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Mechanism and Performance Characterization of Dry-Process Asphalt Mixtures Modified with LDPE/EVA/SBS Composite Particles

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Abstract

This study employed a dry-process method to prepare SBS/recycled LDPE/EVA composite-modified particles (CMP) for asphalt mixture modification. Conventional performance tests, including penetration tests, determined the optimal CMP dosage to be 8% by mass of asphalt. The rheological properties and microstructure of base asphalt, SBS-modified asphalt, and composite-modified asphalt were systematically compared, and the road performance of the corresponding mixtures was evaluated. The results demonstrated that the composite modifier forms a uniform elastic network within the asphalt, significantly enhancing both high- and low-temperature performance and fatigue life while also improving thermal stability and deformation resistance. The modification mechanism is predominantly based on physical blending, and the system exhibits good thermal stability. The outstanding performance of the mixture, including a 284.4% increase in dynamic stability and a 60.1% extension in fatigue life, is attributed to the formation of a “skeleton–asphalt–particle” multiphase structure. Comprehensive performance analysis indicated that optimal performance is achieved with an SBS/LDPE/EVA ratio of 1:1:1, highlighting the considerable practical engineering potential of this dry-process composite modification technology.

Keywords: waste plastics; dry composite-modified particles; modification mechanism; performance of asphalt mixture; multi-index comprehensive evaluation



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1. Introduction

To facilitate the recycling of waste plastics, increasing research efforts have focused on incorporating plastic waste into asphalt binders and mixtures. This approach not only improves pavement performance but also consumes large volumes of plastic waste, thereby mitigating environmental pollution and disposal pressures [1–3]. Styrene–Butadiene–Styrene (SBS) block copolymer, owing to its excellent modification capability, is widely applied in road engineering. It significantly enhances rutting resistance, low-temperature cracking resistance, elasticity, and durability under diverse climatic conditions [4]. However, SBS is relatively expensive, and its wet-process modification demands specialized equipment and strict temperature control, which restricts its widespread application.

To reduce cost and improve sustainability, researchers have explored strategies to partially replace SBS with waste plastics or incorporate them synergistically, thereby lowering SBS content while maintaining pavement performance and improving resource utilization [5–7].

Various types of waste plastics, including Polyethylene (PE), Polypropylene (PP), Polyvinyl Chloride (PVC), and olefin copolymers, have been studied as modifiers. EVA and EEA are widely used due to their favorable thermoplastic behavior and abundance. The dry method incorporates discarded polymers directly into hot-mix asphalt as a partial substitute for the bitumen binder or fine aggregates. Waste PP, for example, has been shown to significantly enhance high-temperature stability, flexural strength, residual stability, and freeze–thaw resistance [8–10]. PVC typically requires wet-process modification due to its wide melting range and susceptibility to thermal degradation [11–13]. Polyethylene Terephthalate (PET), with a high melting point, is more suitable for dry-process applications and has been shown to improve moisture resistance and compressive strength, albeit at the cost of increased voids and reduced low-temperature crack resistance [14–17].

LDPE enhances asphalt performance by leveraging its low melting point and favorable compatibility to create a stabilizing three-dimensional network within the binder, thereby boosting stiffness and moisture resistance [18–23]. Recent research trends increasingly emphasize composite modification using multiple materials, including various functional fillers and additives [24–26]. For instance, studies on nanocomposites and hybrid materials have demonstrated the significant role of diverse additives in enhancing material properties [27,28]. In the context of asphalt modification, SBS provides strong modification effects, whereas waste plastics contribute environmental and economic benefits, making their combination particularly promising. Studies have shown that LDPE/SBS composite modification enhances rutting resistance, low-temperature cracking resistance, and durability [29,30]. EVA further improves SBS swelling and dispersion efficiency, accelerating dissolution and enhancing compatibility [31,32].

Although composite modification via the wet-process is well-documented, the direct dry blending of LDPE, EVA, and SBS for asphalt modification has received far less attention. Considering the thermoplastic properties and synergistic effects of LDPE, EVA, and SBS, this study develops a dry-process composite modifier suitable for direct addition during asphalt mixing. Preliminary economic analysis indicates that this dry-process method with composite particles could reduce material costs by approximately 13–22% compared to conventional wet-process SBS modification. Concurrently, the dry process significantly reduces overall energy consumption and potential heat loss by eliminating the separate modified asphalt production step and simplifying on-site construction procedures. The overall framework of this research is presented in Figure 1.

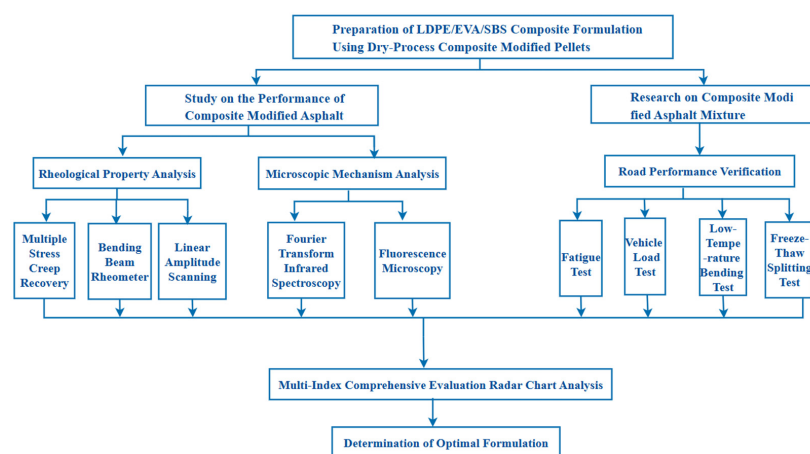


Figure 1. Research framework.

2. Materials and Methods

2.1. Materials

The experimental work adopted two key asphalt binders for comparison: a penetration-grade 70 neat binder and its SBS-modified counterpart. To modify the binders, SBS (SBS 3411, LCY Chemical, Huizhou, China), LDPE, and EVA pellets were introduced. Although LDPE and EVA are commonly sourced from waste materials like plastic bags and agricultural films, this study utilized standardized, commercially produced pellets to guarantee material consistency and experimental reproducibility. Asphalt performance tests were conducted following the Chinese standard JTG 3410-2025 [33]. The essential parameters of the raw materials are listed in Table 1.

Table 1. The primary parameters of the constituent materials.

Material Type	Technology Index	Unit	Test Result	Specification Requirement	Testing Method
No. 70 A grade base asphalt	Needle penetration (25 °C, 100 g, 5 s)	0.1 mm	71	60–80	T0604-2011
	Ductility (15 °C, 5 cm/min)	cm	13.8	≥100	T0605-2011
	Softening point (ball and ring method)	°C	48.3	≥46	T0606-2011
	60 °C dynamic viscosity	Pa·s	192.7	≥180	T06025-2011
	Density (15 °C)	g/cm ³	1.038	Actual measurement	T0603-2011
	Flash point	°C	290	≥260	T06011-2011
	Solubility	%	99.8	≥99.5	T0607-2011
	Adhesion with coarse aggregate	-	5	≥5	T06016-2011
	RTFOT	Mass variation	−0.05	≤±0.8	T06010-2011
	than	Residual penetration ratio (25 °C)	76	≥61	T0604-2011
SBS-modified asphalt		Residual ductility (10 °C)	7.6	≥6	T0605-2011
	Needle penetration (25 °C, 100 g, 5 s)	0.1 mm	53	40–60	T0604-2011
	Ductility (15 °C, 5 cm/min)	cm	37	≥20	T0605-2011
	Softening point (ball and ring method)	°C	72.5	≥60	T0606-2011
	135 °C dynamic viscosity	Pa·s	2.3	≤3	T06025-2011
	Density (15 °C)	g/cm ³	1.039	Actual measurement	T0603-2011
	Flash point	°C	301	≥230	T06011-2011
	Solubility	%	99.9	≥99	T0607-2011
	Adhesion with coarse aggregate	-	5	≥5	T06016-2011
	RTFOT	Mass variation	0.1	≤±1.0	T06010-2011
SBS modifier		Residual penetration ratio (25 °C)	78	≥65	T0604-2011
		Residual ductility (10 °C)	22	≥15	T0605-2011
	Molecular structure	-	-	Star-shaped	-
	Styrene/Butadiene	%	-	30/70	ASTM D5775
	Specific gravity	-	-	0.94	ASTM D792
	Melt index	g/10 min	-	<1	ASTM D1238
EVA	Ash content	%	-	0.3	ASTM D5667
	Volatile content	%	-	0.25	ASTM D5668
	Density	g/cm ³	-	0.960	ASTM D1505
	Melting point	°C	-	62	-
	Melt index	g/10 min	-	45	ASTM D1238
LDPE	Tensile breaking strength	MPa	-	4.5	ASTM D638
	Breaking elongation	%	-	950	ASTM D638
	Density	g/cm ³	-	0.924	ASTM D1505
LDPE	Melting point	°C	-	110	-
	Melt index	g/10 min	-	2.1	ASTM D1238
	Tensile breaking strength	MPa	-	≥11.8	ASTM D638
	Breaking elongation	%	-	≥386	ASTM D638

2.2. Sample Preparation

2.2.1. Preparation of Dry-Process CMP

The key raw materials were composite-modified particles derived from LDPE, EVA, and SBS. Additives included an antioxidant, aromatic oil, sulfur powder, alumina powder, and a titanate coupling agent. The LDPE, EVA, and SBS were first ground to a particle size below 60 µm using a shear mill and then blended. Three composite ratios of LDPE: EVA: SBS (1:1:1, 1:1:2, and 1:1:3, abbreviated as LES-1:1:1, LES-1:1:2, and LES-1:1:3, respectively) were prepared. For each formulation, the weighed LDPE, EVA, and SBS were dried at 80 °C for 4 h. Subsequently, the cross-linking agent (sulfur), coupling agent (titanate), and other additives were incorporated in their designated proportions. The combined raw materials were then mixed in a SHR high-speed mixer for 5 min to produce a homogeneous premix. The selection and proportion of additives were based on their specific functions and common practice in polymer modification. Incorporating antioxidant (≥2%) leads to

significant improvements in the melt flow rate and tensile strength of Polyethylene. Sulfur ($\geq 2\%$) and aromatic oil ($\geq 3\%$) improve the compatibility, dispersibility, and elasticity of the composite system. Alumina powder ($\geq 5\%$) promotes better melting and mixing by facilitating rapid heat transfer and providing oxidation resistance. The titanate coupling agent ($\geq 3\%$) offers versatility, acting not only as a coupling agent but also as a dispersant, adhesive, cross-linking aid, and catalyst, with additional benefits such as antioxidant and flame-retardant properties.

