Sustainable Flexible Pavement Performance with Waste Materials Integration

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ABSTRACT

The growing demand for sustainable and eco-friendly road infrastructure has encouraged the use of industrial waste materials in flexible pavement construction. This study evaluates the performance of flexible pavements incorporating waste materials such as fly ash, ground granulated blast furnace slag (GGBFS), waste plastic, and crumb rubber as partial replacements or modifiers in bituminous mixes. The main objective is to assess improvements in mechanical strength, durability, and resistance to pavement distresses. Laboratory investigations were conducted using the Marshall Mix design method, and performance parameters such as Marshall Stability, flow value, rutting resistance, fatigue life, and moisture susceptibility were analysed. Results indicate that modified mixes significantly outperform conventional mixes in terms of load-bearing capacity, resistance to deformation, and durability. Waste plastic and crumb rubber showed the highest improvement in performance characteristics. The study confirms that industrial waste incorporation enhances pavement sustainability while reducing environmental pollution and construction costs.

Keywords: *Flexible Pavement, Industrial Waste, Sustainability, Bituminous Mix.*

I. INTRODUCTION

Flexible pavements are one of the most widely used forms of road infrastructure due to their cost-effectiveness, ease of construction, and ability to efficiently distribute traffic loads through layered systems consisting of subgrade, sub-base, base course, and bituminous surfacing. However, conventional pavement construction relies heavily on natural aggregates and petroleum-based bitumen, which leads to significant environmental degradation, depletion of natural resources, and high energy consumption during extraction and processing. With rapid urbanization, industrial growth, and increasing transportation demand, there is a pressing need to develop sustainable pavement systems that can balance performance requirements with environmental responsibility. In this context, the use of industrial waste materials in flexible pavements has gained considerable attention as an innovative and eco-friendly solution. Industrial by-products such as fly ash, ground granulated blast furnace slag (GGBFS), waste plastic, crumb rubber, and silica fume, which were previously considered disposal burdens, are now being effectively utilized as modifiers or partial replacements in bituminous mixes. These materials not only address waste management issues but also enhance pavement performance by improving strength, durability, and resistance to rutting, fatigue, and moisture damage. For instance, fly ash contributes to improved stiffness and stability due to its fine particle structure, while slag enhances compressive strength and long-term durability. Waste plastic improves binding properties and water resistance, and crumb rubber increases elasticity and flexibility under repeated traffic loading. Moreover, the incorporation of industrial waste materials reduces construction costs by lowering dependence on expensive conventional resources and minimizing transportation and procurement expenses. Despite these advantages, proper mix design and proportioning are essential, as inappropriate use may lead to reduced workability or performance inconsistencies. Therefore, performance evaluation through laboratory testing such as

Marshall Stability, flow value, indirect tensile strength, and rutting resistance is crucial to determine optimal compositions and ensure structural reliability. Overall, the integration of industrial waste materials in flexible pavements represents a significant step toward sustainable road infrastructure development by combining environmental conservation with improved engineering performance and economic efficiency.

II. RESEARCH BACKGROUND

Bedi et al. (2026) had stated that the use of crumb rubber as an alternative sustainable material in asphalt pavement had gained popularity in recent years and had become one of the key elements for enhancing the durability and load-carrying capacity of pavements while addressing environmental concerns. It had been observed that crumb rubber was utilized to improve pavement performance and asphalt binder properties. Due to the increasing population and rising vehicular traffic, pavements had been subjected to higher stresses, which had led to issues such as fatigue cracking and other deformations caused by overloading on roads. The study had aimed to examine various experimental approaches to assess the effects of crumb rubber on mechanical properties, durability, and load-bearing capacity. It had compared mix design variations and performance outcomes using both wet and dry blending methods. A comparative analysis had been conducted to evaluate modifications in crumb rubber particles and their influence on binder properties and pavement deflection. The results had shown that crumb rubber, used in different forms such as aggregates or powder, had improved Marshall stability, flow, and resilience modulus, thereby enhancing pavement longevity and overall durability.

