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State of the Art in Modified Asphalt Research for Highway Pavement Engineering

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Abstract

The purpose of this review is to systematically sort out the research status of modified asphalt, address the performance deficiencies of traditional asphalt pavements, and provide theoretical and technical support for its engineering application. Methods include synthesizing research progress of modified asphalt from 2020 to 2026, focusing on four main types of modifiers (polymer, nanomaterial, composite, and sustainable modifiers), and analyzing their effects on asphalt performance via key characterization techniques. Results show that different modifiers have distinct advantages: polymer modifiers improve high/low-temperature performance, nanomaterials enhance aging resistance and functionality, composite modifiers achieve synergistic effects, and sustainable modifiers realize environmental and economic benefits. Critical challenges such as poor modifier dispersion and high cost are also identified. Conclusions indicate that modified asphalt is pivotal for enhancing pavement durability, and future research should focus on solving existing challenges to promote its large-scale and high-quality application.

Keywords

Modified Asphalt; Polymer Modifier; Nanomaterial; Composite Modification; Sustainable Pavement; Aging Resistance; Rheological Characterization

1. Introduction

As the core binding material of flexible pavements, asphalt binder degrades under environmental and traffic loads, causing rutting, thermal cracking, and fatigue cracking. Conventional neat asphalt cannot meet modern highway performance requirements, so asphalt modification—adding functional additives to adjust its composition and microstructure—has become a key way to enhance pavement durability and reduce maintenance costs.

Advancements in materials and pavement engineering have led to diverse modifiers (polymers, nanomaterials, composites) that optimize asphalt properties. However, poor compatibility, uneven dispersion, and high costs restrict their large-scale

application. This review collates latest research, compares modifier effects, summarizes characterization techniques, and proposes research directions to support modified asphalt's engineering popularization.

2. Classification and Research Progress of Modified Asphalt

2.1. Polymer-Modified Asphalt

Polymer modification is the most widely used and technically mature technology in the field of asphalt modification. According to the chemical structure and performance characteristics of polymers, they can be categorized into elastomeric modifiers, plastomeric modifiers, and recycled polymer modifiers. The modification mechanism primarily relies on physical blending or chemical reaction between polymers and asphalt molecules, forming a stable cross-linked network structure to improve the rheological and mechanical properties of asphalt. This section focuses on the research progress, performance enhancement effects, and existing technical challenges of different types of polymer modifiers.

2.1.1. Elastomeric Modifiers (Representative: SBS, SBR, CR)

Elastomeric modifiers form a stable cross-linked network in asphalt, significantly improving its low-temperature flexibility and elastic recovery. The most widely used is SBS, ideal for high-grade highways due to its balanced high and low-temperature performance; SBR and CR (a sustainable, waste tire-derived modifier) are also commonly studied.

SBS-modified asphalt forms a dense polymer network, greatly enhancing high-temperature stability—with 3%–6% SBS, its dynamic stability is 50%–100% higher than neat asphalt, and it shows better resistance to permanent deformation and low-temperature crack resistance. Both SBS and SBR modified asphalt have good aging resistance. Key challenges: high SBS cost, potential phase separation between SBS and asphalt, and poor SBR storage stability with high mixing viscosity.

CR, a sustainable elastomeric modifier from waste tires, improves asphalt's elasticity and fatigue resistance, suitable for heavy traffic and cold regions. With 10%–20% CR, the mixture's fatigue life extends by 80%–150%, but its high viscosity complicates mixing, and it requires compatibilizers for storage stability; costly desulfurization limits its large-scale use.

2.1.2. Plastomeric Modifiers (Representative: EVA, EBA, PE, PP)

Plastomeric modifiers improve asphalt's high-temperature stability and hardness but have poor low-temperature flexibility. EVA is the most representative, widely used for its low cost and processability; EBA, PE and PP (mostly recycled waste plastics) are also common.

EVA (2%–5% content) raises asphalt's softening point and mixture dynamic stability by 60%–120%, with good rutting resistance; PE (3%–6% content) improves dynamic stability by 50%–80%. EVA's low-temperature flexibility is

inferior to SBS, suitable for moderate cold regions; PE/PP have poorer low-temperature performance, limiting cold-region use. EVA is cheaper than SBS; recycled PE/PP cut costs and recycle resources. Key challenges: poor low-temperature performance, EVA-asphalt incompatibility (easy phase separation), and poor recycled plastic dispersion (solved by compatibilizers/surface modification).