The selection and proportion of additives aim to synergistically address key issues in the blend system: inhibiting thermal aging, promoting compatibility and dispersion, constructing an elastic network, and improving processability. The specific explanations are as follows.

Antioxidant (2%): Its primary role is to capture free radicals generated during high-temperature processing, inhibit the thermo-oxidative aging of LDPE/EVA, and maintain the processing stability and mechanical properties of the polymers. This dosage achieves a balance between ensuring effective protection and avoiding negative effects.

Sulfur (2%) and aromatic oil (3%): Sulfur acts as a cross-linking agent, forming a moderate sulfur-crosslinked network between SBS molecules to enhance the elasticity of the system. Aromatic oil serves as a compatibilizer and plasticizer, promoting compatibility among the polymer components and adjusting viscosity. This proportion allows for effective cross-linking while maintaining material flexibility and processability.

Alumina powder (5%): It primarily functions as a processing aid and functional filler. Its high thermal conductivity accelerates the melting and homogenization of the blend, while its surface characteristics help improve the thermal stability of the system. This proportion balances optimizing heat transfer effects and avoiding excessive viscosity increase.

Titanate coupling agent (3%): It is used to enhance the interfacial bonding between the alumina filler and the polymer matrix, promote filler dispersion, and improve the overall performance of the composite material. This dosage is sufficient to achieve effective modification of the filler surface while also considering economic efficiency.

Accordingly, the preliminary formulation for the additives (antioxidant, aromatic oil, sulfur powder, alumina powder, and titanate) was fixed at a mass ratio of 2:3:2:5:3. The CMP illustrated in Figure 2.



Figure 2. Finished composite-modified particles for asphalt pavement.

2.2.2. Preparation of LDPE/EVA/SBS Composite-Modified Asphalt

The wet process was employed to prepare polymer-blended asphalt specimens, aiming to investigate their flow and deformation properties. We heated the base asphalt to 160–180 °C and then incrementally added the pretreated CMPs at ratios of 1:1:1, 1:1:2, and 1:1:3 [34]. The mixture was first mechanically stirred and then sheared at 3000 rpm and 180 °C for 30 min to achieve a uniform texture. Based on conventional performance metrics from penetration, softening point, and ductility, the optimal CMP dosage was determined to be 8% by mass of the asphalt [35]. This dosage was maintained for all subsequent binder and mixture tests.

2.2.3. Production of Composite-Modified Asphalt with Its Paving Mixture

All mixtures were designed using the AC-13 gradation. The aggregate gradation and optimum asphalt content were determined using the Marshall mix design method (JTG 3410-2025 T0709), which is based on volumetric analysis and performance tests. This approach ensures a densely packed aggregate skeleton, a principle aligned with the concept of stone skeleton design in methods like the Bailey method or VCA design. Three asphalt mixtures (base asphalt, SBS-modified, and dry-process composite) were produced in accordance with standards JTG 3410-2025 and JTG F40-2004 [36] for performance evaluation. Based on Marshall test results, the optimum asphalt contents were established at 4.9%, 5.0%, and 4.8%, respectively. The mixing protocol varied by type. The base asphalt mixtures and SBS-modified mixtures followed standard procedures. However, the dry-process CMP mixture utilized a specific sequence designed to actively form the characteristic “skeleton–asphalt–particle” multiphase structure during mixing (not a separate mix design method).

This structure emerges from the unique dry-mixing process where CMPs partially interact with the asphalt binder and aggregates:

Dry Mixing: CMPs were mixed with coarse aggregates at 185 °C for 90 s. This allows the CMPs to initially adhere to and potentially partially coat the hot aggregate surface.

Wet Mixing: Preheated asphalt, fine aggregates, and mineral filler were added sequentially, followed by mixing for 120 s. This ensures further dispersion of CMPs and the development of a composite mastic that bonds the aggregate skeleton, ultimately forming the target multiphase structure. Temperature parameters for mixing are detailed in Table 2.

Table 2. Temperature parameters of asphalt mixture preparation.

Temperature	Base Asphalt Mixture	SBS-Modified Asphalt	Dry-Modified Asphalt Mixture
Aggregate heating temperature	185 °C	200 °C	185 °C
Asphalt heating temperature	163 °C	175 °C	163 °C
Mixing temperature	170 °C	170 °C	170 °C

2.3. Test Scheme

This study systematically evaluated the performance enhancement provided by dry-process LDPE/EVA/SBS composite particles at two levels: the viscoelastic response of the binder and the mechanical/durability properties of the asphalt mixture. Additionally, economic analysis and a multi-index comprehensive evaluation method were employed to construct an integrated material performance assessment system.

2.3.1. Modification Mechanism and Performance Tests for Composite-Modified Asphalt

(1) Multiple stress creep recovery (MSCR) test

This study followed the AASHTO T 350 standard test procedure for conducting the MSCR test on base asphalt, SBS-modified asphalt, and various composite-modified

asphalts [37]. Measurements of non-recoverable creep compliance and recovery rate were taken at 58 °C, 64 °C, and 70 °C under 0.1 and 3.2 kPa stress to quantify their resistance to rutting.

(2) Bending beam rheometer (BBR) test

To assess low-temperature performance, BBR tests were performed per AASHTO T313. Specimens ($12.5 \times 12.5 \times 6.25$ mm) of the base asphalt, SBS-modified asphalt, and composite-modified asphalts were tested at -24 °C, -18 °C, and -12 °C to determine their creep stiffness and m-value at a 60 s loading period.

(3) Linear amplitude scanning (LAS) test

To evaluate fatigue resistance, LAS testing was employed in accordance with AASHTO TP101. A 10 Hz sinusoidal shear load was applied at 25 °C with the amplitude increased linearly to failure. The stress–strain response was recorded and processed using the Viscoelastic Continuum Damage (VECD) model to generate the fatigue damage evolution curve and extrapolate the fatigue life at 2.5% and 5.0% strain levels.

(4) Fluorescence microscopy (FM) image analysis

The micro-morphology of various asphalt binders, including base asphalt, SBS-modified, and composite-modified types, was examined using fluorescence microscopy at $200\times$ magnification. Aimed at elucidating the micro-scale modification mechanism, this analysis examined the distribution and structure of the dispersed particles within the LDPE/EVA/SBS composite system.

(5) Fourier transform infrared spectroscopy (FTIR) test

We performed FTIR analysis on the three asphalt binder types (base asphalt, SBS-modified, composite-modified) over the spectral range of $4000\text{--}650\text{ cm}^{-1}$. The examination of functional group and peak differences aimed to reveal the underlying modification mechanism.

2.3.2. Road Performance Tests for Dry-Process Composite-Modified Asphalt Mixture

In compliance with JTG 3410-2025 and JTG F40-2004, laboratory specimens of base asphalt, SBS-modified asphalt, and dry-process composite-modified asphalt mixtures were prepared. To assess their performance, the following tests were conducted: the wheel tracking test for high-temperature stability; the bending beam test at -10 °C to assess low-temperature crack resistance. The freeze–thaw splitting test for moisture susceptibility; and indirect tensile fatigue tests under stress control (10 Hz half-sine wave, stress ratios: 0.3, 0.4, 0.5, 0.6) to determine fatigue life.

2.3.3. Comprehensive Performance Evaluation

Four primary performance indicators were evaluated: high-temperature stability, low-temperature crack resistance, moisture susceptibility, and fatigue resistance were selected for a multi-criteria comparative analysis. Following data normalization, a radar chart was used to visualize and assess the comprehensive performance across these dimensions.

3. Test Results and Analysis

3.1. Performance Characterization and Action Mechanism of Composite Modifiers in Asphalt

3.1.1. High-Temperature Performance of Composite Modifiers in Asphalt

In accordance with the AASHTO T 350 standard, multiple stress creep recovery (MSCR) tests were conducted on base asphalt, SBS-modified asphalt, and composite-modified asphalts with varying formulations at temperatures of 58 °C, 64 °C, and 70 °C [38]. Figure 3 presents the creep recovery rates (R) at two characteristic stress levels of 0.1 kPa and 3.2 kPa, while Figure 4 displays the corresponding non-recoverable creep compliance (J_{nr}).

These results are used to evaluate the high-temperature deformation resistance and stress sensitivity of the asphalt binders.

