Journal for Re Attach Therapy and Developmental Diversities
eISSN: 2589-7799
2023 December; 6 (10s2): 1642-1648

Enhancing Sustainability and Cost-Effectiveness of Flexible Pavements through Recycled Materials and By-Products

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Received: 19-July -2023 **Revised:** 02-Aug -2023 **Accepted:** 10-Sept-2023

Abstract

Flexible pavements play a crucial role in modern infrastructure, offering safe and reliable transportation routes. Nevertheless, the conventional construction and maintenance of flexible pavements carry significant environmental and economic implications, originate from the extensive utilization of natural resources and the generation of substantial amounts of waste. This paper delves into the potential of employing recycled materials and by-products in flexible pavements as an environmentally sustainable and cost-effective alternative. The study examines the technical performance, economic feasibility, and environmental benefits associated with incorporating recycled materials and by-products in the design, construction, and maintenance of flexible pavements. The findings demonstrate that the utilization of recycled materials and by-products in flexible pavements can contribute to resource conservation, waste reduction, and improved sustainability, all while maintaining the required structural and functional characteristics of the pavement.

Keywords: Flexible pavement; recycled material; by-products; sustainability; environmental impact, cost-effectiveness.

1. INTRODUCTION

Flexible pavements play a pivotal role in the transportation infrastructure by serving as pathways for the efficient movement of people and goods. These pavements are composed of multiple layers, including a surface, base, and sub base layer, strategically designed to evenly distribute traffic loads and create a durable, smooth surface. Nevertheless, the conventional construction and maintenance practices associated with these pavements pose significant environmental and economic challenges by depletion of finite natural resources. In recent times, there has been a growing interest in addressing these challenges by incorporating by-products and recycled materials into flexible pavement construction. Utilizing recycled materials and by-products presents potential benefits, including resource conservation, waste reduction, and enhanced sustainability. These materials can be derived from various sources, such as recycled concrete aggregate, reclaimed asphalt pavement, and industrial by-products like slag, fly ash, plastic, glass, and rubber and many more. Many of these materials can be added to bituminous mixes and a few can be utilized to modify the bitumen. Even though bituminous binders are commonly employed in the construction of flexible pavements, their performance has not been adequate under certain conditions due to insufficient tensile strength and limited endurance in harsh weather conditions. In response to these concerns use of polymers, natural rubber, crumb rubber has been made in modification of the binder and the same is being explored for a few other recycled materials.

India has witnessed a surge in the popularity of recycling pavements. The scarcity of unprocessed aggregate resources and the escalating costs associated with processing have prompted the adoption of recycled materials like Reclaimed Asphalt Pavement (RAP) and Recycled Concrete Aggregates (RCA) as viable alternatives.

Numerous research efforts have performed into the utilization of recycled materials, waste by-products, and alternative construction methods to enhance the performance, durability, and environmental impact of flexible pavements. In 1819, Wen et al. [1] explored the use of crumbled asphalt pavements combined with fly ash and water as a base course material, demonstrating the cost-effectiveness of Cold In-place Recycling (CIR) with self-cementing fly ash. An alternative stabilisation agent, foaming tar, was identified to improve workability and extend placement time.Li et al. [2] assessed the efficacy of recycled pavement materials (RPMs) stabilized with cementitious high-carbon fly ash (CHCFA) as a base course, considering performance, costs, energy consumption, and greenhouse gas emissions. Frantzis [3] investigated the incorporation of discarded tires in flexible pavements, highlighting the potential of waste tire rubber as reinforcement in bituminous binder for durable wearing courses in all weather conditions. Nascimento et al. [4] introduced a methodology employing life cycle assessment and data envelopment analysis to identify suitable constructions for flexible road pavement, emphasizing the environmentally friendly profile of a bitumen-stabilized foundation incorporating 15%

recycled material, specifically waste tire rubber. The study underscored the significance of recycling municipal and industrial waste in response to escalating urbanization and population growth. Modified binders incorporating municipal plastic and rubber wastes exhibited improved resistance to permanent deformation and fatigue. Modarres and Hamedi [5] explored the resilience modulus and fatigue properties of asphalt mixtures modified with waste plastic bottles, observing enhancements in fatigue life. The effective use of plastic waste in hot mix asphalt (HMA) was identified as a viable method for road paving, enhancing properties like indirect tensile strength and traction coefficient. This technology gained recognition for its role in reducing plastic incineration, cutting waste management expenses, and lowering greenhouse gas emissions.

