

Review

Application and Development of Polyurethane-Modified Asphalt for Pavement Engineering: A Review

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Abstract

Polyurethane (PU) is widely used in construction, transportation, automotive products, decorative materials, and related industries because its molecular structure can be tailored to diverse service requirements. This versatility has stimulated growing interest in polyurethane-modified asphalt for pavement engineering. This review examines the chemical structure, reaction mechanisms, and principal synthesis routes of polyurethane-modified asphalt and discusses polyurethane-modified emulsified asphalt, polyurethane composite-modified asphalt, and polyurethane-modified asphalt mixtures. Engineering applications in permeable pavements, bridge and tunnel surfacing, as well as crack and pothole repair are also considered. The review further addresses green in situ polymerization, high-content polyurethane systems, waterborne polyurethane, interfacial adhesion, bio-based formulations, recycled asphalt mixtures, and life-cycle performance. The available evidence indicates that polyurethane can improve high-temperature stability, durability, fatigue resistance, mechanical strength, adhesion, and aging resistance. In suitable formulations, it can also reduce production temperatures and construction-related emissions. Economic feasibility, unresolved technical issues, and future research priorities are discussed at the end of the review.

Keywords: polyurethane-modified asphalt; modification mechanism; interfacial adhesion; waterborne polyurethane; composite binders; porous pavement; life-cycle performance



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1. Introduction

Asphalt pavements are widely used in road engineering because they provide continuous riding surfaces, good driving comfort, convenient construction, and adaptability to different structural forms [1]. During service, traffic loading, temperature, moisture, oxygen, and ultraviolet radiation alter the chemical composition and colloidal equilibrium of bitumen, promoting aging-related stiffening and damage [2–5]. These changes contribute to rutting, cracking, raveling, and pothole development, thereby motivating the use of modified binders to improve durability while reducing construction energy demand and environmental impacts [1,3,6].

Asphalt modification has therefore evolved around several polymer and reactive-resin families with distinct performance targets. Styrene–butadiene–styrene (SBS) is the

most established thermoplastic elastomer for improving high-temperature deformation resistance, elastic recovery, and fatigue response, whereas styrene–butadiene rubber (SBR) is particularly effective in improving flexibility and low-temperature performance. Crumb-rubber modification also offers recycling benefits and can improve elasticity and durability, but it commonly requires higher processing temperatures and careful control of both viscosity and storage stability. Reactive elastomeric terpolymer (RET) and thermosetting epoxy systems can form stronger reactive or crosslinked structures and provide high rutting resistance and adhesion, although reaction control, low-temperature stress relaxation, and construction time can become more restrictive [3,6–9]. Recent work on phenol–cresol–formaldehyde resin-modified road bitumen further illustrates the potential of reactive-resin modification: at 1.0 wt.% resin, Demchuk et al. reported markedly improved binder–mineral adhesion while maintaining aging resistance and reducing dynamic viscosity within the 140–160 °C construction-temperature range [10].

These developments reflect a broader shift from simple physical blending toward chemically tailored interfaces. Reactive modification can strengthen binder networks and interfacial adhesion, but no conventional modifier simultaneously maximizes high-temperature strength, low-temperature flexibility, adhesion, storage stability, constructability, and cost-effectiveness under all service conditions [8–12]. Polyurethane (PU) is therefore of particular interest because its soft/hard-segment architecture and reactive chemistry can be tailored to optimize this balance for specific pavement applications rather than merely increasing binder stiffness.

Polyurethane (PU) contains carbamate groups (–NHCOO–) generated by reactions between isocyanates and polyols [13]. Its soft/hard-segment architecture can be tailored over a wide range, enabling adjustable elasticity, strength, adhesion, and durability; these features have supported the increasing use of PU-based materials in pavement construction and maintenance [14–16]. Conventional thermoplastic-elastomer- or rubber-modified asphalt is generally produced by high-temperature physical blending and shear dispersion [3,7,8]. By contrast, reactive PU–asphalt systems can be formed through prepolymer reactions or in situ polymerization. Isocyanate-containing precursors can react with active-hydrogen-containing polar asphalt constituents, while hydrogen bonding, adsorption, and chain entanglement contribute to network development [11,12,17–20]. These coupled effects can improve high-temperature stability, adhesion, durability, and fatigue-related performance, although the magnitude of improvement and the low-temperature response depend strongly on PU chemistry, dosage, and curing history [15,16,19,21,22].

This review examines the application and development of polyurethane-modified asphalt in pavement engineering, and its overall framework is shown in Figure 1. Existing SCI/SCIE reviews provide important foundations but differ in scope and emphasis. Cong et al. [15] surveyed PU applications across pavement engineering; Li et al. [14] covered PU-modified asphalt, PU-bound mixtures, sealants, foam injection, and sustainability; Huang et al. [16] systematically reviewed PU raw materials, synthesis routes, mechanisms, preparation methods, and road performance; Lu et al. [23] emphasized binder synthesis, characterization, composite systems, and emerging applications; and the recent review by Sheng et al. [24] focused specifically on molecular design, structural evolution, storage stability, and performance optimization within the prepolymer route. Therefore, the present review does not seek to duplicate these summaries. Its distinct contribution is to integrate PU chemistry and preparation with binder/mixture behavior, construction workability, application-specific evidence (emulsified and composite binders, porous pavement, bridge/tunnel paving, maintenance, and reclaimed-asphalt systems), and economic/life-cycle constraints within a single engineering-decision framework. The synthesis focuses on when a PU technology is technically appropriate, which performance–constructability

trade-offs accompany that choice, and what evidence is still required for large-scale pavement implementation.

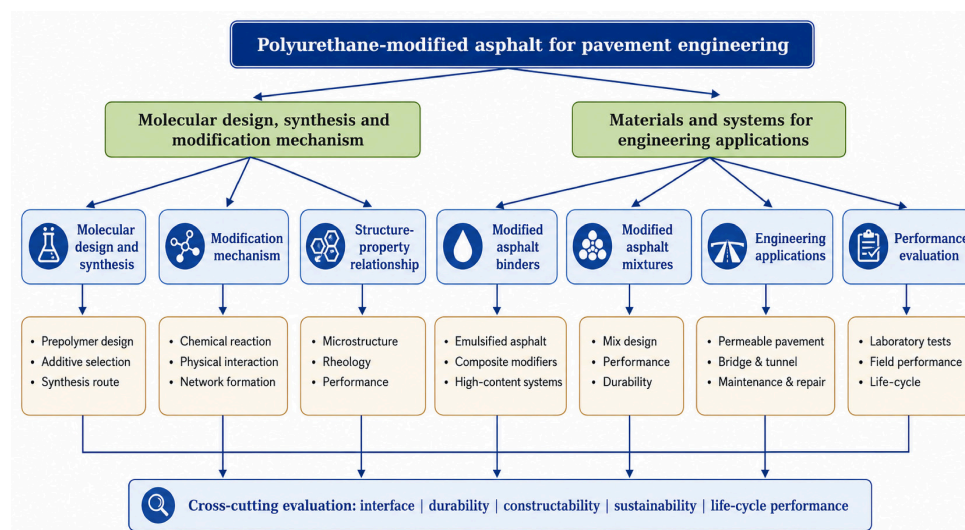


Figure 1. Technology roadmap for the review of polyurethane-modified asphalt in pavement engineering. Developed by the authors.

