

Sustainable Pavement Solutions: Integrating Waste Plastics into Bituminous Mixes for Performance Enhancement

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ABSTRACT

The rapid growth of transportation infrastructure has increased the demand for durable, high-performance pavements. Traditional bituminous pavements face challenges like rutting, fatigue cracking, and moisture susceptibility. Waste plastic integration into bituminous mixes offers a sustainable solution, improving both performance and waste management. Plastics such as PET, PP, and PE enhance mechanical properties, moisture resistance, and rutting resistance. However, compatibility issues and low-temperature flexibility remain concerns. Research has focused on optimal plastic dosages and advanced techniques like machine learning for predicting asphalt mixture performance. These efforts support the adoption of plastic-modified asphalt for a sustainable future in pavement engineering.

Keywords: *Plastic-Modified Asphalt, Waste Plastic, Bituminous Mix, Sustainability.*

I. INTRODUCTION

The rapid growth of transportation infrastructure across the globe has significantly increased the demand for durable and high-performance pavement materials. Conventional bituminous pavements, though widely used, face several challenges such as rutting, fatigue cracking, moisture susceptibility, and temperature-related distresses. Simultaneously, the rising accumulation of waste materials—particularly plastics—has emerged as a major environmental concern. In this context, the integration of waste plastic into bituminous mixes has gained attention as a sustainable and cost-effective solution that addresses both pavement performance and environmental management issues (Ameur et al., 2025). Bitumen, a petroleum-derived product, is increasingly becoming scarce due to the depletion of crude oil resources. This has encouraged researchers to explore alternative materials and modifiers to enhance the performance characteristics of asphalt mixtures. Waste plastics such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) have shown significant potential as modifiers due to their thermoplastic nature, which allows them to blend effectively with bitumen at elevated temperatures (Xu et al., 2021). The incorporation of such materials not only improves mechanical properties but also contributes to waste management by reducing landfill disposal. Recent studies have emphasized the role of waste-based modifiers in improving interfacial bonding and enhancing the overall performance of asphalt mixtures. For instance, Xu et al. (2026) demonstrated that solid waste fillers, including industrial by-products, exhibited stronger adhesion with asphalt compared to traditional fillers, resulting in improved bonding strength and resistance to cohesive failure. Similarly, Li et al. (2026) explored the use of biochar derived from waste coffee grounds and found that it significantly enhanced high-temperature performance while maintaining compatibility with asphalt binders. These findings highlight the importance of understanding both macro-level performance and micro-level interactions in modified asphalt systems. Plastic waste, in particular, has been extensively studied due to its abundance and favorable properties. Ameur et al. (2025) reported that plastic-modified asphalt mixtures exhibited improved rutting resistance, fatigue life, and moisture resistance. However, challenges such as poor compatibility and reduced low-temperature flexibility remain areas of concern. To overcome these

limitations, researchers have explored various processing techniques, including wet and dry mixing methods, as well as chemical treatments to enhance the interaction between plastic and bitumen. Experimental investigations have also focused on optimizing the proportion of plastic content in bituminous mixes. Jexembayeva et al. (2024) identified that incorporating 5–8% PET resulted in optimal performance, improving water resistance and mechanical strength. Similarly, Krithiga et al. (2022) found that adding 5% e-waste plastic enhanced the stability and flow properties of bitumen by approximately 10%. These studies underscore the importance of determining optimal dosages to achieve a balance between performance enhancement and material compatibility. In addition to laboratory-based studies, advanced computational approaches have been employed to predict and optimize the performance of plastic-modified asphalt mixtures. Alqubaysi et al. (2025) utilized machine learning models to predict key parameters such as Marshall Stability and Flow, identifying optimal ranges for plastic size and content. Such approaches enable efficient mix design and reduce the need for extensive experimental trials, thereby accelerating the adoption of sustainable materials in pavement engineering. Another important aspect of sustainable pavement design is recyclability. Di Mino et al. (2023) demonstrated that asphalt mixtures modified with recycled plastics could undergo multiple recycling cycles without significant degradation in performance. This finding aligns with circular economy principles, promoting the reuse of materials and reducing environmental impact. Additionally, Vishnu and Singh (2023) highlighted that plastic and rubber-modified mixes significantly reduced rut depth, indicating improved resistance to permanent deformation under heavy traffic loads. Despite these advancements, several challenges remain in the widespread implementation of plastic-modified bituminous mixes. Issues such as variability in plastic waste composition, processing difficulties, long-term durability, and environmental concerns related to microplastics need to be addressed through further research. Moreover, the interaction mechanisms at the molecular level and their influence on macroscopic properties require deeper investigation to develop standardized guidelines for practical applications.

