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Recycled Plastic–Modified Asphalt Mixtures: Material Behavior, Durability, and Sustainability Implications for Contemporary Road Construction

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Abstract: The increasing accumulation of plastic waste and the escalating demand for durable, cost-effective, and sustainable road infrastructure have jointly intensified scholarly and practical interest in the incorporation of recycled plastics into asphalt mixtures. Over recent decades, asphalt modification has evolved from conventional polymer enhancement toward more environmentally responsive material strategies, among which recycled plastic utilization has emerged as a prominent and contested innovation. This research article presents an extensive, theoretically grounded, and critically elaborated investigation into the use of recycled plastic materials in asphalt mixtures for road construction, drawing strictly upon established literature and standardized testing frameworks. The study synthesizes empirical findings, methodological paradigms, and theoretical interpretations concerning mechanical performance, rheological behavior, moisture susceptibility, aging resistance, and long-term durability of plastic-modified asphalt systems. Particular emphasis is placed on reconciling material science perspectives with pavement engineering requirements and environmental sustainability imperatives.

The analysis integrates insights from laboratory-based performance evaluations, binder-level rheological investigations, mixture-level mechanical testing, and aging and moisture damage assessments. It critically examines the influence of plastic type, particle size, incorporation method, and dosage on asphalt behavior across temperature ranges and loading conditions. The

study further situates recycled plastic asphalt within the broader discourse on polymer-modified binders, comparing its performance characteristics with crumb rubber, conventional polymers, and hybrid modification strategies. Environmental and socio-technical dimensions are also explored, including lifecycle considerations, waste diversion potential, constructability challenges, and regulatory compatibility.

By systematically engaging with the existing body of knowledge, including recent investigations into recycled plastic asphalt mixtures for road construction (Use Of Recycled Plastic In Asphalt Mixtures For Road Construction, 2025), this article identifies persistent knowledge gaps related to long-term field performance, microstructural stability, aging mechanisms, and standardization of design protocols. The findings underscore that while recycled plastic modification can enhance rutting resistance, stiffness, and durability under certain conditions, its performance is highly sensitive to material selection and processing controls. The article concludes by articulating a comprehensive research agenda aimed at advancing recycled plastic asphalt from experimental application toward mainstream, performance-based pavement engineering practice.

Keywords: Recycled plastics; asphalt mixtures; pavement engineering; polymer modification; sustainability; durability; road construction

Introduction

Over The global proliferation of plastic waste has emerged as one of the most pressing environmental challenges of the modern era, with far-reaching implications for land use, ecosystem integrity, and resource efficiency. Concurrently, road infrastructure systems worldwide are experiencing unprecedented stress due to increased traffic volumes, heavier axle loads, and climatic variability, all of which accelerate pavement deterioration and maintenance demands. These parallel pressures have catalyzed interdisciplinary research efforts aimed at transforming waste materials into value-added constituents of construction materials, particularly within asphalt pavement engineering. Among these efforts, the incorporation of recycled plastic into asphalt mixtures has gained significant attention as a potential strategy to simultaneously address waste management challenges and enhance pavement performance (Angelone et al., 2016; Brasileiro et al., 2019).

Historically, asphalt modification has been driven by the need to overcome the inherent limitations of conventional bituminous binders, including susceptibility to temperature-induced deformation, moisture damage, and oxidative aging. Early approaches focused on the use of virgin polymers such as styrene–butadiene–styrene and polyethylene to improve elasticity, stiffness, and resistance to permanent deformation (Becker et al., 2001). While effective, these solutions often entailed high material costs and raised concerns regarding environmental sustainability. The emergence of recycled plastics as alternative modifiers represents a paradigm shift toward circular material use, aligning pavement engineering practices with broader sustainability objectives (Fernandes et al., 2017).

The theoretical rationale for incorporating recycled plastic into asphalt mixtures is grounded in polymer–bitumen interaction theory and composite material behavior. Plastics such as polyethylene, polypropylene, and polyethylene terephthalate exhibit viscoelastic properties that can alter the rheological response of bitumen when appropriately dispersed. At the binder level, these interactions may increase stiffness at high service temperatures, thereby reducing rutting potential, while also influencing low-temperature cracking behavior depending on compatibility and dispersion quality (Ahmadinia et al., 2011; Ahmadinia et al., 2012). At the mixture level, plastic particles may function as either binder modifiers or aggregate substitutes, each mechanism producing distinct structural and mechanical outcomes (Attaelmanan et al., 2011).

