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Research on TPS-SBS Composite-Modified Asphalt with High Viscosity and High Elasticity in Cold Regions

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Abstract: Considering the harsh service environment of asphalt pavements in cold regions, there is an urgent need to develop high-viscosity, and high-elasticity modified asphalt. This study focuses on the composite modification effects of SBS (Styrene-Butadiene-Styrene) and TPS (TAFPACK-Super) modifiers. A multivariate regression analysis model was established to evaluate the effects of different external additive proportions on the properties of high-viscosity and high-elasticity modified asphalt, including softening point, penetration, ductility, and dynamic viscosity. The results indicate that the constructed quadratic nonlinear regression models exhibit excellent goodness of fit (0.929, 0.994, 0.882, and 0.939), verifying their reliability. The model further elucidates the influence patterns of different materials on asphalt properties: SBS has the greatest impact on the softening point and dynamic viscosity, TPS significantly enhances ductility, while aromatic oil primarily affects penetration. By considering performance and cost, an optimized formulation for TPS-SBS composite-modified asphalt was determined: 9% SBS, 1% TPS, and 3% aromatic oil. Validation tests demonstrate that the modified asphalt prepared with the optimal formulation meets all performance criteria, with a dynamic viscosity of 55.32×10^4 Pa·s at 60 °C. Additionally, this composite-modified asphalt exhibits excellent aging resistance, construction workability, and high-temperature stability, providing scientific support and reference for the development of durable asphalt pavements in cold regions.

Keywords: cold-region high-viscosity and high-elasticity modified asphalt; TPS-SBS composite modifier; proportion optimization; multivariate regression analysis; performance evaluation

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1. Introduction

With the increase in traffic volume and the extended service life of highways, road maintenance costs are rising annually, highlighting challenges in funding and management. Asphalt mixtures, the primary material for high-grade highways, often suffer from early damage, primarily manifesting as pavement cracking, which has become a critical factor limiting their performance and service life [1,2]. Pavement cracking mainly is reflective cracking from the base layer and fatigue effects in the asphalt surface layer, which is under long-term traffic loads and environmental influences [3–6]. This issue is particularly severe in cold regions such as Northeast China, where extreme climate conditions exacerbate the problem. These regions not only experience heavy traffic but also endure summer temperatures exceeding 65 °C and winter temperatures dropping below −30 °C. Frequent freeze-thaw cycles significantly accelerate asphalt pavement damage, leading to a damage rate for asphalt surfaces in high-grade [7–9].

Crack prevention and control have become critical to extending the service life of asphalt pavements. The introduction of high-viscosity and high-elasticity modified asphalt offers a promising technical solution [10,11]. First proposed in Japan, the core technical criterion of this technology is that the dynamic viscosity at 60 °C must be no less than 20,000 Pa·s [12,13]. Currently, this remains the primary technical requirement for most high-viscosity and high-elasticity modified asphalts. Only a few modified asphalts achieve a dynamic viscosity of 200,000 Pa·s or higher at 60 °C [14]. However, the unique service environment in cold regions demands even higher performance, particularly in bonding properties across a wide temperature range. This necessitates the development of superior high-viscosity and high-elasticity modified asphalts. Based on the characteristics of cold-region environments, engineering practices, literature reviews, and relevant standards, new technical performance requirements for cold-region high-viscosity and high-elasticity modified asphalts have been summarized, as shown in Table 1.

Table 1. Performance Requirements for High-Viscosity and High-Elasticity Modified Asphalt.

Test Item		Unit	Technical Requirement	Test Method
Penetration at 25 °C, 100 g, 5 s		0.1 mm	40–60	T 0604
Softening Point (TR&B)		°C	≥80	T 0606
Ductility (5 cm/min, 5 °C)		cm	≥30	T 0605
Dynamic Viscosity at 60 °C		Pa·s	≥200,000	T 0620
Elastic Recovery at 25 °C		%	≥85	T 0662
Storage Stability at 163 °C		°C	≤2.5	T 0661
TFOT Residue	Mass Loss	%	±1.0	T 0610
	Penetration Ratio (25 °C)	%	≥75	T 0604
	Ductility (5 cm/min, 5 °C)	cm	≥20	T 0605
	DSR G*/sinδ (85 °C)	kPa	≥2.2	T 0628
	Elastic Recovery Ratio at 25 °C	%	≥60	T 0662

Much research indicates that the type and proportion of modifiers significantly influence the performance of modified asphalt. Currently, modifiers such as SBS, rubber powder, and natural asphalt are widely used in engineering applications, with SBS being the mainstream choice due to its excellent modification performance [15–18]. Zhang et al. [19] found that the optimal dosage of SBS modifier for asphalt mixtures in the high-altitude and cold regions of the Qinghai-Tibet Plateau is 4%–5%. Additionally, high-viscosity modifiers (e.g., TPS, HVA, HVA-II) have been introduced to prepare high-viscosity and high-elasticity modified asphalt [20–22]. Among these, TPS has gained significant attention due to its mature technology and excellent performance, but its high cost and large dosage requirements limit its widespread application [23–27]. For high-viscosity modified asphalt prepared using base asphalt, the modifier content is generally above 10% [28,29]. Studies by Xu and Dai, as well as Chen et al. [23,24,30], indicate that the reasonable dosage of TPS ranges from 8% to 16%, while Zhang et al. [31] suggest an optimal range of 13% to 18%, at which the performance indicators of high-viscosity asphalt meet specification requirements.

Single modifiers often struggle to comprehensively meet the complex performance demands of high-viscosity and high-elasticity modified asphalt. As a result, composite modification technology has emerged, combining two or more modifiers to synergistically improve the high- and low-temperature properties, crack resistance, and aging resistance of asphalt [15,32,33]. Research has demonstrated [34] that combining SBS with high-viscosity modifiers (TPS, HVA, HVA-II) significantly enhances asphalt viscosity, with the dynamic viscosity of the resulting high-viscosity and high-elasticity modified asphalt exceeding 200,000 Pa·s at 60 °C. Accordingly, this study aims to prepare composite high-viscosity and high-elasticity modified asphalt suitable for cold regions by incorporating SBS and TPS modifiers.

Most existing studies focus on the technical specifications and performance testing of modified asphalt. While they have identified general trends and principles in performance, systematic research on the proportions and interactions of modifiers remains limited. High-dosage modifiers, while improving asphalt viscosity, may also introduce heterogeneity and instability within the asphalt due to differences in polarity, molecular weight, and viscosity between the modifier and asphalt molecules, potentially compromising overall quality [35–37]. Based on frequency sweep test results for modified asphalt containing varying dosages of SBS, Liang et al. [38] found that compatibility between the modifier and base asphalt decreases as modifier dosage increases. Therefore, systematic analysis of modifier combinations and their impact on asphalt performance is critical.

