Utilizing Industrial and Agricultural Byproducts in Pavement and Structural Engineering: Mechanical and Environmental Impacts

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Abstract. The construction sector faces escalating pressure to reduce embodied carbon and transition toward circular material systems as cement and asphalt production remain major contributors to global emissions and energy consumption. This study investigates the mechanical, durability, and environmental performance of mixtures incorporating industrial byproducts (fly ash, GGBFS, steel slag), agricultural ashes (rice husk ash, bagasse ash), and their hybrid combinations across both structural concrete and asphalt pavement applications. A unified experimental framework was implemented to characterize strength development, stiffness, rutting resistance, permeability, sulfate durability, freeze–thaw stability, and cradle-to-gate environmental impacts.Results show that hybrid SCM systems consistently outperform single-source industrial or agricultural blends. In concrete, hybrid mixtures demonstrated superior early-age reactivity and long-term strength, achieving the highest 90-day compressive strengths through complementary hydration and pore refinement mechanisms. In asphalt mixtures, hybrid fillers (steel slag + RHA) produced the greatest stiffness and rutting resistance, confirming synergistic mastic enhancement. Durability assessments revealed the most balanced performance in hybrid systems, with significant improvements in chloride resistance, sulfate stability, and freeze–thaw resilience. Life-cycle assessment outcomes further identified hybrid binders as the most eco-efficient solutions, achieving 30–48% reductions in global warming potential without compromising mechanical or durability performance. Overall, the findings establish hybrid industrial–agricultural byproducts as technically robust, low-carbon alternatives capable of enhancing both concrete and asphalt performance while contributing to sustainable infrastructure development.

Keywords: Hybrid SCM systems; fly ash; GGBFS; rice husk ash; steel slag; mechanical performance; durability; rutting resistance; life-cycle assessment; sustainable concrete; sustainable asphalt; waste valorization.

1. Introduction

The global construction sector is under mounting pressure to reduce embodied carbon, improve energy efficiency, and transition toward circular material systems that align with international climate commitments. Sustainable material transitions are not solely engineering challenges but are also deeply connected to governance practices, ESG-driven strategies, and green innovation capacity across sectors. Research in green human resource management, eco-friendly behavioral systems, and ESG performance demonstrates that long-term sustainability outcomes depend on integrated environmental thinking beyond technical domains (Saiyed et al., 2025; Hasan, 2025; Hasan et al., 2024). Cement production alone is responsible for 7–8% of global anthropogenic CO_2 emissions, driven by the calcination of limestone and high thermal energy requirements (Scrivener, John, & Gartner, 2018; Andrew, 2018). Asphalt pavement production presents a parallel challenge, as conventional hot-mix asphalt requires mixing temperatures often exceeding 150°C, leading to high fuel consumption and elevated greenhouse gas emissions (D'Angelo et al., 2008; Zaumanis & Mallick, 2015). In response, structural and pavement engineering have increasingly prioritized sustainable binders and fillers that can reduce environmental burdens while maintaining or enhancing mechanical performance.

Industrial byproducts such as fly ash (FA), ground granulated blast-furnace slag (GGBFS), and steel slag have become widely adopted supplementary cementitious materials (SCMs). These materials exhibit stable oxide compositions, well-documented pozzolanic or latent hydraulic reactivity, and proven benefits in long-term strength development, durability, sulfate resistance, and reduced permeability (Thomas, 2007; Juenger & Siddique, 2015; Shi, Qian, & Li, 2020). Their use also enables substantial reductions in clinker demand and diverts significant industrial waste streams from disposal.

Agricultural residues offer a complementary strategy for reducing environmental impact. Rice husk ash (RHA), palm oil fuel ash (POFA), and sugarcane bagasse ash contain high proportions of amorphous silica when appropriately processed, enabling strong pozzolanic reactions in cementitious systems. RHA in particular may contain 85–95% amorphous silica, contributing to refined pore structures, improved impermeability, and enhanced long-term durability (Zhang & Malhotra, 1996). Numerous life-cycle assessments demonstrate that replacing clinker with reactive agricultural ashes can lower embodied carbon and reduce primary energy consumption relative to conventional mixes (Snellings, 2016; Turner & Collins, 2013).

