

Review

Polymer Modification in Asphalt: Reviewing the Synergistic Effects of SBS and Styrene–Methyl Methacrylate Copolymer-Based Modifier

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Abstract

Polymer-modified asphalt has been widely used to improve pavement durability under increasing traffic loads and complex environmental conditions. Styrene–butadiene–styrene (SBS) is one of the most effective elastomer modifiers. It can form a polymer-rich network within asphalt. Styrene–methyl methacrylate copolymer-based modifier (SMC) can be produced from recycled rubber and plastic resources. It has attracted increasing attention because of its potential compatibility, processability, and environmental benefits. This paper reviews the modification mechanisms, rheological properties, fatigue performance, aging resistance, and engineering applications of SBS-, SMC-, and SMC–SBS-modified asphalt and mixtures. Particular attention is given to the synergistic effects between SBS and SMC, including polymer swelling, phase morphology, network formation, interfacial compatibility, and durability evolution. Existing studies indicate that SBS mainly improves elastic recovery and high-temperature deformation resistance. In contrast, SMC can enhance workability, low-temperature flexibility, and construction compatibility. Their composite modification shows strong potential for balancing high-temperature, low-temperature, fatigue, and aging performance. However, current studies are still limited by insufficient quantitative comparisons, unclear microstructural mechanisms, and the lack of unified evaluation methods. Future studies should establish multi-scale structure–property–durability models. The modifier dosage range should also be optimized. This review provides a systematic reference for the development of high-performance and sustainable polymer-modified asphalt materials.

Keywords: styrene–butadiene–styrene (SBS); styrene–methyl methacrylate copolymer-based modifier (SMC); modified asphalt; modification mechanism; mechanical performance

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1. Introduction

In recent years, the rapid development of transportation has raised higher demands on asphalt materials. Key requirements include better high-temperature stability, low-temperature crack resistance, and aging resistance. Traditional base asphalt often suffers from rutting and cracking during long-term service [1]. It fails to meet the durability and performance needs of modern roads. Therefore, developing high-performance modified asphalt has become crucial to improving road quality and extending service life.

SBS, a thermoplastic elastomer, is widely used in asphalt modification. It offers good elasticity and toughness. SBS-modified asphalt significantly enhances resistance to high-temperature deformation and low-temperature cracking [2–4]. It is one of the most commonly used modifiers today. However, SBS-modified asphalt still faces challenges, such as phase separation and thermo-oxidative aging, which affect its stability and durability. The modification behavior of polymer-modified asphalt is strongly influenced by polymer–asphalt interactions, swelling behavior, and phase compatibility [5].

To address these issues, researchers have introduced SMC as a novel modifier [6]. SMC shows good thermal stability and compatibility. It effectively improves the rheological behavior and anti-aging performance of asphalt. Studies indicate that SMC-modified asphalt has promising potential for enhancing overall performance [7].

Given the complementary advantages of SBS and SMC, composite modification has attracted growing interest. The combination aims to achieve synergy and improve high-temperature stability, low-temperature crack resistance, and aging resistance. Research on SBS–SMC composite-modified asphalt is progressing. Preliminary studies indicate that SBS–SMC composites provide performance advantages under specific material combinations and testing conditions. This includes the high- and low-temperature rheological response of SMC–SBS binders [8], the engineering application of SMC–SBS thin-layer surfacing [9], the fatigue behavior of SMC–SBS mixtures [10], and the regeneration performance of SMC-treated aged SBS-modified asphalt [11]. However, the optimum dosage, applicable conditions, and modification mechanisms remain unclear and require further investigation.

This review provides a thematic and qualitative synthesis of the current knowledge on SBS-, SMC-, and SBS–SMC-modified asphalt. It covers their applications in asphalt binders and asphalt mixtures. It also discusses the modification mechanisms, performance characteristics, and remaining research challenges. The goal is to provide theoretical insights and technical references for future research and development of modified asphalt materials.

Compared with existing reviews on polymer-modified asphalt, this review focuses on the complementary and synergistic effects of SBS and SMC in asphalt modification. Previous reviews mainly discussed the general properties of polymer-modified asphalt, the phase structure of SBS, or storage stability issues. However, the coupling mechanism between SBS and SMC has not been systematically summarized. In particular, the relationships among polymer structure, phase compatibility, rheological response, mixture performance, and sustainable application remain insufficiently understood. Therefore, this review aims to address the following three key questions:

- (1) How do SBS and SMC individually modify asphalt binders and mixtures?
- (2) How do SBS and SMC interact in composite-modified asphalt systems?
- (3) What scientific and engineering challenges must be resolved before wider application?

To provide a clearer overview of the research scope and review structure, the framework of this review is illustrated in Figure 1. This review is proceeded from material development to viscoelastic and fatigue behavior. It then discusses the individual

modification effects of SBS and SMC, SBS–SMC composite systems, synergistic mechanisms, and future research directions.

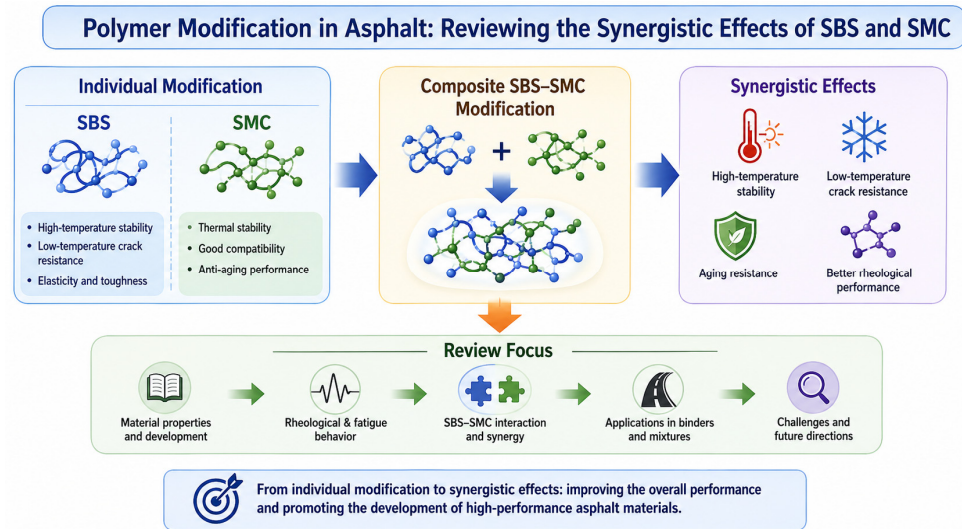


Figure 1. Research framework of this review. (The figure was generated using an AI-assisted tool for visualization purposes. All scientific content was verified by the authors.)

2. Review Methodology

This review adopted a theme-oriented literature selection strategy combined with a PRISMA-inspired screening procedure to improve the transparency and reproducibility of the review process. Although this study is not a systematic review or a meta-analysis, the general workflow of literature identification, screening, eligibility assessment, and final inclusion was followed to organize the literature selection.

The literature search was conducted in the Web of Science and Scopus databases. The final search was completed on 1 January 2026. The search primarily covered studies published between January 2000 and December 2025. In addition, earlier studies published before 2000 were also included if they provided fundamental theories, widely accepted testing methods, or historically significant findings related to asphalt viscoelasticity, fatigue behavior, or polymer modification. A total of seven such studies were ultimately identified.

The main search terms included “SBS-modified asphalt”, “styrene–butadiene–styrene modified asphalt”, “SMC-modified asphalt”, “styrene–methyl methacrylate copolymer modified asphalt”, “SMC–SBS composite modified asphalt”, “SBS–SMC modified asphalt”, “polymer-modified asphalt”, “modified asphalt mixture”, “storage stability”, “phase separation”, “rheological properties”, “fatigue performance”, “aging resistance”, “reclaimed asphalt pavement”, and “sustainable asphalt materials”. Boolean operators were used to combine material-related and performance-related terms. For example, the search string (“SBS” OR “styrene–butadiene–styrene”) AND (“modified asphalt”) AND (“rheology” OR “storage stability” OR “aging”) was adopted. In addition, the reference lists of relevant review papers and highly cited articles were manually screened to identify additional studies.

The inclusion criteria were as follows: (1) studies on SBS-, SMC-, or SBS–SMC-modified asphalt binders or asphalt mixtures, (2) studies reporting modification mechanisms, rheological properties, storage stability, fatigue performance, aging behavior, mixture performance, environmental benefits, or engineering applications, (3) peer-reviewed journal articles, conference papers, theses, technical reports, or regional

engineering studies containing sufficient technical information, and (4) publications written in English or Chinese. Chinese theses, technical reports, and regional engineering studies were included only when they provided unique information on SMC-modified asphalt or SBS–SMC composite systems that was rarely reported in international journals.

The exclusion criteria were as follows: (1) studies unrelated to asphalt binders or asphalt mixtures, (2) studies focusing only on general polymers without asphalt modification, (3) duplicate records, (4) studies lacking sufficient experimental, theoretical, or engineering information, (5) non-technical news, patents, product advertisements, or documents with inaccessible full texts, and (6) studies whose conclusions could not be directly linked to SBS, SMC, or SBS–SMC composite modification.

A total of 449 records were initially identified, including 238 from the Web of Science Core Collection and 211 from Scopus. After removing 143 duplicate records, 306 records remained for title and abstract screening. Subsequently, 157 records were excluded because they were not directly related to SBS-, SMC-, or SBS–SMC-modified asphalt systems. A total of 149 full-text documents were then assessed for eligibility. Among them, 25 documents were excluded because of insufficient relevance, inadequate technical details, inaccessible full texts, duplicated data, or non-technical content. Finally, 124 publications were included in this review. The selected studies were analyzed from four aspects: material composition, modification mechanism, performance evaluation, and engineering application. For SBS-modified asphalt, the review focused on swelling behavior, phase structure, compatibility, aging resistance, and storage stability. For SMC-modified asphalt, emphasis was placed on construction performance, low-temperature properties, recycling potential, and environmental benefits. For SBS–SMC composite systems, the review mainly concentrated on synergistic modification mechanisms, performance balance, and unresolved scientific issues.