The scope and thematic framework of this review were defined before the literature search, based on the major research directions of polyurethane-modified asphalt in pavement engineering. The framework covers the molecular design and synthesis of polyurethane, modification mechanisms and structure-property relationships of polyurethane-modified asphalt, polyurethane-modified emulsified asphalt, composite modification systems, polyurethane-modified asphalt mixtures, and engineering applications including permeable pavements, bridge and tunnel paving, crack and pothole repair, reclaimed asphalt mixtures, and economic and life-cycle assessment. The literature search and subsequent screening were therefore organized around this predefined framework to ensure adequate coverage of the major topics addressed in the review.

The literature search was conducted primarily in the Web of Science Core Collection, and the final search update was completed on 26 August 2026. The principal publication period was 2000–2026, although earlier representative studies were retained when necessary to establish fundamental bitumen chemistry, basic principles of polymer modification, or the historical development of reactive polyurethane modification. The main search terms included “polyurethane”, “polyurethane prepolymer”, “thermoplastic polyurethane”, and “waterborne polyurethane”, which were combined with pavement-related terms such as “asphalt”, “bitumen”, “asphalt mixture”, and “pavement”. For example, the core search expression was $TS = ((\text{“polyurethane” OR “polyurethane prepolymer” OR “thermoplastic polyurethane” OR “waterborne polyurethane”}) \text{ AND } (\text{“asphalt” OR “bitumen” OR “asphalt mixture” OR “pavement”}))$.

The core search retrieved 792 records. Restricting the language to English reduced the number to 788 records. After limiting the Web of Science index to the Science Citation Index Expanded (SCI-EXPANDED), 752 records remained, and further restriction to Articles and Review Articles resulted in 750 records.

Topic-specific searches were subsequently conducted according to the predefined review framework. Additional search terms included “modification mechanism”, “emulsified asphalt”, “epoxy”, “SBS”, “RET”, “porous pavement”, “permeable pavement”, “bridge deck”, “tunnel”, “crack repair”, “pothole repair”, “recycled asphalt”, “RAP”, “adhesion”, “aging”, “fatigue”, “life-cycle assessment”, and “economic analysis”. These topic-specific searches retrieved 493 records, of which 477 were Articles or Review Articles indexed in

SCI-EXPANDED. Because substantial overlap existed between the core and topic-specific searches, the two sets of records were not simply combined. The 477 topic-specific records constituted the principal candidate literature pool, while the broader core search was also used to identify fundamental or representative studies that might not have been captured by the additional topic-specific terms.

The main inclusion criteria were as follows: (1) studies directly addressing polyurethane-modified asphalt, polyurethane-modified emulsified asphalt, polyurethane composite-modified asphalt, polyurethane-related asphalt mixtures, or their applications in pavement engineering; (2) studies providing direct evidence for at least one topic within the predefined review framework, including modification mechanisms, material design, rheological or pavement performance, interfacial adhesion, durability, engineering applications, or economic and life-cycle performance; (3) peer-reviewed English-language journal publications, with priority given to studies indexed in SCI/SCIE; and (4) where multiple publications addressed highly similar research questions, preference was given to studies with representative research content, more complete experimental or analytical evidence, stronger relevance to the review topic, or greater value in reflecting recent research developments.

Candidate publications were first screened on the basis of title and abstract relevance to the predefined review topics. Potentially relevant papers were then assessed in greater detail using the full text, with particular attention to their research objectives, methods, principal findings, and ability to provide substantive evidence for the corresponding section of the review. Conference papers, theses, book chapters, patents, standards, retracted publications, duplicate or bibliographically incorrect records, and studies without direct relevance to the predefined review topics or without sufficient supporting evidence were excluded. Following this assessment of thematic relevance, evidence quality, representativeness, and coverage of the review framework, 71 English-language journal publications were ultimately retained in the final reference set. These publications include PU-focused studies together with a limited number of background and contextual journal articles required to establish conventional bitumen chemistry, polymer-modification principles, and comparisons with related reactive-resin systems. The synthesis, comparison, and discussion presented in this review were developed based on this final literature set.

As this study is a narrative review, the literature-search and screening procedures were intended to improve the transparency, traceability, and reproducibility of literature selection rather than to present the review as a PRISMA-based systematic review.

During manuscript preparation, OpenAI ChatGPT (GPT-5.6) was used to assist with language editing, bibliographic verification, and the preparation of author-designed conceptual schematics. It was not used as an autonomous decision-maker for study inclusion or exclusion, nor to determine scientific conclusions. All literature-selection decisions, bibliographic corrections, scientific interpretations, and AI-assisted graphical or textual outputs were independently checked against the cited sources and approved by the authors.

2. Modification Mechanism and Synthesis Principles of Polyurethane-Modified Asphalt

2.1. Modification Mechanism of Polyurethane-Modified Asphalt

Polyurethane-modified asphalt is commonly prepared using a polyurethane prepolymer, with chain extenders or crosslinking components added when required. PU chemistry is based primarily on reactions between isocyanate (-NCO) groups and active-hydrogen compounds, most commonly di- or polyisocyanates and polyols containing hydroxyl (-OH) groups [11–14,16,20]. When hydroxyl groups are present in excess, hydroxyl-terminated prepolymers can be obtained; when isocyanate groups are present in excess, isocyanate-terminated prepolymers are formed. Isocyanate-terminated prepolymers are particularly

relevant to reactive asphalt modification because residual -NCO groups can participate in subsequent reactions with polar asphalt constituents [11,12,20].

The modification mechanism involves both chemical reactions and physical associations. Terminal -NCO groups can react with -OH and other active-hydrogen-containing moieties in polar asphalt fractions, while urethane groups and aromatic/polar segments participate in hydrogen bonding, dipole interactions, adsorption, and physical entanglement [8,11,12,25,26]. These processes promote dispersion and the formation of a connected PU–asphalt network. Spectroscopic investigations have reported the consumption of isocyanate-related groups and the formation of urethane-associated structures, while separation and molecular-scale analyses further support the incorporation of reactive asphalt molecules into the polymer network [12,26,27]. The choice of methylene diphenyl diisocyanate (MDI) or toluene diisocyanate (TDI) alters the hard-segment structure, reaction kinetics, rheological reinforcement, low-temperature flexibility, and aging resistance [21]. Molecular-dynamics simulations further show that PU molecular weight and hard-segment polarity affect interfacial energy and macroscopic adhesion [28].

