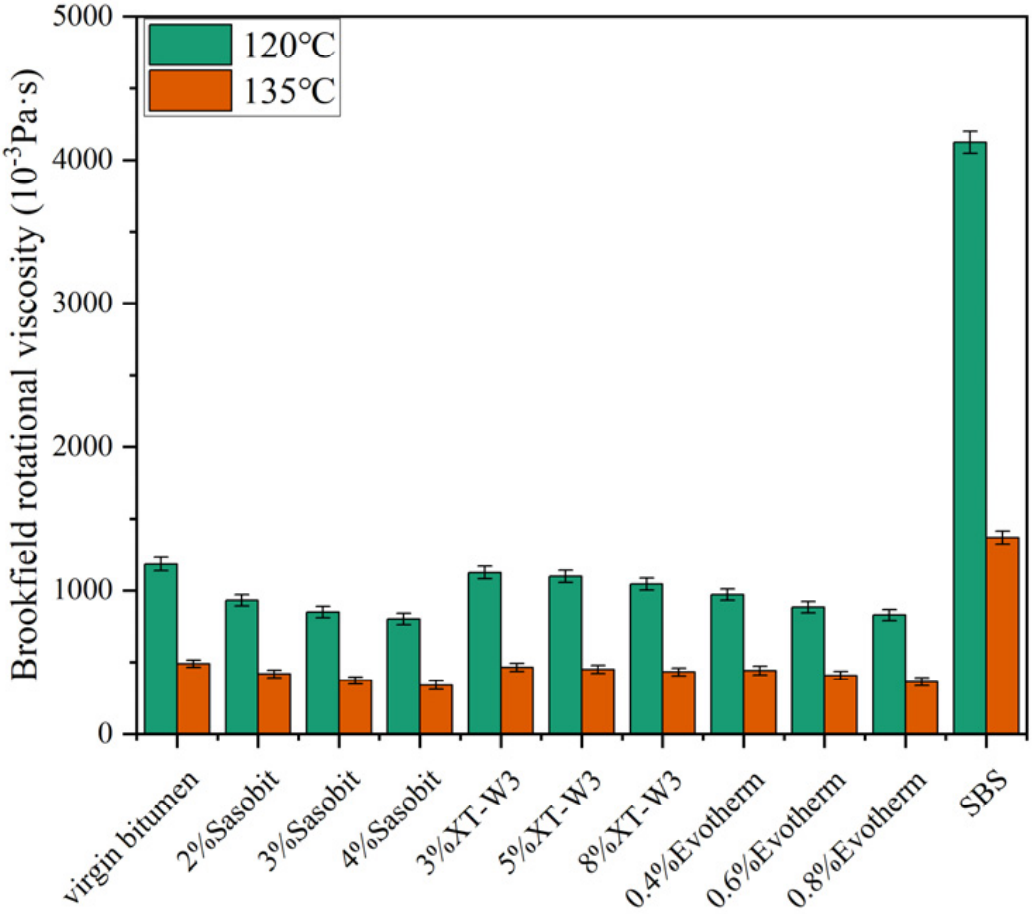


Figure 5. Results of the Brookfield rotational viscosity test.

3.2.2. Dynamic Shear Rheological Test

The results are shown in Figure 6.

Figure 6 shows that at the same temperature, the rutting factor G*/sinδ of the three modified bitumens is more improved than that of the virgin bitumen, which indicates that the elastic component in the bitumen increases after mixing with the modifier, improving the high-temperature rutting resistance of the bitumen. For the same bitumen, the rutting factor G*/sinδ tended to decrease as the temperature increased. This phenomenon indicates that the ability of the bitumen to resist deformation gradually decreases; therefore, the bitumen pavement is vulnerable to rutting in a high-temperature environment. Compared with the rutting resistance factor of the virgin bitumen at 64 °C, Sasobit-modified bitumen increased by 82.5%, 139.4%, and 212.6%; XT-W3-modified bitumen increased by 10.3%, 16.6%, and 34.7%; and Evotherm-modified bitumen increased by 24.3%, 38.4%, and 47.7%, respectively. The three modified bitumens could reduce the deformation of the bitumen binder under high-temperature conditions, thereby improving the rutting resistance of bitumen. At the same test temperature, the rutting resistance factor G*/sinδ of the Sasobit-modified bitumen was greater than that of the SBS-modified bitumen with the increase in admixture, indicating that the Sasobit-modified bitumen exhibited the optimum high-temperature stability among the three modified bitumens. This corresponds with the softening point test results.

