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Recent Advances in Polymer-Modified and Plastic-Reinforced Asphalt: A Comprehensive Review of Performance, Rheology, and Sustainability

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Abstract

Polymer modification of asphalt binders and the integration of recycled plastics in asphalt mixtures have become central strategies in enhancing pavement durability, reducing maintenance costs, and supporting sustainability goals. This review consolidates recent advances (2020–2025) in polymer-modified asphalt (PMA) systems, encompassing elastomeric and plastomeric modifiers, recycled plastic incorporation, performance indicators, rheological characteristics, and environmental implications. The work also identifies emerging trends in multi-factor aging studies, morphology analysis, and rheological characterization (e.g., MSCR, DSR, and BBR testing). Case studies and life-cycle assessments (LCA) demonstrate significant mechanical and ecological benefits of polymer and plastic modifiers, while compatibility and microplastic release remain active challenges.

Keywords: Polymer-Modified Bitumen; SBS; EVA; Recycled Plastics; Rheology; Sustainability; MSCR; Aging

1. Introduction

Modern pavements are required to sustain increasingly heavy traffic loads and extreme temperature fluctuations, conditions under which conventional bitumen often fails. The viscoelastic nature of asphalt binders leads to rutting at high temperatures and cracking at low temperatures. Polymer modification has therefore become a cornerstone in asphalt technology to widen the operational temperature window of bitumen [1–3]. Over the past two decades, the use of styrene–butadiene–styrene (SBS), ethylene–vinyl acetate (EVA), crumb rubber (CR), and recycled plastics (PE, PP, PET) has shown notable improvements in binder elasticity, rutting resistance, fatigue endurance, and environmental sustainability [4–7]. The increasing global concern about plastic waste has accelerated research into utilizing recycled polymers as both binder modifiers and partial bitumen replacements [8–10]. Figure 1 shows the conceptual framework for polymer and recycled plastic modification routes in asphalt binders.

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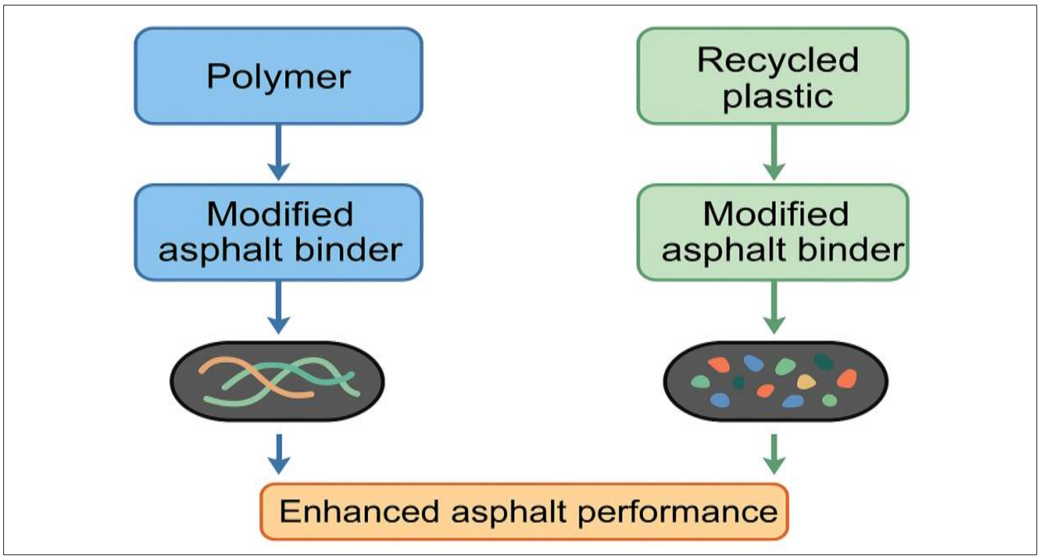


Figure 1 Conceptual schematic of polymer- and plastic-modified asphalt binder systems [2]

2. Classification of Polymers Used in Asphalt Modification

Polymers used in asphalt can be broadly categorized as elastomers, plastomers, and reactive systems. Their effects depend on chemistry, molecular architecture, and interaction with bitumen constituents [11,12].

2.1. Elastomers

Elastomeric polymers such as SBS, SBR, and SEBS impart flexibility and recovery to asphalt. SBS, the most common, forms a dispersed three-dimensional network that enhances elastic recovery and reduces permanent deformation [13]. Recent rheological analyses using the MSCR test have shown that SBS-modified binders can achieve over 70% strain recovery at high stress levels compared to <10% in unmodified binders [14].

