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Study on the Factors Affecting the Compatibility of Modified Asphalt and Its Performance Analysis

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Abstract. Due to the “high traffic volume, heavy axle load, and severe channeling” in modern road traffic, the use of modified asphalt in road engineering can improve the high-temperature stability, low-temperature crack resistance, and anti-aging performance of the road surface, thereby extending the service life of the road and significantly enhancing the quality of road engineering. This paper studies the factors affecting the compatibility of modified asphalt and its performance analysis. Through experimental analysis, the study investigates the impact of the type of SBS modifier, the selection of base asphalt, the use of additives, and the preparation process on the performance of modified asphalt. The research finds that the type, dosage, and kind of base asphalt of the SBS modifier, as well as the use of additives, significantly affect the compatibility and performance of modified asphalt. Appropriately increasing the dosage of stabilizers and compatibilizers can improve the compatibility and performance of modified asphalt, but it needs to be controlled within a certain range to avoid excessively affecting the performance.

Keywords. Modified asphalt, SBS modifier, compatibility, performance analysis, additives, preparation process

1. Introduction

In modern road construction, asphalt is the primary material for pavement, and its performance directly impacts the functionality and lifespan of the road. As traffic volume increases and heavy-load traffic becomes more widespread, the performance requirements for asphalt have also become more demanding. Traditional petroleum-based asphalt, while having good road performance, suffers from shortcomings in high-temperature stability, low-temperature crack resistance, and aging resistance. To enhance the performance of asphalt pavements, modified asphalt has emerged as an indispensable material in road engineering.

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Modified asphalt is produced by adding a certain proportion of modifiers, such as rubber, resins, or polymer compounds, to the base asphalt. These modifiers improve the inherent properties of the asphalt, imparting better high-temperature stability, low-temperature crack resistance, and aging resistance. Among these, SBS (Styrene-Butadiene-Styrene) is a commonly used thermoplastic rubber modifier, which has been widely applied in the production of modified asphalt due to its excellent modification effect [1-4].

However, the preparation of modified asphalt is a complex process that involves multiple interacting factors, including the type and amount of modifier, the selection of base asphalt, the use of additives, and the preparation process itself [5-7]. These factors not only affect the compatibility of modified asphalt but also directly influence its performance. Compatibility refers to the uniformity and stability of the mixture formed when the modifier is blended with the base asphalt, making it a crucial indicator for evaluating the performance of modified asphalt. Poor compatibility can lead to issues such as segregation and sedimentation during storage and use, which can adversely affect its performance [8,9].

Wang [10] summarized six evaluation methods for the compatibility of polymer modifiers with petroleum asphalt, including qualitative observation, rheological methods, thermodynamic methods, chemical analysis, morphological mapping, and numerical simulation. He analyzed and compared the advantages and disadvantages of these methods and their applicability. Specifically, the phase separation coefficient based on rheological methods is sensitive to differences between polymer modifiers and petroleum asphalt, making it suitable for evaluating their compatibility [11-13]. Additionally, molecular dynamics simulation methods, by setting appropriate polymer models and temperature parameters, simulate and explain the interaction mechanisms between polymer modifiers and petroleum asphalt from a microscopic perspective, providing new insights for the study of modified asphalt compatibility [14,15]. These studies have not only deepened the understanding of the factors affecting the compatibility of modified asphalt but also provided a scientific basis for the preparation and application of modified asphalt, helping to improve its storage stability and road performance.

Therefore, in-depth research on the factors influencing the compatibility of modified asphalt and its performance analysis is of great significance for optimizing the preparation process of modified asphalt and improving its performance. This article presents an experimental study that systematically analyzes the effects of SBS modifier types, base asphalt selection, additive usage, and preparation processes on the compatibility and performance of modified asphalt, aiming to provide scientific evidence for the preparation and application of modified asphalt, and offering references for the rational selection and use of modified asphalt in road engineering.