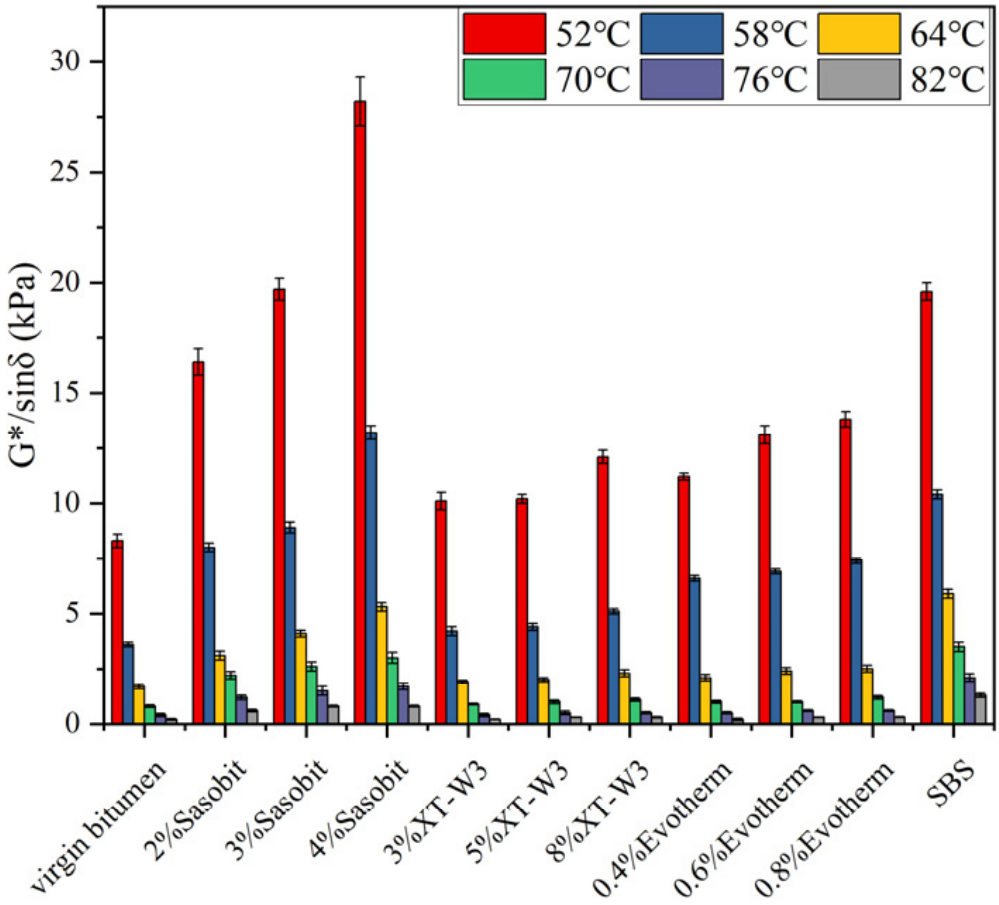


Figure 6. Results of the dynamic shear rheological test.

3.3. Results and Analysis of Modified Bitumen Mixture Test

3.3.1. Marshall Stability Test

The results are shown in Table 6.

Table 6. Results of the Marshall stability test.

