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Preparation and Modification Mechanism of Oil-Rich High-Viscosity, High-Elasticity (OR-HV-HE) Asphalt Modifier

Xin Jin [1,2,3,*], Wenbin Xu [1], Huaizhi Zhang [1], Ye Yang [1], Zhixing Pan [1], Weiyu He [1], Zhichen Wang [1,4,*], Yanhai Yang [1], Jiupeng Zhang [2] and Qingyue Zhou [3]

1 School of Transportation and Geomatics Engineering, Shenyang Jianzhu University, Shenyang 110168, China; yangyanhai168@126.com (Y.Y.)
2 School of Highway, Chang'an University, Xi'an 710064, China; zhjiupeng@163.com
3 Jiangsu Zengguang New Material Technology Co., Ltd., Nantong 226602, China; jszgkjgfyxgs@126.com
4 School of Computer Science and Engineering, Hunan University of Information Technology, Changsha 410151, China
* Correspondence: jinxinzzz@126.com (X.J.); zhichenwang@163.com (Z.W.)

Abstract: An asphalt modifier dry-process direct-cast oil-rich high-viscosity high-elasticity (OR-HV-HE) was developed to address the climatic characteristics of seasonal freezing zones. The chemical composition of the OR-HV-HE modifier was optimized through orthogonal testing. Advanced characterization techniques, including thermogravimetric analysis (TG), differential scanning calorimetry (DSC), scanning electron microscopy (SEM), and Fourier transform infrared spectroscopy (FTIR), were employed to systematically analyze the comprehensive thermal properties, microstructure, and chemical characteristics of the OR-HV-HE asphalt. Test results revealed a linear inverse relationship between the melt index and the OR-HV-HE asphalt grafting rate. The addition of the OR-HV-HE modifier led to the generation of new chemical bonds, and microscopic mechanism analysis illustrated the formation of a cross-linking network structure between the OR-HV-HE and asphalt, in which the cross-linking network structure could enhance the high and low-temperature performance of asphalt. Road performance verification results demonstrated that when compared with the traditional SBS-modified asphalt mixture, the OR-HV-HE modified asphalt mixture exhibited significantly superior road performance indices: the high-temperature dynamic stability was increased by 468% and the low-temperature damage strain was increased by 47.5%, and the residual stability reached 99%.

Keywords: OR-HV-HE modified asphalt; dry-process direct-cast; modification mechanism; microstructure; pavement performance

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1. Introduction

With the development of China's road engineering sector, traffic volume has continued to rise, and vehicle loads have become increasingly heavy, placing higher demands on the performance of pavement materials [1]. Especially in seasonal freezing zones, traditional pavement materials are highly susceptible to diseases such as low-temperature shrinkage cracking, freeze–thaw cracking, and transverse cracks, as shown in Figure 1, when facing complex conditions like low temperatures and heavy loads. These issues severely affect the service life of roads and driving safety. Due to their inherent performance limitations, traditional materials have increasingly failed to meet the actual requirements for pavement performance in seasonal freezing zones. As a common means to improve asphalt performance, modifiers have been widely applied in key fields such as highway construction, bridge paving, airport runway construction, and municipal road maintenance [2,3].

However, some existing modifiers still exhibit performance shortcomings, such as deteriorating compatibility with asphalt when faced with unique climatic conditions, complex geological conditions, and special traffic loads in seasonal freezing zones, making them poorly adapted to local climates. Foreign modifiers, moreover, not only have lengthy supply cycles but also come at high costs, thus restricting the autonomy and sustainable development of China's road engineering projects. Traditional SBS-modified asphalt has been widely applied due to its excellent high-temperature stability. However, in seasonally frozen regions, significant temperature fluctuations and temperature gradients caused by large temperature differences can lead to segregation of different components. As a multiphase system, SBS asphalt is prone to segregation if the compatibility between the SBS-modifier and the asphalt matrix is poor, the interfacial interaction forces are weak, or composition changes occur due to asphalt aging. This makes it difficult to meet the actual engineering requirements of seasonally frozen regions in road transportation [4]. Moreover, OR-HV-HE modifiers can enhance the viscoelastic properties of asphalt, which is expected to solve the thermal cracking problem of high modulus asphalt concrete (HMAC) and improve the overall performance of HMAC [5]. Against this backdrop, developing a new material capable of adapting to complex service conditions and overcoming the deficiencies of existing modifiers in seasonal freezing zones has become imperative.



(**a**) (**b**)

Figure 1. (**a**,**b**) Freeze–Thaw Swelling-Induced Cracking and Transverse Cracks in Expressway.

As a new type of road engineering material, high-viscosity high-elasticity has attracted significant attention in domestic and international road engineering fields [6,7]. Domestic research primarily focuses on using different modifiers to optimize asphalt performance. For example, Li Gaojun et al. prepared high-viscosity and high-elasticity modified asphalt by taking various high-viscosity and high-elasticity modifiers and other additives as raw materials and targeting SBS-modified asphalt, concluding that dry-process prepared high-viscosity and high-elasticity mixtures exhibit excellent pavement performance [8]. Foreign studies mainly concentrate on formula optimization and performance enhancement. In the 1980s, France pioneered the development of high-viscosity and high-elasticity modified asphalt, and its technical standards for high-viscosity asphalt and binding materials have gradually improved. High-viscosity asphalt prepared with additives has been rapidly and widely applied due to its excellent water damage resistance. Japan developed high-performance asphalt mixtures using high-viscosity modified asphalt and created the TPS modifier, defining high-viscosity and high-elasticity modified asphalt as binder with 60 °C dynamic viscosity > 20,000 Pa·s and 25 °C elastic recovery > 85% [9]. Litao Geng et al. synthesized a new self-reactive high-viscosity asphalt (HVA) using ethylene/methacrylic

acid copolymer (EMAA), polyketone (PK), low-density polypropylene (LDPP), and three additives [10]. Germany developed additives such as Sasobit and Lucopren 8000 based on polymer materials, improving road load resistance and durability and enhancing high-temperature rutting resistance [11]. However, current research on the stability of high-viscosity high-elasticity modifiers under complex working conditions remains insufficient, especially in their application in seasonally frozen regions [12,13]. Domestically, product quality varies widely, while imported modifiers suffer from high costs, long supply cycles, and limited technical services, increasing construction costs and restricting the autonomy and sustainable development of China's road engineering. Therefore, domestically produced OR-HV-HE have emerged. As a new material, their unique OR-HV-HE properties are expected to strongly support transportation infrastructure development in seasonally frozen regions [14].

Given the above background, this paper aims to explore and prepare the OR-HV-HE modifier thoroughly. By employing a dry-process direct-cast mixing method, in situ modification is achieved simultaneously during the mixing process, significantly enhancing asphalt performance while simplifying construction and reducing costs. Meanwhile, the study conducts extensive research on modification mechanisms, systematically optimizing the OR-HV-HE formula through orthogonal tests. Advanced characterization techniques—including TG, DSC, SEM, and FTIR—comprehensively analyze the modified asphalt's thermal properties, microstructure, and chemical characteristics. The fluidity and compatibility of internally mixed modified asphalt are assessed through melt index and grafting rate tests to investigate the chemical modification mechanism of the OR-HV-HE. Finally, pavement performance verification is performed using high-temperature dynamic stability tests, low-temperature beam bending tests, and immersion Marshall tests to evaluate the performance of OR-HV-HE modified asphalt mixtures thoroughly. This research offers higher-quality pavement material solutions for the road transportation industry.