Rezende and Carvalho [6] explored the viability of utilizing quarry wastes as a foundational layer material, emphasizing the favorable attributes of quarry waste for flexible pavements. Al-Homidy et al. [7] suggested the integration of Electric Arc Furnace Dust (EAFD) and cement into dune sand, aiming to improve stability for sub-base layers. Aziz et al. [8] investigated alternative binders for bitumen, proposing bio-oil, polymer, and waste cooking oil as feasible substitutes in constructing flexible pavements. Kulkarni & Ranadive [9] found that pyro-oil derived from municipal plastic waste has the potential to serve as a viable alternative to diesel in the production of modified cutback bitumen. Rahman et al. [10] introduced an environmentally conscious methodology to utilize used cigarette filters in bitumen for constructing resilient road surfaces. Rice Husk Ash (RHA) and Bio-oil (BO) can be used as modifiers to enhance the high-temperature properties of the asphalt binder, referred to as RHA Modified Asphalt (RB-MA). Pasandín and Pérez [11] determined that recycled concrete aggregates (RCA) can be effectively utilized in flexible road pavements with hot-mix asphalt (HMA). They recognized recycled concrete aggregate (RCA) as a viable alternative for subbase and light-duty base materials of satisfactory quality in constructing road pavements. El-Hakim and Tighe [12] focused on the viability of eternal flexible pavement design, emphasizing the benefits of recycled bitumen/asphalt pavement in enhancing mechanical properties and optimizing resource utilization. Moghadas et al. [13] conducted experiments to characterize the permanent deformation of warm mix asphalt (WMA) mixes using RAP. Thakur et al. [14] examined the impact of geocell confinement, base course thickness, base course strength, and subgrade strength on the permanent and resilient deformations of reinforced RAP bases. The study found that incorporating hydrophobic substances enhanced moisture sensitivity and rutting resistance. A comparative life cycle assessment (LCA) evaluated various warm mix asphalt (WMA) technologies and recycling rates, indicating that foamed-based WMA mixtures with a 50% RAP component throughout the pavement's lifespan are the most ecologically sustainable option.

This present study investigates the technical, economic, and environmental considerations associated with the integration of recycled materials, by-products, and waste materials in the design, implementation, and upkeep of flexible pavements. It aims to provide a comprehensive review of the potential advantages and challenges related to the utilization of recycled materials and by-products in flexible pavements, drawing insights from available literature on the environmental and economic consequences of such incorporation. As a result, this study contributes to fostering well-informed decision-making processes concerning use or recycled materials and various by-products in highway construction.

2. SELECTION AND CHARACTERISATION OF RECYCLED MATERIALS

Identifying potential waste materials for incorporation into flexible pavements is a crucial undertaking for advancing sustainable and environmentally conscious practices in pavement construction. This process involves assessing the technical, environmental, and economic viability of utilizing waste materials as constituents of pavements. There is a wide range of waste materials that may be utilized in the construction of flexible pavements to improve sustainability and address environmental issues, as detailed in Table 1 and Table 2. These materials may serve as replacements or supplements for traditional pavement components. Selection criteria are determined based on material characterization results, performance evaluations, and compatibility assessments, considering factors such as strength, stiffness, durability, availability, cost-effectiveness, and environmental advantages.

Table 1: Waste materials and their application in road construction.

S. N.	Material	Sources	Used as	Advantages
1.	Reclaimed/recycled asphalt pavement	Milled or crushed asphalt pavement	- Reused in new asphalt mixes - Base and surface courses	- Reducing the need for new aggregates. - Enhance flexibility, durability, and resistance to cracking.
2.	Construction and Demolition waste	Demolished or discarded building materials	- Base and Sub-base material	May either enhance or may dilute pavement durability, flexibility, and resistance to cracking.
3.	Quarry waste	Waste generated during the extraction of natural aggregates.	- Partial substitute for natural aggregates. - Base or sub-base material	- Reduce natural resource consumption
4.	Waste tires rubber	Discarded rubber tires (vehicles)	- Preparing CRMB binder - Lightweight fill material	Improve pavement performance, reduce road noise, and enhance durability, improve temperature susceptibility
5.	Waste plastic	Discarded plastic items	Partial replacement for bitumen	Enhance pavement flexibility and reduce environmental impact.