Bitumen Mixture	MS (KN)	FL (mm)
Virgin Bitumen	13.52	2.34
3% Sasobit	16.72	2.25
5% XT-W3	14.26	2.31
0.6% Evotherm	15.86	3.15
SBS	14.73	2.10

Table 6 shows: ① The Marshall stability of the bitumen mixture with modifiers has different degrees of improvement compared to the virgin bitumen. Among the three warm-mix modified bitumen mixtures, compared to the Marshall stability of the virgin bitumen mixture, the Marshall stability of the Sasobit-modified bitumen mixture has the largest MS with an increase of 3.2 KN and the Evotherm and XT-W3-modified bitumen mixture increased by 2.34 KN and 0.74 KN, respectively, indicating that the warm-mix modifier improved the compressive capacity of bitumen, with Sasobit-modified bitumen mixture having the strongest compressive capacity. ② The flow values of the Sasobit-modified and XT-W3-modified bitumen mixtures are lower than those of the virgin bitumen mixture, indicating that the incorporation of Sasobit and XT-W3 modifiers enhanced the resistance to deformation of the bitumen mixture. However, the flow values became larger than those of the virgin bitumen mixture after incorporating the Evotherm modifier, indicating that the Evotherm modifier harms the resistance to deformation of the bitumen mixture but

meets the requirements of the corresponding technical specifications. ③ The Marshall stabilities of the Sasobit-modified and Evotherm-modified bitumen mixtures were higher than those of the SBS-modified bitumen mixture, but the flow value was higher than that of the SBS-modified bitumen mixture. The Marshall stability of the XT-W3-modified bitumen mixture was lower than that of the SBS-modified bitumen mixture, but the difference was insignificant. This indicates that the compressive performance of the Sasobit-modified and Evotherm-modified bitumen mixtures is stronger than that of the SBS-modified bitumen mixture; however, the resistance to deformation is lower than that of the SBS-modified bitumen mixture. This conclusion corresponds to the results of the needle penetration test of the bitumen.

3.3.2. High-Temperature Rutting Test

The test results are listed in Table 7.

Table 7. Results of the high-temperature rutting test.

Bitumen Mixture	DS/Time/mm	
	Testing Value	Technical Requirements
Virgin Bitumen	1204	≥1000
3% Sasobit	2870	
5% XT-W3	2294	
0.6% Evotherm	2571	
SBS	5012	

According to Table 7, the dynamic stability of the Sasobit-modified bitumen mixture improved by 138% compared to the virgin bitumen mixture, the XT-W3-modified bitumen mixture improved by 91%, and the Evotherm-modified bitumen mixture improved by 113%. This shows that incorporating modifiers can effectively improve the rutting resistance of bitumen mixtures, among which the Sasobit modifier exhibits the most significant improvement. The SBS-modified bitumen mixtures had better rutting resistance, as evidenced by the fact that the dynamic stability of the three modified bitumen mixtures was lower than that of the SBS-modified bitumen mixtures.

3.3.3. Water Stability Test

The results are shown in Tables 8 and 9.

Table 8. Results of the soak Marshall test.

Bitumen Mixture	Marshall Stability/KN		MS_0/%	Technical Requirements/%
	MS	48 h MS_1		
Virgin Bitumen	10.46	8.78	83.94	≥75
3% Sasobit	16.83	16.31	96.91	≥85
5% XT-W3	13.64	12.01	88.05	≥85
0.6% Evotherm	14.21	12.42	87.40	≥85
SBS	14.73	13.16	89.31	≥85

Table 9. Results of the freeze-thaw splitting test.

Bitumen Mixture	RT_1/MPa	RT_2/MPa	TSR/%	Technical Requirements/%
Virgin Bitumen	0.947	0.786	83.00	≥70
3% Sasobit	1.005	0.844	83.98	≥80
5% XT-W3	0.985	0.854	86.70	≥80
0.6% Evotherm	0.846	0.739	87.35	≥80
SBS	1.184	1.054	89.03	≥80

