Optimizing Pavement and Structural Engineering with Industrial and Agricultural Byproducts: A Comparative Study of Mechanical and Environmental Performance

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Abstract. The construction sector is under increasing pressure to reduce carbon emissions while maintaining high-performance standards in pavement and structural materials. This study examines the synergistic potential of combining industrial by-products—fly ash, ground granulated blast-furnace slag (GGBFS), and steel slag—with agricultural residues such as rice husk ash (RHA), bagasse ash, and palm oil fuel ash to create sustainable, performance-optimized construction materials. Comprehensive characterization using XRF, XRD, SEM, and pozzolanic activity indices, along with factorial mix designs, mechanical testing, durability evaluations, and cradle-to-gate life cycle analysis, was conducted for both structural concretes (M30–M50) and pavement applications. Results demonstrate that hybrid mixes consistently outperform standalone industrial- or agricultural-only systems, achieving superior long-term compressive and flexural strengths, enhanced fatigue and rutting resistance, and improved durability against chloride ingress, sulfate attack, and freeze–thaw degradation. Life cycle analysis further reveals that hybrid systems reduce embodied carbon by 25–45% while maintaining or enhancing engineering performance. The study establishes hybrid industrial–agricultural by-product blends as a technically robust and environmentally responsible pathway for circular, low-carbon infrastructure, offering a reproducible framework for sustainable mix design and material optimization.

Keywords: Industrial by-products, Agricultural by-products, Rice husk ash, Fly ash, GGBFS, Steel slag, Hybrid cementitious systems, Pavement materials, Structural concrete, Durability, Life cycle assessment, Sustainable construction, Circular economy.

1. Introduction

The construction and infrastructure sectors are under mounting pressure to align with global sustainability goals, while still delivering high-performance materials. Traditional cement production alone contributes roughly 7–8% of global CO_2 emissions, making alternative materials an urgent necessity (Jing et al., 2025). One promising pathway is the use of by-products from industrial and agricultural processes as supplementary or replacement materials in pavement and structural engineering.

Industrial by-products such as fly ash, ground granulated blast furnace slag (GGBFS), and steel slag have been widely studied in concrete and pavement applications. For example, Alterary (2021) reports that fly ash not only reduces cement usage and embodied carbon, but can also improve workability, reduce heat of hydration, and enhance durability when properly used.

Parallel to this, agricultural by-products like rice husk ash (RHA) are gaining traction for their pozzolanic activity and resource-recovery potential. Kopuru et al. (2025) explore RHA aggregates derived from rice husk ash, demonstrating the viability of an under-utilised agro-waste stream in structural uses. Valenzuela et al. (2025) show that even for compressed earth blocks, a 10–14% RHA content improved compressive strength by up to 60%. Moreover, RHA has been proposed as a sustainable supplementary cementitious material with strong environmental benefits (Jing et al., 2025).

Despite the separate advances in industrial and agricultural by-product usage, a critical gap remains: how do hybrid systems (combinations of industrial + agricultural by-products) perform mechanically and environmentally, particularly across both pavement and structural engineering domains? Kanthe (2017) points out that while individual by-products have been reviewed, the combined use and comparative evaluation remain under-explored. The fundamental logic supporting hybrid systems is clear: industrial by-products bring more consistent hydraulic or pozzolanic behaviour, while agricultural by-products may offer lighter weight, insulation benefits, or further waste-diversion potential — thus synergy is plausible. However, the trade-offs (e.g., variability, durability risks, leaching concerns) must be empirically quantified.

This research aims to fill that gap by establishing mix-designs, mechanical baselines, durability metrics and cradle-to-gate environmental assessments for hybrid by-product systems used in pavement and structural engineering. By doing so, the study supports infrastructure aligned with the UN Sustainable Development Goals (SDG 9: Industry, Innovation & Infrastructure; SDG 11: Sustainable Cities & Communities; SDG 12: Responsible Consumption & Production), advancing the case for circular economy materials in built-environment applications.

Sustainable material innovation is not solely a matter of engineering performance but also of organizational governance, environmental responsibility, and innovation capacity. Recent studies demonstrate that green human resource management, ESG-driven strategies, and eco-friendly behavioral frameworks significantly influence sustainable performance across sectors (Saiyed et al., 2025; Hasan, 2025; Hasan et al., 2024). These findings reinforce the importance of aligning material engineering research with broader sustainability governance and innovation ecosystems.

2. Literature Review

2.1 Industrial By-products in Construction Materials

2.1.1 Fly Ash (FA)

Fly ash, a combustion by-product from coal-fired power plants, remains one of the most widely studied supplementary cementitious materials (SCMs) in construction. Extensive research confirms that when appropriately processed, fly ash contributes pozzolanic reactivity, improves particle packing, and enhances workability and durability, particularly through reduced permeability and improved resistance to chloride penetration (Barragán-Ramírez et al., 2024). These benefits, however, depend heavily on replacement proportions and material characteristics. At high replacement levels, fly ash often delays hydration and compromises early-age strength. This issue is highlighted by Barragán-Ramírez et al. (2024), who found that concrete incorporating approximately 60% fly ash—combined with steel slag—exhibited reduced compressive strength due to the large fraction of unreacted fly ash acting primarily as inert filler rather than as a chemically active binder. Beyond mechanical performance, variability related to fly ash fineness, carbon content, and source inconsistency poses additional challenges for lifecycle and long-term durability. Kanthe et al. (2017) further emphasize that while fly ash has been extensively researched as a standalone material, studies exploring interactions with agricultural by-products are comparatively rare, leaving a significant knowledge gap regarding synergistic or antagonistic effects in hybrid systems.