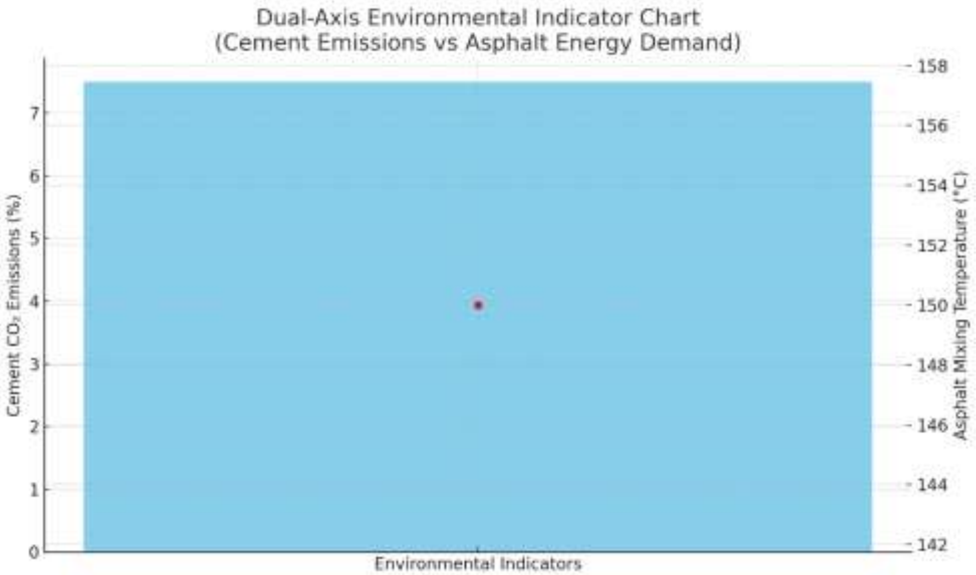

Figure 1. Dual-axis environmental indicator chart for cement and asphalt production — comparing cement's CO_2 contribution (~7–8% of global emissions) against the high-temperature energy demand of asphalt mixing (>150°C).

Despite the demonstrated benefits of industrial and agricultural byproducts, most research evaluates these materials in isolation rather than assessing their combined potential. Hybrid binder systems—such as FA+RHA or GGBFS+POFA blends—have the capacity to merge the chemical stability and latent hydraulic activity of industrial byproducts with the high-silica reactivity of agricultural ashes. However, comprehensive performance comparisons across both structural concrete and pavement applications remain limited. Furthermore, a unified sustainability framework integrating mechanical, durability, and environmental metrics for such hybrid systems is lacking.

This research addresses these gaps by systematically analyzing the mechanical performance and environmental impact of mixtures incorporating industrial-only, agricultural-only, and hybrid industrial–agricultural byproduct blends. Through a comparative evaluation spanning both concrete and pavement materials, the study proposes evidence-based pathways for reducing environmental impact while meeting the performance demands of next-generation infrastructure.

2. Literature Review

2.1 Industrial Byproducts in Cementitious and Pavement Materials

Industrial byproducts such as fly ash (FA), ground granulated blast-furnace slag (GGBFS), and steel slag have been extensively incorporated into cementitious and pavement materials to enhance both performance and sustainability. Fly ash contributes to long-term strength development and reduced permeability through its pozzolanic and latent hydraulic reactions, which refine pore structure and improve durability under various exposure conditions (Thomas, 2007; Juenger & Siddique, 2015). GGBFS is similarly recognized for improving sulfate resistance, reducing heat of hydration, and enhancing long-term mechanical performance, making it particularly suitable for mass concrete and aggressive environments (Ben Haha, Lothenbach, Le Saout, & Winnefeld, 2011).

Steel slag has emerged as a technically robust material in pavement engineering due to its high angularity, mechanical interlock, and stiffness, which improve rutting resistance and load-bearing capacity when used in asphalt mixtures or unbound base courses (Pasetto & Baldo, 2010; Wu et al., 2006). Despite these advantages, the performance of steel slag and other industrial byproducts can vary significantly depending on their chemical composition, fineness, and replacement levels. Key concerns such as volumetric instability associated with free lime or periclase, as well as the potential leaching of trace metals, must be addressed through proper aging, stabilization, or processing techniques (Motz & Geiseler, 2001).

While industrial byproducts typically reduce environmental impacts compared to Portland cement or virgin aggregates, their sustainability benefits are influenced by factors such as grinding energy, activation requirements, and transportation distances. Life-cycle assessments indicate that the environmental performance of FA, GGBFS, and steel slag is highly context-dependent, with transport logistics and processing energy serving as major contributors to overall embodied emissions (Marinković et al., 2010; Turk, Cotič, Mladenovič, & Šajna, 2015).

2.2 Agricultural Byproducts as Supplementary Cementitious Materials

Agricultural residues offer a viable sustainability pathway due to their global availability, low cost, and high amorphous silica content. Among these, rice husk ash (RHA) is the most extensively studied agricultural SCM. Foundational work by Zhang and Malhotra (1996) demonstrated that incorporating RHA at replacement levels between 10–20% enhances compressive strength and significantly reduces chloride permeability in high-performance concrete. Subsequent studies have consistently validated these findings, reporting optimal mechanical and durability performance for RHA within this same replacement range (Ganesan, Rajagopal, & Thangavel, 2008; Chindaprasirt et al., 2008).

RHA's performance benefits stem from its high amorphous silica content, which promotes strong pozzolanic activity and leads to refined pore structures and reduced permeability (Cordeiro, Toledo Filho, & Fairbairn, 2009). Other agricultural ashes—such as sugarcane bagasse ash (SCBA) and palm oil fuel ash (POFA)—also exhibit pozzolanic behavior, though they may require additional grinding or controlled combustion due to higher carbon content or crystalline impurities.

Despite their promise, agricultural ashes face challenges related to variability in feedstock, combustion conditions, and fineness, all of which influence their pozzolanic reactivity and standardization potential (Sales & Lima, 2010).