2. Preparation and Formulation Optimization of OR-HV-HE Modifier

2.1. Raw Material Composition and Preparation Process of OR-HV-HE Modifier

In the preparation process of the OR-HV-HE modifier, high-density resin and thermoplastic elastomer materials, as the primary raw materials, play complementary roles (Figure 2). The high-density resin has a unique molecular structure with a high degree of compactness, which gives it excellent stability and strength. The thermoplastic elastomer material possesses outstanding elastic properties and deformation recovery ability, allowing it to quickly rebound to its initial state after being deformed by an external force. Incorporating thermoplastic elastomer material into the mixture can effectively absorb and disperse stress, reduce the generation and propagation of cracks, improve the crack resistance of the mixture, and ensure the road's structural integrity during long-term use [15].

The preparation process of the OR-HV-HE modifier takes thermoplastic elastomer SEBS, other thermoplastic elastomer materials, and high-density resin as raw materials. First, the raw materials undergo an oil-extending process at 130~150 °C, mixed for 10~15 min to achieve a semi-molten state, followed by treatment with high-speed mixing equipment at room temperature for 5 min. After the resulting mixture was subjected to 4 mm vibrating screening, melt blending and pelletization were performed using a twin-screw extruder, finally yielding the OR-HV-HE asphalt modifier. This process achieves uniform dispersion of modifier components and performance optimization by controlling raw material ratios and processing parameters. The OR-HV-HE modifier product is shown in Figure 3.

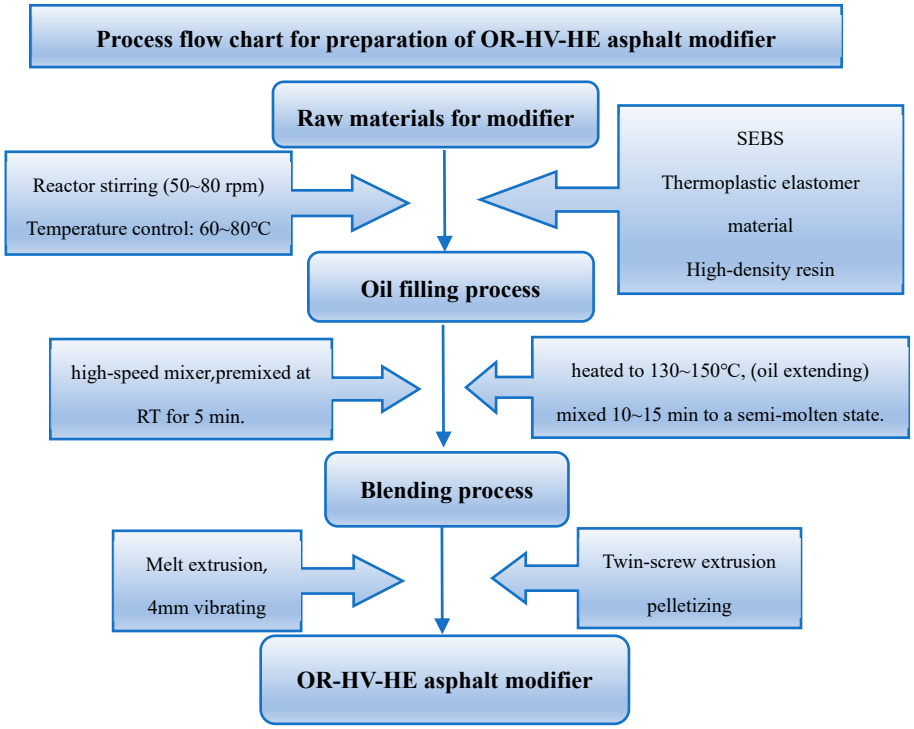


Figure 2. Process flow chart for the preparation of OR-HV-HE asphalt.



Figure 3. OR-HV-HE modifier.

2.2. Formulation Optimization of OR-HV-HE

Orthogonal Design

To explore the optimal formulation, this study adopted an orthogonal experimental design with five factors and four levels, constructing orthogonal Tables 1 and 2 $L_{16}(4^5)$ to systematically optimize the dosages of thermoplastic elastomer materials, modified resins, compatibilizers, and other additives [16]. Part of the experimental process is illustrated in Figure 4.

Table 1. Orthogonal Experimental Factors and Levels.

	Test Number	1	2	3	4
A	SEBS Thermoplastic Elastomer (%)	76	78	80	82
B	Modified resin (%)	8	9	12	14
C	Compatilizer (%)	0.7	0.9	1.2	1.5
D	Grafting agent (%)	0.1	0.2	0.3	0.4
E	catalytic converter (%)	1.1	1.2	1.3	1.5

Table 2. Five-factor four-level orthogonal experiment table.

Lab Number	A	B	C	D	E
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	1	2
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2



Figure 4. Marshall Test in Orthogonal Test Design.

To meet the critical needs of resisting low-temperature cracking and fatigue damage in seasonal frozen areas, based on 16 sets of experimental data, weighted calculations were performed on three core indicators of 16 modifier formulations: high-temperature performance, low-temperature performance, and fatigue life (with weights of 40%, 30%, and 30%, respectively). A complete signal-to-noise (SNR) ranking was obtained (sorted by comprehensive SNR from highest to lowest), as shown in Table 3. Accordingly, six OR-HV-HE formulations that meet the high-viscosity and high-elasticity performance requirements in seasonal frozen areas were screened out. The preferred OR-HV-HE modification agent formulations are shown in Table 4.

Table 3. Comprehensive signal-to-noise ratio (SNR) ranking.

Recipe Number	Comprehensive SNR (dB)	Softening Point (°C)	Brittle Point (°C)	Fatigue Life (Cycles)
13	51.23	87	−34	20,000
12	50.15	85	−32	19,500
14	50.02	88	−33	19,000
3	49.58	85	−32	18,500
7	49.26	92	−31	18,800
10	48.92	82	−31	18,500
15	48.56	84	−31	17,800
2	47.89	90	−30	17,500
8	47.50	83	−30	17,000
4	46.52	78	−35	16,000
11	45.15	80	−29	16,500
5	44.78	76	−27	15,500
6	43.21	75	−28	15,000
16	43.68	78	−28	14,500
9	42.54	72	−26	14,000
1	40.12	70	−25	12,000

Table 4. Optimized OR-HV-HE Modified Asphalt Formulations.

Optimized OR-HV-HE Modified Asphalt Formulations	Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 4	Sample No. 5	Sample No. 6
SEBS Thermoplastic Elastomer (%)	82	80	82	76	78	80
Modified resin (%)	8	14	9	12	12	9
Compatilizer (%)	1.5	0.9	1.2	1.2	1.5	1.5
Grafting agent (%)	0.2	0.1	0.1	0.3	0.1	0.3
catalytic converter (%)	1.3	1.3	1.5	1.3	1.2	1.1
The remaining additives (%)	7	4.7	6.2	9.2	7.2	8.1

3. Chemical Analysis of Modified Asphalt and the Mechanism of Action of OR-HV-HE Modifier

3.1. Study on the Performance of Asphalt with OR-HV-HE Modifier

The grafting rate reflects the chemical bonding strength between the OR-HV-HE modifier and asphalt, directly related to the material's low-temperature cracking and fatigue resistance. The melt index and grafting rate of OR-HV-HE modified asphalt were analyzed.

