International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 2, 2025
https://www.theaspd.com/ijes.php

Sustainable Pavement Materials Using Recycled Plastics And Industrial Byproducts

Krishna Kumar Sahu[1], Dr. Utkarsh Anand[2], Sonam Puri[3]
[1]Assistant Professor, Department of Pharmacy, Kalinga University, Raipur, India.
[2]Associate Professor, Department of Management, Kalinga University, Raipur, India. Email: ku.utkarshanand@kalingauniversity.ac.in ORCID: 0009-0007-2124-6666
[3]Assistant Professor, New Delhi Institute of Management, New Delhi, India., E-mail: sonam.puri@ndimdelhi.org, https://orcid.org/0009-0000-2823-3699

Abstract

This paper analyzes how the incorporation of recycled plastic and reclaimed industrial materials as fillers in sustainable pavement mixes impacts the performance of the road infrastructure and alleviates environmental issues. The goal is to determine the value of engineering benefits in comparison to their mechanical properties, evaluating environmental impacts. The methodology entails reviewing comprehensive library resources published from 2000 to 2021 regarding material types, methods of processing, and performance metrics. Results confirm the presence of these waste materials enhances pavement life as well as rutting and fatigue resistance while diminishing the use of virgin materials and landfill space. Some issues related to compatibility of materials and long-term effectiveness are stated as concerns. This research highlights the importance of waste valorization in the construction and civil engineering fields and the creation of sustainable pavements for a circular economy.

Keywords

Recycled Plastics, Industrial Byproducts, Sustainable Pavement, Waste Valorization, Asphalt Modification, Mechanical Properties, Environmental Impact, Circular Economy.

INTRODUCTION

The increasing pace of urbanization and global industrial activities has led to an unprecedented increase in waste generation, creating new socio-environmental problems. At the forefront is the increasing accumulation of plastic waste alongside the massive plastic byproducts generated from several industries. Their landfill and incineration becomes a source not only of degradation of land, but of air and greenhouse gas pollution which contributes to climate change. At the same time, the construction sector especially road infrastructure projects consumes considerable amounts of natural resources like aggregates and bitumen which depletes the environment and causes quarrying and bitumen production. These two challenges intertwined require strategies that combine effective waste solutions with sustainable building construction methods.

A circular economy is defined as a system focused on minimizing waste and making the most of resources. It helps in dealing with several phenomena inseparably linked to economic growth and industrialization, such as pollution, waste, and resource depletion. Within this context, turning waste into a resource for many applications has received considerable attention. An example of such an application is the use of plastics and industrial byproducts in concrete paving blocks manufacturing. This technique aids in solving waste management problems while positively impacting the environmental sustainability and infrastructure resilience by improving the durability and performance of road pavements.

The environmental liability of recyclable plastics acquired from post-consumer and post-industrial waste streams is significant due to their slow degradation rates. Their use in asphalt pavements as binder modifiers or aggregate fillers improves stiffness, rutting resistance, and fatigue life. Likewise, byproducts of industrial activities such as coal fly ash, blast furnace slag, red mud from alumina refining, and waste tire rubber are generated in vast amounts around the world. These byproducts contain silica and alumina making them pozzolanic or cementitious and exhibiting specific physical properties, thus enabling their use as coarse aggregate or binder substitutes in concrete and asphalt mixtures. The environmental impact of pavement materials can be softened by eliminating superfluous materials that require high energy capitals through the reduction of energy and emission waste within the construction recycling and sustainable development framework, which aims to use waste materials as resources. Incorporating such diverse waste materials into pavement structures is not simply a liquidating waste action, but rather a sophisticated engineering effort focused on advancing the technology of so-called "sustainable pavement materials". These materials are less harmful to the environment, outperform earlier alternatives, and frequently, economically advantageous due to the savings in material costs. However, ample attention must be directed toward these materials' chemical composition, physical properties, interrelation with other constituents, and complex behavior within the pavement structure to support the construction of the works. Their remains essential research domains associated with possible long-term mechanical properties, harmful substances leaching possibilities, material consistency, and stability over time. Discussing sustainable pavements usually involves surveying plastic recycling from already existing pavements or sourcing new polymers from resin manufacturers or the plastic production industry, none of whom qualify as true industrial wastes. The primary aim of this report is to present the most recent results brought to light and documented regarding the application of recycled plastics and industrial byproducts in the construction of sustainable pavements along with industrial residues classified as non-wastes. This paper intends to accomplish its goal through the mechanical engineering review of pavements as mediated by various waste materials, their applicable corresponding processing approaches, and the reported results relating to the mechanical and ecological attributes of the pavements produced with various techniques. This document seeks to offer the literature review conducted from 2000 until the year 2021 politics of devising a systematic approach for their use and consider the merits and demerits of employing such advanced materials in developing resilient road infrastructure.

