Journal Publication of International Research for Engineering and Management (JOIREM)
Volume: 04 Issue: 09 | Sep-2026
ISSN (O) 3107-6696

Sustainable flexible pavements: a comprehensive review of waste plastic, crumb rubber, and basalt fiber integration

Advancing Durability and Sustainability in Road Infrastructure

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Abstract - Rapidly increasing traffic loads and climatic variations have accelerated the deterioration of flexible pavements. At the same time, the exponential accumulation of solid waste, such as plastic packaging and end-of-life tires, presents a severe global environmental crisis. To address these dual challenges, this literature review evaluates the integration of waste plastic, crumb rubber, and basalt fiber as modifiers and reinforcing agents to simultaneously enhance road durability and mitigate waste disposal issues. By synthesizing recent experimental studies, life-cycle assessments, and field applications, the review examines various incorporation techniques, including the "dry process" for coating aggregates with plastic, the "wet process" for blending rubber and polymers into bitumen, and the three-dimensional dispersed reinforcement mechanism provided by basalt fibers. Investigations reveal that waste plastics (such as high-density polyethylene, low-density polyethylene, and polyethylene terephthalate) significantly increase Marshall stability, minimize aggregate water absorption, and substantially enhance resistance to high-temperature rutting. Similarly, crumb rubber-modified bitumen substantially improves the binder's viscosity, elastic recovery, and resistance to fatigue and thermal cracking. Furthermore, the introduction of basalt fiber provides structural reinforcement that amplifies flexural tensile strength, frost resistance, and overall durability against climatic fluctuations. At the same time, hybrid combinations of these materials demonstrate an optimized balance between mixture stiffness and elasticity. Ultimately, transitioning to emissions- and e-modified, and fiber-reinforced asphalt mixtures extends the service life and structural integrity of road networks, lowers life-cycle construction costs, significantly reduces carbon footprint emissions, and firmly anchors civil infrastructure development within the principles of a circular economy.

Index Terms—Flexible Pavement, Waste Plastic, Crumb Rubber, Basalt Fiber, Modified Bitumen, Marshall Stability, Sustainable Construction, Circular Economy, Rutting Resistance, Pavement Distress.

I. Introduction

The rapid expansion of global transportation networks and the exponential growth in vehicular traffic have placed unprecedented stress on road infrastructure. This surge in heavy axle loads, combined with drastic daily and seasonal climatic variations, frequently leads to premature pavement distresses such as rutting, fatigue cracking, and pothole formation. Conventional bituminous courses often struggle to withstand these extreme conditions, leading to reduced service life and costly, reactive maintenance cycles. Parallel to these infrastructural challenges is the escalating global crisis of solid waste management. Rapid urbanization and industrialization generate millions of tons of plastic waste and end-of-life automobile tires annually. Because plastics and synthetic rubbers are non-biodegradable—with some materials persisting in the environment for up to 4,500 years without degrading—improper disposal in landfills or through open burning causes severe ecological pollution, greenhouse gas emissions, and serious public health hazards.

To address the demands for stronger pavements and the urgent need for eco-friendly waste disposal, researchers and highway agencies are increasingly turning to sustainable, circular-economy solutions by integrating recycled materials and advanced fibers into hot mix asphalt. Specifically, utilizing discarded polymers, such as high-density polyethylene, low-density polyethylene, and polyethylene terephthalate, to modify bitumen or coat aggregates substantially improves the mixture's Marshall stability, reduces moisture absorption, and mitigates rutting. Similarly, crumb rubber sourced from shredded scrap tires interacts with bitumen to dramatically increase its viscosity, elasticity, and softening point, thereby enhancing the pavement's resistance to thermal variations and fatigue. Furthermore, the introduction of eco-friendly, inorganic basalt fiber provides dispersed, three-dimensional reinforcement within the asphalt matrix, significantly boosting flexural tensile strength, dynamic stability, and resistance to low-temperature cracking.

This literature review comprehensively evaluates the individual and combined effects of waste plastic, crumb rubber, and basalt fiber on the mechanical, rheological, and volumetric properties of flexible pavements. It also explores the economic and environmental implications of these modifications, demonstrating how the transition to waste-integrated paving materials yields greener, stronger, and more cost-effective road networks.