Parmar et al. (2026) had stated that India was a developing country where constructive developments in the modern era significantly influenced the nation's economic growth. It had been noted that India possessed the second-largest road network in the world, and the continuous expansion of road transportation had resulted in considerable environmental degradation. The study had reported that road construction activities generated greenhouse gas (GHG) emissions, which acted as a major driver of climate change. It had been emphasized that the government had been undertaking sustainability initiatives aimed at reducing carbon emissions and promoting environmental protection through the green highway concept. The research had focused on developing a carbon emission reduction approach by utilizing alternative and recycled materials while maintaining required strength at lower cost. It had also explained a methodology for estimating emissions from natural and waste-based material substitutions. The case study of the Dhrol–Amran–Maliya Road section in Gujarat had been analysed, focusing on rigid pavement materials, machinery, and energy use. The findings had revealed a reduction of 56,313.01 MT (19.20%) CO_2 emissions and a financial saving of Rs. 48.11 crores (16.85%) through proposed alternatives.

Dayma and Rajput (2025) had reported that the increasing accumulation of non-biodegradable plastic and rubber waste had emerged as a significant environmental concern, thereby necessitating innovative approaches for sustainable disposal and utilization. They had emphasized that the modification of bitumen with waste plastic and rubber provided a dual advantage by improving pavement performance while simultaneously reducing ecological burden. Their review had synthesized findings from 25 national and international studies on flexible pavements incorporating waste plastic and rubber-modified bitumen. It had been observed that consistent improvements were recorded in key engineering properties such as Marshall stability, rutting resistance, fatigue life, tensile strength, and stripping resistance when compared to conventional bituminous mixes. Waste plastics like LDPE, HDPE, and PET had primarily enhanced stiffness, moisture resistance, and rutting performance, whereas crumb rubber from waste tires had improved elasticity, fatigue resistance, and temperature susceptibility. The combined use of both materials had exhibited complementary benefits, ensuring rigidity and flexibility under varying traffic and climatic conditions. Field applications had further validated laboratory outcomes, indicating reduced maintenance costs and extended service life. The study had concluded that this approach was technically feasible, economically viable, and environmentally sustainable, while recommending further research on standardized mix design and long-term performance evaluation.

Zhao and Yang (2024) had investigated the efficient utilization of recycled asphalt pavement (RAP) generated during road maintenance and expansion, along with addressing the low utilization of steel slag and desulfurization ash produced in the steel industry. They had proposed a sustainable pavement system by combining RAP with waste rubber powder–modified asphalt to develop a matrix skeleton with high void content, which was further filled with grouting materials prepared from desulfurization ash and steel slag. The study had revealed that the developed pavement exhibited superior resistance to high-temperature permanent deformation and enhanced durability. It had also been observed that, compared to conventional asphalt pavement, the proposed sustainable pavement could reduce energy consumption and emissions by approximately 45% over a single life cycle. Additionally, its economic benefits were reported to exceed 500%. Furthermore, the improved fatigue resistance had indicated that its environmental and economic advantages would become more significant over an equivalent analysis period.

Kedar et al. (2024) investigated sustainable utilization of fly ash, glass fiber, and ground granulated blast furnace slag (GGBS) as stabilizing materials for base and subbase layers of flexible pavements. Design Expert 13 software and Response Surface Methodology (RSM) were used to determine optimal mix proportions satisfying requirements. A blend containing 88% fly ash, 3% glass fiber, and 9% GGBS achieved Unconfined Compressive Strength (UCS) exceeding 3 MPa at 28 days, suitable for subbase applications. Additionally, 83% fly ash, 5% glass fiber, and 12% GGBS yielded maximum UCS of 6.76 MPa, appropriate for base layers. Modified Compaction, UCS, and California Bearing Ratio (CBR) tests were conducted, and ANOVA validated results. Increased glass fiber content significantly improved UCS and CBR values. The optimum mix achieved a CBR of 67.20%, surpassing requirements for heavy traffic pavements, highlighting sustainable pavement enhancement potential in road infrastructure applications for enhanced sustainability performance evaluation outcomes analysis.

Shwetambra & Berwal (2024) had investigated the role of rigid pavements in transportation infrastructure, emphasizing their durability and high load-bearing capacity. The study had focused on improving structural stability by incorporating industrial waste materials, particularly iron slag, which had been identified as a promising supplementary construction material due to its favourable engineering properties. Various performance parameters such as impact resistance, abrasion resistance, specific gravity, water absorption, and crushing strength had been assessed and compared with relevant Indian Standard (IS) specifications. The results had revealed that the iron slag–aggregate blend had satisfied or exceeded most IS requirements, indicating its suitability for pavement applications. Furthermore, the findings had demonstrated that the modified aggregate system had exhibited performance comparable to or better than conventional natural aggregates, suggesting its potential for sustainable pavement construction and waste utilization in civil engineering practices. The study also highlighted environmental benefits through recycling of industrial by-products efficiently utilized.