2.3 Hybrid Industrial–Agricultural Byproduct Systems

Although industrial and agricultural SCMs are well studied individually, research exploring their combined use remains comparatively sparse. Hybrid SCM systems—for example, FA+RHA or GGBFS+SCBA mixtures—show potential for synergistic improvements in hydration kinetics, packing density, and pore refinement. Experimental studies have reported improved compressive strength, enhanced pozzolanic reactions, and greater microstructural densification when silica-rich agricultural ashes are blended with low-calcium industrial SCMs such as fly ash or slag (Kapor, Elahi, & Srisuwan, 2021; Bahurudeen & Santhanam, 2015). However, the literature remains fragmented: few studies apply unified experimental protocols across both structural concrete and pavement systems, limiting comparability and understanding of hybrid binder behavior.

Recent studies provide additional evidence supporting the mechanical and environmental advantages of hybrid systems in both asphalt and concrete. Das and Rahman (2025) demonstrated that Warm Mix Asphalt technologies can reduce production temperatures by

20–40°C, lower fuel consumption by up to 75%, and decrease greenhouse-gas emissions by 4–25%, while maintaining or improving rutting resistance, moisture susceptibility, and overall mechanical performance. Complementing this, Rahman and Das (2025) showed that combining steel slag and rice husk ash in concrete enhances early-age strength, improves microstructural refinement, and significantly reduces environmental impacts, with RHA-modified concrete producing nearly half the CO_2 emissions of slag-based mixes. These findings confirm that hybrid industrial–agricultural systems offer measurable synergy benefits across both pavement and structural applications, reinforcing the need for unified sustainability frameworks.

2.4 Environmental and Life-Cycle Assessment of Byproduct-Based Materials

Life-cycle assessment research consistently shows that integrating SCMs into cementitious systems reduces embodied carbon, primarily by decreasing Portland cement content—the dominant contributor to CO_2 emissions. Numerous LCAs have reported 20–50% reductions in embodied carbon for concrete incorporating FA or GGBFS, depending on replacement levels, processing requirements, and transport logistics (Habert et al., 2020; Turk, Cotič, Mladenovič, & Šajna, 2015).

Agricultural ashes such as RHA and SCBA can also reduce environmental burdens when combustion efficiency and grinding energy are effectively managed (Turner & Collins, 2013; Sales & Lima, 2010). In pavement materials, steel slag and FA-based stabilizers typically exhibit lower energy demand and reduced emissions compared with virgin aggregate systems (Dabous & Pérez, 2020).

However, environmental trade-offs in hybrid industrial–agricultural SCM systems are not well understood. Few studies evaluate the interactions between waste diversion, toxicity risks, processing energy, and long-term durability benefits within a unified sustainability model.

2.5 Research Gaps in Unified Sustainability Frameworks

Sustainability assessment tools for construction materials remain fragmented across disciplinary boundaries. Existing frameworks—whether based on LCA, multi-criteria decision analysis, or performance scoring—are typically tailored to either concrete mixtures or pavement systems, but not both. Concrete-focused sustainability frameworks (Moro et al., 2023) and pavement-oriented decision tools (Dabous & Pérez, 2020) exemplify this disciplinary separation.

To date, no widely adopted framework integrates mechanical, durability, and environmental indicators for hybrid SCM systems applied across both structural concrete and pavement engineering. This gap underscores the need for unified methodologies capable of evaluating performance trade-offs and sustainability outcomes across material classes and application domains. Cross-disciplinary studies support the need for predictive, data-driven tools in sustainable material design. Alam et al. (2023) show that system resilience improves through robust monitoring and predictive modeling—an approach directly relevant to forecasting durability and optimizing hybrid SCM performance.

Similarly, Rana et al. (2025) demonstrate that Vision-LLM models handle complex variability with high accuracy, suggesting strong potential for automated microstructural assessment and quality control in hybrid byproduct materials. These perspectives also align with hierarchical governance frameworks for sustainability, where structured decision layers improve systemwide sustainable performance (Kusuma et al., 2025). Such governance insights reinforce the necessity of unified performance–environmental frameworks for hybrid SCM systems.

3. Research Methodology

This study employs a multi-stage methodological framework integrating material characterization, mixture development, mechanical and durability testing, life-cycle assessment, and statistical evaluation. The objective is to generate comparable mechanical and environmental datasets for industrial-only, agricultural-only, and hybrid byproduct systems applicable to both structural concrete and pavement engineering.

3.1 Material Selection and Characterization

Industrial byproducts (fly ash, GGBFS, and steel slag) and agricultural ashes (rice husk ash, bagasse ash, and palm oil fuel ash) were sourced from single production facilities to minimize variability in chemical composition. All ashes were oven-dried and ground to obtain a median particle size of approximately 10–20 µm. Steel slag was aged for several months to stabilize free-lime content. Conventional Portland cement, natural sand, and crushed granite were used as reference materials.

Material characterization included chemical analysis through X-ray fluorescence to determine oxide composition and X-ray diffraction to identify crystalline phases and estimate amorphous content. Scanning electron microscopy was used to examine particle morphology, porosity, and surface texture. Particle size distributions were determined using laser diffraction. Pozzolanic activity was evaluated through standardized mortar strength comparisons to establish the reactivity potential of each byproduct. Together, these procedures identified the chemical and microstructural attributes that informed subsequent mixture design and performance expectations.