II. Characterization of Waste Materials and Fibers

The efficacy of modified bituminous mixtures depends fundamentally on the physical and thermal properties of the raw materials used. A comprehensive understanding of these modifiers is essential for predicting their interaction with bitumen and mineral aggregates.

A. Waste Plastics

Waste plastics used in flexible pavements are predominantly thermoplastics, which possess the ability to soften upon heating and regain their solid state at room temperature. The most utilized polymers include Low-Density Polyethylene (LDPE) sourced from thin carry bags, High-Density Polyethylene (HDPE) from thicker packaging, and Polyethylene Terephthalate (PET) from discarded beverage bottles. These plastics vary in their thermal properties; for instance, LDPE and HDPE melt at temperatures compatible with standard hot mix asphalt production, whereas PET has a significantly higher melting point. Due to their linear and non-polar molecular structures, polyolefins like polyethylene and polypropylene can face solubility and chemical compatibility challenges when mixed directly with bitumen, though LDPE generally exhibits better compatibility than HDPE.

B. Crumb Rubber

Crumb rubber is an elastomeric material produced by processing end-of-life automobile and truck tires. The material is primarily composed of natural rubber, synthetic rubber, and carbon black, which acts as an antioxidant to prevent binder aging. The production of crumb rubber involves size reduction through ambient grinding (such as a crack mill) or cryogenic fracturing, yielding fine particle sizes suitable for asphalt blending. Unlike thermoplastics, crumb rubber does not simply melt into the bitumen; instead, it undergoes a physical diffusion process where it absorbs aromatic oils from the binder and swells, resulting in a highly viscous, elastic matrix.

C. Basalt Fibers

Basalt fiber is an eco-friendly, inorganic material derived from melted basalt rock, offering superior mechanical properties for pavement reinforcement. For asphalt modification, these fibers are typically chopped into short strands with micro-scale diameters. Basalt fibers are characterized by exceptionally high tensile strength, elastic modulus, and thermal stability, allowing them to withstand the extreme temperatures of hot mix asphalt without degrading. Furthermore, they exhibit high resistance to corrosion, alkalis, and acids, ensuring long-term durability within the pavement structure.

III. Characterization of Waste Materials and Fibers

The integration of waste materials and advanced fibers into flexible pavements has evolved significantly, transitioning from elementary disposal methods to performance-engineered structural designs. A critical evaluation of recent literature demonstrates that incorporating waste plastics, crumb rubber, and basalt fibers substantially modifies the physical, rheological, and mechanical properties of bituminous mixtures.

A. Evaluation of Waste Plastics in Asphalt Mixtures

The utilization of post-consumer plastics, such as Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), and Polyethylene Terephthalate (PET), has been widely investigated using both dry and wet mixing processes. Pioneering work by Vasudevan et al. [27] established the dry process, wherein coating hot aggregates with shredded municipal plastics effectively seals surface pores, eliminates aggregate moisture absorption, and prevents moisture-induced stripping. Expanding on optimal dosage thresholds, Rajput and Yadav [21] observed that incorporating 12% plastic waste by weight of bitumen yields a peak Marshall stability of 13.0 kN, noting a subsequent decrease in stability at higher concentrations. Similarly, Hridoy et al. [12] determined that introducing 3% waste LDPE optimizes the bitumen content—reducing the required optimum binder content from 5.67% to 5.22%—while elevating Marshall stability to 19.58 kN and controlling air voids within the optimal 3% to 5% range. Conversely, evaluating the wet process, Appiah et al. [4] blended HDPE and Polypropylene (PP) into AC-20 bitumen, concluding that PP demonstrates superior binder compatibility and a more stable linear increase in softening point and viscosity compared to HDPE.

B. Advancements in Crumb Rubber Modification

Crumb rubber derived from end-of-life automobiles and truck tires serves as a prominent elastomeric modifier used to enhance the elasticity and crack resistance of asphalt binders. Deshmukh and Kshirsagar [11] demonstrated that modifying bitumen via the wet process with up to 14% crumb rubber significantly reduces penetration values (dropping from 69 mm to 14.33 mm) and increases the softening point to 55°C, creating a stiffer binder highly resilient to high-temperature

rutting. Reinforcing these findings, Costa et al. [7] conducted a comparative assessment revealing that elastomeric modifiers like crumb rubber and Styrene-Butadiene-Styrene (SBS) provide exceptional elastic recovery and resilience, outperforming pure plastomers in low-temperature crack mitigation.