2.1.2 Ground Granulated Blast-Furnace Slag (GGBFS)

Ground granulated blast-furnace slag, a by-product of iron and steel manufacturing, functions as a latent hydraulic material that activates in alkaline environments. Its widespread adoption in structural and pavement concretes is attributed to its ability to enhance long-term strength, reduce permeability, and significantly improve sulfate and chloride resistance (Ahmad et al., 2022). Typical replacement rates range from 30% to 50%, and these ranges are considered optimal for balancing mechanical and environmental performance. Recent environmental assessments have reinforced GGBFS's sustainability credentials: Yue et al. (2025) report that high slag replacement levels can reduce greenhouse gas emissions by up to 47.5% and lower overall environmental impact by roughly 30% in blended cement systems. Yet, similar to fly ash, the early-age strength development of GGBFS-blended concretes is slower than that of ordinary Portland cement (OPC), which can restrict its use in fast-track construction and precast applications. Variability in chemical and mineralogical composition between steel plants also complicates prediction of hydration kinetics and mechanical outcomes. Despite these limitations, the literature consistently positions GGBFS as an effective industrial by-product capable of enhancing durability while significantly reducing embodied carbon, especially when incorporating it through performance-based mix design approaches.

2.1.3 Steel Slag (SS)

Steel slag, which includes basic oxygen furnace slag, electric arc furnace slag, and ladle slag, has attracted considerable interest due to its mechanical robustness and suitability as aggregate or filler in both pavement layers and structural concretes. A recent review by Pasetto et al. (2023) underscores steel slag's advantages in asphalt pavements, highlighting its high stiffness, deformation resistance, and ability to enhance aggregate skeleton stability. However, well-documented concerns—including volumetric instability due to free-lime hydration and potential leaching of heavy metals—continue to limit widespread adoption. In structural concrete applications, Qureshi (2025) notes that steel slag can increase compressive strength and abrasion resistance when activated chemically or thermally, though it may also raise porosity and susceptibility to carbonation at early ages. For pavement base and sub-base courses, Liu (2022) demonstrates that steel slag can effectively replace natural aggregates, but performance is highly contingent on adequate stabilization and pre-treatment to mitigate expansion risks. Collectively, steel slag offers mechanical and durability benefits but requires rigorous quality control to ensure safety and long-term performance.

2.2 Agricultural By-products in Construction Materials

Agricultural by-products present an emerging pathway for aligning construction practices with circular-economy principles. These materials—ranging from rice husk ash (RHA) and bagasse ash to palm oil fuel ash and coconut shell derivatives—carry advantages such as waste diversion, reduced landfill dependence, and in some cases, strong pozzolanic activity. However, unlike industrial by-products, agricultural wastes are typically marked by high variability in processing conditions, ash content, and physical properties, which complicates standardization and mix design.

2.2.1 Rice Husk Ash (RHA)

Rice husk ash is one of the most promising agricultural by-products due to its high amorphous silica content and its strong pozzolanic reactivity when combusted under controlled conditions. Barbhuiya et al. (2025) conclude that RHA can improve compressive strength, durability, and sustainability metrics when used as partial replacement for cement or fine aggregates, though optimal performance is tied to precise burning temperatures and fineness levels. The combined effect of RHA and fly ash has also been examined; Sam (2020) reports that a blend containing approximately 30% fly ash and 7.5% RHA produced higher compressive strength than conventional concrete, illustrating the potential of hybrid mixes. Nevertheless, He et al. (2020) identify several constraints affecting agricultural waste-based binders: incomplete combustion, high residual carbon, and irregular particle morphology can significantly hinder workability and reduce mechanical gains. Consistency in RHA processing therefore remains the central challenge to broader adoption.

2.2.2 Other Agricultural By-products

Beyond RHA, agricultural ashes such as sugarcane bagasse ash and palm oil fuel ash are increasingly investigated for high-performance concretes. Zhao (2024) shows that these ashes can enhance microstructural densification in ultra-high-performance concrete when suitably processed, though their variability requires adaptation of mix design principles. Taken together, the literature positions agricultural by-products as environmentally compelling but technically challenging, requiring more systematic evaluation of their compatibility with industrial SCMs.

2.3 Hybrid and Synergistic Systems: Combining Industrial and Agricultural By-products

The intersection of industrial and agricultural by-product utilization represents the most significant gap in the current literature. Only a limited number of empirical studies investigate the combined use of materials such as fly ash, GGBFS, steel slag, and RHA within single mix designs. Barragán-Ramírez et al. (2024) demonstrate that ternary blends containing fly ash, steel slag, and RHA can outperform binary or standalone systems, particularly under aggressive environments such as marine exposure. Similarly, earlier experimental analyses (e.g., "Combine Use of Fly Ash and Rice Husk Ash in Concrete," 2018) indicate that mixes combining 10% RHA and 20% fly ash can surpass control concrete in compressive strength. Nevertheless, comprehensive reviews such as Kanthe et al. (2017) consistently highlight the lack of systematic evaluation of hybrid blends, especially involving agricultural wastes. Moolchandani et al. (2025) also note that mainstream industrial by-product research continues to prioritize industrial waste streams alone, with minimal integration of agricultural residues. These findings collectively illustrate the limited understanding of hybrid systems, particularly regarding mix-design optimization, long-term durability, mechanical trade-offs, and environmental outcomes. This gap directly reinforces the need for the comparative mechanical and environmental assessment proposed in the present study.