2. Raw Materials and Preparation Process

2.1 SBS Modifier

The types of SBS modifiers include star-shaped, linear, and a combination of star and linear types. Their grades are 161B, 6302, 791H, and 1331, with specific performance parameters listed in Table 1.

Differential scanning calorimetry (DSC) tests were conducted on different types of SBS modifiers. The experimental parameters were set to a heating rate of 10 K/min, with a temperature scanning range from room temperature to 500°C. The heat flow vs. temperature curve is shown in Figure 1.

Table 1. Basic performance parameters of SBS modifiers

Modifier	YH801	YH802	LG411	T161B
Molecular Weight ($x10^4$)	/	/	/	22-26
S/B	30/70	30/70	31/69	30/70
Volatile Content/%	0. 5	≤0. 5	≤0. 5	≤1. 0
Ash Content/%	0. 2	0. 3	≤0. 5	/
300% Elongation Strength/MPa	2	/	/	/
Tensile Strength /MPa	14	32	/	/
Elongation at Break/%	650	800	/	/
Shore A Hardness/A	82	≥79	84	82
Melt Flow Rate / (g/10min)	0. 2	≤1. 0	/	/

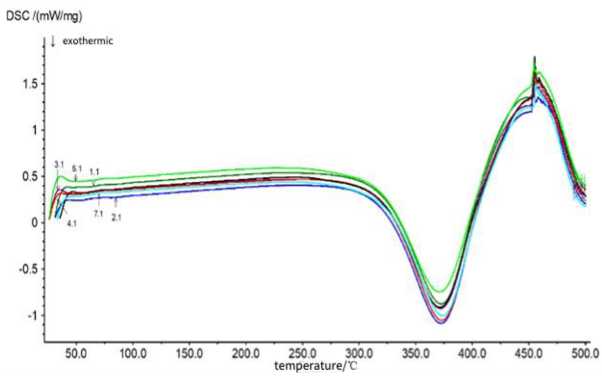


Figure 1. DSC test results and analysis

As shown in Figure 1, the SBS modifiers exhibit similar heat flow variation trends. In the temperature range of room temperature to 320°C, the DSC curve shows a slight, slow, and steady upward trend. This phenomenon is attributed to baseline drift, and the resulting heat change is negligible, meaning SBS does not undergo decomposition, oxidation, or other chemical reactions in this temperature range.

In the temperature range of 320°C to 400°C, the SBS modifier undergoes an exothermic reaction, with the most intense reaction occurring around 372°C, releasing heat enthalpy of approximately 450 J/g - 500 J/g. This is followed by an endothermic reaction in the 400°C to 500°C temperature range, with the most intense reaction around 455°C, and the heat absorption enthalpy ranging from 300 J/g to 330 J/g. Since the processing temperature of SBS-modified asphalt is generally controlled between 170°C and 190°C, and occasionally exceeds 190°C but does not exceed 300°C, SBS does not show significant heat changes within the normal processing temperature range. Therefore, it can be concluded that SBS does not degrade during normal processing.

2.2 Base Asphalt

According to the climatic zoning requirements of Shandong, the base asphalt selected is 70-grade petroleum asphalt. The brands used include common asphalt brands in the Shandong region, such as SK, Shuanglong, Shell, Donghai, and Jingbo. Conventional tests, infrared spectrum analysis, four-component analysis, and fluorescence microscopic analysis were conducted, as detailed in Table 2.