C. Integration of Basalt Fibers and Hybrid Matrix Systems

To address the limitations of individual modifiers, recent research has explored inorganic fibers and multi-material hybrid systems. Krayushkina and Prentkovskis [15] evaluated the incorporation of chopped basalt fibers as a mineral filler replacement, proving that a three-dimensional dispersed fiber network increases the compressive strength of asphalt concrete from 1.4 MPa to 3.2 MPa and substantially enhances frost and water resistance. Furthermore, Bansal et al. [5] formulated advanced hybrid matrices by combining waste plastic and crumb rubber into a tertiary bituminous concrete mix consisting of 84% bitumen, 6% plastic, and 10% rubber. Their evaluation indicated a remarkable 53% increase in Marshall stability over unmodified control mixes, achieving an optimal balance between mixture rigidity and flexibility.

IV. METHODOLOGIES OF INCORPORATION

The physicochemical interactions between waste modifiers, bituminous binders, and mineral aggregates are fundamentally dictated by the incorporation method. In modern pavement engineering, these integration strategies are primarily classified into the dry process, the wet process, and emerging hybrid approaches.

A. The Dry Process (Aggregate Modification)

The dry process involves mixing shredded modifiers, typically waste plastics (such as high-density polyethylene and low-density polyethylene), directly with heated mineral aggregates before the introduction of the bituminous binder. Aggregates are pre-heated to temperatures typically between 160°C and 175°C. When shredded plastic is sprayed over the hot aggregates, it melts within 30 to 45 seconds, forming a thin, highly impermeable, oily coating over the aggregate surface. This coating dramatically reduces aggregate porosity, effectively eliminating water absorption and preventing moisture-induced stripping by creating a superior adhesive bond with the subsequent bitumen layer. The dry process is highly advantageous for incorporating diverse municipal plastics without risking the polymer phase separation often seen when plastics are melted directly into bitumen.

B. The Wet Process (Binder Modification)

The wet process requires modifiers to blend directly into the hot bitumen before mixing with aggregates. This method is primarily utilized for elastomeric modifiers like crumb rubber, which are blended into the binder at elevated temperatures ranging from 160°C to 200°C using high-shear mechanical stirrers. Crumb rubber does not completely melt; rather, it undergoes a physical diffusion process where it absorbs aromatic oils from the bitumen, causing the rubber particles to swell and significantly increasing the binder's viscosity and elasticity. While the wet process can also be used for plastomers like polypropylene (PP) and high-density polyethylene (HDPE), it requires precise temperature control and continuous agitation to prevent phase separation and poor storage stability at high temperatures.

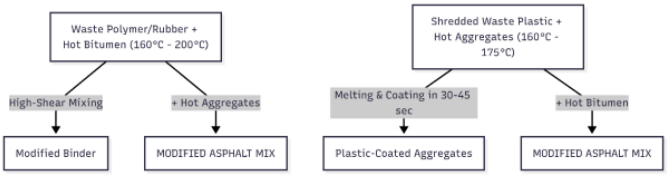


Figure 1. Schematic representation illustrating the contrasting mechanisms of the Wet Process and Dry Process for incorporating waste polymers into asphalt mixtures.

C. Chemical and Microstructural Interactions

Understanding the chemical bonding and microstructural compatibility between waste modifiers and bitumen is crucial for long-term pavement performance. Fourier Transform Infra-Red (FTIR) spectroscopy provides critical insights into these blending mechanisms. In their evaluation of HDPE and PP-modified bitumen, Appiah et al. [4] utilized FTIR spectroscopy and observed no formation of new distinct functional groups, indicating that the modification is primarily a physical blending process rather than a chemical reaction. However, they noted a profound increase in the intensity of prominent peaks in the 3000 to 2850 cm-1 range, which corresponds to aliphatic C-H symmetrical and asymmetrical stretches, confirming the successful integration of polymer strands into the bitumen matrix. Despite successful blending, microstructural compatibility remains a challenge during the wet process. Costa et al. [7] demonstrated that while elastomers like SBS and plastomers like polyethylene significantly improve softening points, they often suffer from poor high-temperature storage stability. Phase separation frequently occurs with these polymers due to density differentials, whereas modifiers like Acrylonitrile-Butadiene-Styrene (ABS) and crumb rubber exhibit much higher storage stability, making them more reliable for extended storage before paving.

