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Comparative Review of Polymer-Modified Asphalt Mixtures: Effects of Styrene-Butadiene-Styrene, Ethylene-Vinyl Acetate, and Low-Density Polyethylene on Pavement Performance

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ABSTRACT

Polymer modification is widely employed to enhance asphalt-mixture performance, with styrene-butadiene-styrene (SBS), ethylene-vinyl acetate (EVA), and polyethylene-based modifiers—including low-density polyethylene (LDPE), polyethylene (PE), and recycled polyethylene (rPE)—representing the major modifier families. This comparative scoping review, based on a structured search strategy, critically compares SBS-, EVA-, and LDPE/PE/rPE-modified asphalt systems in terms of rutting, fatigue, moisture damage, low-temperature cracking, durability, field-oriented evidence, and sustainability. Peer-reviewed studies published between 2015 and 2025 were synthesized, with selected pre-2015 studies retained where they provided foundational mechanisms or benchmark evidence. After deduplication and two-stage screening, 32 studies were retained for structured evidence mapping and narrative comparative synthesis. Within the reviewed evidence, SBS generally shows the most consistent balance between rutting resistance and fatigue improvement, although low-temperature conclusions require caution because direct mixture-scale fracture evidence remains limited. EVA provides clear rutting and moisture-resistance benefits, but its fatigue and low-temperature responses are more formulation-sensitive. Compatibilized LDPE/PE/rPE systems can approach SBS in selected rutting and moisture-resistance outcomes and offer sustainability advantages; however, further validation is required for fatigue, low-temperature cracking, and long-term field performance.

1. INTRODUCTION

Asphalt pavements are subjected to increasingly severe traffic loading and widening climatic extremes, which manifest as a spectrum of distress: rutting at high temperatures, fatigue cracking under repeated traffic, thermal cracking at low temperatures, and moisture-induced damage that leads to stripping and ravelling. Improving the viscoelastic and interfacial properties of asphalt binders has therefore become a central strategy for enhancing pavement durability across this multi-mechanism context. Polymer modification of asphalt binders is now widely recognized as one of the most effective approaches to extend pavement service life, particularly under high traffic and harsh environmental conditions [1-3].

Conventional polymer-modified binders (PMBs) have largely been developed and characterized within the context of hot-mix asphalt (HMA) production, where elevated mixing and compaction temperatures promote polymer dispersion, swelling, and in some cases chemical reaction with the base binder. However, the growing adoption of warm-mix asphalt (WMA) technologies, motivated by reductions in fuel consumption, emissions, and worker exposure, has fundamentally altered binder thermal and oxidative histories during production [4-6]. Lower production temperatures and shorter aging intervals can influence polymer network development, phase morphology, and binder-aggregate adhesion, with potentially significant consequences for rutting resistance, fatigue performance, low-temperature cracking susceptibility, and moisture damage.

Recent advances in polymer modification have expanded beyond conventional styrene-butadiene-styrene (SBS) systems to include ethylene-vinyl acetate (EVA), recycled polyethylene (rPE), and compatibilized polymer technologies. In this review, "compatibilized" LDPE/PE/rPE systems refer to formulations in which a documented compatibilizing agent or strategy, such as maleic-anhydride-grafted polyethylene (PE-g-MAH), is incorporated to improve polymer–bitumen compatibility, dispersion, or phase stability. In contrast, "uncompatibilized" systems refer to LDPE/PE/rPE-modified binders without a dedicated compatibilizing agent or documented compatibilization strategy. Although these modifiers have demonstrated promising improvements in asphalt performance, their comparative behavior across different distress mechanisms and production technologies remains insufficiently understood [1, 3, 7-9].

A rigorous, multi-scale comparison of SBS-sulfur, EVA, and compatibilized LDPE under HMA and WMA production

conditions is thus needed to clarify the trade-offs among high-temperature rutting control, intermediate-temperature fatigue resistance, low-temperature cracking performance, and moisture susceptibility, and to inform rational selection and design of PMBs for modern pavement structures.

Accordingly, this paper is positioned as a comparative scoping review based on a structured literature search and narrative evidence synthesis. The aim is not to conduct a statistical meta-analysis, because the reviewed studies differ substantially in base binder grade, polymer dosage, modifier form, aggregate type, mixture gradation, air voids, aging protocol, production process, and test method. Instead, this review consolidates the direction and consistency of reported performance trends at binder and mixture scales, while identifying the boundary conditions under which SBS, EVA, and LDPE/PE/rPE systems show similar, divergent, or uncertain performance.

2. BACKGROUND ON POLYMER-MODIFIED ASPHALT

2.1 Polymer modification of asphalt binders

2.1.1 Elastomeric vs. plastomeric modification

Polymer modifiers used in asphalt binders are generally classified into elastomeric and plastomeric materials according to their rheological behavior and modification mechanisms. Elastomeric modifiers, such as SBS and styrene-butadiene rubber (SBR), primarily enhance elasticity and strain recovery, thereby improving fatigue resistance and resistance to thermal cracking. In contrast, plastomeric modifiers, including EVA and low-density polyethylene (LDPE), increase binder stiffness by forming semi-crystalline structures, resulting in improved rutting resistance but, in some cases, reduced flexibility at intermediate and low temperatures [1, 3, 7].

Comparative studies consistently indicate that elastomeric and plastomeric modifiers provide different performance advantages depending on the dominant pavement distress mechanism. Binder-scale investigations have shown that both SBS and EVA improve high-temperature rutting parameters, whereas mixture-scale evaluations demonstrate that EVA generally provides greater resistance to permanent deformation, while SBS-modified mixtures exhibit superior fatigue and cracking resistance, particularly after aging [1]. These findings suggest that modifier selection should be based on the target performance requirements rather than on a single mechanical property, highlighting the need for multi-mechanism evaluation of polymer-modified asphalt systems.

2.1.2 Sulfur cross-linked styrene-butadiene-styrene systems

SBS can be further enhanced through sulfur cross-linking, in which sulfur reacts with the unsaturated polybutadiene segments to form a three-dimensional polymer network. Compared with conventional SBS-modified binders, sulfur cross-linking improves polymer network stability, reduces phase separation, enhances elastic recovery, and increases resistance to permanent deformation by strengthening the interaction between the polymer and the asphalt binder [9].

Within the literature reviewed in this study, sulfur-polymer interactions are primarily represented by polymeric sulfur systems containing SBS- and EVA-based copolymers. Abo-Shanab et al. [9] demonstrated that these systems significantly modified binder viscoelastic properties, including complex modulus, temperature susceptibility, and stress relaxation behavior, indicating that sulfur-containing polymer networks can substantially improve the structural stability of asphalt binders.

Although the available evidence remains limited, existing studies suggest that sulfur cross-linking is a promising strategy for improving the long-term stability and elastic response of SBS-modified binders. However, further comparative investigations under both HMA and WMA production conditions are still required to clarify its influence on pavement performance. The detailed modification mechanism of SBS–sulfur systems is discussed in Section 4.1.

2.1.3 Ethylene-vinyl acetate-modified binders

EVA is one of the most widely used plastomeric modifiers for asphalt binders. Its performance is governed by the proportion of vinyl acetate (VA), which influences binder compatibility, phase stability, and the balance between stiffness and flexibility. Owing to its semi-crystalline structure, EVA generally increases binder stiffness and improves resistance to permanent deformation, making it particularly suitable for enhancing high-temperature pavement performance [1, 9].

Experimental studies have consistently shown that EVA-modified binders and mixtures provide excellent rutting resistance; however, their resistance to fatigue and low-temperature cracking is generally inferior to that of elastomeric modifiers such as SBS, especially after oxidative aging [1]. Differences in rheological behavior between EVA- and SBS-based polymeric sulfur systems further highlight the influence of polymer structure and crystallinity on asphalt performance [9].

Overall, the available evidence indicates that EVA is an effective modifier for improving rutting resistance, provided that its formulation is carefully optimized to maintain adequate flexibility. Nevertheless, its performance under WMA production conditions remains insufficiently understood, highlighting the need for further comparative studies on the interaction between EVA crystallinity, dispersion, and reduced-temperature asphalt production.

2.1.4 Low-density polyethylene and compatibilized low-density polyethylene systems

LDPE has attracted considerable attention as a cost-effective plastomeric modifier because of its ability to increase binder stiffness and improve resistance to permanent deformation. However, the performance of LDPE-modified binders depends strongly on polymer dispersion and compatibility with the asphalt matrix [3].

Binder-scale investigations have shown that conventional LDPE, similar to SBS and SBR, improves rutting resistance but provides limited enhancement in low-temperature performance, as evidenced by Bending Beam Rheometer (BBR) testing [3]. Nevertheless, these findings primarily relate to uncompatibilized LDPE, which is susceptible to poor compatibility with polar asphalt fractions, resulting in phase separation and storage instability.