Mondal et al. (2023) had investigated the sustainable utilization of several widely produced fine-grained industrial wastes along with reclaimed asphalt pavement (RAP) in warm mix asphalt (WMA) production. In this study, fine industrial wastes such as Ground Granulated Blast Furnace Slag (GS), dried Limestone Sludge (LS), and Fly Ash (FA) were used as fillers in varying proportions (2–6% by weight of aggregates), while conventional aggregates were partially replaced with RAP to develop recycled WMA mixtures. The experimental results had indicated satisfactory engineering performance and superior environmental suitability of the recycled WMA. It was observed that mixes containing LS and GS exhibited better resistance to major pavement distresses such as rutting and cracking, mainly due to their high porosity, specific surface area, fine particle size, and predominance of calcareous minerals. Furthermore, the design of a one-kilometre, two-lane asphalt pavement using optimized mixes following mechanistic–empirical guidelines had demonstrated savings of conventional filler materials, cost reduction, and significant greenhouse gas emission reduction, thereby highlighting its environmental and engineering benefits.

Singh et al. (2023) had reported that rapid waste accumulation had posed a significant challenge due to population growth, industrial activities, consumerism, and technological advancement. It had been observed that proper waste disposal had been crucial for preventing pollution and preserving valuable land resources. Plastic waste had been identified as particularly threatening because it was non-biodegradable. The study had highlighted that the use of recycled materials, such as plastic waste mixed with bitumen, in road construction had shown promising results by improving mechanical properties. It had focused on addressing two major issues in Nepal, mainly in urban areas: solid waste management with emphasis on used plastics that had heavily accumulated in cities, and the development of potholes in roads due to heavy traffic loads and environmental factors such as excessive precipitation, flooding, and infiltration. The study had also examined thermoplastic polymers like HDPE, PET, and PP in flexible pavement design, concluding that up to 10% plastic content had improved pavement performance significantly.

Kumar and Shukla (2022) had reported that flexible pavement had remained the most preferred pavement system for road construction, particularly in developing countries like India, where rapid industrialization and construction activities had been continuously increasing. They had highlighted that the growing demand for exhaustible natural resources had posed a significant challenge to the global pavement industry, as the extraction of virgin materials was considered unsustainable. The authors had further observed that uncontrolled industrialization and infrastructure growth had led to the generation of large quantities of waste materials, and improper disposal of such wastes had resulted in environmental pollution and health hazards, along with increased landfill requirements. Their study had indicated that several laboratory investigations conducted by researchers had supported the use of industrial waste in unbound base and sub-base layers of pavements as coarse aggregates, fine aggregates, and mineral fillers. It had been concluded that recycled materials had provided an economical and sustainable alternative, reducing dependence on conventional resources while maintaining pavement strength and durability. They had also noted that construction and demolition wastes and reclaimed asphalt pavement (RAP) had been major sources of recycled aggregates, which were processed and reused effectively in pavement construction.

Vishnu and Singh (2021) had described various methods through which large volumes of waste generated from urban and semi-urban regions could be optimally reutilized as additives in bituminous pavement construction. They had reported that waste materials such as scrap tyres, plastic waste, glass, coal waste, fly ash, concrete debris, and wood waste could be effectively incorporated into pavement layers. It had been observed that in countries like India, such wastes were commonly disposed of through incineration, open burning, landfilling, dumping into water bodies, or discharge into sewers, indicating improper waste management practices. The authors had highlighted the growing necessity for sustainable alternatives due to increasing consumption, limited disposal space, energy constraints, and climate change concerns. The study had evaluated the applications of solid waste in sustainable pavement engineering and reviewed existing literature on waste reutilization. A life cycle assessment (LCA) had been conducted to assess environmental impacts. The findings had indicated that solid waste could be effectively used as aggregates, fillers, Fibers, and additives, improving pavement strength, durability, and reducing environmental burden, energy use, and overall construction costs.