Table 2. Conventional performance indicators of 70-grade petroleum asphalt

No.	Test Item		Imported 1	Imported 2	Imported 3	Domestic 1	Domestic 2	Domestic 3	Domestic 4
			Shell	Shuanglong	SK	Qilu	Kelida	Jingbo	Kelei
1	Penetration at 25°C (dmm)		82	68	61	66	68	71	68
PI	-0. 8		-1. 1	-0. 4	-0. 9	-1. 4	-0. 5	-0. 6	
2	Softening Point (R&B) (°C)		48. 0	47. 0	48. 0	46. 0	47. 0	46. 5	47. 0
3	Dynamic Viscosity at 60°C (Pa·s)		206	232	228	226	216	232	218
4	Elongation at 10°C (cm)		>100	36	36	36	30	82	41
5	Elongation at 15°C (cm)		>100	>100	>100	>100	>100	>100	>100
6	Wax Content (Distillation Method) (%)		1. 8	1. 7	1. 9	1. 8	1. 8	1. 8	1. 3
7	Flash Point (°C)		312	290	308	286	292	292	298
8	Solubility (%)		99. 90	99. 90	99. 94	99. 94	99. 88	99. 92	99. 91
9	Density at 15°C (g/cm³)		1. 036	1. 030	1. 030	1. 030	1. 034	1. 032	1. 033
10	Thin Film Heating Test	Mass Change (%)	0. 011	-0. 126	-0. 009	-0. 064	0. 049	-0. 006	Mass Change (%)
		Residual Penetration Ratio (%)	71	69	72	70	75	75	65
		Residual Elongation at 10°C (cm)	27	8	7	8	9	10	6

2.3 Other Additives

During the production of SBS-modified asphalt, certain additives are also incorporated, mainly compatibilizers and stabilizers. Compatibilizers are used to improve the hardness and fluidity of SBS rubber, while stabilizers are used to address the segregation issue in SBS-modified asphalt. The additives chosen by the research team include extract oil and stabilizers, with the stabilizers being in powdered form.

2.4 Preparation Process

The laboratory preparation of SBS-modified asphalt samples is a prerequisite for industrial production. The basic preparation process for asphalt samples is as follows:

Raw Materials: 70# Road Petroleum Asphalt, SBS Modifier (Star-shaped, Linear), Stabilizers, Solvents

Production Equipment: High-speed emulsification shear machine (Model: Fluke FA300), Heating equipment, cylindrical heating jacket

Basic Preparation Process: Heat 70# petroleum asphalt to 140-150°C. Add the predetermined amount of SBS modifier and compatibilizer, and stir at low speed (approximately 100 rpm) for 5 minutes to ensure the mixture is homogeneous. Use a high-speed emulsification shear machine to shear the mixture at a shear rate of 3800-4000 rpm for 20 minutes. After shearing, place the SBS-modified asphalt sample in a stirrer, and stir at 800 rpm until the specified temperature is reached. Add stabilizers to allow the mixture to develop for 180 minutes, or adjust the development time according to experimental requirements (as shown in Figure 2).

Sample Testing: After development, pour the mixture into test molds for testing. Key performance indicators to be tested include penetration, elongation, softening point, and segregation.

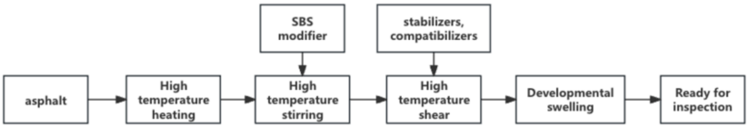


Figure 2. Basic preparation process of SBS modified asphalt

3. Results and Analysis

3.1 Effect of Additives

The SBS-modified asphalt prepared was tested for conventional performance indicators, and the data is organized in Table 3.

Table 3. Performance indicators of SBS modified asphalt

SBS Dosage		4. 30%	4. 30%	4. 30%	4. 30%	4. 30%
Stabilizer Dosage		0. 20%	0. 30%	0. 40%	0. 40%	0. 40%
Compatibilizer Dosage		3%	3%	3%	2%	0%
Penetration	15°C	26	29	33	27	23
	25°C	64	71	74	66	55
	30°C	98	107	111	103	89
PI		0. 25	0. 35	0. 89	0. 21	0. 17
Elongation5°C		73	64	62	53	39
Softening Point °C		73	69	70	73	77
Viscosity at 135°C (Pa·s)		1. 3	1. 4	1. 8	2	2. 5
Segregation (°C)		15	3	0. 5	1	1. 5
Residual Elongation at 5°C		41	32	30	27	16