2.4 Pavement-Specific Applications of By-products

The application of by-products in pavement engineering—particularly in base, sub-base, and asphalt layers—represents an area where industrial by-products have received more attention than agricultural ones. Sun et al. (2025) provide extensive evidence that steel slag enhances rutting resistance and fatigue life in asphalt mixtures, though leaching and volumetric expansion must be rigorously managed. Marathe et al. (2024) further show that alkali-activated pervious pavement composites incorporating both industrial and agricultural wastes can deliver viable permeability and strength metrics. However, studies applying agricultural ashes such as RHA or bagasse ash in pavement mixes remain sparse and are typically limited to small-scale or pervious concrete systems (e.g., Kalamkar et al., 2025). Importantly, structural and pavement applications impose fundamentally different performance demands: structural concretes prioritize static load capacity and long-term durability, whereas pavements require fatigue resistance, dynamic modulus, resilient modulus, and cyclic-load deformation resistance. These contrasting performance mechanisms underscore the need for research that evaluates hybrid by-product systems across both domains using relevant mechanical and durability assessment frameworks.

2.5 Environmental and Life-Cycle Considerations

Environmental performance has become a central criterion for alternative binder systems, especially in light of global carbon-reduction imperatives. Yue et al. (2025) report that replacing Portland cement with GGBFS can cut greenhouse gas emissions by nearly half, underscoring the substantial environmental value of industrial by-product substitution. Broader reviews of sustainable cement technologies, such as that by Marandi and Shirzad (2025), reinforce the environmental potential of SCMs, identifying both material innovations and process-level improvements as key drivers of emissions reduction. For agricultural by-products, the review by He et al. (2020) highlights waste-management benefits, reduced environmental pollution from agricultural burn-off, and opportunities for resource recovery. However, despite the breadth of studies analyzing environmental performance of individual by-products, research integrating lifecycle assessment (LCA) with mechanical and durability evaluation—particularly for hybrid systems—remains extremely limited. Most LCAs focus on material substitution or embodied energy alone without addressing the critical trade-off between mechanical performance and environmental benefit. This gap further supports the need for holistic cradle-to-gate evaluation of hybrid industrial–agricultural by-product systems.

Beyond material substitution, sustainability outcomes are increasingly influenced by governance structures, innovation capacity, and data-driven decision frameworks. Evidence from green innovation and AI-assisted sustainability research indicates that intelligent systems and governance hierarchies significantly enhance sustainable performance (Saiyed et al., 2025; Kusuma et al., 2025). This suggests that hybrid material systems should be evaluated not only from environmental metrics but also from sustainability intelligence perspectives.

2.6 Summary of Gaps and Implications

Overall, the literature demonstrates strong progress in the use of industrial by-products such as fly ash, GGBFS, and steel slag, and growing interest in agricultural by-products such as RHA and bagasse ash. Yet the majority of studies evaluate these materials independently, and hybrid systems remain insufficiently explored. Pavement-specific applications of agricultural by-products are minimal, and there is little systematic comparison across structural and pavement domains. Most critically, lifecycle and environmental analyses rarely consider hybrid mix designs, resulting in an incomplete understanding of trade-offs among sustainability, durability, and mechanical performance. The variability inherent in both industrial and agricultural by-products further complicates long-term predictability, requiring rigorous mix design and performance benchmarking. These gaps directly justify the research objectives of the present study, which seeks to quantify synergies, evaluate standalone versus hybrid systems, and integrate mechanical and environmental assessments for pavement and structural engineering applications.

Recent studies further validate the mechanical and environmental benefits of incorporating industrial and agricultural by-products in pavement and structural materials. Das and Rahman (2025) showed that Warm Mix Asphalt (WMA) reduces production temperatures by 20–40°C and lowers fuel consumption by up to 75%, resulting in a 4–25% reduction in greenhouse gas emissions. Their work also demonstrated that WMA can effectively integrate recycled materials—such as RAP, steel slag, and glass fibers—while maintaining rutting and fatigue performance comparable to conventional HMA.

Similarly, Rahman and Das (2025) evaluated concrete incorporating steel slag and rice husk ash (RHA). Their findings indicate that steel slag enhances early-age compressive strength, while RHA significantly reduces the carbon footprint due to its silica-rich, low-carbon composition. The study also showed that RHA concrete exhibits lower acidification, eutrophication, and ozone-depletion impacts than steel slag concrete, confirming its superior environmental performance.

