



ABSTRACT

The serious degradation of road infrastructure and the demand for green pavement materials and lifecycle cost-effective solutions have prompted the embracing of green pavement materials and lifecycle cost-effective practices. The research explores optimization of blends of sustainable road materials through an approach having a materials engineering method with no application of artificial intelligence strategies. Five asphalt mixes with various

A I-FREE OPTIMIZATION OF SUSTAINABLE PAVEMENT MATERIALS FOR COST-EFFICIENT HIGHWAY CONSTRUCTION: A LIFECYCLE- BASED ENGINEERING APPROACH

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Introduction

The global transportation sector is witnessing an urgent call for sustainable infrastructure solutions, particularly in highway construction, where traditional practices heavily rely on energy-intensive materials and non-renewable resources. Pavements, which account for a significant portion of highway systems, not only consume vast amounts of raw materials but also contribute substantially to greenhouse gas (GHG) emissions throughout their lifecycle (Chen et al., 2022). The transition to sustainable pavement materials is not just an



percentages (0%–40%) of industrial by-products and recycled materials like Reclaimed Asphalt Pavement (RAP), Fly Ash, and Ground Granulated Blast Furnace Slag (GGBS) were tested as part of a systematic experimental program. A range of laboratory tests including Marshall Stability, Indirect Tensile Strength, Rutting Resistance, and Fatigue Life for determining mechanical properties and durability were conducted. In addition to the mechanical testing, Lifecycle Cost Analysis (LCA) and an Environmental Lifecycle Assessment (LCA) were performed to identify long-term economic and environmental effects. Outcomes indicate 30% sustainable content blends with improved balance when performance, cost, and environmental performance metrics are taken into account. The use of Multi-Criteria Decision Analysis (MCDA) identified the 30% mix as the most suitable composition that facilitated up to 22% cost saving and 35% CO₂ reduction against the control blend. This study provides data-based, reproducible framework for highway authorities to make infrastructure more sustainable without using AI software, advancing global sustainable development objectives.

Keywords: Sustainable Pavement Materials, Highway Construction; Lifecycle Cost Analysis Cost-Efficient Infrastructure; Recycled Materials; Green Engineering, Pavement Performance, Environmental Impact; Infrastructure Sustainability; Materials Optimization.

environmental imperative but also an economic necessity, especially in developing economies where budget constraints and environmental regulations must be carefully balanced (Singh & Ghosh, 2021). In recent years, significant attention has been directed toward the incorporation of sustainable and waste-derived materials in pavement design such as Reclaimed Asphalt Pavement (RAP), fly ash, Ground Granulated Blast Furnace Slag (GGBS), and plastic additives. These materials have shown promising mechanical and environmental performance when integrated properly, often improving durability while reducing lifecycle costs (Al-Busaltan et al., 2023). However, despite their advantages, the optimal utilization of such materials remains a complex engineering challenge, especially when not relying on artificial intelligence or machine learning tools to aid decision-making.

Lifecycle-based assessment frameworks have emerged as vital tools for evaluating the long-term implications of pavement material choices. These frameworks combine lifecycle cost analysis (LCCA) and environmental lifecycle assessment (LCA) to offer a comprehensive perspective on material performance across construction, maintenance, and disposal phases (Mukherjee et al., 2022). By incorporating both economic and environmental indicators, researchers can identify material



configurations that deliver maximum value over extended service periods without sacrificing mechanical integrity.

Past studies have adopted AI-powered optimization approaches for such evaluations, leveraging machine learning algorithms for predictive performance modelling (Zhang et al., 2020). While these techniques offer predictive accuracy, they often lack transparency and are inaccessible to low-resource agencies. There remains a critical need for empirical, data-driven approaches rooted in physical testing and classical engineering analysis that can yield reliable, verifiable results without requiring advanced computational tools (Rahman & Islam, 2023).

This research bridges this gap by developing a comprehensive experimental methodology for evaluating sustainable pavement materials based on real-world mechanical testing and lifecycle evaluations, completely excluding AI-based tools. The study analyses five different asphalt mix designs with varying proportions of sustainable content and assesses them using standardized laboratory tests, cost estimation models, and environmental impact metrics. A multi-criteria decision analysis (MCDA) framework is employed to identify the optimal mix design based on performance, cost, and ecological footprint.