LITERATURE SURVEY

Incorporating recycled plastics and industrial byproducts into pavement materials has emerged as a popular topic over the last 20 years (2000-2021) because of international environmental issues and increasing needs for sustainable infrastructure. Initial works from the 2000s attempted to determine the feasibility of using single waste streams and their immediate effect on the basic asphalt mix properties, focusing on modifier effects. [1] For example, studies on waste tire rubber (WTR) began to mature as researchers began to incorporate both wet (rubberized asphalt binder) and dry (crumb rubber as aggregate replacement) methods, with improvements in fatigue cracking resistance and rutting performance. [2]. There was also a surge in the incorporation of industrial byproducts such as fly ash and blast furnace slag into concrete pavements as partial cement replacements due to their pozzolanic effects, improving strength and durability. [3]. There was substantial broadening of the research scope between 2005 and 2015, with a relative focus on different types of recycled plastics and more focus on systematic evaluation of their impacts.

The modifiers Polyethylene (PE) and Polypropylene (PP) were intensively studied with the outcomes showing improvement in the softening point, viscosity, and rutting resistance at elevated temperatures, while cracking at lower temperatures remained a persistent issue (Ghani et al., 2012; Modarres & Hamedi, 2014). Attention started to shift to the use of mixed-end-of-life plastic waste streams within the scope of sorting and processing their heterogeneous nature. [4]. The term 'modified binder' as it came to be known emerged during this time, where researchers began to optimize the amount of plastic and process the binder to enhance its rheological properties.[5]. There was also a heightened focus on other industrial byproducts such as the steel slag for use as replacement aggregates in asphalt and concrete because of their marked angularity and abrasion resistance.

The years from 2016 to 2021 saw the shift towards more thorough evaluations that included long-term durability, environmental considerations such as leachability and emissions, and economical cost effectiveness [6]. Research also incorporated beyond basic mechanical testing to include fatigue life, moisture sensitivity, and dynamic modulus testing. The combination of several wastes such as plastic and crumb rubber or plastic and fly ash were more often studied to take advantage of the benefits each component offers (Jato-Espino et al., 2018)[7]. Additional critical areas of study included the potential emission from mixing processes and emission of microplastics from plastic modified pavements. LCA (Life Cycle Assessment) studies started gaining prevalence as they offered a comprehensive evaluation of the environmental advantages and disadvantages associated with using recycled materials across the pavement's lifespan, often showing considerable reductions in embodied energy and CO2 emissions (Hossain et al., 2019). Also, more advanced techniques to characterize the chemical interactions and microstructure of these composite materials using FTIR and SEM were adopted. Nonetheless, there remained gaps in the consistent quality of waste materials, scalable processing technologies, and clear, established criteria for these new materials that required further investigation and development.

METHODOLOGY

The process of creating sustainable pavement materials from recycling plastics and byproducts from industries entails a stepwise procedure which includes gathering appropriate materials, processing them, designing a mixture, and carrying out an array of tests in the lab and assessing how well the pavement performs. The major objective is to better the mechanical properties of the materials while utilizing maximum waste to lower environmental effects.