To overcome these limitations, compatibilized LDPE systems, such as maleic anhydride-grafted LDPE (LDPE-g-MAH), have been proposed to improve polymer dispersion, interfacial adhesion, and storage stability. Although such systems are beyond the scope of the studies reviewed here, they represent a promising direction for future research. In

particular, direct comparative evaluations of compatibilized LDPE, SBS–sulfur, and EVA under both HMA and WMA conditions remain limited and deserve further investigation.

2.2 Warm-mix asphalt technologies and their interactions with polymer modifiers

2.2.1 Warm-mix asphalt technologies and their benefits

WMA technologies, including organic waxes, chemical additives, foaming processes, and hybrid systems, reduce production and compaction temperatures by approximately 20–40 ℃ compared with conventional HMA, thereby lowering fuel consumption, greenhouse gas emissions, and fume generation [4-6]. Organic additives such as Sasobit also reduce binder viscosity during mixing but may increase stiffness at service temperatures because of crystallization effects, influencing rutting and low-temperature performance [3].

As WMA technologies have evolved, research has increasingly focused on pavement durability rather than construction benefits alone. Recent studies indicate that reduced production temperatures and WMA additives can significantly influence moisture susceptibility and low-temperature cracking performance [4-6].

2.2.2 Moisture susceptibility of warm-mix asphalt binders and mixtures

Moisture susceptibility is one of the major durability concerns associated with WMA technologies because reduced production temperatures can influence binder–aggregate adhesion and stripping resistance. Experimental studies have shown that different WMA technologies modify the adhesive behavior of asphalt mixtures and may affect their resistance to moisture damage compared with conventional HMA [5, 6].

Surface free energy (SFE)-based approaches have further demonstrated that WMA additives should be considered integral components of the binder–aggregate system rather than simple viscosity-reducing agents. Overall, current evidence indicates that moisture performance in WMA mixtures depends on both the additive type and the resulting binder–aggregate interactions, highlighting the need for system-specific evaluation [5, 6].

2.2.3 Polymer-specific interactions under warm-mix asphalt conditions

Although WMA technologies have been widely investigated for conventional asphalt mixtures, their interaction with polymer-modified binders remains insufficiently understood. Reduced production temperatures can influence polymer swelling, dispersion, crystallization, binder aging, and binder–aggregate adhesion; therefore, the performance of polymer-modified WMA systems should be evaluated according to the chemistry and morphology of each modifier rather than by temperature reduction alone.

Among the commonly used modifiers, SBS has received the greatest attention under WMA conditions. Reduced mixing temperatures may improve workability and limit short-term aging but can also affect polymer dispersion and network development. Huo et al. [8] demonstrated that a warm-mix SBS formulation improved binder viscoelasticity, thermal stability, and adhesion compared with conventional SBS systems.

In contrast, evidence for EVA- and LDPE-modified binders under WMA conditions remains limited. Available studies suggest that reduced production temperatures may alter EVA crystallinity and polymer dispersion, while conventional LDPE systems continue to exhibit compatibility and low-temperature performance limitations [3]. Overall, the combined effects of WMA technologies and polymer chemistry remain insufficiently understood, highlighting the need for systematic comparative studies under both HMA and WMA conditions.

2.3 Binder- vs. mixture-scale evaluation and multi-mechanism performance

2.3.1 Multi-scale testing frameworks

Reliable evaluation of polymer-modified asphalt requires the integration of binder- and mixture-level performance because binder properties alone cannot fully predict field behavior. Consequently, rheological indicators for rutting, fatigue, low-temperature cracking, and moisture resistance should be interpreted together with mixture-scale performance to support material selection and pavement design [1-3].

Recent studies have demonstrated the value of this multi-scale approach. Diab et al. [1] showed good agreement between binder- and mixture-level performance for SBS- and EVA-modified systems, while also highlighting differences in the aging response of elastomeric and plastomeric modifiers. In contrast, other investigations have focused primarily on either binder-scale [3] or mixture-scale evaluations [2], limiting a comprehensive understanding of polymer performance across different distress mechanisms.

2.3.2 Multi-mechanism characterization and aging

The long-term performance of polymer-modified asphalt is strongly influenced by oxidative and physical aging, with different polymer systems exhibiting distinct aging responses. Therefore, evaluating rutting, fatigue, low-temperature cracking, and moisture susceptibility under both short- and long-term aging conditions is essential for a comprehensive assessment of polymer-modified binders and mixtures [1, 3].

Available studies indicate that elastomeric modifiers such as SBS generally retain better resistance to fatigue and low-temperature cracking after aging, whereas plastomeric modifiers, including EVA and LDPE, are more sensitive to aging-induced stiffening [1, 3]. Although sulfur-extended binders have shown promising rheological characteristics [9], their long-term aging behavior has not yet been systematically evaluated. Overall, existing evidence suggests that coordinated aging protocols at both binder and mixture scales are necessary to reliably compare SBS–sulfur, EVA, and LDPE systems, particularly under WMA production conditions.

2.4 Knowledge gaps and need for an integrated comparative study

Although considerable progress has been achieved in understanding polymer-modified asphalt binders and WMA technologies, several important knowledge gaps remain. Existing studies have generally focused on individual polymer systems or limited pairwise comparisons. For example, previous investigations have compared elastomeric and plastomeric modifiers such as SBS and EVA [1], evaluated SBS, SBR, and conventional LDPE in conjunction with WMA additives [3], or examined sulfur-based polymer systems [9]. However, a systematic comparison of sulfur-cross-linked

SBS, EVA, and compatibilized LDPE under consistent material, dosage, and testing conditions is still lacking.

Another important limitation concerns the interaction between polymer chemistry and WMA technologies. Although the influence of WMA on moisture susceptibility, low-temperature cracking, and binder–aggregate adhesion has been widely investigated [4-6], most studies have considered conventional asphalt systems rather than polymer-specific responses. Available evidence is relatively well established for SBS-based binders [8], whereas comparable studies on EVA- and LDPE-modified systems under controlled HMA and WMA conditions remain scarce. Consequently, the extent to which reduced production temperatures influence different polymer modifiers has not yet been fully established.

A further research gap lies in the lack of comprehensive multi-scale and multi-mechanism evaluation. While some studies have successfully linked binder- and mixture-level performance [1], they generally address only selected distress mechanisms or polymer types. Likewise, investigations focusing on WMA often emphasize moisture or low-temperature performance without systematically comparing different polymer chemistries [4-6]. As a result, an integrated framework capable of simultaneously evaluating rutting, fatigue, low-temperature cracking, and moisture resistance across both binder and mixture scales is still unavailable.

In addition, compatibilized LDPE systems remain largely unexplored within the current HMA–WMA literature despite their potential to improve polymer dispersion, phase stability, and binder–aggregate interaction [3]. Addressing these knowledge gaps requires an integrated comparative approach that considers polymer chemistry, production technology, aging, and performance across multiple distress mechanisms. Accordingly, the review is structured around an integrated comparison of polymer chemistry and production technology, examining how SBS, EVA, and compatibilized LDPE respond to HMA and WMA conditions, aging, and different distress mechanisms at both binder and mixture scales.

3. METHODOLOGY

3.1 Review design

This study is a comparative scoping review based on a structured literature search, evidence mapping, and narrative comparative synthesis. It was designed to synthesize and compare the performance of SBS-, EVA-, and LDPE/PE/rPE-modified asphalt binders and mixtures across rutting, fatigue cracking, moisture damage, low-temperature cracking, aging durability, constructability, field-oriented evidence, and sustainability.

3.2 Literature search strategy

A structured literature search was conducted using Scopus, Web of Science, ScienceDirect, and TRID, with supplementary searches in Google Scholar to identify relevant technical reports and conference proceedings. The primary search covered publications from 2015 to 2025, while highly cited pre-2015 studies were included selectively when they provided fundamental concepts, standard testing methodologies, or benchmark evidence relevant to polymer-modified asphalt.

The search strategy combined terms related to polymer-modified asphalt, polymer type, and performance characteristics. Representative search strings included:

•("polymer modified asphalt" OR PMB) AND (SBS OR "styrene butadiene styrene") AND (rutting OR fatigue OR MSCR OR "wheel tracking").

•("polymer modified asphalt" OR PMB) AND (EVA OR LDPE OR polyethylene OR rPE) AND ("low-temperature cracking" OR moisture OR BBR OR TSR).

The search syntax was adapted to the indexing requirements of each database while maintaining a consistent conceptual framework to ensure comprehensive coverage of studies addressing the mechanical performance, durability, rheological behavior, and sustainability of polymer-modified asphalt systems.

3.3 Study selection

Following the literature search, duplicate records were removed before the screening process. The remaining studies were screened in two stages: (i) title and abstract screening and (ii) full-text eligibility assessment. Studies were included if they were peer-reviewed journal articles or major technical reports investigating SBS, EVA, and/or LDPE/PE/rPE as asphalt modifiers at the binder and/or mixture level, and reported standardized performance outcomes related to rutting, fatigue cracking, moisture susceptibility, low-temperature behavior, aging, or durability. Preference was given to studies providing direct comparisons between modifier families or integrating both binder- and mixture-scale evaluations.