II. RESEARCH BACKGROUND

Xu et al. (2026) investigated the interfacial interaction behavior between asphalt and various solid waste fillers to support the development of low-carbon pavements. They selected five types of solid wastes—iron tailings (IT), waste cement, steel slag (SS), desulfurization gypsum, and blast furnace slag—as asphalt mixture fillers and examined their interactions through molecular dynamics (MD) simulations and experimental characterization. The study reported that solid waste fillers exhibited stronger adhesion and interactions with asphalt compared to conventional mineral fillers, particularly SS and IT, which resulted in asphalt mastic with higher resistance to cohesive failure, greater adhesion energy, and improved macroscopic bonding strength. The research highlighted that the mineralogical characteristics of these fillers explained these advantages at the molecular scale, as the rock-forming minerals in solid waste fillers demonstrated higher peak stress and fracture energy when interacting with asphalt molecules. Additionally, molecular models under tensile loading revealed a shift from adhesive to cohesive cracking with decreasing tensile rate, and the interfaces with solid waste fillers showed greater resistance to adhesive failure, offering valuable insights for sustainable, low-carbon pavement design.

Latief (2026) examined the increasing concerns over oil depletion and the rising demand for eco-friendly alternatives to crude oil asphalt (COA), which had prompted the exploration of natural bitumen (NB) in pavement applications, particularly in Iraq where lake bitumen (LB) and Gilsonite bitumen (GB) were abundant. The study investigated the enhancement of LB performance through partial modification with GB at 30%, 35%, and 40% replacement levels. Physical and chemical properties of the bitumen, including specific gravity, solubility, softening point, ductility, penetration, viscosity, and X-ray diffraction (XRD)

patterns, were analyzed, alongside indirect tensile strength and wheel tracking tests on the optimal NB-modified mixture compared with a COA control mix. The findings indicated that GB modification substantially reduced LB fluidity, increasing rotational viscosity by 1.7, 2.6, and 4.3 times for the respective blends, and enhanced stiffness, as evidenced by a 67.4% reduction in penetration at 35% GB. XRD results revealed a transformation from the amorphous structure of LB to a crystalline structure in modified blends, reflecting GB's dominant influence. The NB-modified mixture achieved higher tensile strength ratio (TSR) and lower rut depth, improving resistance to moisture damage and rutting by 13.9% and 53.9%, respectively, with the 35% GB blend identified as optimal.

Li et al. (2026) investigated the environmental impacts of landfilling waste coffee grounds and proposed the use of coffee grounds charcoal (CGC) as an innovative asphalt modifier to promote sustainable pavement technology. They employed a combined experimental and molecular dynamics simulation approach to assess the compatibility and performance of CGC-modified asphalt. The study reported that storage stability tests indicated significant compatibility of CGC with base asphalt, while physical performance tests showed a 33.6 % decrease in penetration value and a 22.8 % increase in softening point, suggesting enhanced high-temperature deformation resistance, although low-temperature flexibility was slightly reduced. Rheological property analysis further confirmed these findings. Molecular dynamics simulations revealed a solubility parameter difference of $1.96 \text{ (J/cm}^3)^{0.5}$, indicating favorable miscibility, and a high binding energy of -154 kcal/mol , implying strong intermolecular interactions with light asphalt components. Additionally, the diffusion coefficient decreased from 1.348×10^{-2} to 1.068×10^{-2} , corresponding to increased viscosity due to restricted light component motion. The study concluded that CGC provided dual benefits in waste valorization and asphalt performance enhancement, and the integrated macro-micro approach offered a basis for optimizing biochar-modified asphalt for sustainable road applications.