This study employs different proportions of TPS and SBS modifiers to prepare composite high-viscosity and high-elasticity modified asphalt tailored for cold regions. Using uniform experimental design and multivariate regression analysis, the effects of modifier proportions on the fundamental physical properties of the composite-modified asphalt are investigated, and the optimal formulation for cold-region high-viscosity and high-elasticity modified asphalt is preliminarily determined. Finally, the performance of composite-modified asphalt is validated through tests on basic physical properties, short-term aging, rotational viscosity, and rheological performance. This study provides a scientific basis for promoting and applying this asphalt in engineering practices, aiming to support the development of durable and long-lasting asphalt pavements in cold regions, with significant theoretical and practical implications.

2. Materials and Methodology

2.1. Raw Materials

The primary raw materials used in this study include 90# base asphalt, a linear 1301 SBS modifier, a TPS modifier, a compatibilizer, and a stabilizer. The 90# base asphalt was supplied by Panjin Dali Petrochemical Co., Ltd. in Panjin, China, with its technical specifications shown in Table 2. The TPS modifier, a high-viscosity agent, was produced by Bochao Engineering Materials Co., Ltd. in Changzhou, China. The compatibilizer used was furfural extract oil, characterized by a high aromatic content, and sulfur was used as the stabilizer.

Table 2. Technical Specifications of Base Asphalt.

Test Item		Unit	Test Value	Specification
Penetration at 25 °C, 100 g, 5 s		0.1 mm	81.7	80~100
Softening Point		°C	47.3	≥45
Ductility (5 cm/min, 5 °C)		cm	>125	≥100
TFOT Residue	Mass Loss	%	−0.13	≤±0.8
	Penetration Ratio (25 °C)	%	77.1	≥57
	Ductility (5 cm/min, 5 °C)	cm	106.5	≥20

2.2. Preparation of Modified Asphalt

To produce composite-modified asphalt, SBS was selected as the asphalt modifier, TPS as the viscosity regulator, aromatic oil as the compatibilizer, and sulfur as the stabilizer.

Studies have shown [34] that when SBS is combined with high viscosity modifiers (TPS, HVA, and HVA-II), the viscosity of asphalt can be significantly increased, with a weight ratio of 1:9.5–11.5 between high viscosity modifier and SBS modified asphalt. SBS-modified asphalt consists of an SBS modifier and matrix asphalt, with a weight ratio of 1:18–25 between the SBS modifier and matrix asphalt.

The research object of our article is high viscosity and high elasticity modified asphalt in cold regions, and the low-temperature performance of asphalt is also a major consideration. Studies have shown [37] that in TPS-modified asphalt (without SBS), the low-temperature performance of asphalt is optimal when the TPS content is around 10%. while in TPS-modified asphalt [38], the SBS modifier content is generally around 5%. Therefore, based on the above analysis, the SBS modifier ratio range is set to 3%~10%, the TPS dosage ratio range is 1%~13%, the aromatic oil ratio range is 1.5%~4.7%, and the sulfur dosage is 0.1%.

On this basis, this study also conducted preliminary experiments to provide actual data basis for further design of experiment. The pre-experiment is equipped with three types of asphalt, and the dosage of external additives and performance tests are shown below (Tables 3 and 4). According to the data, the elastic recovery is much greater than the technical requirements, so in subsequent asphalt performance tests, elastic recovery will not be used as a control indicator for ratio optimization.

Table 3. The Dosage of External Additives of Pre-experiment.

External Additives	Number 1	Number 2	Number 3	Number 4
SBS	5.0%	4.0%	9.5%	9.0%
TPS	12%	10%	1%	0%
Aromatic Oil	2.0%	4.0%	3.0%	3.0%
Sulfur	0.10%	0.10%	0.10%	0.10%

Table 4. Performance Test of Pre-experiment.

Project of Test	Number 1	Number 2	Number 3	Number 4	Technical Requirement
Penetration	46.1	51	50.9	48.9	40–60
Ductility	46.1	52.2	41.6	44.5	≥80
Softening Point	107.05	100.55	104.4	104.4	≥30
Elastic Recovery	99.80%	99.90%	99.60%	99.60%	≥85%
Dynamic Viscosity	436,670	173,347	553,161	248,775	≥200,000

Using 90# base asphalt as the base material (100%), the additives were incorporated in varying proportions: SBS (3%–10%), TPS (1%–13%), aromatic oil (1.5%–4.7%), and sulfur (0.1%).

SBS modifier, as a widely used asphalt modifier, can form a three-dimensional network structure in the matrix asphalt, effectively improving the high- and low-temperature performance of the matrix asphalt. TPS, similar to rubber powder, acts as a viscosity modifier. Under shear action, it can absorb light components in asphalt and transform the original network structure into a flocculent structure. Under swelling action, it can increase the viscosity of asphalt. Aromatic oil can enhance the swelling effect of SBS, increase the volume expansion rate of SBS, make SBS more compatible with the matrix asphalt, reduce the high-temperature viscosity of asphalt, and lower the construction temperature. Sulfur, as a stabilizer, can undergo cross-linking reactions in asphalt during the "development" stage, making the structure of asphalt more stable and enhancing the overall stability of modified asphalt.

Similar to the preparation of crumb rubber-modified asphalt, the preparation of TPS-SBS-based high-viscosity and high-elasticity modified asphalt involves three main stages: the preliminary stirring and swelling phase, the intermediate shearing and dispersing phase, and the final stirring and maturation phase. The detailed preparation process is as follows [39–44]:

1. Melting Base Asphalt: Heat the 90# base asphalt in an oven at 135 °C until fully melted.
2. Adding Aromatic Oil and SBS: Weigh the specified amount of aromatic oil and SBS according to the experimental design. Gradually add these into the base asphalt under stirring at 160 °C, with a stirring rate of 600 rpm for 15 min.
3. Incorporating TPS: Heat the asphalt mixture to 180 °C, weigh the specified amount of TPS, and add it in portions under stirring. Maintain the stirring temperature at 180 °C, with a stirring rate of 600 rpm for 30 min.
4. High-Speed Shearing: Subject the stirred modified asphalt to high-speed shearing using a shearing machine. Shear the mixture at 180 °C, with a shearing speed of 5000 rpm for 1 h.
5. Adding Sulfur and Final Stirring: Weigh the specified amount of sulfur stabilizer and add it to the asphalt mixture. Stir the mixture at 180 °C for 1 h to allow full development. Immediately mold the final modified asphalt for testing upon completion. The detailed preparation workflow is illustrated in Figure 1.