It should be noted that the evidence base for SBS and SMC is not equivalent. SBS-modified asphalt has been extensively studied worldwide. Existing studies cover polymer structure, phase morphology, rheological behavior, aging, storage stability, and composite modification. In contrast, the literature on SMC as an asphalt modifier is much more limited. Some SMC studies are available only in Chinese journals, regional technical reports, or engineering application reports. These sources were included because they provide useful information on material design, construction practice, and engineering applications of SMC. However, they do not provide evidence with the same level of generalizability as the well-established international literature on SBS. Therefore, conclusions regarding the synergistic effects of SBS and SMC should be interpreted with caution. They are primarily intended to identify emerging research trends and knowledge gaps.

In addition, this review did not calculate integrated performance metrics, such as the strength enhancement ratio of the composites or the cumulative fatigue damage coefficient. This is because substantial variations exist among the reviewed studies in terms of asphalt source, modifier type and dosage, mixture design, aging condition, test temperature, loading frequency, fatigue loading protocol, and failure criterion. Moreover, many experiments were not conducted under identical controlled conditions. Therefore, directly averaging the results across different studies may lead to misleading quantitative conclusions. Accordingly, this review emphasizes qualitative analysis and mechanistic comparison rather than quantitative synthesis. It also identifies the current research gaps.

3. Modified Asphalt and Modified Asphalt Mixtures

3.1. Development of Modified Asphalt

Modified asphalt is a type of asphalt binder enhanced with additives, such as rubber, resin, polymers, finely ground rubber powder, or other fillers. It can also be produced by

mild oxidation of asphalt. These modifications improve the performance of asphalt or asphalt mixtures. Its appearance is shown in Figure 2. Research and development of modified asphalt date back to the early 20th century. Additives play a critical role in modified asphalt and its mixtures. This initiative started in the UK and was later adopted by many European countries. Global dissemination was actively encouraged [12]. Modified asphalt gained wide attention in highway engineering. Since the late 1970s, polymer-modified asphalt became the primary material for road construction. This shift gradually expanded its applications. In the 1980s, China began research on modified asphalt. Nationwide projects followed, focusing on modifiers and their physical properties [13].



Figure 2. Modified asphalt.

Modification of asphalt mixtures is a key research area in pavement engineering. The main motivation is to overcome limitations of conventional asphalt. Traditional asphalt often fails under heavy traffic loads and extreme weather. Failures include rutting, cracking, and fatigue. These lead to increased maintenance costs and shortened pavement life [14]. Modified asphalt aims to enhance fundamental mechanical properties. This improves pavement durability and performance. Meanwhile, researchers also focus on reducing environmental impacts to enhance sustainability [15].

Various modifiers have been developed and tested to improve asphalt mixture performance. These include polymers, fibers, chemical additives, and recycled materials. Among polymer modifiers, SBS, SMC, and EVA are the most common. These polymers improve elasticity and thermal stability. They enhance durability under varying climates. SBS increases high-temperature deformation resistance and prevents low-temperature cracking [16]. SMC is a novel modifier that boosts flexibility and durability. It provides resilience against temperature fluctuations and mechanical stress. It is particularly effective in preventing low-temperature cracking and high-temperature deformation, ensuring long-term pavement performance.

Fibers are another common modifier. Cellulose, polyester, and glass fibers are added to improve tensile strength [17]. These fibers reinforce the asphalt matrix and reduce rutting and cracking under heavy traffic. Recent studies show fiber-reinforced mixtures exhibit excellent durability and mechanical stress resistance. Chemical additives are also used. Anti-stripping agents and warm mix asphalt (WMA) additives improve moisture resistance and workability. These additives reduce production temperatures, lowering energy use and greenhouse gas emissions [18]. Recycled materials, such as reclaimed asphalt pavement (RAP) and crumb rubber, are increasingly used as sustainable modifiers. They reduce waste while improving flexibility and durability. Studies show recycled materials enhance asphalt performance and address environmental issues [19].

In summary, these modifiers enhance the comprehensive performance of asphalt mixtures. Each modifier has specific advantages and disadvantages, as shown in Table 1. Their application can be tailored to engineering needs, significantly improving the feasibility and practicality of asphalt mixture design.

Table 1. Comparison of typical asphalt modifiers.

Modifier Type	Representative Materials	Modification Mechanism	Performance Benefits	Limitations	Suitable Applications
Elastomeric polymers	SBS, SBR	Polymer swelling, elastic network formation, improved recovery behavior	Rutting resistance, fatigue resistance, low-temperature cracking resistance	Phase separation, aging sensitivity, high cost	Heavy-duty pavements, highways, airport pavements
Plastomeric polymers	EVA, PE, PP	Increased stiffness and softening point	High-temperature stability, deformation resistance	Reduced low-temperature flexibility, compatibility problems	Hot regions, rutting-prone roads
Rubber-based modifiers	Crumb rubber, activated rubber powder	Rubber swelling, particle reinforcement, asphalt–rubber interaction	Aging resistance, elasticity, recycling benefit	High viscosity, construction difficulty, storage instability	Sustainable pavements, noise reduction pavements
Fiber modifiers	Cellulose, polyester, glass fiber	Reinforcement and crack-bridging effect	Tensile strength, fatigue resistance, rutting resistance	Dispersion difficulty, cost	SMA mixtures, thin overlays
SMC modifier	Styrene–methyl methacrylate copolymer-based modifier	Compatibility improvement, workability enhancement, polymer–asphalt interaction	Low-temperature flexibility, workability, emission reduction, recycling potential	Limited mechanism studies, lack of standardized evaluation, binder-level storage stability and segregation resistance remain insufficiently verified	Cold regions, preventive maintenance, green road materials
Composite modifiers	SBS–SMC, SBS–rubber powder, SBS–PPA	Coupled network formation and multi-phase interaction	Balanced high-temperature, low-temperature, fatigue, and aging performance	Complex preparation process, dosage optimization difficulty	High-performance and durable pavements

3.2. Development of Viscoelastic Performance on Modified Asphalt Mixtures

The viscoelasticity of asphalt mixtures has long been a key research focus in road materials. Their mechanical behavior is influenced by multiple factors, including loading frequency, duration, temperature, and strain rate. Asphalt mixtures exhibit various mechanical states over time and temperature changes, such as glassy, viscoelastic, hyperelastic, and viscous flow states. These states lead to typical phenomena like creeping, delayed recovery, and stress relaxation. Consequently, extensive studies have combined experiments and mathematical modeling to explore these behaviors.

Since the 20th century, Monismith et al. [20] introduced the Burgers model based on rheological theory, laying the foundation for understanding asphalt viscoelasticity. With growing attention to modifiers, Vlachovicova et al. [21] revealed the regulatory effects of SBS modification on creep behavior through experiments. Building on this, Lee et al. [22] incorporated the Schapery model and damage factors into uniaxial tension tests. They

proposed a viscoelastic damage equation describing micro-damage evolution, thus expanding constitutive modeling of asphalt mixtures.

Recently, scholars have innovated in both experimental methods and theoretical models to deepen understanding of various asphalt types. Graziani et al. [23] used 3D linear viscoelastic analysis to reveal strain responses of cement-emulsified asphalt under temperature and frequency variations, determining its complex modulus and Poisson's ratio. Similarly, Kuna et al. [24] constructed stress-dependent master curves from dynamic modulus tests to characterize time–temperature dependency of modified asphalt. In the same year, Kuchiishi et al. [25] performed dynamic modulus tests on cold recycled asphalt mixtures, highlighting their practical potential in pavement construction and maintenance. Additionally, Cherif et al. [26] applied the generalized self-consistent scheme (GSCS) method, combining theoretical predictions with experimental data to analyze complex modulus of recycled mixtures, confirming its engineering feasibility. These efforts advance viscoelastic constitutive model development.

Beyond complex modulus, creep behavior in modified asphalt mixtures is also studied extensively. Cheng et al. [27] used uniaxial compression creep tests and applied time–temperature superposition and Arrhenius equations to evaluate creep compliance across multiple modified mixtures. Burgers, generalized Kelvin, and generalized Maxwell models were employed for multi-temperature zone analysis. Zhen et al. [28] constructed relaxation modulus master curves to study the effect of interlayer contact conditions on viscoelastic response. In China, Wu et al. [29] combined Eshelby's equivalent inclusion theory with uniaxial compression tests to systematically analyze temperature and stress effects on mixture viscoelasticity. Meanwhile, Ma's [30] dynamic modulus tests on unaged and aged base and modified binders showed that modifiers increase modulus and reduce phase angle, while aging significantly raises modulus at all frequencies. Yang [31] integrated various mechanical tests to develop dynamic modulus master curves for CR/SBS CMA mixtures, verifying their superior resistance to high-temperature deformation and low-temperature cracking.

Regarding structural performance, Chu [32] investigated dynamic modulus changes in dense-graded asphalt concrete and SMC pavement structures, finding that SMC enhances elasticity. Zhang [33] used dynamic creep tests and a four-element five-parameter model to simulate high-temperature viscoelasticity of rubber-powder-modified mixtures. Wang et al. [34] compared responses of base and SBS-modified asphalt under different conditions via uniaxial static creep tests, showing the Burgers model fits the data well.

Research on composite modifiers continues to expand. Liu [35] evaluated dynamic modulus of hot-mix asphalt with varying volcanic ash content, observing low Poisson's ratio and high mechanical stability. Kang [36] developed dynamic modulus curves for rubber powder/SBS composites, noting increased rubber content improves high-temperature stability. Chai [37] combined Burgers model and uniaxial creep tests to theoretically model the viscoelastic response of composite porous steel slag mixtures, extending understanding of their creep behavior.