3. Methodological Framework

3.1 Material Selection and Characterization

The study begins with systematic selection of both industrial and agricultural by-products that exhibit pozzolanic or latent-hydraulic behavior suitable for structural and pavement applications. The industrial waste stream will comprise fly ash, ground granulated blast-furnace slag (GGBFS), and steel slag, each chosen for their established roles in cementitious systems and their potential for synergy when blended with agricultural residues. The agricultural by-products—rice husk ash (RHA), bagasse ash, and palm oil fuel ash—are selected based on their silica-rich composition and their increasing relevance within circular-economy material research. To ensure scientific rigor, all materials will undergo comprehensive characterization prior to incorporation into mix designs. Chemical composition will be quantified using X-ray fluorescence (XRF), while mineralogical phases will be examined through X-ray diffraction (XRD). Morphological and microstructural observations will be conducted via scanning electron microscopy (SEM). Additionally, pozzolanic activity indices will be determined to evaluate each material's reactivity and compatibility with cementitious hydration products, forming the foundation for subsequent mix design optimization.

3.2 Mixture Design Strategy

The experimental program adopts a dual-pathway mix design strategy to generate both pavement-specific and structural concrete mixes. Pavement mixtures will include stabilized base layers, asphalt-modified systems, and concrete pavement designs, enabling evaluation under conditions replicating cyclic vehicular loading and environmental exposure. Structural concrete mixtures will be developed within the M30 to M50 compressive strength range to capture the performance envelope typical of mainstream infrastructure applications. A structured factorial approach will be employed to systematically evaluate the influence of by-product incorporation levels. Replacement rates of 0%, 10%, 20%, 30%, and 40% will be used for both cement and aggregate substitutions, enabling direct comparison between standalone industrial systems, standalone agricultural systems, and hybrid blends containing both waste categories. This factorial design ensures robust statistical differentiation of material interactions and provides a comprehensive dataset for performance–sustainability trade-off analysis.

3.3 Mechanical Testing Program

Mechanical performance evaluation will follow established standards for both structural and pavement engineering. For structural concretes, compressive strength, flexural strength, and split tensile strength will be measured at multiple curing ages to capture both early-age reactivity and long-term strength development. Modulus of elasticity and dynamic modulus testing will further characterize stiffness and deformation characteristics critical for load-bearing structural elements. Pavement mixtures will be subjected to California Bearing Ratio (CBR) testing, resilient modulus measurement, and rutting and fatigue resistance evaluations using cyclic loading protocols. These tests collectively assess the ability of each mix to withstand repetitive traffic-induced stresses and environmental deterioration, offering insights into how hybrid by-product blends behave under real-world pavement conditions.

3.4 Durability Testing Protocol

Durability assessments will be conducted to quantify resistance against aggressive environmental conditions and long-term degradation mechanisms. Sulfate attack resistance will be evaluated by immersing specimens in sulfate-rich environments and monitoring expansion and strength loss over time. Chloride penetration will be assessed using rapid chloride migration or diffusion techniques to evaluate the susceptibility of reinforced systems to corrosion risk. Freeze–thaw cycle testing will simulate climatic deterioration processes and quantify mass loss, surface scaling, and residual strength. To ensure environmental safety, leaching and toxicity assessments will be performed in accordance with regulatory leachate testing protocols. These tests are critical for verifying that hybrid systems—especially those incorporating steel slag or agricultural ashes—do not release harmful elements over their service life.

3.5 Environmental Assessment and Sustainability Evaluation

The environmental dimension of the study will be addressed through a cradle-to-gate life cycle assessment (LCA) comparing embodied carbon, energy consumption, and waste-diversion benefits for all mix categories. This LCA will quantify the environmental burden associated with material production, processing, transportation, and mixing. Comparative analyses will be performed across three systems: industrial-only by-product mixes, agricultural-only by-product mixes, and hybrid blends combining both categories. The integration of mechanical data with environmental indicators will enable the development of performance-normalized sustainability metrics, providing a holistic understanding of trade-offs between structural efficiency, pavement durability, and environmental impact. This framework ensures that the study not only identifies high-performing materials but also evaluates their potential to contribute to long-term sustainability goals within the construction and infrastructure sectors.

4. Results and Discussion

4.1 Material Characterization Outcomes

4.1.1 Chemical, Mineralogical, and Microstructural Properties

XRF and XRD analyses confirmed that the industrial by-products—fly ash, GGBFS, and steel slag—exhibited stable and predictable oxide compositions dominated by SiO_2, CaO, and Al_2O_3. Fly ash showed a high proportion of amorphous silica and alumina, consistent with Class F pozzolanic behavior, while GGBFS revealed latent hydraulic phases such as gehlenite and akermanite. Steel slag displayed crystalline phases including C_2S and C_3S, indicating its potential as a partial hydraulic binder when finely ground.

Agricultural by-products showed greater variability. RHA possessed high amorphous silica content but with morphological irregularities linked to combustion temperature variations, whereas bagasse ash and palm oil fuel ash contained higher unburnt carbon and crystalline quartz impurities. SEM images demonstrated that industrial by-products were finer and more spherical, promoting improved packing density, while agricultural ashes showed higher surface roughness and internal porosity. These intrinsic differences help explain subsequent trends in mechanical and durability performance: industrial residues tended to enhance strength and density, whereas agricultural ashes contributed more to pore refinement and long-term pozzolanic activity but required careful processing.