Tables 8 and 9 show that compared with the virgin bitumen mixture, the residual stability MS_0 and the splitting strength of the Sasobit-modified bitumen mixture, XT-W3 modified bitumen mixture, and Evotherm-modified bitumen mixture were significantly higher than TSR, and the residual stability MS_0 increased by 15.5%, 4.9%, and 4.1%, respectively, and the splitting strength increased by 1.2%, 4.5%, and 5.2%, respectively. This shows that the water stability of the bitumen mixtures improved after mixing with modifiers. Among them, the Sasobit-modified bitumen mixture has the highest residual stability but lower splitting strength than the TSR, probably because the Sasobit modifier contains waxy components, and its nature constantly changes under the low- and high-temperatures environment, which negatively affects the splitting tensile strength of the bitumen mixture, which is related to the incorporation of the Sasobit modifier to reduce the void ratio of the bitumen mixture. Thus, this phenomenon and the Sasobit modifier to reduce the mix void ratio improve the bitumen mixture resistance to water damage and the results of each other, which ultimately makes the Sasobit-modified bitumen mixture freeze-thaw split strength compared to the virgin bitumen mixture not particularly obvious.

3.3.4. Low-Temperature Crack Resistance Test

The results are listed in Table 10.

Table 10. Results of the low-temperature small beam bending test.

Bitumen Mixture	R_B/MPa	ε_B/με	S_B/MPa
Virgin Bitumen	11.85	3062.9	3868.88
3% Sasobit	13.11	2989.66	4385.11
5% XT-W3	12.42	3114.54	3987.75
0.6% Evotherm	10.84	3189.17	3399.00
SBS	13.48	3364.49	4006.55

Table 10 shows that the bending tensile strain of the virgin bitumen mixture is 3062.9 με and that of the Sasobit-modified bitumen mixture is reduced by 2.4%, while the bending tensile strain of the bitumen mixture is increased by 1.7% and 4.1% compared with the virgin bitumen mixture after mixing with the XT-W3 and Evotherm modifiers, respectively. This shows that the Sasobit modifier harms the low-temperature crack resistance of bitumen mixtures, and the XT-W3 and Evotherm modifiers can improve the low-temperature crack resistance of bitumen mixtures. However, the low-temperature cracking resistance of the SBS-modified bitumen was optimal compared to that of the SBS-modified bitumen. This result is consistent with the results of the ductility tests.

3.3.5. Fatigue Test

The test results are shown in Table 11.

As shown in Table 11, the K values of the Sasobit-modified, XT-W3-modified, and Evotherm-modified bitumen mixtures increased, and the n values decreased compared with the K and n values of the base bitumen mixtures. The K values of the Sasobit-modified, XT-W3-modified, and Evotherm-modified bitumen mixtures increased by 47.74%, 11.97%, and 25.92%, respectively, indicating that incorporating modifiers can effectively improve the fatigue resistance of bitumen mixtures. However, the K values of all three modified bitumen mixtures were lower than those of the SBS-modified bitumen mixtures, whereas the n values were higher than those of the SBS-modified bitumen mixtures. Therefore, the fatigue resistance of the SBS-modified bitumen mixture was optimal.

Table 11. Results of the fatigue test.

Bitumen Mixture	Stress Ratio	Stress Level/MPa	Logarithmic Value of Stress Level	Fatigue Life	Logarithmic Value of Fatigue Life	Regression Equation
Virgin Bitumen	0.3	1.77	0.2480	18,891	4.2763	K = 199,986 n = 3.9743 R^2 = 0.9914
	0.4	2.36	0.3729	7715	3.8873	
	0.5	2.95	0.4698	2694	3.4304	
	0.6	3.54	0.5490	1239	3.0931	
3% Sasobit	0.3	1.95	0.2900	23,879	4.3780	K = 295,461 n = 3.6818 R^2 = 0.9961
	0.4	2.60	0.4150	9541	3.9796	
	0.5	3.25	0.5119	3958	3.5975	
	0.6	3.90	0.5911	1864	3.2704	
5% XT-W3	0.3	1.83	0.2625	22,148	4.3453	K = 223,924 n = 3.7675 R^2 = 0.9971
	0.4	2.44	0.3874	8469	3.9278	
	0.5	3.05	0.4843	3189	3.5037	
	0.6	3.66	0.5635	1690	3.2279	
0.6% Evotherm	0.3	1.89	0.2765	23,116	4.3639	K = 251,826 n = 3.7081 R^2 = 0.9917
	0.4	2.52	0.4014	8046	3.9056	
	0.5	3.15	0.4983	4121	3.6150	
	0.6	3.78	0.5775	1649	3.2172	
SBS	0.3	2.02	0.3058	24,059	4.3813	K = 316,446 n = 3.5099 R^2 = 0.9834
	0.4	2.70	0.4307	11,896	4.0754	
	0.5	3.37	0.5276	4259	3.6293	
	0.6	4.04	0.6068	2231	3.3485	