Despite growing enthusiasm, the literature reveals considerable heterogeneity in reported performance outcomes, reflecting variations in plastic type, processing methods, dosage rates, and testing protocols. Some studies report substantial improvements in rutting resistance and moisture damage tolerance, while others highlight challenges related to workability, phase separation, and long-term aging behavior (Hamzah et al., 2017; Aguiar-Moya et al., 2015). This divergence underscores the necessity of rigorous, theory-driven analysis that situates empirical findings within a coherent conceptual framework.

Recent scholarship has further emphasized the need to distinguish between dry and wet incorporation processes, as these approaches fundamentally alter the interaction pathways between plastic materials and bitumen. The dry process, wherein plastic is introduced as a solid additive during mixing, may influence aggregate interlock and internal friction, whereas the wet process aims to modify binder rheology through melting or swelling mechanisms (González et al., 2012). Each approach presents unique advantages and limitations, particularly with respect to scalability, quality control, and performance predictability.

Within this evolving research landscape, contemporary investigations into the use of recycled plastic in asphalt mixtures for road construction have provided valuable empirical evidence while also revealing unresolved theoretical and methodological questions (Use Of Recycled Plastic In Asphalt Mixtures For Road Construction, 2025). These studies highlight performance gains under controlled laboratory conditions but caution against premature generalization in the absence of long-term field validation and standardized design guidelines.

The present research article responds to this intellectual context by offering an extensive, critical, and integrative examination of recycled plastic–modified asphalt mixtures. Rather than summarizing existing findings, it elaborates on the underlying mechanisms, scholarly debates, and practical implications that define this research domain. The central problem addressed herein is the lack of conceptual and methodological coherence across studies, which impedes the translation of experimental success into routine engineering practice. By synthesizing diverse strands of literature within a unified analytical narrative, this article seeks to clarify the conditions under which recycled plastic asphalt can deliver durable, sustainable, and economically viable road infrastructure solutions.

The literature gap addressed by this study lies not in the absence of experimental data, but in the insufficient integration of material science theory, pavement performance modeling, and sustainability assessment. While numerous studies have evaluated specific performance metrics, fewer have interrogated the broader implications of plastic modification for pavement lifecycle behavior, standardization, and policy adoption. This article therefore aims to advance scholarly understanding by contextualizing recycled plastic asphalt within the historical evolution of asphalt modification, critically assessing its performance through multiple analytical lenses, and articulating future research directions that can support evidence-based implementation.

Methodology

The methodological approach adopted in this research is grounded in comprehensive qualitative synthesis and critical analysis of peer-reviewed literature, technical standards, and empirical investigations related to recycled plastic–modified asphalt mixtures. Rather than generating new experimental data, the study employs an interpretive research design that emphasizes methodological transparency, theoretical rigor, and analytical depth. This approach is particularly appropriate given the diversity of experimental configurations and performance metrics reported across the existing body of knowledge, which necessitates careful contextualization rather than direct quantitative comparison (Brasileiro et al., 2019).

The first methodological pillar involves systematic examination of asphalt mixture design frameworks and standardized testing protocols commonly employed in the evaluation of plastic-modified systems. These include Marshall stability and flow testing, indirect tensile strength assessments, moisture susceptibility evaluations, wheel tracking tests, and rheological characterization of binders using empirical and performance-based methods (ASTM D1559-89; AASHTO T283, 2014; BS EN 12697-22). By analyzing how these methods are applied across studies, the research identifies patterns in performance reporting and sources of variability linked to test selection and interpretation.

A second methodological dimension centers on comparative material analysis. Studies involving recycled plastics are examined alongside investigations of crumb rubber, sulfur-extended asphalt, and conventional polymer modifiers to elucidate similarities and divergences in behavior (Abdul Hassan et al., 2019; Alghrafy et al., 2021). This comparative lens enables the identification of material-specific mechanisms, such as elasticity enhancement, stiffness modulation, and aging resistance, while also revealing the trade-offs inherent in different modification strategies.

The third methodological component addresses aging and durability assessment. Oxidative, ultraviolet, and moisture-induced aging processes are critically evaluated through the lens of both laboratory simulation and theoretical modeling (Polo-Mendoza et al., 2022; Aguiar-Moya et al., 2015). Particular attention is given to how recycled plastic modifiers influence binder composition, microstructural stability, and long-term performance trajectories under repeated loading and environmental exposure.

Throughout the methodological analysis, explicit consideration is given to limitations and sources of uncertainty. These include inconsistencies in plastic waste characterization, lack of standardized processing protocols, and the predominance of short-term laboratory studies over long-term field trials. By foregrounding these limitations, the methodology supports a balanced and critical interpretation of reported findings, in alignment with recent evaluations of recycled plastic asphalt performance (Use Of Recycled Plastic In Asphalt Mixtures For Road Construction, 2025).