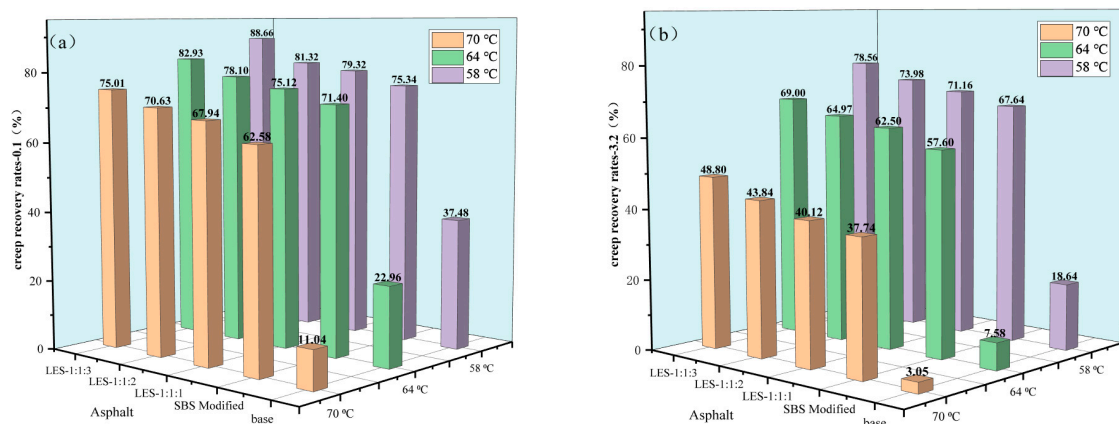


Figure 3. Test results of asphalt creep recovery rate (R): (a) 0.1 kPa. The creep recovery rates (R) at stress levels of 0.1 kPa; (b) 3.2 kPa. The creep recovery rates (R) at stress levels of 3.2 kPa.

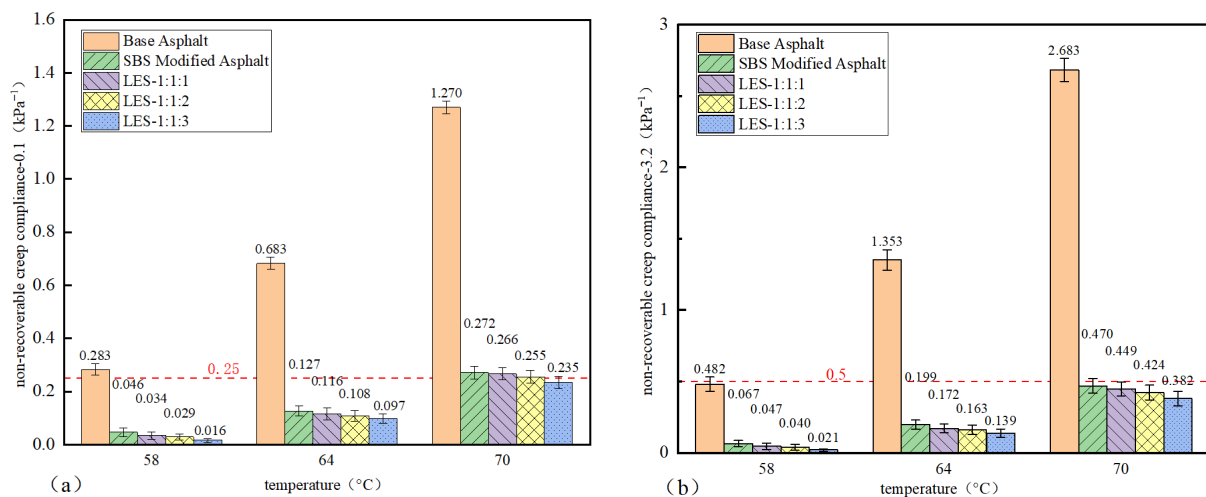


Figure 4. Test results of non-recoverable creep compliance (J_{nr}) of asphalt: (a) 0.1 kPa, the non-recoverable creep compliance (J_{nr}) at stress levels of 0.1 kPa; (b) 3.2 kPa, the non-recoverable creep compliance (J_{nr}) at stress levels of 3.2 kPa.

As illustrated in Figure 3, the creep recovery rate (R) of all asphalt binders exhibits a declining trend with increasing stress levels and temperatures. An increase in temperature from 58 °C to 70 °C at 0.1 kPa triggered sharp declines of 70.85% and 16.9% in the R values of the base asphalt and SBS-modified asphalts, respectively; in contrast, the three composite-modified asphalts (LES-1:1:1, LES-1:1:2, and LES-1:1:3) showed superior stability, with reductions of only 14.3%, 13.1%, and 15.4%. Under a higher stress level of 3.2 kPa, the reductions for the base asphalt and SBS-modified asphalts further expanded to 83.6% and 44.2%, while the composite binders maintained relatively lower decreases (43.6%, 40.7%, and 39.15%). Across all test conditions, the R values followed the hierarchy of LES-1:1:3 > LES-1:1:2 > LES-1:1:1 > SBS-modified asphalt > base asphalt. The 8.5–19.7% higher R values of composite asphalts at 64 °C and 3.2 kPa serve as a clear indicator of their enhanced elastic and high-temperature performance under heat.

As shown in Figure 4, the non-recoverable creep compliance (J_{nr}) values exhibited a consistent rise with temperature across all five asphalt types under each stress level (0.1 and 3.2 kPa), attributable to a decline in viscosity and a corresponding rise in the viscous component at elevated temperatures, which reduces its anti-deformation

capability. At a constant temperature, the J_{nr} values consistently ranked as follows: base asphalt > SBS-modified asphalt > composite-modified (LES-1:1:1) > composite-modified (LES-1:1:2) > composite-modified (LES-1:1:3). The differences were more pronounced at 3.2 kPa. Under 0.1 kPa at 64 °C, J_{nr} reductions of 8.7%, 14.9%, and 23.6% were attained by the three composite-modified asphalts compared to the SBS-modified asphalt and 13.6%, 18.1%, and 30.2% lower under 3.2 kPa. The findings attest to the efficacy of dry-process composite particles in improving deformation resistance at elevated temperatures. Additionally, stress sensitivity was evaluated using the $J_{nr-diff}$ parameter in Equation (1) per AASHTO specifications, where a higher value indicates greater susceptibility to deformation under high stress. The calculation formula is as follows [39]:

$$J_{nr-diff} = \frac{J_{nr-3.2} - J_{nr-0.1}}{J_{nr-0.1}} \times 100\% \quad (1)$$

where $J_{nr-3.2}$ and $J_{nr-0.1}$ represent the non-recoverable creep compliance of asphalt at stress levels of 3.2 kPa and 0.1 kPa, respectively.

The calculated $J_{nr-diff}$ values for the five asphalt binders are presented in Figure 5. The data indicate an increasing trend in $J_{nr-diff}$ values as temperature rises across all samples, indicating an enhanced sensitivity to stress at higher thermal conditions. Within the specified test temperature range, the base asphalt failed to meet the requirements at temperatures of 64 °C and above, with the permissible limits being met by the SBS-modified asphalt and each composite formulation. Specifically, at 58 °C and 64 °C, the $J_{nr-diff}$ values followed the descending order SBS-modified > LES-1:1:2 > LES-1:1:1 > LES-1:1:3 formulations. However, at 70 °C, the ranking shifted slightly to SBS-modified > LES-1:1:1 > LES-1:1:2 > LES-1:1:3. These results indicate that the composite modifiers effectively reduce the stress sensitivity of the binder compared to the base asphalt.

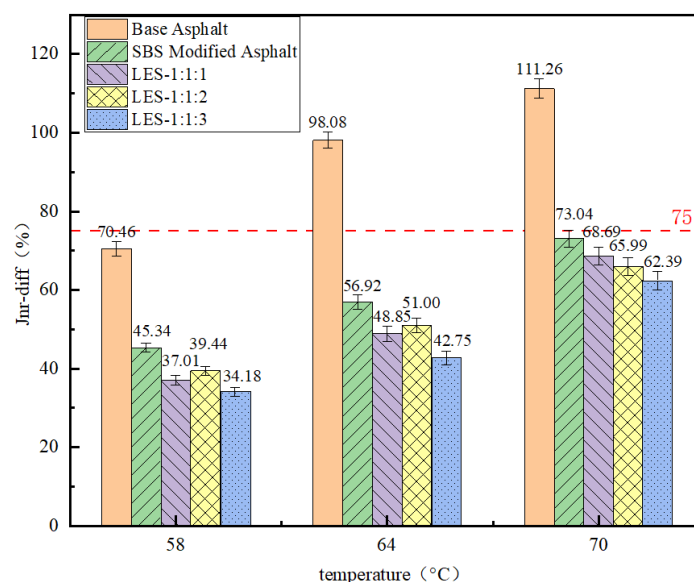


Figure 5. Test results of asphalt stress sensitivity evaluation index.

3.1.2. Low-Temperature Performance of Composite Modifiers in Asphalt

A drop in temperature resulted in elevated creep stiffness (S) and a corresponding reduction in the m -value, as revealed by the BBR test results in Figures 6 and 7. The composite-modified asphalts demonstrated superior low-temperature flexibility compared to the base asphalt. Specifically, at −18 °C, the S values for the LES-1:1:1, LES-1:1:2, and LES-1:1:3 formulations were reduced by 40.5%, 54.6%, and 50.3%, respectively. The

1:1:2 formulation performed best, likely due to EVA facilitating a synergistic “bridge” between LDPE and SBS, thereby enhancing stress relaxation.