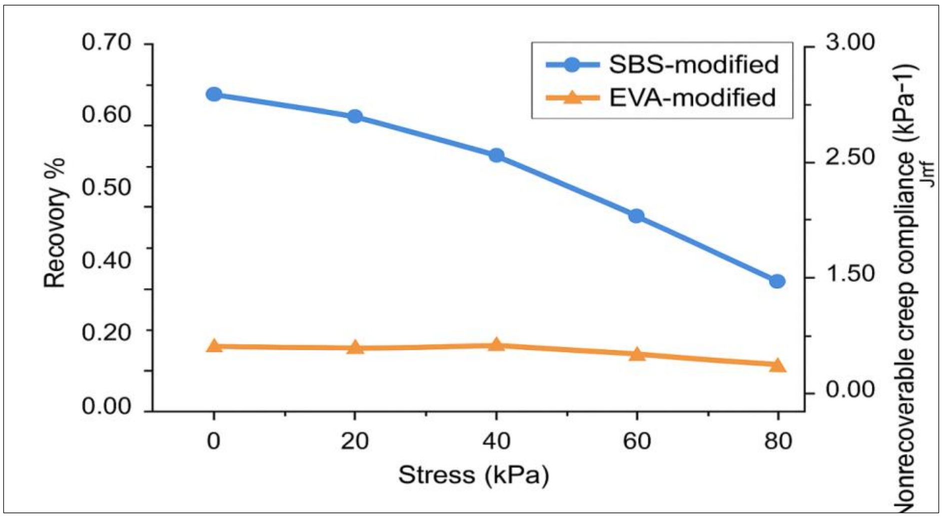


Figure 2 MSCR results for SBS- and EVA-modified binders

2.2. Plastomers

Plastomeric modifiers such as EVA, HDPE, and PP increase stiffness and improve high-temperature performance but may reduce low-temperature flexibility [15]. EVA-modified binders have been shown to provide a good balance of stiffness and flexibility due to the polar vinyl acetate groups that improve miscibility [16].

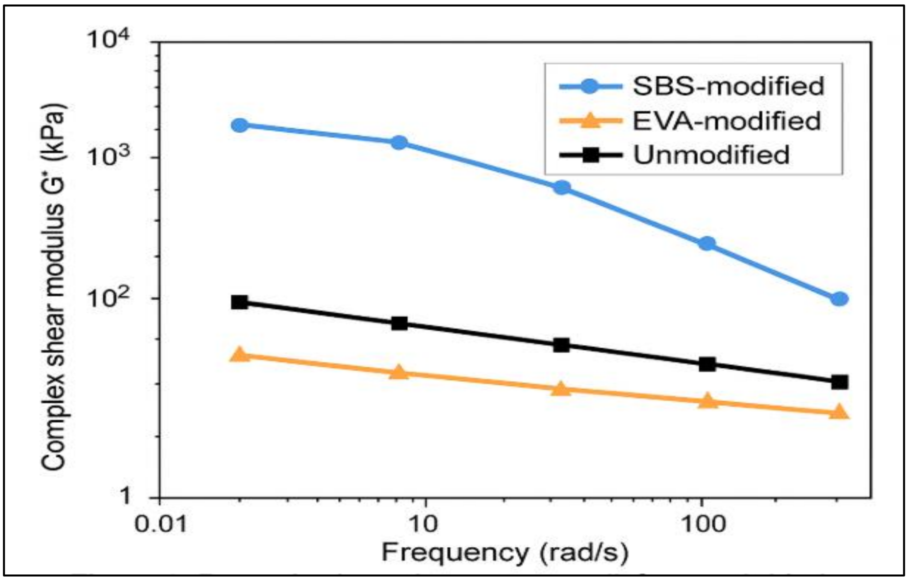


Figure 3 Effect of EVA content on complex modulus (G*) and phase angle (δ) using DSR tests [16].

2.3. Crumb Rubber (CR) and Reactive Polymers

Crumb rubber from end-of-life tires enhances elasticity, fatigue resistance, and aging stability by swelling in aromatic oils of the binder [17]. Reactive polymers (such as polyurethane-based systems) create chemical bonding that enhances compatibility and storage stability [18].

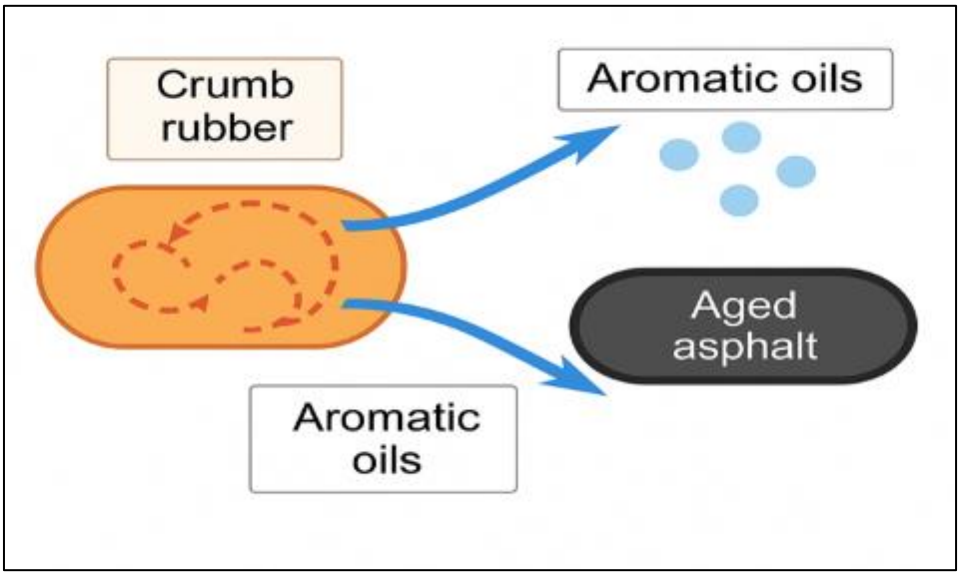


Figure 4 Swelling and diffusion mechanism of crumb rubber particles in asphalt matrix [17]