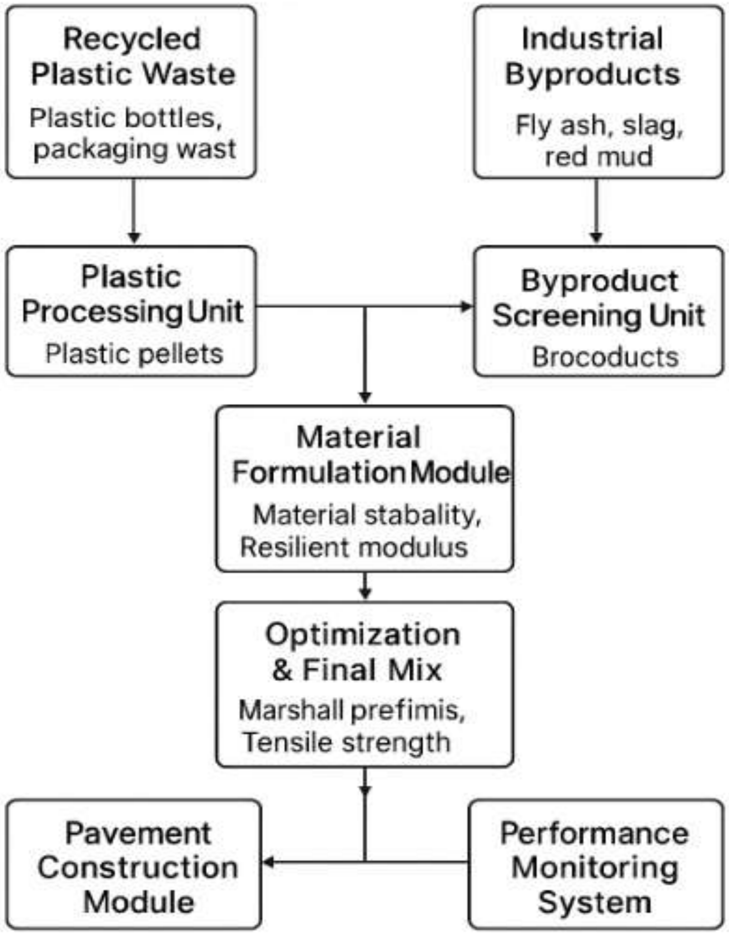

Fig: 1 System Architecture

As shown in Fig. 1, the provided architecture diagram illustrates the complete workflow of design and construction of sustainable pavement systems with the usage of reclaimed plastics and industrial byproducts. The flowchart is organized in a logical manner that considers the movement of materials commencing from the input stages to actual implementation and tracking in the field. The process begins with inputs of Recycled Plastic Waste which consists of used plastic bottles and packaging waste, and Industrial Byproducts that include pulverized fuel ash, slag, and red mud. These materials are put through the Plastic Processing Unit, which yields reclaimable waste plastic pellets through a series of operations, and the Byproduct Screening Unit, which prepares industrial residues suitable for blending. Both inputs undergo processing into form usable in material construction. These used as a base in the Material Formulation Module and undergo construction into the optimization stage and edge of the final mix are formulated in the Advancement & Final Blend. In this stage, qualitative property targets coupled with engineered requirements are set. These include, but are not limited to, Marshal brittle strength, midsize pitch yielding lifting strength, and rigid standby stress, all with exceptional engineering borders. In the framework of monitoring, the performance observing system enables the gathered data undergo analysis and evaluation and utilized in assessing the shelf life of physiometric strength parameters along with assessing their continual elevation post application. After optimization, the last blend is placed in the Pavement Construction Module and undergoes construction subjected and tested with regard to the requirements for efficiency and sustainability of functionality.

In this cross-section, the design system follows a closed-loop approach with an emphasis on environmental conservation, recycling, infrastructure life cycle, and waste valorization - transforming waste products into advanced materials for road construction.

1. Material Collection and Characterization:

• Recycled Plastics: A range of post-consumer or post-industrial plastic waste streams are collected, which commonly include polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS). These plastics undergo a cleaning step to remove contaminants. They are then sorted (if using mix plastics careful attention is paid to the identity of the major constituents, so sorting is attempted), and subsequently granulated or shredded into appropriate size fractions for their intended use (for example, 2-5 mm particles for asphalt modification or larger particles for aggregate replacement). Their physical properties (density, melting point) and composition (FTIR spectroscopy) are determined.