In summary, significant progress has been made in the study of viscoelasticity of asphalt mixtures, both in theoretical modeling and experimental methods. The research framework has expanded. Model adaptability and prediction accuracy have improved. However, models such as Burgers, generalized Kelvin, and generalized Maxwell perform well in data fitting but lack strong physical interpretation. They struggle to capture material evolution under complex loading paths. Most studies rely on experimental data for model development and parameter inversion. They lack coupling with the material's microstructure and component behavior. This limits the generality of constitutive models. Moreover, with the introduction of various modified and composite materials, current models face new challenges in scalability and engineering applicability. Future research

should enhance experimental validation. It should also deepen understanding of the fundamental mechanisms of viscoelastic behavior. This will better support pavement design and material optimization.

3.3. Development of Fatigue Performance on Modified Asphalt Mixtures

Research on the fatigue performance of asphalt mixtures dates back to the 20th century, with early and systematic studies initiated in the UK and the US. In the UK, P.S. Pell at the University of Nottingham conducted extensive laboratory fatigue tests. He collected rich data on various asphalt mixtures and promoted the development of fatigue equations in British design standards. Building on this, S.F. Brown incorporated Pell's results into the framework of pavement structural responses. This strengthened the connection between experiments and engineering applications [38–42]. At the same time, C.L. Monismith and his team at the University of California, Berkeley, carried out similar research. They adopted both stress- and strain-controlled loading modes. Combining laboratory and field tests, they systematically validated the applicability of fatigue equations. Their findings were eventually included in the Asphalt Institute's pavement design guidelines. Notably, Monismith's work complemented Pell's methodologically. His validation of fatigue damage evolution also laid the foundation for regression models.

With the launch of the Strategic Highway Research Program (SHRP), the research focus shifted to identifying and quantifying influencing factors. These included asphalt content, air voids, aggregate gradation, temperature, specimen preparation, and loading conditions. This phase relied heavily on experimental data and facilitated the transition from empirical models to more accurate predictive tools.

Beyond the traditional stress-strain framework, researchers at Ohio University introduced fracture mechanics into fatigue studies. They considered crack shapes, specimen geometry, boundary conditions, and material heterogeneity. This approach clarified the role of crack propagation in fatigue performance and deepened understanding of failure mechanisms. It also addressed the limitations of traditional models in describing micro-damage evolution. Based on this, researchers at UC Berkeley and other institutions introduced energy-based fatigue methods. They examined the relationship between energy dissipation and loading cycles. Especially under the SHRP, cumulative dissipated energy became a new and sensitive indicator of fatigue life.

In recent years, studies have expanded to modified asphalt mixtures. He et al. [43] combined fracture mechanics with finite element methods. They compared crack propagation in conventional and sisal fiber-reinforced mixtures under fatigue loading. Results showed improved fatigue resistance due to fiber reinforcement. Similarly, Gao [44] followed a phenomenological path. Using the indirect tensile test (IDT) and semi-circular bending (SCB) tests, he developed fatigue equations for cold-recycled emulsion mixtures, providing theoretical support for reclaimed materials. Additionally, Shen et al. [45] used four-point bending tests and BP neural networks. They modeled damage evolution in CR-modified asphalt and developed a life prediction model covering the full fatigue life, showing excellent accuracy. In the same year, Dong [46] focused on polyphosphoric acid (PPA)-modified asphalt and its synergy with SBS and styrene butadiene rubber (SBR). Tests confirmed PPA's significant advantage in enhancing fatigue crack resistance.

For fiber-reinforced asphalt concrete, Zhang [47] used a phenomenological approach. He developed fatigue equations and analyzed the effects of nominal stress ratio and stress level. His results were well validated within the tested range. Similarly, Wu [48] conducted fatigue tests on warm-mix SMC ultra-thin overlays under strain control. He proposed a new life prediction method based on dissipated energy. The method used the transition point between fatigue stages II and III as a criterion, offering new insights for life prediction under complex loading.

In summary, the study of asphalt mixture fatigue performance has evolved from traditional stress–life methods to fracture mechanics and energy-based approaches. The theoretical basis and experimental methods have become increasingly refined. However, most existing fatigue models still rely on specific test conditions and material parameters. A universally applicable framework is lacking. Fracture mechanics offers mechanistic insights, but challenges remain in parameter acquisition and model simplification for practical use. Artificial intelligence methods, such as neural networks, show potential for fatigue life prediction. Yet, their black-box nature and lack of interpretability remain unresolved. Future research should focus on developing a multi-scale, scalable fatigue analysis system. It should integrate mechanistic and data-driven models. Emphasis should also be placed on model validation and adaptation in real engineering scenarios to achieve more predictive and practical fatigue evaluation methods.

4. SBS Application for Modified Asphalt and Modified Asphalt Mixtures

SBS is a thermoplastic elastomer, specifically a block copolymer. It consists of three blocks: two polystyrene blocks at the end and a polybutadiene block in the middle. This structure gives SBS both rubber-like properties (from butadiene) and plastic-like properties (from styrene). The rubber-like segments provide elasticity and flexibility. The plastic-like segments enhance strength and durability. SBS is widely used in asphalt modification due to its ability to improve mixture performance, especially elasticity, deformation resistance, and temperature stability. SBS-modified asphalt is typically produced by blending SBS into asphalt through a hot mixing process. The preparation process is shown in Figure 3. The asphalt is first heated to 150–180 °C to achieve a flow state suitable for mixing with SBS. SBS pellets or granules are then slowly added, typically ranging from 3% to 7% of the asphalt mass. A high-shear mixer is used to disperse SBS in the asphalt. Stirring continues to ensure uniform distribution, producing stable modified asphalt. The prepared SBS-modified asphalt can be directly used for asphalt mixture production.

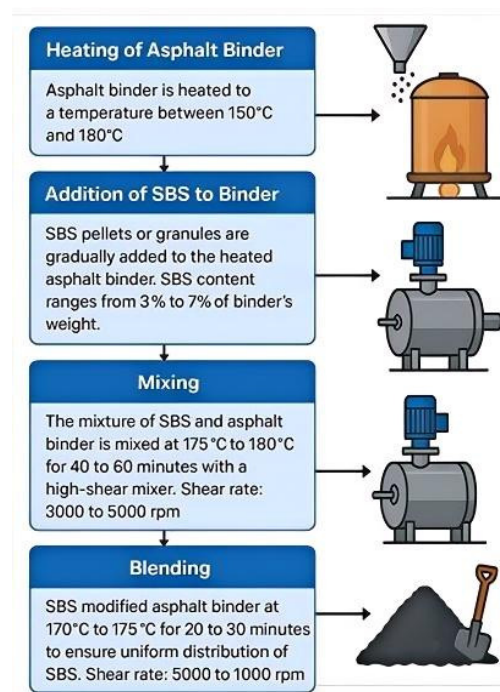


Figure 3. Preparation process of SBS-modified asphalt.

In recent years, various polymers have been widely used in asphalt modification. Among them, the thermoplastic elastomer SBS has gained broad application in road construction due to its excellent performance [49,50]. SBS features a unique microstructure, with spherical polystyrene phases dispersed in a continuous butadiene matrix [51,52], and exists in linear or star-shaped forms. As shown in Table 2 and Figure 4, SBS-modified asphalt and its mixtures have been extensively studied. Studies by Wang, Lin, and Zhan et al. [53–55] show that SBS modification significantly improves high-temperature storage stability and aging resistance. It also enhances overall performance. Improving phase compatibility and suppressing polymer separation are key approaches for enhancing long-term storage stability [56]. However, these improvements depend not only on the modifier itself but also on the composition of the base asphalt.

Storage stability should be assessed using a unified segregation indicator. In this study, the softening point difference between the top and bottom sections of the binder after high-temperature storage was adopted to be the primary segregation indicator [56], as following Equation (1), where $T_{s,top}$ and $T_{s,bottom}$ are the softening points of the upper and lower portions of the stored binder, respectively. A smaller ΔT_s value indicates less vertical phase separation and better storage stability:

$$\Delta T_s = |T_{s,top} - T_{s,bottom}|. \quad (1)$$

To compare binders with different initial softening points, a normalized phase separation index can be defined, as expressed in Equation (2). Here, $T_{s,initial}$ is the softening point of the original homogeneous binder before storage. In the following comparison, SBS-modified asphalt is used as the reference. Under identical storage conditions, lower ΔT_s or SI_s values for the SBS-SMC composite-modified asphalt than those of the SBS-modified asphalt indicate improved resistance to phase separation:

$$SI_s = \frac{|T_{s,top} - T_{s,bottom}|}{T_{s,initial}} \times 100\%. \quad (2)$$

The phase characteristics of SBS-modified asphalt significantly affect its rheological behavior, storage stability, and mechanical properties. Fluorescence microscopy, AFM, and SEM have been widely used to characterize the phase evolution and polymer dispersion behavior of SBS-modified asphalt [57]. Regarding the mechanism of SBS molecular structure, Schaur et al. [58] used fluorescence microscopy to compare linear and star-shaped SBS with different styrene/butadiene ratios. Linear SBS showed more uniform dispersion and more complete swelling. Differential scanning calorimetry (DSC) analysis further revealed that linear SBS-modified asphalt had lower wax recrystallization energy, indicating stronger absorption of light components. Liang and Gao et al. [59,60] confirmed the significant role of asphalt composition. Base asphalt with high aromatics and low asphaltene content was found to enhance SBS performance. This aligns with the colloidal index (CI) theory proposed by JSR Corporation. Experimental results by Oli-Ville et al. [61] supported this theory, showing that low-CI asphalt promotes SBS dispersion, improving low-temperature performance and storage stability. Wang et al. [62] further quantified this theory and proposed parameter ranges for optimal modification under specific CI and component ratios.

The mechanism of SBS in asphalt is generally considered similar to rubber swelling. SBS swells by absorbing light components. However, compared to conventional rubber, SBS degrades more easily. Feng et al. [63] found that degradation occurs during mixing, reducing temperature sensitivity. Wang [53] further noted that absorption improves elasticity and low-temperature properties. Despite these benefits, aging remains a major challenge. Liu et al. [64] found that SBS degrades faster than SBR in the short term under UV aging, but is more stable in the long run. Zhang et al. [65] showed that the

emulsification process of SBS-modified asphalt does not damage the microstructure significantly but adversely affects thermal stability and road performance.