6.	Fly ash	By-product of coal combustion in power plants	- Stabilization of soil and subgrade	Enhancing pavement's strength, durability, and resistance to deformation under traffic loads
7.	Blast furnace slag	By-product of the iron and steel industry	- Asphalt aggregate - Filler materials	Enhance fatigue life, rutting resistance, and asphalt mixture performance.
8.	Electric arc furnace slag	By-product of the steel-making process	- Partial replacement for conventional materials such as aggregates and mineral fillers.	Enhance rutting resistance, stiffness, and fatigue performance.
9.	Amorphous carbon powder	Carbon-rich waste material	Asphalt modifier	Exhibit higher rutting resistance
10.	Rice husk ash	By product of burning rice husks	- Stabilization of soil and subgrade	- Enhance the strength, resistance to water infiltration and stability of the pavement mixture. - may Reduce the permeability, and susceptibility to cracking
11.	Brick dust waste	Waste generated during brick production	Pozzolanic material in pavement mixes. Stabilizer for sub-grade soil	Enhance strength, durability, and long-term performance of pavements
12.	Palm oil fuel ash	By-product of palm oil combustion	Asphalt modifier	Improve the visco-elastic properties of the bitumen
13.	Bio-oil and waste cooking oil	Waste from cooking processes	Partial replacement for conventional asphalt binder	Improve flexibility, adhesion, and resistance to temperature-related distress
14.	Fluorescent lamp waste	Discarded fluorescent lamps	Filler material	Enhance skid resistance and pavement performance

Table 2: Materials used in flexible pavement as bitumen and granular materials.

Materials	**Waste Materials**	**Application**	**Use limit**	**Reference**
Bitumen	Waste tires rubber	Wearing course /Binder course	20% (by weight of bitumen)	IRC: SP-107 [15]
	Waste plastic	Wearing course /Binder course	5-10% (by weight of bitumen)	IRC: SP-9-2013 [16]
	Reclaimed asphalt	Wearing and binder course	100 %	IRC: 120-2015 [17]
	Amorphous carbon powder	Wearing course /Binder course	10%	[18]
	Bio-oil and waste cooking oil	Wearing course /Binder course	5 %	[19]
Granular materials	Reclaimed asphalt aggregates	Granular layer	30-50%	IRC: 120-2015 [17]
	Construction and demolition waste	- Embankment - Granular layer	Upto 100%	IRC: 121-2017 [20]
	Blast furnace slag	Granular layer	3 %	[2]
	Electric arc furnace slag	Granular layer	Upto 50%	[2]
	Quarry waste	Granular layer	40%	[21]
	Fly ash	- Embankment - Stabilization	As per IRC:SP-58	IRC:SP-58 [22]
	Palm oil fuel ash	Filler	10 % (by weight of total aggregate)	[23]

3. ECONOMIC FEASIBILITY ANALYSIS

Evaluating the economic feasibility of integrating recycled materials and by-products into flexible pavements is a critical consideration. The cost-benefit analysis begins by identifying and quantifying the expenses related to the use of recycled materials, encompassing collection, processing, transportation, and quality control. These expenses are then compared to those associated with acquiring and using conventional materials. Furthermore, the analysis considers potential savings resulting from reduced waste disposal fees and the utilization of locally available recycled materials. Moreover, the assessment explores the advantages of incorporating recycled materials into flexible pavements, which may involve diminishing dependence on virgin materials, lowering energy consumption in manufacturing processes, and enhancing waste management practices. Additionally, potential long-term benefits such as an extended pavement service life and decreased maintenance requirements are considered.

To ensure a thorough cost-benefit analysis, both short-term and long-term financial implications are examined. This includes evaluating initial construction costs, life cycle costs, and potential savings throughout the pavement's lifespan. These provide valuable insights into the economic viability of integrating recycled materials and by-products into flexible pavements. Ultimately, these findings serve as a guide for policymakers, contractors, and infrastructure owners, enabling them to make informed decisions about the utilization of recycled materials and promoting more sustainable and cost-effective pavement construction practices.