Ameur et al. (2025) investigated the growing problem of plastic waste resulting from rising industrialization and population growth, highlighting its environmental and health impacts. They noted that, despite plastic's potential as a resource, it was frequently discarded without proper treatment. The study examined the incorporation of various types of plastic waste into asphalt mixtures, analyzing both wet and dry processing methods and their effects on bituminous binders and overall asphalt performance. It was observed that using waste plastics in asphalt improved fatigue resistance, rutting resistance, moisture resistance, and high-temperature performance, although challenges related to compatibility and low-temperature behavior remained. The authors reported that modified approaches, including chemical additives, were effective in enhancing bonding between plastics and binders and in increasing the allowable plastic content. They concluded that, while plastic-modified asphalt showed considerable promise, addressing these challenges through targeted research and careful implementation was essential to ensure sustainable and long-term performance in asphalt mixtures.

Alqubaysi et al. (2025) investigated the integration of recycled plastics into asphalt mixtures to address environmental challenges associated with plastic waste and the need for sustainable pavement construction. They highlighted the difficulty of accurately predicting the performance characteristics of plastic-modified asphalt, particularly Marshall Stability (MS) and Marshall Flow (MF), due to complex nonlinear interactions among mixture constituents. The study applied machine learning models, including Support Vector Machine (SVM), Decision Tree (DT), Random Forest (RF), Extreme Gradient Boosting (XGB), and Light Gradient Boosting Machine (LGBM), further optimized with Particle Swarm Optimization (PSO), on a dataset of 210 plastic-modified asphalt samples. Inputs such as plastic content and size, bitumen content, maximum aggregate size, mixing temperature, and compaction effort were

used to predict MS and MF. Findings indicated that the PSO-optimized XGB model achieved the highest predictive accuracy ($R^2 = 0.82$ for MS and 0.83 for MF), while interpretability analyses using SHAP, PDP, ICE plots, and Taylor diagrams identified optimal plastic particle sizes (2.5–4 mm), bitumen content (5.3–5.5%), and plastic content (20–30%). The study concluded that these results provided guidance for durable pavements, sustainable plastic reuse, and cost-effective mix design strategies.

Jexembayeva et al. (2024) investigated the modification of bituminous mixtures by incorporating varying percentages of PET particles (1%, 3%, 5%, 8%, 10%, and 12%) and analyzed the resulting samples using methods such as the ring-and-ball softening point (ASTM D36/D36M-14), Fraass breaking point (EN 12593:2015), elongation (EN 13589:2014), and needle penetration depth (EN 1426:2015). The study identified optimal bitumen/PET ratios (5% and 8% PET) that produced modified bituminous mixtures (MBMs) with improved operational characteristics. The physical and mechanical properties of the bitumen samples and PET were determined, followed by a comparative analysis of the MBM samples based on these properties. Microstructural observations of the modified mixture surfaces were conducted, and X-ray structural analyses were performed to assess the internal composition across different PET contents. Additionally, the study examined the dependencies of moisture absorption over time and evaluated fatigue behavior by determining the stress intensity factor under three-point bending tests for MBM samples with varying modifier contents.

Vishnu and Singh (2023) investigated the physical properties of modified asphalt binders and the performance of asphalt mixes with the incorporation of various modifiers, including crumb rubber (CR) from different automobile waste tyres and low-density polyethylene (LDPE). They conducted wheel tracker tests up to 5000 wheel passes at 60°C to measure rut depth for both unmodified and modified asphalt mixtures. The study revealed that specimens modified with heavy automobile tyres exhibited 13.36%, 19%, and 38.11% lower rut depths compared to those modified with medium and light automobile tyres and unmodified specimens, respectively. LDPE-modified asphalt specimens showed 30% and 56.54% lower rut depths than heavy-tyre modified and unmodified mixtures. Among crumb rubber modifications, the heavy vehicle tyre-modified mixture at 9% dosage demonstrated superior performance, whereas the LDPE-modified mixture at 3% dosage outperformed all modifiers based on Marshall stability, tensile strength, and wheel tracker test results. The significance of these findings was further supported through ANOVA analysis.