Recycled plastics (PE, PP, PET) improve asphalt's high-temperature stability and durability, with environmental benefits. PE (3%–6% content) enhances rutting resistance by 50%–80% but reduces low-temperature crack resistance by 10%–20%. Improving their compatibility with asphalt via compatibilizers or surface modification is key for engineering application, e.g., maleic anhydride grafted PE boosts compatibility and low-temperature performance.

2.1.3. Sustainable Polymer Modifiers (Representative: RAP, Recycled Polymer)

RAP and recycled polymers are key to sustainable modified asphalt: RAP (containing aged asphalt and aggregate) reduces virgin material use and construction waste; recycled polymers (plastics, rubber, fibers) further enhance sustainability, aligning with green pavement engineering concepts.

RAP's aged asphalt boosts mixture stiffness and rutting resistance but impairs fatigue resistance; ≤30% RAP improves high-temperature performance (dynamic stability +40%–60%) with slight fatigue life reduction. Rejuvenators (3%–5%) restore RAP's low-temperature ductility. Combining RAP with recycled polymers (e.g., PE, rubber) enhances performance—recycled PE improves high-temperature/moisture resistance, recycled rubber extends fatigue life by 70%–120%. Key challenges: variable RAP quality, low recycled polymer recycling rate, and poor RAP-polymer compatibility (solved by compatibilizers/mixing optimization).

2.2. Nanomaterial-Modified Asphalt

Nanomaterial modifiers possess the characteristics of small particle size, large specific surface area, and strong surface activity, which can significantly improve the performance of asphalt at a low dosage. Common nanomaterial modifiers include carbon nanomaterials, inorganic nanoparticles, and two-dimensional nanomaterials. The modification mechanism is mainly based on surface adsorption and chemical reaction between nanomaterials and asphalt molecules, forming a dense spatial network structure to enhance the cohesion and mechanical properties of asphalt.

2.2.1. Carbon Nanomaterial-Modified Asphalt

Carbon nanomaterials (graphene, CNTs, GO) have excellent mechanical, thermal and electrical properties, forming a dense spatial network in asphalt to enhance its rheological and mechanical performance; GO, a graphene derivative, has better dispersion.

Graphene (0.3%–0.8% content) increases mixture dynamic stability by 80%–150%

and fatigue life by 100%–200%, interacting with asphalt molecules via van der Waals forces and π-π stacking. CNTs improve tensile strength by 30%–50%. Both enhance UV aging resistance (graphene-modified asphalt has 85%–92% penetration retention after 1000-hour UV aging). They endow asphalt with self-healing, thermal conductivity and electrical conductivity (e.g., CNTs enable microwave-induced crack healing; graphene is suitable for snow-melting pavements). Challenges: high cost, poor dispersion, and increased production cost from surface modification.

2.2.2. Inorganic Nanoparticle-Modified Asphalt

Inorganic nanoparticles (nano-SiO_2, nano-TiO_2, nano-$CaCO_3$) are low-cost, well-dispersed and stable, improving asphalt's high-temperature stability, aging resistance and moisture resistance.

Nano-SiO_2 (1%–3% content) increases mixture dynamic stability by 50%–100%; nano-$CaCO_3$ (2%–4% content) raises asphalt softening point by 8–15℃. Nano-TiO_2 has photocatalytic activity to degrade pollutants and improve UV aging resistance (70%–80% ductility retention after UV aging); nano-SiO_2 slows aging (20%–30% higher penetration retention after thermal aging). They enhance asphalt-aggregate adhesion, reducing moisture damage (nano-$CaCO_3$ mixture has over 80% freeze-thaw split strength ratio). Challenges: limited low-temperature improvement (excessive nano-SiO_2 reduces mixture ductility by 15%–25%) and poor compatibility (solved by dispersants).