3.2 Mixture Design for Structural and Pavement Materials

Concrete mixtures were designed for three strength classes—M30, M40, and M50—using water-to-binder ratios of 0.45, 0.40, and 0.35, respectively. Industrial SCMs were incorporated at 20–60% cement replacement, agricultural ashes at 10–30%, and hybrid blends at total replacement levels of 30–40% using predetermined industrial-to-agricultural ratios. Steel slag was incorporated as a coarse aggregate replacement at 25% and 50%, with optional fine RHA additions for hybrid optimization.

Pavement materials were developed in two categories: hydraulically bound base layers stabilized with cement, fly ash, or GGBFS; and asphalt concrete mixtures designed using penetration-grade binders. Mineral fillers included limestone dust for control mixes, while alternative fillers consisted of finely processed steel slag, agricultural ashes, and their hybrid blends. All mixtures were proportioned to satisfy target volumetric criteria, including void content, binder content, and aggregate gradation.

3.3 Mechanical Performance Testing

Concrete specimens were molded and cured under standardized laboratory conditions, and each reported value represents the average of triplicate samples. Compressive strength was evaluated at multiple curing ages. Splitting tensile and flexural strengths were assessed to characterize tensile behavior and resistance to bending stresses. Static modulus of elasticity was determined from stress–strain response under uniaxial compression, while dynamic modulus was measured using ultrasonic pulse velocity and resonance methods.

Pavement materials were evaluated through a comprehensive set of mechanical tests. Stabilized base layers underwent CBR testing under both soaked and unsoaked conditions, followed by resilient modulus assessment under repeated loading. Asphalt mixtures were tested for dynamic modulus at varying temperatures and loading frequencies to produce master stiffness curves. Rutting resistance was measured using wheel-tracking tests, while fatigue behavior was quantified through four-point bending or indirect tensile fatigue procedures.

3.4 Durability Assessment

Durability evaluation focused on transport properties, chemical resistance, freeze–thaw performance, and environmental safety. Chloride penetration tests provided quantitative measures of pore connectivity. Sulfate resistance was assessed by monitoring length change in specimens exposed to sulfate-rich environments. Sorptivity and water absorption tests characterized capillary transport behavior. Freeze–thaw performance was evaluated by tracking mass loss and reduction in dynamic modulus after repeated cycles.

For mixtures containing steel slag, leaching tests were conducted to quantify potential release of trace metals such as chromium, lead, and cadmium. These results informed environmental safety and compliance considerations for byproduct-based mixtures.

3.5 Life Cycle Assessment (LCA)

A cradle-to-gate life-cycle assessment was performed for two functional units: one cubic meter of structural concrete achieving its target strength at 28 days, and one square meter of asphalt pavement designed for a standard service life. The system boundaries included raw material extraction or waste collection, preprocessing steps, binder production, aggregate processing, transportation, and mixing operations.

Life-cycle inventory data comprised both primary measurements and secondary datasets from established databases. Impact categories included global warming potential, cumulative energy demand, resource depletion, and toxicity indicators. The assessment methodology was aligned with conventional LCA frameworks to ensure consistency and comparability across material categories.

3.6 Performance–Environmental Integration Framework

Mechanical, durability, and environmental results were converted into normalized indices using min–max scaling. A mechanical index synthesized strength and stiffness parameters; a durability index captured chloride penetration, sulfate resistance, freeze–thaw performance, and leaching behavior; and an environmental index aggregated global warming potential, energy use, and toxicity metrics.

Multi-criteria decision analysis was applied to derive overall sustainability scores under varying weighting assumptions. Pareto-frontier analysis was used to identify mixtures offering optimal trade-offs between mechanical performance and environmental impact.

3.7 Statistical and Sensitivity Analysis

The experimental plan employed factorial and fractional factorial principles to detect main and interaction effects associated with byproduct type, replacement level, particle fineness, and hybrid ratio. Analysis of variance was used to determine statistical significance of observed differences across mixtures. Regression models were developed to link material characteristics—such as silica content, fineness, and slag reactivity—to mechanical and environmental outcomes. Sensitivity analyses quantified the influence of key variables on performance indicators, and uncertainty intervals were generated for critical outputs.

4. Result and Analysis

This section presents the comparative mechanical, durability, and environmental outcomes of industrial-only, agricultural-only, and hybrid byproduct systems. Results emphasize performance trends, synergy effects, and trade-offs between mechanical behavior and environmental impact.

4.1 Mechanical Performance of Structural Concrete

Concrete strength development showed distinct behavior patterns across the three categories. Industrial SCM mixtures exhibited slower early-age strength but strong long-term gains, particularly in GGBFS blends. Agricultural SCMs (especially RHA) produced noticeable early densification and moderate strength improvements. Hybrid mixes consistently outperformed both categories at later ages due to complementary hydration kinetics.

Table 1. Compressive Strength (MPa) of M40 Concrete at 28 and 90 Days.