V. RHEOLOGICAL AND MECHANICAL PERFORMANCE

The primary objective of integrating waste polymers, rubber, and basalt fibers is to address severe pavement distresses such as high-temperature rutting, thermal cracking, and moisture-induced damage. By fundamentally altering the binder's rheological properties to increase stiffness and elasticity, these recycled materials provide enhanced shear resistance against heavy vehicular axle loads. Furthermore, the addition of dispersed basalt fibers creates a three-dimensional reinforcement network within the matrix that bridges micro-cracks, ultimately extending the structural integrity and overall service life of the road.

A. Impact on Binder Rheology

The rheological properties of the binder—penetration, softening point, and viscosity—determine the pavement's response to environmental and traffic-induced stresses. The incorporation of crumb rubber and waste plastics consistently decreases the penetration value of the base bitumen, indicating a stiffer binder with enhanced shear resistance against heavy axle loads. Concurrently, modifying bitumen with these waste materials substantially elevates the softening point, making the mixture highly resilient to bleeding and rutting in high-temperature climates.

Table 1 Effect of Crumb Rubber Concentration on Binder Rheology (Wet Process)

Crumb Rubber Content (%)	Penetration Value (mm)	Softening Point (°C)	Ductility (cm)
0% (Control)	69.00	42.75	73.0
8%	49.33	50.30	40.0
10%	38.67	51.65	35.0
12%	19.67	54.50	28.5
14%	14.33	55.00	24.6

As demonstrated in Table 1, increasing crumb rubber content up to 14% yields a significantly harder binder, reducing penetration from 69.00 mm to 14.33 mm and increasing the softening point from 42.75°C to 55.00°C. However, this increased stiffness is accompanied by a reduction in ductility (from 73.0 cm to 24.6 cm), meaning the binder becomes highly viscous and requires careful temperature management during compaction.

B. Marshall Stability and Load-Bearing Capacity

The Marshall mix design method is the global standard for evaluating the load-bearing capacity and deformation resistance (flow) of flexible pavements. Coating aggregates with shredded waste plastic via the dry process yields dramatic improvements in Marshall stability. For instance, Rajput and Yadav [21] identified that incorporating 12% plastic waste by weight of bitumen produces a peak Marshall stability of 13.0 kN, a vast improvement over the 9.6 kN baseline of unmodified mixes. Furthermore, hybrid matrices combining multiple waste streams have demonstrated extraordinary structural gains. Bansal et al. [5] formulated a tertiary mix utilizing 6% waste plastic and 10% crumb rubber, achieving a maximum stability of 13.89 kN, representing a 53% increase over the conventional control mix of 9.06 kN.

Table 2 Comparative Marshall Stability Improvements Using Various Waste Modifiers

Study (Source)	Modifier & Process	Control Stability (kN)	Modified Stability (kN)	Performance Increase
Hridoy et al. [12]	3% Waste Plastic (LDPE)	18.25	19.58	+ 7.2%
Rajput & Yadav [21]	12% Plastic Waste (Dry)	9.60	13.00	+ 35.4%
Bansal et al. [5]	Tertiary (6% Plastic + 10% Rubber)	9.06	13.89	+ 53.3%
Mishra & Mishra [19]	9.73% Plastic Coated Aggregate	15.34	18.50	+ 20.6%

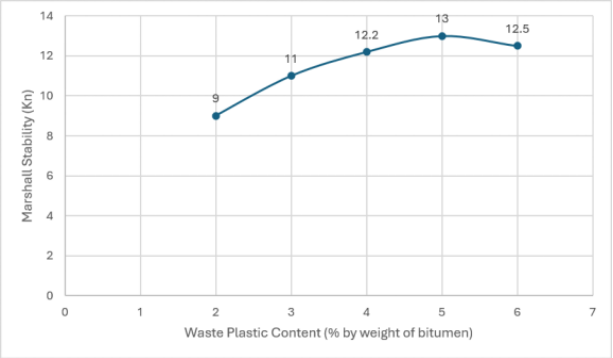


Figure. 2. Variation of Marshall Stability with increasing plastic waste content, demonstrating peak load-bearing capacity at the 12% optimum threshold.