For deeper understanding of aging mechanisms, Gan et al. [66] used a composite rate equation to model the aging behavior. Yao and Wang et al. [67,68] focused on the role of asphalt components. They found that saturates promote SBS swelling but have limited effect on final performance. In contrast, aromatics and resins enhance SBS solubility and stability, strengthening the dual-phase structure and improving performance. These findings highlight the importance of synergistic interaction between base asphalt and modifiers in improving overall properties.

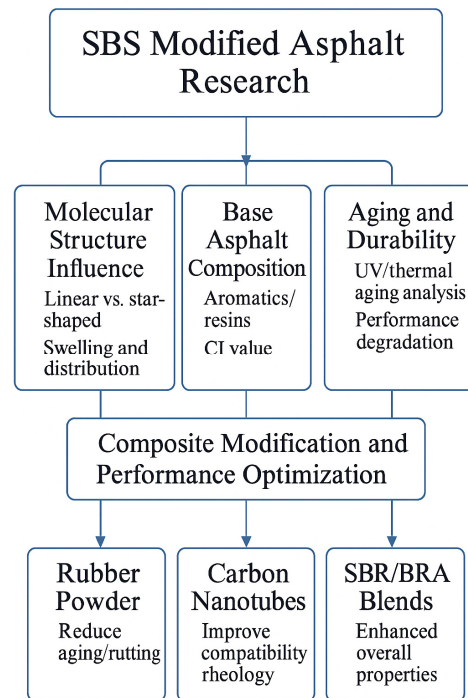
Although SBS significantly enhances asphalt performance, it still faces issues with compatibility, storage stability, and aging resistance [69–71]. Thus, composite modification has become a research focus. Studies by Yan [72], Dong [73], and Zhang [74] confirm that combining rubber powder with SBS maintains high-temperature deformation and fatigue resistance while reducing SBS dosage, thus improving cost-effectiveness. Zhang et al. [75] used penetration ratio and FTIR analysis to show that oxygen and sulfur in rubber powder react with asphalt to form sulfoxide groups, delaying aging.

Rubber powder particle size also affects composite properties. Jiang et al. [76] found that larger particles improve high-temperature and fatigue performance but also impair low-temperature performance. To explore the mechanism, Qian et al. [77] used DSC and scanning electron microscopy (SEM). Their results showed that rubber powder and SBS act synergistically to optimize glass transition and internal structure, enhancing drainage and noise reduction. For applications in rainy regions, Zhang [78] and Zhou et al. [79] demonstrated that SBS–rubber powder composite-modified high-viscosity asphalt improves permeability and storage stability. Fluorescence microscopy confirmed a network structure favorable to permanent deformation resistance. To further improve performance, Ye [80] recommended blending SBR with SBS to enhance elasticity and rutting resistance. While low-temperature properties improved slightly, high-temperature fatigue resistance declined. Fu et al. [81] introduced carbon nanotubes to enhance compatibility between SBS and asphalt. The nanotubes suppressed SBS migration, promoting uniform dispersion and improving high-temperature resistance, though with some loss in low-temperature properties and thermal sensitivity. Zhang [82] found that combining high-ash Buton rock asphalt (BRA) with SBS improved water stability, moisture resistance, and skid resistance, indicating good engineering adaptability. To improve aging resistance, Guo et al. [83] used polyolefin elastomer (POE) as a co-modifier for SBS-modified asphalt. The results showed enhanced high-temperature performance, albeit at the cost of some low-temperature properties. Furthermore, Suo [84] confirmed that adding an appropriate amount of rubber powder to SBS-modified asphalt can improve aging resistance, whereas excessive amounts can cause adverse effects.

In summary, SBS modification markedly improves asphalt's high-temperature stability and low-temperature performance. Additives such as rubber powder, SBR, carbon nanotubes, and BRA further enhance high-temperature performance, delay aging, and improve moisture resistance. These additives also offer economic and engineering adaptability. However, current research mainly focuses on performance characterization and modification mechanisms. Studies on long-term service behavior, aging evolution, and multi-factor synergy remain limited. Future work should explore the interaction mechanisms of composite modifiers. A systematic structure–performance–service life model should be developed to advance the engineering application of high-performance SBS composite-modified asphalt.

Table 2. Summary of current research on SBS-modified asphalt and mixtures.

Research Contents	References	Research Scope	Performances
Influence of SBS Molecular Structure	[53–55,58]	Linear and star-shaped structure; styrene/butadiene ratio; swelling capacity and dispersion uniformity	Linear SBS shows better dispersion; lower wax recrystallization energy; stronger absorption of light components; improves low-temperature performance
Base Asphalt Composition	[59–62]	Proportion of four fractions (saturates, aromatics, resins, asphaltenes); colloidal index	High aromatics and low asphaltenes enhance SBS compatibility; low colloidal index favors uniform distribution and stability
Aging Performance	[63,64,66–68]	UV aging; DSR shear test; chemical composition changes	SBS is sensitive to aging but degrades slowly; aromatics and resins improve post-aging properties
Composite Modification Methods	[72–84]	Combinations include rubber powder, SBR, carbon nanotubes, BRA, thermoplastic elastomers	Enhance rutting resistance, temperature sensitivity, moisture stability, and aging resistance; offer economic and practical advantages

**Figure 4.** Research framework of SBS-modified asphalt and mixtures. (Original conceptual illustrations prepared by the authors.)

5. SMC Application for Modified Asphalt and Modified Asphalt Mixtures

SMC is used in this review to denote a styrene–methyl methacrylate copolymer-based modifier for asphalt materials. It should be noted that SMC is not a universally standardized abbreviation in pavement engineering. In the cited pavement studies, SMC generally refers to a styrenic copolymer-based modifier that can be prepared from recycled rubber and plastic resources and blended with surfactants, resins, and other additives to improve asphalt mixture workability, low-temperature adaptability, and construction performance [85]. Surfactants include lignin, polyester, polyacrylonitrile, ethylene oxide polymer surfactants, and AB block polymer surfactants. Resins include

epoxy resin, phenolic resin, and polyamide resin [86]. Extracting SMC from waste tires is a complex chemical process, detailed in Figure 5. First, waste tires are mechanically shredded into rubber particles or powder. Steel wires and fiber impurities are removed to improve subsequent chemical processing efficiency. Second, pyrolysis is carried out between 300 °C and 700 °C under anaerobic or low-oxygen conditions, decomposing the rubber into gases, pyrolysis oil, and solid residues. Product composition is strongly affected by reaction conditions. Third, high-value monomers, such as styrene and methyl methacrylate, are recovered by distillation or extraction, ensuring high purity and yield. Finally, polymerization is performed under strict control of catalyst, temperature, and pressure to synthesize SMC for use in high-performance materials, such as modified asphalt. After production, the final SMC product requires further processing, such as blending, molding, or mixing with additives, to prepare materials suitable for road construction or other industrial uses.

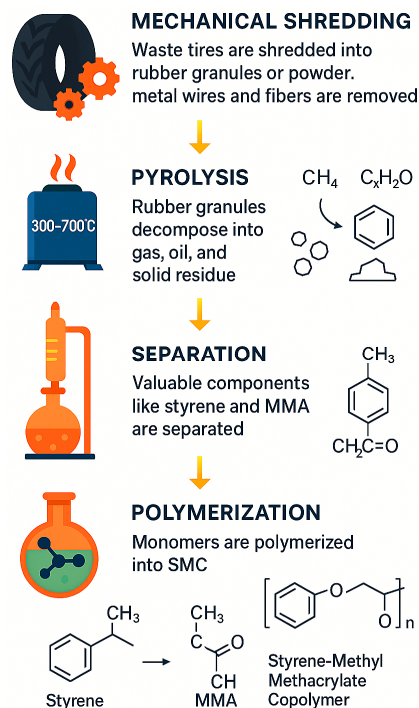


Figure 5. Detailed preparation process of SMC.

Since the late 1970s, polymer-modified asphalt has gradually become a major material in road construction. Its applications have steadily expanded. Among them, SBS modification technology has dominated due to its superior performance. However, growing environmental awareness has shifted research interest toward recycling waste plastics and rubber, especially in cold-mix asphalt mixtures. Against this background, SMC-modified asphalt mixtures (SMCMA) have gained attention. Research has begun to focus on performance optimization and engineering applicability.

As shown in Table 3 and Figure 6, current research on SMCMA mainly covers four areas. These are material design, performance evaluation, engineering application, and environmental and green development. Early studies on SMCMA centered on its strength formation mechanism and influencing factors. Chu et al. [87] analyzed compaction, solvent volatilization, and curing conditions. They revealed a close link between mixture strength, gradation, and solvent control. Building on this, Xia [88] compared SMCMA with other cold-patch asphalts. The results showed stronger time dependence in early stability and strength growth, further supporting Chu's findings.

Subsequent research explored material composition and mechanisms. Huang [89] studied the relationship between mix design and performance. He confirmed the suitability of the SMC-13 gradation for specific regions, such as Xichang, providing theoretical support for practical applications. Qu [90] evaluated the material from a macro perspective. He emphasized its advantages in construction convenience and environmental friendliness. Gong et al. [91] validated these findings through field tests. They monitored a 2290 m section of the Dashan Expressway and confirmed the excellent performance of SMC thin overlays in cold environments.

With further progress, Liu [92] examined the high-temperature performance of ultra-thin SMCMA overlays. He highlighted the composite enhancement effect of SBS. Meanwhile, Xie et al. [93,94] optimized the composition of cold-mix modifiers and evaluated their performance in recycled asphalt mixtures. Their findings showed that SMC maintained good performance even under the high content of reclaimed asphalt pavement (RAP). Feng et al. [95] extended these results. They confirmed excellent temperature adaptability of SMCMA under varying thermal conditions.