Although the coexistence of chemical bonding and physical association is well supported, the relative contributions of covalent reactions, hydrogen bonding, adsorption, and chain entanglement to macroscopic performance have not been quantitatively resolved. This limitation is important because PU chemistry, base-asphalt composition, NCO/OH ratio, curing history, and test methods vary substantially among studies. Consequently, similar macroscopic improvements may arise from different combinations of reaction pathways and morphologies, and multiscale experiments coupled with validated molecular models are still required to establish transferable structure–interface–performance relationships [26,28]. The combined chemical and physical modification mechanisms are schematically summarized in Figure 2.

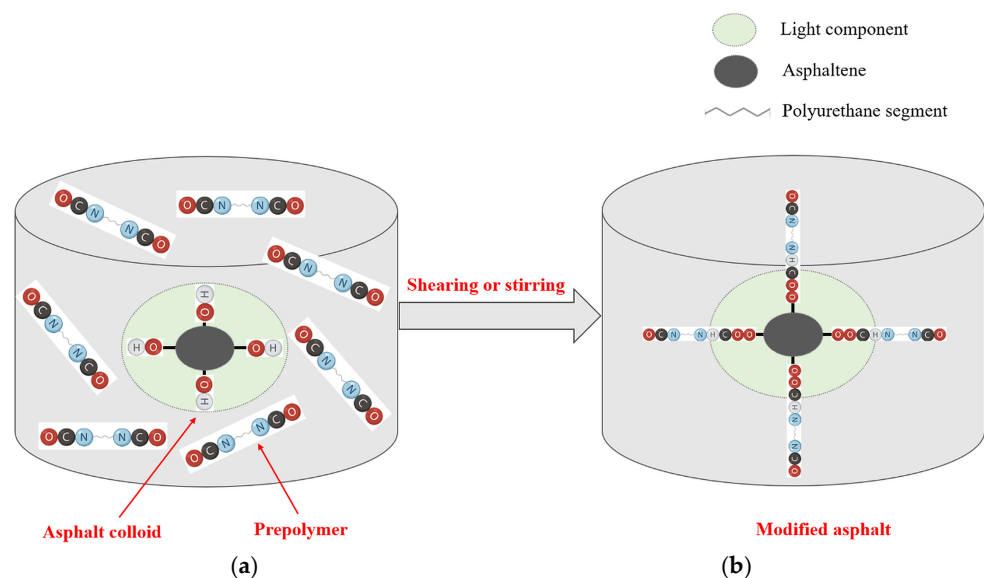


Figure 2. Conceptual modification mechanism: (a) base asphalt containing a reactive polyurethane precursor; (b) formation of a chemically and physically connected polyurethane–asphalt network. Developed by the authors based on Refs. [8,11,12,25,26].

2.2. Synthesis Principles of Polyurethane-Modified Asphalt

According to structural and curing characteristics, polyurethane-modified asphalt can be broadly divided into thermosetting and thermoplastic systems [14–16,27,29,30]. Thermosetting PU-modified asphalt is prepared from reactive precursors that cure to form a three-dimensional network, whereas thermoplastic PU is introduced mainly through

melting, swelling, shear dispersion, and physical association. Thermosetting systems can provide high strength and adhesion, but their viscosity evolves with reaction time and is sensitive to temperature, moisture, NCO/OH ratio, and addition sequence. Thermoplastic systems avoid an irreversible chemical-cure window and are reprocessable, but their performance depends on melt dispersion, hard/soft-segment morphology, compatibility, and hot-storage stability [27,29–31]. The two classes therefore require different processing and acceptance criteria rather than a single generic definition of PU-modified asphalt [14–16,27,29–31].

Overall, polyurethane can modify asphalt through chemical bonding and physical association, thereby changing phase morphology, interfacial interactions, and rheological response. Selected thermosetting and thermoplastic PU systems have shown substantial improvements in high-temperature performance, adhesion, aging resistance, and fatigue-related behavior, although low-temperature response and constructability remain formulation-dependent [21,22,27,29–33]. High-content reactive systems should be evaluated in conjunction with early-age curing and workability because increasing dosage can shorten the construction window [34]. Semi-prepolymer technology provides another route for balancing storage, construction, and final performance, although low-temperature cracking resistance may remain weaker than that of SBS-modified asphalt in some formulations [35]. Polyether-based PU studies directly link preparation parameters to binder and mixture performance [36], while dynamically crosslinked systems show that the NCO/OH ratio can regulate stiffness, elasticity, phase stability, and storage performance [37].

3. Polyurethane-Modified Asphalt Applications

3.1. Polyurethane-Modified Emulsified Asphalt

Emulsified asphalt can be applied at ambient or reduced temperatures for interlayer bonding, maintenance, and repair. PU modification is attractive because it can enhance cohesive strength, elasticity, film formation, and polar interfacial interactions while preserving the low-temperature-processing advantages of emulsion technology [15,38,39]. However, storage stability, demulsification and film formation, ionic compatibility, curing behavior, and cost must all be considered together.

Two preparation routes are commonly reported. The first prepares polyurethane-modified asphalt and subsequently emulsifies it; the second prepares a waterborne polyurethane dispersion and blends it with emulsified asphalt. For the first route, Sheng et al. [38] investigated 0, 2, 4, 6, and 8% polyurethane. Polyurethane was uniformly dispersed in the evaporation residue at contents below 6%, while 6% was proposed as the suitable dosage: the 5 °C ductility increased from 2.6 cm for the unmodified emulsion residue to 26.3 cm at 6% polyurethane, the glass-transition temperature decreased to −18.8 °C, and the calculated crystallite size decreased to 113 Å. At 8% polyurethane, ductility decreased to 22.7 cm and crystallite size increased to 167 Å; the authors attributed this reversal to polyurethane aggregation that disrupted the network structure. Figure 3 is therefore a qualitative representation of this reported morphology/performance progression rather than a reproduction of measured microscopy or quantitative data [38]. Carrera et al. [39], using a different emulsion formulation, found a storage-stability limit between approximately 1 and 2 wt.% modifier for a 50 wt.% bitumen fraction despite improved deformation resistance of the residue. These results demonstrate that an “optimum polyurethane content” is formulation-specific rather than transferable between emulsion systems.

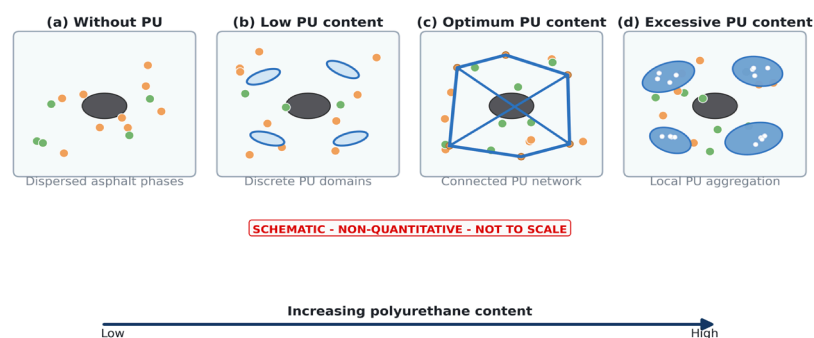


Figure 3. Conceptual morphology evolution with increasing polyurethane content: (a) emulsified asphalt without polyurethane; (b) low polyurethane content with discrete domains; (c) moderate polyurethane content with a connected network; (d) excessive polyurethane content with local aggregation. Developed by the authors based on the microscopic observations reported in Ref. [38]. The schematic is non-quantitative and not to scale. In Ref. [38], the optimum and excessive conditions represented qualitatively here correspond to approximately 6% and 8% PU, respectively; the panels are not reproductions of experimental micrographs. Colors and shapes are used only to distinguish schematic domains and network connectivity; they do not represent quantitative composition or specific chemical species.