Studies were excluded if they lacked sufficient experimental details (e.g., polymer dosage or test conditions), focused on non-asphalt polymer applications, or presented conceptual discussions without supporting experimental evidence.

The study selection process followed a PRISMA-inspired workflow. A total of 62 records were initially identified, of which 10 duplicates were removed. The remaining 52 records were screened, 45 full-text articles were assessed for eligibility, and 32 studies were ultimately included in the comparative synthesis.

3.4 Data extraction, quality assessment, and comparative synthesis

For each included study, information was systematically extracted regarding the polymer modifier (SBS, EVA, or LDPE/PE/rPE), polymer content and incorporation method (wet or dry process; compatibilized or uncompatibilized), base binder characteristics, mixture type, test methods, and the reported performance outcomes related to rutting, fatigue cracking, low-temperature behavior, moisture susceptibility, aging, and field performance.

Because the included studies differed considerably in materials, modifier dosages, laboratory procedures, aging protocols, and performance evaluation methods, a narrative comparative synthesis was adopted instead of a quantitative meta-analysis. The synthesis focused on identifying consistent performance trends, comparing the strengths and limitations of different polymer systems, and highlighting conditions under which their performance diverged.

Direct numerical comparisons between SBS-, EVA-, and LDPE-modified systems were interpreted with caution because the available studies were not conducted under a

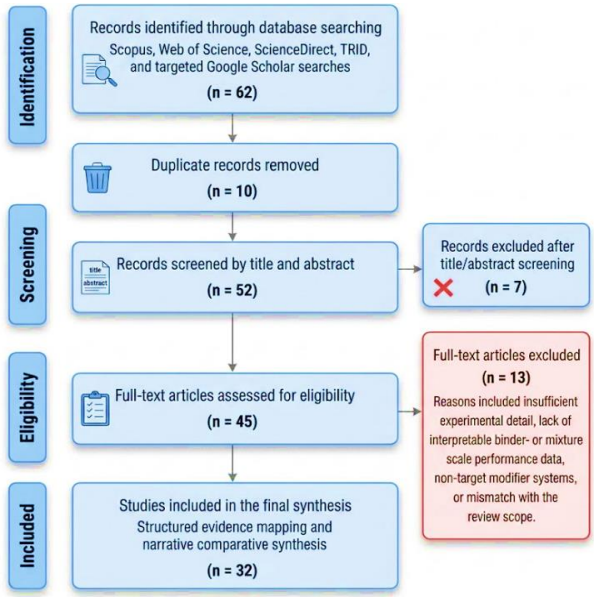
common experimental framework. Accordingly, comparisons considered factors such as base binder grade, polymer dosage, incorporation method, aggregate characteristics, aging procedure, testing conditions, and the scale of evidence (binder, mixture, field, or modeling). Throughout this review, qualitative terms such as *higher*, *lower*, and *more balanced* describe trends within the available evidence rather than absolute rankings of material performance.

To improve the reliability of the synthesis, each study was also assessed for reporting completeness, including disclosure of modifier content, testing standards and conditions, and the use of an appropriate reference (neat) binder or mixture. Studies with incomplete methodological reporting were interpreted cautiously during the comparative analysis.

3.5 Evidence mapping

To enhance transparency regarding evidence coverage across modifier families and performance domains, an evidence map was constructed based on the in-text citations used in the synthesis. Table 1 presents a qualitative evidence map of cited studies for SBS, EVA, and LDPE/PE/rPE systems, including compatibilized and uncompatibilized forms, across binder-, mixture-, field-, and sustainability-related evidence domains within the main review window of 2015–2025. Selected pre-2015 studies were retained only where they provided foundational mechanisms, standard test interpretations, or benchmark evidence.

The evidence levels presented in Table 1 are intended solely as qualitative indicators of evidence coverage within each modifier–performance domain. They reflect the breadth and consistency of the available literature rather than statistical effect sizes, numerical rankings, or direct performance superiority. Supporting references for each evidence domain are provided in the corresponding text sections to preserve the sequential numbering of references throughout the manuscript. The overall review workflow, including literature search, study selection, data extraction, evidence mapping, and comparative narrative synthesis, is summarized in Figure 1.



PRISMA-style workflow of the literature search, screening, eligibility assessment, and final study inclusion for the comparative review of SBS-, EVA-, and LDPE/PE/rPE-modified asphalt systems.

Figure 1. Workflow of the comparative review (SBS vs. EVA vs. LDPE/PE/rPE)
Note: SBS = styrene-butadiene-styrene, EVA = ethylene-vinyl acetate, LDPE/PE/rPE = low-density polyethylene/polyethylene/recycled polyethylene.

Table 1. Qualitative evidence map summarizing the level of evidence available for each modifier-performance domain

Evidence Domain (Typical Tests/Metrics)	SBS (Including SBS-Sulfur)	EVA (Including Compound Systems)	LDPE/PE/rPE (Compatibilized)	LDPE/PE/rPE (Uncompatibilized)
Binder rheology–DSR (G*, phase angle, G*/sinδ, G·sinδ)	High	High	Moderate	Moderate
Binder rheology–MSCR (Jnr, % recovery)	Moderate	Limited	Moderate	Limited
Binder low-temperature behavior–BBR (S, *m*-value)	Moderate	Limited	Limited	Moderate
Binder viscosity/workability (mixing/compaction temperatures, Brookfield viscosity)	Limited	Sparse	Sparse	Limited
Aging resistance (RTFO/PAV indicators, aging-related rheology)	Moderate	Limited	Moderate	Limited
Mixture rutting (Hamburg/HWTD, wheel tracking, flow number)	High	High	Moderate	High
Mixture fatigue/cracking at intermediate temperature (4PB, SCB, FlexPAVE/VECD, IDEAL-CT)	High	Moderate	Moderate	Moderate
Moisture susceptibility (TSR/AASHTO T283, bond strength, Hamburg moisture indicators)	Limited	Moderate	Moderate	Moderate
Mixture low-temperature cracking (TSRST, low-temperature SCB, DCT, fracture energy)	Limited	Limited	Sparse; direct mixture-scale evidence remains limited	Sparse; most evidence is binder-level or indirect
Field performance/field-oriented evidence (test tracks, in-service monitoring, mechanistic-empirical prediction)	Moderate	Sparse; recent field validation remains limited	Limited	Moderate

Sustainability and economics (LCA/LCCA, cost, ROI, waste diversion)	Limited; mainly used as a performance and cost benchmark	Limited	Moderate	High
Implementation/process reporting (wet/dry process, compatibilizers, storage stability, mixing/shear, crosslinking)	High	High	High	High

Note: Evidence levels indicate the relative coverage of published studies within each modifier-performance domain and do not represent statistical effect sizes or performance rankings. Supporting references are cited in the corresponding sections of the manuscript. Supporting references are provided in the corresponding text sections.
SBS = styrene-butadiene-styrene, EVA = ethylene-vinyl acetate, LDPE/PE/rPE = low-density polyethylene/polyethylene/recycled polyethylene.

4. POLYMER CHEMISTRY AND MODIFICATION MECHANISMS

4.1 Styrene-butadiene-styrene

SBS is a linear or radial triblock copolymer with hard polystyrene (PS) end blocks and a soft polybutadiene (PB) mid-block. In asphalt, SBS swells by absorbing maltenes, forming a microphase-separated morphology where PS domains act as physical crosslinks connecting a rubbery PB network, leading to high elastic recovery and improved rutting and fatigue resistance at service temperatures [10, 11].

Compatibility issues (density/solubility mismatch) can cause phase separation and poor storage stability. Crosslinking with sulfur and/or polyphosphoric acid (PPA) covalently connects PB units and reactive asphalt species, stabilizing morphology and increasing high-temperature stiffness, but excessive crosslinking can induce brittleness [12, 13].

4.2 Ethylene-vinyl acetate

EVA is a semi-crystalline copolymer of ethylene and VA. Lower VA content, higher crystallinity and stiffness; higher VA content, better compatibility and low-temperature flexibility but lower crystallinity [10, 14]. In asphalt, EVA usually forms discrete polymer-rich domains; crystallites act as physical crosslinks above their melting temperature, stiffening the binder and improving rutting resistance, with smaller gains in elasticity than SBS [10, 14, 15].

EVA is generally more compatible with asphalt than LDPE, with good storage stability at moderate dosages; however, its elastic recovery and fatigue resistance are typically inferior to SBS, especially without additional elastomeric co-modifiers or crosslinkers [13, 14, 16].

4.3 Low-density polyethylene, polyethylene, and recycled polyethylene

LDPE and related PE and rPE grades are semi-crystalline, largely nonpolar polyolefins. Unmodified LDPE has limited solubility in asphalt aromatics, leading to coarse phase separation, a high softening point, but poor storage stability and limited elastic recovery [17-19].