4. ENVIRONMENTAL IMPACT ASSESSMENT

4.1. Environmental life cycle assessment

The Environmental Life Cycle Assessment (LCA) is a systematic approach used to assess the environmental effects linked to a product or process throughout its entire life cycle, covering the extraction of raw materials to waste disposal at the end of its lifespan. In the context of flexible pavements, Life Cycle Assessment (LCA) provides a comprehensive analysis of the environmental impacts and advantages associated with the use of recycled materials and by-products.

The primary objective of Life Cycle Assessment (LCA) is to evaluate the environmental sustainability of flexible pavements incorporating recycled materials and by-products, in contrast to traditional pavements. This study encompasses various stages of the pavement life cycle, including raw material extraction and manufacturing, transportation, pavement construction, maintenance operations, and end-of-life scenarios.

4.2. Carbon footprint analysis

Evaluating the environmental impact of incorporating recycled materials and by-products in flexible pavements relies heavily on the performance of a carbon footprint study. This study must quantify greenhouse gas emissions throughout the entire life cycle of the pavement, covering stages such as raw material extraction, manufacturing, transportation, construction, maintenance, and disposal.

The initial phase of the carbon footprint study involves identifying and quantifying greenhouse gas emissions associated with each stage of the pavement's life cycle. This includes emissions from manufacturing recycled materials and by-products, as well as those from the conventional materials and processes they replace. The study also considers energy consumption, fuel utilization, and transportation requirements related to the use of recycled materials. By comparing the carbon footprint of pavements incorporating recycled materials with traditional pavements, the research provides valuable insights into environmental advantages and potential reductions in greenhouse gas emissions. This assessment contributes to a comprehensive evaluation of the sustainability of using recycled materials in flexible pavements, aiding in making well-informed decisions about material selection and design. Furthermore, the carbon footprint analysis can identify areas for improvement to mitigate emissions, such as enhancing industrial processes, reducing energy consumption in production, improving transportation efficiency, and adopting sustainable practices in construction and maintenance.

The findings from the carbon footprint study offer essential data for policymakers, engineers, and stakeholders to make informed choices regarding the adoption and promotion of sustainable pavement practices. It supports the development of environmentally conscious plans and policies to reduce the carbon footprint associated with the construction and maintenance of flexible pavements. In summary, the carbon footprint analysis is a crucial aspect of the environmental impact assessment, enabling a thorough evaluation of the sustainability and environmental benefits of incorporating recycled materials and by-products in flexible pavements.

4.3. Waste reduction potential

Plans to reduce waste are developed based on an assessment of waste generation, with the goal of mitigating the environmental consequences associated with the building and maintenance of flexible pavements.

4.3.1. Utilization of Recycled Materials:

By integrating recycled materials and by-products into the construction of pavements, it is possible to decrease the need for virgin materials, thereby mitigating the extraction of natural resources. Typical instances of recycled materials employed in the construction of flexible pavements encompass RAP, recycled concrete aggregate (RCA), and reclaimed asphalt shingles (RAS).

4.3.2. Waste Minimization Techniques:

Incorporating strategies for waste minimization, such as optimizing material handling, enhancing construction practices, and recycling construction and demolition waste, can significantly decrease the volume of waste produced in pavement construction and maintenance activities. This involves the proper segregation and sorting of waste materials at the construction site and ensuring their proper disposal or recycling.

4.3.3. Design Optimization:

By strategically optimizing design, it is possible to maximize the utilization of recycled materials, ensuring their efficient use while meeting the necessary pavement performance standards. This involves considering the characteristics and properties of recycled materials during the design phase and integrating suitable quality control measures.

5. CHALLENGES AND FUTURE DIRECTIONS

5.1. Technical challenges and constraints

While the utilization of recycled materials and by-products in flexible pavements offers various benefits, there exist technical challenges and limitations that require attention for a successful implementation. This section outlines some key obstacles that may emerge when integrating recycled materials and by-products into pavement construction and maintenance.

5.2. Material Variability

Materials such as reclaimed asphalt pavement (RAP), recycled concrete aggregate (RCA), and industrial by-products, which are derived from recycling processes, exhibit inherent variations in their physical, chemical, and mechanical characteristics. These variations have the potential to influence the overall performance and uniformity of pavement mixtures. Therefore, it is essential to establish suitable measures for quality control and assurance to guarantee consistent material properties.

5.3. Durability Concerns

The extended resilience of flexible pavements relies on the capacity of materials to endure environmental elements such as freeze-thaw cycles, moisture infiltration, and chemical degradation. It is crucial to evaluate the endurance of recycled materials and by-products and pinpoint any possible concerns that may jeopardize the pavement's long-term effectiveness.

