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Review on Utilization of Industrial By-Products as Sustainable Pavement Construction Materials

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ABSTRACT

The increasing demand for sustainable pavement construction has encouraged the utilization of industrial by-products as alternative construction materials. This review examines the potential use of materials such as fly ash, steel slag, copper slag, ground granulated blast-furnace slag, foundry sand, and waste glass in pavement applications. Their engineering properties, environmental benefits, and effects on pavement performance are discussed. The review highlights that appropriate utilization of industrial by-products can reduce dependence on natural aggregates, minimize industrial waste disposal, and lower the environmental impact of road construction. However, material variability, durability, leaching concerns, and standardization remain important challenges. Overall, industrial by-products offer significant potential for developing cost-effective, durable, and environmentally sustainable pavement materials.

Keywords: Industrial By-Products; Sustainable Pavement; Waste Utilization; Recycled Materials; Pavement Construction.

1. INTRODUCTION

The rapid growth of infrastructure and transportation networks has increased the demand for pavement construction materials, particularly natural aggregates, cement, bitumen, and other conventional resources. Continuous extraction and consumption of these materials have resulted in depletion of natural resources, increased energy consumption, and environmental degradation. At the same time, rapid industrialization generates large quantities of industrial by-products such as fly ash, steel slag, copper slag, blast-furnace slag, foundry sand, and other mineral residues [1]. Improper disposal of these materials can create serious environmental problems, including land occupation, dust generation, and potential contamination of soil and water. Therefore, the utilization of industrial by-products in pavement construction has emerged as an important approach toward sustainable infrastructure development [2].

Industrial by-products possess several engineering characteristics that make them suitable for pavement applications. Materials such as steel slag and copper slag can be used as partial or complete substitutes for conventional aggregates, while fly ash and ground granulated blast-furnace slag can be incorporated as supplementary cementitious materials in pavement concrete [3].

Waste foundry sand and other industrial residues can also be utilized in pavement subgrade, sub-base, base-course, asphalt mixtures, and concrete systems. Their incorporation can

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reduce the consumption of virgin materials, minimize waste disposal requirements, and potentially improve selected mechanical and durability properties of pavement materials [4].

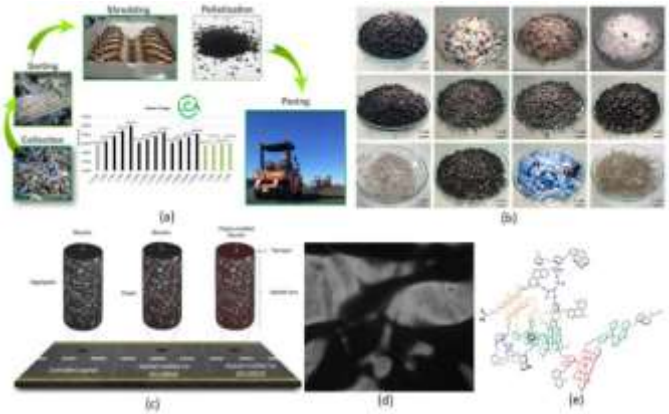


Fig.1. Sustainable Pavement Construction Materials

The use of industrial by-products also contributes to the principles of the circular economy by converting waste materials into valuable construction resources [5]. From an environmental perspective, such utilization can reduce the pressure on natural aggregate sources and decrease the quantity of industrial waste sent to landfills [6]. So, replacing energy-intensive conventional materials with suitable industrial residues may contribute to reductions in embodied energy and greenhouse-gas emissions associated with pavement construction [7].

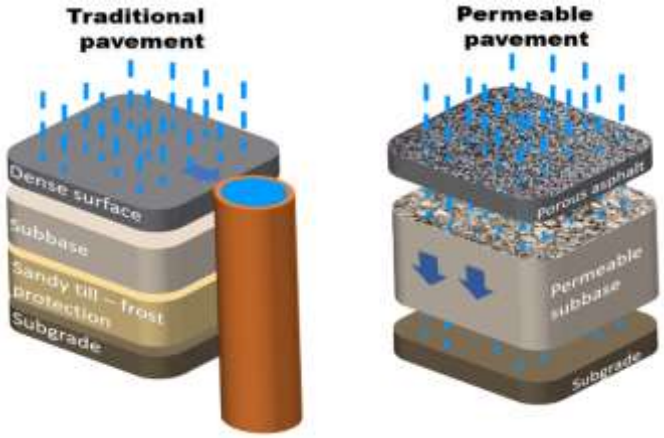


Fig.2. Permeable Pavements a Sustainable Solution.