For the second method, waterborne polyurethane is blended with emulsified asphalt after the asphalt-water ratio and ionic compatibility are adjusted. Increasing the amount of waterborne PU can reduce temperature sensitivity and improve the elastic response of the evaporation residue [15]. Waterborne acrylate/PU composite emulsions have also been used for fog seals [40,41]. The two-phase structure of waterborne PU-modified bitumen is important for balancing high- and low-temperature rheological properties [42]. Waterborne PU/SBS composite-modified emulsified asphalt combines the elasticity of SBS with the film-forming and polar characteristics of PU [43]. Comparisons between anionic and cationic waterborne PU show that ionic type affects particle distribution, storage stability, atomic force microscopy (AFM) morphology, and compatibility [44].

In summary, the preparation route, polyurethane type, emulsifier type and concentration, particle charge, and mixing sequence jointly control storage stability, temperature sensitivity, mechanical properties, and film formation. For reactive emulsions, the balance between penetration and continuous film formation should be considered. Epoxy-functionalized waterborne polyurethane can simultaneously improve tensile behavior and interfacial adhesion [45], while waterborne epoxy resin/polyurethane composite emulsions can reduce the brittleness of the epoxy network [46]. Multiscale characterization reported in 2026 showed that an appropriate waterborne polyurethane dosage improved wet adhesion and spalling resistance, and aggregate type also exerted an important influence [47]. Therefore, compatibility and interfacial performance should be evaluated before large-scale application.

Across studies of emulsified systems, the dominant pattern is a dosage–compatibility trade-off rather than a monotonic benefit. Reactive or waterborne polyurethane can increase cohesion, deformation resistance, low-temperature ductility, and wet adhesion, but higher modifier contents may destabilize droplets, reduce storage stability, or promote phase aggregation. The limiting dosage varies with polyurethane chemistry, ionic type, asphalt fraction, and preparation route [38,39,42–47]. Consequently, polyurethane content should not be treated as a transferable design parameter unless the emulsion chemistry and processing conditions are clearly specified.

3.2. Polyurethane Composite-Modified Asphalt

Styrene–butadiene–styrene (SBS), styrene–butadiene rubber (SBR), epoxy resin, reactive elastomeric terpolymer (RET), crumb rubber, and other modifiers occupy distinct performance envelopes in pavement engineering [3,6–9]. PU can serve as a secondary modifier when the design objective is to introduce polar interactions, chemical crosslinking, cohesive strength, or toughness into an existing network [48,49]. Composite modification should therefore be designed around complementary functions and phase compatibility, rather than being treated as a simple increase in total modifier content.

3.2.1. Polyurethane and Epoxy Resin Composite-Modified Bitumen

Epoxy asphalt is produced by combining epoxy resin, curing agents, and asphalt. The cured network provides high strength, adhesion, and sealing capacity; however, brittleness and limited deformation compatibility remain concerns [9]. PU is therefore used in epoxy/PU systems to improve toughness and low-temperature cracking resistance while retaining the strength of the epoxy network [50].

He et al. investigated polyurethane/epoxy resin composite-modified asphalt for bridge-deck bonding. At 60 °C, its tensile strength substantially exceeded that of SBS-modified asphalt, while its viscosity development period provided a limited but usable construction window [51]. Waterborne epoxy resin and waterborne polyurethane can also be combined to prepare a cold-applied composite emulsified asphalt [52]. However, excessive polyurethane may reduce tensile strength; therefore, the proportions of polyurethane, epoxy resin, and curing agent must be optimized [50]. A 2024 study further reported that waterborne polyurethane improved the toughness, aging resistance, aggregate adhesion, moisture resistance, and environmental performance of epoxy emulsified asphalt by forming an interpenetrating polymer network [53].

Overall, an appropriate polyurethane/epoxy ratio can significantly improve low-temperature cracking resistance, tensile toughness, and interfacial bonding while retaining the strength and chemical resistance of epoxy asphalt. Construction time, curing temperature, and moisture sensitivity should be evaluated concurrently [9,50–53].

3.2.2. Polyurethane and SBS Composite-Modified Asphalt

SBS-modified asphalt is widely used in pavement engineering, but porous or otherwise demanding applications may require a binder that combines high viscosity with high elastic recovery. Tian et al. [54] combined polyurethane prepolymer (PUP) with SBS and, for the investigated base asphalt, recommended approximately 4% SBS, 5% PUP, 0.5% chain extender, and 1% sulfur crosslinker; FTIR and morphology/rheology results indicated combined physical and chemical interactions together with improved high-temperature and storage performance. Waste-polyurethane/SBS systems provide an additional recycling route [55], while polyurethane–polyurea binders demonstrate that urethane/urea linkages can enhance strength and deformation resistance, but require stricter control of rapid reactions and construction time [56].

3.2.3. Polyurethane and Reactive Elastomeric Terpolymer (RET) Composite-Modified Asphalt

RET can increase asphalt viscosity and rutting resistance, but its low-temperature performance may remain limited. Xu et al. [57] demonstrated that polyurethane prepolymer (PUP) can complement RET by improving low-temperature behavior; for the investigated system, they recommended approximately 1.5% RET and 8–10% PUP by base-asphalt mass, together with high-speed shearing at about 5000 rpm for at least 1 h. Other composite routes address different deficiencies: thermoplastic PU can act synergisti-

cally with mineral/polymer phases [58], PU can improve the low-temperature response of unsaturated-polyester-modified asphalt [59], hydroxylated crumb rubber can form a chemically connected rubber-PU network [60], and bio-based PU components can reduce petroleum dependence while improving aging resistance [61]. Because these formulations involve different chemistries, dosage definitions, and performance targets, their reported proportions should not be interpreted as universal optimum contents.

Across composite systems, polyurethane serves different complementary functions rather than acting as a universal secondary modifier. In epoxy systems, it primarily improves toughness and deformation compatibility, although excessive polyurethane may reduce tensile strength [50,51,53]. In SBS systems, reactive and polar polyurethane interactions complement the physical SBS network but increase formulation and viscosity-control demands [54–56]. In RET or unsaturated-polyester systems, polyurethane mainly mitigates low-temperature brittleness, sometimes with a modest reduction in high-temperature stiffness [57–59]. The practical design objective, therefore, is not to maximize polyurethane dosage, but to identify the minimum chemically compatible dosage required to correct the dominant performance deficit without unduly narrowing the construction window. A cross-study synthesis of these performance, processing, and application trade-offs is provided in Table 1.