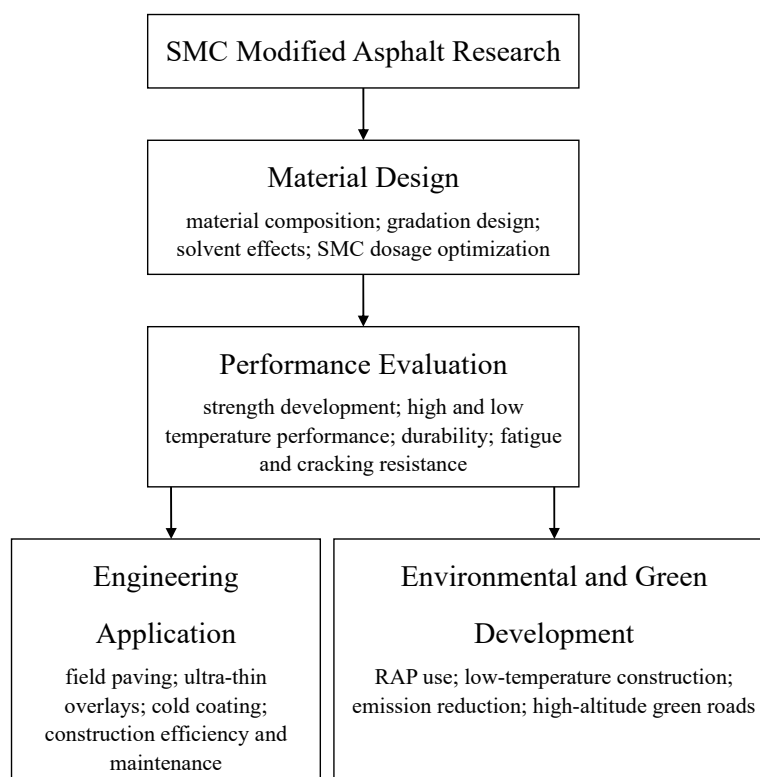
In engineering practice, Zhang [96] successfully applied SMCMA to preventive maintenance of a salt bridge in Qinghai's cold region. The treatment effectively mitigated pavement issues caused by aging and salt expansion. Inspired by these outcomes, Cao [9] explored a cold-spray thin overlay using SMC-SBS composites. He found that the composite system significantly improved mechanical properties and reduced temperature dependency, enhancing construction flexibility.

Meanwhile, to improve environmental performance, Luo et al. [97] investigated the impact of SMC dosage on emissions and volatiles. They identified optimal dosage ranges for SMC-13 and SMC-20 mixtures, achieving over 40% emission reduction. In high-RAP applications, Tian et al. [98] and Liang [99] studied fatigue resistance. They found that SMCMA with 50% RAP and 10% additive performed best at RAP30%, while RAP50% mixtures still showed stable durability. Ouyang [100] further supported these findings. His comparison of AC-13 and AC-20 mixtures showed that SMCMA improved low-temperature crack resistance and reduced construction temperature requirements. In green road construction, Lu et al. [101] proposed applying SMCMA in high-altitude cold regions. They highlighted its strong low-temperature adaptability and environmental benefits. These features make it highly promising, especially for areas like Tibet with unique geographic conditions.

In summary, although existing studies have systematically revealed the strength formation mechanism, material proportion optimization, temperature performance, and engineering applications of SMCMA, some limitations remain. First, most research focuses on specific regions or engineering cases. A unified performance evaluation system and broad regional adaptability validation are lacking. This limits large-scale promotion. Second, although some studies address high recycled content and environmental performance, key issues remain underexplored. These include long-term service performance, interface bonding behavior, and microstructural evolution. Third, the synergistic mechanism of SMC and SBS composite systems and their adaptability under various climates need further clarification. Therefore, future research should strengthen material mechanism analysis. It should also integrate multi-scale experiments with numerical simulations. This approach will promote the standardization, engineering application, and sustainable development of SMCMA.

Table 3. The research status summary of SMC-modified asphalt and mixtures.

Research Contents	References	Research Scope	Performances
Material design	[87,90,97,100]	Material composition; gradation design; solvent effects; SMC dosage optimization	SMC-13/20 gradation shows wide applicability; optimized dosage reduces temperature and emissions
Performance evaluation	[88,92,93,95,98]	Strength development; high- and low-temperature performance; durability; fatigue and cracking resistance	SMC significantly enhances stability and durability; suitable for various environmental conditions
Engineering application	[9,91,96]	Field paving; ultra-thin overlays; cold coating; construction efficiency and maintenance	Improves pavement performance; adapts to cold climates; reduces time and cost of construction
Environmental and green development	[90,94,99,101]	RAP use; low-temperature construction; emission reduction; high-altitude green roads	Enables high RAP utilization and greenhouse gas reduction; applicable to green road construction

**Figure 6.** Research framework of SMC-modified asphalt and mixtures. (Original conceptual illustrations prepared by the authors.)

6. SMC–SBS Composite Application for Modified Asphalt and Modified Asphalt Mixtures

SBS is the most commonly used modifier among polymers. Other typical composite modification methods include high-ash SBR, BRA, thermoplastic elastomers, and rubber powder. Recently, SMC, a composite reinforcing material, has gained attention in asphalt modification. Its combination with SBS shows clear synergistic effects. This blend enhances the overall mechanical properties of asphalt mixtures. Recent studies confirmed that SBS–SMC composite modification can simultaneously enhance high-temperature

rutting resistance and low-temperature crack resistance. Microstructural analyses further indicated that the SBS–SMC system formed a more stable polymer network than single-modified asphalt systems [8]. It also improves elasticity, moisture resistance, and thermal stability. As a result, pavement durability and flexibility are significantly increased.

Current experimental findings on SBS–SMC composite-modified materials should be interpreted according to the evaluated performance. At the binder level, Sun et al. [8] investigated SBS–SMC composite-modified asphalt using viscosity, DSR, BBR, SEM, and FTIR tests. They reported improved low-temperature performance within a specific SMC dosage range. At the mixture level, Sun et al. [10] evaluated SBS–SMC composite-modified asphalt mixtures with different SMC contents. They found that fatigue life depended on the SMC dosage. When the SBS content was fixed at 4%, the mixture containing 10% SMC exhibited the best fatigue performance. At the engineering level, Cao reported the application of SBS–SMC composite-modified asphalt mixtures in indoor thin-layer paving for preventive maintenance [9]. In addition, Wu et al. used SMC technology to rejuvenate aged SBS-modified asphalt. They further verified the performance of the recycled mixtures in road applications [11]. These studies demonstrate the application potential of SBS–SMC systems. However, they do not provide sufficient evidence that the synergistic mechanism is universally applicable to all asphalt types, modifier ratios, and service conditions.

Cao et al. [9] were among the first to study SMC–SBSMA composite modified asphalt in room-temperature thin-layer surfacing. Their results confirmed the system's effectiveness in resisting softening, rutting, and impact damage. It also maintained good compressive strength and waterproof performance. Furthermore, they found that this system reduced mixing temperature and shortened traffic recovery time. It retained excellent flexibility under low temperatures, effectively suppressing cracking.

Subsequently, Wan [102] investigated rubber powder–SBS composite-modified SMA mixtures. Although its water stability and fatigue resistance were slightly lower than SBS-modified asphalt, the overall performance remained comparable. The mix also showed strong high-temperature stability and low-temperature cracking resistance, supporting further composite modification strategies. Building on this, Yang [31] used dynamic modulus and low-temperature creep tests to further validate the viscoelasticity and flexibility of the rubber powder–SBS system under cold conditions. The findings echoed Wan's conclusions, offering experimental support for its application in cold regions. With ongoing research, the SBS–SMC combination continues to show superior rutting resistance, crack resistance, and fatigue resistance [9,10]. These properties are key to extending pavement life and improving durability under heavy loads. The system is particularly beneficial in high-stress applications, such as highways and airports.

However, as noted by Abtahi et al. [17], the practical adoption of SMC–SBS composite-modified asphalt faces challenges. First, the initial material cost will increase because SBS is relatively expensive. In addition, the quality of SMC depends on the source, composition, and stability of recycled rubber or plastic materials. Second, the production process often requires specialized equipment, such as high-shear mixers, temperature-controlled mixing systems, agitated storage tanks, and equipment suitable for ambient-temperature thin-layer paving. These requirements increase equipment investment and limit its application in small-scale maintenance projects. Third, process control is more complex than that of conventional asphalt mixtures. Mixing temperature, shear rate, mixing duration, additive sequence, and storage conditions must be carefully controlled to ensure uniform dispersion and prevent over-modification. Material performance can also be affected by high viscosity, modifier segregation, and phase separation. Furthermore, the lack of standardized construction specifications and quality control criteria makes it difficult to compare results across different projects. Therefore, the

engineering evaluation of SBS–SMC composite-modified asphalt should consider not only its mechanical performance but also material cost, equipment requirements, construction adaptability, storage stability, and long-term field performance.

On the other hand, the synergistic modification of SBS and SMC is strongly dosage dependent. In SBS-modified asphalt, the typical SBS content is 3–7% of the binder. An appropriate SBS dosage absorbs the light fractions and forms an elastic polymer network. Excessive SBS markedly increases viscosity, reduces workability and storage stability, and will even induce phase separation [49,57,59,61,62]. The optimum SMC dosage depends on mixture gradation and overall pavement performance. Luo et al. [97] reported optimum SMC contents of 6–10% for SMC-13/AC-13 mixtures and 6–8% for SMC-20/AC-20 mixtures. These dosage ranges were also adopted in the performance-balanced design method proposed by Li et al. [103].