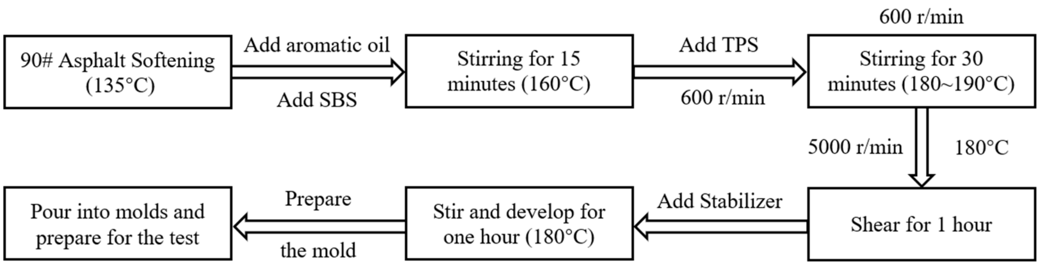


Figure 1. Preparation Workflow for TPS-SBS-Based High-Viscosity and High-Elasticity Modified Asphalt.

2.3. Methodology

This study employs a uniform experimental design to plan the experimental scheme, test the fundamental asphalt properties, and analyze data using multiple regression analysis for proportion optimization. Based on the optimized proportions, further tests on basic physical properties, short-term aging performance, rotational viscosity, and rheological performance are conducted.

2.3.1. Uniform Experimental Design

A uniform experimental design was employed to efficiently investigate the effect of modifier dosages on asphalt performance with relatively fewer tests. The entire experimental domain was divided into two regions: Low SBS Dosage with High TPS Dosage; High SBS Dosage with Low TPS Dosage. Testing zones with both low SBS and low TPS dosages were excluded due to evident non-compliance with performance standards, as well as zones with high SBS and high TPS dosages due to economic infeasibility. This approach enhances the focus of the experiments, making it more likely to achieve a TPS-SBS-based high-viscosity and high-elasticity modified asphalt suitable for cold regions and practical engineering applications.

(1) Low SBS Dosage with High TPS Dosage

Three factors were selected for the experiment: SBS dosage, TPS dosage, and aromatic oil dosage. Each factor was assigned nine levels, forming a three-factor, nine-level experimental design, as shown in Table 5. Based on the uniform experimental design methodology, nine combination schemes were finalized, representing the test plan for the low SBS and high TPS dosage region. The detailed combinations are presented in Table 6.

Table 5. Three-Factor Nine-Level Table for Low SBS Dosage with High TPS Dosage.

Factor	SBS (A)	TPS (B)	Aromatic Oil (C)
1	3.0%	5.0%	1.5%
2	3.5%	6.0%	1.9%
3	4.0%	7.0%	2.3%
4	4.5%	8%	2.7%
5	5.0%	9%	3.1%
6	5.5%	10%	3.5%
7	6.0%	11.0%	3.9%
8	6.5%	12.0%	4.3%
9	7.0%	13.0%	4.7%

Table 6. Uniform Experimental Design Plan for Low SBS Dosage and High TPS Dosage Region.

Experiment No.	Level Distribution			Combination	Factors		
	A	B	C		SBS	TPS	Aromatic Oil
1	1	4	7	A1B4C7	3.0%	8%	3.9%
2	2	8	5	A2B8C5	3.5%	12%	3.1%
3	3	3	3	A3B3C3	4.0%	7%	2.3%
4	4	7	1	A4B7C1	4.5%	11%	1.5%
5	5	2	8	A5B2C8	5.0%	6%	4.3%
6	6	6	6	A6B6C6	5.5%	10%	3.5%
7	7	1	4	A17B1C4	6.0%	5%	2.7%
8	8	5	2	A8B5C2	6.5%	9%	1.9%
9	9	9	9	A9B9C9	7.0%	13%	4.7%

(2) High SBS Dosage with Low TPS Dosage

Three factors—SBS, TPS, and aromatic oil dosage—were selected, with four levels for each factor, resulting in a three-factor, four-level experiment, as shown in Table 7. Based on the uniform experimental design method, four combination schemes were finalized for the high SBS and low TPS dosage region, as detailed in Table 8.

Table 7. Three-Factor Nine-Level Table for High SBS Dosage with Low TPS Dosage.

Factor	SBS (A)	TPS (B)	Aromatic Oil (C)
1	8.5%	1%	2.7%
2	9%	2%	3.1%
3	9.5%	3%	3.5%
4	10%	4%	3.9%

Table 8. Uniform Experimental Design Plan for High SBS Dosage and Low TPS Dosage Region.

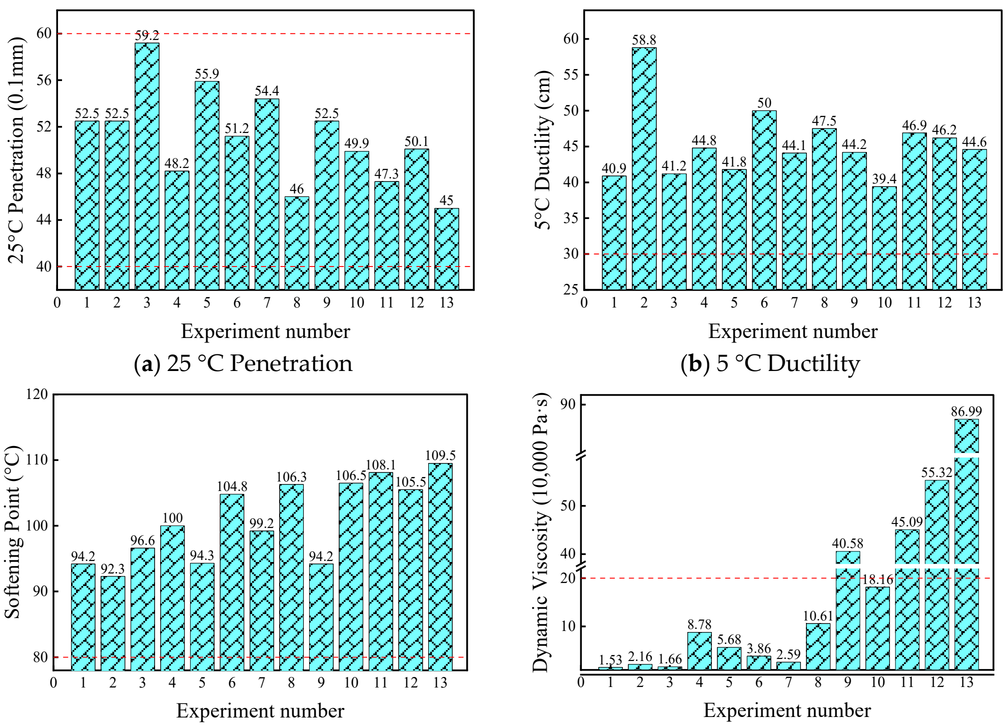
Experiment No.	Level Distribution			Combination	Factors		
	A	B	C		SBS	TPS	Aromatic Oil
10	1	2	4	A1B2C4	8.5%	2%	3.9%
11	2	4	3	A2B4C3	9.0%	4%	3.5%
12	3	1	2	A3B1C3	9.5%	1%	3.1%
13	4	3	1	A4B3C1	10.0%	3%	2.7%