3. Incorporation Methods: Wet vs. Dry Process

Polymer incorporation can be achieved by either the wet process, where polymers are blended into the binder prior to mixing with aggregates, or the dry process, where plastics or rubbers are added directly into the mix. The wet process allows for homogeneous dispersion and controlled rheology but requires specialized equipment. The dry process is simpler and cost-effective for recycled plastics yet may suffer from non-uniform dispersion and segregation [19,20].

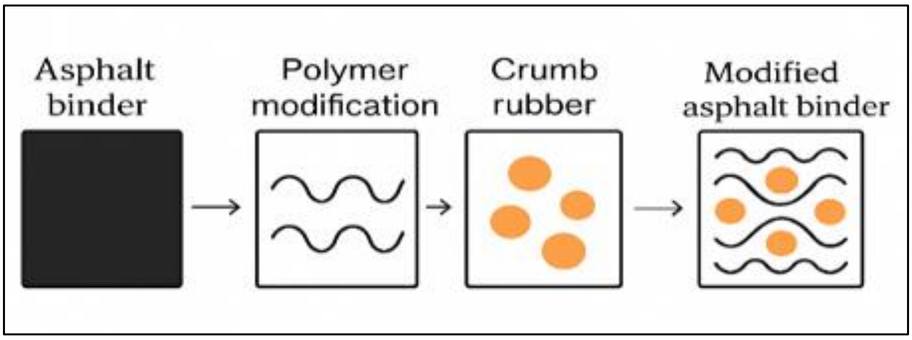


Figure 5 Comparative flowchart of wet and dry incorporation methods for polymer and recycled plastic modification [20]

4. Morphology and rheological behaviour

4.1. Phase Morphology and Compatibility

The morphology of polymer-modified asphalt (PMA) largely determines its mechanical performance and storage stability. Elastomers such as SBS tend to form a continuous polymer-rich network dispersed in the asphalt matrix, while plastomers often yield discrete phase morphologies. The degree of compatibility is affected by polymer polarity, molecular weight, and bitumen composition [21]. Modern imaging techniques such as Atomic Force Microscopy (AFM) and Confocal Laser Scanning Microscopy (CLSM) reveal that the phase distribution directly influences rutting resistance and fatigue performance [22]. Reactive agents such as maleic anhydride-grafted polyethylene (PE-g-MA) and silane coupling agents are often employed to improve polymer-bitumen compatibility [23].

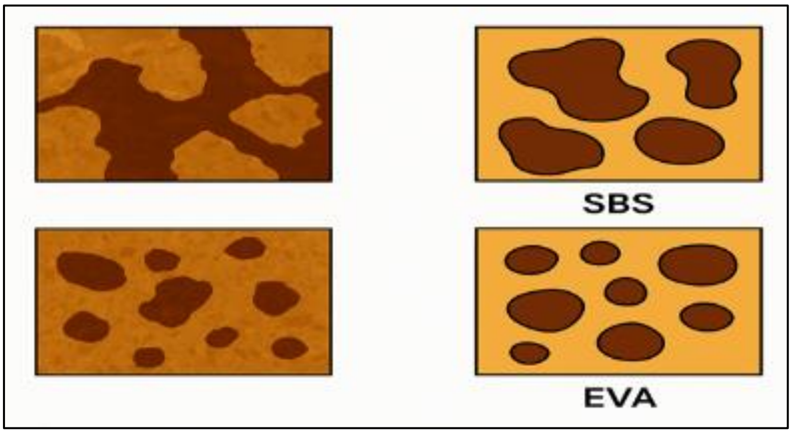


Figure 6 AFM images showing phase morphology of SBS- and EVA-modified binders with distinct dispersed polymer domains [2]

4.2. Rheological Properties

Rheology is a key indicator of binder performance. The Dynamic Shear Rheometer (DSR) test quantifies viscoelastic parameters such as complex modulus (G*) and phase angle (δ), which correlate with rutting and fatigue resistance [24]. Meanwhile, the Multiple Stress Creep Recovery (MSCR) test provides a more realistic measure of elastic recovery under repeated loading [25]. Polymer modification significantly increases $G^*/\sin\delta$ (rutting parameter) and reduces phase angle, indicating greater elasticity. Elastomeric systems like SBS achieve high recovery (>60%) in MSCR tests, while plastomeric PE/PP systems show less recovery but superior stiffness [26].