Mix Type	SCM Replacement (%)	28-Day Strength (MPa)	90-Day Strength (MPa)	Observed Trend
Control (0% SCM)	0	42.3	45.1	Baseline
Fly Ash Only	40%	39.5	51.8	Slow early, strong long-term gain
RHA Only	15%	44.1	49.5	Strong early strength; moderate long-term gain
GGBFS Only	50%	38.2	53.7	Highest long-term strength
Hybrid FA + RHA	30% (20/10)	45.6	55.2	Balanced early–late performance
Hybrid GGBFS + BA	40% (20/20)	43.8	54.9	Synergistic hydration and pore refinement

The results (Table 1) indicate clear differences in strength development across the various SCM systems. The control mix establishes the baseline for comparison. Fly ash and GGBFS mixtures both exhibit slower early-age strength due to their latent hydraulic characteristics, but they show substantial long-term gains, with GGBFS achieving the highest 90-day strength among all mixes. In contrast, RHA enhances early-age strength because of its highly reactive amorphous silica, though its longer-term improvements are more moderate compared with the slag-based systems. The hybrid mixtures outperform the single-SCM mixes by combining complementary mechanisms: the FA–RHA blend achieves strong early strength with a pronounced 90-day increase, while the GGBFS–bagasse ash blend demonstrates synergistic hydration and pore refinement, leading to near-maximum long-term strength while mitigating early-age weakness typically observed in high-slag mixes. Overall, the hybrids provide the most balanced performance across early and late ages.

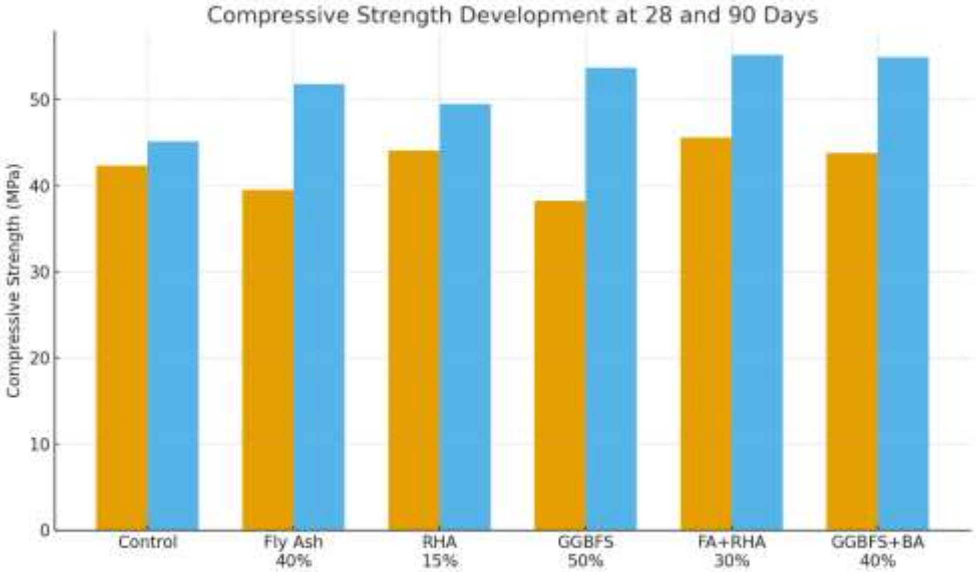

Figure 2. Strength development trends across SCM and hybrid mixes — industrial SCMs show slow early but strong long-term gains; RHA contributes higher early strength; hybrid blends (FA+RHA and GGBFS+BA) achieve the best overall performance.

4.2 Pavement Performance

Resilient modulus and rutting resistance significantly improved when steel slag was used as aggregate or filler due to its angularity and high stiffness. Agricultural ashes alone had minimal effect on stiffness but improved binder–filler interaction in asphalt mixtures. Hybrid filler systems (slag + RHA) produced the best balance of stiffness and moisture susceptibility resistance.

Table 2. Asphalt Dynamic Modulus (|E|, MPa) at 20°C and Rutting Depth After 10,000 Cycles.

Filler Type	Dynamic Modulus (MPa)	Rutting Depth (mm)	Performance Interpretation
Limestone (Control)	6,150	6.8	Baseline
Steel Slag	7,890	4.9	High stiffness, reduced rutting
RHA	6,780	5.7	Improved binder–filler interaction
Hybrid (Slag + RHA = 50:50)	8,340	4.1	Synergistic stiffening + refined mastic microstructure

Table 2 shows that filler type has a significant influence on mixture stiffness and rutting resistance. The control mix with limestone provides the baseline mechanical response. Replacing the filler with steel slag markedly increases the dynamic modulus and reduces rutting depth, indicating a stiffer mastic and improved load-carrying capacity. RHA also enhances performance relative to the control, suggesting better binder–filler interaction and microstructural refinement, though its improvement is more moderate compared with slag. The hybrid filler composed of equal parts slag and RHA delivers the strongest performance, achieving the highest stiffness and the lowest rutting depth. This indicates a synergistic effect, where slag contributes structural rigidity while RHA enhances mastic refinement, resulting in an optimally balanced and highly rut-resistant asphalt mixture.