2.3.2. Asphalt Performance Testing

In this study, asphalt performance tests include determining basic physical properties (penetration, softening point, ductility, elasticity recovery, and 60 °C dynamic viscosity), short-term aging tests (RTFOT aging test), rotational viscosity, and rheological performance. The 60 °C dynamic viscosity was measured using the vacuum capillary method. The short-term aging resistance of the composite-modified asphalt was tested using the Thin Film Oven Test (TFOT). The rotational viscosity at 135 °C and 175 °C was measured using a Brookfield viscometer. Temperature scanning tests were performed on high-viscosity, high-elasticity modified asphalt using a Dynamic Shear Rheometer (DSR) to clarify its high-temperature deformation resistance. The specific testing methods can be referenced from the "Highway Engineering Asphalt and Asphalt Mixture Test Specifications" (JTG E20-2011) [45] and will not be elaborated here. The models of the instruments used in this study are listed in Table 9, and the detailed experimental setup is shown in Figure 2.

Table 9. Instrument Models and Standard/Method for Test.

Test	Instrument Model	Instrument Manufacturer	Standard/Method [45]
Penetration	SYD-2801E1	Shanghai Changji Geological Instrument Co., Ltd. in Shanghai, China	T 0604-2011
Softening Point	SYD-2806E/F		T 0606-2011
Ductility	SYD-4508D		T 0605-2011
Elastic Recovery	SYD-4508D		T 0662-2011
Dynamic Viscosity	TD620-3	Cangzhou Taiding Hengye Testing Instrument Co., Ltd. in Cangzhou, China	T 0620-2011
Short-Term Aging	LBH-1	Road Instrument Branch of Nanjing Soil Instrument Factory Co., Ltd. in Nanjing, China	T 0610-2011
Rheological Properties	DHR-2	Waters Technology (Shanghai) Co., Ltd. in Shanghai, China	T 0628-2011



(**a**) 25 °C Penetration (**b**) 5 °C Ductility

(**c**) Softening Point (**d**) 60 °C Dynamic Viscosity

Figure 2. Performance Test Results of TPS-SBS High Viscosity and High Elasticity Modified Asphalt (Note: The test numbers in the figure correspond to those in Tables 6 and 8, representing samples under the mix ratios in Tables 6 and 8. The red dashed line in the figure represents the technical specification range limit or the minimum limit).

3. Results and Discussion

3.1. Mix Design of Composite-Modified Asphalt with High Viscosity and High Elasticity

3.1.1. Basic Asphalt Performance Test Results

The test results for the three key indicators of TPS-SBS composite-modified asphalt and the 60 °C dynamic viscosity are shown in Table 10 and Figure 2, which completed four parallel samples for each individual combination. As shown in Figure 2, the 25 °C penetration values range from 48.2 to 59.2 (0.1 mm), with an overall average of approximately 52.1 (0.1 mm), which meets the required range of 40–60 (0.1 mm). This indicates that the TPS-SBS modified asphalt exhibits good flowability under normal temperature conditions, which can meet the work requirements in road construction. The 5 °C ductility results show values ranging from 39.4 to 58.8 (cm), with Test No. 2 achieving the highest ductility of 58.8 (cm), significantly exceeding the technical requirement of ≥30 (cm). These data indicate that the modified asphalt still has good ductility at low temperatures, which can effectively resist brittle failure caused by temperature changes. The improvement in 5 °C ductility lays a good foundation for the use and stability of the asphalt in cold environments during winter.

Table 10. Performance Testing of TPS-SBS Composite-Modified Asphalt with High Viscosity and High Elasticity.

Test Number	25 °C Penetration (0.1 mm)	5 °C Ductility (cm)	Softening Point (°C)	Dynamic Viscosity (10,000 Pa·s)
1	52.5	40.9	94.2	1.53
2	52.5	58.8	92.3	2.16
3	59.2	41.2	96.6	1.66
4	48.2	44.8	100	8.78
5	55.9	41.8	94.3	5.68
6	51.2	50.0	104.8	3.86
7	54.4	44.1	99.2	2.59
8	46.0	47.5	106.3	10.61
9	52.5	44.2	94.2	40.58
10	49.9	39.4	106.5	18.16
11	47.3	46.9	108.1	45.09
12	50.1	46.2	105.5	55.32
13	45.0	44.6	109.5	86.99
Technical Requirements	40–60	≥30	≥80	≥20

Note: The test numbers in this table correspond to those in Tables 6 and 8, representing the samples under the mix ratios listed in Tables 6 and 8.

As shown in Figure 2c, the softening point range of the 13 samples is from 92.3 °C to 109.5 °C, and all samples meet the technical requirement (≥80 °C). Among them, sample 12 has the highest softening point, reaching 105.5 °C, indicating that the modified asphalt has excellent high-temperature performance, with better resistance to flow deformation under high summer temperatures. A higher softening point can effectively delay the flowability of asphalt in high-temperature environments, reduce rutting effects, and enhance the overall stability of the pavement.

Dynamic viscosity is a key indicator for evaluating the high-temperature flow performance of asphalt. Based on the test results in Figure 2d, the dynamic viscosity values fluctuate between 1.53×10^4 Pa·s and 86.99×10^4 Pa·s, showing a wide dynamic range. Specifically, only samples 9, 11, 12, and 13 have dynamic viscosities greater than 20×10^4 Pa·s. Notably, the dynamic viscosity of sample 13 reaches 86.99×10^4 Pa·s. This fully demonstrates that the TPS-SBS composite-modified asphalt has greater cohesion, a more stable network structure, and excellent overall bonding performance.

3.1.2. Multiple Regression Analysis

To optimize the mix ratio, the quantitative relationship between the independent variables and the dependent variables is studied to determine the impact of the three materials' dosages on the modified asphalt performance. Specifically, regression analysis is conducted on the three key indicators and dynamic viscosity of the TPS-SBS-based high-viscosity and high-elasticity modified asphalt using the data in Table 9.