For the SMC–SBS composite system, existing studies indicate that the synergistic effect first improves and then declines with increasing SMC content. Sun et al. [8] found that, at 4% SBS, the high-temperature performance of the binder initially increased and then decreased as the SMC content increased. Fatigue performance reached a favorable level at approximately 12% SMC. They, therefore, recommended that the SMC dosage should not exceed 12%. SCB fatigue tests further showed that mixtures containing 4% SBS achieved the longest fatigue life at 10% SMC. Fatigue performance declined when the SMC content exceeded this level [10]. Overall, current evidence suggests that the synergistic effect of the SMC–SBS system begins to diminish at an SMC content of approximately 10–12%. A dosage of 10% is more suitable when fatigue resistance is the primary objective. A dosage of about 12% is preferable when rutting resistance is prioritized.

In summary, SBS-modified asphalt significantly enhances asphalt's rutting resistance at high temperatures and cracking resistance at low temperatures. SMC-modified asphalt exhibits excellent low-temperature flexibility and crack resistance in cold regions. Some studies have shown that SBS–SMC composite-modified asphalt outperforms single-modifier systems in rutting resistance, low-temperature cracking resistance, fatigue resistance, and moisture damage resistance. However, a general conclusion cannot be drawn because the reported results vary with material source, modifier dosage, blending ratio, and testing method. Therefore, no universal ranking can be established among SBSMA, SMCMA, and SMC–SBSMA. Table 4 summarizes the performance comparison of these three modified asphalt systems. However, current studies remain limited and lack systematic analysis. Its application still faces high equipment investment and strict process control requirements, uncertain material supply stability, inadequate material dispersion, poor storage stability, and insufficient field validation. These limitations indicate that the widespread adoption of SBS–SMC composite-modified asphalt should be supported by standardized performance testing, construction feasibility assessment, life-cycle cost analysis, and long-term pavement monitoring. Future research should focus on experimental and theoretical studies of performance mechanisms, with particular attention to compressive strength, fatigue resistance, and aging resistance. The optimal proportion ranges for different performance indicators remain inconsistent. Developing a systematic proportion–performance–durability correlation model is needed to establish a unified performance optimization framework. These efforts will improve the engineering applicability of SBS–SMC composite asphalt and provide solid technical support for broader practical applications.

Table 4. Performance comparison of SBSMA, SMCMA, and SMC–SBSMA systems.

Performance Indicator	SBSMA	SMCMA	SMC–SBSMA	Main Knowledge Gap
High-temperature rutting resistance	Strong improvement due to elastic network and higher complex modulus	Moderate improvement; depends on dosage and mixture design	Stronger improvement due to combined stiffness and elasticity	Lack of normalized rutting index comparison
Low-temperature cracking resistance	Improved flexibility, but aging will reduce benefit	Good low-temperature adaptability, especially in cold-mix or room-temperature systems	Balanced flexibility and strength	Insufficient fracture-energy-based evaluation
Fatigue resistance	Generally improved by enhanced elasticity and recovery	Improved in some cold-region and RAP systems	Potential improvement through stress redistribution and interface stability	Limited full-life fatigue damage modeling
Aging resistance	Vulnerable to polymer degradation and oxidation	Potential anti-aging benefit, but mechanism remains unclear	Reduce SBS aging sensitivity if compatibility is improved	Long-term PAV/UV/moisture coupled aging data are insufficient
Storage stability	Often limited by SBS–asphalt density and polarity differences	Better workability and compatibility potential	Improved workability and construction compatibility have been reported, but binder-level storage stability and segregation resistance remain insufficiently verified	Lack of systematic segregation tests
Sustainability	Reduces pavement distress but depends on polymer source	Uses recycled rubber/plastic-related resources; lower construction temperature potential	Combines performance and sustainability benefits	Life-cycle assessment remains limited

7. Proposed Framework for Future Investigation of SBS–SMC Composite Asphalt

This section distinguishes evidence-supported findings from mechanisms that remain to be validated. Published studies have shown that SBS-modified asphalt mixtures improve asphalt elasticity, high-temperature performance, and polymer network formation. In contrast, SMC-modified asphalt mixtures enhance construction adaptability and low-temperature performance. They can also provide greater environmental benefits under specific conditions. However, the synergistic mechanism of SBS–SMC composite-modified asphalt has not been systematically verified. This is particularly true for polymer network stability, interfacial compatibility, storage stability, and aging resistance. Comprehensive chemical characterization, morphological analysis, rheological evaluation, and long-term field investigations are still lacking. Therefore, the following discussion should be regarded as an evidence-based perspective for future research rather than an established conclusion.

To better understand the interaction mechanism between SBS and SMC in asphalt systems, a mechanism–performance–application framework for future investigation of SMC–SBSMA was proposed, as shown in Figure 7. This framework summarizes the

relationships among polymer swelling, phase morphology evolution, rheological coupling, mechanical performance enhancement, engineering applications, and future research directions. As illustrated in Figure 7, the synergistic modification behavior of SBS–SMC composite asphalt involves several coupled processes. These include polymer swelling, phase morphology evolution, network formation, and rheological interactions. SBS mainly contributes to the formation of an elastic polymer-rich network. In contrast, SMC improves compatibility, dispersion stability, and workability. The combined effect enhances rutting resistance, low-temperature crack resistance, fatigue durability, and aging stability. In addition, the framework highlights the engineering applications of SBS–SMC systems in heavy-duty pavements, cold-region roads, airport pavements, and sustainable asphalt mixtures containing recycled materials.

The synergistic effect between SBS and SMC in asphalt cannot be regarded as a simple superposition of two modifiers. It is influenced by polymer swelling, phase morphology, interfacial compatibility, rheological coupling, and aging evolution [5]. SBS is an elastomeric block copolymer. During high-temperature shearing, SBS absorbs light components from asphalt and gradually swells. The swollen SBS phase forms a continuous or semi-continuous polymer-rich network. This network improves elastic recovery, complex modulus, and rutting resistance. However, excessive swelling or poor compatibility induces phase separation during high-temperature storage. This is one of the major limitations of SBS-modified asphalt.

SMC plays a complementary role in this system. However, this mechanism should currently be regarded as a working hypothesis rather than a fully validated conclusion. Existing studies indicate that SMC can improve workability, low-temperature flexibility, and construction adaptability [87,88]. However, direct experimental evidence that SMC enhances SBS dispersion, reduces polarity differences, or stabilizes the polymer-rich phase remains limited. Therefore, the proposed SBS–SMC synergistic mechanism should be considered an evidence-informed hypothesis. It requires further validation through integrated chemical, morphological, and rheological characterization. In addition, SMC improves low-temperature flexibility and workability. Therefore, the SBS–SMC system achieves a better balance between high-temperature stiffness and low-temperature deformability.

On the other hand, compared with conventional SBS-modified asphalt, the potential advantage of SBS–SMC composite modification lies in its ability to reduce the ΔT_s or SI_s value after the same high-temperature storage treatment. In principle, if SMC improves the compatibility between the SBS-rich phase and the asphalt matrix, the ΔT_s or SI_s value of the composite binder should be lower than that of SBS-modified asphalt. However, direct comparative data between SBS and SBS–SMC binders under identical storage conditions remain limited. Therefore, the potential improvement in the storage stability of SBS–SMC composite asphalt requires further investigation.

From a rheological perspective, SBS mainly increases the elastic modulus of asphalt, whereas SMC regulates viscosity and temperature sensitivity. Consequently, the composite system exhibits superior rutting resistance at high temperatures and lower cracking risk at low temperatures. From a microscopic perspective, a stable SBS–SMC-modified asphalt should possess uniform polymer dispersion, fewer interfacial defects, and a denser polymer–asphalt network. These mechanisms can be verified by SEM, fluorescence microscopy, atomic force microscopy (AFM), Fourier transform infrared spectroscopy (FTIR), and molecular dynamics simulations. Existing experimental evidence on SBS-, SMC-, and SBS–SMC-modified asphalt is systematically summarized in Table 5.

As summarized in Table 5, the modification mechanism of SBS-modified asphalt has been well validated by multiple techniques, including fluorescence microscopy, FTIR, gel

permeation chromatography (GPC), AFM, and rheological tests. These studies have confirmed the significance of SBS swelling, the formation of polymer-rich phases, phase separation, and SBS degradation during aging. In contrast, the modification mechanisms of SMC-modified asphalt and SBS–SMC composite asphalt remain insufficiently verified. Existing studies mainly report improvements in performance, construction applicability, and environmental benefits. However, direct evidence from SEM, AFM, FTIR, and GPC is still limited. Therefore, the proposed SBS–SMC synergistic mechanism should not be regarded as a definitive conclusion. Instead, it should be considered a mechanistic framework synthesized from the available evidence. This framework provides directions for future experimental validation.

The aging behavior of SBS–SMC composite asphalt also deserves attention because direct evidence of its chemical aging remains limited. For SBS-modified asphalt, thermo-oxidative and UV aging induce asphalt oxidation and SBS polymer degradation. These changes are commonly characterized by FTIR-based carbonyl and sulfoxide indices, together with variations in SBS-related characteristic peaks [104–106]. The carbonyl and sulfoxide indices are widely used to quantify asphalt oxidation and to correlate chemical aging with rheological deterioration [105,106].