2.3. Composite-Modified Asphalt

Composite modification refers to the combination of two or more modifiers to exert their respective advantages, achieve a synergistic enhancement effect, and comprehensively improve the performance of asphalt. Common composite modification systems include polymer-fiber hybrid systems, polymer-nanomaterial hybrid systems, and fiber-nanomaterial hybrid systems. The core of composite modification is to realize the performance complementarity between different modifiers, solving the problem that single modifiers cannot meet the comprehensive performance requirements of modern highway pavements.

2.3.1. Polymer-Fiber Composite-Modified Asphalt

Polymer-fiber composite modification combines the elasticity of polymers and the reinforcement effect of fibers, significantly improving the mechanical performance and durability of asphalt. Common fibers include basalt fiber, carbon fiber, polyester fiber, and lignin fiber, among which basalt fiber is the most widely used due to its low cost, good heat resistance, and corrosion resistance.

Basalt fiber, with high strength, heat and corrosion resistance, improves the fatigue resistance and high-temperature stability of polymer-modified asphalt. With 4%–5% SBS and 0.3%–0.5% basalt fiber, the mixture's dynamic stability (3000–3500 times/mm) and low-temperature bending strain (2800–3200 με) are superior to

single SBS-modified asphalt. Its fiber network disperses loads, reducing stress concentration and extending fatigue life by 50%–80%. It also enhances aging resistance (80%–90% viscosity retention after thermal aging, UV blocking). Challenges: increased mixing difficulty, need for optimized mixing to ensure uniform fiber dispersion (agglomeration reduces effect), and high carbon fiber cost limiting large-scale use.

2.3.2. Polymer-Nanomaterial Hybrid-Modified Asphalt

Polymer-nanomaterial hybrid modification combines polymer cross-linking networks and nanomaterial spatial networks to form a stable multi-level structure, comprehensively improving asphalt performance. Common systems (SBS-graphene, SBS-nano-SiO_2, CR-CNTs) simultaneously enhance high-temperature stability, low-temperature crack resistance, and aging resistance.

SBS-graphene (4% SBS + 0.5% graphene) increases mixture dynamic stability by 120%–150% and low-temperature bending strain by 80%–100%, with better anti-UV aging. SBS-nano-SiO_2 improves high-temperature stability and moisture resistance (freeze-thaw split strength ratio +20%–30%). Polymer-conductive nanomaterial combinations endow asphalt with self-healing properties—SBS-CNTs achieve over 80% crack healing after 5–10 minutes of microwave radiation. Challenges: high cost, complex preparation, unproven long-term durability, and poor polymer-nanomaterial compatibility (solved by compatibilizers/nanomaterial surface modification).

2.4. Sustainable Modified Asphalt

Sustainable modified asphalt uses recycled materials/industrial by-products, reducing virgin resource consumption and pollution, aligning with the "double carbon" strategy. Common modifiers include crumb rubber, RAP, waste plastic, lignin, and fly ash.

2.4.1. Crumb Rubber-Modified Asphalt

Crumb rubber (recycled waste tires) improves asphalt elasticity, fatigue resistance, and noise reduction, consuming 100–200 waste tires per ton. With 10%–20% content, its fatigue life extends by 80%–150%, suitable for heavy traffic and cold regions (low-temperature bending strain 30%–50% higher than neat asphalt). It reduces virgin asphalt use by 5%–10% but has high viscosity (increasing mixing cost), poor storage stability (needing compatibilizers), and costly desulfurization limits large-scale application.

Lignin (paper industry by-product) enhances asphalt anti-UV aging (3%–6% content, penetration retention +20%–30% after 1000-hour UV aging) and asphalt-aggregate adhesion (freeze-thaw split strength ratio +15%–25%), slightly improving low-temperature flexibility. Fly ash (industrial solid waste) improves high-temperature stability (5%–10% content, dynamic stability +40%–60%) and wear resistance (+30%–40%), filling asphalt micro-pores to slow aging and reduce

virgin aggregate use. Challenges: poor lignin-asphalt compatibility (surface modification increases cost); fly ash high water absorption may reduce moisture stability and variable quality is hard to control.

2.4.2. Lignin and Fly Ash-Modified Asphalt

Lignin (paper industry by-product) and fly ash (industrial solid waste) improve asphalt performance and reduce costs, with significant sustainability. Lignin enhances anti-aging and adhesion; fly ash boosts high-temperature stability and wear resistance, but both have compatibility and quality control challenges.