C. Moisture Susceptibility and Volumetric Properties

Moisture-induced stripping is a critical failure mechanism, particularly in regions subjected to heavy monsoons. The dry process completely mitigates this by forming an impermeable plastic layer around the aggregate, reducing water absorption to 0% and ensuring excellent adhesion. Additionally, incorporating waste concrete dust, brick dust, or basalt fibers as mineral fillers significantly reduces the voids in mineral aggregate, promoting a denser, more moisture-resistant pavement structure while keeping air voids within the optimal 3% to 5% range.

D. Volumetric Property Optimization

The durability of flexible pavements is heavily reliant on achieving optimal volumetric properties, specifically air voids, voids in mineral aggregate, and voids filled with bitumen. Hridoy et al. determined that introducing 3% waste plastic into the bituminous mix effectively reduces air voids to 4.8%, safely within the Asphalt Institute's strict 3% to 5% tolerance. This reduction minimizes pavement permeability and subsequent moisture damage. Furthermore, their study recorded a voids in mineral aggregate value of 13.2% and an increased voids filled with bitumen value of 62% for the modified mix, ensuring that the aggregates are adequately coated with binder to resist cracking and deformation.

The type of waste material used as a mineral filler also drastically alters these volumetrics. Sutradhar et al. compared the use of waste concrete dust and brick dust as fillers, discovering that while waste concrete dust maintains a voids in mineral aggregate value of 16.40%, the coarser nature of brick dust increases the value to 20.30%, requiring mix design adjustments to prevent over-lubrication of the aggregate matrix. When evaluating bulk density, Bansal et al. noted that replacing virgin bitumen with combinations of waste plastic and rubber generally increases the bulk density of the mix (reaching 2.362 g/cc for an 8% plastic replacement), contributing to a more tightly packed, load-resistant structural layer.

6. Field Performance and Real-World Case Studies

Laboratory results must ultimately translate into field reliability. Real-world case studies of waste-integrated pavements confirm their enhanced service life and resistance to environmental degradation.

A. Trial Road Sections and Durability

Extensive field testing of the "Plastic Coated Aggregate" (PCA) technology, as documented by Vasudevan et al., revealed that roads constructed using this dry-process method exhibit zero pothole formation and negligible rutting after years of exposure to heavy traffic and monsoon rains. According to Trimbakwala (2017), standard highway-quality roads typically require extensive maintenance after four to five years, whereas plastic-bitumen roads demonstrate an extended lifespan of up to 10 years. The impermeable nature of the plastic-coated aggregates prevents rainwater seepage, fundamentally solving the primary cause of pothole proliferation in humid, high-rainfall climates.

B. Localized Rehabilitation and Pothole Repair

Beyond full-scale paving, waste materials offer highly effective solutions for localized distress rehabilitation. Alyamani (2026) evaluated the field performance of a Thermo-Geo-Plastic (TGP) composite—created by melting waste PET and mixing it with gravel—specifically for pothole repairs. Monitored over a year under heavy industrial traffic loads, the TGP-repaired sections displayed no signs of surface deformation, cracking, or delamination. This success is attributed to the molten PET tightly encasing the gravel, forming a monolithic, highly impermeable mass that effectively distributes traffic stresses and entirely blocks subsurface moisture intrusion.

7. Research Gaps and Future Directions

Despite the extensive proven benefits of incorporating waste plastics, crumb rubber, and basalt fibers into flexible pavements, a critical review of the recent literature reveals several knowledge gaps and operational challenges that must be addressed before global standardization can be achieved.