Recent developments have focused on three main strategies to improve the compatibility of LDPE with asphalt. The first involves reactive compatibilizers such as Elvaloy and maleic-anhydride-grafted polyethylene, which introduce polar functional groups and improve polymer dispersion and storage stability [20-23]. The second employs sulfur or PPA to promote limited crosslinking and enhance high-temperature stiffness and fatigue performance [13, 21]. The third combines LDPE with elastomeric modifiers such as SBS to achieve a more balanced combination of stiffness and elasticity [20, 24-26].

Collectively, these strategies convert poorly compatible LDPE into “compatibilized PE” systems with finer morphology, better storage stability, and more balanced rutting/fatigue behavior [20, 21, 25, 26].

5. RHEOLOGICAL PROPERTIES (BINDER LEVEL)

The rheological performance of polymer-modified binders is governed by the interaction between polymer chemistry, binder composition, and modification strategy. Although SBS, EVA, and LDPE all improve high-temperature performance, they do so through different mechanisms, resulting in distinct trade-offs in elasticity, fatigue resistance, low-temperature behavior, and storage stability. Table 2 summarizes these comparative characteristics.

Key high-level findings (binder phase):

•SBS: large increases in complex modulus (G*) and rutting factor (G*/sinδ) at high temperature, strong reduction in phase angle (δ), and high percent recovery and low Jnr in MSCR, especially at ≥3–4 by weight % SBS in suitable base binders [14, 16, 27]. Crosslinked SBS-sulfur systems can either enhance or slightly reduce rutting resistance depending on network stability and ageing [12, 13].

Table 2. Qualitative comparison of binder-level rheological behavior (typical trends)

Modifier Family	High Temperature Rutting (DSR/MSCR)	Intermediate Temperature Fatigue (e.g., LAS/phase angle)	Low-Temperature Creep Bending Beam Rheometer (BBR)	Storage Stability and Compatibility
SBS (incl. SBS-sulfur)	High G* and G*/sinδ; low phase angle (δ); low Jnr and high MSCR recovery; PG typically 76–82 °C at 3–5 wt% SBS; excellent rutting resistance.	High elastic recovery and fatigue resistance; improved aging resistance through crosslinking; excessive crosslinking may reduce ductility. Compared with SBS, EVA generally exhibits lower elastic	Lower BBR stiffness and higher *m*-value than the base binder; improved low-temperature relaxation under moderate crosslink density. Compared with SBS, EVA generally exhibits higher low-temperature stiffness,	Storage instability in non-crosslinked SBS; improved storage stability with sulfur, PPA, nanoclays, or reactive compatibilizers. Compared with SBS, EVA generally exhibits good compatibility and storage

		recovery and more moderate fatigue improvement, with performance strongly dependent on VA content (higher VA typically improving fatigue resistance but reducing rutting resistance).	particularly at low VA content and high crystallinity; higher-VA grades are less detrimental.	stability at approximately 4–6% dosage; plastomeric behavior; no continuous elastic network.
LDPE/PE/rPE (uncompatibilized)	High G* and G*/sinδ; reduced phase angle; limited elastic recovery; significant PG improvement; moderate-to-high rutting resistance.	High stiffness; limited elastic recovery; fatigue performance reduced at high PE contents; low dosages generally associated with neutral or modest improvement.	Higher BBR stiffness and lower *m*-value; limited stress relaxation; increased susceptibility to low-temperature cracking.	Pronounced phase separation; large softening-point differences at high temperature; poor storage stability.
Compatibilized LDPE/PE/rPE (RET, Elvaloy, S, PPA, grafted PE)	High G* and G*/sinδ; very low Jnr; improved elastic recovery relative to uncompatibilized PE; PG up to ~110 ℃ (e.g., PE-g-MAH); excellent rutting resistance.	Fatigue resistance comparable to SBS at low-to-moderate strain; PE+S exhibiting the highest low-strain fatigue resistance; lower aging susceptibility in Elvaloy-modified systems.	Improved low-temperature performance relative to uncompatibilized PE; more balanced low-/high-temperature response in LDPE–EVA blends; limited mixture-scale validation.	Fine polymer dispersion; improved phase stability; enhanced storage stability; superior aging resistance in PE + S and LDPE–Elvaloy systems.

Note: SBS = styrene-butadiene-styrene, EVA = ethylene-vinyl acetate, LDPE/PE/rPE = low-density polyethylene/polyethylene/recycled polyethylene, polyphosphoric acid (PPA).

•EVA: increases (G*) and softening point; decreases penetration and (δ), improving high-temperature stiffness but with weaker elastic recovery than SBS [10, 14, 15]. At high contents (~9%), EVA's temperature susceptibility can approach or even surpass SBS in some PG metrics, but fatigue benefits are modest [13, 14].

•LDPE/PE/rPE: uncompatibilized LDPE markedly raises (G*) and (G*/sinδ), with limited decrease in (δ), giving stiff but relatively brittle behavior [19, 26]. Compatibilized systems (LDPE+RET/Elvaloy/ sulfur, PE-g-MAH) achieve high PG grades (up to PG 110/℃ for PE-g-MAH; PG 76V-10 for PE+S), lower Jnr and much better storage stability than neat LDPE [21, 23, 28].

Low-temperature binder behavior:

•SBS often reduces BBR stiffness or increases *m*-value relative to base binders, yielding improved relaxation [11, 16].

•EVA's impact on BBR is mixed: low-VA, high-crystallinity grades can increase low-temperature stiffness, whereas higher-VA grades are more benign [10, 14].

Recent studies have shown that hybrid modification using EVA and crumb rubber can simultaneously enhance rutting resistance and low-temperature performance. DSR and BBR results identified optimum EVA–rubber formulations that significantly improved high-temperature rheological properties while reducing low-temperature creep stiffness compared with the base binder [29, 30].

•LDPE generally increases low-temperature stiffness and/or lowers *m*-value [26, 31], unless heavily compatibilized or co-modified. Gao et al. [23] show that LDPE+EVA blends and PE-g-MAH can partially mitigate low-temperature penalties compared with straight LDPE.

Although BBR stiffness and *m*-value provide valuable indicators of binder creep and stress relaxation, they should not be interpreted as direct predictors of mixture thermal cracking. Mixture cracking is also governed by aggregate structure, binder content, air voids, aging, cooling rate, and fracture characteristics. Therefore, BBR results in this review are interpreted as indicators of binder-level low-temperature susceptibility rather than direct evidence of mixture cracking performance.

6. MIXTURE-LEVEL PERFORMANCE

6.1 Rutting

Resistance to permanent deformation is one of the principal advantages of polymer modification in asphalt mixtures. Although SBS, EVA, and LDPE-based modifiers all enhance rutting resistance relative to conventional HMA, they do so through different mechanisms. SBS primarily improves rutting resistance through the formation of an elastic polymer network, EVA mainly increases mixture stiffness through its semi-crystalline structure, whereas LDPE-based systems rely largely on stiffness enhancement and can benefit substantially from compatibilization to improve dispersion and stability. Consequently, direct comparisons should consider not only rut depth or flow number, but also the underlying modification mechanism and the associated trade-offs in fatigue and low-temperature performance.

6.1.1 Styrene-butadiene-styrene modified mixtures

The available evidence consistently identifies SBS as one of the most effective modifiers for improving rutting resistance. Wheel-tracking, flow-number, and dynamic-modulus studies generally report substantially lower permanent deformation than conventional HMA, with improvements typically increasing as polymer dosage rises to approximately 3–5 wt%, while maintaining acceptable workability under appropriate mixing conditions [16, 27, 32]. Owing to its elastomeric network, SBS improves rutting resistance without relying solely on increased stiffness, thereby providing a more balanced mechanical response than many plastomeric modifiers.

6.1.2 Ethylene-vinyl acetate modified mixtures

EVA-modified mixtures also demonstrate significant improvements in rutting resistance through increased stiffness and enhanced resistance to permanent deformation. Several studies have reported higher Marshall stability, reduced rut depth, and improved resilient modulus compared with unmodified mixtures, particularly at EVA contents between 2

and 6% [15, 33, 34]. Optimized compound systems, such as APAO/EVA blends, have in some cases matched or even exceeded the rutting performance of conventional SBS-modified mixtures under specific testing conditions [33]. Nevertheless, binder-level evidence generally indicates lower elastic recovery than SBS, suggesting that EVA achieves rutting resistance primarily through stiffness enhancement rather than elastic deformation recovery [14, 27].

6.1.3 Low-density polyethylene/polyethylene/recycled polyethylene mixtures

LDPE/PE/rPE-modified mixtures generally exhibit substantial improvements in rutting resistance, particularly when compatibilization techniques are employed. Uncompatibilized LDPE primarily increases mixture stiffness and resilient modulus, thereby reducing permanent deformation, although excessive polymer contents may produce overly stiff mixtures with potential adverse effects on other performance characteristics [35, 36]. By contrast, compatibilized systems incorporating reactive terpolymers, Elvaloy, PPA, sulfur, or mineral coupling agents demonstrate improved polymer dispersion, higher flow numbers, reduced permanent strain, and enhanced storage stability, resulting in rutting performance comparable to or, in some cases, exceeding that of SBS-modified mixtures [20, 28, 31, 37-39].