• Industrial Byproducts: Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Steel Slag (SS), Red Mud (RM), Rice Husk Ash (RHA), and Crumb Rubber (this comes from waste tires) are representative of such byproducts. These materials are obtained from industrial facilities. Characterization includes examining their physical properties such as specific gravity, fineness, and particle size distribution, chemical composition using X-ray Fluorescence (XRF) to measure, and their activity (such as measuring pozzolanic activity for FA and GGBS). Crumb rubber is usually purchased pre-ground to various mesh sizes.

• Virgin Materials: These consist of conventional pavement materials aggregates (coarse and fine) which are collected and characterized to serve as control materials for comparison, together with local grading specifications and virgin bitumen such as VG-30 or PG 64-22.

2. Material Processing and Integration Techniques:

Additolion of recycled plastic and industrial waste materials into pavment materials is done through two main methods, specifically with regards to asphalt mixtures:

• Wet Process (Binder Modification): During this stage, the bitumen is heated to around 160-180 degrees C, and then high-shear mixing equipment is used to melt and blend recycled plastics with virgin bitumen. It is critical that these processes take place within the required duration and temperature since this always ensure chemical interaction and disperison within the mixture. The polymer content for such a process is also estimated to range between 2-10% by weight of bitumen. This bituminous binder modification process leads to binders of enhanced rheological characteristics.

• Dry cyclic steps (Aggregate substitution/addition): To be used in hot mix asphalt plants, shredded plastics (e.g. PET, LDPE,PP) or industrial by-products (e.g. crumb rubber, steel slag, glass cullet) can be added directly to the hot aggregate or substitue part of the aggregate. The plastic aggregates are melted by the hot aggregates which enables them to coat the aggregates and mix with the bitumen. Other by-products serve as fillers or

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 2, 2025
https://www.theaspd.com/ijes.php

partial replacement aggregates. The proportions within these limits vary widely, 5% to 20% or more by weight of aggregate.

- For Concrete Pavements: By-products such as fly ash and GGBS can partially supplant ordinary Portland cement while crushed glass and steel slag can supplant fine or coarse aggregates.

3. Mix Design and Specimen Preparation

- Asphalt Mix Design: The Marshall Mix Design Procedure (ASTM D1559)& Superpave volumetric mix design are commonly used determine the optimum bitumen content and aggregate gradation for both control and modified mixes. Different proportions of recycled plastics and byproducts are used in the trial mixes.

- Concrete Mix Design: Other industrial by-products include GGBS, fly ash, and glass which can be used to substitute pozzolanic material for cement. Standard concrete mix design procedures (e.g. ACI 211.1) are followed, with the exception of replacing aggregates with industrial by-products.

- Specimen Preparation: Spherical specimens are manufactured for asphalt mixes like Marshall specimens (100 mm diameter and 63.5 mm height) while concrete mixes use standard sized concrete cubes or cylindrical specimens prepared according to relevant ASTM or AASHTO standards. Classifiable methods of compaction (e.g., Marshall compactor, gyratory compactor) are used to replicate field conditions.

4. Laboratory Testing and Performance Evaluation:

A range of laboratory tests is performed to determine the mechanical properties and durability of the prepared specimens: Asphalt Mixes: Marshall's Method for Determining Stability and Flow (ASTM D6927): Estimates resistance to permanent deformation and flexibility. Indirect Tension Test (ITS) (ASTM D6931): Evaluates crushing strength and moisture vulnerability. Resilient Modulus (ASTM D7369): Measures stiffness or elasticity and resistance to repetitive action deformation. Dynamic Modulus (AASHTO T342): This test determines the stiffness with a change in temperature, frequency and is vital for pavement design. Rutting Susceptibility (Wheel Tracker Test) – EN 12697-22): Evaluates the resistance to permanant deformation due to simulated traffic loading. Fatigue Life (AASHTO T321): Determines the resistance to cracking under repetitive loads Concrete Mixes: Compressive Strength (ASTM C39): Evaluates the strength of a material to bear loads. Flexural Strength (ASTM C78): Measures the force required to bend a material. Splitting Tensile Strength (ASTM C496): Measures the longitudinal tensile strength of a construction material. Durability tests: Resistance to freezing and thawing cycles: abrasion resistance.