3.1.1. Grafting Rate

In this experiment, the samples were first vacuum-treated in a vacuum desiccator at 160 °C for 3 h, The measured wavenumber range is from 1450 to 1600 cm^{-1}. They were tableted using a plate vulcanizer and finally tested with the SYD-0673M portable asphalt infrared spectrometer produced by Shanghai Changji Geological Instrument Co., Ltd., Shanghai, China. The grafting rate was calculated using the relative grafting rate calculation Formula (1). In Formula (1), R_1 represents the intensity ratio of the characteristic peak to the internal standard peak before modification, R_2 represents the intensity ratio of the characteristic peak to the internal standard peak after modification, and G_r represents the relative grafting rate (%). The test data are shown in Figure 5.

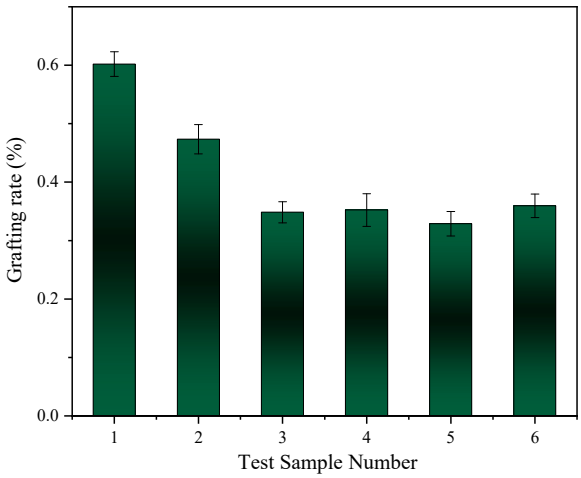


Figure 5. Grafting Rate Test Results.

The grafting rate reflects the chemical bonding strength between the OR-HV-HE modifier and asphalt, directly related to the material's low-temperature cracking and fatigue resistance [17]. A high grafting rate indicates that the OR-HV-HE modifier has good interfacial compatibility and can fully exert its high-viscosity and high-elastic properties, effectively preventing the formation of low-temperature cracks and prolonging the fatigue life.

$$G_r = \frac{R_2 - R_1}{R_1} \times 100\% \quad (1)$$

3.1.2. Melt Index

The SMT-3001 MFR Melt Flow Rate Tester, produced by Yangzhou Saisi Testing Equipment Co., Ltd., Yangzhou, China, was used in this test. Three sample segments (each approximately 10 mm long) were taken and weighed, and the melt index was calculated.

The melting index can represent the flow characteristics of highly viscous, highly elastic modified asphalt in the melting state [18]. By determining the melting index, the dispersion of the OR-HV-HE modifier in the asphalt can be determined. In this experiment, six modified bitumens with different ratios were tested to provide data support for the study of OR-HV-HE formulation and the study of OR-HV-HE modification mechanism, the results of which are shown in Figure 6.

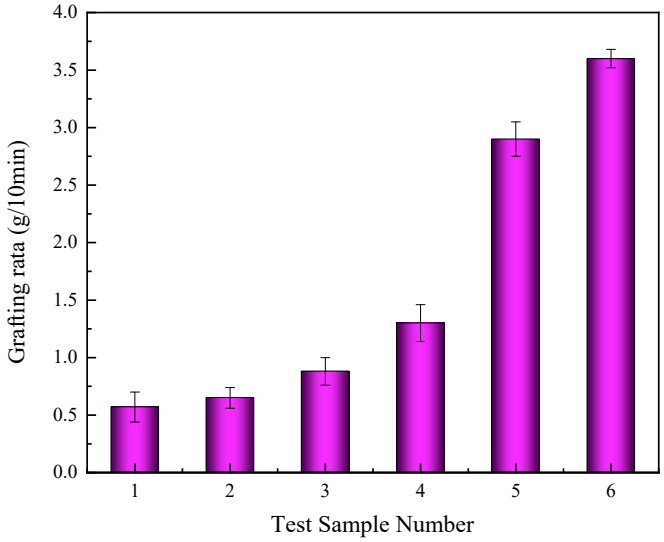


Figure 6. Melt Index Test Results.

The results show that the relationship between grafting rate and melt index test data is linear and inverse. This phenomenon can be attributed to the OR-HV-HE's molecular structure and reaction mechanism. OR-HV-HE modifiers in the reaction process, and the formation and fluidity of the branching chain on the molecular chain interact with each other. Increased grafting rates mean that more polar groups are introduced into the molecular chain of OR-HV-HE modifiers. The addition of polar functional groups improves the compatibility of OR-HV-HE modifiers with asphalt. A more stable interface transition zone is formed in the OR-HV-HE modified asphalt mixture. This structure enhances the adhesion of OR-HV-HE modifiers to the surface of asphalt, asphalt, and asphalt. Interfacial stripping due to resistance to moisture osmosis [19]. The decrease in the melt index indicates that the OR-HV-HE molecular chain is less active. Dispersion of OR-HV-HEs in asphalt from "Free movement" to "cross-linking structure". This structural feature effectively improves the adhesion of asphalt to aggregate surfaces and reduces the impact of water damage on roads [20].

3.2. Analysis of the Modification Mechanism of OR-HV-HE Modifier

Based on the overall comprehensive performance, the No. 5 OR-HV-HE modifier is optimal. This chapter takes Sample No. 5 OR-HV-HE modifier as an example to explore the modification mechanism of the OR-HV-HE modifier in depth.

3.2.1. FTIR

The study was tested using the 4300 Handheld FTIR instrument produced by Agilent Technology, Santa Clara, CA, USA. With a test range of 400~4000 cm^{-1}, the position, shape, and strength of the asphalt absorption peaks were analyzed by comparing FTIR maps of matrix asphalt, OR-HV-HE modifier, and modified asphalt. A precise mechanism of chemical modification, whether to produce new functional groups or for original functional groups to disappear or move. The FTIR map of matrix bitumen, OR-HV-HE modifier, and OR-HV-HE modified bitumen is shown in Figure 7.