A. Lack of Long-Term Field Validation

Most of the current research relies heavily on short-term laboratory performance analyses, such as standard Marshall stability or Superpave gyratory compaction. Saudy et al. emphasize that there is a critical gap in long-term performance testing—specifically regarding oxidative aging, long-term fatigue, creep, and low-temperature cracking under real-world climatic fluctuations. Similarly, Alyamani (2026) notes that field conditions introduce unpredictable variables such as uneven compaction and unregulated traffic movement,

necessitating long-term studies that incorporate thermal aging, cyclic loading, and freeze-thaw cycles to validate laboratory predictions.

B. Storage Stability and Phase Separation

A persistent technical challenge in the wet process is the physicochemical incompatibility between certain polymers and the bituminous binder at high temperatures. Costa et al. reported that plastomers like High-Density Polyethylene (HDPE) and elastomers like Styrene-Butadiene-Styrene (SBS) frequently suffer from severe phase separation and poor storage stability when kept in holding tanks, due to density differentials between the polymer and the asphalt matrix. Ahmed et al. (2026) recommend that future research must focus on experimental field sections specifically designed to measure and mitigate segregation between the asphalt binder and additives during the transportation and laying phases. The development of chemical compatibilizers or anti-separation agents remains a vital area for future exploration.

C. Standardization of Hybrid Mix Designs

While hybrid modifications (e.g., combining crumb rubber and waste plastics) show immense structural promise, there is a distinct lack of standardized processing and testing procedures for these complex mixtures. Saudy et al. (2025) point out that the interactions of multiple waste components with virgin bitumen and aggregates are highly complex, and without unified guidelines, predicting field performance across different material sources and climates remains difficult. Furthermore, while base and sub-base layers show profound improvements, some modified wearing surfaces have exhibited lower Tensile Strength Ratios (TSR), indicating increased moisture susceptibility. Future research must evaluate the integration of specific anti-stripping agents, such as hydrated lime or silane-based additives, to secure the moisture resistance of waste-modified wearing courses.

8. Conclusion

The accelerating deterioration of flexible pavements, compounded by the escalating global crisis of solid waste accumulation, demands paradigm-shifting engineering solutions. This comprehensive review synthesized recent experimental data, field studies, and life-cycle assessments to evaluate the efficacy of integrating waste plastics, crumb rubber, and basalt fibers into bituminous mixtures. Based on the synthesized literature, it is evident that the modification of bitumen and aggregates with waste plastics (such as HDPE and LDPE) and elastomeric crumb rubber significantly elevates the binder's softening point and viscosity while decreasing penetration. These rheological enhancements translate to substantial increases in Marshall stability—frequently exceeding 30% to 50% improvements over conventional mixes—thereby providing exceptional resistance to high-temperature rutting and permanent deformation. Furthermore, employing the dry process to coat aggregates with waste plastic creates a highly impermeable barrier that reduces water absorption and stripping to near zero. Concurrently, the inclusion of crumb rubber and three-dimensional dispersed basalt fibers bridges micro-cracks, significantly enhancing fatigue life and low-temperature thermal cracking resistance.

The most profound structural improvements are realized in hybrid, tertiary mixes that combine multiple waste streams. Matrices integrating both waste plastic and crumb rubber, for instance, achieve an optimal balance between rigidity and flexibility, ensuring robust field performance. Beyond mechanical advantages, substituting expensive virgin bitumen with municipal and industrial waste materials lowers life-cycle construction costs by up to 14% to 16%. Crucially, this practice diverts non-biodegradable waste from landfills and incineration, reducing the life-cycle carbon footprint (LCCF) of road construction by over 80% and firmly embedding pavement engineering within a circular economy framework. While challenges such as high-temperature storage stability and the need for standardized hybrid mix designs remain, the large-scale adoption of waste-modified and fiber-reinforced asphalt mixtures represents a highly viable, eco-friendly evolution in infrastructure development.

Acknowledgements

The authors take this opportunity to express their sincere gratitude to the pavement engineering and materials science communities. The foundational research, extensive experimental data, and long-term field studies provided by various researchers have been instrumental in the completion of this review. It is a pleasure to acknowledge the ongoing global efforts in sustainable infrastructure and the dedicated individuals whose prior investigations made this comprehensive evaluation possible.

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