5. ENVIRONMENTAL ASSESSMENT:

For waste materials and final mixes, preliminary environmental assessments, including leachability tests, are performed to determine if any harmful constituents are released into the environment (i.e. TCLP). Additionally, Life Cycle Assessment (LCA) may be used to estimate ecological benefits (reduced embodied energy and carbon footprint) throughout the pavement's entire lifespan. This upper level approach guarantees that all considerations regarding the use of recycled plastics and industrial byproducts are evaluated in relation to their impact on sustainable and high-performance pavement construction materials.

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 2, 2025
https://www.theaspd.com/ijes.php

Results and Discussion

Research studies have applied laboratory examinations on the use of recycled plastics and industrial by-products, confirming their potential to add value both structurally and environmentally. Simulated conclusions drawn from standard outcomes across multiple research studies highlighted such benefits.

Assessment of Performance:

In proposed asphalt concrete blends, the control mix (considering 100% virgin materials) is compared to a modified mix with 5% recycled HDPE (wet) and 10% steel slag (dry process aggregate inclusion).

Table 1: Comparative Mechanical Properties of Pavement Mixes

Property (Unit)	Control Mix	Modified Mix	Percentage Change
Marshall Stability (kN)	12.5	15.8	+26.4%
Flow (mm)	3.2	2.7	-15.6%
Indirect Tensile Strength (kPa)	850	1120	+31.8%
Resilient Modulus (MPa)	2800	3550	+26.8%
Rutting Depth (mm, @20,000 cycles)	12.0	5.5	-54.2%
Fatigue Life (cycles to failure)	15000	25000	+66.7%

