

Eco-Friendly Road Construction Through Waste Plastic Modified Bituminous Pavements

Brijesh Kaushik

M. Tech. in Transportation Engineering, CBS Group of Institutions, Jhajjar, Haryana.

Minakshi

A.P Civil Department, CBS Group of Institutions, Jhajjar, Haryana.

ABSTRACT

This study investigates the performance of bituminous mixes modified with waste plastic for improving pavement strength and durability. Waste plastic was cleaned, shredded, and added to hot aggregates in different proportions before mixing with bitumen. Marshall mix design was used to evaluate stability, flow value, density, and air voids. The results showed that the addition of waste plastic improved aggregate-bitumen bonding and increased load-bearing capacity. The optimum performance was observed at 8% plastic content by weight of bitumen. Thus, waste plastic-modified bituminous mix provides an eco-friendly and sustainable solution for durable pavement construction.

Keywords: *Waste Plastic, Bituminous Mix, Marshall Stability, Sustainable Pavement.*

I. INTRODUCTION

Bituminous pavements are one of the most commonly used pavement systems in highway and road construction because they provide smooth riding quality, flexibility, quick construction, and comparatively economical maintenance. In many developing countries, including India, the demand for durable road infrastructure has increased rapidly due to rising population, industrial growth, urbanization, and continuous growth in vehicle ownership. However, conventional bituminous pavements are increasingly exposed to heavy axle loads, high traffic intensity, extreme temperature variation, rainfall, and poor drainage conditions. These factors cause several types of pavement failures such as rutting, cracking, pothole formation, stripping, bleeding, ravelling, and deformation of the surface layer. As a result, the service life of flexible pavements is reduced, and frequent maintenance becomes necessary. The performance of a bituminous mix mainly depends on the quality of aggregates, bitumen grade, gradation, binder content, compaction, temperature, and the bonding between bitumen and aggregates. Traditional bituminous mixes sometimes fail to provide adequate resistance against heavy traffic and environmental stress because ordinary bitumen may soften at high temperatures and become brittle at low temperatures. Therefore, modification of bituminous mixes has become an important area of research in pavement engineering. Various modifiers such as polymers, crumb rubber, fibres, fly ash, natural additives, and industrial waste materials have been studied to improve the strength, stability, durability, and resistance of bituminous pavements. Among these materials, waste plastic has gained special attention because it offers both engineering and environmental benefits. Waste plastic can improve the binding properties of bitumen and enhance the load-bearing capacity of the pavement, while also providing a useful solution for the disposal of plastic waste.

Plastic waste has become one of the most serious environmental problems in the modern world. Due to the widespread use of plastic in packaging, household products, carry bags, bottles, food wrappers, containers, and industrial applications, a huge quantity of plastic waste is generated every day. Most plastics are non-biodegradable and remain in the environment for many years, causing land pollution, drainage blockage, soil contamination, water pollution, and harm to animals and aquatic life. Improper

disposal of plastic waste creates serious ecological and health-related problems. Burning of plastic releases harmful gases and toxic compounds, while dumping plastic in open areas reduces the quality of land and affects natural ecosystems. Therefore, the reuse and recycling of waste plastic have become essential for sustainable development. Road construction provides a practical and large-scale opportunity for utilizing waste plastic in a productive way. In bituminous mixes, waste plastic can be used as a modifier either through the dry process or the wet process. In the dry process, shredded waste plastic is mixed with heated aggregates, allowing the plastic to soften and coat the aggregate surface before bitumen is added. This plastic coating improves the adhesion between aggregate and bitumen, reduces moisture absorption, and enhances the strength of the mix. In the wet process, plastic is blended directly with hot bitumen to produce modified binder. However, the dry process is generally considered simpler, more economical, and more suitable for field application. When used in controlled proportions, waste plastic improves Marshall stability, reduces air voids, increases resistance to water damage, improves fatigue performance, and enhances the overall durability of pavement. It also helps in reducing the quantity of bitumen required to some extent, which may contribute to cost saving and conservation of petroleum-based materials.