3.3.6. Results and Analysis of Compaction Performance of Modified Bitumen Mixtures

Effect of Compaction Temperature

The test set four initial compaction temperatures, i.e., 100 °C, 120 °C, 140 °C, and 160 °C, and calculated the gross bulk density and compaction degree under different compaction temperatures. The test results are shown in Figures 7 and 8, respectively.

Figures 7 and 8 show that the gross bulk density and compaction of the bitumen mixture Marshall specimens increased linearly with an increase in compaction temperature. If the same compaction degree is achieved, the Sasobit-modified, XT-W3-modified, and Evotherm-modified bitumen mixtures require a temperature reduction of approximately 10–30 °C compared to the virgin bitumen mixture and the SBS-modified bitumen. This indicates that these modifiers can effectively reduce the mixing and construction temperatures of the bitumen mixture and save energy in line with the current energy-saving demands. Among them, the Sasobit-modified bitumen mixture exhibited the best performance.

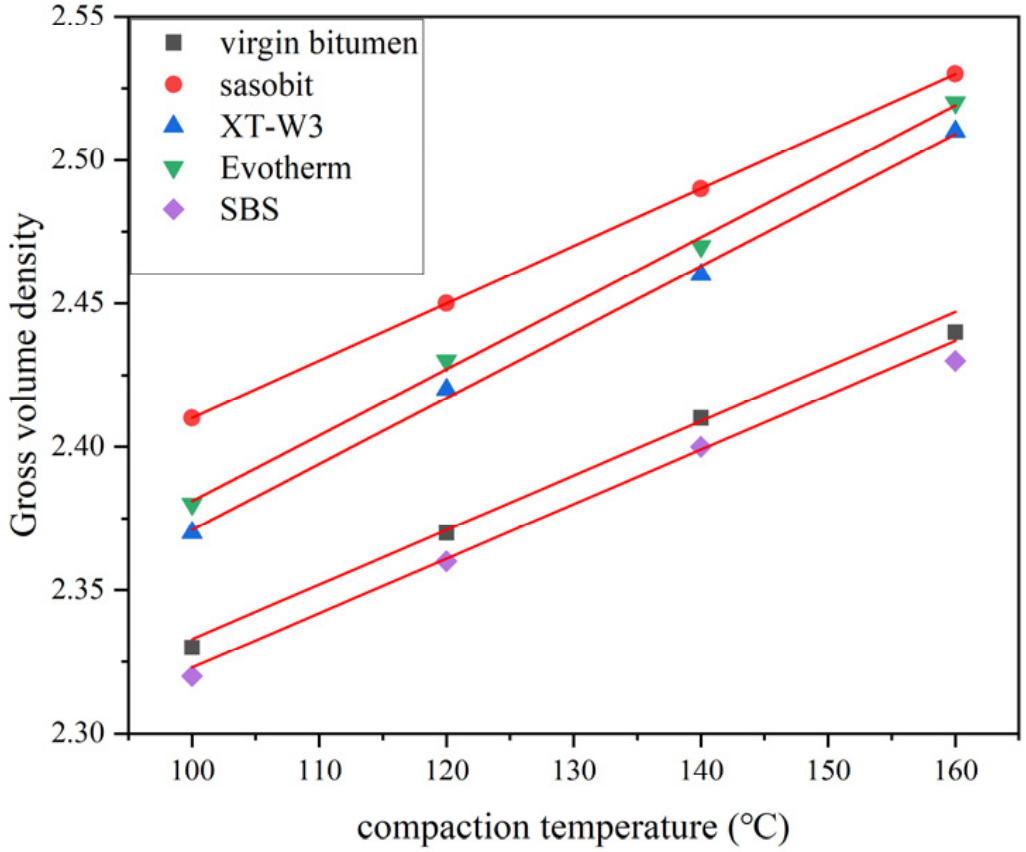


Figure 7. Relationship between gross bulk density and compaction temperature.