6.1.4 Comparative synthesis

Overall, the reviewed literature indicates that all three modifier families generally improve rutting resistance relative to conventional asphalt mixtures, although through different mechanisms and to varying degrees. Within the reviewed evidence, SBS consistently demonstrates a well-balanced combination of rutting resistance and elastic recovery across a broad range of materials and loading conditions. EVA generally enhances resistance to permanent deformation through increased stiffness and, in optimized compound formulations, can approach or, in some cases, exceed the rutting performance of SBS. Compatibilized LDPE and recycled PE systems also tend to achieve rutting resistance comparable to SBS while offering additional economic and sustainability benefits. However, uncompatibilized LDPE systems rely primarily on increased stiffness and therefore require careful dosage optimization to minimize potential trade-offs in fatigue and low-temperature performance.

6.2 Fatigue

Fatigue resistance is strongly influenced by the ability of polymer modifiers to dissipate repeated traffic-induced stresses while delaying crack initiation and propagation. Unlike rutting resistance, which generally improves with increasing mixture stiffness, fatigue performance depends on achieving a balance between stiffness and elasticity. Consequently, the relative performance of SBS, EVA, and LDPE-based systems is governed not only by polymer type but also by modifier dosage, compatibilization strategy, aging condition, and mixture composition.

6.2.1 Styrene-butadiene-styrene modified mixtures

Among the reviewed modifiers, SBS consistently provides the most reliable improvement in mixture fatigue performance. Owing to its elastomeric network, SBS-modified mixtures generally exhibit longer fatigue life, reduced stiffness degradation under repeated loading, and improved resistance to bottom-up cracking compared with conventional mixtures [27, 32]. Mechanistic analyses further indicate superior fatigue performance under identical traffic and climatic conditions, although improvements may vary depending on the fatigue evaluation method employed [40]. Overall, the available evidence identifies SBS as the benchmark modifier for fatigue resistance.

6.2.2 Ethylene-vinyl acetate modified mixtures

The fatigue performance of EVA-modified mixtures is more variable than that of SBS. Most studies report moderate improvements in tensile strength and resistance to stiffness degradation compared with unmodified mixtures, although fatigue benefits are generally smaller than those achieved with SBS at comparable polymer contents [10, 41]. Nevertheless, optimized compound systems, such as APAO/EVA blends, have demonstrated fatigue performance comparable to or exceeding SBS under specific loading conditions [33]. Evidence from porous asphalt mixtures also suggests improved durability following EVA modification, although direct cyclic fatigue data remain limited [15].

6.2.3 Low-density polyethylene/polyethylene/recycled polyethylene-modified mixtures

Fatigue performance of LDPE/PE/rPE-modified mixtures is highly dependent on formulation and compatibilization. Uncompatibilized LDPE primarily enhances mixture stiffness, which may improve rutting resistance but can reduce fatigue life when excessive stiffness promotes brittle behavior [31, 35]. In contrast, compatibilized or co-modified systems incorporating reactive terpolymers, Elvaloy, sulfur, or SBS generally exhibit improved fatigue performance through better polymer dispersion and enhanced elasticity [20, 21, 24]. Although several studies have reported improved predicted fatigue life relative to conventional mixtures, the improvement is typically smaller than that observed for rutting resistance, and some recycled PE systems remain more susceptible to intermediate-temperature cracking than SBS-modified mixtures, particularly after aging [28, 37, 42].

6.2.4 Comparative synthesis

The reviewed evidence indicates that fatigue performance is more sensitive to polymer chemistry than rutting resistance. SBS consistently provides the most balanced improvement owing to its superior elastic recovery and crack-arresting capability. EVA offers moderate fatigue enhancement and can achieve SBS-like performance in carefully optimized compound formulations, although conventional EVA systems generally remain less effective. Compatibilized LDPE and recycled PE systems can substantially narrow the performance gap with SBS by improving polymer dispersion and reducing brittleness, whereas uncompatibilized LDPE often exhibits a trade-off between increased rutting resistance and reduced fatigue life at higher polymer contents. These findings highlight that optimization of polymer compatibility is considerably more important for fatigue performance than for rutting resistance.

6.3 Moisture susceptibility

Moisture susceptibility is governed by the combined effects of binder–aggregate adhesion, polymer compatibility, mixture morphology, and environmental conditioning. Although SBS, EVA, and LDPE-based modifiers generally improve moisture

resistance compared with conventional mixtures, the extent of improvement depends strongly on aggregate type, polymer chemistry, and the use of compatibilizing agents.

6.3.1 Styrene-butadiene-styrene modified mixtures

SBS-modified mixtures generally exhibit improved resistance to moisture-induced damage owing to enhanced binder cohesion and stronger aggregate adhesion. Most studies report higher tensile strength ratio (TSR) and reduced moisture susceptibility than conventional HMA, although the magnitude of improvement varies with aggregate mineralogy and mixture composition [32, 41]. Overall, SBS provides a reliable benchmark for moisture durability in polymer-modified asphalt mixtures.

6.3.2 Ethylene-vinyl acetate modified mixtures

EVA modification also contributes to improved moisture resistance because of its hydrophobic nature and favorable interaction with the asphalt matrix. Laboratory studies have demonstrated reduced moisture-induced softening at the binder level and improved durability of asphalt mixtures following water conditioning [10, 14, 15]. In optimized compound systems, such as waste tire rubber/EVA blends, moisture resistance has been reported to be comparable with SBS-modified mixtures while simultaneously maintaining favorable rutting and cracking performance [41].

6.3.3 Low-density polyethylene/polyethylene/recycled polyethylene mixtures

The moisture performance of LDPE/PE/rPE-modified mixtures is strongly influenced by polymer morphology and compatibilization. Uncompatibilized polyethylene systems generally provide neutral to moderate improvements because of their hydrophobic characteristics, whereas compatibilized systems achieve substantially better binder–aggregate adhesion and resistance to moisture damage [25, 31, 35, 37, 38, 43]. The incorporation of reactive compatibilizers or coupling agents has consistently been shown to improve polymer dispersion, increase TSR, and enhance bond durability after moisture conditioning and aging [31, 37, 38].

6.3.4 Comparative synthesis

Overall, the reviewed studies indicate that all three modifier families can improve moisture resistance relative to conventional mixtures. SBS remains the most consistently validated system across different aggregate types and testing methods. EVA demonstrates moisture durability comparable to SBS in optimized formulations, while compatibilized LDPE and recycled PE systems can achieve similar performance through improved polymer dispersion and binder–aggregate interaction. In contrast, uncompatibilized polyethylene systems generally exhibit more variable behavior, highlighting the importance of compatibilization for achieving durable moisture resistance.

6.4 Low-temperature performance

Compared with rutting and fatigue, considerably fewer studies have directly compared the low-temperature performance of SBS-, EVA-, and LDPE-modified mixtures using mixture-scale fracture tests. Consequently, much of the available evidence is derived from binder-level rheological indicators such as BBR stiffness and *m*-value, which provide useful but indirect information regarding thermal cracking susceptibility.

6.4.1 Styrene-butadiene-styrene modified mixtures

Among the reviewed modifiers, SBS generally provides the most favorable low-temperature performance. Its elastomeric network enhances stress relaxation and crack resistance, resulting in lower BBR stiffness and higher *m*-values than conventional binders under many conditions [12, 16, 32]. These characteristics suggest improved resistance to thermal cracking, particularly when crosslinking is appropriately controlled.

6.4.2 Ethylene-vinyl acetate modified mixtures

The low-temperature performance of EVA depends primarily on VA content and polymer crystallinity. High-crystallinity EVA grades tend to increase binder stiffness at low temperatures, whereas higher-VA formulations generally exhibit better flexibility and reduced thermal cracking susceptibility [10, 14]. Nevertheless, aging can progressively reduce these benefits, particularly in mixtures containing highly crystalline EVA.

6.4.3 Low-density polyethylene/polyethylene/recycled polyethylene mixtures

Most studies indicate that uncompatibilized LDPE and related polyethylene systems increase BBR stiffness and reduce *m*-values, suggesting a greater susceptibility to thermal cracking than SBS-modified binders [19, 25, 26, 31]. Compatibilized systems may partially mitigate these effects through improved polymer dispersion and modified microstructure, although comprehensive mixture-level validation remains limited. Available evidence therefore indicates that improvements in rutting resistance are not necessarily accompanied by comparable gains in low-temperature cracking resistance.

6.4.4 Comparative synthesis

Current evidence does not support a definitive ranking of polymer modifiers for low-temperature performance because direct mixture-scale comparisons remain scarce. Nevertheless, the available literature consistently suggests that SBS provides the most balanced low-temperature response through enhanced elasticity and stress relaxation. EVA can also provide satisfactory performance when appropriate polymer grades are selected, whereas conventional LDPE systems generally exhibit a greater tendency toward increased stiffness and thermal cracking. Compatibilized polyethylene systems appear promising for reducing this limitation, but additional mixture-scale fracture studies are required before firm conclusions can be drawn.