The present experimental investigation, titled “Experimental Investigation of Bituminous Mixes Modified with Waste Plastic for Improved Pavement Performance,” focuses on evaluating the effect of waste plastic on the engineering properties of bituminous mixes. The main purpose of the study is to determine whether the addition of waste plastic can improve pavement performance compared with conventional bituminous mixes. For this purpose, different percentages of shredded waste plastic are added to the bituminous mix, and the prepared specimens are tested using the Marshall mix design method. Important parameters such as Marshall stability, flow value, bulk density, air voids, voids in mineral aggregate, voids filled with bitumen, and optimum plastic content are studied. These parameters help in understanding the strength, flexibility, durability, and suitability of the modified mix for pavement construction. The study is significant because it combines two important needs: improving road performance and reducing plastic waste pollution. If waste plastic-modified bituminous mixes show better results than conventional mixes, they can be recommended for sustainable pavement construction, especially in areas with heavy traffic and frequent pavement deterioration. The use of waste plastic in bituminous roads can support the concept of green infrastructure by converting harmful waste into a useful construction material. It may also reduce maintenance costs, extend pavement life, improve resistance against deformation, and minimize the environmental burden caused by plastic disposal. Thus, this research is important not only from the technical point of view but also from the perspective of environmental protection and sustainable development. The experimental study aims to provide practical results that can help engineers, researchers, contractors, and policymakers promote eco-friendly road construction practices using waste plastic as a beneficial modifier in bituminous pavement systems.

II. RESEARCH BACKGROUND

La Macchia et al. (2026) investigated the use of sustainable materials in road construction, emphasizing the growing interest in incorporating recycled components into bituminous mixtures due to environmental concerns and resource scarcity. They examined bituminous mixtures containing a recycled plastic compound (RPC) derived from waste plastics combined with 50 % reclaimed asphalt pavement (RAP) through a detailed laboratory testing program, assessing stiffness properties, cracking resistance, and anti-rutting potential. The study also considered the influence of binder type by combining RPC with either a softer binder or a harder binder with a bio-based rejuvenator, and compared these with a control mixture using neat bitumen and another mixture containing an SBS highly-modified binder. Statistical analyses

were performed to evaluate differences in mechanical behavior among the mixtures. The results suggested that the combined use of RPC and high RAP content could provide a viable approach for sustainable asphalt production, with performance levels comparable to or exceeding those of SBS-modified mixtures when used with an appropriate binder and rejuvenator.

Li et al. (2026) investigated the influence mechanisms of carbon nanotubes (CNTs) on asphalt binder and mixture performance through multiscale experimental characterization. They employed dynamic shear rheometry (DSR), multistress creep recovery (MSCR), single-edge notched beam (SENB) fracture testing, and atomic force microscopy (AFM) to quantitatively correlate CNT concentrations with improvements in rheological properties and creep resistance. The study determined the recommended CNT dosage based on homogeneous dispersion, performance enhancement, and cost-effectiveness analysis. Subsequent evaluations addressed high- and low-temperature stability, viscoelastic behavior, and fatigue resistance of CNT-modified asphalt mixtures at the identified dosage. Microstructural analyses revealed that CNT-induced wax crystallization and chemical interactions reorganized the colloidal structure of the asphalt. A 1.0% CNT dosage was identified as optimal, achieving uniform dispersion, performance gains, and cost-effectiveness. Validation tests indicated a 27% reduction in rutting depth, a 9.9% to 45.1% increase in dynamic modulus, and a 28% increase in flexural strength, confirming cross-scale synergies from nanomodification to macroscopic performance. The research established a theoretical-experimental framework for designing nanoengineered asphalt materials for durable pavements under extreme environmental and mechanical stresses.