The outcome of this study contributes to the body of knowledge on sustainable transportation infrastructure by providing a replicable, low-tech framework that can be adopted by agencies in both developed and developing countries. Furthermore, it reinforces the feasibility of achieving sustainability goals in highway construction through traditional materials engineering and decision science.

Review of Related Literature

1. Sustainable Pavement Materials in Highway Construction

In the past two decades, the pursuit of sustainability in infrastructure has driven researchers and practitioners to explore alternative pavement materials that reduce environmental impact without compromising performance. Reclaimed Asphalt Pavement (RAP), industrial by-products like fly ash and Ground Granulated Blast Furnace Slag (GGBS), and recycled plastic composites have gained traction due to their durability, cost efficiency, and environmental benefits (Zhou et al., 2021). These materials not only reduce reliance on virgin aggregates and binders but also lower greenhouse gas (GHG) emissions and landfill dependency (Mousavi et al., 2022).

Fly ash, a by-product of coal combustion, enhances the workability and durability of asphalt mixtures, especially when used as a filler or binder modifier (Ahmed et al., 2021). GGBS, with its high latent hydraulic reactivity, contributes to long-term strength and moisture resistance, making it a valuable additive in pavement base layers (Kim et al., 2020). These benefits are maximized when optimal proportions are established through performance-based mix designs.



2. Performance Evaluation Techniques for Pavement Mixtures

Standard mechanical performance evaluations such as Indirect Tensile Strength (ITS), Marshall Stability, and rutting resistance tests are widely used to assess the suitability of pavement materials. These tests provide empirical data on structural integrity, load distribution, fatigue performance, and moisture sensitivity (Singh et al., 2023). When sustainable materials are used, performance testing becomes crucial in ensuring that recycled content does not degrade mechanical behaviour.

Field studies have revealed that RAP-inclusive mixtures perform comparably to virgin mixes when RAP content is kept below 30–40%, beyond which stiffness and cracking susceptibility may increase (Jahanian et al., 2022). However, proper binder rejuvenation and blending techniques have been shown to mitigate these drawbacks effectively.

3. Lifecycle Cost Analysis (LCCA) and Environmental Assessment (LCA)

Lifecycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) are essential tools in evaluating the economic and environmental sustainability of pavement systems. LCCA helps quantify the total costs associated with construction, maintenance, rehabilitation, and salvage over the entire life of the pavement (Walls & Smith, 2021). On the other hand, LCA considers raw material extraction, processing, transport, and emissions, offering a holistic picture of environmental impact.

For example, a study by Ali et al. (2020) reported that pavement systems incorporating 25% RAP and 10% fly ash achieved 20% lower lifecycle costs and 30% less CO₂ emissions compared to conventional designs. These findings highlight the significance of integrating LCCA and LCA in early-stage pavement design decisions, especially when sustainable alternatives are considered.

4. Multi-Criteria Decision Analysis (MCDA) in Pavement Material Selection

MCDA provides a structured decision-making approach for evaluating competing alternatives based on multiple criteria such as cost, performance, and environmental impact. Techniques like the Analytic Hierarchy Process (AHP) and Weighted Sum Model (WSM) have been used in material selection frameworks (Huang et al., 2022). AHP-based studies have demonstrated that when proper weights are assigned based on project-specific goals, sustainable mix designs often outperform conventional materials in overall rankings. Importantly, MCDA frameworks can be executed without AI or machine learning tools, making them accessible and transparent for engineers and stakeholders operating in non-digital environments (Chowdhury & Khare, 2023).

5. Limitations of AI-Based Pavement Design Models

While artificial intelligence techniques such as Artificial Neural Networks (ANNs) and Support Vector Machines (SVMs) have demonstrated efficacy in forecasting pavement performance and optimizing material combinations, their dependency on large datasets, complex programming, and black-box behaviour poses challenges



(Wang et al., 2023). These methods may not be practical for agencies with limited technical capacity or in regions lacking digital infrastructure.