7. FIELD PERFORMANCE: CASE STUDIES

Laboratory characterization provides valuable information on binder rheology and mixture performance; however, field observations remain essential for evaluating the long-term effectiveness of polymer-modified asphalt under realistic traffic and environmental conditions. Compared with laboratory studies, field evidence is considerably more limited, particularly for recently developed polymer systems and compatibilized polyethylene modifiers. Nevertheless, the available studies provide useful insight into the practical performance of SBS-, EVA-, and LDPE-based asphalt

pavements.

7.1 Styrene-butadiene-styrene modified pavements

SBS remains the most extensively documented polymer modifier in field applications. Decades of highway experience consistently demonstrate improved resistance to rutting and cracking together with extended pavement service life compared with conventional asphalt mixtures [27, 32]. Recent full-scale evaluations, including the NCAT Test Track, further confirm that SBS-modified mixtures provide reliable long-term structural performance under heavy traffic loading, making SBS the current benchmark for field validation of polymer-modified asphalt technologies [43].

7.2 Ethylene-vinyl acetate modified pavements

Field evidence for EVA-modified pavements is considerably more limited than for SBS. Historical European applications reported improved rutting resistance, particularly in warm climates, although long-term comparative data on fatigue and cracking remain scarce [10]. More recent compound systems, including EVA/APAO and EVA/WTR blends, have demonstrated encouraging laboratory performance, but comprehensive long-term field validation has not yet been widely reported [33, 41].

7.3 Low-density polyethylene/polyethylene/recycled polyethylene modified pavements

Field implementation of polyethylene-based modifiers has increased rapidly in recent years, largely driven by sustainability objectives and plastic waste recycling. Mechanistic–empirical analyses and trial sections generally indicate improved rutting resistance together with favorable life-cycle economic performance compared with conventional mixtures [28]. Large-scale reviews also report satisfactory early field performance for wet- and dry-process PE systems in several countries, with no significant moisture-related failures during the initial years of service [25, 37, 43]. However, long-term observations extending beyond one pavement life cycle remain relatively limited, particularly for fatigue and thermal cracking performance.

7.4 Comparative synthesis

Current field evidence indicates that SBS remains the most comprehensively validated polymer modifier, with consistent long-term performance across a wide range of climates and traffic conditions. EVA has demonstrated favorable field performance in selected applications, although recent compound systems still require multi-year validation. PE- and rPE-based modifiers represent a promising and increasingly sustainable alternative, particularly when compatibilization techniques are employed. Nevertheless, additional long-term monitoring under diverse environmental conditions is required before their field performance can be considered equivalent to the extensive evidence currently available for SBS.

Table 3 summarizes representative field and field-oriented studies included in this review, highlighting the current level of practical evidence for SBS-, EVA-, and LDPE/PE/rPE-modified asphalt systems.

Table 3. Field performance evidence for styrene-butadiene-styrene (SBS), ethylene-vinyl acetate (EVA), and low-density polyethylene/polyethylene/recycled polyethylene (LDPE/PE/rPE) systems

Case/Source	Location/Climate	Traffic Level	Modifier System	Distress/Performance Observed	Service Life	Key Takeaway
SBS PMA baseline (multiple studies)	Multiple highways; climate/design dependent.	High-traffic highways.	SBS-modified asphalt (PMA).	Reduced rutting and improved cracking vs neat binder.	Reported service-life extension ~20–50%.	SBS remains the most field-documented "benchmark" polymer with consistent performance benefits.
NCAT Test Track comparative field sections	NCAT Test Track (field test track; climate not specified here).	Test-track trafficking.	SBS vs. RET vs RET-compatibilized rPE.	All PMA sections outperformed unmodified; SBS & RET slightly better fatigue prediction than rPE; while rPE still met targets.	Track section evaluation (timeframe not specified here).	Compatibilized rPE can reach acceptable field-level targets, but SBS/RET may retain an edge in fatigue-related indicators.
Field-oriented performance predictions + economic	Design-scenario based (not a constructed field section).	Mechanistic-empirical evaluation.	rPE mixtures (dry vs wet process).	Predicted lower rutting and fatigue cracking vs control; higher ROI; dry-process favorable; wet-process also positive but less cost-effective.	30-year LCCA (simulation horizon).	Mechanistic-empirical + LCCA evidence supports rPE (especially dry process) as a financially attractive option when performance targets are satisfied.

Synthesized PE waste trial sections	UK; US; Australia; Middle East; multi-climate.	In-service trial sections.	LDPE/HDPE/rPE via wet & dry processes.	Good early rutting resistance; no immediate low-T cracking or moisture problems reported; long-term cracking evidence remains sparse.	Long-term cracking data ≥10 years still limited.	Real-world trials look promising short-medium term, but Q1-grade claim should explicitly flag the lack of long-term cracking datasets.
EVA field experience (historical + recent compounds)	Historical European use (warm climates noted); modern compounds limited.	Not consistently reported.	EVA-modified rolled asphalt; newer APAO; EVA & WTR; EVA compound systems.	Improved rutting in warm climates historically; long-term cracking vs SBS limited; recent EVA compound systems lack multi-year field validation beyond lab/short monitoring.	Older (pre-PG era) evidence + short-term monitoring for newer compounds.	EVA has field precedent, but the modern "compound EVA" value proposition still needs robust long-term field confirmation.

8. SUSTAINABILITY AND ECONOMIC ASSESSMENT

8.1 Material circularity and environmental impacts

The sustainability benefits of polymer-modified asphalt vary considerably among different modifier families. rPE and waste LDPE offer the greatest contribution to material circularity by diverting plastic waste from landfills while reducing the demand for virgin bitumen. Depending on polymer dosage and pavement thickness, polyethylene-modified pavements have been reported to consume approximately 0.75–2 t of waste plastic per kilometer of a single-lane roadway [35, 3]. Life-cycle assessment studies further indicate reductions in greenhouse gas emissions and overall life-cycle costs, primarily because improved pavement durability reduces maintenance frequency and rehabilitation requirements [25, 42, 43].

In contrast, EVA is generally manufactured from virgin polymer rather than recycled feedstock. Consequently, its environmental benefits arise mainly from extending pavement service life rather than from direct waste utilization [15, 32]. Similarly, SBS is produced from petrochemical monomers and therefore contributes little to waste diversion, although its well-established durability can indirectly reduce environmental impacts by extending pavement life and lowering maintenance demands [25, 32].

8.2 Economic considerations

Economic performance reflects both initial construction costs and long-term maintenance requirements. SBS-modified binders generally have the highest material cost among the polymer systems reviewed, although this is often offset by superior long-term pavement performance [30, 35, 41]. EVA typically occupies an intermediate position, providing lower initial costs than SBS while maintaining satisfactory mechanical performance. Optimized compound systems, such as waste tire rubber/EVA blends, have demonstrated material cost reductions while achieving performance comparable to or better than conventional SBS-modified mixtures [41].

Polyethylene-based systems present the strongest economic advantages, particularly when recycled materials are used. Several studies have reported lower life-cycle costs, improved return on investment, and reduced binder consumption for LDPE- and rPE-modified pavements compared with both conventional mixtures and SBS-modified systems [25, 35, 38]. These benefits are especially pronounced when dry-process technologies and locally available waste plastics are employed.

8.3 Sustainability synthesis

From a sustainability perspective, each polymer family offers distinct advantages and limitations. SBS provides the most consistently validated engineering performance but has the highest material cost and limited contribution to circular economy objectives. EVA represents an intermediate solution, balancing mechanical performance with moderate economic benefits, although its environmental advantages remain largely dependent on extended pavement life rather than waste utilization. In contrast, LDPE/PE/rPE-based modifiers provide the strongest sustainability potential by simultaneously reducing plastic waste, lowering life-cycle costs, and maintaining satisfactory engineering performance. However, these benefits depend on appropriate compatibilization and mixture design to minimize potential reductions in fatigue and low-temperature performance.

The comparisons presented in this review are derived primarily from evidence synthesized across independent studies rather than from controlled head-to-head experimental investigations. Consequently, the conclusions should be interpreted as evidence-based performance trends rather than definitive rankings of individual polymer modifiers.

9. COMPARATIVE SYNTHESIS AND DISCUSSION

The comparative findings presented in this review should be interpreted within the context of differences among the reviewed studies. Polymer performance is influenced not only by polymer chemistry but also by binder grade, polymer dosage, compatibilization strategy, aging condition, aggregate characteristics, mixture design, and production technology. In addition, WMA conditions may alter polymer dispersion, oxidative aging, and binder–aggregate interaction compared with conventional HMA. Consequently, this review emphasizes recurring performance trends and practical boundary conditions rather than absolute rankings of polymer modifiers.