Zeida et al. (2026) investigated the incorporation of recycled plastics into asphalt mixtures as a strategy to enhance pavement performance and mitigate environmental impacts from plastic waste. They examined the use of recycled High-Density Polyethylene (HDPE) and Polyethylene Terephthalate (PET) in asphalt concrete (AC) mixtures designed according to the Superpave volumetric method. A Novel Hybrid Dry Mixing (HDM) technique was applied to improve plastic dispersion and avoid clumping, and a comprehensive experimental program was conducted to assess thermal, chemical, rheological, volumetric, compactability, and dynamic modulus ($|E^*|$) properties for stiffness and viscoelastic performance. Thermal and degradation behaviors of HDPE and PET were characterized via Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA), while chemical properties were evaluated using Fourier Transform Infrared Spectroscopy (FTIR). Rheological properties of extracted binders were analyzed through a Dynamic Shear Rheometer (DSR), and Superpave volumetric properties and compactability were assessed using gyratory compaction parameters, including the Compaction Energy Index (CEI) and densification slope (K_{id}). The study revealed that HDPE softened at mixing temperatures, partially interacted with the base binder, and enhanced mixture stiffness and compaction resistance, whereas PET remained solid, acted as a rigid particulate, influenced void distribution, and promoted a more compliant viscoelastic response. The $|E^*|$ results indicated that HDPE improved high-temperature stiffness and rutting resistance, while PET reduced stiffness and increased compliance, demonstrating dosage-dependent trade-offs between rutting resistance and cracking susceptibility. The HDM technique was found to produce uniform mixtures compatible with standard plant operations, underscoring its practical relevance for integrating recycled plastics into asphalt pavement construction.

Hridoy et al. (2025) examined the environmental challenges posed by plastic due to its nonbiodegradable nature and long-lasting effects on ecosystems, noting that its accumulation in landfills and natural habitats threatens both terrestrial and marine wildlife. They highlighted that the rising global population exacerbates plastic waste generation, necessitating effective management strategies. The study investigated the use of waste plastic as a binder with bitumen in road construction, testing blends with

3 %, 5 %, and 7 % plastic content to evaluate their effects on the Marshall characteristics of asphalt mixes, including stability, flow, and void properties. The research reported that incorporating 3 % plastic yielded optimized performance, with experimental findings indicating optimal bitumen percentages of 5.67 % for conventional asphalt concrete and 5.22 %, 5.33 %, and 5.23 % for plastic-modified mixes. Marshall stability for the conventional mix was 18.25 kN, while the 3 % plastic-modified mix reached 19.58 kN, demonstrating improved binding, stability, and density. The study suggested that plastic-modified asphalt could support sustainable pavement design, reduce reliance on virgin materials, and enable cost-effective road construction, thereby addressing plastic waste concerns while enhancing infrastructure sustainability.

Singh et al. (2025) examined the incorporation of plastic waste into VG-40 grade bitumen as a potential solution to environmental challenges posed by plastic disposal, aiming to enhance asphalt mixture properties while reducing plastic accumulation. They reported that plastic waste was initially ground into powder and subsequently blended with bitumen in proportions ranging from 6 to 10% using a shear mixer at 160–170 °C in accordance with codal provisions. The study analyzed the physiochemical characteristics of the modified bitumen through penetration, ring and ball, softening point, and viscosity tests, and observed that the Marshall stability of the mixtures increased with higher plastic content, peaking at 8% for both low- and high-density plastics, with high-density plastic exhibiting superior stability. It was also noted that flow values inversely correlated with plastic content, highlighting the complex interaction between plastic composition and bitumen properties, and providing insights into sustainable road construction practices.

Vargas and El Hanandeh (2024) investigated the potential of incorporating plastic waste in road construction to promote recycling and reduce environmental impact. They examined the effects of polyethylene (PE) pyrolytic wax-modified bitumen on asphalt properties by formulating samples with virgin bitumen, 7% PE wax-modified bitumen, 5% polypropylene (PP), and a combination of both. The study reported that optimal bitumen contents were determined as 6.05% for virgin bitumen, 6.6% for 5% PP, 6.0% for 7% wax, and 6.15% for the blend. Despite the lower indirect tensile strength (ITS) of the 7% wax sample (1.76 MPa) compared to the 5% PP sample (2.11 MPa), it did not significantly differ from virgin bitumen. Similar trends were observed for ITS at cold (3.46 MPa for 7% wax vs. 3.399 MPa for 5% PP) and high temperatures (0.697 MPa for 7% wax vs. 0.861 MPa for 5% PP). The PE wax-modified bitumen samples were found to satisfy dense-graded specifications, demonstrating consistent resistance to common deterioration mechanisms. The study concluded that PE wax-modified bitumen offered a sustainable approach to plastic waste management, reducing bitumen and energy demand, lowering mixing and compaction temperatures by 14 °C, allowing a 7.83% reduction in virgin bitumen content, and supporting higher recycling rates compared to asphalt modified with untreated plastic waste.