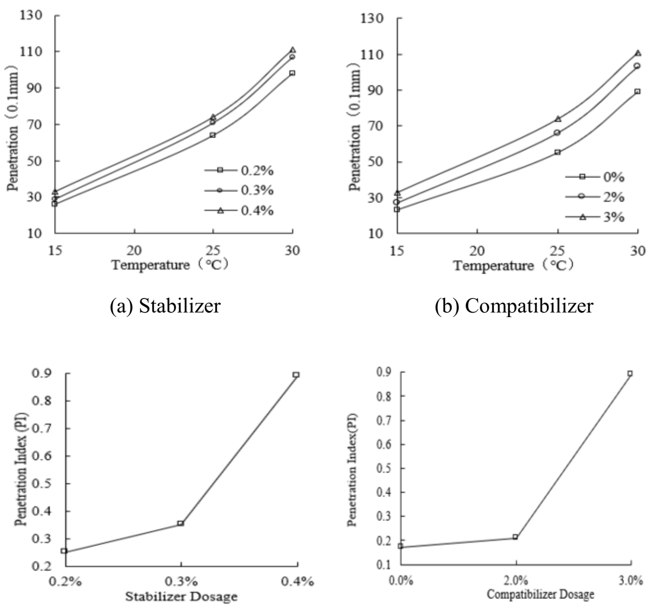
3.1.1 Temperature sensitivity

The addition of the SBS modifier changes the temperature sensitivity of the asphalt but does not alter its essential properties, meaning the modified asphalt remains a viscoelastic material. The incorporation of stabilizers and compatibilizers improves the compatibility between the asphalt and the modifier, stabilizing the colloidal structure of the modified asphalt. As the dosage of stabilizers and compatibilizers changes, the temperature sensitivity of the modified asphalt also changes.

Figure 3(a) shows the relationship between penetration and temperature at different stabilizer dosages when the SBS modifier and compatibilizer are dosed at 4. 3% and 0. 3%, respectively. From the graph, it is evident that as the stabilizer dosage increases, the penetration at a fixed temperature gradually increases. Figure 3(b) shows the relationship between penetration and temperature at different compatibilizer dosages when the SBS modifier and stabilizer are dosed at 4. 3% and 0. 4%, respectively.

Figure 3(c) displays the relationship between the penetration index (PI) and stabilizer dosage when the SBS modifier and compatibilizer are dosed at 4. 3% and 3%, respectively. As the stabilizer dosage increases, the PI increases non-linearly, and the temperature sensitivity decreases. This indicates that the addition of stabilizers can improve the compatibility between the SBS modifier and the base asphalt, reducing the temperature sensitivity of the modified asphalt.

Figure 3(d) shows the relationship between the PI and compatibilizer dosage when the SBS modifier and stabilizer are dosed at 4. 3% and 0. 4%, respectively. When the compatibilizer dosage is between 0%-0. 2%, there is little change in the PI, but when the dosage exceeds 0. 2%, the PI increases rapidly. The addition of compatibilizers primarily softens the SBS modifier, making it more uniform and improving the mixing of the modifier with the asphalt, thus improving the temperature sensitivity of the modified asphalt.