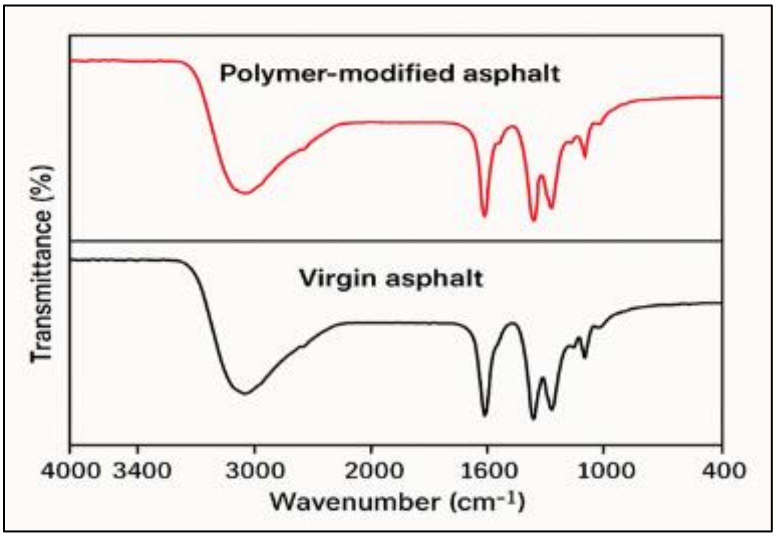


Figure 7 FTIR analysis of polymer-modified asphalt

5. Performance characteristics of polymer-modified asphalt

5.1. Rutting Resistance

Rutting is a major distress mechanism in asphalt pavements, typically associated with permanent deformation under high temperatures and loads. Polymer modification particularly using SBS and EVA effectively enhances high-temperature stiffness and rutting resistance [27]. Recent MSCR-based studies confirm that SBS-modified binders reduce the non-recoverable creep compliance (Jnr) by up to 80% compared with unmodified binders [28].

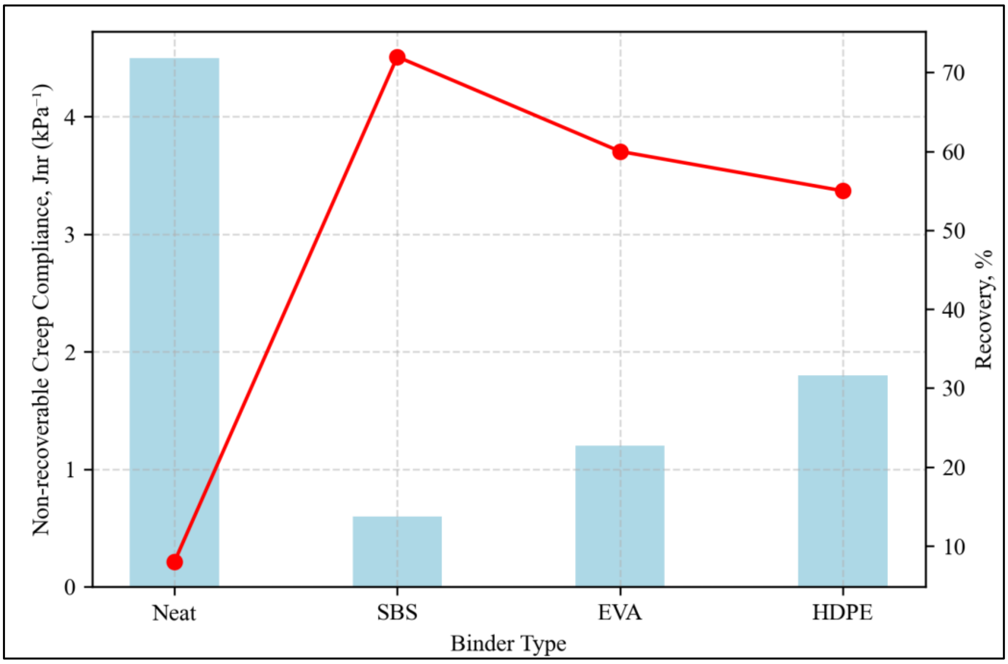


Figure 8 Comparison of Jnr and percent recovery for SBS-, EVA-, and HDPE-modified binders [28].

5.2. Fatigue Resistance

Fatigue cracking results from repeated load applications that lead to micro-crack propagation. Elastomeric polymers like SBS improve the binder's ability to recover deformation, thereby increasing fatigue life [29]. Mixtures containing SBS or crumb rubber show significantly enhanced fatigue resistance due to the elastic energy recovery within the polymer network [30].

5.3. Low-Temperature Cracking

At low temperatures, asphalt binders' contract and may crack due to brittleness. Plastomers such as HDPE and PP can increase stiffness excessively, while elastomers like SBS and rubber maintain flexibility [31]. Hybrid modifications (SBS + EVA or PE) are being developed to achieve balanced performance across temperature ranges [32].