Akkouri et al. (2023) conducted a study that aimed to develop prediction and optimization models for polymer-modified bitumen (PMB) using various types of recycled plastic wastes from the Moroccan industry, including recycled low-density polyethylene (R-LDPE) and recycled polypropylene (R-PP) combined with styrene–butadiene–styrene (SBS) and styrene–ethylene–butylene–styrene (SEBS) as commercial raw materials. The study employed an experimental design method to validate the models, adopting control parameters such as softening point, penetration, and elastic recovery in line with Moroccan bitumen manufacturing practices. The effects of the added components on the mixture responses were described using Scheffé polynomial models, with a quadratic model applied for softening point and penetration and a special cubic model for elastic recovery. Model validation using ANOVA analysis showed average absolute relative deviations of 1.1%, 4.7%, and 3.3% for softening point, penetration, and elastic recovery, respectively. Based on the developed models, an optimized PMB

formulation was defined to meet Moroccan standards, demonstrating the potential of these models as alternative optimization tools for hybrid polymer-modified bitumen development. The authors indicated that subsequent studies would investigate the rheological properties, rutting and fatigue behavior, and storage stability of the hybrid PMB, and confirmed that the numerical optimization models were validated through industrial-scale tests.

Li et al. (2023) investigated the use of waste plastics as asphalt modifiers to address the global environmental problem of plastic disposal. They examined three types of waste plastic-modified asphalts (WPMA) using polypropylene (PP), polyethylene (PE), and ethylene-vinyl acetate copolymer (EVA) as modifiers and evaluated their effects on conventional asphalt performance. An orthogonal experimental design (OED) was applied to determine the optimal preparation parameters for WPMA, followed by thermogravimetric-differential scanning calorimetry (TG-DSC) and Fourier transform infrared spectroscopy (FTIR) analyses to elucidate the modification mechanisms. The study reported that the optimal preparation conditions for PP-modified asphalt (PPMA) and PE-modified asphalt (PEMA) were 170 °C, 3000 rpm, and 30 min, while EVA-modified asphalt (EVAMA) required 180 °C, 3000 rpm, and 30 min. The results indicated that WPMA exhibited enhanced high-temperature performance, making it particularly suitable for pavements in hot climates. The research concluded that WPMA could provide an effective solution for waste plastic disposal while advancing its application in asphalt pavement technology.

Mashaan et al. (2022) investigated the potential of using waste plastic as a sustainable and cost-effective polymer for modifying bitumen binders. They explored different types of waste plastics, including polyethylene terephthalate (PET), high-density polyethylene (HDPE), and low-density polyethylene (LDPE), to assess their impact on the physical and rheological properties of bitumen and its resistance to ageing. Both short- and long-term ageing effects were examined using rolling thin film oven tests (RTFOT) and pressure ageing vessels (PAVs). Penetration tests and dynamic shear rheometer (DSR) analyses were conducted to evaluate stiffness, elasticity, complex shear modulus, and viscous behavior. The study found that 2–4% of HDPE and LDPE provided optimal performance according to penetration tests, while higher contents (6–8%) did not significantly improve stiffness, elasticity, or ageing resistance, making them more prone to permanent deformation. In contrast, PET-modified bitumen showed notable improvements in all assessed properties, with 6–8% PET identified as the ideal content for enhanced durability and performance.