(a) Stabilizer (b) Compatibilizer

(c) Stabilizer (d) Compatibilizer

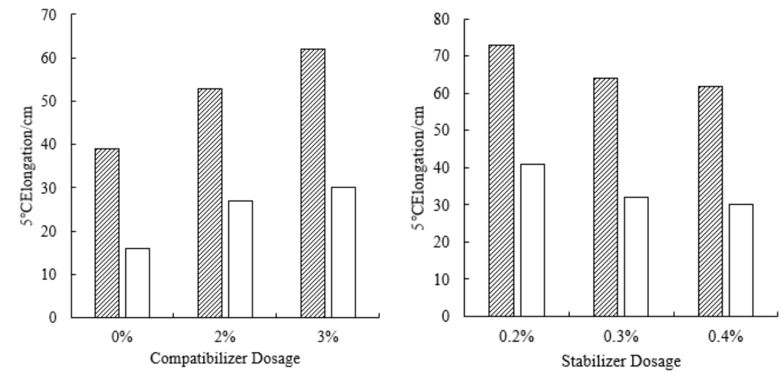
Figure 3. Changes in asphalt temperature sensitivity indicators at different doses and temperatures of compatibilizers and stabilizers

3.1.2 Low-temperature performance and anti-aging performance

The low-temperature crack resistance of asphalt pavement depends on its tensile deformation performance at low temperatures. In China, elongation at 5°C is used as the evaluation indicator for low-temperature performance. As shown in Figure 4, as the dosage of compatibilizer increases, both pre-aging and post-aging elongation gradually increase. Conversely, as the dosage of stabilizer increases, both pre-aging and post-aging elongation gradually decrease. This indicates that increasing the dosage of stabilizer reduces the low-temperature performance of SBS-modified asphalt, while increasing the dosage of compatibilizer improves its low-temperature performance.

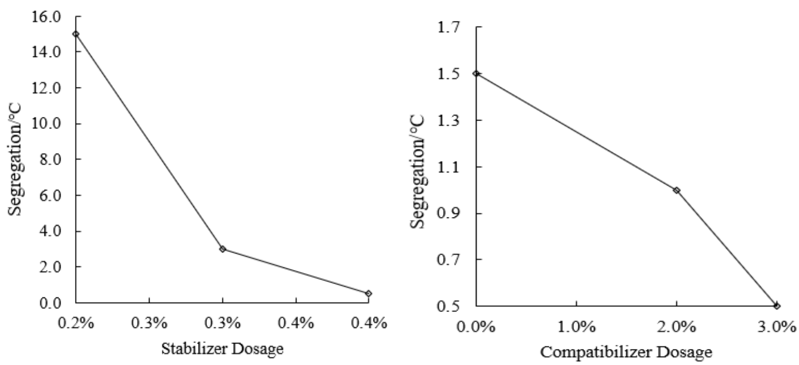
SBS-modified asphalt is a blend of SBS modifiers and asphalt, forming a multiphase mixed system. Under the influence of gravity over time, polymers and asphalt tend to undergo phase separation. To ensure the various performance characteristics of modified asphalt, it must exhibit good storage stability.

As shown in Figure 5, as the dosage of stabilizer increases, the segregation temperature of modified asphalt decreases from 15°C to 0. 5°C, indicating that stabilizers significantly enhance the compatibility between the modifier and asphalt, contributing to the stability of the modified asphalt system. Similarly, as the dosage of compatibilizer increases, the segregation temperature of modified asphalt decreases from 1. 5°C to 0. 5°C. This demonstrates that compatibilizers provide some assistance in stabilizing the modified asphalt system; however, stabilizers play the primary role in improving stability.



(a) Compatibilizer (b) Stabilizer

Figure 4. Changes in asphalt low-temperature and anti-aging performance indicators at different doses and temperatures of compatibilizers and stabilizers