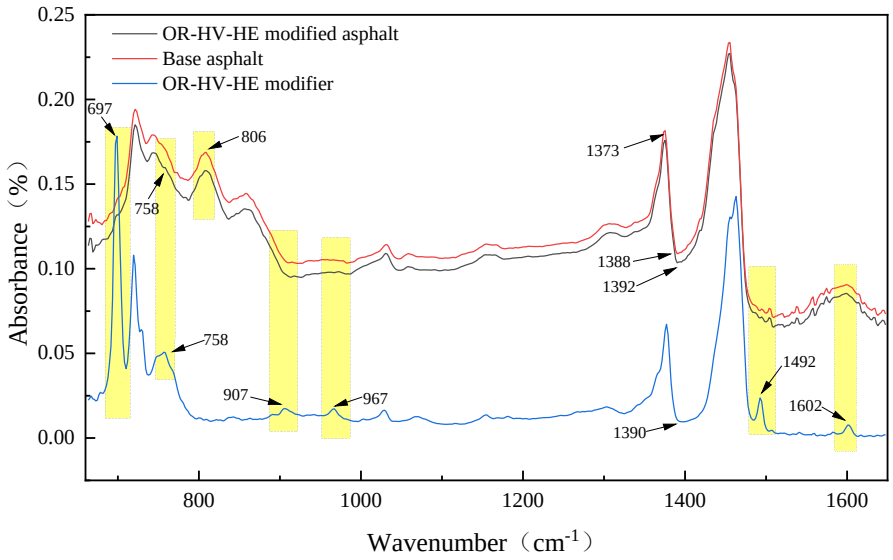


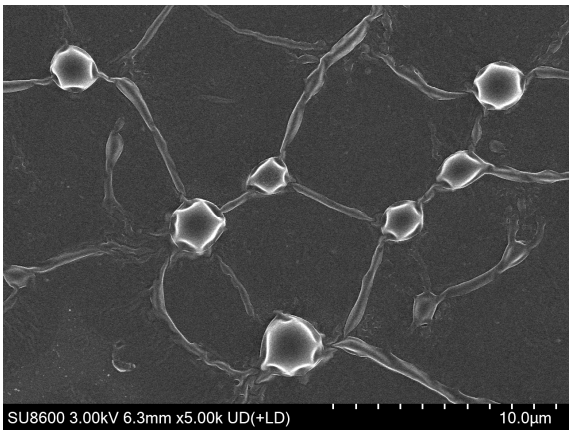
Figure 7. FTIR spectrum.

Figure 7 shows prominent absorption peaks between the base and modified asphalt at 806 cm^{-1} and 1373 cm^{-1}. The absorption peak at 1373 cm^{-1} is dominated by the symmetric bending vibration of the methyl group (-CH_3) of alkanes in the base asphalt, while the one at 806 cm^{-1} is attributed to the out-of-plane bending vibration of C-H in the aromatic ring. By comparing the FTIR spectra of the base asphalt, the OR-HV-HE modifier, and

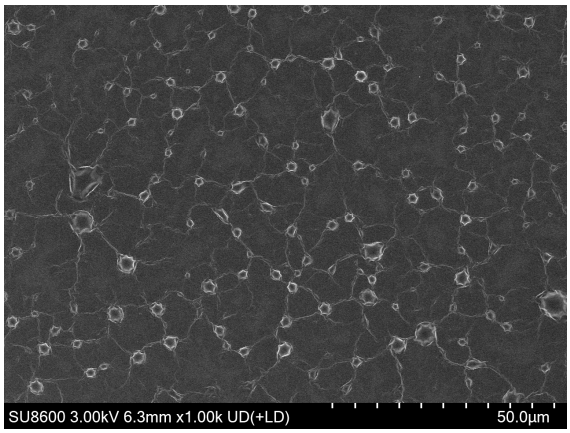
the OR-HV-HE modified asphalt, the firm absorption peaks of the OR-HV-HE modifier at 758 cm^{-1} (out-of-plane bending vibration of ortho-substituted benzene rings), 1602 cm^{-1} (characteristic of the skeletal stretching vibration of aromatic rings, i.e., stretching vibration of aromatic C-C), and the characteristic peak of the benzene ring at 1492 cm^{-1} (in-plane bending vibration of C-H bonds in aromatic rings) do not appear in the FTIR image of the base asphalt. These characteristic peaks of the OR-HV-HE modifier significantly disappear in the OR-HV-HE modified asphalt, indicating a chemical reaction between the OR-HV-HE modifier and the asphalt. The change in the characteristic peak at 758 cm^{-1} (out-of-plane bending vibration peak of C-H in mono-substituted benzene rings) of the OR-HV-HE modified asphalt further verifies that the OR-HV-HE modifier reacts with the asphalt to form new chemical functional groups, and confirms that a free-radical copolymerization reaction occurs between the OR-HV-HE modifier and the asphalt components, generating cross-linked structural units containing benzene-ring side groups [21]. The FTIR analysis reveals the mechanism of chemical modification from the perspective of the evolution of functional groups, indicating that the OR-HV-HE modifier has the effect of chemical modification. Subsequent SEM experiments will further corroborate this modification mechanism from the perspective of micro-morphology.

3.2.2. SEM

This study used the Japanese production of Hitachi SU8600 type SEM (SEM) (Hitachi, Tokyo, Japan) for testing and an accelerated voltage selection of 10 kV. Figure 8 shows an SEM image of OR-HV-HE modified bitumen.



(**a**) SEM micrograph at 2500× magnification



(**b**) SEM micrograph at 500× magnification

Figure 8. SEM Image.

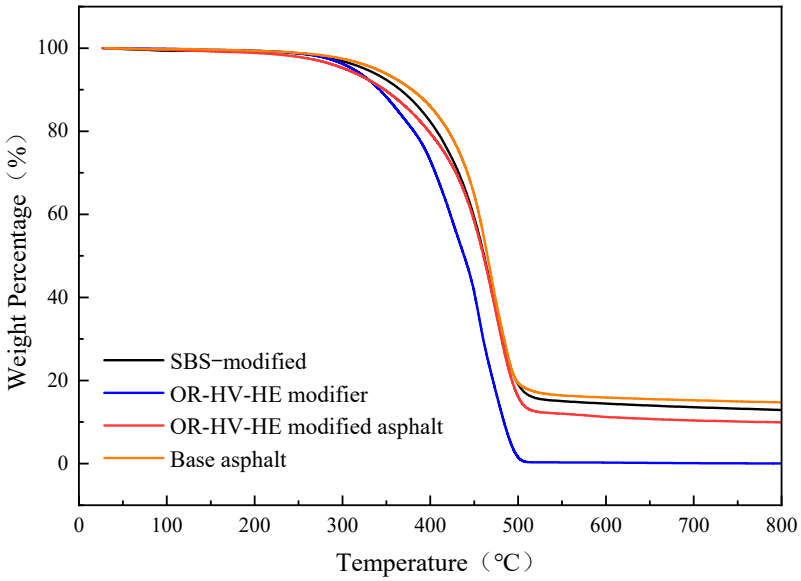
The SEM images presented in Figure 8 disclose the microscopic interaction characteristics between the OR-HV-HE modifier and asphalt in the OR-HV-HE modified asphalt. The images illustrate that the OR-HV-HE modifier is uniformly embedded within the asphalt matrix, forming an orderly entangled polymer network with dense cross-linking nodes among asphalt molecules. This structure takes OR-HV-HE modifier molecules as core nodes, establishing spatial network connections with polar groups (such as asphaltenes and resins) in asphalt components via radial molecular chains. The orderliness and compactness of this polymer network indicate that physical interactions occur between the OR-HV-HE modifier and asphalt components, generating cross-linked products with long-chain structures.

In the special climatic environment of seasonal frozen regions, temperature fluctuations subject asphalt materials to more complex freeze–thaw cycles and stress–strain changes. The polymer network formed by the interaction between OR-HV-HE and asphalt endows the asphalt material with enhanced cohesive strength and flexibility. On one hand, this network restricts the excessive shrinkage of asphalt molecules at low temperatures, effectively suppressing the initiation and propagation of cracks and improving frost resistance, which is macroscopically manifested as enhanced low-temperature crack resistance and water damage resistance of asphalt mixtures. On the other hand, when temperatures rise, the network structure constrains the excessive flow of asphalt molecules, maintaining material stability and preventing deformation caused by high-temperature softening, which is macroscopically reflected as improved high-temperature performance of asphalt mixtures [22]. The chemical structure changes revealed by FTIR and the microscopic morphological evolution observed by SEM mutually corroborate each other. The former confirms the formation of cross-linked units containing benzene rings at the molecular vibration level, while the latter visually presents the polymer network skeleton structure from a morphological perspective. Together, they indicate that free-radical copolymerization reactions not only construct cross-linked units with benzene ring side chains as nodes in the chemical structure but also facilitate the transformation of the asphalt system from a dispersed phase to a continuous network at the macroscopic scale, providing a structural basis for improving the high-viscosity and high-elasticity properties of the material.