Mashaan et al. (2021) investigated the potential of reusing waste polymers in asphalt and highlighted the substantial benefits of incorporating waste plastics as sustainable additives to improve asphalt properties, enhance environmental stability, and generate industrial-economic advantages. They noted that trial sections of roads constructed with waste plastic-modified asphalt in Australia during 2019 emphasized the importance of comprehensive laboratory assessments. The study aimed to examine the effects of locally sourced waste Polyethylene Terephthalate (PET) plastic in binder class C320, a common bitumen type for local road surfacing. Evaluations of various PET contents were conducted under unaged and aged conditions using Dynamic Shear Rheometer (DSR), Rolling Thin Film Oven (RTFOT), and Pressure Aging Vessel (PAV) tests to assess rutting, fatigue, and aging behavior. The findings indicated that 6–8% PET content optimized rutting and aging resistance, while 8% PET enhanced fatigue cracking resistance by exhibiting a low fatigue factor ($G^* \sin \delta$). The study concluded that incorporating locally available PET in pavements could reduce costs and improve environmental sustainability, and recommended further rutting and fatigue testing on asphalt mixtures to confirm mechanical performance and maximize the potential benefits of PET utilization in Australia.

III. METHODOLOGY

The present study was conducted to evaluate the performance of bituminous mixes modified with waste plastic. First, the required materials such as aggregates, bitumen, filler, and waste plastic were collected. The aggregates were tested for physical properties such as impact value, crushing value, abrasion value, specific gravity, and water absorption. Bitumen was tested for penetration value, softening point, ductility, flash point, and specific gravity to ensure its suitability for pavement construction. Waste plastic was cleaned, dried, and shredded into small pieces for proper mixing. The Marshall mix design method was adopted to prepare both conventional and plastic-modified bituminous mixes. Initially, a control mix without plastic was prepared to determine the basic properties of the mix. After that, waste plastic was added in different proportions, such as 4%, 6%, 8%, and 10% by weight of bitumen. In the dry process, heated aggregates were mixed with shredded plastic so that the plastic could coat the aggregate surface. Then hot bitumen was added and mixed uniformly. Marshall specimens were compacted and tested for stability, flow value, density, air voids, VMA, and VFB. Finally, the results were compared to determine the optimum waste plastic content for improved pavement performance.

IV. RESULT

The experimental results showed that the addition of waste plastic improved the overall performance of bituminous mixes when compared with the conventional mix. The Marshall stability value increased gradually with the addition of waste plastic up to an optimum percentage, indicating better load-carrying capacity and improved resistance against pavement deformation. The conventional bituminous mix without plastic showed lower stability because the bonding between bitumen and aggregates was normal. When waste plastic was added, it formed a thin coating around the aggregates and improved the adhesion between aggregate and bitumen. This resulted in higher strength, better compactness, and improved resistance to moisture damage. However, after a certain percentage of plastic, the stability value slightly decreased because excess plastic reduced workability and affected proper coating of the aggregates. Therefore, the optimum plastic content was found to be 8% by weight of bitumen, which gave the best balance between strength, flexibility, density, and void properties.

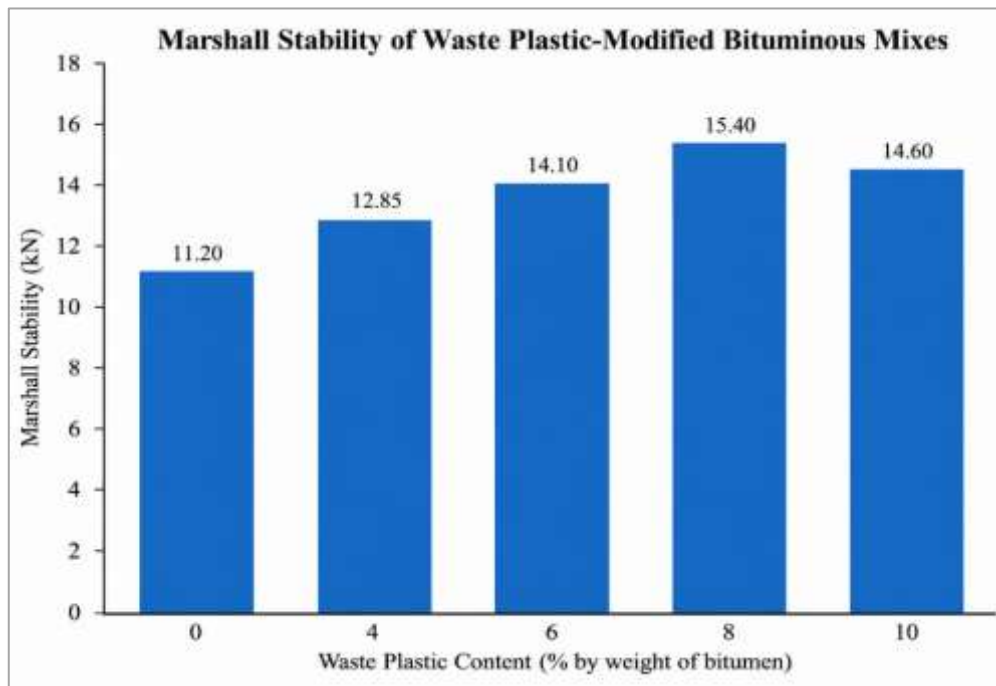
Table: Experimental Results of Waste Plastic-Modified Bituminous Mixes