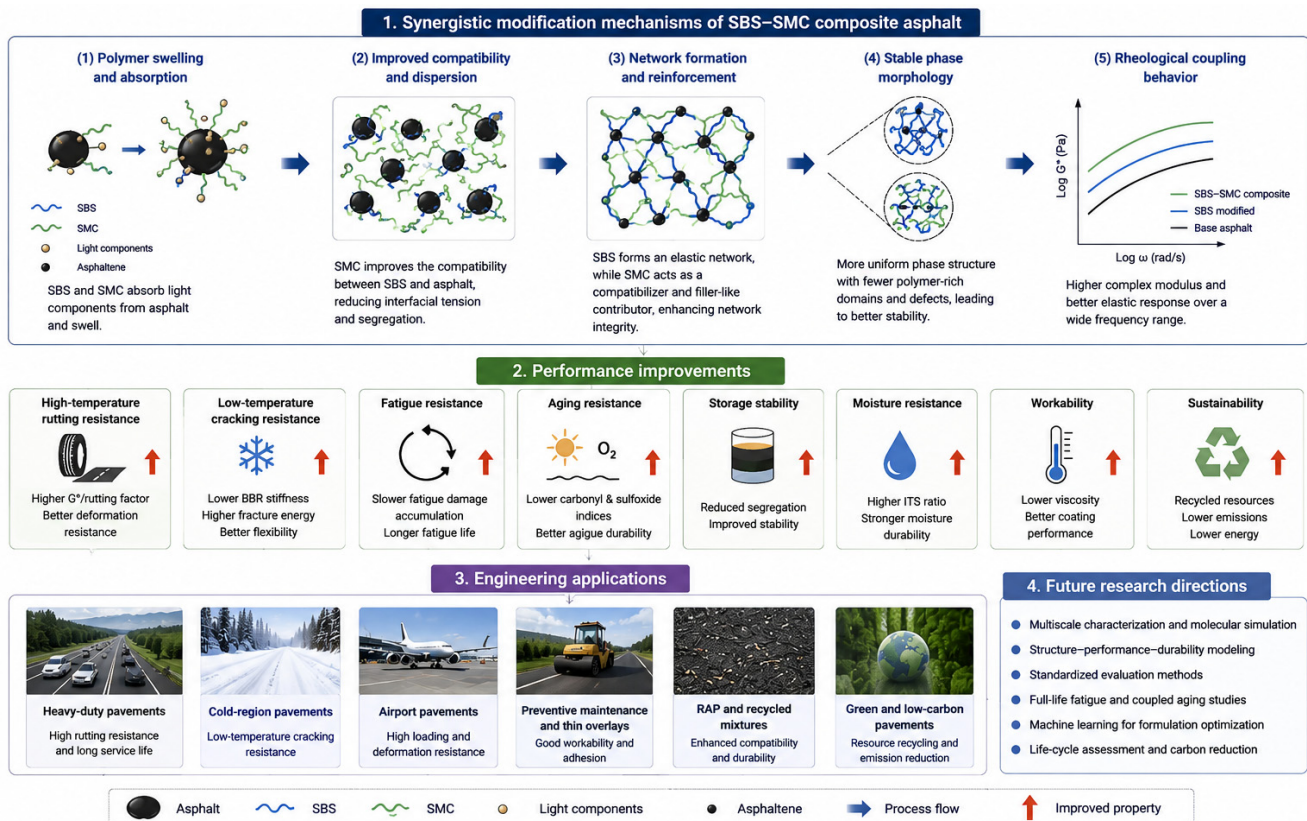


Figure 7. Proposed mechanism–performance–application framework for future investigation of SMC–SBSMA. (The figure was generated using an AI-assisted tool for visualization purposes. All scientific content was verified by the authors.)

However, the available evidence for SBS–SMC composite asphalt is still insufficient. SBS–SMC binders with different SMC contents were investigated by using SEM and FTIR. They observed changes in the microstructure and functional groups. However, their study did not report carbonyl or sulfoxide indices after thermo-oxidative, thermal, or UV aging [8]. Therefore, the anti-aging effect of SMC in SBS–SMC composite asphalt remains a

hypothesis rather than a confirmed mechanism. Future studies should quantify the carbonyl index, sulfoxide index, SBS degradation index, and rheological aging indices before and after standard aging procedures. Such analyses are needed to determine whether SMC can effectively retard the aging of SBS-modified asphalt.

Overall, based on the reviewed evidence and the current research gaps, the synergistic mechanism of SBS–SMC can be summarized into a conceptual framework for future research. The framework comprises four key aspects:

- (1) the elastic polymer network provided by SBS;
- (2) the contribution of SMC to improving compatibility, dispersion, and workability;
- (3) the balance among stiffness, elasticity, and flexibility in the composite-modified system;
- (4) the need to verify whether improved phase stability can enhance aging resistance and service life.

These mechanisms require further validation through fluorescence microscopy, SEM, AFM, FTIR, GPC, DSC, rheological aging indices, storage stability tests, and long-term field monitoring.

Table 5. Summary of experimental evidence on the modification mechanisms of SBS-, SMC-, and SBS–SMC-modified asphalt.

Characterization Method	Main Observable Indicators	Mechanism Interpretation	Evidence In Existing Studies	Limitations
Fluorescence microscopy	Polymer-rich phase distribution, phase continuity, particle dispersion, phase separation after storage	Used to identify SBS swelling, polymer-rich network formation, and compatibility between polymer and asphalt	Relatively mature for SBS-modified asphalt; some evidence supports improved phase morphology in composite polymer-modified systems	Mostly qualitative; image-processing-based quantitative parameters are still insufficient
SEM	Surface morphology, fracture surface, polymer dispersion, interfacial defects	Can reveal whether modifiers are uniformly dispersed and whether a denser asphalt–polymer matrix is formed	Commonly used for polymer- or rubber-modified asphalt mixtures; direct SBS–SMC evidence remains limited	Sample preparation will influence morphology; binder-scale SEM evidence is less direct than mixture-scale observations
AFM	Bee-like structures, surface roughness, phase contrast, micro-mechanical response	Useful for evaluating microstructural evolution, phase-domain changes, and aging-induced surface changes	Widely used in SBS-modified asphalt and aged asphalt studies; useful for linking morphology with rheological response	Limited direct application to SMC or SBS–SMC systems; interpretation of bee structures remains debated
FTIR/ATR-FTIR	Carbonyl index, sulfoxide index, butadiene-related peaks, styrene-related peaks, functional group changes	Used to identify asphalt oxidation, SBS degradation, and chemical interactions between modifiers and asphalt	Strong evidence exists for tracking SBS degradation and asphalt oxidation during aging	For SBS–SMC systems, FTIR evidence is still insufficient to distinguish physical blending from chemical interaction
GPC	Molecular weight distribution, large molecular size fraction, SBS degradation products	Can identify polymer degradation, asphalt molecular aggregation, and aging-related molecular changes	Used in SBS aging studies and polymer-modified asphalt research	Rarely applied to SMC or SBS–SMC composite systems

DSC/thermal analysis	Glass transition behavior, crystallization behavior, thermal stability	Can evaluate polymer compatibility, phase transition behavior, and thermal stability	Useful for SBS structure and polymer–asphalt compatibility evaluation	Limited direct data for SBS–SMC systems
DSR/MSCR/BR	Complex modulus, phase angle, rutting factor, recovery rate, non-recoverable creep compliance, creep stiffness	Provides macro-rheological evidence for elastic network formation, high-temperature stability, and low-temperature cracking resistance	Strongly developed for SBS-modified asphalt; increasingly used for composite-modified asphalt	Rheological improvement alone cannot prove molecular-level synergistic interaction
Mixture performance tests	Rutting depth, fatigue life, fracture energy, TSR, low-temperature cracking index	Reflects engineering consequences of binder-level modification	Some studies report improved performance of SMC- or SBS–SMC-modified mixtures	Results are sensitive to gradation, RAP content, binder dosage, temperature, and test protocol

8. Critical Discussion and Future Perspectives

The future research directions discussed in this section are based on the comparative results and main knowledge gaps summarized in Table 4. Specifically, although SBS-, SMC-, and SBS–SMC-modified asphalt systems exhibit promising performance, existing studies mainly focus on empirical characterization. More in-depth analysis is still required. The relationships among polymer structure, compatibility, rheological response, mixture performance, and long-term durability remain unclear. In particular, the synergistic effect between SBS and SMC should not be regarded as a simple superposition of two modifiers. Instead, it should be considered a multi-scale coupling process involving intermolecular interactions, phase morphology evolution, viscoelastic network formation, and performance development. To make this qualitative analysis more comparable and critical, the relevant quantitative indicators are also summarized in Table 6. These indicators include crack-related indices, fatigue life parameters, modulus-related indices, aging indices, and storage stability indices.

Table 6. Representative quantitative indicators for evaluating SBS-, SMC-, and SBS–SMC-modified asphalt systems.

Performance	Quantitative Indicators	Main Interpretation	Limitations
High-temperature rutting resistance	Rutting factor, MSCR recovery rate, non-recoverable creep compliance, rutting depth	Higher rutting factor and MSCR recovery rate, lower non-recoverable creep compliance and rutting depth indicate better rutting resistance	Test temperature, stress level, asphalt source, and modifier dosage differ among studies
Viscoelastic stiffness	Complex modulus, dynamic modulus, phase angle	Higher modulus usually indicates greater stiffness and deformation resistance, while phase angle reflects elastic–viscous balance	Direct comparison requires identical temperature, frequency, aging state, and mixture gradation
Fatigue resistance	Fatigue life, fatigue life ratio, stiffness degradation rate, fracture energy	Longer fatigue life and slower stiffness degradation indicate better fatigue durability	Failure criteria and loading modes vary considerably among studies

Low-temperature cracking resistance	BBR stiffness, m-value, SCB fracture energy, cracking index	Lower stiffness and higher relaxation capacity indicates better low-temperature crack resistance	Binder-level and mixture-level indicators are not always directly comparable
Aging resistance	Carbonyl index, sulfoxide index, SBS degradation index, rheological aging index	Lower chemical and rheological aging indices indicate better aging resistance	Direct FTIR-based aging data for SBS–SMC systems remain limited
Storage stability	Softening-point difference, normalized segregation index	Lower softening-point difference or normalized segregation index indicates weaker segregation and better storage stability	Direct storage tube comparisons between SBS and SBS–SMC binders remain insufficient

8.1. Differences Between the Modification Mechanisms of SBS and SMC

SBS mainly improves asphalt performance through polymer swelling and elastic network formation. During mixing, SBS absorbs light asphalt fractions and forms a polymer-rich phase. This structure enhances elastic recovery, complex modulus, rutting resistance, and fatigue performance. However, the effectiveness of SBS strongly depends on the source and composition of base asphalt, SBS type, polymer dosage, and aging conditions. Previous studies have shown that the morphology and rheological behavior of SBS-modified asphalt are significantly influenced by asphalt composition and polymer structure. Aging simultaneously induces asphalt oxidation and SBS degradation, resulting in complex rheological changes.