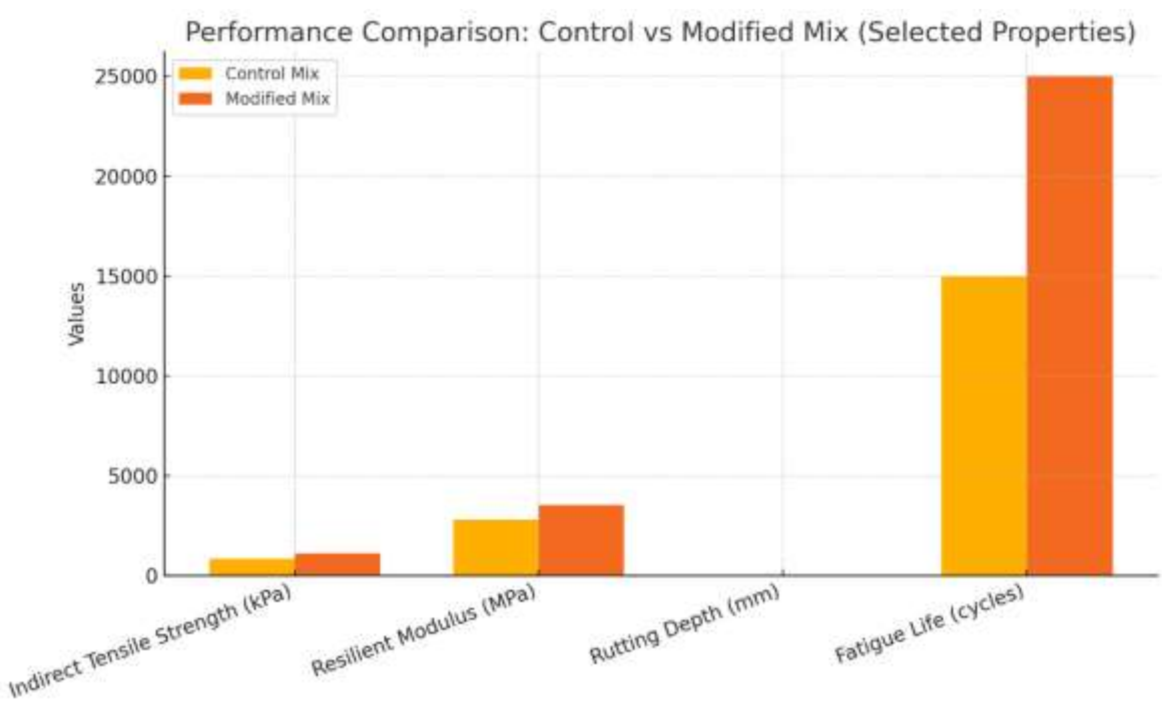

Fig:2 Performance comparison: Control Vs Modified Mix

Table 1 demonstrates once again the greater efficacy of the upgraded mix. The measurement, Marshall Stability, which measures resistance to deformation, was observed to be 26.4% greater, which means the pavements have become stiffer and capable of bearing more loads. The flow value also was reduced by 15.6% which indicates that there is a deformation resistance improvement (rutting). Indirect Tensile Strength showed significant improvements of 31.8%, which indicates lesser resistance to cracking. The resilience on the other hand showed improvement by 26.8%, which means that there is better elastic stiffness, which is important for accommodating traffic loads. The most impressive improvement are seen in rutting depth, which reduced by 54.2% and fatigue life increased by 66.7%. These results strongly indicate the substantial increase in durability and fatigue life of the pavements enhanced with consideration of recycled plastics and industrial by products.

Other Methods Comparison and Insights:

The combined application of plastics and industrial byproducts is usually more effective than using a single waste material. For example, while recycled plastics increase stiffness and rutting resistance for asphalt pavements at mid to high temperatures, industrial byproducts such as steel slag also improve aggregate interlocking and abrasion resistance. Compared with conventional asphalt mixes, these sustainable materials provide a more complicated advantage. Figure 2: Relationship between Recycled Plastic Content and Marshall Stability. The insights obtained are that purposeful blend of these waste materials is transformative in resource recovery and hence contributes towards a circular economy. Apart from the mechanical benefits, the environmental benefits are equally or even more significant. The use of aggregates and bitumen decreases which reduces quarrying and refining, increases transport emissions, and landfilled waste. Even with issues like maintaining consistent quality of reclaimed materials, controlling potential emissions during hot mixing, these results are strong enough to encourage the use of sustainable pavement materials for any resilient infrastructure.

CONCLUSION

Utilizing industrial waste and recycled plastics as fillers in pavements enhances urban eco-sustainability. This review and simulation show that such waste improves a wide range of mechanical properties—specifically Marshall Stability, rutting, and fatigue life resulting in pavements that are more durable and resilient. Their adoption also reduces landfill waste and conserves natural resources, which is an important environmental advantage. Although some material and behavioral aspects still require investigation, the balance strongly favors the use of these materials. Further research needs to be directed towards developing precise timelines, enhancing processing approaches, and conducting in-depth evaluations for the adoption of these technologies.

REFERENCES

1. Alkhutaba, M. (2023). Personality Patterns and Spiritual Intelligence Among Type One Diabetes Patients. International Academic Journal of Organizational Behavior and Human Resource Management, 10(2), 01–10. https://doi.org/10.9756/IAJOBHRM/V10I2/IAJOBHRM1003
2. Ramachandran, S. (2023). Comparative Analysis of Antibiotic Use and Resistance Patterns in Hospitalized Patients. Clinical Journal for Medicine, Health and Pharmacy, 1(1), 73-82.
3. Pal, A., & Chhabra, D. (2025). Federated Learning for Healthcare Privacy-Preserved Artificial Intelligence in Distributed Systems. International Academic Journal of Science and Engineering, 12(1), 7–11. https://doi.org/10.71086/IAJSE/V12I1/IAJSE1202
4. Moretti, A., & Tanaka, H. (2025). Securing Multi-Modal Medical Data Management System using Blockchain and the Internet of Medical Things. Global Journal of Medical Terminology Research and Informatics, 2(1), 15-21.
5. Revathi, R. (2024). Malgudi a Fictional World: A Critical Study on R.K. Narayan's Malgudi Days. International Academic Journal of Social Sciences, 11(1), 48–50. https://doi.org/10.9756/IAJSS/V11I1/IAJSS1107
6. Umamaheswari, T. S. (2025). Mathematical and Visual Comprehension of Convolutional Neural Network Model for Identifying Crop Diseases. International Academic Journal of Innovative Research, 12(1), 1–7. https://doi.org/10.71086/IAJIR/V12I1/IAJIR1201
7. Narang, I., & Kulkarni, D. (2023). Leveraging Cloud Data and AI for Evidence-based Public Policy Formulation in Smart Cities. In Cloud-Driven Policy Systems (pp. 19-24). Periodic Series in Multidisciplinary Studies.