9.1 Binder-level comparison

At the binder level, SBS consistently provides the most balanced rheological response by combining high-temperature

stiffness with excellent elastic recovery and favorable low-temperature relaxation. Its well-established modification mechanism and extensive field experience have made SBS the reference modifier against which newer polymer systems are commonly evaluated [12, 13, 16].

EVA primarily enhances binder performance through increased stiffness associated with its semi-crystalline structure. While it generally improves rutting resistance and exhibits good compatibility with asphalt, its elastic recovery and fatigue resistance are typically lower than those of SBS. Furthermore, its low-temperature performance depends strongly on VA content and polymer crystallinity, making formulation an important consideration [10, 14].

In contrast, uncompatibilized LDPE, PE, and recycled PE mainly function as plastomeric stiffeners, producing substantial improvements in rutting resistance but often at the expense of elasticity, storage stability, and low-temperature performance [17, 18, 26]. However, the reviewed evidence demonstrates that compatibilization strategies—including reactive terpolymers, Elvaloy, sulfur, PPA, and grafting techniques—can substantially improve polymer dispersion, phase stability, and viscoelastic behavior, enabling polyethylene-based systems to achieve performance approaching that of SBS while simultaneously providing significant sustainability advantages [20, 21, 23, 42].

9.2 Mixture-level comparison

At the mixture level, the differences among polymer families become less pronounced because aggregate characteristics, mixture design, and construction variables increasingly influence pavement performance. SBS remains the most consistently balanced modifier across rutting resistance, fatigue performance, moisture durability, and low-temperature cracking, supported by both laboratory and long-term field evidence. EVA demonstrates excellent resistance to permanent deformation and satisfactory moisture performance, although its fatigue and low-temperature behavior are generally more dependent on polymer formulation. Compatibilized LDPE and recycled PE systems exhibit substantial improvements in rutting resistance and increasingly competitive performance in fatigue and moisture resistance, while also offering clear environmental and economic benefits. Nevertheless, additional long-term field validation is still required before these systems can be considered fully equivalent to SBS under a wide range of climatic and traffic conditions.

Table 4 summarizes the qualitative comparison of mixture-level performance across the reviewed modifier families. The overall performance assessment reflects the synthesis of the available evidence rather than a direct ranking of polymer modifiers. Because the reviewed studies differ in binder grade, polymer dosage, aggregate type, mixture design, production method, aging protocol, and testing conditions, the comparisons presented here should be interpreted as evidence-based performance tendencies rather than universal performance rankings.

Table 4. Qualitative mixture-level performance comparison

Modifier	Rutting Resistance	Fatigue/Cracking (Intermediate T)	Moisture Damage	Low-T Cracking (Mixture-Scale Evidence)	Overall Performance Balance*
SBS	Strongly improved rutting vs neat; widely validated in dense HMA and SMA.	Generally improved fatigue life; validated in field and simulations (e.g., FlexPAVE).	Often improved TSR and Hamburg performance; aggregate-dependent.	Generally favorable when crosslink density controlled; limited modern SCB data.	Broadest evidence base; strong all-round applicability, but with higher cost and no direct waste-diversion benefit
EVA	Clearly improved vs neat; can match SBS in optimized compound systems (e.g. APAO; EVA, WTR; EVA).	Modest improvement vs neat; can approach SBS in compound systems; pure EVA systems often below SBS.	Good water stability; WT; EVA mixtures show similar water stability to SBS.	Mixed; risk of increased low-T stiffness for low-VA/high-crystallinity EVA; little direct mixture fracture data.	Strong rutting and moisture-resistance evidence; fatigue and low-temperature response remain formulation- and climate-sensitive
Uncompatibilized LDPE/PE	Substantial rutting improvement; very high stiffness.	Often poorer fatigue, especially at high polymer contents; some studies show neutral or slight improvement at low dosages.	Moisture performance is usually neutral to slightly positive.	Often worsened due to higher stiffness; increased thermal cracking risk.	Useful stiffening option for rutting-dominated hot climates; fatigue and low-temperature cracking risks require conservative dosage control
Compatibilized LDPE/PE/rPE	Rutting resistance comparable to, or exceeding, SBS in many studies.	Fatigue is roughly comparable to SBS when sulfur, reactive terpolymers, and elastomeric co-modifiers are used; otherwise, intermediate.	Moisture resistance clearly improved (higher TSR, bond strength) relative to neat and often comparable to SBS.	Still the least documented; BBR suggests better than uncompatibilized LDPE but generally worse than SBS.	Promising option for hot to temperate climates with sustainability benefits; low-temperature and long-term cracking evidence remains limited.

Note: *The final column summarizes evidence coverage and context-dependent applicability within the reviewed literature. It is not a comparative performance ranking or a field specification.

9.3 Practical and contextual considerations

The practical selection of polymer modifiers should be guided by climatic conditions, traffic demand, and construction requirements rather than by a single performance indicator. SBS remains the most versatile modifier across a broad range of climatic conditions because it provides a balanced combination of rutting resistance, fatigue performance, and low-temperature flexibility. EVA and polyethylene-based systems are generally more sensitive to environmental conditions and mixture formulation, with LDPE-based modifiers being particularly attractive for warm climates where rutting is the dominant distress. Under heavy traffic conditions, both SBS and compatibilized LDPE/PE systems demonstrate excellent resistance to permanent deformation, while optimized EVA compound systems also provide competitive structural performance. From an implementation perspective, SBS and EVA benefit from decades of industrial application and well-established production procedures. In contrast, compatibilized polyethylene systems represent a rapidly developing technology whose performance depends more strongly on polymer formulation, compatibilization strategy, and quality control during production. Nevertheless, recent studies indicate that properly compatibilized polyethylene systems can achieve storage stability and engineering performance comparable to conventional SBS-modified binders [21, 22, 28].

10. CURRENT RESEARCH GAPS

Despite the considerable progress achieved in polymer-modified asphalt technologies, the reviewed literature reveals several important knowledge gaps that continue to limit direct comparison among SBS-, EVA-, and LDPE/PE/rPE-modified systems.

One of the most significant limitations is the lack of controlled comparative studies evaluating SBS, EVA, and compatibilized polyethylene within a common experimental framework. Most available investigations compare only two modifier families or focus on a single polymer system, making it difficult to distinguish the effects of polymer chemistry from those of binder type, aggregate characteristics, polymer dosage, or mixture design. Well-controlled side-by-side studies using identical materials and testing protocols are therefore needed to establish more reliable comparative conclusions.

Another major gap concerns low-temperature performance at the mixture scale. Although binder-level BBR results provide useful indications of thermal cracking susceptibility, relatively few studies have employed modern fracture-based mixture tests such as SCB, TSRST, or DCT to compare different polymer families under identical cold-climate conditions. As a result, the current evidence remains insufficient to establish a definitive hierarchy for thermal cracking resistance among SBS, EVA, and polyethylene-based modifiers.

The available field evidence is also unevenly distributed among polymer families. SBS benefits from decades of practical implementation and long-term monitoring, whereas field validation of EVA and especially rPE systems remains relatively limited. Most polyethylene-based studies rely on short-term observations or mechanistic–empirical performance predictions, highlighting the need for long-term monitoring under diverse climatic and traffic conditions [28, 37].

Additional challenges remain regarding the standardization of rPE materials. Variations in waste-plastic source, processing method, polymer composition, and contamination levels introduce significant variability into engineering performance, and standardized specifications for rPE modifiers are still lacking [37]. Similarly, the interaction between polymer modifiers and WMA technologies remains insufficiently understood. Existing evidence is dominated by conventional HMA applications, while the influence of reduced production temperatures on polymer dispersion, aging, and binder–aggregate interaction requires further experimental investigation.

Finally, relatively few studies have attempted to integrate polymer microstructure with engineering performance across multiple distress mechanisms. Although microscopy and spectroscopy have improved understanding of polymer morphology [14, 21, 23], quantitative relationships between microstructural characteristics and pavement performance remain poorly established, particularly for compatibilized and multi-polymer systems. Likewise, most published studies investigate rutting, fatigue, moisture susceptibility, or thermal cracking separately, whereas future research should adopt integrated multi-mechanism evaluation frameworks capable of assessing the combined effects of loading, environmental conditioning, moisture damage, and aging within a single experimental program.

11. FUTURE RESEARCH DIRECTIONS

Addressing the knowledge gaps identified in this review requires more comprehensive and standardized experimental frameworks. Future studies should prioritize direct comparisons of SBS-, EVA-, and LDPE/PE/rPE-modified asphalt systems under identical experimental conditions. Such investigations should employ the same base binder, aggregate source, mixture gradation, target air-void content, aging protocol, and comparable polymer dosages while considering both compatibilized and uncompatibilized polyethylene systems. Standardized experimental designs would allow differences in performance to be attributed primarily to polymer chemistry rather than variations in materials or testing procedures.