Table 1. Cross-study comparison of performance characteristics, processing constraints, and representative quantitative evidence for selected asphalt-modifier systems. Numerical values are reported only when directly traceable to the cited study; because binder sources, test methods, modifier chemistries, and conditioning protocols differ, these values should not be interpreted as pooled rankings.

Representative Quantitative Evidence	Cost/Application	Processability	Fatigue/Adhesion	Low-Temperature Cracking	High-Temperature Resistance	Modifier/System
No single transferable dosage is assigned here because polymer architecture, base-asphalt chemistry, and compatibility strongly affect the usable formulation [3,8].	Mature supply chain and specifications	High-temperature shear; hot-storage phase separation can occur	Good fatigue response; adhesion depends on binder-polymer compatibility	Generally improved flexibility versus base asphalt	Strong and mature benchmark; polymer network improves rutting resistance	SBS-modified asphalt [3,8]
For one EPU system, 8 wt.% PU + 32 wt.% epoxy resin was selected as the optimum formulation; low-temperature cracking resistance improved versus epoxy asphalt [50].	High initial cost; mainly special/bridge applications	Thermoset curing and limited construction window	High adhesion and good fatigue resistance	Epoxy can be brittle; PU improves flexibility	Very high strength and rutting resistance after cure	Epoxy asphalt/EPU [9,50]
1.5% RET + 8%–10% PUP; ~5000 rpm shear and at least 1 h were recommended for the investigated system [57].	Added formulation complexity	Requires adequate reaction/shearing control	Moisture resistance and composite performance improved	PUP mainly compensates low-temperature weakness	RET primarily reinforces high-temperature response	RET + PUP [57]
Representative formulation: 4% SBS + 5% PUP + 0.5% chain extender + 1% sulfur crosslinker [54].	Suitable for porous/high-demand sections	Formulation- and viscosity-sensitive	Improved cohesion and network stability	Balanced by combined physical/reactive networks	High viscosity and high elastic recovery	SBS + PUP [54]
At 130 °C, 30% and 50% isocyanate-prepolymer systems had workable times of ~72 and 46 min; the 50% system showed a 142.1% increase in rutting factor after 14 d curing [34].	Higher initial material cost; special applications	Time-dependent viscosity; short pot/workable time	Strong cohesive and interfacial response	Relaxation capacity may decrease when crosslink density is excessive	Strong, curing-dependent rutting resistance and stiffness	Thermosetting/high-content PU [34]
A direct TS-PU/TP-PU mixture comparison showed strong high-temperature and fatigue performance for both PU systems; TP-PU outperformed SBS in low-temperature cracking resistance, while water stability remained a limitation [30].	Potentially easier processing than thermosetting systems	Reprocessable; no irreversible thermoset curing window, although compatibility and storage stability remain important	Reported fatigue and strength advantages over SBS in a direct mixture comparison	Good flexibility; may outperform SBS at low temperatures in reported mixtures	High-temperature performance improved relative to base asphalt; performance versus SBS is system-dependent	Thermoplastic PU [30]

3.3. Polyurethane-Modified Asphalt Mixtures

PU is incorporated into pavement mixtures in two fundamentally different ways: as a modifier or co-binder while asphalt remains the continuous binder phase, or as the principal polymer binder in polyurethane-bound mixtures. These systems should not be directly compared as compositionally equivalent materials. Binder- and mixture-scale studies generally report improvements in high-temperature stability, moisture resistance, cohesion, and durability for appropriately designed PU systems [22,36,62–64]. PU pre-polymer has also been introduced into mixtures containing reclaimed asphalt pavement (RAP), where reactions with aged binder components and stronger binder–aggregate/RAP interfaces improved high-temperature stability, moisture resistance, and low-temperature cracking resistance [65].

3.3.1. Permeable Pavements

Permeable pavement uses a large, interconnected-void structure to promote drainage and mitigate surface runoff [62]. Conventional porous asphalt (PA), including open-graded friction course (OGFC) mixtures, can suffer aggregate raveling and loss of shear strength because the aggregate skeleton is only weakly restrained by a thin asphalt film. Selected studies report that polyurethane-bound porous mixtures can provide higher compressive and tensile strength, improved fatigue and stability performance, and lower Cantabro loss than asphalt-bound porous mixtures under the investigated conditions [63,64]. Freeze–thaw conditioning can still reduce mechanical properties, so these results should be interpreted with respect to binder chemistry, mixture design, curing age, and test protocol. Figure 4 provides an author-developed, qualitative synthesis of these reported tendencies rather than a reproduction of the original experimental figures or data graphics.

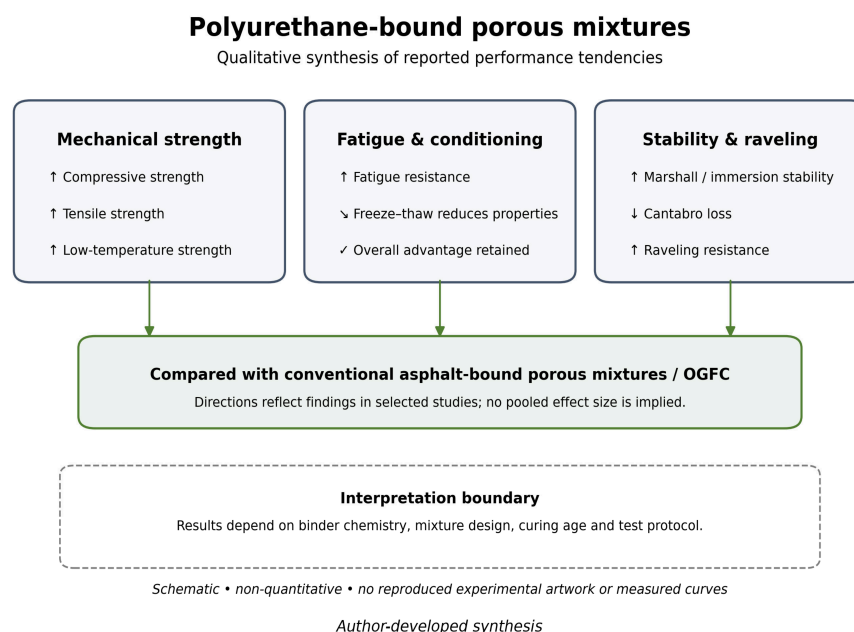


Figure 4. Qualitative synthesis of mechanical-performance and durability tendencies reported for polyurethane-bound porous mixtures relative to conventional asphalt-bound porous mixtures/OGFC. The selected studies report higher compressive and tensile strength, improved fatigue and stability performance, and lower Cantabro loss for the investigated polyurethane-bound systems, although freeze–thaw conditioning may reduce some properties. Developed independently by the authors based on the findings in Refs. [63,64]. The schematic is non-quantitative, not to scale, and does not reproduce any original figure, measured curve, graphical layout, or artwork from the cited publications.