The methodological rationale underpinning this study is therefore not to privilege any single experimental outcome, but to construct a coherent analytical framework that can accommodate diverse evidence while advancing theoretical and practical understanding. This approach aligns with best practices in pavement engineering research, where material complexity and contextual variability demand interpretive synthesis rather than reductive quantification (De Carteret et al., 2019).

Results

The results derived from the integrated examination of recycled plastic–modified asphalt mixtures reveal a complex and highly conditional performance landscape, shaped by material characteristics, processing methods, and testing frameworks. Rather than yielding uniform outcomes, the collective findings demonstrate that recycled plastics can significantly alter asphalt behavior in both beneficial and problematic ways, depending on contextual parameters documented across the literature (Angelone et al., 2016; Ahmadinia et al., 2012). These results are therefore best understood as interpretive patterns rather than absolute performance claims.

At the binder level, studies consistently report that the incorporation of recycled plastic materials increases the stiffness of the asphalt binder, particularly at medium to high service temperatures. This stiffening effect is attributed to the semi-crystalline structure of plastics such as polyethylene and polypropylene, which restrict molecular mobility within the bituminous matrix (Al-Adham & Al-Abdul Wahhab, 2018). Rheological assessments described in the literature indicate improved resistance to permanent deformation, as evidenced by enhanced recovery behavior and reduced susceptibility to shear-induced flow under loading. These findings align with broader observations from polymer-modified asphalt research, where increased stiffness correlates with improved rutting performance (Becker et al., 2001).

However, the results also indicate that excessive stiffening may adversely affect low-temperature performance. Several investigations highlight an increased risk of thermal cracking when recycled plastic content exceeds optimal thresholds, particularly in colder climates or under rapid temperature fluctuations (Holý & Remišová, 2019). This duality underscores the importance of dosage control and material compatibility, as the same mechanism that enhances rutting resistance may compromise flexibility at low temperatures. Such trade-offs are echoed in studies examining sulfur-extended and rubberized binders, suggesting that recycled plastic modification is subject to similar performance balancing constraints (Alghrafy et al., 2021).

At the asphalt mixture level, results from Marshall stability and wheel tracking evaluations generally demonstrate increased load-bearing capacity and reduced permanent deformation for plastic-modified mixtures compared to conventional controls (ASTM D1559-89; BS EN 12697-22). These improvements are frequently attributed to enhanced aggregate interlock and binder stiffness, particularly in mixtures produced using the dry process. The dry incorporation of plastic particles appears to influence mixture structure by acting as a pseudo-aggregate, thereby modifying internal frictional resistance (Attaelmanan et al., 2011).

Moisture susceptibility results present a more nuanced picture. Some studies report improved resistance to moisture-induced damage, as indicated by higher tensile strength ratios and reduced stripping potential (AASHTO T283, 2014). This behavior is often linked to reduced binder permeability and improved coating of aggregates. Conversely, other investigations document increased moisture sensitivity when plastic dispersion is inadequate or when plastic surfaces exhibit poor adhesion with bitumen (Hamzah et al., 2017). These conflicting outcomes suggest that moisture performance is highly sensitive to surface chemistry, particle morphology, and mixing quality.

Aging-related results further complicate the performance narrative. Short-term aging simulations generally indicate that recycled plastic modification can slow oxidative hardening due to reduced oxygen diffusion within the binder matrix (Ali et al., 2013). However, long-term aging studies raise concerns regarding phase separation, embrittlement, and microstructural instability over extended service periods (Polo-Mendoza et al., 2022). These findings resonate with recent comprehensive evaluations of recycled plastic asphalt mixtures, which caution against extrapolating short-term laboratory gains to long-term field performance without robust validation (Use Of Recycled Plastic In Asphalt Mixtures For Road Construction, 2025).

Collectively, the results demonstrate that recycled plastic–modified asphalt mixtures can outperform conventional mixtures under specific conditions, particularly with respect to rutting resistance and structural stability. At the same time, they reveal vulnerabilities related to temperature sensitivity, moisture interaction, and aging behavior. These outcomes reinforce the conclusion that recycled plastic asphalt is not a universally superior solution, but rather a context-dependent material system requiring careful design and performance-based evaluation (Brasileiro et al., 2019).

Discussion

The discussion of recycled plastic–modified asphalt mixtures must be situated within the broader theoretical and practical evolution of pavement engineering, where material innovation is continuously negotiated against performance reliability, constructability, and sustainability imperatives. The results synthesized in this study reveal not only material-specific behaviors, but also deeper epistemological challenges related to how performance is conceptualized, measured, and translated into engineering practice (De Carteret et al., 2019).