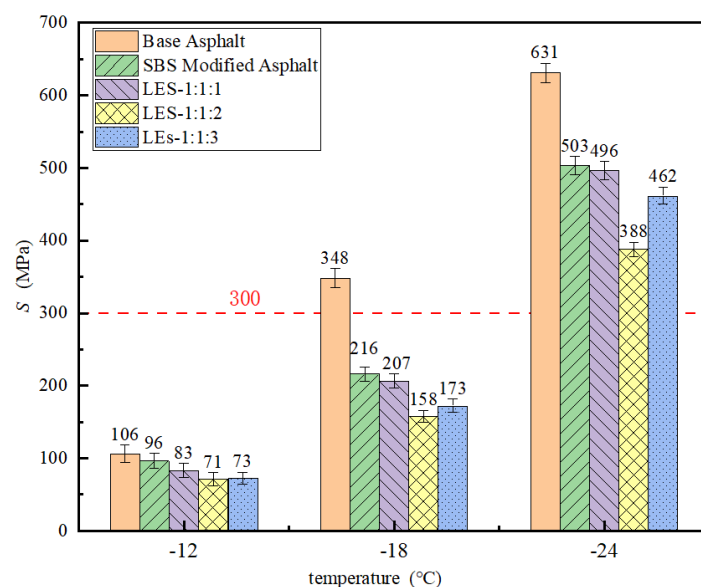


Figure 6. Creep stiffness test results of asphalt.

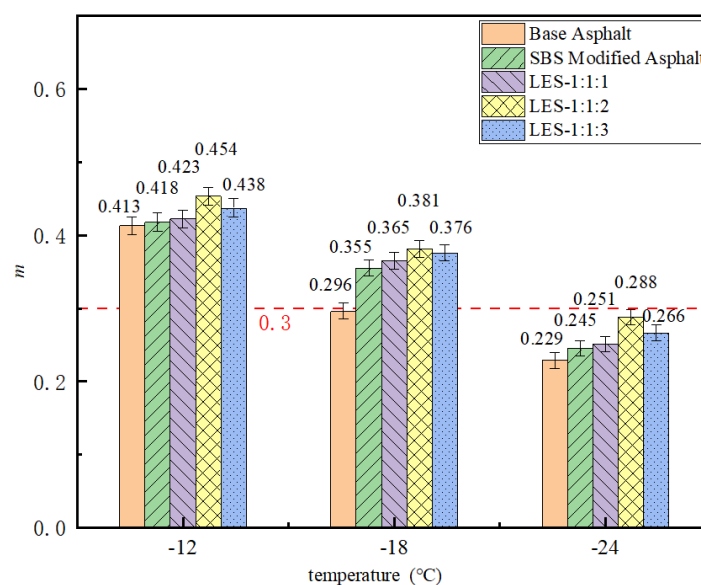


Figure 7. Creep rate test results of asphalt.

3.1.3. Fatigue Performance of Composite Modifiers in Asphalt

Figures 8 and 9 illustrate the stress–strain responses and fatigue damage curves of the five asphalt binders at 25 °C, respectively. As observed, all binders underwent a consistent sequence: their shear stress first rose with strain, attained a maximum, and then diminished. The yield strains of the composite-modified asphalts (LES-1:1:1, LES-1:1:2, and LES-1:1:3) are 15.1%, 16.2%, and 16.7%, respectively. Surpassing the values recorded for SBS-modified asphalt and base asphalt. These elevated yield strains signify a robust resistance to fatigue-induced failure. Furthermore, the fatigue damage curves, modeled via the VECD theory, reveal flatter trajectories and slower damage accumulation in the composite-modified binders. This underscores their superior fatigue durability compared to both SBS-modified and base asphalts.

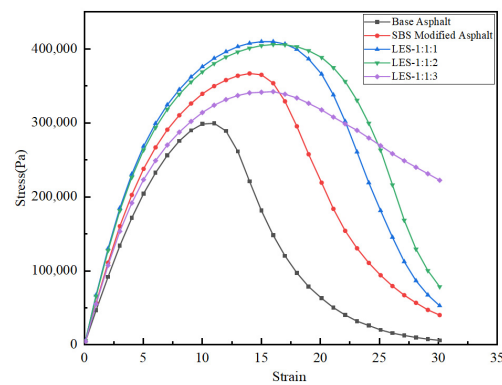


Figure 8. Shear stress–strain response.

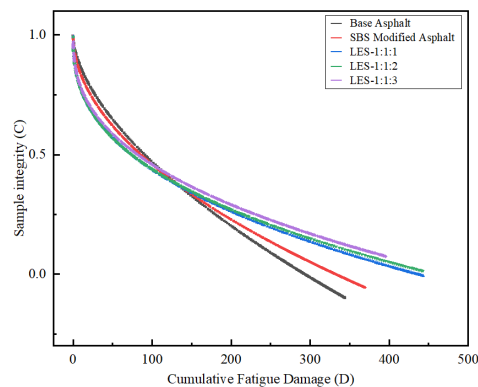


Figure 9. Damage accumulation from LAS test.

Fatigue life data for the various asphalt binders, encompassing the three composite ratios as well as the base asphalt and SBS-modified binders, are presented in Figure 10. At 2.5% shear strain, the composite-modified asphalts (LES-1:1:1, LES-1:1:2, LES-1:1:3) demonstrated fatigue life extensions by factors of 13.32, 17.44, and 21.91 over the base asphalt and by factors of 3.93, 5.15, and 6.47 over the SBS-modified asphalt. Even at a higher shear strain level of 5%, the composite-modified binders continued to exhibit superior performance, with fatigue lives 2.54 to 3.6 times greater than the SBS-modified control. Collectively, the evidence establishes that adding composite-modified particles markedly enhances the fatigue resistance and durability of asphalt binder.

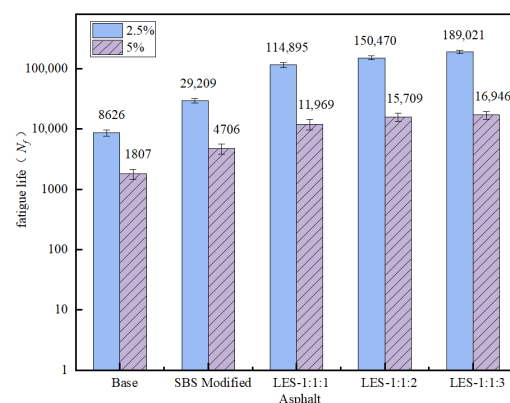


Figure 10. Results of asphalt fatigue life test.

3.1.4. Fluorescence Microscopy Analysis

Figure 11 depicts the microstructure of all five asphalt samples, with evident disparities in how their modifiers are distributed and shaped. The base asphalt (a) appears

homogeneous and black, with no discernible fluorescence. In contrast, the SBS-modified asphalt (b) exhibits uniformly distributed fine fluorescent spots, indicating excellent SBS dispersion. The composite-modified asphalts (c, d, e) display distinct fluorescent structures: the LES-1:1:1 formulation (c) forms a uniformly cross-linked filamentous network; the LES-1:1:2 formulation (d) develops a denser ternary synergistic network of LDPE, SBS, and EVA; and the LES-1:1:3 formulation (e) shows a reduction in filamentous structures and the appearance of aggregated, island-like fluorescent spots. These results indicate that an appropriate amount of SBS can synergize with LDPE and EVA to form a stable three-dimensional network. However, excessive SBS content, as in the LES-1:1:3 formulation, exceeds the accommodation capacity of the system, leading to phase separation, structural fragmentation, and a consequent weakening of the modification effect.

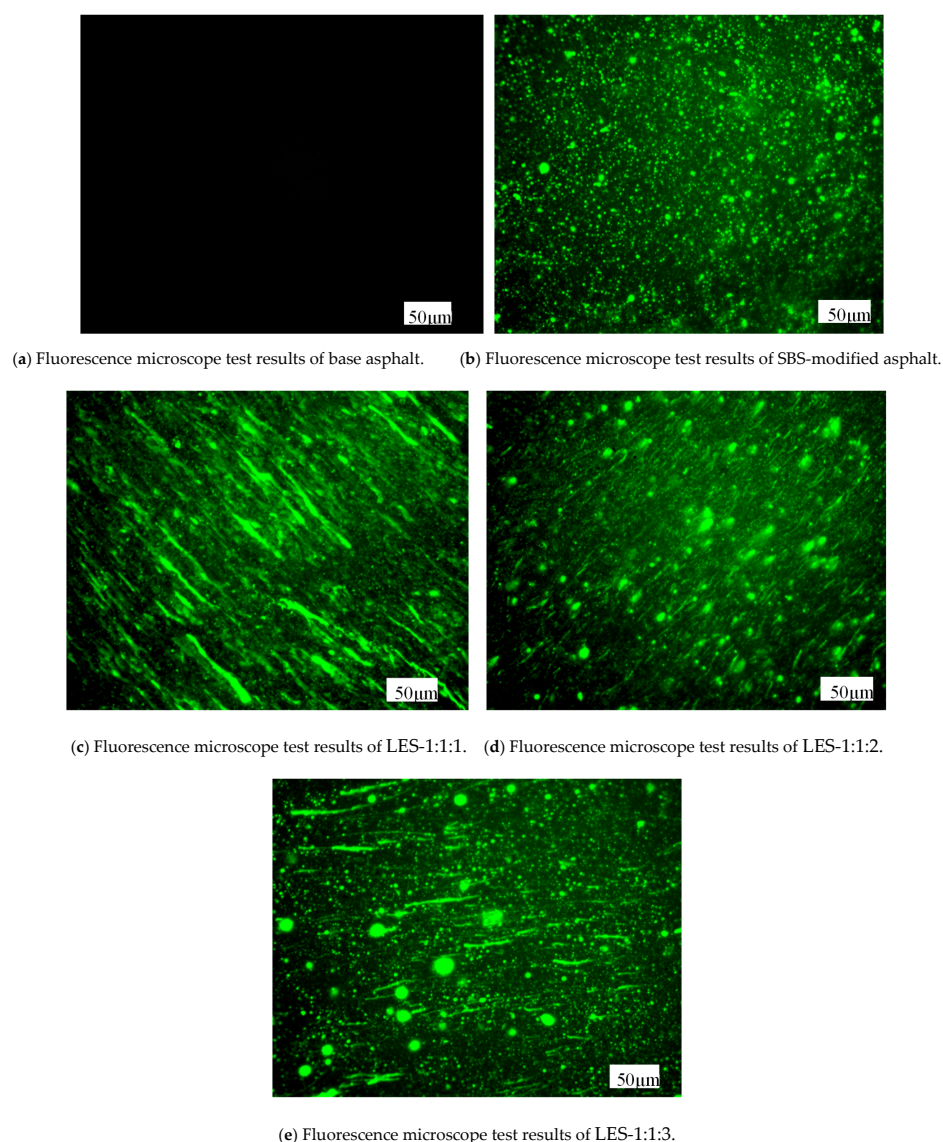


Figure 11. Different asphalt fluorescence microscope test results: (a) Fluorescence microscope test results of Base base asphalt; (b) Fluorescence microscope test results of SBS-modified asphalt; (c) Fluorescence microscope test results of LES-1:1:1; (d) Fluorescence microscope test results of LES-1:1:2; (e) Fluorescence microscope test results of LES-1:1:3.