3.3. Analysis of High and Low-Temperature Performance

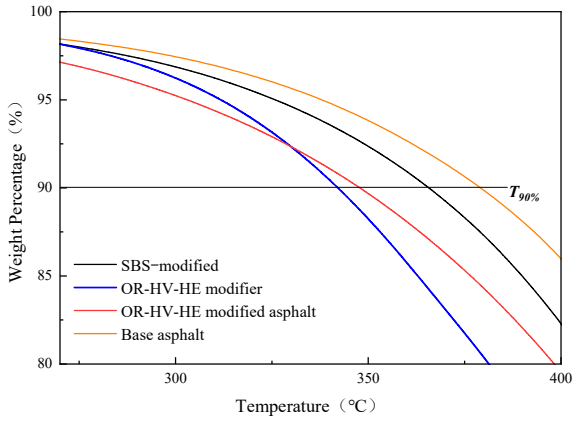
3.3.1. TG

In this study, the HITACHI STA200 TG analyzer manufactured by Hitachi, Ltd. of Tokyo, Japan, was used for testing. Using nitrogen as the protective gas, the OR-HV-HE modifier, OR-HV-HE modified asphalt, SBS-modified asphalt, and base asphalt were, respectively, heated from 0 °C to 800 °C at a rate of 20 °C/min, and the TG and DTA curves were recorded. The test results are shown in Figure 9.

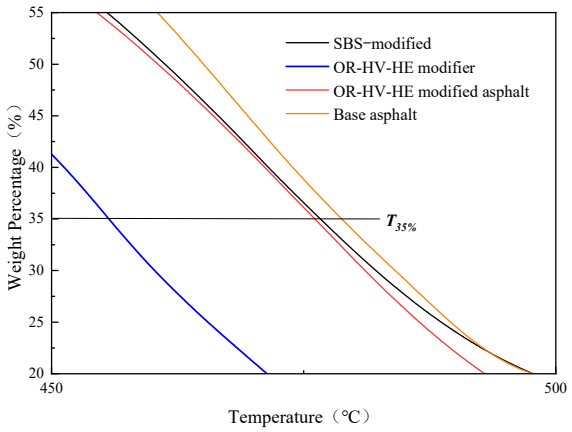


(**a**) Overall view of the TG curve

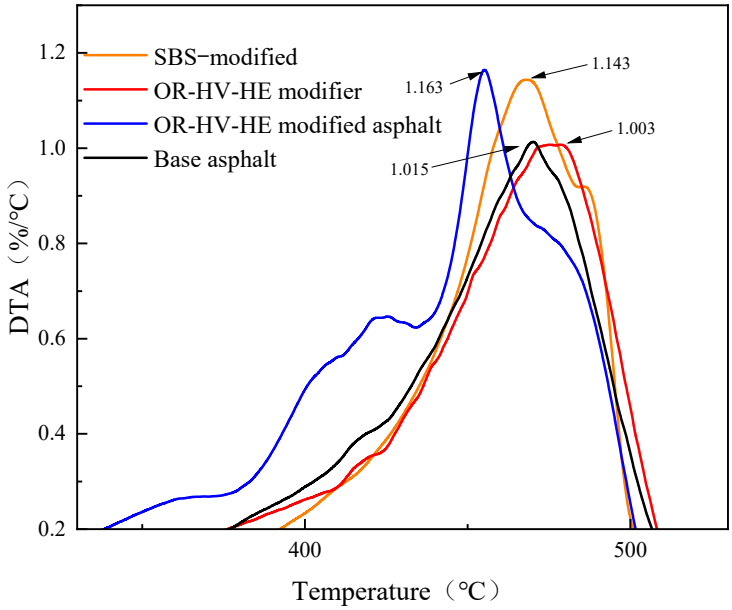
Figure 9. *Cont.*



(**b**) Partial enlarged view of $T_{90\%}$



(**c**) Partial enlarged view of $T_{35\%}$



(**d**) The partial curve diagram of DTA

Figure 9. TG and DTA.

As shown by the TG curves in Figure 8, the temperature order at $T_{90\%}$ (90% weight loss temperature) and $T_{35\%}$ (35% weight loss temperature) is consistent: OR-HV-HE modifier < modified asphalt < SBS-modified asphalt < base asphalt. This indicates that the OR-HV-HE modifier exhibits significant weight loss in lower temperature ranges, with its initial decomposition temperature and maximum weight loss rate temperature being lower than other components.

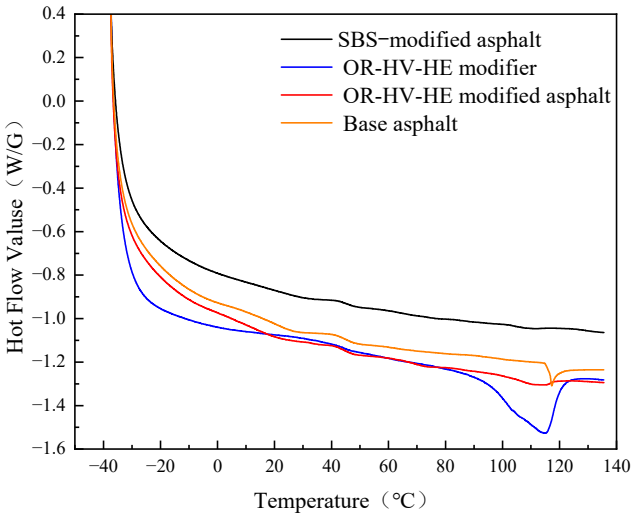
This phenomenon is primarily attributed to the introduction of a large number of low-molecular-weight flexible oil fractions and polar functional group-containing polymer segments in the OR-HV-HE modifier design, which endow these components with high thermal activity and make them prone to chain scission or volatilization reactions under thermo-oxidative conditions, resulting in the OR-HV-HE modifier's overall low thermal stability. On the other hand, it demonstrates the synergistic effect between the OR-HV-HE modifier and asphalt. Although the OR-HV-HE modifier has relatively low thermal stability, it forms a more stable chemical structure with asphalt components through intermolecular forces, significantly increasing the thermal decomposition temperature of the modified asphalt compared to the OR-HV-HE modifier alone. This suggests that the introduction of the OR-HV-HE modifier does not solely rely on its high heat resistance but

somewhat improves the system's flexibility and energy dissipation capacity by altering the molecular structure of asphalt and delaying molecular chain scission, thereby forming an enhanced network with excellent viscoelastic response characteristics in the asphalt system. This enables the modified asphalt to exhibit more balanced thermal stability in actual service, avoiding the defect of easy decomposition at high temperatures in base asphalt and overcoming the potential performance degradation of SBS-modified asphalt caused by insufficient additive compatibility [23]. The OR-HV-HE modified asphalt system forms a spatial network structure with OR-HV-HE modifier molecules as nodes through chemical cross-linking reactions between the OR-HV-HE modifier and base asphalt, significantly enhancing the overall thermal stability of the material. This enables it to exhibit excellent resistance to permanent deformation in high-temperature service environments while demonstrating good crack resistance under low-temperature conditions. The results of thermogravimetric analysis (TGA) validate the effectiveness and pertinence of this OR-HV-HE modifier in improving the comprehensive performance of asphalt systems.