Lu et al. [64] reported lower Cantabro loss for polyurethane-bound pervious mixtures than for conventional porous asphalt, consistent with stronger aggregate–binder cohesion. Their long-term cyclic-creep results also showed distinct deformation patterns: the porous asphalt mixture entered a rapid-yield stage after approximately 800 loading pulses, whereas the permanent deformation/mean strain of the polyurethane-bound mixtures changed only slightly as the number of cycles increased. Figure 5b is a conceptual normalization of this experimentally reported contrast; its axes and curves are not original measured values and should not be interpreted quantitatively. Because polyurethane-bound mixtures exhibit deformation and stiffness characteristics that differ from conventional asphalt mixtures, existing asphalt-mixture test procedures may require adaptation, and curing age, temperature, loading rate, and failure criteria should be explicitly reported [64].

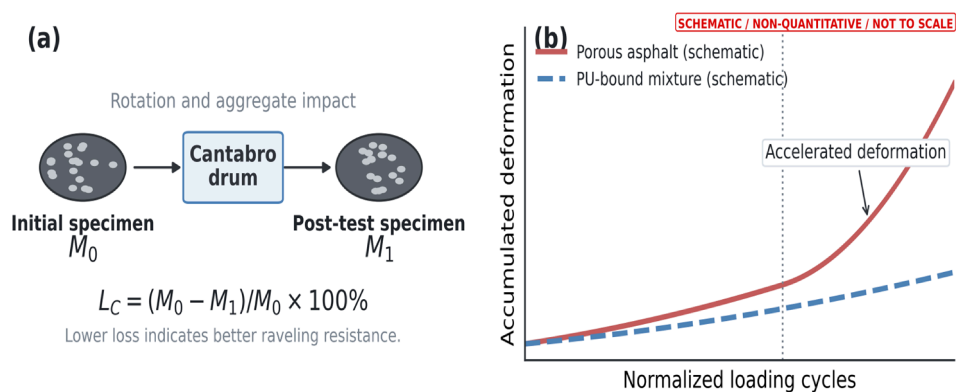


Figure 5. Schematic representation of the mechanical evaluation of polyurethane-bound porous mixtures: (a) Cantabro test workflow and loss calculation; (b) conceptual accumulation of deformation under repeated loading. Developed independently by the authors based on the test procedure and qualitative findings reported in Ref. [64]. Panel (b) is schematic, non-quantitative, and not to scale; it does not reproduce any original measured curves, graphical layouts, or artwork from Ref. [64]. Ref. [64] reported rapid yielding of porous asphalt after approximately 800 loading pulses, whereas deformation of the PU-bound mixtures changed only slightly with continued cycling.

The high void ratio of permeable pavement enables rapid drainage, but external loading may displace aggregates and reduce the effective void ratio [62]. Fine particles may also clog the upper portion of the pavement. Figure 6 conceptually illustrates the vertical- and lateral-flow principles described for permeability evaluation of polyurethane-bound open-graded mixtures [64]. The schematic was developed independently to communicate the flow pathways and boundary conditions, and it does not reproduce the original experimental apparatus or artwork. Lu et al. [64] reported a higher clogging rate for porous asphalt than for the polyurethane-bound mixture. X-ray scanning further showed that clogging was concentrated near the upper surface, while the connected pore structure below remained important for hydraulic performance [66]. These findings indicate that binder strength, aggregate gradation, pore connectivity, and maintenance strategy should be considered together.

Overall, polyurethane-bound open-graded mixtures can provide favorable mechanical and hydraulic performance and can be produced at relatively low temperatures. However, their high material cost remains a concern. A 2026 life-cycle assessment and life-cycle cost analysis showed that polyurethane prepolymer-modified porous asphalt had a higher initial cost and global-warming potential than SBS porous asphalt, but became environmentally and economically advantageous when its service life was extended by approximately 35% [67]. Accordingly, durability improvements should be verified through field monitoring before sustainability benefits are claimed.

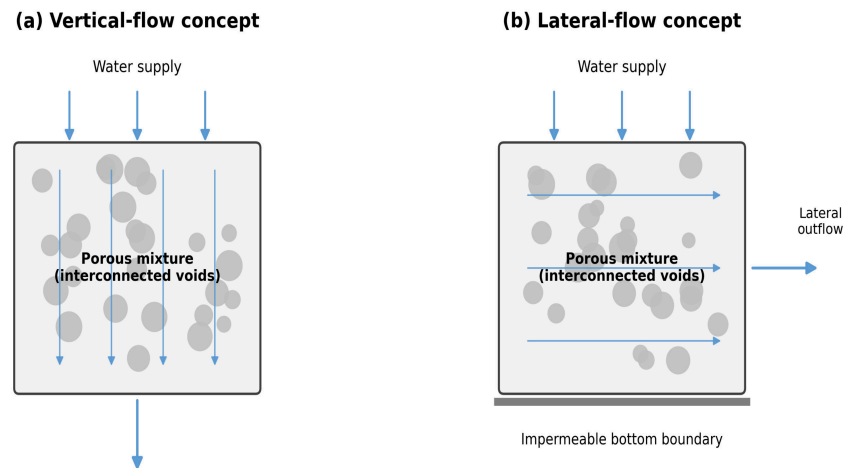


Figure 6. Conceptual schematic of permeability pathways for polyurethane-bound open-graded mixtures: (a) vertical-flow mode; (b) lateral-flow mode with an impermeable bottom boundary. Developed independently by the authors based on the permeability principles described in Ref. [64]. The schematic illustrates the test concept only and does not reproduce the original experimental apparatus, graphical layout, or artwork.

Direct numerical comparisons between polyurethane-bound and asphalt-bound porous mixtures should nevertheless be interpreted cautiously because binder type, aggregate gradation, curing age, and test protocols differ across studies [62–64]. Although the available evidence supports superior cohesion and durability in polyurethane-bound systems, it does not justify a universal performance multiplier; application-specific mixture design and standardized curing and testing conditions remain necessary.

3.3.2. Bridge and Tunnel Paving

Bridge and tunnel pavements impose stringent requirements on adhesion, waterproofing, fatigue resistance, construction temperature, and emissions. In the cited pavement studies, the term ‘polyurethane concrete’ does not refer to Portland-cement concrete; rather, it denotes an aggregate mixture in which two-component polyurethane replaces asphalt as the principal binder. This polyurethane-bound material, therefore, falls outside the narrow definition of PU-modified asphalt, but it is retained here as a closely related pavement application because it demonstrates how PU chemistry performs when polyurethane becomes the continuous binder phase. Hong et al. developed a vacuum-assisted prefabrication approach for such polyurethane-bound mixtures that reduced entrapped voids and improved mechanical and water-stability performance [68]. For tunnel paving, room-temperature PU-based open-graded friction courses and PU concrete reduced heating demand and construction emissions while providing strong mechanical and functional performance [69]. These results should be interpreted separately from those for PU-modified asphalt mixtures, in which asphalt remains the principal binder.