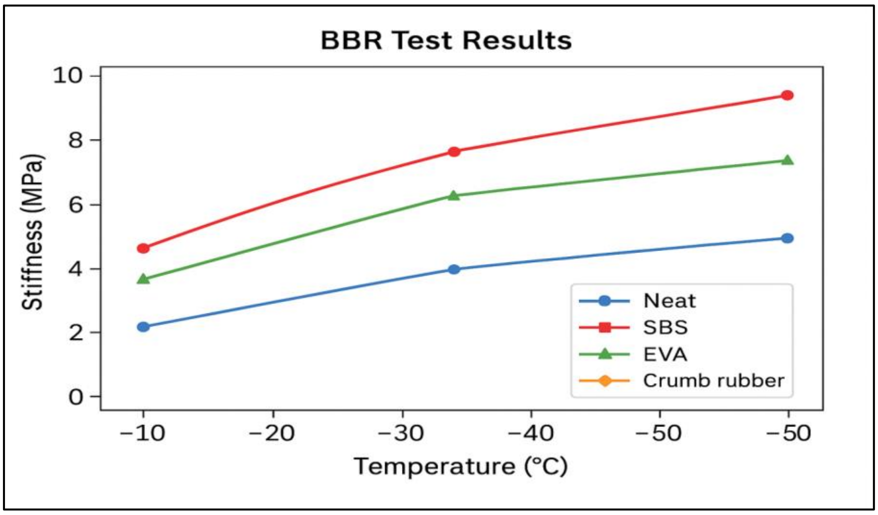


Figure 9 Bending Beam Rheometer (BBR) test results showing improved low-temperature creep compliance for SBS- and rubber-modified binders [32].

5.4. Aging Resistance

Aging caused by oxidation and UV exposure alters the chemical composition of bitumen, increasing stiffness and reducing elasticity. Polymers can mitigate aging by acting as diffusion barriers or scavenging radicals [33]. Crumb rubber modification has shown strong anti-aging performance, slowing carbonyl formation during thermal oxidation [34].

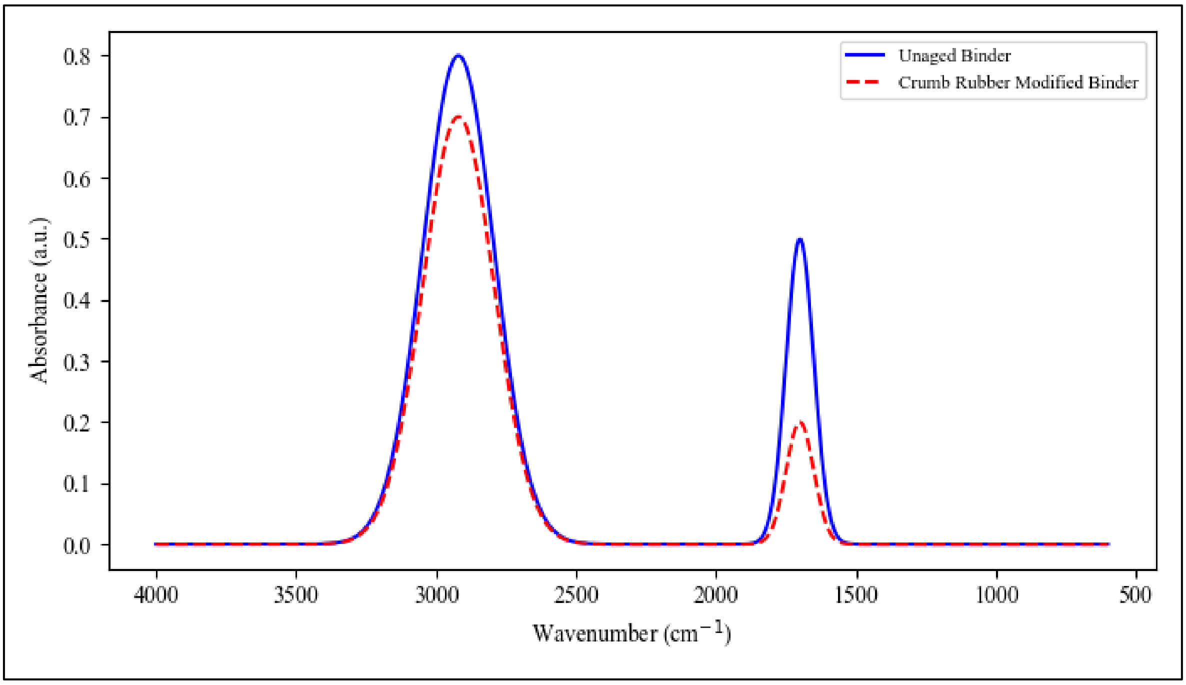


Figure 10 FTIR spectra of unaged and aged binders showing reduced oxidation peaks in crumb rubber-modified asphalt [34]

6. Recycled plastics in asphalt

6.1. Motivation and Materials

Global plastic waste generation exceeds 400 million tons annually, with less than 10% effectively recycled [35]. Incorporating plastics into asphalt not only diverts waste but also reduces virgin bitumen demand and emissions [36]. Common recycled plastics include LDPE, HDPE, PP, PET, and EVA waste [37].

6.2. Processing Methods

- Two key methods exist:
- Wet method: Plastics melted and mixed with bitumen at high shear.
- Dry method: Plastics added directly to hot aggregates before binder addition.

Dry methods are cost-effective but sensitive to melting temperature and particle size [38]. Compatibilizers such as PE-g-MA and EVA improve dispersion and storage stability [39].