Despite significant research in this area, challenges remain regarding material variability, moisture sensitivity, volume stability, heavy-metal leaching, durability, compatibility with conventional pavement materials, and the absence of uniform standards for large-scale application. Furthermore, the performance of industrial by-products can vary considerably depending on their source, processing method, replacement percentage, and pavement layer in which they are incorporated. Therefore, systematic evaluation is necessary before recommending their widespread field application [8].

In this context, the present review examines the utilization of industrial by-products as sustainable pavement construction materials. The review focuses on major industrial residues, their physical and engineering properties, applications in different pavement layers, effects on

mechanical and durability performance, environmental and economic benefits, and associated limitations. The study also identifies existing research gaps and future opportunities for developing durable, economical, and environmentally sustainable pavement systems through effective industrial waste utilization [9].

2. PAVEMENT CONSTRUCTION MATERIALS

Pavement construction materials are the fundamental components used to construct different layers of a road pavement system and are responsible for providing adequate strength, stability, durability, load-bearing capacity, and resistance to environmental actions [10]. A conventional flexible or rigid pavement generally consists of several layers, including the subgrade, sub-base, base course, binder or intermediate layer, and surface course. The selection and quality of materials used in these layers directly influence pavement performance, service life, maintenance requirements, and overall construction cost. Traditionally, pavement construction relies heavily on natural aggregates, cement, bitumen, soil, and mineral fillers. However, increasing environmental concerns and depletion of natural resources have encouraged researchers to investigate alternative and recycled materials [1, 2, 3].

1. Natural Aggregates

Natural aggregates such as crushed stone, gravel, and sand are extensively used in pavement base, sub-base, asphalt mixtures, and concrete pavements. Aggregates provide the structural skeleton of pavement materials and are required to possess adequate crushing strength, abrasion resistance, impact resistance, toughness, hardness, particle shape, and durability. Good-quality aggregates contribute to the development of stable pavement layers capable of resisting repeated traffic loading. However, excessive quarrying of natural aggregates results in land degradation, habitat disturbance, dust generation, and depletion of non-renewable resources. Consequently, replacing a portion of natural aggregates with suitable industrial by-products has become an important area of sustainable pavement research.

2. Cement

Portland cement is primarily used as a binding material in rigid pavement and cement-treated base layers. It binds aggregates together and provides high compressive strength and structural stability. However, cement production is highly energy-intensive and contributes substantially to global carbon dioxide emissions. This environmental impact has encouraged the use of supplementary cementitious materials such as fly ash, ground granulated blast-furnace slag (GGBFS), silica-rich industrial residues, and other mineral by-products. Partial replacement of cement with suitable industrial residues can reduce cement consumption while maintaining or improving selected strength and durability characteristics.

3. Bitumen

Bitumen acts as the principal binder in flexible pavement and asphalt mixtures. It coats and binds aggregate particles, providing cohesion and flexibility to the pavement surface. Important properties of bitumen include viscosity, penetration, softening point, ductility, temperature susceptibility, and resistance to ageing. Conventional petroleum-derived bitumen is a non-renewable material, and its production and processing have environmental

implications. Sustainable pavement research therefore increasingly investigates modified binders, recycled materials, industrial residues, and waste-derived additives to reduce dependence on conventional bituminous materials.

4. Soil and Subgrade Materials

The subgrade forms the foundation of the pavement structure and supports the loads transferred from the upper pavement layers. Its performance depends on properties such as particle-size distribution, plasticity, compaction characteristics, moisture content, bearing capacity, shear strength, and swelling behaviour. Weak or expansive soils may require stabilization before pavement construction. Industrial by-products such as fly ash, lime-rich residues, slag, and other suitable materials can be incorporated into problematic soils to improve strength, reduce plasticity, control swelling, and enhance bearing capacity.

5. Granular Base and Sub-Base Materials

The base and sub-base layers distribute traffic loads over the underlying subgrade and provide drainage and structural support. Crushed aggregates, granular soil, gravel, and sand are commonly used in these layers. Materials used for base and sub-base construction should exhibit adequate CBR, resilient modulus, shear strength, drainage characteristics, compaction, and resistance to deformation. Industrial by-products such as steel slag, copper slag, foundry sand, fly ash, and processed industrial aggregates have been investigated as alternatives to conventional granular materials.

6. Mineral Fillers

Mineral fillers are fine particles incorporated into asphalt mixtures to fill voids between aggregate particles and improve the stiffness and stability of asphalt mastic. Conventional fillers include limestone dust, stone dust, cement, and hydrated lime. Certain industrial by-products, including fly ash, steel slag fines, copper slag fines, and other mineral residues, can potentially serve as alternative fillers. Their effectiveness depends on particle size, chemical composition, surface characteristics, and interaction with the bituminous binder.