Furthermore, the interpretability of AI models is limited, often leaving engineers without clear insights into material behaviour. As a result, several researchers have advocated for empirical, transparent, and replicable optimization methods grounded in laboratory data (Niazi et al., 2021). This supports the methodology used in this study, which avoids AI tools and emphasizes engineering judgment and physical testing.

Sustainable Pavement Materials in Highway Construction

Sustainable pavement materials are engineered to reduce environmental impact, promote resource efficiency, and enhance long-term performance in highway construction. Unlike traditional materials that rely heavily on virgin aggregates and bitumen, sustainable alternatives focus on recycling, renewable sources, and low-energy production techniques (Zhao et al., 2023).

Key examples include Reclaimed Asphalt Pavement (RAP), Warm Mix Asphalt (WMA), Recycled Concrete Aggregate (RCA), and bio-based binders, all of which contribute to lower greenhouse gas emissions, reduced landfill waste, and improved lifecycle cost-efficiency (Karakas et al., 2022). These materials also support circular economy principles by reusing construction and demolition waste while maintaining mechanical performance standards (Chen et al., 2024).

The integration of sustainable materials is increasingly supported by life cycle assessment (LCA) methodologies and performance-based design standards that ensure structural reliability and cost-effectiveness over time (Li et al., 2022). As global infrastructure demands grow, these materials are vital to building resilient, climate-adaptive, and environmentally responsible road networks.

Brief Overview of Pavement

Pavements are engineered layers of materials laid on the natural ground to provide a stable surface for vehicular and pedestrian traffic. Their primary function is to distribute traffic loads to the underlying subgrade while maintaining riding comfort, safety, and durability (Mroueh & Lahdar, 2021). Pavements are generally categorized into two main types: flexible pavements, which consist of multiple layers including asphalt bound surfaces, and rigid pavements, typically made of reinforced or plain concrete slabs (Sarsam, 2020).

The design and performance of pavement systems depend on various factors including traffic load, climate conditions, material properties, and subgrade strength. Advances in pavement engineering have emphasized life-cycle performance, Joshua Chukwuemeka Emeghai (2021), cost-efficiency, and sustainability. As transportation demands grow, modern pavement design integrates concepts such as perpetual pavement, mechanistic-empirical (M-E) design, and smart infrastructure technologies



for real-time monitoring and maintenance (Alhassan et al., 2022). Innovations like intelligent compaction, geosynthetics, and recycled materials have significantly improved the structural integrity and environmental footprint of pavements (Jasim et al., 2023). Furthermore, global interest in climate-resilient pavements has prompted the use of permeable pavements and reflective surfaces to mitigate urban heat island effects and surface runoff (Hasheminejad & Afshar, 2021).

A Lifecycle-Based Engineering Approach

A lifecycle-based engineering approach in pavement construction considers the entire lifespan of pavement materials from raw material extraction and production, through construction and use, to end-of-life disposal or recycling. This method aims to optimize performance, cost-efficiency, and environmental sustainability throughout the pavement's service life (Singh et al., 2023).

By integrating Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA), engineers can quantitatively evaluate the environmental impacts, energy consumption, and long-term maintenance needs of various pavement material choices (Adeyemi & Jamshidi, 2022). This enables the selection of materials and processes that reduce greenhouse gas emissions, minimize resource depletion, and extend pavement longevity without compromising structural integrity (Wang et al., 2021).

Such an approach is essential for sustainable highway infrastructure, especially under growing climate and economic constraints. It allows for evidence-based decision-making and supports the adoption of recycled and renewable materials that align with circular economy principles and green construction policies (González-Torre et al., 2024).

Cost-Efficient Highway Construction

Cost-efficiency in highway construction transcends mere budget reduction; it emphasizes strategic resource use, performance sustainability, and long-term economic return. One of the foundational principles is Life Cycle Cost Analysis (LCCA), which helps stakeholders assess not just the initial construction cost, but also future expenditures related to maintenance, rehabilitation, and disposal (Li et al., 2021). LCCA allows engineers and policymakers to make data-driven decisions on materials and design configurations that offer the best value over time.

Another important aspect is the use of alternative and locally sourced materials, such as recycled asphalt pavement (RAP), fly ash, and crushed concrete aggregates, which significantly lower material costs and reduce environmental impact (Agyekum et al., 2022). The use of these sustainable materials also aligns with green construction policies while cutting down on transportation and processing expenses.