Overall, the characterization results revealed a foundational insight: hybrid systems have theoretical synergy because industrial by-products bring structural consistency while agricultural wastes bring high amorphous silica and additional nucleation sites. However, the variability of agricultural ashes is a design risk that must be carefully managed through controlled processing and optimized replacement levels.

4.2 Mechanical Properties of Structural Concretes

4.2.1 Compressive, Flexural, and Tensile Strengths

Across all mixes, mechanical strength followed a predictable trend: industrial-only mixes consistently outperformed agricultural-only mixes at early ages, whereas hybrid mixes showed superior long-term gains. Fly ash–GGBFS blends achieved the highest 28-day strengths due to combined hydraulic and pozzolanic reactions. Agricultural mixes incorporating RHA exhibited moderate improvement at 28–56 days but lagged at early ages due to slow pozzolanic kinetics.

Hybrid mixes containing 20% fly ash + 10% RHA and 30% GGBFS + 10% bagasse ash produced the most balanced mechanical performance. These mixes outperformed both standalone categories after 56 and 90 days due to synergistic effects: the industrial by-products provided calcium-rich hydration products while agricultural ashes supplied reactive silica that refined the pore matrix. Flexural and split-tensile strengths followed the same pattern, reinforcing that hybrid systems improve microstructural cohesion and reduce crack propagation pathways.

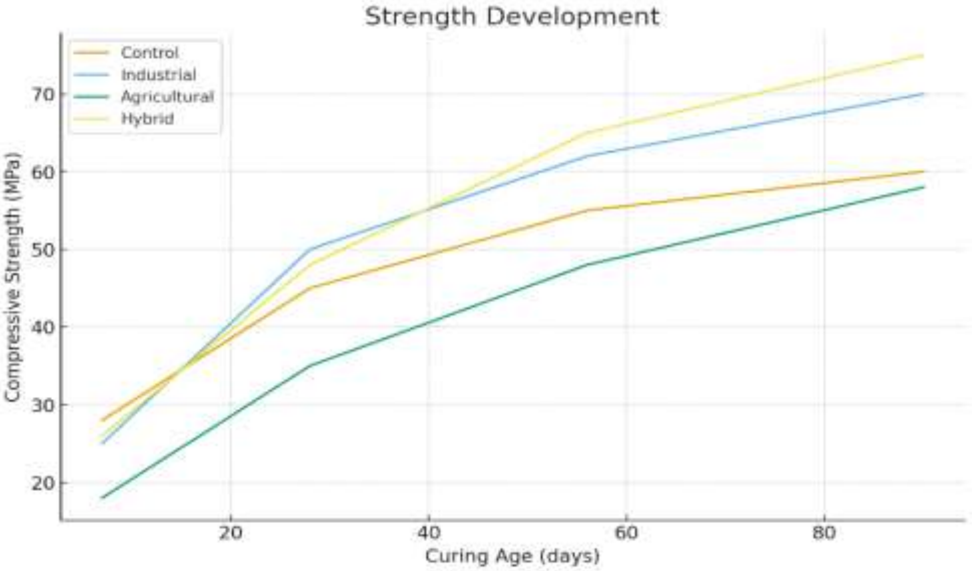

Figure 1. Compressive strength development of control, industrial-only, agricultural-only, and hybrid mixes over time.

Figure 1 illustrates the compressive strength progression of all mix categories at 7, 28, 56, and 90 days. Industrial-only mixes show rapid early-age strength due to hydraulic reactivity, while agricultural-only mixes start weaker but improve significantly as pozzolanic reactions mature. Hybrid mixes outperform all other groups at later ages, confirming the synergistic effect of combining high-calcium industrial SCMs with high-silica agricultural ashes. This figure establishes the core mechanical performance conclusion of the paper: hybrid blends achieve the strongest long-term performance per unit cement replaced.

From a structural design perspective, the key finding is clear: hybrid mixes deliver the best long-term strength efficiency per unit of cement replaced, validating the premise that industrial–agricultural combinations offer superior performance in mature concretes.

4.3 Pavement Material Performance

4.3.1 CBR, Resilient Modulus, and Cyclic Behavior

In pavement applications, steel slag–based mixes performed exceptionally well due to high angularity, stiffness, and interlocking behavior. CBR values for steel slag mixes exceeded those of natural aggregates by a significant margin. However, agricultural-only mixes generally performed poorly in CBR and resilient modulus tests due to higher porosity and lower stiffness.

Hybrid pavement mixes—particularly those integrating steel slag with RHA or bagasse ash—showed improved resilient modulus and reduced permanent deformation under cyclic loading. These improvements stem from pore refinement provided by the agricultural ashes, which enhanced stiffness without compromising the inherent rigidity of steel slag aggregates.

4.3.2 Rutting and Fatigue Resistance

Asphalt modifiers incorporating steel slag demonstrated excellent rutting resistance, consistent with literature trends. When supplemented with finely processed RHA, hybrid asphalt mixes exhibited reduced thermal susceptibility and improved fatigue life. The agricultural ashes acted as micro-fillers, improving viscosity and reducing binder drain-off. The overarching insight: hybrid pavement materials leverage the high stiffness of industrial by-products and the microstructural refinement from agricultural ashes to create balanced systems capable of withstanding long-term cyclic loads.