7. Industrial By-Products as Alternative Pavement Materials

Industrial by-products have gained considerable attention because many of them possess physical and chemical properties suitable for pavement construction. Fly ash can be used in soil stabilization and cementitious pavement systems, while steel slag can serve as an aggregate in asphalt mixtures and granular layers. Copper slag has been investigated as an alternative fine or coarse aggregate, and GGBFS can partially replace Portland cement in concrete pavement. Foundry sand can be utilized in sub-base, base, soil stabilization, and concrete applications after appropriate processing and environmental evaluation.

The selection of an industrial by-product should not be based solely on its availability. Its chemical composition, particle-size distribution, specific gravity, water absorption, strength, durability, leaching characteristics, and compatibility with other pavement materials must be evaluated. Appropriate processing, grading, blending, and treatment may be necessary to achieve the required engineering performance.

3. PROBLEM IDENTIFICATION

The rapid expansion of road infrastructure has significantly increased the demand for natural aggregates, cement, bituminous materials, and other conventional pavement construction resources. Continuous extraction of natural materials has resulted in depletion of finite resources, environmental degradation, and increased energy consumption. At the same time, industries such as steel, power generation, mining, foundries, and metal processing produce large quantities of by-products including fly ash, steel slag, copper slag, blast-furnace slag, foundry sand, and other industrial residues. Improper disposal of these materials occupies valuable land and may create environmental risks through dust generation and leaching of potentially harmful constituents. Although many industrial by-products possess suitable engineering properties for pavement applications, their utilization remains limited. The major problem is the lack of systematic assessment regarding their strength, durability, moisture resistance, volume stability, environmental safety, and long-term field performance. The properties of industrial by-products can also vary according to their source, chemical composition, processing method, and particle characteristics, making direct substitution of conventional pavement materials difficult.

Another important issue is the absence of comprehensive guidelines for determining the optimum replacement level of different industrial by-products in pavement materials. Excessive incorporation may adversely affect properties such as workability, strength, fatigue resistance, thermal stability, and durability. In addition, potential heavy-metal leaching and other environmental concerns need to be evaluated before large-scale application. Therefore, there is a need to systematically review and compare the available research on the utilization of industrial by-products in pavement construction. Such an assessment can help identify suitable industrial residues, their appropriate pavement applications, performance benefits, limitations, environmental implications, and research gaps. The present study addresses this problem by reviewing the potential of industrial by-products as sustainable, economical, and technically viable alternatives to conventional pavement construction materials.

4. LITERATURE REVIEW

1. Fiore et al. (2025) investigated the utilization of waste foundry sand (WFS) in pavement base and sub-base applications. The study evaluated compaction characteristics, California Bearing Ratio (CBR), compressive strength, and resilient modulus of WFS blended with sandy soil and hydrated lime. The findings demonstrated that WFS has considerable potential as an alternative pavement construction material and can reduce the consumption of natural aggregates while providing an effective route for industrial waste management.

2. Zhang et al. (2025) reviewed recent developments in the use of steel slag in asphalt pavements. Their review reported that steel-slag asphalt mixtures can provide improved deformation resistance, fatigue performance, skid resistance, and thermal properties because of the strong interfacial characteristics and angular aggregate structure of steel slag. However, volume expansion and potential heavy-metal leaching remain important concerns. The authors indicated that appropriate treatment and optimization of steel-slag content are essential for large-scale pavement applications.

3. Pal, Panda and Bhuyan (2025) examined the combined utilization of fly ash and copper slag in pavement-quality concrete. Fly ash was considered as a partial replacement for ordinary Portland cement, while copper slag was used as a substitute for natural river sand. The study highlighted the potential of combining industrial by-products to reduce the demand for virgin construction materials and improve the sustainability of concrete pavement construction.

4. Fiore et al. (2024/2025) assessed the engineering feasibility of waste foundry sand for pavement applications and emphasized its potential in pavement bases and sub-bases. The research considered mechanical and deformation-related properties, which are particularly important for pavement structural layers. The results support the use of properly processed foundry sand as a sustainable alternative to conventional granular materials.

5. A 2025 systematic review by Niyonyungu, Ogra and Ngcobo evaluated the environmental performance, engineering feasibility, contamination risks, and regulatory requirements associated with waste foundry sand. The review analyzed 152 peer-reviewed studies and reported that approximately 10–30% replacement levels can provide satisfactory performance in concrete and asphalt applications. Nevertheless, the authors emphasized contaminant assessment, preprocessing, certification, and regulatory monitoring before large-scale implementation.