DTA can reflect the rate of weight percentage change in the test materials during temperature variation [24]. As shown in the DTA curve, within the temperature range of 400 °C~500 °C, the peak order of the four materials is OR-HV-HE modifier > base asphalt > SBS-modified asphalt > OR-HV-HE modified asphalt. The weight percentage change in the OR-HV-HE modified asphalt is relatively gentle between approximately 400 °C and 500 °C, indicating excellent high-temperature stability. This phenomenon is mainly attributed to the cross-linked network structure between the asphalt and the OR-HV-HE modifier. These network structures increase the intermolecular cohesive force, making relative movement between molecules difficult, which is macroscopically manifested as enhanced high-temperature stability. This provides an important basis for analyzing the relationship between the properties and chemical structure of the OR-HV-HE modifier.

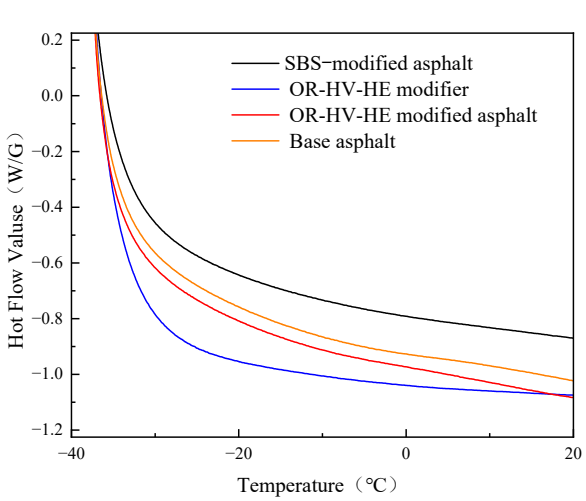
3.3.2. DSC

This study tested the Q2000 DSC instrument manufactured by TA Instruments, New Castle, DE, USA, for testing. The test was conducted by first cooling from room temperature (30 °C) to −45 °C at a rate of 10 °C/min, followed by heating to 140 °C. The DSC curves of the OR-HV-HE asphalt, base asphalt, OR-HV-HE modifier, and SBS-modified asphalt obtained from the test are shown in Figure 10.

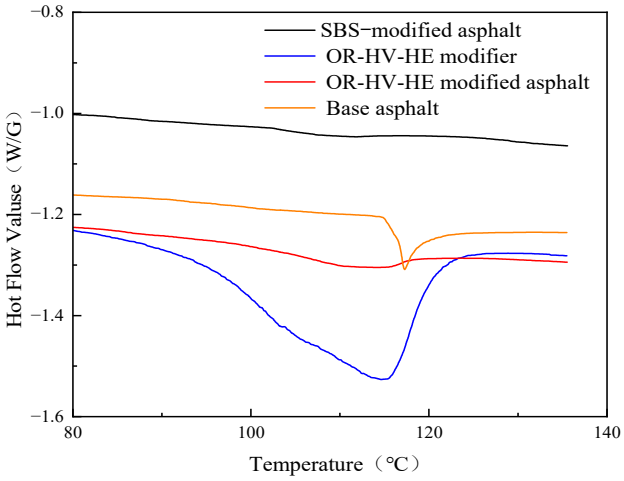


(**a**) Overall view of the DSC curve

Figure 10. *Cont.*



(**b**) Enlarged view of DSC −40 °C~20 °C



(**c**) Enlarged view of DSC 80 °C~140 °C

Figure 10. DSC Curve.

Table 5. Test Data Table of ΔH and T_g.

	Thermal Enthalpy Value (ΔH) (J/g)	**Glass Transition Temperature (T_g) (°C)**
SBS-modified asphalt	1.5	−12
OR-HV-HE modified asphalt	1.2	−15
Base asphalt	0.79	−8

As shown in Figure 10b, the modified asphalt exhibits no prominent exothermic or endothermic peaks at −40 °C~20 °C, indicating that the modified asphalt is stable under low-temperature conditions. Adding OR-HV-HE modifiers does not negatively affect the low-temperature performance of the base asphalt, and performance degradation is not prone to occur. In Figure 10c, within the temperature range of 80 °C~140 °C, the base asphalt's exothermic peak decreases significantly with OR-HV-HE modifiers. The OR-HV-HE modified asphalt shows small fluctuations in heat flow values within the temperature range of 80 °C~140 °C, macroscopically demonstrating good thermal stability. The DSC test results show a relatively prominent endothermic peak in the temperature interval of 20~60 °C. The peak area corresponding to this endothermic peak is the enthalpy value (ΔH), which reflects the thermodynamic process of asphalt transitioning from a viscoelastic state to a viscoplastic state. The smaller the peak area and the flatter the curve, the better the thermal stability of the material [25]. The test results are shown in Table 4. The ΔH of the OR-HV-HE modified asphalt is higher than that of the base asphalt. While enhancing the elastic recovery ability, this network structure can also reduce water penetration by restricting molecular movement, inhibiting asphalt-aggregate interface debonding, improving low-temperature cracking resistance and water damage resistance, thereby enhancing water stability [26]. The water immersion Marshall test will validate the pavement performance verification stage. Due to the cross-linking of the triblock copolymer structure in SBS-modified asphalt, which restricts molecular movement, its ΔH is higher than that of the OR-HV-HE modified asphalt [27].

The T_g is a crucial indicator for evaluating asphalt materials' performance and molecular motion characteristics in low-temperature environments. It reflects the temperature range where the material transitions from a glassy state to a rubbery state, directly influencing the low-temperature cracking resistance and overall mechanical behavior of asphalt [28]. The T_g of the OR-HV-HE modified asphalt, base asphalt, OR-HV-HE modifier,

and SBS-modified asphalt are shown in Table 5. The OR-HV-HE modified asphalt has a lower T_g than the base and SBS-modified asphalt. This indicates that adding the OR-HV-HE modifier introduces polar functional groups and generates a chemical cross-linking network. The long-chain alkane side groups enhance the flexibility of the system. The flexible molecular chains reduce the intermolecular forces of the material, thereby improving the low-temperature cracking resistance of the base asphalt. The modified asphalt maintains a relatively high elastic modulus at low temperatures (with ΔH between that of the base asphalt and SBS-modified asphalt) and has a lower T_g. This chemical cross-linking network structure endows the material with a higher elongation at break, effectively inhibits low-temperature embrittlement and cracking, and improves the freeze–thaw cycle resistance. This is consistent with the results of the previous FTIR and SEM tests. The analysis results consistently show that the cross-linking network generated between the OR-HV-HE modifier and asphalt can effectively enhance the intermolecular forces and improve the high–low-temperature performance of the asphalt.