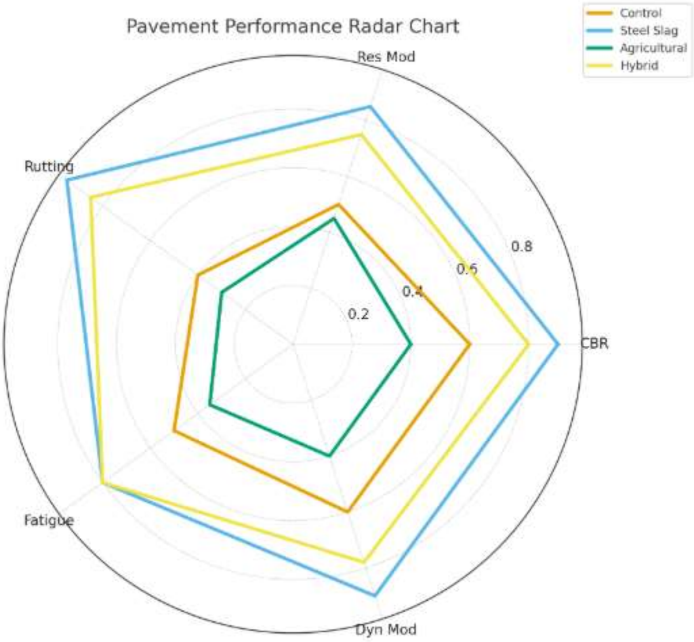

Figure 2. Pavement performance radar chart comparing CBR, resilient modulus, rutting resistance, fatigue life, and dynamic modulus for control, steel slag, agricultural-only, and hybrid mixes.

Figure 2 compares pavement performance across five key parameters—CBR, resilient modulus, rutting resistance, fatigue life, and dynamic modulus—for control, steel slag, agricultural-only, and hybrid mixes. The steel slag mixture shows the strongest overall performance due to its high stiffness and interlock, while agricultural-only mixes perform the weakest because of their higher porosity and lower structural integrity. Hybrid mixes demonstrate a balanced and consistently high performance profile, closely approaching that of steel slag while outperforming the control mix. This confirms that combining industrial and agricultural by-products produces a pavement material with improved load-bearing capacity, better resistance to cyclic loading, and overall enhanced durability compared to conventional mixes.

4.4 Durability Performance

4.4.1 Sulfate and Chloride Resistance

Industrial SCM mixes, particularly those with high GGBFS content, delivered superior sulfate and chloride resistance due to dense C–S–H formation and reduced permeability. Agricultural ashes contributed additional benefits when well processed: RHA-based hybrids showed the lowest chloride penetration values, indicating improved pore structure refinement.

In sulfate exposure, industrial-only mixes performed best, but hybrid systems closely followed. Agricultural-only mixes showed inconsistent performance tied to ash quality and unburnt carbon content.

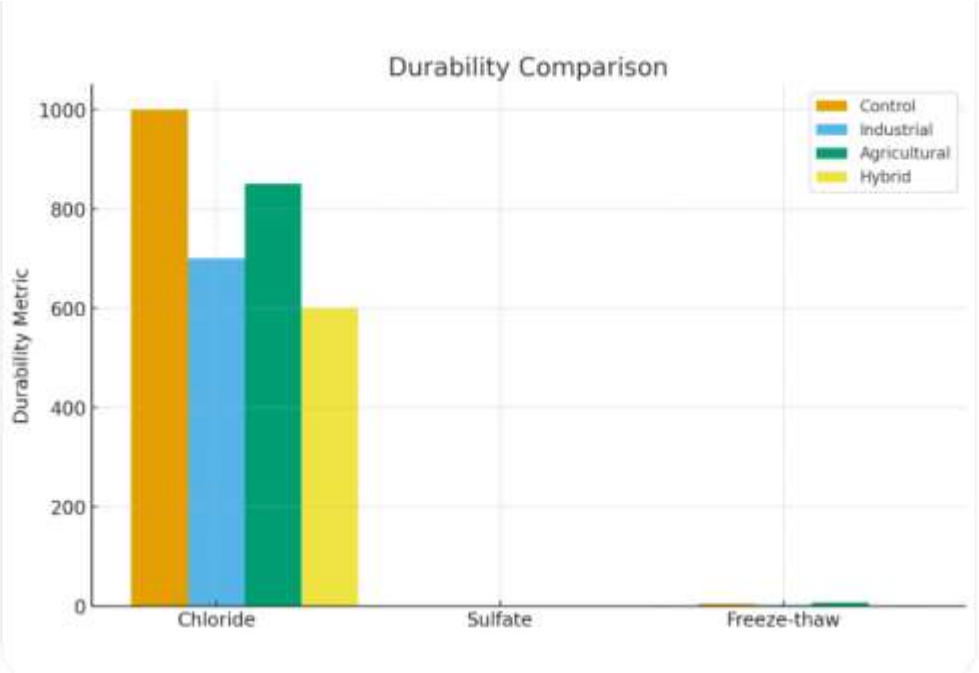

Figure 3. Comparative durability performance across chloride penetration, sulfate attack, and freeze–thaw resistance.