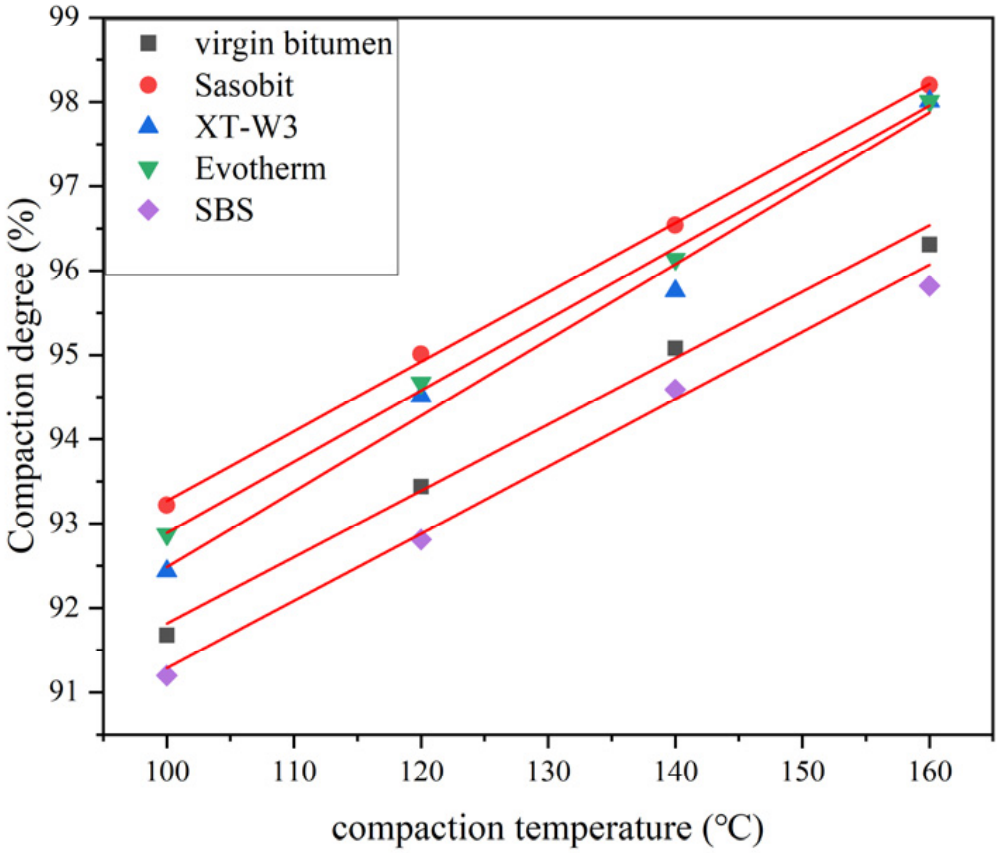


Figure 8. Relationship between compaction degree and compaction temperature.

Effect of the Number of Compactions

The initial compaction temperatures of 145 °C, 135 °C, 135 °C, 135 °C, and 160 °C were set for the virgin, Sasobit-modified, XT-W3-modified, and Evotherm-modified bitumen mixtures. The SBS-modified bitumen mixture was processed with five different compaction times, i.e., 50, 60, 75, 85, and 100, to calculate the gross bulk density and compaction degree. The test results are shown in Figures 9 and 10.