Future research should also integrate binder- and mixture-level characterization within a unified testing framework. Binder rheology should be evaluated using complementary methods such as DSR, MSCR, LAS, BBR, storage stability, and aging-related rheological tests, while mixture performance should be assessed through rutting, fatigue, moisture susceptibility, and low-temperature fracture tests. Such multi-scale approaches would improve understanding of how binder properties translate into pavement performance under realistic service conditions.

The interaction between polymer modifiers and WMA technologies deserves particular attention. Systematic HMA–WMA comparative studies are needed to quantify the influence of reduced production temperatures on polymer dispersion, crystallinity, crosslink development, oxidative aging, binder–aggregate adhesion, constructability, moisture resistance, and early pavement performance. This topic remains one of the least explored areas identified in the current

literature.

Greater emphasis should also be placed on long-term field validation. Future demonstration projects should include matched pavement sections incorporating SBS, EVA, and selected rPE formulations produced through both wet and dry processes. Performance monitoring should extend beyond ten years whenever possible and include rutting, cracking, moisture damage, binder aging, environmental durability, and material characterization throughout the pavement service life.

Another priority is the development of performance-based specifications for rPE modifiers. Future standards should define acceptable ranges for material properties such as melt flow index, density, crystallinity, contamination level, particle size, and processing method, together with practical quality-control procedures suitable for routine engineering applications.

Finally, future investigations should strengthen the links between polymer microstructure, engineering performance, and sustainability. Advanced microscopy and spectroscopy techniques, combined with rheological testing and mixture performance evaluation, can support the development of microstructure-informed performance models. In parallel, life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) should be integrated with mechanistic–empirical pavement design to identify the most appropriate polymer systems for different climatic conditions, traffic levels, and sustainability objectives.

Table 5 summarizes the comparative evidence presented throughout this review and provides a practical decision matrix for selecting SBS-, EVA-, and LDPE/PE/rPE-modified asphalt systems under different climatic, traffic, and economic conditions. The recommendations are intended as evidence-based guidance derived from the reviewed literature rather than prescriptive design criteria. Because the underlying studies differ in materials, mixture designs, polymer dosages, testing protocols, and environmental conditions, the suitability ratings should be interpreted as context-dependent trends rather than universal performance rankings or engineering specifications.

Table 5. Decision matrix for selecting SBS vs. EVA vs. LDPE/PE/rPE

Climate/Traffic/Cost Priority	SBS (incl. SBS-Sulfur)	EVA (incl. EVA Compound Systems)	LDPE/PE/rPE (Compatibilized†)	LDPE/PE/rPE (Uncompatibilized)
Hot-arid; very heavy traffic (rutting-dominated; moderate low-temperature concern; high budget).	High; field-proven rutting and fatigue; broadest performance balance.	Moderate to high suitability; good rutting; slightly weaker fatigue than SBS; compound systems (APAO/EVA, WTR/EVA) can rival SBS.	High; excellent rutting, acceptable fatigue with good compatibilization; strong sustainability and ROI	Medium; strong rutting but risk of fatigue and low-temperature cracking; use cautiously and at low dosages.
Temperate climate, heavy traffic (balanced rutting; fatigue; low-temperature).	High; best balance of rutting, fatigue, and low-temperature when appropriately formulated.	Medium; acceptable rutting & moisture; fatigue and low-temperature acceptable but less robust than SBS; better with compound systems.	Moderate to high suitability; promising, but low-temperature and long-term cracking still uncertain; recommended with elastomeric; chemical compatibilization and careful validation.	Low to moderate suitability; generally not recommended as primary modifier without additional elastomer in climates with significant freezing.
Cold climate, moderate traffic (low-temperature cracking; dominated).	High; strongest evidence for low-temperature creep and cracking resistance among the three families.	Medium; risk of increased low-temperature stiffness for low-VA EVA; choose high-VA grades and moderate contents; more data needed	Medium to low; possible with carefully designed compatibilized LDPE/PE blends at low dosage, but evidence is thin; further low-temperature mixture testing required.	Low; consistently worsens low-temperature behavior in binder and mixtures; generally unsuitable as main modifier in cold regions.
Budget; constrained; sustainability-driven; warm; temperate climate.	Medium; high binder cost; strong performance but weaker sustainability gains. vs plastic-waste systems	Moderate to high suitability; moderate cost; can use some recycled EVA in future; good performance.	High; best fit: significant waste diversion, good rutting, acceptable fatigue and moisture, competitive life-cycle cost and ROI.	Medium; strong waste benefit and low cost but larger performance risk; consider only where rutting dominates and low-temperature; fatigue demands are modest
Short-term overlays; moderate traffic; hot climate	Moderate to high suitability; robust but may be over-designed for short life.	High; good rutting and moisture; cost-effective for overlays.	High; excellent for extending life with added sustainability; particularly attractive via dry process.	Moderate to high suitability; acceptable if rutting control is main goal and overlay design life is relatively short; monitor cracking.

Note: † Compatibilized LDPE/PE/rPE systems are those incorporating a documented compatibilizing agent or strategy, whereas uncompatibilized systems do not use a dedicated compatibilization strategy.

12. CONCLUSIONS

This review comparatively synthesized the current evidence on SBS-, EVA-, and LDPE/PE/rPE-modified asphalt systems with respect to rutting resistance, fatigue performance, moisture susceptibility, low-temperature behavior, aging, field performance, and sustainability. Rather than ranking polymer modifiers universally, the review identified the conditions under which each modifier family offers distinct engineering advantages and highlighted the factors governing their

practical application.

SBS remains the most consistently balanced system, providing a favorable combination of rutting resistance, fatigue performance, and long-term field validation across a wide range of climatic and traffic conditions. EVA primarily functions as a plastomeric modifier that effectively improves rutting resistance and moisture performance, although its fatigue and low-temperature behavior remain highly dependent on VA content and formulation. LDPE/PE/rPE systems offer important sustainability and economic benefits through recycled materials and, when compatibilized or co-modified, can achieve performance approaching that of conventional SBS-modified binders, particularly for rutting resistance and moisture durability. However, their long-term cracking behavior and field validation remain comparatively limited.

The review also demonstrates that polymer performance cannot be evaluated independently of material formulation and construction conditions. Polymer dosage, compatibilization, base binder characteristics, aggregate properties, aging, and production technology all influence pavement performance. In particular, the interaction between polymer modifiers and WMA technologies remains insufficiently understood. Although warm-mix SBS formulations have shown promising results, comparable evidence for EVA- and compatibilized LDPE/PE/rPE-based WMA systems is still scarce, preventing reliable recommendations regarding optimum production temperatures and long-term performance.

Several important research needs remain. Direct side-by-side comparisons of SBS, EVA, and compatibilized polyethylene systems under identical experimental conditions are still uncommon, while mixture-scale low-temperature fracture data and long-term multi-climate field studies remain limited. Future research should therefore emphasize integrated binder- and mixture-level evaluation, standardized comparative experimental programs, long-term field validation, and performance-based specifications supported by microstructure-informed characterization.

Overall, the findings presented in this review should be interpreted as evidence-based performance trends rather than definitive rankings of polymer modifiers. Because the reviewed studies differ substantially in materials, polymer dosage, mixture design, aging procedures, and testing protocols, the suitability of each modifier should ultimately be evaluated within the specific climatic, traffic, economic, and sustainability requirements of the intended pavement application.

AUTHOR CONTRIBUTION

S.K. Hussien conducted the literature search, collected and organized the data, and prepared the initial draft of the manuscript. M.H. Dehnad conceived the study, supervised the research, designed the review methodology, critically revised the manuscript, interpreted the findings, and approved the final version for publication. Both authors reviewed and approved the final manuscript.

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NOMENCLATURE

SBS	Styrene-butadiene-styrene
EVA	Ethylene-vinyl acetate
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
HDPE	High-density polyethylene
PE	Polyethylene
rPE	Recycled polyethylene
VA	Vinyl acetate
$CaCO_3$	Calcium carbonate
PMA	Polymer-modified asphalt
PMB	Polymer-modified binder
HMA	Hot-mix asphalt
WMA	Warm-mix asphalt
SMA	Stone mastic asphalt
WTR	Waste tire rubber
APAO	Amorphous poly-α-olefin
PPA	Polyphosphoric acid
RET	Reactive elastomeric terpolymer
DSR	Dynamic Shear Rheometer
MSCR	Multiple Stress Creep Recovery
BBR	Bending Beam Rheometer
LAS	Linear Amplitude Sweep
SCB	Semi-Circular Bend
TSRST	Thermal Stress Restrained Specimen Test
DCT	Disk-shaped Compact Tension test
HWTD	Hamburg Wheel Tracking Device
TSR	Tensile Strength Ratio
IDEAL-CT	Indirect Tensile Asphalt Cracking Test
CT-index	Cracking Tolerance Index
PG	Performance Grade
PMED	AASHTOWare Pavement ME Design
FlexPAVE	FlexPAVE software
NCAT	National Center for Asphalt Technology
AFM	Atomic Force Microscopy
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
ROI	Return on Investment