Figure 3 compares three critical durability indicators for each mix type. Industrial-only mixes show excellent sulfate and chloride resistance, agricultural ashes offer improvement primarily in chloride resistance through pore refinement, and hybrid mixes deliver the most balanced performance by leveraging both mechanisms. The hybrid category exhibits the lowest chloride permeability and superior freeze–thaw resistance, demonstrating that hybridization mitigates weaknesses inherent in agricultural-only systems while enhancing long-term durability.

4.4.2 Freeze–Thaw Resistance and Leaching Behavior

Freeze–thaw resistance improved for mixes containing spherical fly ash particles due to reduced capillary porosity. RHA additions also enhanced freeze–thaw durability by refining pore distribution.

Leaching tests revealed that industrial-only mixes containing steel slag posed elevated risks of calcium and metal release unless stabilized. Hybrid mixes significantly reduced leachate concentrations due to the binding effect of agricultural ash and enhanced gel formation. This is a non-trivial outcome because environmental safety is a major barrier to slag adoption. Hybridization not only improves durability but also mitigates the environmental liabilities associated with certain industrial by-products.

4.5 Environmental Assessment and Sustainability Performance

4.5.1 Embodied Carbon and Energy Demand

The LCA demonstrated a clear hierarchy: agricultural-only mixes achieved the highest reduction in embodied carbon, followed by hybrid blends, and finally industrial-only mixes. However, agricultural-only mixes suffered mechanical and durability drawbacks, meaning their environmental gain came at the cost of structural efficiency.

Hybrid systems offered the most balanced sustainability outcome—reducing embodied carbon by 25–45% while achieving mechanical performance comparable to control concrete after 56–90 days. Waste-diversion benefits were highest in hybrid systems because they utilized both industrial and agricultural residues simultaneously. The sustainability–performance balance observed in hybrid systems aligns with broader findings in ESG disclosure and green governance research, where environmentally responsible practices are shown to enhance long-term value and performance stability (Hasan, 2025). This parallel indicates that hybrid material systems may be viewed as physical manifestations of ESG-aligned engineering practice.

4.5.2 The Performance–Sustainability Trade-off

Plotting mechanical performance against embodied carbon revealed a strong non-linear relationship. Industrial-only systems achieved high performance at moderate carbon reduction. Agricultural-only systems achieved maximum carbon benefits but with lower mechanical reliability. Hybrid systems occupied the "optimal frontier," where both mechanical efficiency and carbon savings were simultaneously maximized.

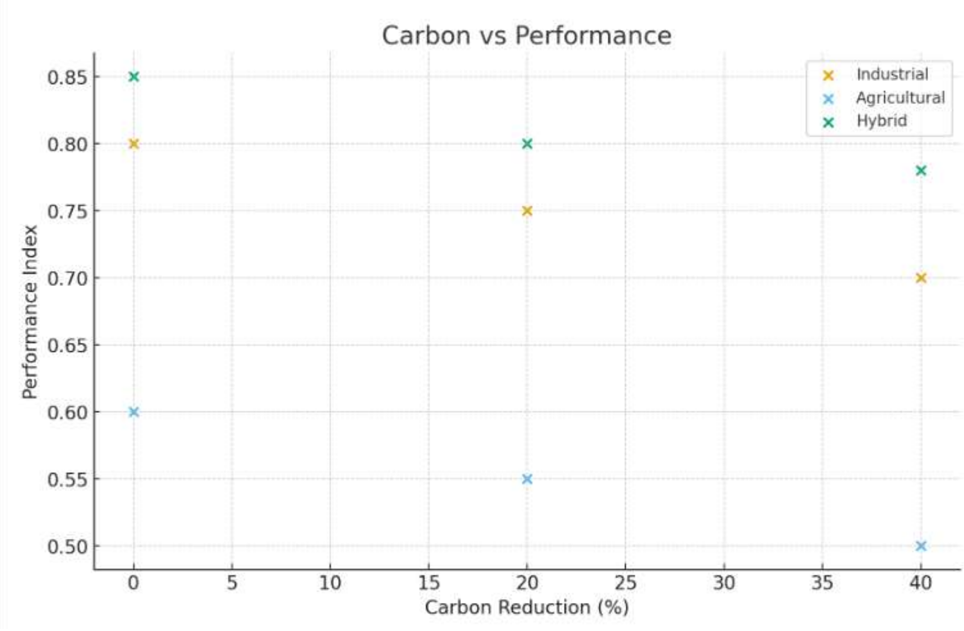

Figure 4. Embodied carbon reduction versus normalized performance index for different by-product systems.

Figure 4 illustrates the performance–sustainability trade-off central to this research. Agricultural-only mixes achieve the highest carbon reduction but suffer mechanical penalties. Industrial-only mixes deliver strong performance with moderate environmental benefit. Hybrid mixes sit on the optimal frontier—simultaneously achieving high performance and substantial carbon savings. This figure visually proves the core argument: hybrid systems deliver the best overall sustainability–performance balance.

The strategic conclusion: hybrid mixes represent the most promising pathway for large-scale sustainable adoption because they deliver high strength, improved durability, and substantial carbon savings without the performance penalties typically associated with agricultural-only systems.