Overall, polyurethane pavement materials can provide high stability and durability and can be prepared at lower temperatures with reduced construction emissions. However, three issues remain: (1) construction and acceptance specifications require further development; (2) long-term field performance must be monitored before large-scale application; and (3) the short curing window of reactive polyurethane binders must be controlled through material design and construction management [68,69].

3.3.3. Maintenance of Cracks and Potholes

Vehicle loading, temperature variation, moisture, and aging generate cracks, potholes, and local material loss that require timely maintenance. Polyurethane-based repair sys-

tems are attractive because they can provide strong aggregate adhesion, rapid strength development, and ambient- or low-temperature construction. Studies on polyurethane-modified emulsified asphalt support the use of PU chemistry in pavement-maintenance binders [38,39]. For crack repair, Xiong et al. [70] showed that mineral powder can reduce cost and improve ultraviolet, low-temperature, and water-damage resistance of polyurethane grouting materials, although excessive powder causes agglomeration and mechanical deterioration. For pothole repair, blocked waterborne polyurethane emulsified asphalt separates storage from thermal deblocking/curing; a 2025 study reported an optimal blocked-WPU content of 15% and Marshall stability above 2.5 kN after 60 d of storage [71].

Overall, polyurethane repair materials can provide high cohesion, fatigue resistance, fluidity, and rapid strength development. Future research should focus on crack-width adaptability, bond durability under water and freeze–thaw actions, storage stability, construction temperature, and compatibility between the repair material and the aged pavement [38,39,70,71].

4. Economic Applicability Analysis

Economic feasibility should be assessed as an application-specific life-cycle issue rather than by comparing modifier unit prices alone. PU binders and precursors can have higher initial material costs than conventional SBS systems, but binder/modifier dosage, production temperature, construction organization, maintenance frequency, traffic disruption, and service-life extension all influence the final engineering costs. Sun et al. [22] reported that the optimum asphalt content of the investigated PU-modified mixture was about 5% lower than that of the comparison mixtures and that its total mixture cost was similar to that of the SBS-modified mixture despite the higher PU unit price. Thermosetting PU has also been developed for bridge-deck applications, where strength, adhesion, durability, and construction window must be considered together [48]. These findings support evaluating a performance–cost balance rather than making a universal claim that PU is intrinsically cheaper. The reported mixture-cost comparison is summarized in Figure 7 using an independently generated visualization based on the numerical data reported in Ref. [22].

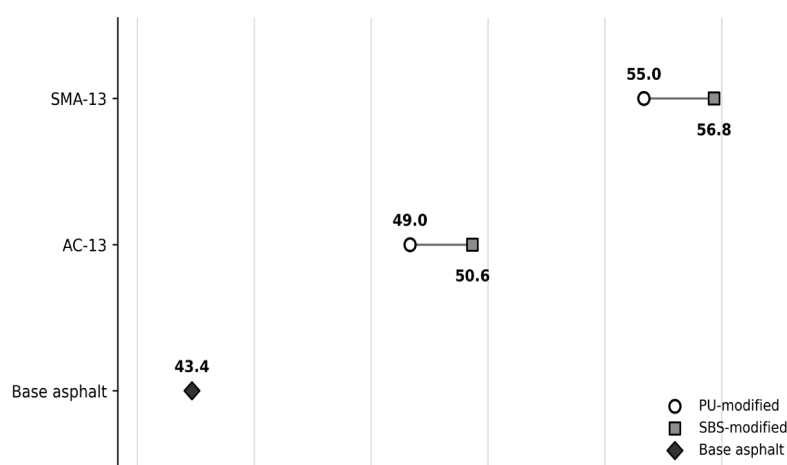


Figure 7. Author-generated comparison of reported costs for polyurethane-modified, SBS-modified, and base-asphalt systems. The visualization was independently created by the authors using the numerical values reported in Ref. [22] and does not reproduce the original figure layout or artwork.

The economic variables identified in the literature can be organized into four practical groups. First, dosage affects both material cost and reaction/workability: increasing PU

content can strengthen a reactive network, but it also increases material consumption and may shorten the construction window. Second, durability determines whether a higher initial cost can be recovered through fewer interventions; this favors applications in which closure or repair costs are high, such as bridge decks, tunnels, porous pavements, and rapid-maintenance locations. Third, energy and construction requirements depend on PU type: room- or reduced-temperature systems can reduce heating demand, whereas two-component mixing and curing control can increase process-management requirements. Fourth, the repair scenario is important because rapid reopening and reduced repeat maintenance may be more valuable than material unit price alone. Accordingly, PU should not be presented as a universal economic substitute for SBS, but rather as an option for applications in which its durability, adhesion, or low-temperature/rapid-curing benefits provide sufficient engineering value [22,34,48,67,69–71].

The most detailed quantitative life-cycle evidence currently available is the 2026 Hong Kong assessment of PU-prepolymer-modified porous asphalt [67]. Although the PU system had a higher initial cost and global-warming potential than SBS porous asphalt, the life-cycle assessment (LCA) and life-cycle cost assessment (LCCA) became simultaneously favorable when the PU pavement service life exceeded that of the SBS alternative by approximately 35%. Sensitivity analysis identified service life, PUP content, and PUP unit price as the dominant economic variables. This threshold-based result is more informative than a simple material-price comparison and indicates that future economic studies should explicitly report the functional unit, service-life assumption, maintenance scenario, energy mix, and binder dosage [67].

5. Discussion and Prospects

Research on PU-based asphalt and pavement materials now spans reactive and thermoplastic binders, emulsified systems, composite networks, porous and special pavements, maintenance, recycled mixtures, and life-cycle sustainability [14–16,23,24,37,61,65,67]. However, the evidence remains uneven: laboratory performance data are abundant, whereas standardized workability criteria, long-term field validation, consistent dosage definitions, and complete life-cycle comparisons remain limited. The following discussion therefore focuses on cross-study limitations that constrain the translation of promising laboratory formulations into reproducible engineering designs.

A recurring finding across the reviewed studies is that the reported ‘optimum polyurethane dosage’ is formulation-specific. Thermosetting versus thermoplastic chemistry; isocyanate/polyol selection; NCO/OH ratio; base-asphalt composition; waterborne ionic type; curing history; and test temperature can shift the balance among stiffness, toughness, adhesion, storage stability, and workability [21,26,28,34–38,42,44]. Apparent inconsistencies—particularly in low-temperature response and storage stability—should therefore be interpreted in relation to these boundary conditions rather than treated as direct contradictions. Future comparative studies should report the relevant chemical and processing variables before cross-study dosage comparisons are made.