Design optimization using modern tools like Building Information Modeling (BIM) and geographic information systems (GIS) can improve efficiency by reducing rework, minimizing waste, and optimizing logistics (Karthik & Marzouk, 2023). Moreover, modular and prefabricated pavement systems have shown promise in accelerating project timelines, thus reducing labor costs and avoiding prolonged road closures that impact productivity and fuel consumption (Ramachandran et al., 2020).

Importantly, adopting performance-based specifications ensures that materials and designs are selected based on actual service expectations rather than generic standards, further promoting cost-effectiveness (Gordillo et al., 2021). Together, these practices help deliver highway infrastructure that is not only economically viable but also environmentally responsible and technically robust.

“AI simulates human intelligence processes by machines, especially computer systems. AI encompasses intelligent robotics, reinforcement learning, machine learning, and deep learning. It involves various techniques, such as reinforcement learning, supervised/unsupervised machine learning, neural networks, deep learning, and generative AI algorithms. Green AI is assessing the CO₂ emissions during computing AI to minimise environmental impact. Green AI or sustainable AI should be the new direction for AI to maintain computational sustainability. Integrating AI and green artificial intelligence (GAI) in sustainable construction engineering heralds a new transformative era, fostering innovation across various domains Haytham Elmousalami, et al (2025).

Technological Integration:

Exploring the use of technology to enhance human-building interaction, such as smart building systems and adaptive environments Confidence Adimchi, et al (2025).

Traditional materials and initial recycling needs

Historically, pavement structures were made up of asphalt (rigid bituminous, flexible layers) and Portland-cement concrete (rigid slabs), with performance determined by traffic loading, climate, and subgrade support. An influential review by Huang, Bird, and Heidrich (2007) collated initial results on the use of recycled solid wastes—waste glass, steel slag, tires, plastics materials in asphalt mixtures and noted the promise and need for stringent specifications and durability testing.

Reclaimed asphalt pavement (RAP) in asphalt mixtures

RAP is the most commonly used recycled material for flexible pavements. Zaumanis and Mallick reviews and case syntheses document mix design practices, manufacturing limitations, and rejuvenator application for high and very high RAP contents, demonstrating that with adequate binder control and quality assurance,



structural and functional characteristics can be retained with less environmental impact.

Warm-mix asphalt (WMA) and energy/emission savings

Compared to hot-mix asphalt, WMA allows for production temperatures 20–40 °C lower, reducing fuel consumption and emissions and in most cases enhancing compaction/working windows. Rubio, Martínez, Baena, and Moreno (2012) review is a highly cited WMA technology, mechanism (foaming/chemical/organic), and field performance synthesis that confirms WMA as an alternative route to sustainability with RAP.

Life-cycle thinking: environmental LCA and cost LCCA

For comparison of material selection outside of initial cost, some studies apply life-cycle assessment (LCA). Hybrid LCA was utilized by Aurangzeb, Al-Qadi, Ozer, and Yang to demonstrate the environmental benefits of high-RAP mixes following accounting for manufacturing and maintenance phases. Comparison of options like WMA and cold in-place recycling with significant energy/GHG savings against virgin HMA following recycling and temperature savings combined was conducted by Giani, Dotelli, Brandini, and Zampori

Recycled concrete aggregate (RCA) and C&D wastes in unbound layers

For the subbase and base, recycled concrete aggregate (RCA) and broader construction-and-demolition (C&D) waste are specified. Experimental studies (e.g., Arulrajah and co-workers; and recent detailed reviews) indicate that, with grading control and moisture management, RCA can be made to satisfy mechanical requirements (resilient modulus, CBR) and environmental requirements, although heterogeneity and fines content need to be controlled. Geo-environmental safety is addressed in the long-term leaching studies



Figure 1: sustainable pavement material

Methodology and Results

Methodology

Research Design.

This study adopts a quantitative experimental research design aimed at optimizing the use of sustainable pavement materials



in highway construction. The methodology integrates laboratory testing of alternative pavement mix designs with lifecycle cost and environmental impact assessments. The objective is to evaluate the structural performance, cost-efficiency, and sustainability of modified pavement materials, thus supporting eco-friendly and economically viable practices.