Figures 9 and 10 show that the gross bulk density and compaction number of bitumen mixture Marshall specimens increased exponentially with the increase in compaction number. The increase in gross bulk density and compaction leveled off with the increase in compaction number. If the same compaction degree is achieved, the number of compaction times required for the Sasobit-modified, XT-W3-modified, and Evotherm-modified bitumen mixtures is reduced compared to those for the virgin and SBS-modified bitumen mixtures. This indicates that the work required to achieve the same degree of compaction is much lower for the three modified bitumen mixtures than for the base bitumen mixtures, reducing energy consumption. Compared with the three warm mixtures, the gross bulk density and compaction of the Sasobit-modified bitumen mixtures were higher than those of the XT-W3-modified and Evotherm-modified bitumen mixtures at the same number of compaction times, indicating that the modification effect of the Sasobit modifier was better than that of the other two modifiers.

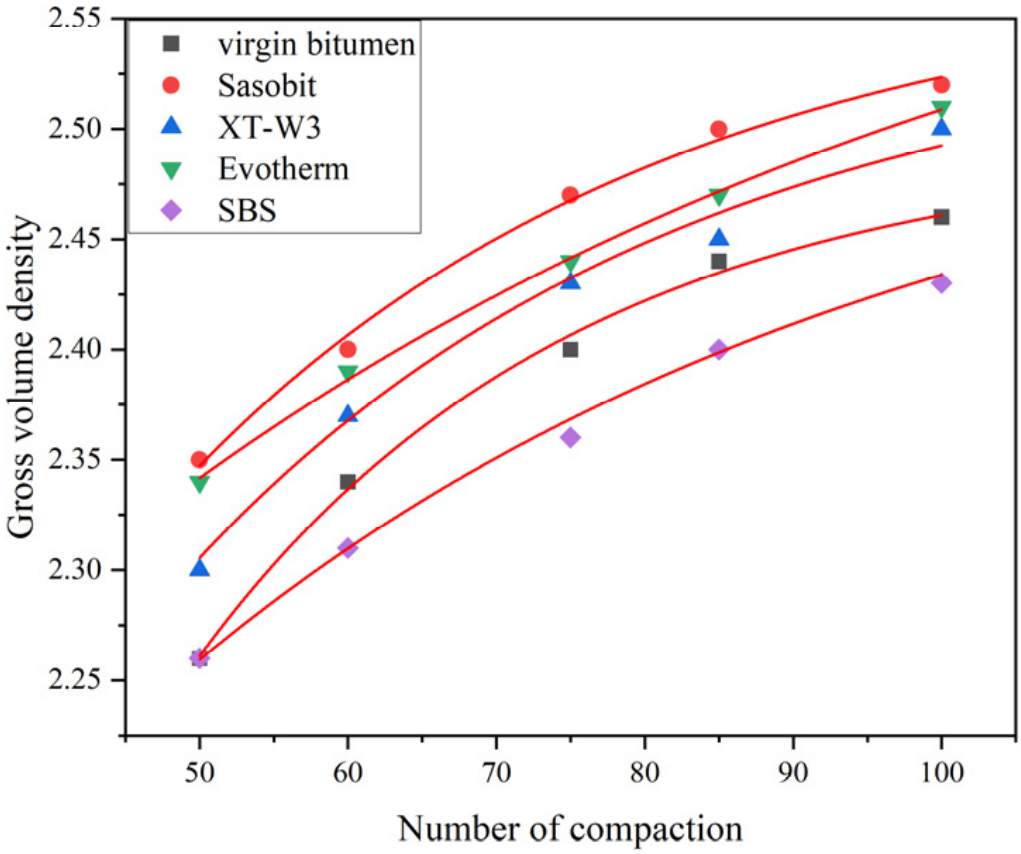


Figure 9. Relationship between gross volume density and number of compactions.