6. A 2025 review on solid-waste valorization for low-carbon pavements examined the application of different solid waste materials in sustainable pavement systems. The study reported that incorporation of suitable waste materials can reduce waste disposal and improve the sustainability of concrete pavement. It also indicated that approximately 20–50% solid-waste incorporation can provide reasonable mechanical performance depending on the material and pavement application.

7. A 2025 comprehensive study investigated the utilization of industrial solid waste in a regenerated pavement system. The researchers incorporated materials including desulfurization ash, steel slag, and blast-furnace slag into a composite pavement system containing recycled asphalt pavement. The study evaluated mechanical performance, durability, environmental effects, and economic benefits, demonstrating the potential for integrating multiple industrial by-products with recycled pavement materials to achieve resource-efficient pavement construction.

8. Wang et al. (2024) investigated the use of copper tailings as an alternative filler in asphalt paving mastic. The researchers found that copper tailings could improve high-temperature performance because of their surface characteristics and interaction with asphalt. Although some reduction in low-temperature and moisture performance was observed, the performance remained acceptable. Leaching investigations also indicated no substantial environmental risk under the investigated conditions, supporting copper tailings as a potential sustainable asphalt material.

9. Brante Lara (2024) evaluated copper slag as an aggregate for asphalt surface treatments. The material exhibited high cubicity, low absorption, high density, and favorable adhesion with asphalt binder. The study concluded that copper slag can satisfy relevant requirements

for asphalt surface treatments and represents a sustainable alternative for low-traffic road construction while reducing dependence on conventional aggregates. 10. Sheshadri et al. (2024) investigated the use of foundry waste as aggregate in alkali-activated and conventional concrete for sustainable pavement infrastructure. The research explored the replacement of conventional fine aggregate with waste foundry sand and highlighted its potential environmental and economic advantages. The study supports the broader concept of converting industrial waste into functional pavement construction materials while reducing the demand for virgin resources.

Research Gap

The recent literature indicates that steel slag, fly ash, copper slag, copper tailings, blast-furnace slag, and waste foundry sand have substantial potential for pavement construction. However, most studies concentrate on individual by-products or specific pavement layers. There remains a need for a comprehensive comparison of mechanical performance, durability, environmental safety, carbon reduction, economic feasibility, and life-cycle impacts of different industrial by-products. In particular, long-term field performance, standardization of preprocessing methods, contaminant/leaching assessment, and development of practical guidelines for large-scale road construction require further investigation.

5. CONCLUSION

The utilization of industrial by-products in pavement construction represents a promising approach toward developing sustainable, economical, and resource-efficient transportation infrastructure. The review demonstrates that materials such as fly ash, steel slag, copper slag, ground granulated blast-furnace slag (GGBFS), foundry sand, and other industrial residues possess considerable potential for replacing or partially replacing conventional pavement materials. Their appropriate incorporation into subgrade, sub-base, base course, asphalt mixtures, and concrete pavement can reduce the consumption of natural aggregates and cement while providing an effective alternative for industrial waste management. The reviewed studies indicate that steel slag and copper slag can provide satisfactory aggregate characteristics because of their hardness, angularity, and abrasion resistance, making them particularly suitable for asphalt and granular pavement applications. Fly ash and GGBFS can contribute to soil stabilization and cementitious systems through their pozzolanic and hydraulic properties. Similarly, foundry sand has demonstrated potential as a replacement for natural sand and granular materials in pavement-related applications. However, the performance of these materials depends strongly on their physical and chemical characteristics, source, processing method, and replacement percentage. From an environmental perspective, the use of industrial by-products can provide multiple benefits, including reduction in landfill disposal, conservation of natural resources, reduction in quarrying activities, and potential reduction in embodied energy and greenhouse-gas emissions. Their utilization also supports the principles of the circular economy by converting industrial waste into valuable construction resources. In addition, the use of locally available industrial residues may reduce material transportation requirements and

contribute to cost savings in pavement construction. Despite these advantages, several limitations need to be addressed before large-scale implementation. Material variability, volume expansion of certain slags, moisture sensitivity, durability, leaching of potentially harmful constituents, compatibility with conventional materials, and lack of standardized specifications remain important concerns. Therefore, industrial by-products should not be directly incorporated into pavement systems without appropriate characterization, processing, laboratory testing, and environmental assessment. Overall, industrial by-products have significant potential to serve as technically viable and environmentally sustainable alternatives to conventional pavement construction materials. Future research should focus on long-term field performance, life-cycle assessment, carbon reduction, economic evaluation, advanced material treatment, and the development of standardized guidelines for different industrial by-products. A systematic engineering performance and environmental safety assessment can facilitate the wider adoption of these materials and contribute to the development of durable, cost-effective, and sustainable pavement infrastructure.

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