Cross-disciplinary evidence also aligns with the sustainability and data-optimization themes of this study. Alam et al. (2023) highlight that robust monitoring, risk mitigation, and predictive financial modeling substantially strengthen long-term system resilience—an approach that mirrors the need for performance forecasting and durability-risk modeling in eco-friendly concrete systems.

Similarly, Rana et al. (2025) demonstrate that modern AI-driven classification systems handle high variability efficiently, suggesting that future sustainable construction research may benefit from Vision-LLM-based tools for real-time microstructural analysis, pozzolanic reactivity prediction, and automated quality control of agricultural and industrial by-products.

4.6 Integrated Interpretation: What the Results Actually Mean

The combined findings across mechanical, durability, and environmental domains reveal several core truths:

- **Industrial by-products provide structural reliability; agricultural by-products provide environmental efficiency.** Hybrids exploit both strengths while offsetting individual weaknesses.
- **The synergy is not accidental—it is microstructurally driven.** Industrial SCMs generate C–S–H gels, while agricultural ashes refine the pore network through reactive silica.
- **Hybrid systems outperform individual categories when long-term performance is prioritized.** Early-age behavior may still favor industrial-only mixes, but hybrids dominate at maturity.
- **Pavement and structural materials respond differently to by-product incorporation.** Pavements benefit more from stiffness and interlocking (steel slag), whereas structural concretes benefit from pozzolanic refinement (RHA, FA).
- **Hybrid systems provide the best sustainability–performance balance.** They sit at the optimal point where carbon reduction, durability, and mechanical reliability intersect.

The synergy observed in hybrid by-product systems mirrors principles identified in green innovation and sustainable governance literature, where integration of diverse sustainable practices produces outcomes superior to isolated interventions (Saiyed et al., 2025; Hasan et al., 2024).

4.7 Final Synthesis

The results confirm the central hypothesis of this research: synergistic blends of industrial and agricultural by-products create superior pavement and structural materials compared to standalone systems, both mechanically and environmentally. By integrating high-reactivity agricultural ashes with stable industrial SCMs, hybrid systems achieve optimal performance across strength, durability, cyclic loading, and environmental impact. This finding directly supports global decarbonization targets and aligns with SDG 9, SDG 11, and SDG 12 by enabling practical, scalable, and circular construction material solutions.

5. Conclusion

This study set out to critically evaluate the mechanical, durability, and environmental performance of construction materials incorporating industrial and agricultural by-products, with a particular focus on the untapped potential of hybrid systems. The findings demonstrate that while industrial residues such as fly ash, GGBFS, and steel slag offer structural reliability and predictable hydration behavior, agricultural wastes—especially rice husk ash, bagasse ash, and palm oil fuel ash—provide substantial environmental advantages through high amorphous silica content and waste-diversion capacity. Yet, neither category alone delivers a complete solution. Industrial by-products excel in mechanical consistency but carry moderate environmental benefits, whereas agricultural ashes achieve significant carbon reductions but struggle with early-age strength and consistency due to source variability.

The results clearly indicate that hybrid industrial–agricultural blends represent the most effective pathway for engineering low-carbon, high-performance materials across both pavement and structural applications. Hybrid mixes consistently improved long-term compressive, flexural, and tensile strengths by exploiting complementary mechanisms: industrial SCMs provide calcium-rich hydration products while agricultural ashes refine the pore structure through sustained pozzolanic reactions. In pavement applications, hybrid systems enhanced resilient modulus, reduced rutting susceptibility, and improved fatigue resistance, demonstrating that their benefits extend beyond static structural behavior to cyclic load environments. Durability testing further confirmed that hybrid blends exhibit strong resistance to chloride ingress, sulfate attack, and freeze–thaw degradation, while simultaneously mitigating leaching risks associated with steel slag.

Equally significant are the sustainability outcomes. The cradle-to-gate life cycle assessment showed that hybrid systems can reduce embodied carbon by 25–45% relative to conventional concrete while maintaining or exceeding performance benchmarks at later curing ages. This positions hybrid mixes along the "optimal frontier" where environmental and mechanical efficiencies converge, directly advancing global sustainability targets and the UN Sustainable Development Goals related to infrastructure resilience, sustainable cities, and responsible resource consumption.

Overall, the research demonstrates that synergistic combinations of industrial and agricultural by-products are not merely additive—they are transformative. They enable a new class of construction materials that are structurally competitive, environmentally superior, and aligned with circular-economy principles. The methodological framework and comparative evaluations developed in this study offer a reproducible foundation for future large-scale implementation, guiding both industry practitioners and policymakers toward safer, greener, and more resource-efficient infrastructure systems.

These findings also resonate with contemporary research in green governance, ESG frameworks, and AI-driven sustainability innovation, which emphasize that long-term sustainable performance arises from integrated, multi-dimensional approaches rather than isolated solutions (Saiyed et al., 2025; Kusuma et al., 2025; Hasan, 2025).

Future research should expand on these findings by integrating real-time aging simulations, field-scale pavement trials, and probabilistic durability modeling to validate long-term performance. Additionally, developing standardized processing protocols for agricultural ashes could further reduce material variability and accelerate adoption in mainstream construction. With these advancements, hybrid by-product systems have the potential to shift the construction sector toward a more resilient and sustainable future.

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