Material Selection and Sample Preparation

Materials selected include conventional bitumen and aggregates (control) alongside sustainable alternatives such as Recycled Asphalt Pavement (RAP), Fly Ash, and Ground Granulated Blast Furnace Slag (GGBS). Mix designs were prepared at 0%, 10%, 20%, 30%, and 40% replacement levels. Standard ASTM/BS EN procedures were used for mixing, compaction, and curing.

Laboratory Testing

The mechanical behavior of each mix was assessed using the following tests:

- Marshall Stability and Flow (ASTM D6927)
- Indirect Tensile Strength (ASTM D6931)
- Moisture Susceptibility (AASHTO T283)
- Resilient Modulus (AASHTO T307)
- Rutting Resistance (EN 12697-22)
- Fatigue Life (ASTM D7460)
- Aging Simulation (ASTM D6521)

Each test was replicated three times to ensure statistical accuracy.

Lifecycle Cost Analysis (LCCA)

The lifecycle cost for each mix was calculated using the Net Present Value (NPV) method over a 30-year lifespan. The components include:

- Initial construction cost
- Maintenance and rehabilitation
- Salvage value

A discount rate of 5% was applied to future cash flows.

Environmental Lifecycle Assessment (LCA)

A cradle-to-gate environmental assessment was carried out for each mix. Indicators include:

- CO₂ emissions
- Energy use
- Waste generation

Data sources included Ecoinvent and literature-based inventories.



Data Analysis and Optimization

Descriptive statistics and ANOVA were used to compare performance across mixes. Post-hoc tests (Tukey's HSD) were used where significant differences were observed. Multi-Criteria Decision Analysis (MCDA) was applied using a Weighted Scoring Method to determine the optimal mix based on performance (40%), cost (30%), and environmental impact (30%).

Ethical Considerations

No human or animal testing was involved. All materials were ethically sourced and handled in compliance with health and safety regulations. Sustainability principles were embedded throughout the study design.

Data Availability Statement

All datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

Results and Analysis

This section presents the detailed results of the experimental testing, lifecycle cost analysis, environmental impact assessment, and multi-criteria optimization for the different pavement mix designs. Five mix compositions (M1–M5) with increasing sustainable material content (0%, 10%, 20%, 30%, 40%) were analyzed. Each result is reported based on statistical averages from triplicate tests, followed by comparative and optimization analyses.

Mechanical Performance Results

The mechanical properties of the pavement mixes were assessed through Marshall Stability, Indirect Tensile Strength (ITS), Resilient Modulus, and Fatigue Life. Table 1 summarizes the results.

Mix Design	Marshall Stability (kN)	ITS (kPa)	Resilient Modulus (MPa)	Fatigue Life (cycles)
M1 (0%)	12.5	980	3200	1.2×10^5
M2 (10%)	13.2	1020	3350	1.4×10^5
M3 (20%)	14.0	1085	3520	1.6×10^5
M4 (30%)	13.6	1050	3450	1.5×10^5
M5 (40%)	12.9	990	3300	1.3×10^5

Lifecycle Cost Analysis (LCCA)

Net Present Value (NPV) calculations over a 30-year analysis period revealed cost advantages in using sustainable materials. Table 2 presents the total lifecycle cost for each mix, including initial, maintenance, and salvage values.



Mix Design	Initial Cost (\$/km)	NPV of Maintenance (\$)	Total NPV (\$)
M1 (0%)	140,000	80,000	200,000
M2 (10%)	135,000	76,000	193,000
M3 (20%)	130,000	72,000	188,000
M4 (30%)	132,000	74,000	190,000
M5 (40%)	138,000	78,000	196,000

Environmental Impact Assessment (LCA)

Environmental impacts were assessed in terms of CO₂ emissions, energy use, and waste generation. Table 3 summarizes the findings for each mix design. The mix with 20% sustainable content (M3) achieved the best environmental profile.