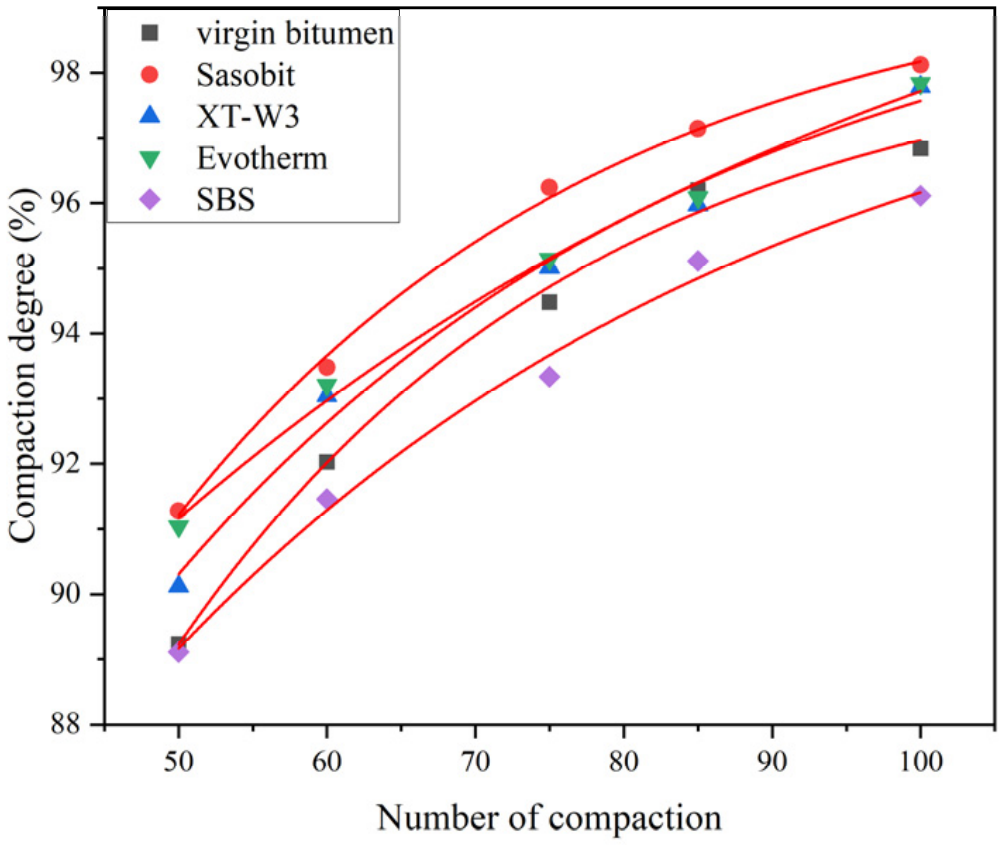


Figure 10. Relationship between compaction degree and number of compactions.

4. Conclusions

(1) Sasobit modifiers can enhance the resistance to deformation, high-temperature stability, and anti-aging properties of bitumen; however, they can reduce its low-temperature ductility. After mixing with XT-W3 and Evotherm modifiers, there is a reduction in its deformation resistance and high-temperature stability and improvement in its aging resistance and low-temperature ductility.

(2) Brookfield rotational viscosity tests indicated that incorporating Sasobit, XT-W3, and Evotherm modifiers can effectively reduce the high-temperature viscosity of bitumen and improve its construction and ease.

(3) The dynamic shear rheology test of Sasobit, XT-W3, and Evotherm-modified bitumen indicated that the elastic component in the bitumen increases after incorporating modifiers, improving the high-temperature rutting resistance of bitumen with Sasobit-modified bitumen having the strongest high-temperature rutting resistance.

(4) Incorporating Sasobit, XT-W3, and Evotherm modifiers into bitumen mixtures can enhance the compressive properties, high-temperature rutting resistance, water stability, and fatigue resistance of bitumen mixtures. However, Evotherm modifiers reduce the deformation resistance of bitumen mixtures. XT-W3 and Evotherm modifiers can effectively improve the low-temperature crack resistance, but the Sasobit modifier has a negative impact.

(5) The compaction performance of the modified bitumen mixtures demonstrated that the gross bulk density of the bitumen mixture Marshall specimens and the compaction degree increased linearly with the increase in compaction temperature and exponentially as a function of the increase in the number of compactions. If the same compaction degree is achieved, the number of compaction times and temperatures required for the Sasobit-modified, XT-W3-modified, and Evotherm-modified bitumen mixtures are reduced by about 10 °C–30 °C compared with the virgin and SBS-modified bitumen mixtures.

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