Di Mino et al. (2023) investigated the multi-recyclability of asphalt mixtures containing 50% Reclaimed Asphalt Pavement (RAP) with and without a recycled plastic asphalt modifier and a rejuvenating agent, highlighting a research gap in recycling RAPs containing elastomeric or plastomeric modifiers. They followed circular economy principles and sustainability considerations, producing RAP artificially in the laboratory through an ageing protocol to maintain consistency and control variables. The study characterized binders using conventional, rheological, and chemical analyses and introduced the recycled plastic modifier, made from hard recycled plastics, via a dry method. The findings indicated that across three cycles of binder recycling, the extracted binders from both the plastic-modified and control mixtures, as well as the reference 50/70 bitumen, exhibited comparable properties. Furthermore, the rejuvenator optimization process required nearly similar quantities across the mixtures. The authors concluded that, from a binder-scale perspective, the mixture containing the recycled plastic additive could undergo multiple recycling cycles without deterioration of its mechanical or physical properties.

Krithiga et al. (2022, December) investigated the challenges of electronic waste (e-waste) management arising from the rapid increase in electronic products and their pervasive role in daily human activities through devices such as personal computers, mobile phones, and other gadgets. They highlighted that

improper disposal of e-waste posed significant environmental and health hazards. The study examined the potential use of e-waste plastic, specifically polyethylene—a widely produced thermoplastic polymer—as a filler in bitumen to improve its strength. The research employed the Marshall Stability test to assess the bitumen’s performance, analyzing stability and flow values across various bitumen percentages while maintaining a constant 5% e-waste plastic filler. Their findings indicated that incorporating 5% e-waste plastic optimized the stability and flow values, and enhanced the bitumen’s strength by approximately 10% compared to conventional bitumen.

Xu et al. (2021) examined the increasing use of waste products in asphalt binders and mixtures, emphasizing the growing attention toward recycled waste plastics due to their economic and environmental advantages. They analyzed and compared various forms of waste plastics for asphalt modification and discussed methods of incorporating them into single or composite asphalt mixtures, highlighting the influence of plastic properties, binder characteristics, and mixture behavior. The study indicated that integrating waste plastics could substantially enhance high-temperature performance while offering potential cost and ecological benefits. Xu et al. emphasized that the performance of modified asphalt depended on factors such as waste sources, dosages, blending conditions, and pretreatment methods. They reviewed different blending approaches and addressed challenges including stability, low-temperature performance, modification mechanisms, and laboratory testing issues. Chemical methods, such as additives and functionalization, were identified as effective for improving interactions between plastics and binders, yet the optimal material proportions and underlying micro-mechanisms of composite-modified asphalt remained unclear, warranting further investigation.

III. KEY FINDINGS FROM STUDY

Author & Year	Material Used	Methodology	Key Findings	Contribution
Xu et al. (2026)	Solid waste fillers	MD simulation + experiments	Improved adhesion, bonding strength	Low-carbon pavement design
Latief (2026)	Natural bitumen + Gilsonite	Lab testing (TSR, rutting)	53.9% rut reduction	Alternative binder development
Li et al. (2026)	Coffee ground biochar	Experimental + MD	Increased viscosity & stability	Waste valorization
Ameur et al. (2025)	Waste plastics	Review (wet & dry methods)	Improved rutting & fatigue resistance	Sustainable asphalt technology
Alqubaysi et al. (2025)	Plastic-modified asphalt	ML models (XGB, SVM)	High prediction accuracy ($R^2 \approx 0.83$)	Smart mix optimization
Jexembayeva et al. (2024)	PET plastic	Lab testing + XRD	Optimal at 5–8% PET	Strength & moisture resistance
Vishnu & Singh (2023)	LDPE, crumb rubber	Wheel tracking test	56.5% rut reduction	Performance improvement
Di Mino et al. (2023)	Recycled plastic + RAP	Recycling cycles	No performance loss	Circular economy support
Krithiga et al. (2022)	E-waste plastic	Marshall Stability	10% strength increase	Waste reuse
Xu et al. (2021)	Waste plastics	Review study	Improved high-temp performance	Fundamental insights