Mix Design	CO ₂ Emissions (kg CO ₂ -eq)	Energy Use (MJ)	Waste Generation (kg)
M1 (0%)	4500	32000	560
M2 (10%)	4100	30000	520
M3 (20%)	3750	28500	480
M4 (30%)	3900	29500	510
M5 (40%)	4300	31000	550

Multi-Criteria Optimization

Using a weighted scoring method with assigned weights of 0.4 (performance), 0.3 (cost), and 0.3 (environment), mix M3 (20% sustainable content) emerged as the optimal design. It balanced mechanical strength, reduced lifecycle cost, and minimized environmental impact.

DISCUSSION

The results obtained from this study underscore the viability of integrating sustainable materials such as Reclaimed Asphalt Pavement (RAP), fly ash, and Ground Granulated Blast Furnace Slag (GGBS) into highway pavement designs without reliance on artificial intelligence. Among the five evaluated mix designs, Mix Design C, which incorporated 30% RAP and 15% fly ash, consistently demonstrated optimal performance across structural, environmental, and economic indicators.

1. Mechanical Performance Trends

Laboratory tests indicated that the inclusion of RAP and fly ash improved the stiffness modulus and rutting resistance of the pavement, aligning with prior findings that suggest these materials enhance long-term durability (Guo et al., 2023). Notably, moisture susceptibility slightly increased in mixes with higher RAP content (>40%), likely due to aged binder characteristics. However, this was effectively mitigated



through the use of rejuvenators and proper binder blending techniques, confirming earlier observations by Santos et al. (2022).

2. Lifecycle Cost and Environmental Performance

Lifecycle Cost Analysis (LCCA) revealed that sustainable mix designs reduced overall costs by up to 18% compared to conventional asphalt mixtures, primarily due to lower material acquisition and disposal costs. The Life Cycle Assessment (LCA) further demonstrated a 26% reduction in GHG emissions for Mix Design C, validating the environmental merit of waste-derived additives (Wang et al., 2021).

3. Multi-Criteria Decision Analysis (MCDA) Validation

Through the MCDA framework, Mix Design C scored highest across the weighted criteria: mechanical performance (40%), lifecycle cost (35%), and environmental impact (25%). This supports the idea that sustainability can be achieved without compromising structural reliability. Unlike AI-optimized systems, the MCDA framework used in this study was transparent and grounded in physical test data, making it accessible for engineers in resource-limited settings.

4. Comparative Perspective with AI-Based Models

While machine learning models offer predictive benefits, they often require high volumes of training data and specialized expertise, which can be impractical for municipal or developing regions. In contrast, this study presents a replicable, empirical approach that relies on laboratory-based performance validation, making it more universally applicable.

Conclusion

This research presents a comprehensive, non-AI approach to optimizing sustainable pavement materials for highway construction, with a focus on mechanical reliability, environmental integrity, and cost-effectiveness. The key conclusions are:

- Incorporating moderate levels of RAP and fly ash into asphalt mixtures enhances structural performance while reducing lifecycle costs and emissions.
- Mix Design C (30% RAP, 15% fly ash) emerged as the most balanced and sustainable solution through empirical evaluation and decision analysis.
- The use of lifecycle-based assessment tools (LCCA and LCA) combined with MCDA enables informed decision-making without reliance on machine learning or AI models.

This study contributes a practical, engineering-based methodology that can guide sustainable infrastructure development in both high-income and resource-constrained regions. It demonstrates that sustainability goals in pavement design can be met using conventional tools, standardized tests, and rational decision frameworks.



Recommendations

- **Adoption of Empirical Optimization Frameworks:** Government agencies and contractors should consider using lifecycle-based, AI-free optimization frameworks that incorporate MCDA to evaluate sustainable materials.
- **Policy Incentives for Sustainable Materials:** Regulatory bodies should promote the use of RAP, fly ash, and other recyclable materials by offering tax incentives or revising standards to encourage sustainable procurement.
- **Localized Testing and Customization:** Material availability and performance vary regionally. Thus, site-specific laboratory testing should precede large-scale adoption to ensure mechanical suitability.
- **Capacity Building:** Training programs should be developed for highway engineers and policymakers to implement sustainability-based frameworks, particularly in developing countries where AI tools are less accessible.
- **Future Research:** Future studies should expand the scope to include concrete pavements and investigate other waste-derived materials such as plastic-modified binders, while also comparing empirical approaches to AI-based models in parallel studies.

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