1. Multiple Linear Regression Analysis

The performance indicators of the modified asphalt were subjected to multiple linear regression analysis using SPSS software(SPSS Statistics 26.0), and the specific analysis results are shown in Table 10. As can be seen from Table 11, the multiple linear model for all indicators, except for ductility (R^2 = 0.981), has relatively poor R^2 values, with the lowest being 0.659. Additionally, in the model for ductility, the coefficient before X_1 is negative, which does not conform to the objective laws. Therefore, the four multiple linear models are not suitable and cannot be used for the optimization and adjustment of the modified asphalt mix ratio.

Table 11. Multiple Linear Regression Analysis Table.

Performance	Multiple Linear Model	R^2
Penetration	$Y = 60.807 - 170.009X_1 - 60.9388X_2 + 156.5072X_3$	0.667
Ductility	$Y = 0 - 315.44X_1 + 235.2999X_2 - 285.8768X_3$	0.981
Softening Point	$Y = 89.39302 + 257.6501X_1 + 32.12977X_2 - 192.651X_3$	0.659
Dynamic Viscosity	$Y = 0 + 768.4032X_1 - 4.074481X_2 - 730.931X_3$	0.779

Note: Y is the dependent variable (i.e., penetration, ductility, softening point, or dynamic viscosity), and X_1, X_2, X_3 correspond to the dosages of SBS, TPS, and aromatic oil, respectively. This also applies to the multiple nonlinear regression analysis in the following text.

2. Multiple Nonlinear Regression Analysis

SPSS software was used for multiple nonlinear regression analyses of each asphalt performance index. First, univariate curve fitting for a single index was conducted, and by comparing the R^2 values of each fitting function curve, a multivariate quadratic regression model (as shown in Formula (1)) was selected for model construction. The fitting was divided into constrained and unconstrained conditions. Constrained conditions mean that the constant term and the coefficients before the independent variables are constrained before fitting, while unconstrained conditions mean that both the constant term and coefficients are unconstrained. Table 12 shows the results of the multiple nonlinear regression analysis.

$$Y = a + bX_1 + cX_2 + dX_3 + eX_1^2 + fX_2^2 + gX_3^2 + hX_1X_2 + iX_1X_3 + jX_2X_3 \quad (1)$$

By comparing the R^2 values of the models in Table 12, the final selected performance regression models are shown in Table 13. To verify the accuracy of the models in Table 13, a validation group was used for verification, and the experimental result data are shown in Table 11. From Table 14, it can be seen that the errors of the three major indicators are all smaller than the experimental error specified by the standards, indicating the reliability of the model. However, the error of the 60 °C dynamic viscosity exceeded the specified error value when the formulation's dynamic viscosity was small. When the dynamic viscosity was large (such as in samples 3 and 4 in Table 14), the percentage error was smaller (0.02%–4.50%). Therefore, the dynamic viscosity regression model is only suitable for high dynamic viscosity modified asphalt.

Table 12. Multiple Nonlinear Regression Analysis.

Performance	Type	Multiple Linear Model	R^2
Penetration	Restricted	$Y = 75.0 - 145.2X_1 - 164.0X_2 - 366.4X_3 - 2776.8X_1^2 - 130.5X_2^2$ $-6445.0X_3^2 - 175.8X_1X_2 + 10525.0X_1X_3 + 3622.4X_2X_3$	0.893
	Unrestricted	$Y = 105.3 - 437.0X_1 - 528.3X_2 - 672.2X_3 - 1333.4X_1^2 + 852.3X_2^2$ $-4337.8X_3^2 + 1697.4X_1X_2 + 8396.4X_1X_3 + 6064.2X_2X_3$	0.929
Ductility	Restricted	$Y = 0 + 375.2X_1 - 100.1X_2 + 2271.9X_3 - 551.9X_1^2 + 1039.1X_2^2$ $-30048.9X_3^2 + 992.3X_1X_2 - 9242.0X_1X_3 + 279.3X_2X_3$	0.994
	Unrestricted	$Y = -74.5 + 1398.4X_1 + 557.0X_2 + 3260.4X_3 - 4797.6X_1^2 - 763.9X_2^2$ $-39079.2X_3^2 - 3507.5X_1X_2 - 12377.5X_1X_3 - 1394.3X_2X_3$	0.778
Softening Point	Restricted	$Y = 45.0 + 364.3X_1 + 642.6X_2 + 1185.5X_3 - 119.3X_1^2 - 2719.0X_2^2$ $-20639.0X_3^2 - 1921.3X_1X_2 + 1513.4X_1X_3 - 1599.6X_2X_3$	0.569
	Unrestricted	$Y = -0.55 + 1168.4X_1 + 696.9X_2 + 2017.8X_3 - 3734.9X_1^2 -$ $1635.7X_2^2 - 17876.0X_3^2 - 2255.3X_1X_2 - 6591.3X_1X_3 - 7300.2X_2X_3$	0.882
Dynamic Viscosity	Restricted	$Y = 0 - 1628.8X_1 - 307.2X_2 + 1796.6X_3 + 28127.4X_1^2 + 3474.6X_2^2$ $+8627.7X_3^2 + 5379.3X_1X_2 - 36599.8X_1X_3 - 5934.2X_2X_3$	0.939
	Unrestricted	$Y = 121.5 - 3389.7X_1 - 833.0X_2 - 1178.1X_3 + 35249.0X_1^2 +$ $1761.7X_2^2 + 24906.7X_3^2 + 9919.4X_1X_2 - 18289.0X_1X_3 + 5535.9X_2X_3$	0.969

Table 13. Multivariable Regression Models for Each Performance.