IV. CONCLUSION

The experimental investigation of bituminous mixes modified with waste plastic clearly demonstrates that plastic incorporation can significantly enhance the overall performance of pavement materials. Across various studies, it has been consistently observed that waste plastic improves key engineering properties of asphalt mixtures, particularly rutting resistance, load-bearing stability, durability, and moisture susceptibility. These improvements are mainly attributed to the thermoplastic nature of plastics, which allows better interaction with bitumen at elevated temperatures, resulting in a stiffer and more resistant binder structure. In addition to performance enhancement, the use of waste plastic in bituminous mixes offers a sustainable solution to the growing problem of plastic waste management. By diverting non-biodegradable plastic materials from landfills and open dumping sites, this approach contributes to environmental protection and promotes resource efficiency in the construction sector. Most research findings suggest that an optimal plastic content in the range of 3% to 8% provides the best balance between improved mechanical performance and mixture workability, beyond which adverse effects such as brittleness or reduced flexibility may occur. Recent advancements in analytical tools, including molecular dynamics simulations and machine learning-based predictive models, have further improved the understanding of the interaction mechanisms between bitumen and plastic modifiers. These technologies have enabled researchers to optimize mix design parameters more effectively and predict pavement performance with higher accuracy, reducing dependency on extensive laboratory experimentation. Furthermore, the recyclability potential of plastic-modified asphalt mixtures aligns well with circular economy principles, allowing repeated reuse of materials without significant degradation in performance. This makes the approach highly suitable for long-term sustainable infrastructure development. However, despite these advantages, certain challenges remain unresolved. Issues such as inconsistent compatibility between different types of waste plastics and bitumen, reduced low-temperature flexibility, and variability in plastic waste composition require further investigation. Therefore, the development of standardized processing methods, improved material characterization techniques, and long-term field performance studies is essential to fully realize the potential of waste plastic-modified bituminous mixes in pavement engineering.

V. FUTURE SCOPE

The study of bituminous mixes modified with waste plastic opens several promising avenues for future research and practical implementation in sustainable pavement engineering. Although significant progress has been made, further advancements are required to optimize performance, ensure durability, and enable large-scale adoption.

- **Hybrid Material Development:** Future research can focus on combining waste plastics with other sustainable modifiers such as crumb rubber, nano-silica, fly ash, or bio-based materials to develop hybrid asphalt mixes with superior performance characteristics.
- **Advanced Nanotechnology Integration:** The incorporation of nanomaterials along with waste plastics may enhance interfacial bonding, improve thermal stability, and significantly increase resistance to rutting and fatigue cracking.
- **Machine Learning and AI-Based Optimization:** Artificial intelligence and machine learning models can be further developed to predict long-term pavement performance, optimize plastic content, and reduce the need for extensive laboratory testing.
- **Long-Term Field Performance Studies:** More real-time field investigations are required to evaluate the durability, aging behavior, and performance of plastic-modified pavements under varying traffic and environmental conditions.

- **Environmental Impact Assessment:** Future studies should focus on assessing microplastic release, leaching behavior, and life-cycle environmental impacts to ensure ecological safety of modified asphalt systems.
- **Standardization of Mix Design Procedures:** Development of universal guidelines and standardized procedures for the preparation, mixing, and application of waste plastic in bituminous mixes is essential for widespread implementation.
- **Improved Compatibility Techniques:** Research can explore chemical additives, compatibilizers, and surface treatments to enhance the bonding between waste plastics and bitumen, reducing phase separation issues.
- **Low-Temperature Performance Enhancement:** Special focus should be given to improving flexibility and crack resistance at low temperatures, which remains a major limitation of plastic-modified mixes.
- **Circular Economy Integration:** Future pavement systems can be designed to support multi-cycle recycling, ensuring that plastic-modified asphalt can be reused multiple times without significant performance degradation.
- **Smart and Sustainable Infrastructure Development:** Integration of plastic-modified asphalt into smart city frameworks and green infrastructure projects can promote environmentally responsible and cost-effective transportation networks.

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