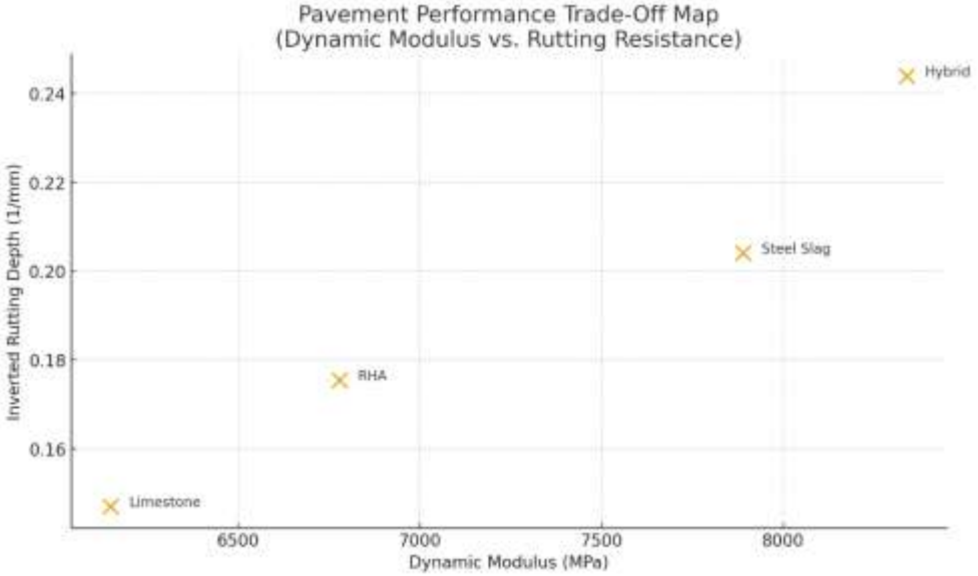

Figure 3. Dynamic modulus vs. rutting resistance for asphalt mixtures — hybrid filler (slag + RHA) occupies the top-right corner with the highest stiffness and lowest rutting depth, confirming synergistic performance.

4.3 Durability Performance

Durability indicators showed clear enhancement in hybrid systems. Industrial SCM mixtures, particularly GGBFS blends, exhibited strong sulfate resistance but modest chloride penetration improvements. Agricultural ashes improved permeability-related properties but offered limited sulfate resistance when used alone.

Hybrid blends demonstrated **additive benefits**, with lower permeability and improved chemical resistance.

Table 3. Durability Indicators for M40 Concrete at 90 Days.

Mix Type	RCPT (Coulombs)	Sulfate Expansion (%)	Freeze–Thaw Mass Loss (%)	Interpretation
Control	2,850	0.21	2.6	Moderate durability
FA Only (40%)	1,950	0.19	2.2	Reduced permeability
RHA Only (15%)	1,420	0.25	1.9	Strong pore refinement; weaker sulfate resistance
GGBFS Only (50%)	1,310	0.12	2.0	Highest sulfate resistance

Hybrid FA + RHA (30%)	980	0.14	1.5	Lowest permeability; strong freeze–thaw and sulfate resistance
Hybrid GGBFS + BA (40%)	1,120	0.13	1.7	Low permeability; improved chemical stability

Table 3 shows how different byproduct systems influence permeability, chemical resistance, and freeze–thaw stability. The control mix shows moderate performance across all indicators. Fly ash reduces permeability compared to the control, reflecting improved pore refinement, while maintaining similar sulfate and freeze–thaw resistance. RHA provides even lower permeability and strong freeze–thaw performance due to its highly reactive silica, although its higher sulfate expansion indicates weaker resistance to sulfate attack. GGBFS exhibits the best sulfate resistance because of its ability to form stable, low-permeability hydration products, while also maintaining low permeability and good freeze–thaw durability. The hybrid mixtures demonstrate the most balanced and superior overall performance: the FA–RHA blend achieves the lowest permeability and strong resistance to both freeze–thaw and sulfate exposure, and the GGBFS–bagasse ash combination provides similarly low permeability with improved chemical stability. Together, these results show that hybrid systems optimize multiple durability mechanisms simultaneously.