3.1.5. FTIR Spectroscopy Analysis

As presented in Figure 12, an FTIR spectroscopic analysis was conducted. The infrared spectra of the modified binders retain the essential chemical fingerprint of the base asphalt,

as evidenced by the methylene and aromatic skeletal vibrations. However, the introduction of SBS and EVA is clearly marked by their signature absorption bands at 966 cm^{-1} , 1739 cm^{-1} , and 1238 cm^{-1} .

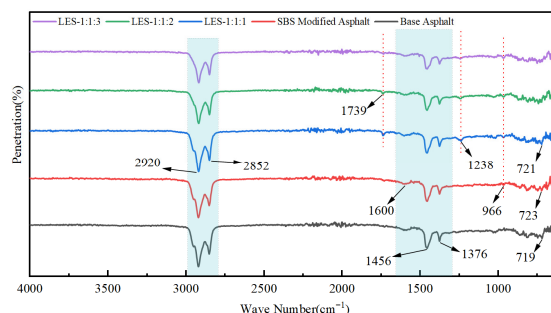


Figure 12. Infrared spectra of asphalt.

The lack of new peaks points to intermolecular physical interaction as the primary mechanism, as opposed to the creation of new covalent bonds. Based on a multi-criteria screening process including melt flowability, microstructural stability, and economic efficiency, the LES-1:1:3 formulation was deemed unsuitable due to excessive phase separation. Therefore, the LES-1:1:1 and LES-1:1:2 composite particles were identified as the optimal modifiers for the following road performance verification phase.

3.2. Pavement Performance in Dry-Process Composite Asphalt Systems

3.2.1. High-Temperature Performance of Asphalt Mixtures

As evidenced by the wheel tracking tests in Figures 13 and 14, high-temperature stability is superior in the dry-process composite mixtures compared to their base asphalt counterparts. Specifically, for the LES-1:1:1 formulation, the dynamic stability (DS) surged by 284.4%, while the final rut depth was reduced by 51.3%. Notably, the DS of the LES-1:1:1 dry-process mixture reached 94.2% of that of the SBS-modified control, indicating comparable performance to traditional wet-process modification. Furthermore, all modified mixtures surpassed the technical requirements (≥ 2400 cycles/mm) for modified asphalt mixtures specified in JTG F40-2004.

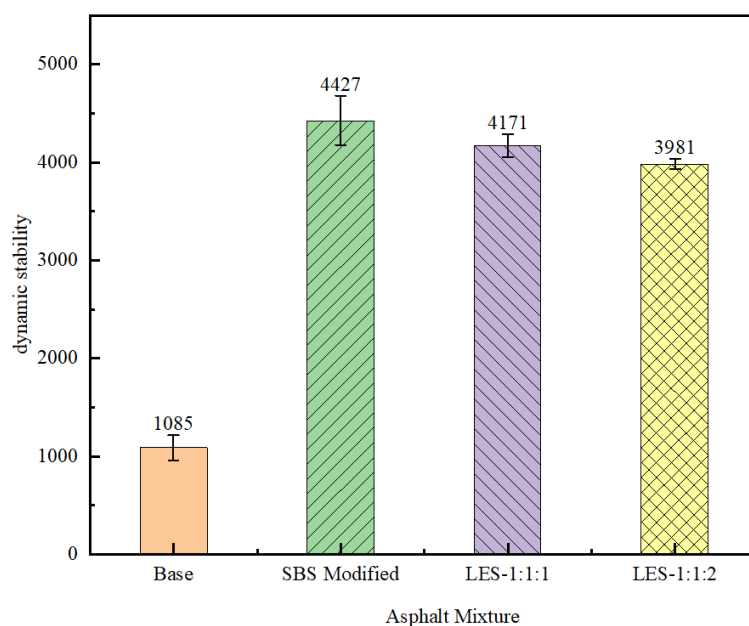


Figure 13. Dynamic stability of asphalt mixture.

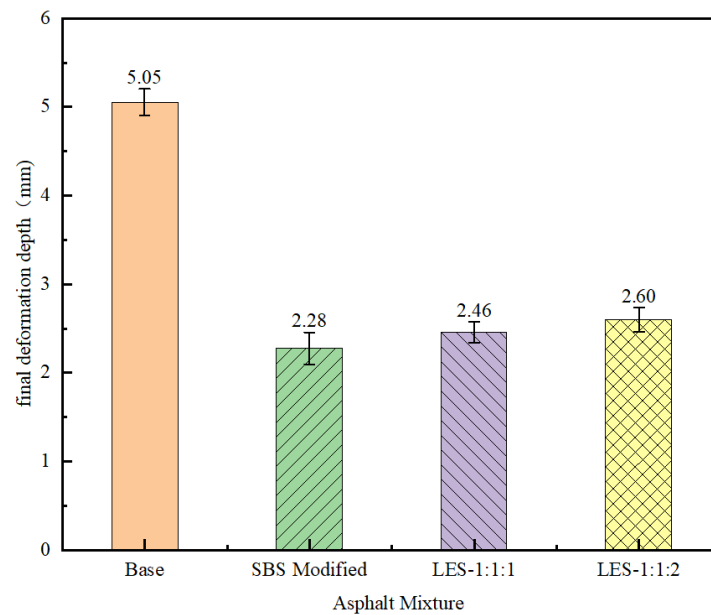


Figure 14. Final deformation depth of asphalt mixture.

3.2.2. Low-Temperature Performance of Asphalt Mixtures

Low-temperature bending test results in Figures 15 and 16 demonstrate that dry-process composite modification significantly enhances the crack resistance of asphalt mixtures at low temperatures. The flexural tensile strength of the LES-1:1:1 formulation is 1.36 and 0.95 times that of the base asphalt and SBS-modified mixtures, respectively. Notably, its maximum flexural tensile strain reached $5283 \mu\epsilon$, which is 1.81 and 0.9 times higher than the respective controls, far surpassing the JTG F40-2004 specification requirement of $\geq 2500 \mu\epsilon$. Bending stiffness modulus of asphalt mixtures test results are shown in Figure 17. It is observed that the LES-1:1:2 formulation exhibited a relatively higher flexural stiffness module 1.2 and 1.34 times that of the LES-1:1:1 and SBS-modified mixtures, indicating a tendency toward higher brittleness. In contrast, the LES-1:1:1 formulation and the SBS-modified mixture demonstrated superior ductility and deformation adaptability under low-temperature conditions.

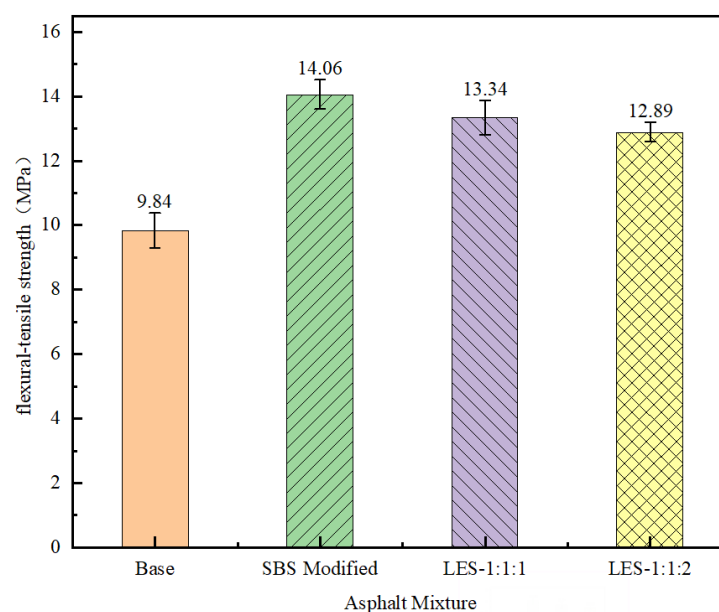


Figure 15. Bending strength of asphalt mixture.