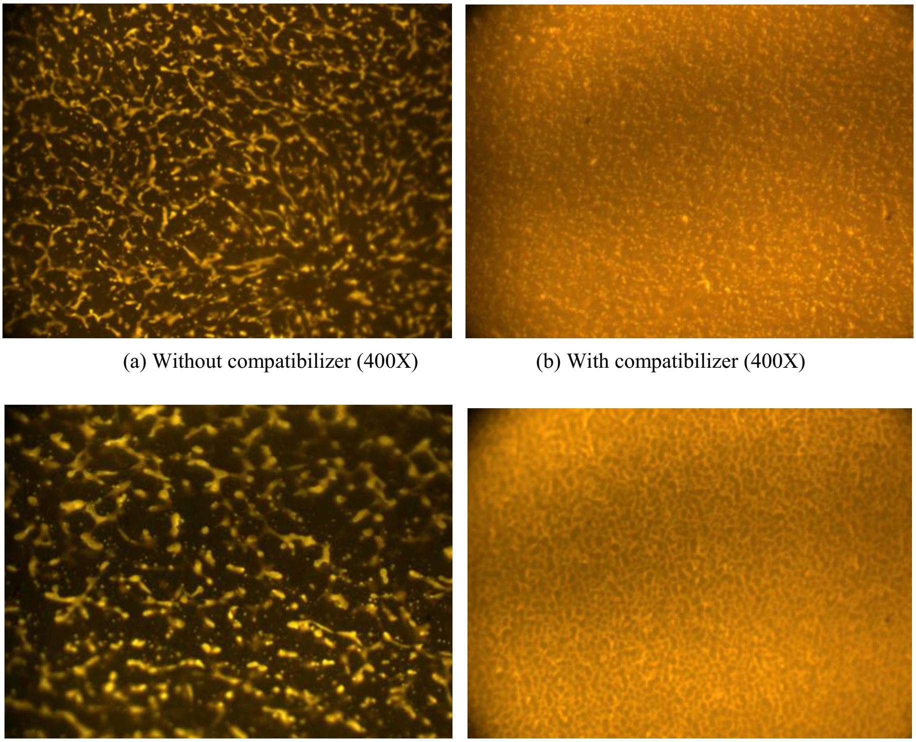
(a) Stabilizer (b) Compatibilizer

Figure 5. Changes in asphalt segregation indicators at different doses and temperatures of compatibilizers and stabilizers

3.1.3 Morphological state

Figure 6(a) and Figure 6(b) compare the morphological states of SBS-modified asphalt with and without the addition of a compatibilizer. The results show that when no compatibilizer is added, the interface between the modifier and the base asphalt is clear, indicating a lower degree of swelling development of the SBS modifier with larger particles. On the other hand, in samples with the addition of a compatibilizer under the same development time, the SBS modifier particles are smaller, and the interface between the modifier and the base asphalt is blurred, suggesting a better swelling effect of the modifier in the asphalt.

Swelling is the foundation for the formation of a continuous phase of SBS modifiers at lower concentrations. Different asphalts, due to their varying amounts of swelling components, exhibit different swelling effects on polymers, leading to different critical phase transition concentrations. In SBS, polystyrene microdomains act as physical cross-linking points, whose quantity and strength determine the plastic strength of SBS. Excessive or overly strong polystyrene microdomains increase the plastic component of SBS, making it more difficult for SBS to swell in asphalt. However, when a compatibilizer with a high aromatic content is added, it can penetrate the polystyrene microdomains in SBS, causing them to swell, increasing the distance between molecular chain segments, relaxing and reducing the intermolecular forces among the segments. This decreases the friction between chain segments, enhances their mobility, and intensifies the motion of the microdomains themselves, promoting a more uniform dispersion of SBS in the asphalt. It also increases the polymer's volume, thereby lowering the polymer concentration at the critical concentration threshold. In cases where the base asphalt lacks sufficient swelling components, the addition of a compatibilizer can reduce the critical concentration for phase transition of the polymer.



(a) Without compatibilizer (400X)   (b) With compatibilizer (400X)

(c) Without stabilizer (200X)   (d) With stabilizer (200X)

Figure 6. Fluorescence micrographs of modified asphalt with additives

Figure 6(c) and Figure 6(d) compare the morphological states of SBS-modified asphalt with and without the addition of a stabilizer. The results show that when no stabilizer is added, the SBS modifier is distributed as a dispersed phase within the asphalt phase, with the SBS modifier and the base asphalt remaining separate, failing to form a continuous phase of modified asphalt. Under this state, the high-temperature and low-temperature performance of SBS-modified asphalt improves to some extent, but the modification effect is not significant. This is because the addition of a stabilizer causes a phase transformation in SBS-modified asphalt, wherein the SBS modifier and asphalt undergo a reaction, forming a continuous phase state with a spatial network structure.