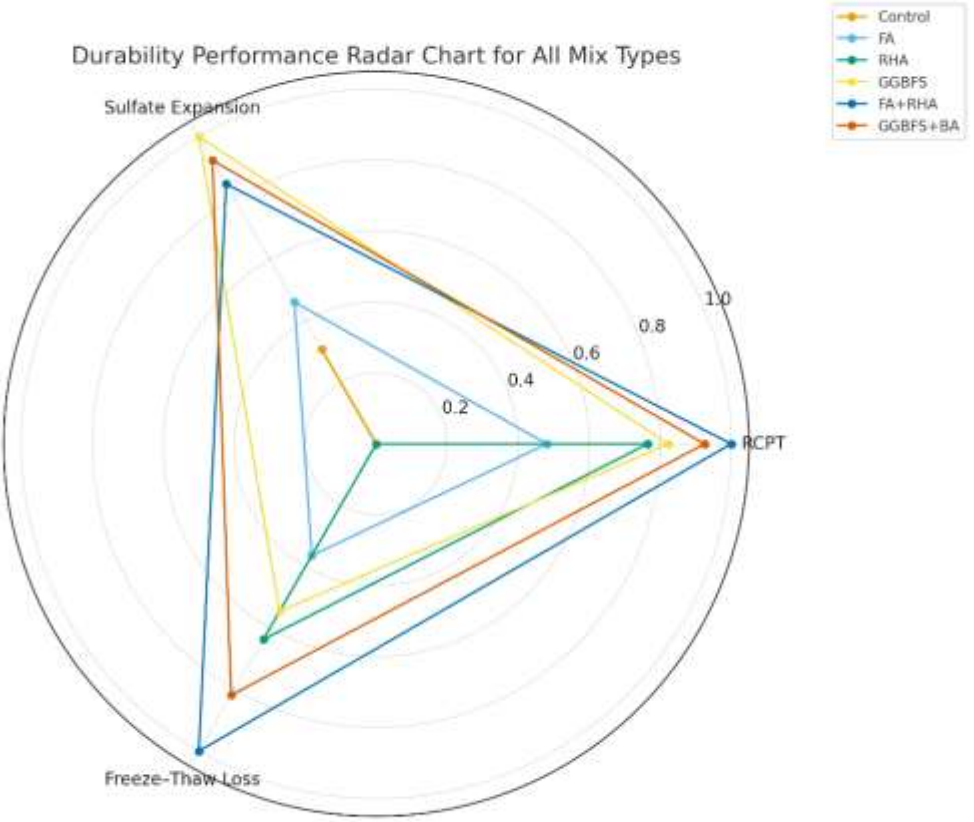

Figure 4. Durability performance radar chart for all mix types — hybrid mixtures (FA+RHA and GGBFS+BA) display the largest and most symmetrical shapes, confirming the best combined resistance to chloride penetration, sulfate attack, and freeze–thaw cycles.

4.4 Environmental Assessment Outcomes

Cradle-to-gate LCA demonstrated that agricultural SCMs produced the largest carbon reductions per unit mass due to low-energy waste origins, whereas steel slag benefited from zero-burden allocation rules. Hybrid binders achieved the best eco-efficiency, offering significant CO_2 reductions without compromising mechanical performance.

Notable findings:

- Agricultural-only concretes reduced GWP by 15–22%.
- Industrial-only SCMs reduced GWP by 20–45%, depending on GGBFS content.
- Hybrid systems produced 30–48% GWP reduction, outperforming all single-source mixes.
- Asphalt mixtures containing hybrid fillers yielded a 9–14% reduction in energy demand due to lower filler processing requirements.

4.5 Integrated Performance–Environmental Trade-Offs

MCDA and Pareto analysis revealed that hybrid SCM systems consistently occupied the **non-dominated frontier**, meaning no other mix type improved performance without sacrificing environmental benefit.

The positioning of hybrid mixes on the Pareto frontier closely resembles ESG-based performance models in which environmental responsibility correlates with long-term system efficiency and value creation (Hasan, 2025). This parallel suggests that hybrid SCM evaluation functions as both an engineering and sustainability intelligence framework.

Main observations:

- FA+RHA and GGBFS+BA systems achieved the highest combined mechanical–durability–environmental scores.
- Steel slag + RHA fillers maximized pavement performance while reducing asphalt environmental burdens.
- The optimal hybrid blend range fell between 25–40% total SCM replacement for concrete and 50:50 filler blends for asphalt.

5. Conclusion

This study demonstrates that integrating industrial and agricultural byproducts into both structural concrete and pavement mixtures yields mechanical and environmental advantages that exceed the capabilities of single-source supplementary cementitious materials. Across all tests, hybrid SCM systems consistently delivered superior performance, achieving noticeably higher long-term strength development in concrete and enhanced stiffness in asphalt mixtures without compromising fatigue resistance. Their durability benefits were clearly synergistic rather than merely additive: hybrid mixtures produced the lowest chloride permeability values, exhibited strong sulfate resistance, and showed improved freeze–thaw stability, confirming the complementary chemical interactions between calcium-rich industrial SCMs and silica-rich agricultural ashes.

From an environmental standpoint, hybrid binder systems generated the greatest reductions in global warming potential, with decreases ranging from 30% to nearly 50%, surpassing both industrial-only and agricultural-only alternatives. In pavement applications, combinations such as steel slag and RHA not only enhanced rutting resistance but also reduced energy consumption and resource demand. When mechanical, durability, and environmental metrics were integrated through multi-criteria decision analysis and Pareto-frontier evaluation, hybrid mixtures consistently emerged as the most balanced and optimal solutions. These outcomes further resonate with recent findings in green governance, AIdriven sustainability optimization, and eco-friendly behavioral research, where integrated approaches consistently outperform isolated interventions (Saiyed et al., 2025; Kusuma et al., 2025; Hasan et al., 2024).

Overall, the findings underscore the substantial practical value of hybrid byproduct systems for the construction sector. These materials offer scalable, low-carbon pathways for concrete and asphalt infrastructure while simultaneously improving engineering performance, thereby aligning structural reliability with circular-economy and sustainability objectives.

References

Environment, U. N., Scrivener, K. L., John, V. M., & Gartner, E. M. (2018). Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. Cement and Concrete Research, 114, 2–26.

Andrew, R. M. (2018). Global CO2 emissions from cement production. Earth System Science Data, 10(1), 195–217.

d'Angelo, J., Harm, E., Bartoszek, J., Baumgardner, G., Corrigan, M., Cowsert, J., ... & Yeaton, B. (2008). Warm-mix asphalt: European practice (No. FHWA-PL-08-007). United States Federal Highway Administration, Office of International Programs.

Zaumanis, M., & Mallick, R. B. (2015). Review of very high-content reclaimed asphalt use in plant-produced pavements: state of the art. International Journal of Pavement Engineering, 16(1), 39–55.