From a theoretical standpoint, the interaction between recycled plastics and bitumen can be interpreted through composite material theory and polymer physics. Plastics introduced into asphalt systems function either as dispersed modifiers within the binder phase or as structural inclusions within the aggregate skeleton. In both cases, the resulting material exhibits hybrid viscoelastic behavior that departs from conventional bitumen models (González et al., 2012). This hybridity complicates predictive modeling, as traditional empirical tests were not designed to capture the multi-phase interactions characteristic of plastic-modified systems.

Scholarly debate persists regarding the relative merits of the dry versus wet incorporation processes. Proponents of the wet process argue that direct modification of binder rheology enables more uniform performance and aligns with established polymer-modified asphalt practices (Becker et al., 2001). Critics counter that the wet process requires precise temperature control and may exacerbate phase separation when recycled plastics exhibit heterogeneous melting characteristics (Fernandes et al., 2017). The dry process, while operationally simpler, raises questions about long-term cohesion and moisture resistance, particularly when plastic particles do not adequately bond with the surrounding bitumen (Hamzah et al., 2017).

Comparative analysis with crumb rubber–modified asphalt further illuminates these debates. Rubberized binders are widely recognized for their elasticity and crack resistance, attributes that recycled plastics may not inherently possess (Abdul Hassan et al., 2019). However, recycled plastics often outperform crumb rubber in terms of stiffness and rutting resistance, suggesting complementary rather than competing modification pathways. This observation has prompted calls for hybrid modification strategies that combine recycled plastics with rubber or other polymers to balance performance attributes (Ansar et al., 2022).

Environmental sustainability considerations add another layer of complexity to the discussion. While recycled plastic asphalt is frequently promoted as an environmentally responsible solution, lifecycle assessments reveal that environmental benefits are contingent upon processing efficiency, transportation distances, and service life extension (Brasileiro et al., 2019). If plastic modification leads to premature pavement failure or increased maintenance demands, the anticipated sustainability gains may be negated. Recent evaluations emphasize that environmental claims must therefore be substantiated through holistic lifecycle analysis rather than isolated material reuse metrics (Use Of Recycled Plastic In Asphalt Mixtures For Road Construction, 2025).

Regulatory and standardization challenges further constrain widespread adoption. Existing pavement design standards and material specifications are largely calibrated for conventional and polymer-modified asphalts, leaving recycled plastic systems in a regulatory gray area (ASTM D4867, 2014). The absence of standardized material characterization protocols for recycled plastics introduces uncertainty into quality control and performance prediction. This uncertainty is compounded by variability in waste plastic sources, which may differ in polymer composition, contamination levels, and degradation history (Zahedi, 2024).

Limitations identified across the literature include the predominance of short-term laboratory studies, limited field performance data, and insufficient exploration of long-term aging mechanisms. While laboratory simulations provide valuable insights, they cannot fully replicate the complex interactions between traffic loading, environmental exposure, and maintenance interventions experienced by in-service pavements (Polo-Mendoza et al., 2022). Addressing these limitations requires longitudinal field studies and the integration of mechanistic–empirical design frameworks capable of accommodating novel material behaviors.

Future research directions emerging from this discussion include the development of compatibility-enhancing additives, improved plastic preprocessing techniques, and advanced microstructural characterization methods. Additionally, interdisciplinary collaboration between material scientists, pavement engineers, and environmental analysts is essential to bridge the gap between experimental innovation and practical implementation. Only through such integrative efforts can recycled plastic asphalt transition from experimental novelty to reliable infrastructure solution (Angelone et al., 2016).

Conclusion

This research article has provided an extensive, theory-driven, and critically elaborated examination of recycled plastic–modified asphalt mixtures within the context of contemporary road construction. By synthesizing and interpreting a diverse body of literature, the study has demonstrated that recycled plastics possess the potential to enhance specific performance attributes of asphalt mixtures, particularly with respect to stiffness, rutting resistance, and structural stability. At the same time, it has highlighted significant challenges related to temperature sensitivity, moisture interaction, aging behavior, and standardization.

The findings underscore that recycled plastic asphalt is not a universally applicable solution, but rather a context-dependent material system whose success hinges on careful material selection, processing control, and performance-based evaluation. The integration of recycled plastics into asphalt mixtures must therefore be guided by rigorous engineering judgment and supported by robust empirical evidence. Recent investigations into the use of recycled plastic in asphalt mixtures for road construction reinforce this conclusion, emphasizing the need for cautious optimism grounded in scientific validation (Use Of Recycled Plastic In Asphalt Mixtures For Road Construction, 2025).

Ultimately, the contribution of recycled plastic asphalt to sustainable infrastructure development will depend not only on its technical performance, but also on its alignment with lifecycle sustainability goals, regulatory frameworks, and societal expectations. Advancing this field requires continued theoretical refinement, methodological innovation, and long-term field validation to ensure that environmental aspirations are matched by durable and reliable pavement performance.

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