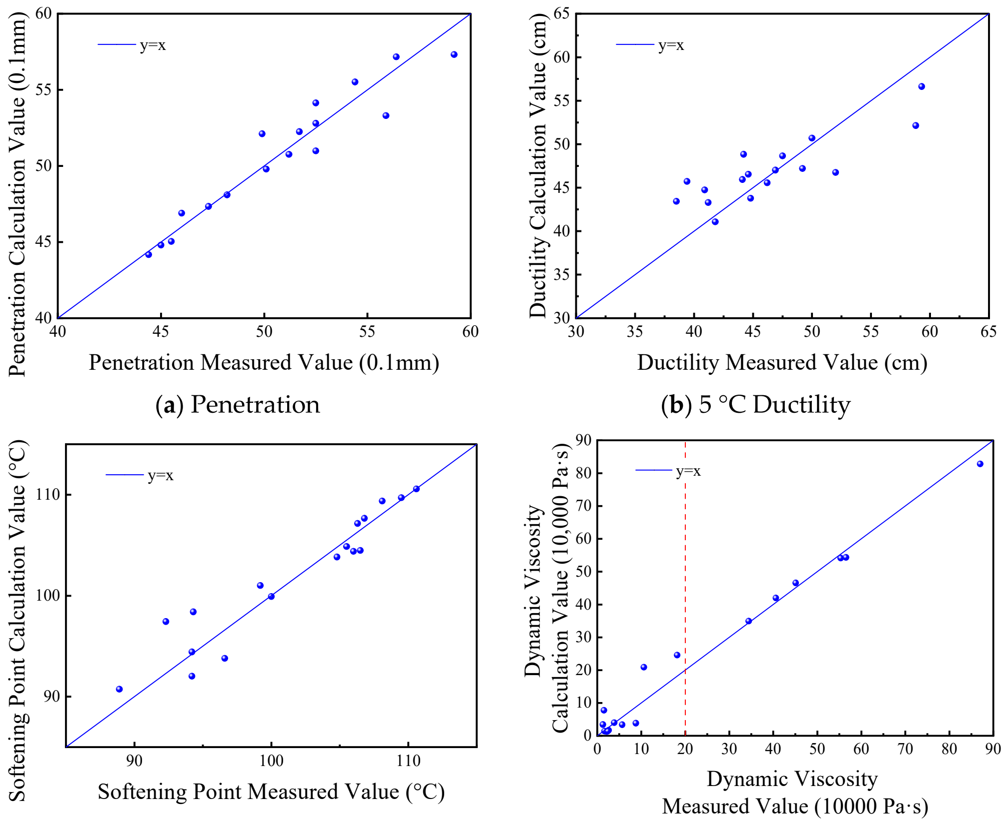
Performance	Multiple Linear Model	R^2
Penetration	$Y = 105.3 - 437.0X_1 - 528.3X_2 - 672.2X_3 - 1333.4X_1^2 + 852.3X_2^2$ $-4337.8X_3^2 + 1697.4X_1X_2 + 8396.4X_1X_3 + 6064.2X_2X_3$	0.929
Ductility	$Y = 0 + 375.2X_1 - 100.1X_2 + 2271.9X_3 - 551.9X_1^2 + 1039.1X_2^2$ $-30048.9X_3^2 + 992.3X_1X_2 - 9242.0X_1X_3 + 279.3X_2X_3$	0.994
Softening Point	$Y = -0.55 + 1168.4X_1 + 696.9X_2 + 2017.8X_3 - 3734.9X_1^2 - 1635.7X_2^2$ $-17876.0X_3^2 - 2255.3X_1X_2 - 6591.3X_1X_3 - 7300.2X_2X_3$	0.882
Dynamic Viscosity	$Y = 121.5 - 3389.7X_1 - 833.0X_2 - 1178.1X_3 + 35249.0X_1^2 + 1761.7X_2^2 +$ $24906.7X_3^2 + 9919.4X_1X_2 - 18289.0X_1X_3 + 5535.9X_2X_3$	0.969

Note: This table is only applicable to TPS-SBS-based high-viscosity and high-elasticity modified asphalt, with the following modifier dosage range: SBS: 3%~10%, TPS content: 1%~13%, and aromatic oil dosage range: 1.5%~4.7%.

Table 14. Validation Group Test Table.

Asphalt No.		1	2	3	4
SBS		3.00%	6.00%	7.00%	8.00%
TPS		8%	7%	9%	11%
Aromatic Oil		2.50%	3.50%	1.50%	3.00%
Sulfur		0.10%	0.10%	0.10%	0.10%
Penetration (0.1 mm)	Measured Value	56.4	51.7	44.4	45.5
	Predicted Value	57.1	52.2	44.1	45.0
	Error	−0.70	−0.50	0.30	0.50
5 °C Ductility (cm)	Measured Value	38.5	52.0	49.2	59.3
	Predicted Value	43.4	46.8	47.2	56.6
	Error	−4.93	5.24	2.00	2.67
Softening Point (°C)	Measured Value	88.9	106.0	106.8	110.6
	Predicted Value	90.7	104.4	107.7	110.6
	Error	−1.84	1.55	−0.87	0.02
60 °C Dynamic Viscosity (10,000 Pa·s)	Measured Value	1.3	2.4	34.4	56.5
	Predicted Value	3.4	1.4	34.9	54.3
	Error	−2.1	1.0	−0.5	2.2

Based on the regression model, the model calculation values of each performance under the experimental mix ratios were calculated and compared with the original experimental values (as shown in Figure 3). As seen in Figure 3, the penetration, ductility, and softening point of the experimental group all meet the technical requirements, while the dynamic viscosity only partially meets the technical requirements. The penetration values are most evenly distributed along the y = x line, particularly in the 45–50 range, where they coincide closely with the line. This indicates that the penetration model is highly accurate. The softening point has the second most uniform distribution, with values in the 100–110 °C range mostly overlapping with the line. The ductility at 5 °C has the third most uniform distribution, and the dynamic viscosity shows the largest scatter in distribution. However, for values above 200,000 Pa·s, except for a few with larger errors, the data are close to the line. This characteristic aligns with the technical requirements of high-viscosity, high-elasticity modified asphalt designed in this study, and therefore, it is concluded that the constructed multivariable quadratic nonlinear model is valid for use.



(**a**) Penetration (**b**) 5 °C Ductility (**c**) Softening Point (**d**) Dynamic Viscosity

Figure 3. Scatter plot of model calculation values vs. experimental values.

3.1.3. Determination of Mix Ratio

Through the analysis of the coefficients of each variable in the multivariate quadratic model, and by inputting different ratios into the constructed multivariate quadratic model, the influence of different modifiers on the four properties of asphalt was compared. The findings are as follows: Penetration: Aromatic oil > SBS > TPS; Ductility: TPS > SBS > Aromatic oil; Softening point: SBS > TPS > Aromatic oil; Dynamic viscosity: SBS > TPS > Aromatic oil.

Considering the prices of the modifiers (SBS at 11,000 RMB/ton and TPS at 21,000 RMB/ton), 1% TPS content is chosen as the baseline. Based on the models in Table 12, optimal solutions were obtained using Python, resulting in the best formulation for TPS-SBS-based high-viscosity and high-elasticity modified asphalt that meets the technical requirements for cold regions, as shown in Table 15. Subsequently, this formulation will be used as a baseline to explore and verify the performance of the TPS-SBS composite-modified asphalt.

Table 15. Best Formulation for TPS-SBS-Based High-Viscosity and High-Elasticity Modified Asphalt.