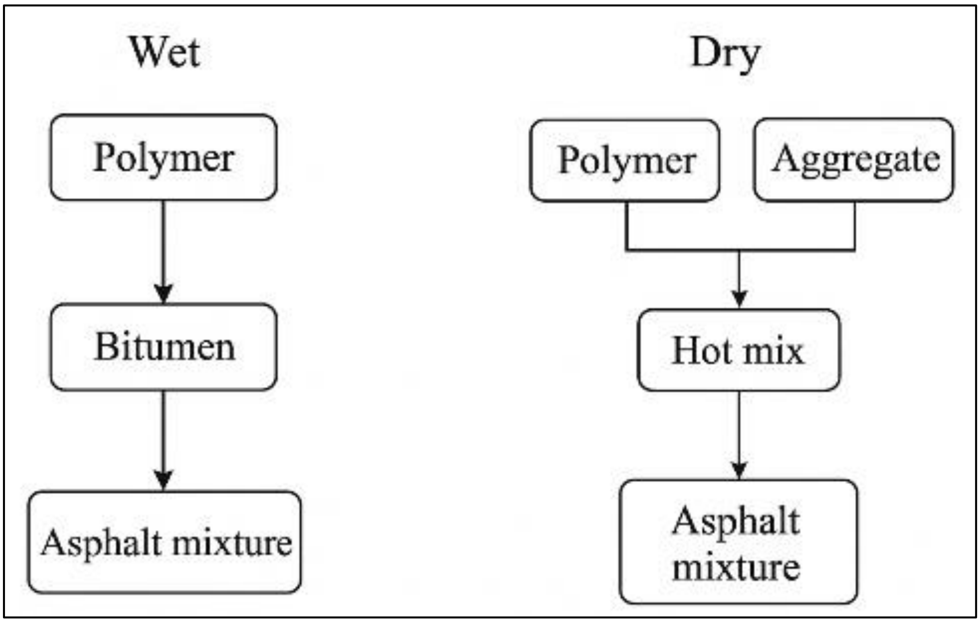


Figure 11 Process diagram illustrating wet and dry incorporation of recycled plastics in asphalt [38].

6.3. Mechanical and Environmental Performance

- Recycled plastic-modified asphalts exhibit:
- Up to 60% higher rutting resistance [40].
- Comparable or improved fatigue resistance at optimum contents (2–8% by binder weight) [41].
- Reduced carbon footprint (5–10% lower GHG emissions per km of pavement) [42].

Environmental assessments highlight the need to monitor microplastic emissions and ensure sustainable end-of-life management [43].

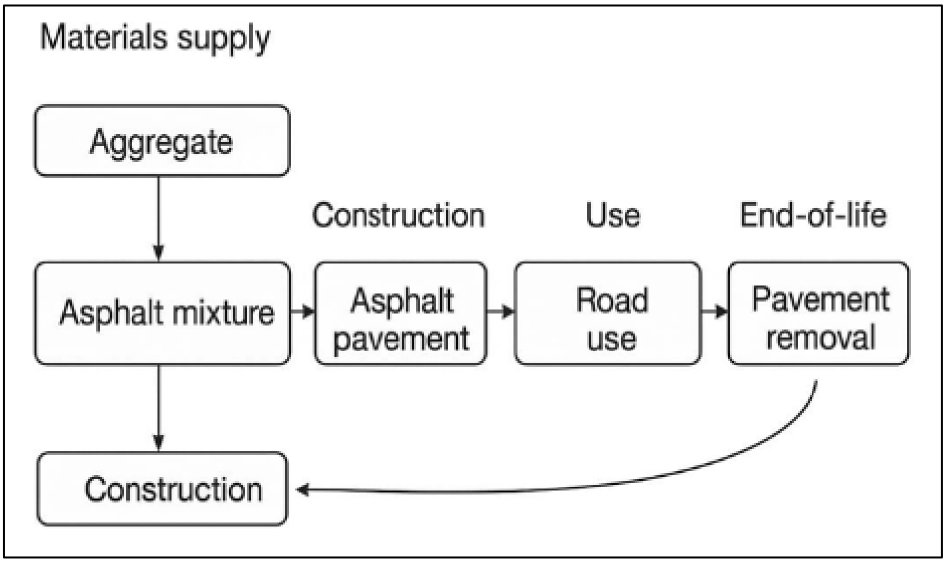


Figure 12 Life-cycle assessment (LCA) comparison between conventional and plastic-modified asphalt pavements [42]

7. Case studies and field performance

- Field data validate laboratory findings.
- SBS-modified roads in Europe and Asia show 2–3× longer service life under heavy traffic [44].
- Crumb rubber pavements in Spain and Brazil demonstrated superior durability and reduced aging rate [45].
- Plastic road pilots in India and the USA reported good rutting resistance but call for further environmental monitoring [46].

Figure 13 Photographic evidence of field trial for HDPE-modified asphalt [46].

8. Durability and Life-Cycle Assessment (LCA)

8.1. Durability and Service Life

Durability depends on how well the modified binder retains its rheological properties over time under environmental and mechanical stresses. Studies show that polymer modification can extend pavement service life by 40–70%, depending on climate and traffic conditions [47]. Hybrid modifications (SBS + PE) provide a synergistic effect that enhances elasticity and stiffness simultaneously [48].