In contrast, SMC appears to be more beneficial for improving workability, low-temperature flexibility, and reducing construction temperature. Its advantage lies in enhancing asphalt compatibility and processing behavior, particularly in cold-mix or ambient-temperature asphalt systems. However, compared with SBS, the molecular-level interaction mechanism between SMC and asphalt is still insufficiently understood. Current studies on SMC mainly focus on engineering performance, regional applications, and specific mixture designs. Therefore, its modification mechanism should be further verified using FTIR, GPC, AFM, fluorescence microscopy, SEM, and rheological master curves.

8.2. Synergistic Effects and Potential Competitive Mechanisms

The SBS–SMC composite system achieves a better balance among rutting resistance, low-temperature cracking resistance, fatigue durability, and aging resistance. SBS contributes to elastic recovery and high-temperature stability, whereas SMC improves compatibility, dispersion stability, and low-temperature adaptability. Therefore, the composite system forms a more stable multiphase network than single-modifier systems.

However, such synergy is not always guaranteed. Excessive polymer content increases viscosity, reduces workability, or induces phase separation. Similarly, excessive SMC weakens the elastic contribution of SBS or alters the stiffness–flexibility balance of the binder. Therefore, the key scientific issue is not whether SBS and SMC are individually effective, but whether their proportions can form a stable and continuous polymer–asphalt network. This requires systematic optimization based on rheological, mechanical, durability, and environmental indicators. Previous studies have also provided methodological insights of numerical simulation and theoretical models for predicting the aging process and durability evolution of SBS–SMC-modified asphalt [107–112].

8.3. Practical Limitations and Barriers of Engineering Implementation

Although SBS–SMC composite-modified asphalt has great potential to improve rutting resistance, low-temperature flexibility, fatigue resistance, and environmental sustainability, its large-scale application still faces several practical challenges. These challenges extend beyond material cost. They also involve production equipment, process control, construction adaptability, quality assurance, and long-term performance evaluation.

From a material perspective, SBS is generally more expensive than conventional asphalt and provides superior performance compared with many traditional modifiers. Although SMC can be produced from recycled rubber or plastic waste, its composition and performance will vary with the source materials and manufacturing process. Therefore, the economic feasibility of SBS–SMC composite modification should not be evaluated solely by the initial material cost. A comprehensive assessment should also consider pavement service life, maintenance frequency, energy consumption, emission reduction, and recycling potential.

From a production perspective, SBS–SMC modification requires high-shear mixing, precise temperature control, sufficient mixing time, and storage facilities with continuous agitation. Poor process control will cause inadequate modifier dispersion, excessive viscosity, phase separation, and unstable rheological properties. These problems can adversely affect pumping, mixing, paving, and compaction. Therefore, the acceptable ranges of key processing parameters should be clearly defined. These include modifier dosage, mixing temperature, shear rate, mixing time, storage duration, and allowable viscosity.

From the perspectives of construction and standardization, current guidance is mainly based on laboratory studies and limited field applications. Standardized quality control criteria for SBS–SMC composite-modified asphalt remain insufficient. Future studies should establish performance-based specifications. These specifications should integrate binder properties, mixture performance, construction workability, storage stability, and durability. In addition, life-cycle cost analysis (LCCA) and life-cycle assessment (LCA) should be incorporated to determine whether the higher initial investment can be offset by longer service life, reduced maintenance, lower production temperatures, and increased use of recycled materials.

8.4. Insufficient Quantitative Comparison and Multi-Scale Structure–Performance–Durability Models

Most existing studies rely on qualitative descriptions, such as “significant improvement” or “excellent performance”. However, few studies quantitatively compare the performance enhancement levels of SBSMA, SMCMA, and SBS–SMCMA using standardized indicators. This limits cross-study comparison and engineering application. Future studies should report standardized performance indicators, including rutting factor, MSCR recovery rate, Jnr value, fatigue life ratio, fracture energy, TSR, aging index, and segregation index. These quantitative indicators are essential for establishing a unified evaluation framework.

In addition, the performance of SBS–SMC composite asphalt should be interpreted from a multi-scale perspective. At the molecular scale, polymer chains interact with asphalt components through swelling, absorption, and physical entanglement. At the microstructural scale, phase morphology and polymer dispersion determine compatibility and storage stability. At the rheological scale, the coupled network governs modulus, phase angle, elastic recovery, and creep behavior. At the mixture scale, these binder-level properties influence rutting, cracking, fatigue, moisture damage, and aging performance.

Therefore, future studies should establish a multi-scale structure–performance–durability model. The model should link chemical composition, morphology, rheology, mixture performance, and field durability. Similar multi-scale approaches have already been applied in SBS-modified asphalt studies, particularly in evaluating chemical, rheological, and aging characteristics.

8.5. Engineering Application and Standardization Challenges

Although SBS–SMC composite asphalt shows promising engineering applicability, its large-scale engineering implementation still faces several challenges. First, the storage stability of the composite binder remains unclear. It should be clarified that this uncertainty refers to binder-level storage stability rather than mixture-level workability. Although SMC-modified mixtures have shown improved construction adaptability, direct storage tube evidence for SBS–SMC composite binders remains insufficient. Second, its preparation process is more complex than that of single-modifier asphalt. Factors such as mixing temperature, shear rate, mixing duration, and modifier addition sequence can significantly affect the final performance. Third, field compaction and construction quality are highly sensitive to temperature and viscosity. Fourth, long-term field monitoring data are still limited.

Additionally, existing specifications mainly focus on conventional asphalt or SBS-modified asphalt. They do not provide a complete evaluation framework for SBS–SMC composite systems. Traditional penetration, softening-point, ductility, and viscosity tests are insufficient for characterizing the complex viscoelastic behavior of polymer-modified asphalt. Future evaluation systems should integrate advanced methods, including DSR, MSCR, LAS, BBR, FTIR, GPC, AFM, and fluorescence microscopy.

8.6. Data-Driven Optimization, Sustainability, and Life-Cycle Assessment

The design of SBS–SMC composite asphalt involves multiple variables, including SBS content, SMC content, base asphalt composition, mixing temperature, shear rate, aging condition, reclaimed asphalt pavement (RAP) content, and aggregate gradation. Traditional trial-and-error approaches are inefficient. Future studies should adopt machine learning, response surface methodology, Bayesian optimization, and multi-objective optimization to determine the optimal dosage range [113–115]. Recent advances in digital twin modeling and machine learning for construction materials also provide valuable methodological insights for future studies on SBS–SMC asphalt materials [116–118]. However, data-driven models should not be treated as black boxes. They should be integrated with physical mechanisms, rheological parameters, and microstructural features to improve interpretability and reliability. Previous calibration approaches combining experimental measurements and numerical modeling provide valuable insights for calibrating predictive models for future SBS–SMC-modified asphalt systems [119–124].

On the other hand, SMC has environmental advantages because it can utilize recycled rubber and plastic resources. It also reduces construction temperature and emissions. However, these claims should be supported by life-cycle assessment (LCA) rather than qualitative descriptions. Previous LCA studies on asphalt mixtures have shown that reclaimed asphalt pavement and warm-mix technologies can reduce environmental impacts, although the results depend on material source, production temperature, transport distance, and recycling rate.

Therefore, future studies on SBS–SMC composite asphalt should evaluate not only mechanical performance, but also carbon emissions, energy consumption, cost, recyclability, and long-term maintenance benefits.

9. Conclusions

This paper reviews the development, modification mechanisms, performance characteristics, and engineering applications of SBS-, SMC-, and SBS-SMC-modified asphalt and mixtures. The following conclusions can be drawn:

(1) Research on SBS-modified asphalt is relatively mature. Its engineering application is widespread. SBS mainly improves rutting resistance, fatigue resistance, elastic recovery, and low-temperature cracking resistance through polymer swelling and elastic network formation. However, SBS-modified asphalt still suffers from phase separation, poor storage stability, and thermo-oxidative aging. These problems are closely related to asphalt composition, SBS structure, modifier dosage, and preparation conditions.

(2) SMC-modified asphalt exhibits potential advantages in construction performance, low-temperature adaptability, recycled resource utilization, and environmental benefits. Existing studies indicate that SMC can be applied in cold mix, ambient-temperature paving, and preventive maintenance. However, its modification mechanism has not been fully clarified. In particular, the molecular interactions between SMC and asphalt components, microstructural evolution, and long-term durability of SMC-modified asphalt still require further investigation.

(3) SBS-SMC composite modification provides a promising approach for balancing high-temperature stability, low-temperature flexibility, fatigue resistance, moisture resistance, and aging performance. Its potential synergistic effects originate from the elastic network of SBS and the compatibility enhancement or processing adjustment effect of SMC. However, current studies remain limited and are mainly based on performance validation. Mechanism-based, quantitative, and standardized evaluation methods are still lacking.

(4) Future studies should focus on multi-scale characterization and modeling. Rheological tests should be combined with fluorescence microscopy, SEM, AFM, FTIR, GPC, differential scanning calorimetry (DSC), and molecular dynamics simulations. These methods can clarify the relationships among polymer structure, phase morphology, and macroscopic performance. In addition, full-life fatigue tests, coupled aging condition tests, moisture damage tests, and field validation should be strengthened.

(5) A unified performance optimization framework for SBS-SMC composite-modified asphalt should be established. This framework should include modifier dosage, preparation process, phase stability, rheological indices, mixture performance, durability, and environmental impact. Machine learning and life-cycle assessment can provide effective tools for developing high-performance, durable, and sustainable asphalt materials.

(6) Particular attention should be given to practical barriers, including high initial material costs, specialized equipment requirements, strict process control, dispersion issues, storage stability, and limited field validation. Life-cycle cost analysis and life-cycle assessment should also be incorporated. Furthermore, future studies should report complete datasets and standardized performance metrics to facilitate reliable quantitative comparisons. These metrics include the composite modulus improvement ratio, fatigue life improvement ratio, and damage accumulation rate.

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