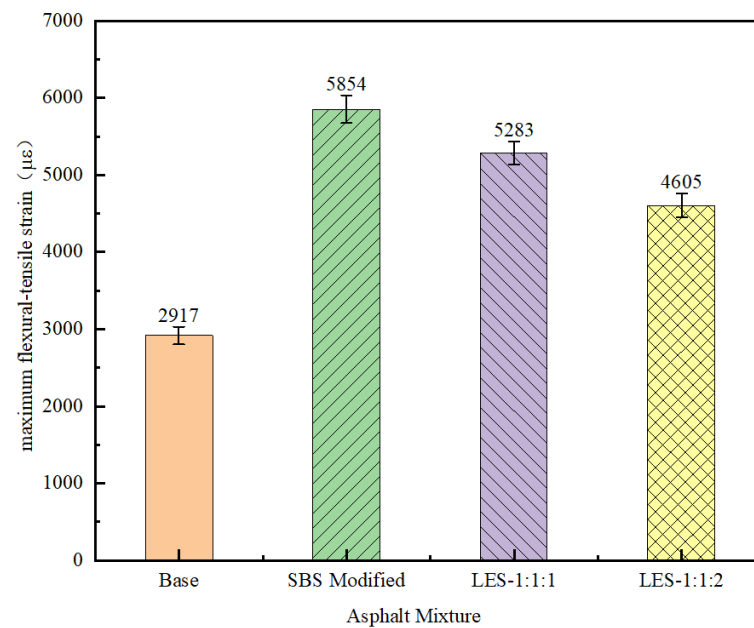


Figure 16. Peak strain recorded in asphalt beam bending test.

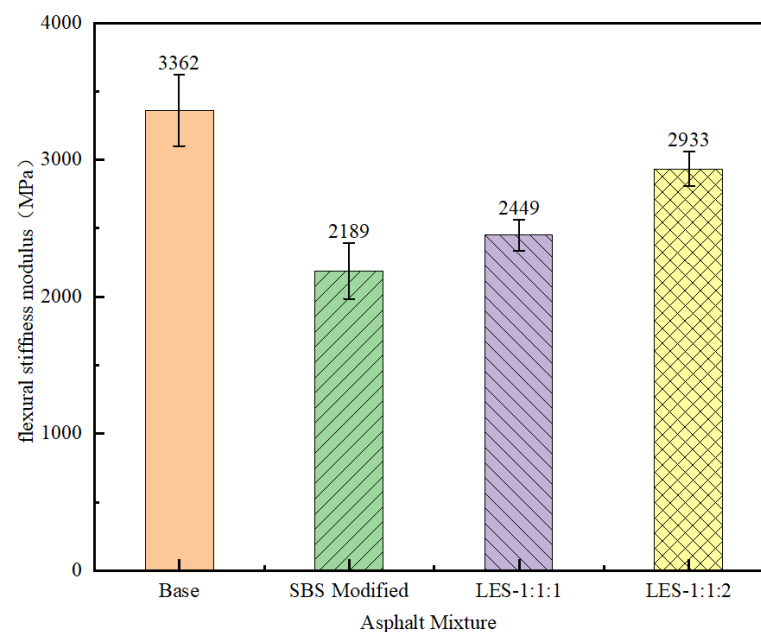


Figure 17. Bending stiffness modulus of asphalt mixtures.

3.2.3. Resistance to Freeze–Thaw Splitting of Asphalt Mixtures

Freeze–thaw splitting test data in Figures 18 and 19 reveal that dry-process composite modification significantly improves the moisture stability of asphalt mixtures. The LES-1:1:1 formulation exhibits outstanding performance: its tensile strength ratio (TSR) comfortably exceeds the specification threshold of $\geq 80\%$. Notably, the splitting strength of the LES-1:1:1 mixture declined by only 7.7% following the freeze–thaw cycle—a markedly smaller reduction compared to the SBS-modified and base asphalt mixtures. Furthermore, after freeze–thaw cycles, the LES-1:1:1 formulation retained a splitting strength equivalent to 96% of the SBS-modified control, highlighting its exceptional resistance to moisture-induced damage.

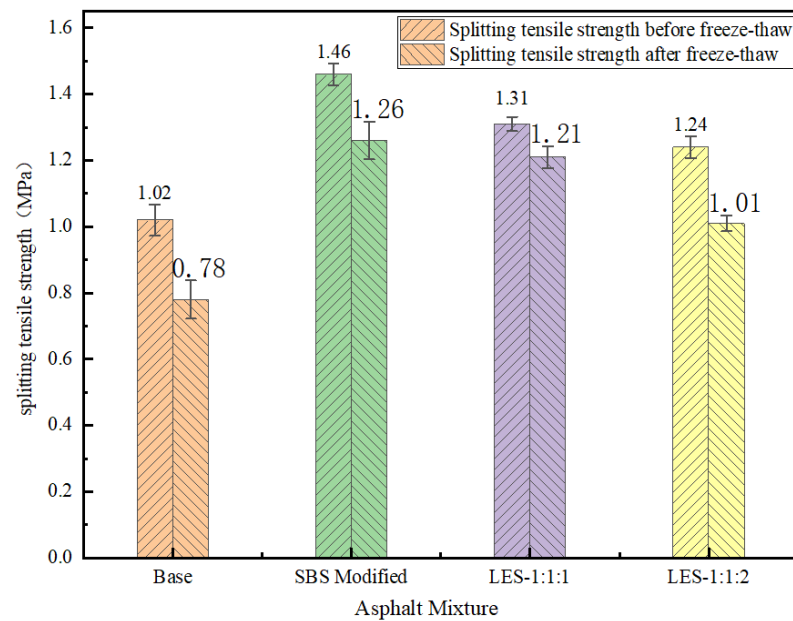


Figure 18. Test results of splitting tensile strength.

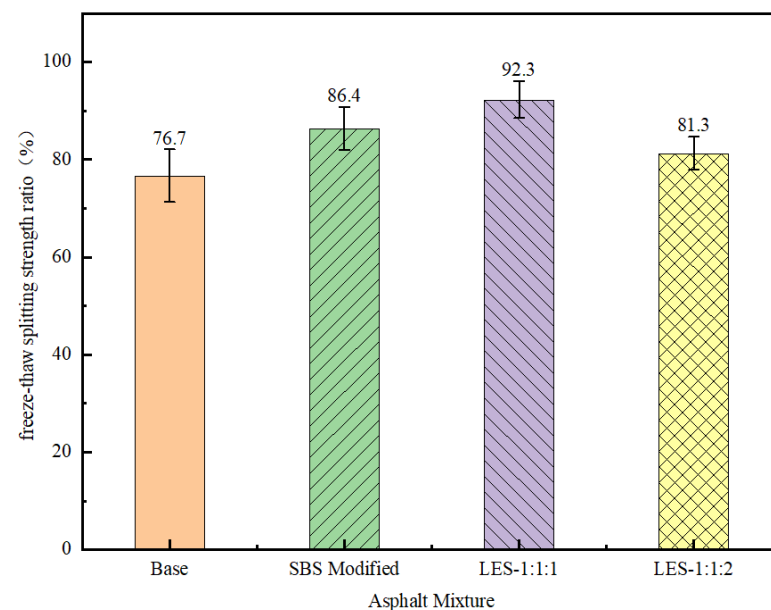


Figure 19. Freeze-thaw splitting strength ratio of asphalt mixture.

3.2.4. Fatigue Performance of Asphalt Mixtures

Data from Figures 20 and 21 and Table 3 establish the following hierarchy for the fatigue life (N_f) of the four mixtures across stress ratios from 0.3 to 0.6: SBS-modified > LES-1:1:1 dry-process > LES-1:1:2 dry-process > base asphalt. Specifically, at a low stress ratio of 0.3, the N_f of the LES-1:1:1 dry-process mixture reached 86.9% of that of the SBS-modified control. Even under a high stress ratio of 0.6, its fatigue life remained robust, accounting for 85.5% of the SBS-modified mixture while outperforming the base asphalt mixture by 60.1%. These results indicate that the LES-1:1:1 dry-process formulation provides highly competitive fatigue resistance, maintaining high durability even under severe loading conditions.

Regression analysis of the fatigue life curves reveals that the correlation coefficients (R^2) for all four asphalt mixtures exceed 0.98, demonstrating a high degree of linear correlation.

The fatigue parameters k_1 , representing the intercept, and k_2 , representing stress sensitivity, were determined from the fitting process. The k_1 values follow the descending order base asphalt > LES-1:1:2 > LES-1:1:1 > SBS-modified, while the k_2 values follow the order SBS-modified > LES-1:1:2 > LES-1:1:1 > base asphalt. Within the stress ratio range of 0.3–0.6, the dry-process composite-modified mixtures exhibit significantly enhanced fatigue resistance and optimized stress sensitivity compared to the base asphalt mixture. Notably, the LES-1:1:1 formulation demonstrates superior fatigue durability, achieving performance on par with the wet-process SBS-modified asphalt mixture.

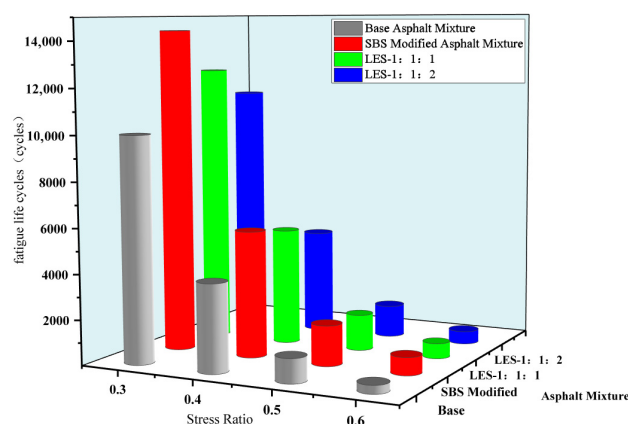


Figure 20. Fatigue life (N_f) of paving mixtures.