Material	Model	Ratio
Asphalt	90#	-
SBS	1301	9%
TPS	-	1%
Aromatic Oil	-	3.0%
Stabilizer	S	0.10%

3.2. Performance Evaluation of TPS-SBS Composite-Modified Asphalt with High Viscosity and High Elasticity

3.2.1. Basic Physical Properties

The best formulation of TPS-SBS high-viscosity and high-elasticity modified asphalt, as determined in the previous section, was tested for basic properties, including the three major indicators, 60 °C dynamic viscosity, and elastic recovery, with SBS modified asphalt (with the composition: 9% SBS + 3.0% aromatic oil + 0.1% sulfur) used as a reference. The test results are shown in Figure 4.

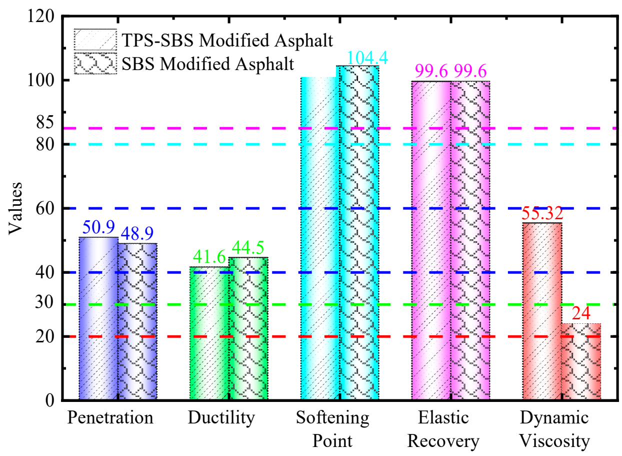


Figure 4. Basic Performance Test Results of Modified Asphalt (Note: The dashed lines in the figure represent the minimum technical limit values for the corresponding color performance. The range between the two blue dashed lines represents the technical specification range for the penetration value).

From Figure 4, it can be seen that the TPS-SBS-modified asphalt and SBS-modified asphalt both fully meet the established technical requirements for penetration, ductility, softening point, and elastic recovery performance indicators. The 5 °C ductility of the asphalt characterizes its low-temperature performance, the softening point characterizes its high-temperature performance, and the elastic recovery characterizes its ability to resist deformation. This fully proves that both asphalt materials have excellent physical properties and chemical stability, ensuring stable performance in various complex environments.

The 60 °C dynamic viscosity of the asphalt is an important indicator of its viscosity and one of the main indicators in this design. According to the test results, both types of asphalt have a 60 °C dynamic viscosity greater than the specification requirement (20×10^4 Pa·s), meeting the target. Furthermore, the 60 °C dynamic viscosity of TPS-SBS modified asphalt reached 55.32×10^4 Pa·s, far exceeding that of SBS-modified asphalt at 24×10^4 Pa·s and also significantly outperforming the dynamic viscosity of modified asphalt (with an optimal value of 35,000 Pa·s) studied by Tian et al. [44]. Therefore, TPS-SBS-modified asphalt demonstrates superior viscosity stability and resistance to flow under high-temperature conditions, making it better suited to meet the application demands in high-temperature environments.

3.2.2. Anti-Short-Term Aging Performance

Table 16 presents the performance indicators of TPS-SBS-based high-viscosity and high-elasticity modified asphalt after short-term aging, including mass loss, penetration ratio, ductility, rutting factor, and elastic recovery ratio. As shown in the figure, after the short-term aging test, the penetration, 5 °C ductility, and dynamic viscosity of the asphalt all showed varying degrees of decrease. The mass loss of the high-viscosity and high-elasticity modified asphalt was less than 0.3%, well below the technical requirement (1%) for modified asphalt in this study. This indicates that the designed high-viscosity and high-elasticity modified asphalt contains fewer light fractions and volatile substances.

Table 16. TFOT Test Results.

Performance	Unit	Before Aging	TPS-SBS Modified Asphalt	Technical Requirement
Mass Loss	%	——	0.172	≤±1.0
Penetration Ratio	%	——	85.7%	≥75
Ductility (5 °C, 5 cm/min)	cm	42.6	32.1	≥20
Rutting Factor (85 °C)	kPa	5.21	5.98	≥2.2
Elastic Recovery Ratio	%	99.6	98.4%	≥60

The penetration ratio of TPS-SBS modified asphalt was 85.7%, significantly higher than the technical requirement of 75%. Compared to the unaged samples, the 5 °C ductility and elastic recovery ratio of the aged samples decreased by 32.7% and 1.2%, respectively, indicating that short-term aging reduced the asphalt's elasticity, particularly its low-temperature elasticity. The slightly increased rutting factor (from 5.21 to 5.98) also confirms this observation.

Furthermore, although short-term aging had some impact on the performance of TPS-SBS-modified asphalt, the performance indicators after aging still significantly exceeded the performance limits, demonstrating excellent performance. Specifically, the penetration ratio of the TPS-SBS modified asphalt before and after aging was 85.7%, well above the technical requirement of 75%. The rutting factor and elastic recovery ratio of the aged samples were 5.98 and 98.4%, respectively, while the corresponding technical requirements were: not less than 2.2 kPa and 60%.

3.2.3. Rotational Viscosity

The rotational viscosity of asphalt is an important indicator for evaluating the road performance of asphalt. As the viscosity of modified asphalt increases, the determination of rotational viscosity at 135 °C has gradually become a key indicator for controlling the construction performance of modified asphalt. The test results of 135 °C and 170 °C rotational viscosities for the two modified asphalt are shown in Figure 5, with SBS-modified asphalt performance used as a reference.

As shown in Figure 5, the 135 °C and 170 °C rotational viscosities of the TPS-SBS-modified asphalt are significantly higher than those of SBS-modified asphalt, increasing by 45.36% and 32.60%, respectively. This indicates that the addition of 1% TPS significantly enhances the bonding performance of the asphalt network structure. However, based on the temperature-viscosity curve of petroleum asphalt, the minimum construction temperature reference values for TPS and SBS-modified asphalts are calculated to be 176.20 °C and 176.32 °C, respectively. This shows that, although the rotational viscosities of the asphalts differ greatly, the addition of TPS has little effect on the construction temperature of SBS-modified asphalt. The construction temperature is determined by the rotational viscosity value and the rate of change of rotational viscosity with temperature. This suggests that the workability and ease of construction for TPS-SBS-modified asphalt are comparable to SBS-modified asphalt.

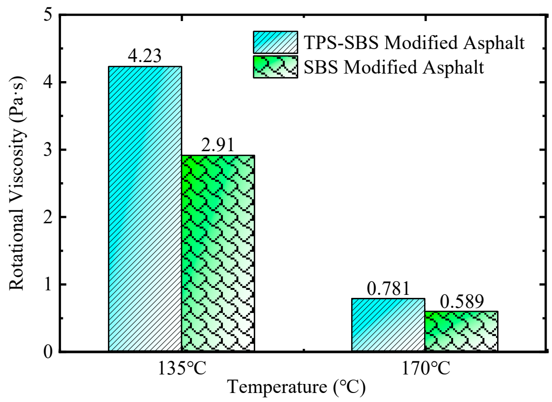


Figure 5. The rotational viscosity test values of asphalt.