4. Pavement Performance Verification of OR-HV-HE Modified Asphalt Mixture

4.1. Gradation Design

In road engineering, the road performance of the asphalt mixture plays a decisive role in the service quality and life of the road. Based on the characteristics of heavy-load traffic and temperature coupling in the frozen quarter, this study selected an AC-20 densely graded asphalt mixture that can effectively balance high-temperature stability and low-temperature crack resistance as the carrier [29]. The grading curve used is shown in Figure 5, which strictly follows the control point pass rate requirements, with a critical screen hole of 4.75 mm passing rate of 38.2% and a 0.075 mm passing rate of 4.8%. The gradation curve is shown in Figure 11.

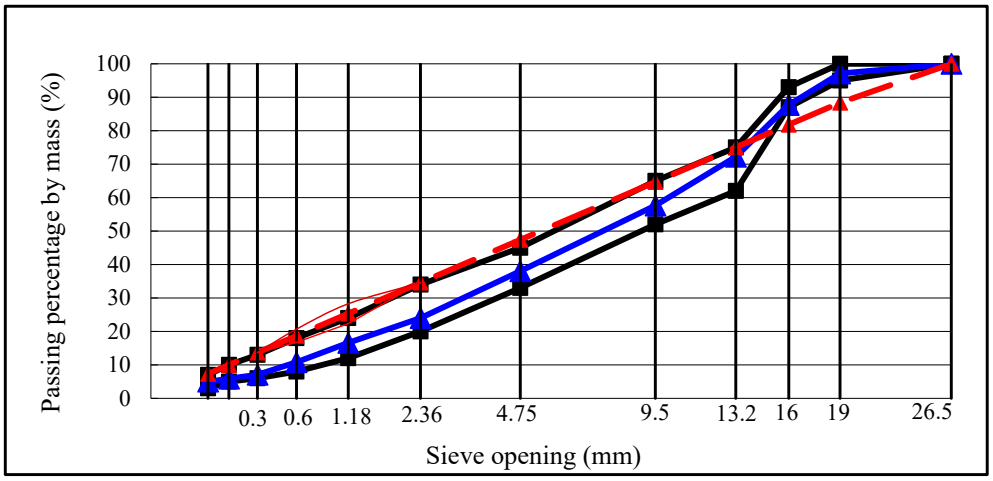


Figure 11. AC-20 grading curve.

To validate the pavement performance of OR-HV-HE modified asphalt mixtures under the climatic conditions of seasonally frozen regions, this study employed Type I-D SBS-modified asphalt with AC-20 gradation as the control group to provide a reference for evaluating the pavement performance of OR-HV-HE modified asphalt. The technical indices of the SBS-modified asphalt are presented in Table 6.

Table 6. Performance Indicators for SBS-modified asphalt.

Types of Indicators	Parameter Values
Optimum asphalt content	4.8%
Air void content	4.0%
Void ratio of mineral aggregates	14.5%
Voids filled with asphalt	73.0%
Stability	11.5 kN
Flow value	28 (0.1 mm)

4.2. High-Temperature Dynamic Stability Test

The high-temperature dynamic stability test is used to determine the number of passes under a wheel pressure of 0.7 MPa required to produce 1 mm deformation on a standard rutting plate (300 mm × 300 mm × 50 mm) for OR-HV-HE modified asphalt mixtures at 60 °C, with the test wheel reciprocating at a speed of 42 passes per minute. Seven samples were set in this test, with the SBS-modified asphalt mixture selected as the control group. The other six test groups used OR-HV-HE modified asphalt mixtures with different formulations to investigate the differences in the impact of various formulations on the high-temperature performance of OR-HV-HE modified asphalt mixtures. Test data are shown in Figure 12.

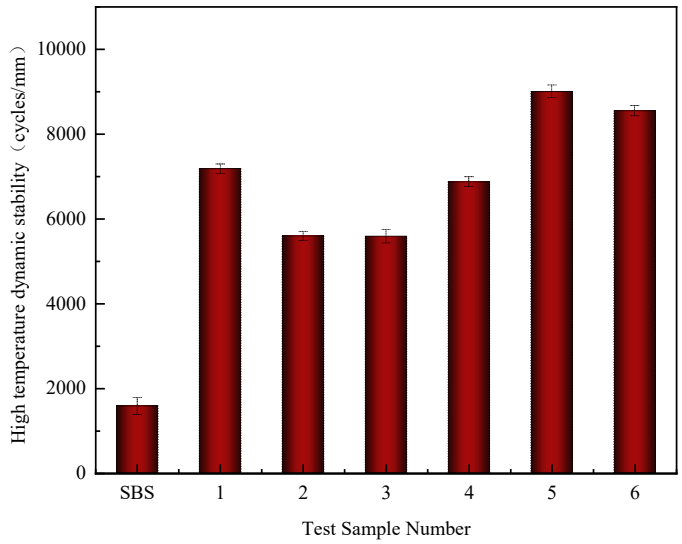


Figure 12. High-Temperature Rutting Test Data.

As shown in Figure 12, the dynamic stability of the six OR-HV-HE modified asphalt mixtures all reaches 5000~10,000 cycles. According to China's Technical Code for Design of Highway Asphalt Pavements (JTGD50-2017) [30,31], the dynamic stability requirement for rutting tests in seasonally frozen regions should be ≥5000 cycles/mm. The OR-HV-HE modified asphalt mixtures meet the actual demand standards for seasonally frozen areas. The optimal formulation achieves 9692 cycles, which is 4692 cycles higher than the national standard, and the overall high-temperature performance is significantly better than that of the SBS-modified asphalt mixture. The addition of the OR-HV-HE modifier can react chemically with asphalt to generate a chemical cross-linking network structure. This network structure can restrain the flow of asphalt molecules, maintain material stability, avoid deformation caused by high temperatures, and improve the high-temperature performance of OR-HV-HE modified asphalt mixtures. The test results are consistent with the previous FTIR, SEM, and TG test analyses, indicating that adding the OR-HV-HE modifier can significantly improve the high-temperature stability of asphalt.

4.3. Low-Temperature Bending Test

In this test, the specimen size used is (250 mm × 30 mm × 35 mm). The specimens are pre-cooled in a −40 °C low-temperature environment for 30 min and then subjected to a bending test at a 1 mm/min loading rate. The low-temperature bending test enables the evaluation of the OR-HV-HE modifier's bending stability and crack resistance at low temperatures, thereby providing a scientific basis for its application in seasonally frozen regions. Low-temperature bending tests were conducted on high-viscosity and high-elasticity asphalt mixtures prepared with different OR-HV-HE modifier formulations, and maximum bending failure strain data were obtained. The test results are shown in Figure 13.

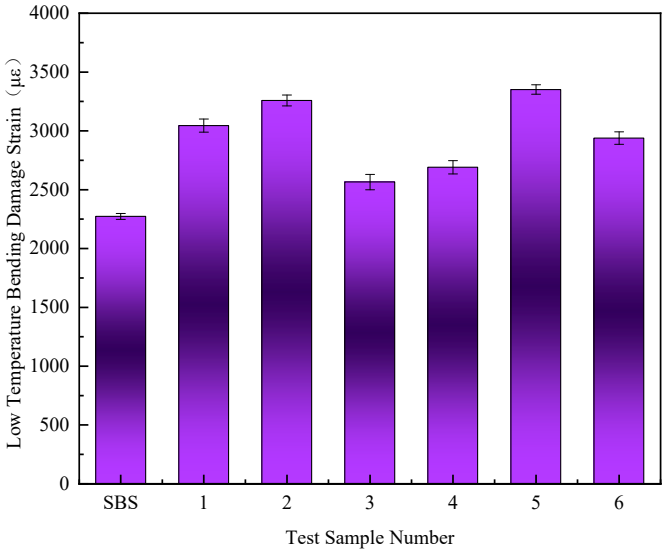


Figure 13. Low-Temperature Bending Test Data.