- (1) As discussed in Section 2.1, current experiments and molecular simulations support the simultaneous occurrence of covalent reactions, hydrogen bonding, adsorption, and physical entanglement in PU–asphalt systems, but their relative contributions remain insufficiently quantified [26,28]. The central research need is therefore not simply to identify additional interactions, but to determine how changes in isocyanate/polyol chemistry, NCO/OH ratio, asphalt polarity, curing history, and interface structure redistribute these interactions and, in turn, alter adhesion, phase stability, rheology, and mixture performance. Comparable multiscale protocols are required before molecular descriptors can be used as transferable material design parameters.

- (2) Thermosetting and thermoplastic PU systems require different workability and performance criteria. For thermosetting PU-modified asphalt, viscosity develops continuously during reaction; useful field-oriented indices therefore include rotational viscosity at the intended construction temperature as a function of time, viscosity-growth rate, and a construction tolerance (workable/pot) time defined by a validated mixing or compaction limit. NCO conversion from Fourier transform infrared spectroscopy can be used as a complementary curing-state indicator. Luo et al. [34] reported workable times of approximately 72 min and 46 min at 130 °C for high-content systems containing 30% and 50% isocyanate prepolymer, respectively. Thermoplastic PU, by contrast, does not rely on irreversible network curing and is more reprocessable; however, its performance is governed by melt dispersion, hard/soft-segment structure, compatibility, and hot-storage stability. A direct comparison of thermosetting- and thermoplastic-PU asphalt mixtures showed that both could outperform SBS-modified mixtures in several strength, high-temperature, and fatigue indicators, while the thermoplastic system showed favorable low-temperature cracking resistance; however, water stability remained insufficient for the investigated PU mixtures [30]. These differences confirm that a single PU workability or acceptance criterion is not scientifically justified.
- (3) Existing standards can provide measurement frameworks, but they do not constitute PU-specific acceptance criteria. ASTM D4402/D4402M-23 [72] describes rotational-viscometer measurement of asphalt viscosity at elevated temperature; EN 13302:2018 [73] specifies rotating-spindle dynamic-viscosity testing for bituminous binders; and the Chinese JTG 3410-2025 (T 0625-2011) [74] method provides Brookfield rotational-viscosity testing. Conventional polymer-modified-asphalt specifications, including JTG F40-2004 [75], can provide reference values for constructability, but their fixed viscosity limits were not developed for reactive PU systems. For thermosetting PU, any acceptance window must also account for elapsed reaction time, curing degree, moisture sensitivity, shear history, and mixture compactability. These documents are identified by their standard designations as normative technical frameworks and are not counted within the 71-journal-article evidence set used for the literature synthesis.
- (4) Environmental impacts and comprehensive life-cycle economic analyses remain insufficiently characterized. The use of bio-based raw materials, waste polyurethane, and RAP can improve resource efficiency, but recyclability, emissions, durability, and cost should be evaluated within the same system boundary [61,65,67].

Taken together, the evidence indicates that PU is not a single modifier with a transferable optimum dosage. Thermosetting, thermoplastic, waterborne, composite, and PU-bound systems occupy different positions in the performance–constructability–cost space. Future research should therefore shift from ‘maximum property improvement’ toward application-specific design: identifying the dominant pavement failure mode, selecting the PU chemistry that addresses that deficit, verifying a practical construction window, and then demonstrating that the durability benefit is sufficient to justify material and process costs. This framework is also necessary for meaningful cross-study comparisons and technical standardization [21,26,28,30,34,37,42,44,61,65,67].

Based on the reviewed research, the following directions are recommended:

- (1) Further investigate low-temperature performance, temperature sensitivity, moisture damage, and fatigue-healing behavior. Dynamic crosslinking and rubber–polyurethane networks provide promising routes for balancing stiffness and toughness [37,60].
- (2) Establish PU-specific workability and construction specifications that combine standardized rotational-viscosity measurement with time-to-threshold, pot life, curing

degree, moisture sensitivity, interfacial adhesion, and mixture compactability. Laboratory viscosity-time criteria should be validated against successful mixing, transport, paving, and compaction, rather than by directly adopting a fixed limit developed for conventional polymer-modified asphalt [34].

- (3) Extend the construction window by using controllable catalysts, blocked isocyanates, semi-prepolymer design, and staged curing while avoiding incomplete reactions and excessive brittleness [35,71].
- (4) Conduct long-term monitoring of existing polyurethane-modified asphalt pavements, including stress and strain responses, crack development, interlayer bonding, hydraulic performance, and maintenance history.
- (5) Develop reuse and recycling methods for waste polyurethane-modified asphalt, and investigate the compatibility of polyurethane prepolymers with aged binders and RAP [65].
- (6) Develop a sustainability assessment framework that covers resource consumption, carbon emissions, construction energy, maintenance, traffic delays, service life, and life-cycle cost. Such quantitative evidence is necessary for future technical standards and large-scale engineering applications [67].

6. Conclusions

This review synthesizes the application and development of polyurethane-modified asphalt from the perspectives of modification mechanisms, synthesis classifications, emulsified asphalt, composite modification, asphalt mixtures, engineering applications, and economic applicability. The main conclusions are as follows:

- (1) PU modifies asphalt through a combination of covalent reactions and physical associations, but the individual contributions of these mechanisms have not yet been sufficiently quantified for transferable formulation design. Thermosetting, thermoplastic, waterborne, and composite systems should therefore be treated as distinct material classes whose performance depends on isocyanate/polyol chemistry, NCO/OH ratio, asphalt composition, and curing/processing history [21,26,28].
- (2) The literature does not support a universal optimum PU dosage. Representative optimized formulations are highly system-specific: 8 wt.% PU + 32 wt.% epoxy resin were selected for one epoxy/PU binder [50]; approximately 4% SBS + 5% PUP were recommended for one high-viscosity/high-elasticity SBS/PUP binder [54]; and 1.5% RET + 8%–10% PUP were recommended for one RET/PUP system [57]. These values should be regarded as design examples rather than transferable specifications.
- (3) Constructability remains a key limitation of reactive PU. At 130 °C, a high-content study reported workable times of approximately 72 min for 30% isocyanate prepolymer and 46 min for 50%. After 14 d of curing, the 50% system showed a 142.1% increase in the high-temperature rutting factor [34]. This result illustrates the principal trade-off in thermosetting systems: stronger curing-dependent reinforcement may be accompanied by a narrower construction window. Thermoplastic PU avoids irreversible curing but requires separate control of compatibility and storage stability [30].
- (4) PU is unlikely to replace SBS or other conventional modifiers in every pavement application. Its strongest application potential lies in cases where adhesion, durability, special functionality, or reduced-temperature/rapid construction can offset higher material and process costs. In the 2026 porous-pavement LCA/LCCA study, PU-prepolymer porous asphalt became both economically and environmentally favorable only when its service life exceeded that of the SBS alternative by approximately 35% [67]. Long-term field validation, standardized workability criteria, re-

cycling routes, and consistent life-cycle boundaries are therefore prerequisites for large-scale implementation.

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