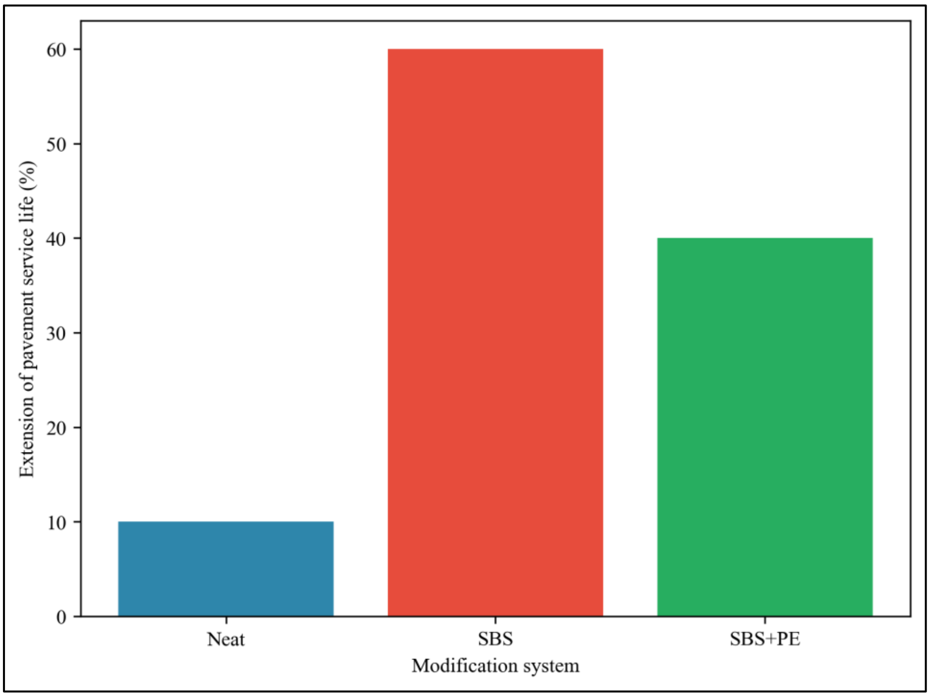
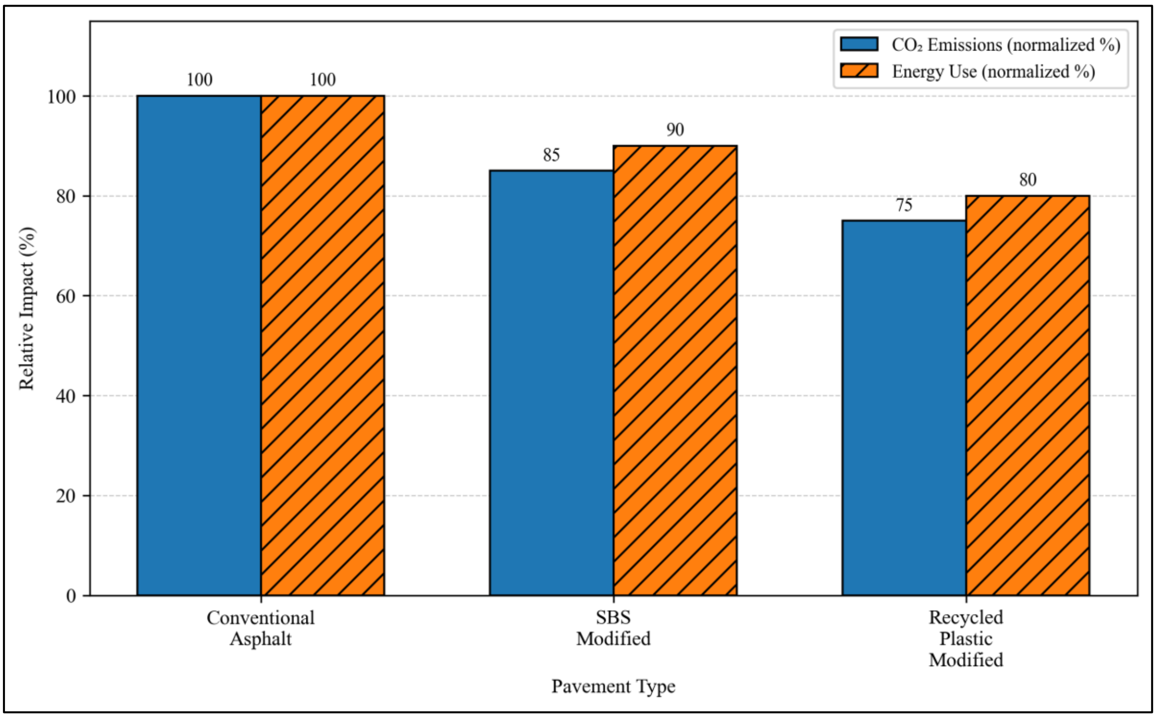


Figure 14 Comparison of pavement service life extension with different polymer modification systems [48].