The formation of a spatial network structure is a prerequisite for the excellent performance of SBS-modified asphalt, and achieving such a network structure requires reaching a critical concentration, which primarily depends on factors such as swelling efficiency and dosage. In practice, due to the differences in properties between the base asphalt and the modifier, the most economical and feasible state of modified asphalt is to add as little polymer as possible to form a polymer network structure. Figures 6(c) and 6(d) show that the addition of a stabilizer can also reduce the critical concentration for phase transformation of modified asphalt.

Compatibilizers and stabilizers can complement each other in SBS-modified asphalt and work synergistically. A compatibilizer can enable the entire SBS molecule to swell more fully, stretching the molecular chain segments more extensively and increasing the number of reactive sites. However, the interaction between the compatibilizer and SBS-modified asphalt is only physical adsorption, which is relatively weak. Under this state, the addition of a stabilizer facilitates cross-linking reactions, forming a spatial network structure that encapsulates the asphalt. Simultaneously, after SBS swells fully, its contact area with the asphalt increases, leading to more complete grafting reactions between SBS and asphalt. The resulting SBS-asphalt graft material can reduce the surface tension and free energy between the SBS phase and the asphalt phase, thereby forming more stable and uniform SBS-modified asphalt.

3.2 Modifier Dosage

Using SBS-6302 from Xinjiang Dushanzi as the modifier, with consistent asphalt and additives, the required temperature to achieve good compatibility for SBS-modified asphalt under different dosages within a limited 180-minute processing time was analyzed, as shown in Figure 7.

The results indicate that when the modifier dosage is 3. 7%, 4. 0%, 4. 3%, 4. 6%, and 4. 9%, the required processing temperatures are 175°C, 175°C, 185°C, 188°C, and 195°C, respectively. This shows that as the modifier dosage increases, the temperature required to achieve good compatibility within the limited time (180 minutes) also increases, displaying a linear relationship. Higher SBS modifier dosage results in lower compatibility between the base asphalt and the SBS modifier, and consequently, higher development temperatures are required.

SBS-modified asphalt is a multiphase mixed system where SBS absorbs saturates and aromatics from the asphalt, causing it to swell. However, the absorption and adsorption of certain oils in the asphalt by SBS are constrained by the colloidal structure of the asphalt. Petroleum asphalt is a colloidal equilibrium system, and the absorption of these components by SBS inevitably disrupts the original colloidal balance of the asphalt. As the swelling of the SBS modifier develops, the equilibrium among the components of the original asphalt changes. Since a stable colloidal structure of asphalt also requires saturates and aromatics, there is a tendency in the modified asphalt system to compete for these components to maintain balance, involving both the new asphalt colloidal equilibrium and the SBS polymer swelling equilibrium.

Establishing this new equilibrium state requires time. The higher the SBS modifier content, the longer the time required for full swelling. Within a limited time and with fixed materials, increasing the temperature can enhance the mobility of modifier molecular chain segments and accelerate the mutual diffusion of asphalt molecules and polymer chain segments.

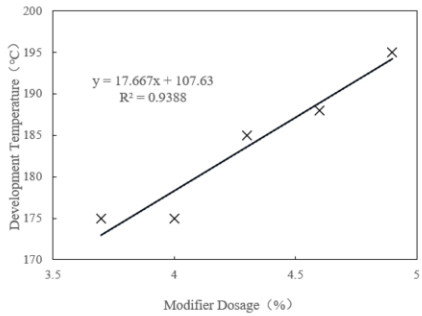


Figure 7. The minimum development temperature for different modifier dosages

3.3 Modifier Type

To compare the impact of different modifiers on compatibility, modified asphalt was produced using modifiers of different grades under consistent production conditions (base asphalt, modifier dosage, additive types, and dosages). The test results show that, under the same modifier dosage, formulation, and processing time, different SBS grades require significantly different temperatures or times to achieve good compatibility. The results are shown in Table 4.