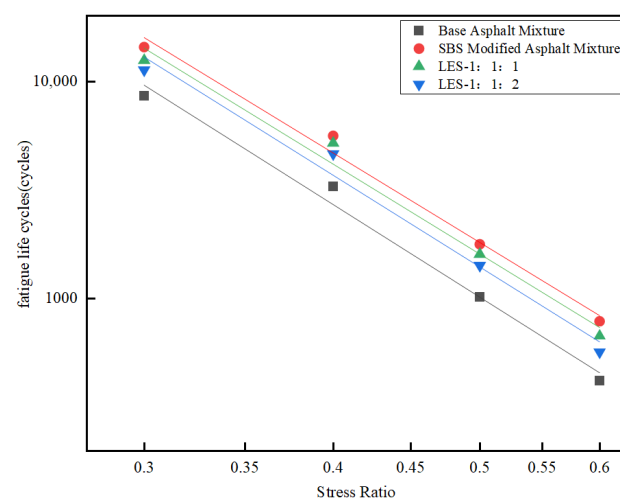


Figure 21. Fatigue prediction model for asphalt mixtures.

Table 3. Asphalt mixture fatigue fitting equation.

Bituminous Mixture	Fatigue Equation	$\lg k$	n	R^2
Base asphalt	$\lg N_f = 1.69 - 4.39 \lg t$	1.69	4.39	0.98
SBS modification asphalt	$\lg N_f = 1.98 - 4.25 \lg t$	1.98	4.25	0.99
Dry-process (LES-1:1:1)	$\lg N_f = 1.92 - 4.27 \lg t$	1.92	4.27	0.98
Dry-process (LES-1:1:2)	$\lg N_f = 1.84 - 4.35 \lg t$	1.84	4.35	0.98

3.2.5. Multi-Indicator Comprehensive Evaluation Analysis of Asphalt Mixtures

To determine the optimal modification scheme, four critical dimensions—high-temperature stability, low-temperature crack resistance, moisture stability, and fatigue

performance—were selected for a holistic evaluation. A multi-criteria comprehensive analysis was performed by comparing the base asphalt, SBS-modified asphalt, and dry-process composite-modified mixtures using a normalized radar chart. Prior to plotting, all performance indicators were normalized to a 0–1.2 scale using the min–max method. For indicators where a lower value denotes better performance (e.g., flexural stiffness modulus), a reverse normalization was applied to maintain the “higher-is-better” convention across the chart. The resulting comparative radar chart is presented in Figure 22.

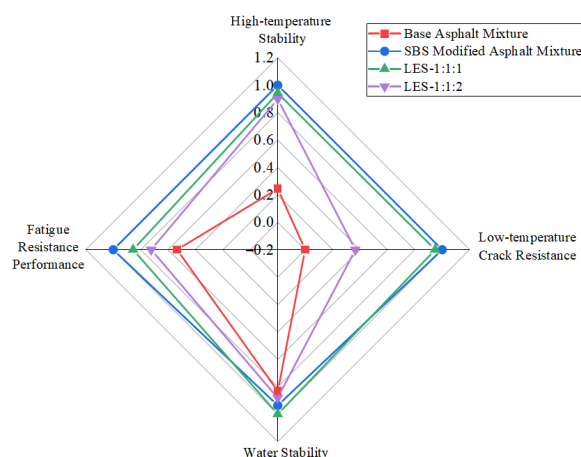


Figure 22. Asphalt mixture performance index normalized contrast radar chart.

As illustrated in the chart, the LES-1:1:1 dry-process composite-modified mixture exhibits the most equilibrated performance profile across all evaluated dimensions. It achieves the peak score in moisture stability, while its low-temperature crack resistance is surpassed only by the SBS-modified mixture. Furthermore, its high-temperature and fatigue performance levels are highly comparable to those of the SBS-modified control.

In contrast, the LES-1:1:2 formulation significantly underperforms across all four technical indicators, notably demonstrating the poorest performance in two key aspects: resistance to deformation at high temperatures and resistance to cracking at low temperatures.

In conclusion, the analysis based on the radar chart verifies that the LES-1:1:1 dry-process composite formulation delivers the most balanced and stable overall performance. Accordingly, the LES-1:1:1 ratio is recommended as the optimal scheme in this research.

4. Conclusions and Limitation

4.1. Conclusions

In this study, CMPs were prepared using a dry process with SBS, LDPE, and EVA. A wet-process system was also prepared for comparison to isolate the effect of the modification process. The conventional properties and the multi-faceted performance of the resulting composite asphalt—encompassing rheological behavior at both high and low temperatures as well as fatigue resistance—were comprehensively assessed. Micro-structural analysis using fluorescence microscopy and Fourier transform infrared spectroscopy (FTIR) were conducted to elucidate the synergistic enhancement mechanism of the CMPs in the asphalt binder. Furthermore, a corresponding asphalt mixture was fabricated via the dry process to assess its practical viability. The pavement performance of these mixtures was comprehensively evaluated in terms of rutting resistance, cracking resistance, moisture stability, fatigue resistance, and skid resistance. The principal findings are as follows:

(1) Relative to SBS-modified asphalt, the composite-modified asphalt with ratios of LES-1:1:1, LES-1:1:2, and LES-1:1:3 demonstrated superior performance; high-temperature

deformation resistance was significantly enhanced, with increases in the R value ranging from 8.5% to 19.7% and decreases in J_{nr} of 13.6% to 30.2%. Fatigue resistance was markedly improved, with fatigue life increasing by a factor of 2.54 to 3.60. In addition, low-temperature cracking resistance was substantially enhanced, as evidenced by reductions in creep stiffness S of 40.5% to 54.6% and increases in the m-value of 23.3% to 28.7% relative to the base asphalt.

(2) Microscopic analysis revealed that an appropriate SBS content (ratios LES-1:1:1 and LES-1:1:2) enabled the formation of a dense, uniform, elastic network structure with LDPE and EVA. Conversely, excessive SBS (ratio LES-1:1:3) reduced compatibility and led to a fragmented structure. FTIR analyses confirmed that the modification occurred primarily through physical blending. The composite also exhibited a higher thermal decomposition onset temperature and greater residual mass, indicating superior thermal stability.

(3) At the mixture level, the comprehensive performance improvements are attributed to the formation of a characteristic “skeleton–asphalt–particle” multiphase structure under dry-process conditions. The mixture with a LES-1:1:1 ratio showed a 284.4% increase in dynamic stability over the base asphalt mixture. Its flexural–tensile strength reached over 95% of the SBS-modified mixture’s performance, with a fatigue life improvement of approximately 60.1% under a high stress ratio. Furthermore, it demonstrated better moisture resistance, with a freeze–thaw splitting TSR of 7.7% loss compared to 13.6% for the SBS-modified mixture.

(4) Based on the analysis of the multi-index normalized radar chart, the dry method (LES-1:1:1) composite-modified asphalt mixture is balanced in performance dimensions, with the best comprehensive performance and excellent road performance, which is the optimal scheme recommended for this study.

4.2. Limitation

(1) It should be noted that the two-phase experimental design adopted in this study—wet-process asphalt modification testing and dry-process mixture performance validation—entails an inherent methodological consideration. The composite-modified asphalt prepared via high-shear wet-processing represents an idealized state in which the modifiers are fully melted and dispersed within the base asphalt. Its rheological properties (e.g., MSCR and BBR test results) reveal the inherent modification potential and fundamental mechanisms of the LDPE/EVA/SBS composite system. However, in the actual dry process, the composite-modified particles (CMP) may not achieve complete dissolution within the short mixing time, which constitutes a key prerequisite for forming its distinctive skeleton–asphalt–particle multiphase structure. Therefore, the test data from the wet-process asphalt cannot directly or precisely reflect the actual properties of the asphalt binder phase in the dry-process mixture. The core conclusions of this study are grounded in the macroscopic road performance of the dry-process mixtures, demonstrating that even under non-ideal melting conditions, this composite system can achieve outstanding performance enhancement through its unique structural effects. Future research could extract and recover the asphalt binder from dry-process mixtures and conduct rheological testing to more directly quantify the actual degree of modification imparted by the dry process to the asphalt phase, thereby further refining the evaluation framework for this technology.

(2) It is important to acknowledge a methodological consideration in this study. The fluorescence microscopy (FM) analysis presented in Figure 11 was conducted on laboratory-prepared wet-process binder samples. While these images effectively reveal the inherent potential of the LDPE/EVA/SBS composite to form an elastic network under idealized, fully-blended conditions and provide valuable insight into the modification mechanism, they do not constitute direct visual evidence of the proposed skeleton–asphalt–particle

structure within the actual dry-process mixture. The state of CMP melting, dispersion, and interfacial bonding with aggregates and mastic in the mixture may differ from the idealized wet-process state. To conclusively validate the micro-mechanism and directly visualize this multiphase architecture, future work should employ direct microstructural characterization of the dry-process mixture itself, such as scanning electron microscopy (SEM) analysis of polished mixture cross-sections. This will provide definitive evidence of the structure and complete the mechanistic evaluation of this promising dry-process technology.