Singh et al. (2020) had reported that plastic waste, including wrappers of chocolates and chips, carry bags, and beverage bottles, had posed significant environmental challenges due to its non-biodegradable nature and high energy consumption during degradation. It was further observed that plastics such as polyethylene, polystyrene, and polypropylene were widely used in packaging and industrial applications owing to their lightweight, cost-effectiveness, and mechanical strength. The study had noted that these materials exhibited a softening temperature range of approximately 120°C to 160°C, which made them suitable for modification processes. It had been explained that waste plastics were shredded and coated onto aggregates and then mixed with hot bitumen for pavement construction. This process had improved pavement strength and durability while reducing air voids and enhancing binding properties. The authors had concluded that the incorporation of plastic waste in road construction had been economical, environmentally friendly, and beneficial for improving structural performance.

Más-López et al. (2020) had investigated the utilization of glass waste, which inherently could not be recycled through conventional methods, as a viable and sustainable alternative material in the production of cement and concrete. They had reported that this approach could reduce landfill accumulation of inert glass residues while simultaneously decreasing the demand for natural raw materials used in cement and concrete manufacturing, thereby contributing to the mitigation of environmental impacts associated with construction activities. In their study, the feasibility of employing a limestone-type material treated with a binder composed of micronized glass powder and basic reagents had been analysed for the development of gravel–cement and soil–cement type materials. They had evaluated key properties such as strength, compact ability, structural capacity, water resistance, stiffness, and durability. The results had indicated that glass powder with a particle size of 16 μm was most suitable, enabling production of environmentally friendly pavement materials for low-cracking road applications.

III. METHODOLOGY

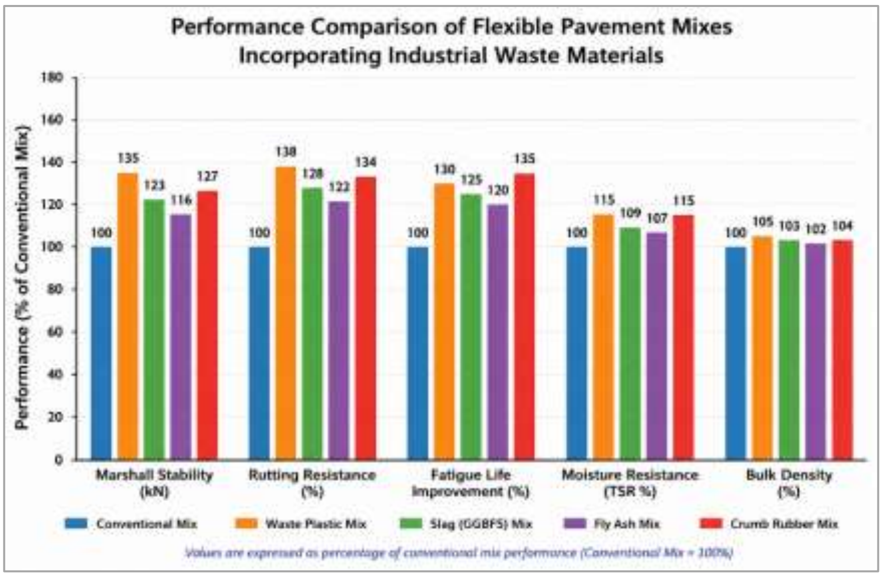
The methodology adopted for the performance evaluation of flexible pavements incorporating industrial waste materials involves a systematic experimental approach to assess and compare the behaviour of modified bituminous mixes with conventional pavement mixes. Initially, suitable materials such as conventional aggregates, bitumen, and selected industrial waste materials including waste plastic, fly ash, ground granulated blast furnace slag (GGBFS), and crumb rubber were collected and characterized based on their physical and engineering properties. The collected aggregates were tested for properties such as specific gravity, gradation, impact value, and abrasion resistance, while bitumen was evaluated for penetration, softening point, ductility, and viscosity to ensure compliance with standard pavement design requirements. In the next stage, the industrial waste materials were processed to achieve the required form for incorporation into the bituminous mix. Waste plastic was shredded into uniform sizes, crumb rubber was processed from discarded tires, while fly ash and slag were sieved to obtain fine and consistent particles. After material preparation, mix design was carried out using the Marshall Method of Mix Design to determine the optimum bitumen content (OBC) for both conventional and modified mixes. Various proportions of industrial waste materials were introduced as partial replacements or modifiers in the bituminous mix, and trial specimens were prepared for each variation.