Table 4. Test results for different types of modifiers

Test ID	Temp	Time	Modifier Dosage	Penetration	Softening Point	Elongation	Segregation
	°C	min	%	mm	°C	cm	°C
6302-5	190	180	4. 3	52	78. 1	30	0. 3
6302-6	175	240	4. 3	57	81. 7	25. 5	10. 7
1331-16	180	180	4. 3	51	78	28	29
1331-18	190	180	4. 3	51	81	29	0. 2
6302-7	180	300	4. 3	49	77. 3	32. 5	1. 2
791-10	180	180	4. 3	53	79. 4	33. 8	0. 9
1331-20	190	90	4. 3	54	83. 2	27. 8	12. 3
1331-21	190	150	4. 3	50	82. 0	29. 5	3. 0
1331-22	180	360	4. 3	50	83. 5	27. 7	5. 0
6302-8	185	180	4. 3	50	76. 4	32. 9	0. 7
161B-1	200	200	4. 3	51	81. 1	29. 1	15. 7

As shown in Figure 8, when the modifier dosage is 4. 3%, the development temperatures for grades YH-791, 6302-H, CH-1331, and 161B are 180°C, 185°C, 190°C, and 200°C, respectively. These temperatures ensure good storage stability (compatibility) of the asphalt within 180 minutes. Otherwise, significant segregation occurs. For example, when the processing temperature of 6302-H is reduced to 175°C and the development time is extended to 240 minutes (6 hours), segregation still reaches 10. 7°C, far exceeding the standard requirement of 2. 5°C. For the star-linear blended 1331 modifier, the processing temperature is 190°C, while the star-shaped modifier 161B still exhibits segregation as high as 15. 7°C even after 200 minutes of development at 200°C. These results indicate that different SBS grades have significantly different processing temperature requirements, which must be appropriately adjusted.

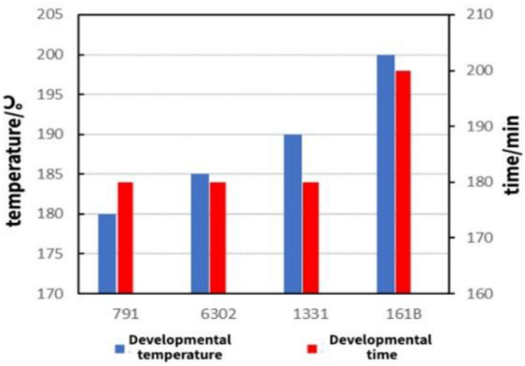


Figure 8. Development temperature and time for different modifiers

4. Conclusions and Analysis

Through systematic experimental studies, this paper deeply investigated the effects of SBS modifier types, base asphalt selection, additive usage, and preparation processes on the compatibility and performance of modified asphalt. The study found that the type and dosage of SBS modifiers, the type of base asphalt, and the use of additives all significantly affect the compatibility and performance of modified asphalt. Appropriate increases in stabilizer and compatibilizer dosages can improve the compatibility and performance of modified asphalt, but these dosages must be controlled within a certain range to avoid excessive impact on performance. Furthermore, the dosage and type of modifiers, as well as the selection of base asphalt, also play critical roles in the performance of modified asphalt.

In summary, optimizing the preparation process of modified asphalt and selecting modifiers and base asphalt rationally are of great importance for enhancing the performance of modified asphalt. The results of this study provide a scientific basis for the preparation and application of modified asphalt and offer a reference for the rational selection and use of modified asphalt in road engineering.

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