5.4. Compatibility and Interaction

When integrating recycled materials and by-products into pavement mixtures, it is crucial to assess their compatibility and interaction with other elements like binders and additives. Potential incompatibilities may result in diminished cohesion, heightened vulnerability to cracking, or reduced resistance to deformation. Hence, it is essential to perform thorough laboratory testing and optimize mix design to guarantee appropriate compatibility.

5.5. Engineering Properties

The engineering characteristics of recycled materials and by-products might vary from those found in traditional construction materials. These distinctions have the potential to impact the structural and functional aspects of pavements, such as strength, stiffness, fatigue resistance, and resistance to rutting. It is essential to adequately characterize and comprehend these properties to design and build pavement structures that fulfil the necessary performance criteria.

5.6. Regulatory and Specification Challenges

Utilizing recycled materials and by-products in flexible pavements might encounter regulatory limitations and specific requirements that require attention. It is crucial to engage with regulatory bodies, standardization organizations, and industry stakeholders to formulate suitable guidelines, specifications, and performance criteria. This collaborative effort is essential for promoting the extensive integration of recycled materials and by-products in the construction of pavements.

5.7. Quality Control and Assurance

Ensuring uniform quality control and assurance throughout the entire process of pavement construction is pivotal for the successful utilization of recycled materials and by-products. This encompasses accurate material characterization, optimization of mix design, adherence to construction practices, and the incorporation of quality testing procedures. It is crucial to establish robust quality control protocols and training programs for construction personnel to uphold the desired pavement performance.

To tackle these technical challenges and limitations, it is necessary to engage in multidisciplinary research efforts, foster collaboration among researchers, practitioners, and industry stakeholders, and promote the development of innovative technologies and methodologies. Overcoming these challenges will contribute significantly to the widespread adoption of recycled materials and by-products in flexible pavements, thereby fostering a more sustainable and cost-effective transportation infrastructure.

6. CONCLUSION

This study regarding the incorporation of recycled materials and by-products in flexible pavements carry significant implications for both the construction industry and the advancement of sustainable infrastructure. The following implications and recommendations have drawn from the conducted research:

- The inclusion of recycled materials and by-products in flexible pavements holds the potential to contribute significantly to sustainable infrastructure development. This contribution is achieved by diminishing the demand for virgin materials, preserving natural resources, and minimizing waste generation. The utilization of these materials can effectively reduce the carbon footprint and environmental impact associated with the construction and maintenance of pavements.
- The economic feasibility analysis undertaken in this study indicates that incorporating recycled materials and by-products in flexible pavements can yield cost advantages compared to conventional materials. The implementation of recycling practices may result in decreased material costs, lower transportation expenses, and potential savings in landfill disposal fees. These cost benefits can positively impact project budgets and overall construction expenditures.
- This study suggests that, with appropriate testing and characterization, recycled materials can fulfil the necessary structural and functional requirements of flexible pavements. Further research is encouraged to optimize the design and mix proportions of recycled material blends, enhancing their performance and long-term durability.
- To ensure the successful integration of recycled materials in flexible pavements, it is crucial to develop quality control and assurance procedures. These procedures should encompass standardized testing protocols, material selection

specifications, and quality monitoring during construction. Establishing guidelines and protocols for the proper processing, handling, and incorporation of recycled materials into pavement layers is essential to ensure consistent performance and quality.

- Governments and regulatory bodies play a pivotal role in promoting the use of recycled materials in infrastructure projects. It is recommended that policymakers formulate supportive regulations, guidelines, and incentives to encourage the adoption of recycled materials in flexible pavements. This may involve incorporating recycled content requirements in project specifications, providing financial incentives or tax credits for the use of recycled materials, and promoting research and development in sustainable pavement technologies.
- Collaboration among stakeholders, including researchers, engineers, contractors, material suppliers, and policymakers, is indispensable for advancing the use of recycled materials in flexible pavements. Establishing platforms for knowledge sharing, such as workshops, conferences, and industry forums, can facilitate the exchange of best practices, lessons learned, and ongoing research in the field. Encouraging collaboration among academia, industry, and government agencies is recommended to foster innovation and the widespread adoption of sustainable pavement practices.

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