Mix Type	Waste Plastic Content by Weight of Bitumen (%)	Marshall Stability (kN)	Flow Value (mm)	Bulk Density (g/cc)	Air Voids (%)	Performance Observation
Conventional Mix	0%	11.20	3.20	2.31	4.50	Normal pavement performance
Modified Mix 1	4%	12.85	3.05	2.33	4.20	Stability improved slightly
Modified Mix 2	6%	14.10	2.95	2.35	4.00	Good strength and compactness
Modified Mix 3	8%	15.40	2.85	2.36	3.80	Best overall performance
Modified Mix 4	10%	14.60	3.10	2.34	4.10	Slight reduction due to excess plastic

From the result table, it can be observed that Marshall stability increased from 11.20 kN for the conventional mix to 15.40 kN for the mix containing 8% waste plastic. This indicates that the waste plastic-modified mix had better strength and higher resistance against traffic loading. The flow value decreased from 3.20 mm to 2.85 mm up to 8% plastic content, showing that the mix became more stable and less prone to excessive deformation. The bulk density also increased from 2.31 g/cc to 2.36 g/cc,

which suggests better compaction and improved aggregate-bitumen bonding. Air voids reduced from 4.50% to 3.80%, indicating that the modified mix became denser and more durable. However, at 10% plastic content, the Marshall stability decreased to 14.60 kN, while air voids increased slightly. This shows that too much plastic can reduce mix workability and affect uniform distribution.

Bar Graph



The bar graph shows the effect of waste plastic content on the Marshall stability of bituminous mixes. The stability value increased from 11.20 kN for the conventional mix to 15.40 kN at 8% waste plastic content, indicating improved load-bearing capacity and better aggregate-bitumen bonding. The rise in stability shows that plastic coating enhanced the strength and compactness of the mix. However, at 10% plastic content, stability slightly decreased to 14.60 kN, which may be due to excess plastic reducing workability and uniform mixing. Therefore, 8% waste plastic was found to provide the best pavement performance.

V. CONCLUSION

The experimental investigation concluded that waste plastic can be effectively used as a modifier in bituminous mixes for improving pavement performance. The results showed that the addition of waste plastic increased Marshall stability, improved density, reduced air voids, and enhanced the bonding between aggregates and bitumen. Compared with the conventional mix, the plastic-modified mix showed better strength and resistance against deformation under traffic loading. Among the different plastic contents used, 8% waste plastic by weight of bitumen gave the best overall performance. At this percentage, the mix achieved maximum stability and suitable flow value, indicating improved load-carrying capacity and durability. However, when the plastic content was increased to 10%, the stability slightly decreased due to reduced workability and improper mixing. Therefore, the study concluded that the use of waste plastic in bituminous pavement construction is both technically suitable and environmentally beneficial. It helps in improving road life, reducing maintenance requirements, and providing a sustainable solution for plastic waste disposal. Thus, waste plastic-modified bituminous mixes can be recommended for eco-friendly and durable road construction.

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