As shown in Figure 13, the bending failure strains of OR-HV-HE modified asphalt mixtures No. 1 to No. 6 all range between approximately 2500 and 3500 με, significantly higher than those of the SBS-modified asphalt mixture. According to China's Technical Code for Design of Highway Asphalt Pavements (JTGD50-2017) [30], the bending failure strain in seasonally frozen regions should be ≥3000 με. The OR-HV-HE modifier reacts with asphalt to generate a chemical cross-linking network structure. This cross-linking network can restrict the excessive shrinkage of asphalt molecules at low temperatures, effectively inhibiting the initiation and propagation of cracks and enhancing freeze resistance, as well as the low-temperature and water damage resistance of OR-HV-HE modified asphalt mixtures. The pavement performance test results are consistent with the previous FTIR, SEM, and DSC analyses. The low-temperature bending test demonstrates that the OR-HV-HE modifier exhibits certain performance advantages at low temperatures, with overall low-temperature performance superior to that of SBS-modified asphalt. This advantage becomes more pronounced due to the unique climatic conditions in seasonally frozen regions.

4.4. Immersion Marshall Test

In this test, the immersion time was set to 48 h, with the temperature at 60 °C ± 1 °C. In the low-temperature stage, the specimens were subjected to a 24 h freezing treatment at −30 °C. Water stability tests were conducted on six types of OR-HV-HE modified asphalt mixtures prepared with different OR-HV-HE modifier formulations, and the residual stability was calculated using Formula (2). In Formula (2), MS_0 represents the residual stability (%), MS_1 represents the Marshall stability (kg) of the specimen after 48 h of

immersion, MS_2 represents the Marshall stability (kg) of the unimmersed specimen, and the test data are shown in Figure 14.

$$MS_0 = \frac{MS_1}{MS_2} \times 100\% \quad (2)$$

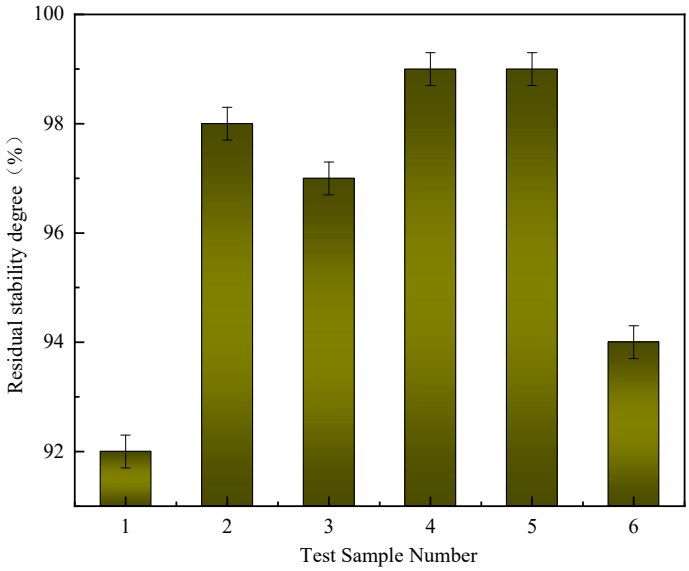


Figure 14. Immersion Marshall Test data.

The residual stability of OR-HV-HE modified asphalt mixtures No. 1 to No. 6 has reached 92%~99%. According to China's Technical Code for Design of Highway Asphalt Pavements (JTGD50-2017) [30], the immersion residual stability shall be ≥85%. The overall water stability has fully met the requirements of national standards. The residual stability of the optimal formulation has been elevated to 99%, representing a 14% improvement over the national standard. The network structure of the OR-HV-HE modified asphalt not only enhances the elastic recovery ability but also reduces water penetration by restricting molecular movement, inhibits asphalt-aggregate interface debonding, and improves low-temperature cracking resistance and water damage resistance, thereby enhancing water stability. This validates the previous T_g test results. The pavement performance results are consistent with the FTIR and SEM test analyses, demonstrating that the OR-HV-HE modified asphalt mixture can adapt to the frequent freeze–thaw cycles in seasonally frozen regions and exhibit certain performance advantages.

In summary, the pavement performance tests revealed that the overall high-temperature, low-temperature, and water stability performances of the six formulated OR-HV-HE modifiers all met the technical specifications for high-viscosity and high-elasticity modified asphalt mixtures (dry process) in seasonally frozen regions [30]. They were significantly superior to those of traditional SBS-asphalt mixtures. However, the asphalt mixtures prepared with OR-HV-HE Modifiers 1 and 6 showed poor water stability, and the grafting rates of the formulations with OR-HV-HE Modifiers 1 and 2 were low, indicating a weak degree of chemical reaction. A comparative analysis showed that the asphalt mixture prepared with OR-HV-HE Modifier 5 exhibited more comprehensive pavement performance; therefore, OR-HV-HE Modifier 5 is recommended as the optimal formulation.

5. Conclusions

This study optimizes the formula of the OR-HV-HE modifier based on the climatic requirements of the seasonally frozen area through a five-level, four-factor orthogonal

experimental design, which achieves the purpose of modification upon mixing by adopting the dry direct injection process.

(1) The melt index and grafting rate data present a linear inverse relationship, indicating that the modified asphalt forms a chemical long-chain structure. This structural feature can enhance the adhesion ability between the asphalt and the aggregate surface and reduce the impact of water damage on the road.
(2) FTIR and SEM test results indicate that physical interactions and chemical cross-linking occur between the OR-HV-HE modifier and asphalt: FTIR confirms the formation of new chemical bonds with benzene ring functional groups, while SEM shows that the modifier forms an orderly entangled polymer network within the asphalt matrix. The results demonstrate that the modification process of OR-HV-HE modified asphalt is a synergistic effect of physical interactions and chemical cross-linking. The polymer network structure formed by this synergistic effect provides a structural basis for improving the high-viscosity and high-elasticity properties of asphalt materials.
(3) The modification mechanism study confirms that the OR-HV-HE modifier and asphalt form a cross-linked network through a free radical copolymerization reaction to delay the breaking of molecular chains.
(4) The TG and DTA test results show that the thermal decomposition rate of the modified asphalt is lower than that of the base asphalt and SBS-modified asphalt, and the molecular chains are stable at high temperatures. DSC indicates that its T_g is as low as -15 °C, which is 7 °C lower than that of the base asphalt, and the flexibility of molecular chains is enhanced at low temperatures, verifying that the OR-HV-HE asphalt modifier can improve the high and low temperature stability of asphalt.
(5) Pavement performance tests show that the high-temperature dynamic stability of the OR-HV-HE modified asphalt mixture reaches 5000~10,000 cycles, with the optimal formulation achieving a 7421-cycle improvement over SBS-modified asphalt. The low-temperature bending failure strain of the optimal formulation reaches 3351με, representing a 351με increase compared to the national standard. The immersion residual stability ranges from 92% to 99%, with the optimal formulation exceeding the national standard by 14%. All indicators comply with the Highway Asphalt Pavement Design Code (JTG D50-2017), and the overall performance is superior to that of SBS-modified asphalt mixtures.

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