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References

1. Ma, J.S.; Xue, Y.B.; Guo, Q.; Liu, Z. Research Progress of Waste Plastic Modifier Modified Asphalt. *China Plast.* **2022**, *36*, 131–138. [[CrossRef](#)]
2. Santos, J.; Pham, A.; Stasinopoulos, P.; Giustozzi, F. Recycling waste plastics in roads: A life-cycle assessment study using primary data. *Sci. Total Environ.* **2021**, *751*, 141842. [[CrossRef](#)]
3. Wu, S.; Montalvo, L. Repurposing waste plastics into cleaner asphalt pavement materials: A critical literature review. *J. Clean. Prod.* **2021**, *280*, 124355. [[CrossRef](#)]
4. Dalhat, M.A.; Al-Adham, K. Review on laboratory preparation processes of polymer modified asphalt binder. *J. Traffic Transp. Eng. (Engl. Ed.)* **2023**, *10*, 159–184. [[CrossRef](#)]
5. Xu, C.H.; Shi, Z.W.; Cheng, Y.K.; Yin, Z.Y. Study on Rheological Properties of Warm-Mix Waste Plastic/SBS Composite Modified Asphalt. *Plast. Sci. Technol.* **2024**, *52*, 70–76.
6. Yildirim, Y. Polymer modified asphalt binders. *Constr. Build. Mater.* **2007**, *21*, 66–72. [[CrossRef](#)]
7. Han, M.; Zeng, X.; Muhammad, Y.; Li, J.; Yang, J.; Yang, S.; Wei, Y.; Meng, F. Preparation of Octadecyl Amine Grafted over Waste Rubber Powder (ODA-WRP) and Properties of Its Incorporation in SBS-Modified Asphalt. *Polymers* **2019**, *11*, 665. [[CrossRef](#)] [[PubMed](#)]
8. Tapkın, S. The effect of polypropylene fibers on asphalt performance. *Build. Environ.* **2008**, *43*, 1065–1071. [[CrossRef](#)]
9. Lastra-González, P.; Calzada-Pérez, M.A.; Castro-Fresno, D.; Vega-Zamanillo, Á.; Indacoechea-Vega, I. Comparative analysis of the performance of asphalt concretes modified by dry way with polymeric waste. *Constr. Build. Mater.* **2016**, *112*, 1133–1140. [[CrossRef](#)]
10. Zachariah, J.P.; Sarkar, P.P.; Pal, M. A study on the moisture damage and rutting resistance of polypropylene modified bituminous mixes with crushed brick aggregate wastes. *Constr. Build. Mater.* **2021**, *269*, 121357. [[CrossRef](#)]
11. Brasileiro, L.; Moreno-Navarro, F.; Tauste-Martínez, R.; De Matos, J.M.; Rubio-Gamez, M.C. Reclaimed Polymers as Asphalt Binder Modifiers for More Sustainable Roads: A Review. *Sustainability* **2019**, *11*, 646. [[CrossRef](#)]
12. Jwaida, Z.; Dulaimi, A.; Mydin, M.A.; Özkılıç, Y.O.; Jaya, R.P.; Ameen, A. The Use of Waste Polymers in Asphalt Mixtures: Bibliometric Analysis and Systematic Review. *J. Compos. Sci.* **2023**, *7*, 415. [[CrossRef](#)]

13. Bueno, I.M.; Teixeira, J.E.S.L. Waste Plastic in Asphalt Mixtures via the Dry Method: A Bibliometric Analysis. *Sustainability* **2024**, *16*, 4675. [\[CrossRef\]](#)
14. Masri, K.A.; Ferdaus, R.; Ramadhansyah, P.J. Sustainable Use of Polymer in Asphalt Mixture: A Review. *Construction* **2022**, *2*, 12–21. [\[CrossRef\]](#)
15. Barot, A.; Panchal, T.; Patel, A.; Vyas, R. Polyester: The Workhorse of Polymers—A Review from Synthesis to Recycling. *Polymers* **2019**, *11*, 19.
16. Leng, Z.; Padhan, R.K.; Sreeram, A. Production of a sustainable paving material through chemical recycling of waste PET into crumb rubber modified asphalt. *J. Clean. Prod.* **2018**, *180*, 682–688. [\[CrossRef\]](#)
17. Movilla-Quesada, D.; Raposeiras, A.C.; Guíñez, E.; Frechilla-Alonso, A. A Comparative Study of the Effect of Moisture Susceptibility on Polyethylene Terephthalate-Modified Asphalt Mixes under Different Regulatory Procedures. *Sustainability* **2023**, *15*, 14519. [\[CrossRef\]](#)
18. Xiao, R.; Shen, Z.; Polaczyk, P.; Huang, B. Thermodynamic Properties of Aggregate Coated by Different Types of Waste Plastic: Adhesion and Moisture Resistance of Asphalt-Aggregate Systems. *J. Mater. Civ. Eng.* **2023**, *35*, 14519. [\[CrossRef\]](#)
19. Xiao, R.; Zhang, M.; Zhong, J.; Baumgardner, G.L.; Huang, B. Waste Plastic Powder Coating on Acidic Aggregates: A New Hydrophobic Coating Technology to Build Moisture-Resistant Asphalt Mixtures. *Transp. Res. Rec. J. Transp. Res. Board* **2023**, *2679*, 992–1005. [\[CrossRef\]](#)
20. Xiao, R.; Polaczyk, P.; Huang, B. Mitigating Stripping in Asphalt Mixtures: Pretreatment of Aggregate by Thermoplastic Polyethylene Powder Coating. *Transp. Res. Rec. J. Transp. Res. Board* **2023**, *2678*, 776–787. [\[CrossRef\]](#)
21. Duarte, G.M.; Faxina, A.L. Asphalt concrete mixtures modified with polymeric waste by the wet and dry processes: A literature review. *Constr. Build. Mater.* **2021**, *312*, 125408. [\[CrossRef\]](#)
22. Xu, F.; Zhao, Y.; Li, K. Using Waste Plastics as Asphalt Modifier: A Review. *Materials* **2022**, *15*, 110. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Liu, H.; Ren, X.; Ge, W.; Yi, Z.; Jin, D.; Peng, X.; Lv, S. Performance characterization and mechanistic study of dry process WR/SBS composite modified asphalt mixture. *Case Stud. Constr. Mater.* **2025**, *22*, e04639. [\[CrossRef\]](#)
24. Wang, C.; Duan, K.; Song, L.; Ji, X.; Shu, C. Stability improvement technology of SBS/crumb rubber composite modified asphalt from Xinjiang China. *J. Clean. Prod.* **2022**, *359*, 132003. [\[CrossRef\]](#)
25. Ghanoon, S.A.; Tanzadeh, J.; Mirsepahi, M. Laboratory evaluation of the composition of nano-clay, nano-lime and SBS modifiers on rutting resistance of asphalt binder. *Constr. Build. Mater.* **2020**, *238*, 117592. [\[CrossRef\]](#)
26. He, Y. Experimental Study on Road Performance of Glass Fiber Reinforced Crumb Rubber/SBS Composite Modified Asphalt Mixture. *Compr. Util. Fly Ash* **2024**, *38*, 138–141.
27. Nandihalli, N.; Liu, C.-J.; Mori, T. Polymer Based Thermoelectric Nanocomposite Materials and Devices: Fabrication and Characteristics. *Nano Energy* **2020**, *78*, 105186. [\[CrossRef\]](#)
28. Pasetto, M.; Pasquini, E.; Giacomello, G.; Baliello, A. Innovative composite materials as reinforcing interlayer systems for asphalt pavements: An experimental study. *Road Mater. Pavement Des.* **2019**, *20*, S617–S631. [\[CrossRef\]](#)
29. Ghani, U.; Zamin, B.; Tariq Bashir, M.; Ahmad, M.; Sabri, M.M.S.; Keawsawasvong, S. Comprehensive Study on the Performance of Waste HDPE and LDPE Modified Asphalt Binders for Construction of Asphalt Pavements Application. *Polymers* **2022**, *14*, 3673. [\[CrossRef\]](#)
30. Ye, F.Q. Anti-Aging Performance Analysis of LDPE/SBS Composite Modified Asphalt. *Fujian Transp. Sci. Technol.* **2024**, *12*, 22–28.
31. Yan, X.; Wu, D.; Hu, K.; Zhang, W.; Xing, J.; Cui, L.; Shi, S.; Yang, J.; Yang, C. The Modification Mechanism, Evaluation Method, and Construction Technology of Direct-to-Plant SBS Modifiers in Asphalt Mixture: A Review. *Polymers* **2023**, *15*, 2768. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Zhang, W.; Jia, Z.; Zhang, Y.; Hu, K.; Ding, L.; Wang, F. The Effect of Direct-to-Plant Styrene-Butadiene-Styrene Block Copolymer Components on Bitumen Modification. *Polymers* **2019**, *11*, 140. [\[CrossRef\]](#) [\[PubMed\]](#)
33. *JTG 3410-2025*; Standard Test Methods of Asphalt and Asphalt Mixture for Highway Engineering. The Ministry of Transport of the People's Republic of China: Beijing, China, 2025.
34. *GB/T 3682.1-2018*; Plastics—Determination of the Melt Mass-Flow Rate (MFR) and Melt Volume-Flow Rate (MVR) of Thermoplastics—Part 1: Standard Method. Standardization Administration of China: Beijing, China, 2018.
35. Cheng, L.; Zhang, Y.; Han, D.; Li, J. Asphalt Modifier Prepared from Waste Plastic Film and Preparation Method Thereof. China Patent CN202010255042.4, 2 April 2020.
36. *JTG F40-2004*; Technical Specifications for Construction of Highway Asphalt Pavements. The Ministry of Transport of the People's Republic of China: Beijing, China, 2004.
37. *AASHTO T 350:2019*; Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer. American Association of State Highway and Transportation Officials: Washington, DC, USA, 2019.

38. Li, Y.; Jiang, G.; Yan, S.; Feng, J.; Li, D. Performance and Mechanism of High-Viscosity and High-Elasticity Bitumen (HVE-MB) Modified with Five Additives. *Sustainability* **2023**, *15*, 14089. [\[CrossRef\]](#)
39. Sun, J.S.; He, Y.F.; Zhang, M.; Wang, W. Rheological Properties and Microstructural Characteristics of Waste Oil Composite Regenerated Asphalt. *J. Funct. Mater.* **2025**, *56*, 3113–3120. [\[CrossRef\]](#)

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