Prepared specimens were subjected to standard laboratory testing to evaluate their performance characteristics. Marshall Stability and flow tests were conducted to assess load-bearing capacity and deformation behaviour under applied stress. Rutting resistance was analysed to determine the ability of the pavement to withstand permanent deformation under repeated wheel loading. Fatigue performance was evaluated based on resistance to cracking under cyclic loading conditions, while moisture susceptibility was assessed using the Tensile Strength Ratio (TSR) to understand the effect of water on pavement durability. Bulk density and air void analysis were also performed to evaluate compaction characteristics and internal structure stability of the mixes. Finally, the results obtained from all modified mixes were compared with the conventional control mix to determine performance improvements and identify the most suitable industrial waste material for pavement applications. The overall methodology ensures a comprehensive assessment of mechanical, structural, and durability properties, enabling reliable conclusions regarding the effectiveness of industrial waste incorporation in sustainable flexible pavement design.

IV.RESULTS

The performance evaluation of flexible pavements incorporating industrial waste materials such as fly ash, slag (GGBFS), waste plastic, and crumb rubber demonstrated significant improvements when compared to conventional bituminous mixes. The Marshall Stability results indicated a notable increase in load-bearing capacity, where the control mix recorded approximately 10.2 kN, while waste plastic-modified mixes achieved up to 13.8 kN, showing enhanced structural strength. Slag and fly ash mixes also exhibited improved stability values ranging from 11.5 kN to 12.5 kN. Flow value analysis revealed that modified mixes maintained adequate flexibility while reducing excessive deformation, with waste plastic mixes showing lower flow values (2.8–3.1 mm) compared to the control mix (3.5 mm), indicating improved stiffness. Rutting resistance was significantly enhanced in modified mixes, with reductions in rut depth ranging from 25% to 40%, particularly in waste plastic and crumb rubber mixes due to improved resistance to high-temperature deformation. Fatigue life was also improved, with crumb rubber-modified mixes showing up to 35% higher resistance to repeated loading cycles. Moisture susceptibility tests showed higher tensile strength ratios (TSR > 85%) in modified mixes, indicating better resistance to stripping and water damage compared to the control mix (≈75%). Density and air void analysis confirmed improved compaction and stability, with all modified mixes maintaining optimal void content within the acceptable range of 3–5%. Overall, the results clearly demonstrate that industrial waste materials significantly enhance the mechanical strength, durability, and sustainability of flexible pavements.

Bar Graph



The bar graph presents a comparative performance analysis of flexible pavement mixes incorporating industrial waste materials against a conventional mix taken as the baseline (100%). It evaluates key parameters such as Marshall Stability, rutting resistance, fatigue life improvement, moisture resistance (TSR%), and bulk density. The results clearly show that all modified mixes outperform the conventional mix. Waste plastic exhibits the highest improvement in Marshall Stability and rutting resistance, while crumb rubber shows superior fatigue life enhancement. Slag and fly ash also contribute moderate improvements across all parameters. Overall, the graph highlights that industrial waste incorporation significantly enhances pavement strength, durability, and sustainability.

V. CONCLUSION

The study on the performance evaluation of flexible pavements incorporating industrial waste materials demonstrates that sustainable pavement construction is both technically feasible and environmentally beneficial. The results clearly indicate that the partial replacement of conventional pavement materials with industrial by-products such as waste plastic, slag (GGBFS), fly ash, and crumb rubber significantly enhances the overall performance of flexible pavements. Improvements were observed in key parameters including Marshall Stability, rutting resistance, fatigue life, and moisture susceptibility, confirming better structural strength and durability compared to conventional mixes. Among the tested materials, waste plastic and crumb rubber showed the most prominent improvements, particularly in load-bearing capacity and resistance to deformation under repeated traffic loading. Slag and fly ash also contributed positively by improving mix stability and compaction characteristics. In addition to performance enhancement, the use of industrial waste materials helps reduce environmental pollution, minimizes landfill disposal issues, and lowers construction costs by reducing dependency on natural aggregates and bitumen. However, careful mix design and proportioning are essential to achieve optimal results and avoid performance inconsistencies.

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