3.2.4. Rheological Properties

The results of the temperature scan test for the TPS-SBS high-viscosity, high-elasticity modified asphalt are shown in Figure 6, including the phase angle-temperature relationship curve and the rutting factor-temperature relationship curve. The composition of asphalt can be divided into elastic and viscous parts. The phase angle value reflects the ratio of viscous components to elastic components in the asphalt; the larger the phase angle, the greater the proportion of viscous components, making the asphalt more prone to plastic deformation. The rutting factor is an indicator of high-temperature performance, where a larger value represents better high-temperature characteristics of the asphalt.

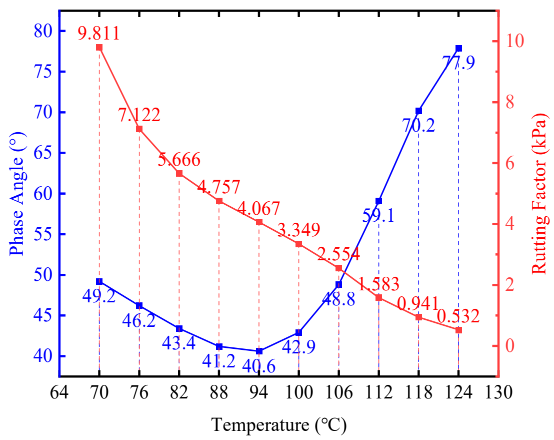


Figure 6. Temperature scanning test results of TPS-SBS modified asphalt.

From Figure 6, it can be seen that the phase angle decreases initially and then increases as the temperature rises, with the minimum value occurring at 94 °C. In the low-temperature range (70 °C to 94 °C), the phase angle decreases from 49.2° to 40.6°, indicating an increase in the proportion of elastic components in the asphalt, making it exhibit stronger deformation resistance and maintaining a certain level of rigidity. However, when the temperature reaches the turning point of 94 °C, the phase angle reaches its lowest value, showing good elastic recovery properties of the asphalt. Subsequently, in the high-temperature range (94 °C to 124 °C), especially at 124 °C, the phase angle increases significantly to 77.9°, indicating that the proportion of viscous components in the asphalt increases, and the internal structure of the modified asphalt starts to become less stable.

As a result, the asphalt's viscosity decreases, its resistance to deformation reduces, and its flowability increases, making it more prone to plastic deformation. This could potentially affect the pavement quality, especially in high-temperature environments where risks of rutting and permanent deformation may occur.

The rutting factor (calculated through the complex modulus and phase angle) is commonly used to evaluate the high-temperature performance of asphalt. As shown in Figure 6, the rutting factor value gradually decreases from 9.811 kPa at 70 °C to 0.532 kPa at 124 °C, reflecting the changes in the asphalt under high-temperature conditions. This could be due to physical or chemical changes in the modified materials inside the asphalt as the temperature increases. This trend is consistent with the changes in phase angle.

In the low-temperature range (70 °C to 94 °C), the rutting factor maintains a higher value, indicating that the asphalt has good high-temperature stability. However, in the high-temperature range (above 94 °C), the sharp decrease in the rutting factor suggests that the asphalt becomes more fluid, its structural stability decreases, and the applied load on the asphalt is more likely to cause permanent deformation. This characteristic reflects the physical property changes of TPS-SBS-based high-viscosity, high-elasticity modified asphalt at different temperatures: it performs excellently at low temperatures, but attention should be paid to potential deformation issues under high-temperature conditions. Therefore, when designing the application of asphalt, the temperature fluctuations in the working environment must be considered to ensure its long-term performance stability and pavement quality.

Additionally, it is important to note that at 106 °C, the TPS-SBS modified asphalt still has a relatively high rutting factor of 2.554 kPa, meeting the performance requirements (≥2.2 kPa). This demonstrates the excellent high-temperature performance of TPS-SBS-modified high-viscosity, high-elasticity asphalt.

4. Conclusions

This study mainly investigates the composite modification of 90# base asphalt using SBS and TPS modifiers. Through regression analysis, a multi-variable mathematical model was established to explore the effects of different additive ratios on the asphalt properties, providing theoretical and experimental support for optimizing the formula of modified asphalt. Meanwhile, performance verification studies of the best design plan were conducted, assessing the physical properties, dynamic viscosity, elastic recovery, short-term aging resistance, rotational viscosity, and rheological performance of the modified asphalt. The main research conclusions are as follows:

1. A basic physical property prediction model for TPS-SBS-based high-viscosity and high-elasticity modified asphalt was established through multi-variable quadratic nonlinear regression analysis. The goodness-of-fit for the models of penetration, ductility, softening point, and 60 °C dynamic viscosity were 0.929, 0.994, 0.882, and 0.939, respectively, confirming the reliability of the models. Additionally, the model successfully predicted the performance of TPS-SBS-based modified asphalt. For high dynamic viscosity asphalt, the prediction accuracy was higher, especially for the penetration, softening point, and ductility indicators.
2. Based on the model, the influence patterns of each material on asphalt performance were revealed: The impact on penetration: Aromatic oil > SBS > TPS; ductility: TPS > SBS > Aromatic oil; softening point: SBS > TPS > Aromatic oil; dynamic viscosity: SBS > TPS > Aromatic oil. Additionally, considering cost, the optimal formula for TPS-SBS composite-modified asphalt meeting the technical specifications of high-viscosity and high-elasticity modified asphalt was determined (9% SBS, 1% TPS, and 3% aromatic oil).

3. The TPS-SBS-based high-viscosity and high-elasticity modified asphalt prepared with the optimal formula showed significant compliance with the technical specifications for penetration, ductility, softening point, elastic recovery, and 60 °C dynamic viscosity. Specifically, its dynamic viscosity was approximately 55.32 $\times$ 10^4 Pa·s, significantly better than SBS-modified asphalt. Furthermore, the TPS-SBS composite-modified asphalt exhibited excellent aging resistance, workability, and high-temperature stability.
4. In recent years, various emerging materials have emerged one after another. Based on the optimal ratio of SBS-TPS composite-modified asphalt discussed in this article, future research should focus on the modification effects of various other modifiers on asphalt and compare them with each other, in order to select the most suitable modifier for application in cold regions. Secondly, the modification effects of various modifiers, especially the main research objects SBS and TPS, under mixed conditions (such as time–temperature coupling conditions) are still unclear, and the modification mechanism has not been deeply explored, which will become the focus of this study in the future.

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