Lignin (3%–6% content) improves asphalt anti-UV aging (penetration retention +20%–30% after 1000-hour UV aging) and adhesion (freeze-thaw split strength ratio +15%–25%), slightly enhancing low-temperature flexibility. Fly ash (5%–10% content) boosts high-temperature stability (dynamic stability +40%–60%) and wear resistance (+30%–40%), filling micro-pores to slow aging and reduce virgin aggregate use. Challenges: poor lignin dispersion (surface modification increases cost); fly ash water absorption and variable quality affect performance.

3. Key Characterization Techniques of Modified Asphalt

The accurate characterization of modified asphalt performance is the foundation for its research and engineering application. With the development of testing technology, a variety of characterization techniques have been applied to evaluate the rheological properties, mechanical performance, aging resistance, and microstructure of modified asphalt. This section summarizes the key characterization techniques commonly used in modified asphalt research, including conventional testing methods, advanced testing methods, and numerical simulation techniques.

3.1. Conventional Characterization Techniques

Conventional characterization techniques, simple and widely used in engineering, evaluate modified asphalt's basic performance via penetration, softening point, ductility, and dynamic stability tests. Penetration reflects hardness/fluidity (polymer-modified asphalt has lower values); softening point indicates high-temperature stability (modified asphalt performs better); ductility evaluates low-temperature flexibility (SBS and CR-modified asphalt have higher values); dynamic stability assesses rutting resistance (composite-modified asphalt is best).

3.2. Advanced Characterization Techniques

Advanced characterization techniques study modified asphalt's microstructure, chemical composition, and rheological properties, providing theoretical support for modification mechanisms. Common methods: DSR (evaluates rheological properties and aging resistance via G* and δ, polymer-modified asphalt performs better); BBR

(assesses low-temperature flexibility via S and m-value, modified asphalt has better performance); FTIR (identifies functional groups and reveals modification/aging mechanisms); SEM (observes modifier dispersion and compatibility, guiding mixing process optimization).

3.3. Numerical Simulation Techniques

Numerical simulation techniques, increasingly used in modified asphalt research, reduce laboratory tests and support design/optimization. Common types: molecular dynamics (studies molecular-level interactions and predicts performance); finite element (simulates pavement mechanical response and service life); discrete element (studies particle interactions, suitable for fiber-modified asphalt).

4. Challenges and Future Research Directions

4.1. Current Challenges

Despite significant progress in modified asphalt research and application, several technical challenges restrict its large-scale, high-quality use. Key challenges include: poor dispersion and compatibility of modifiers (e.g., nanomaterial agglomeration, polymer-asphalt phase separation), insufficient long-term field durability verification due to limited monitoring data, high modifier costs (sustainable modifiers have lower costs but inferior performance), lack of a unified evaluation system for different modified asphalts, and potential environmental pollution from production and construction processes.

4.2. Future Research Directions

To address these challenges, future research will focus on: developing high-performance, low-cost modifiers (e.g., modified recycled polymers, composite nanomaterials, bio-based modifiers); optimizing mixing processes to enhance modifier dispersion and compatibility; strengthening long-term field monitoring to verify durability; establishing a unified evaluation and quality control system; developing intelligent, functional modified asphalt (e.g., self-healing types); and promoting green, low-carbon modification technologies to reduce environmental impact.

5. Conclusion

This review summarizes 2020–2026 modified asphalt research, covering modifier classification, progress, performance effects, challenges, characterization techniques, and future directions. Modified asphalt effectively improves pavement high/low-temperature stability, fatigue and aging resistance, solving traditional asphalt deficiencies.

Each modifier type has unique pros and cons: polymer modifiers are mature but

costly; nanomaterials enhance performance at low dosages but have dispersion and cost issues; composites achieve synergistic enhancement but have complex preparation; sustainable modifiers are eco-economical but unstable. Conventional, advanced, and numerical characterization techniques provide theoretical and experimental support.

Key challenges include poor modifier dispersion/compatibility, insufficient long-term durability, high cost, lack of unified standards, and environmental impact. Future research will address these by developing high-performance low-cost modifiers, optimizing processes, strengthening monitoring, establishing standards, and promoting intelligent green technologies. This review provides technical guidance for modified asphalt research and application.

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