8.2. Life-Cycle Assessment (LCA)

LCA studies quantify environmental benefits and energy savings of polymer and plastic modifications. Using recycled polymers reduces bitumen consumption by up to 10% and CO_2 emissions by 5–15% per kilometer of pavement [49]. The use of recycled plastics further contributes to circular economy goals [50].



(Source: Wang et al., 2024 [50].

Figure 15 Life-cycle impact assessment comparing conventional, SBS-, and recycled plastic-modified asphalts

9. Emerging technologies and research directions

9.1. Nano-Polymer and Composite Modifiers

Nano-silica, graphene oxide, and carbon nanotubes (CNTs) are being combined with polymers to enhance mechanical and thermal stability [51].

9.2. Reactive Compatibilization

New grafting and chemical coupling strategies (e.g., maleated PE, epoxy-functionalized SBS) improve miscibility and storage stability [52].

9.3. Digital Rheology and Machine Learning

Artificial intelligence (AI) is increasingly used to predict binder behavior from composition and temperature history, accelerating material design [53].

Circular Economy and Microplastic Risk Management: Although recycled plastics offer sustainability benefits, concerns about microplastic release from pavements remain critical. Research now focuses on encapsulation, polymer selection, and end-of-life recycling [54].

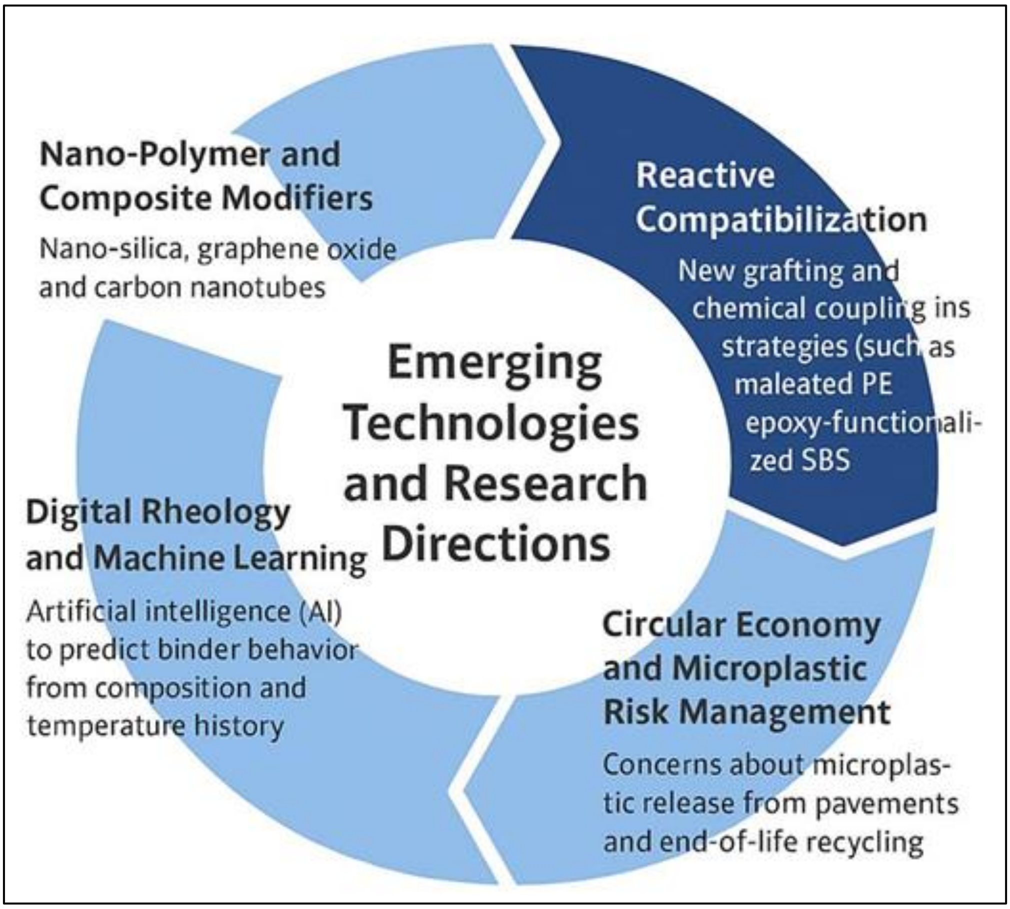


Figure 16 Future directions in polymer-modified asphalt technology, integrating circular economy and AI-based modeling [54]

10. Conclusion

Polymer modification and recycled plastic incorporation represent the most significant advances in asphalt technology in recent decades. These systems enhance performance across all critical distress modes rutting, fatigue, and cracking while contributing to sustainability by reusing waste polymers and reducing environmental footprints.

Key conclusions

- SBS remains the benchmark modifier for balanced rheological and mechanical performance.
- Recycled plastics (PE, PP, PET) are promising for sustainable pavements, especially under dry processes with proper compatibilization.
- Hybrid and nano-enhanced systems show the potential to overcome compatibility and aging issues.
- Comprehensive LCA and field validation remain crucial for global implementation.Future research must integrate AI-driven optimization, chemical compatibilization, and circular economy frameworks to design next-generation, eco-efficient pavement materials.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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