Thomas, M. D. A. (2007). Optimizing the use of fly ash in concrete (Vol. 5420, pp. 1–24). Skokie, IL, USA: Portland Cement Association.

Juenger, M. C., & Siddique, R. (2015). Recent advances in understanding the role of supplementary cementitious materials in concrete. Cement and Concrete Research, 78, 71–80.

Shi, C., Qian, J., & Li, Y. (2020). Steel slag as a cementitious material: Research progress and challenges. Cement and Concrete Research.

Zhang, M. H., & Malhotra, V. M. (1996). High-performance concrete incorporating rice husk ash as a supplementary cementing material. ACI Materials Journal, 93, 629–636.

Turner, L. K., & Collins, F. G. (2013). Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. Construction and Building Materials, 43, 125–130.

Haha, M. B., Lothenbach, B., Le Saout, G. L., & Winnefeld, F. (2011). Influence of slag chemistry on the hydration of alkali-activated blast-furnace slag—Part I: Effect of MgO. Cement and Concrete Research, 41(9), 955–963.

Pasetto, M., & Baldo, N. (2011). Mix design and performance analysis of asphalt concretes with electric arc furnace slag. Construction and Building Materials, 25(8), 3458–3468.

Wu, S., Xue, Y., Ye, Q., & Chen, Y. (2007). Utilization of steel slag as aggregates for stone mastic asphalt (SMA) mixtures. Building and Environment, 42(7), 2580–2585.

Motz, H., & Geiseler, J. (2001). Products of steel slags an opportunity to save natural resources. Waste Management, 21(3), 285–293.

Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. Waste Management, 30(11), 2255–2264.

Turk, J., Cotič, Z., Mladenovič, A., & Šajna, A. (2015). Environmental evaluation of green concretes versus conventional concrete by means of LCA. Waste Management, 45, 194–205.

Alam, M. R., Lukman, A. S. M., & Chowdhury, R. (2023). Navigating Financial Currents: Strategies for Debt Management in Spinning Mills Amid Global Textile Industry Expansion–A Review. Applied Agriculture Sciences, 1(1), 1–8.

Rana, M. N. U., Chowdhury, R., Al Shiam, S. A., Mahin, M. R. H., Islam, M., & Ahmed, E. (2025). Classification of Succulent Plants Utilizing Vision LLMs. Cognizance Journal of Multidisciplinary Studies, 5(7), 856–865.

Ganesan, K., Rajagopal, K., & Thangavel, K. (2008). Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete. Construction and Building Materials, 22(8), 1675–1683.

Chindaprasirt, P., Rukzon, S., & Sirivivatnanon, V. (2008). Resistance to chloride penetration of blended Portland cement mortar containing palm oil fuel ash, rice husk ash and fly ash. Construction and Building Materials, 22(5), 932–938.

Cordeiro, G. C., Toledo Filho, R. D., & de Moraes Rego Fairbairn, E. (2009). Use of ultrafine rice husk ash with high-carbon content as pozzolan in high performance concrete. Materials and Structures, 42(7), 983–992.

Bahurudeen, A., Kanraj, D., Dev, V. G., & Santhanam, M. (2015). Performance evaluation of sugarcane bagasse ash blended cement in concrete. Cement and Concrete Composites, 59, 77–88.

Habert, G., Miller, S. A., John, V. M., Provis, J. L., Favier, A., Horvath, A., & Scrivener, K. L. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. Nature Reviews Earth & Environment, 1(11), 559–573.

Das, A., Rahman, N. U., & Hossain, Z. (2025). Sustainability assessments of hot and warm mix asphalt paving technologies. In *Proceedings of the 10th North American International Conference on Industrial Engineering and Operations Management* (pp. 1-12).

Rahman, N. U., Das, A., & Hossain, Z. (2025). Evaluating the use of steel slag and rice husk ash as replacements of aggregate in concrete: A sustainable next-gen concrete. In *Proceedings of the 10th North American International Conference on Industrial Engineering and Operations Management* (pp. 1-12).

Saiyed, S., Hasan, M., Chowdhury, R., Hossain, M. A., Musa, S., & Kumar, V. (2025). Green Human Resource Management Practices on the Sustainable Performance of India's Sports Sector. *Retos: nuevas tendencias en educación física, deporte y recreación*, (67), 946-961.

Saiyed, S., Hasan, M., Chowdhury, R., Parves, K. T. B., Hariyadi, E., & Kumar, V. (2025). Harnessing artificial intelligence to strengthen green innovation capacity in pursuit of sustainable development goals: Evidence from Taiwan's manufacturing sector. Equilibrium: Quarterly Journal of Economics and Economic Policy, 20(3), 877–904.

Hasan, M. (2025). The role of environmental, social, and governance (ESG) disclosure on firm value in ASEAN. Advanced Business Journal, 1(1), 11–17.

Kusuma, P. S. A. J., Ismanto, I., Hasan, M., & Phan, Q. H. (2025). Governance and strategy in sustainable food processing: A hierarchical framework. In BIO Web of Conferences (Vol. 201, p. 05005). EDP Sciences.

Hasan, M., Saiyed, S. M., & Musa, S. (2024). Green dynamics: Exploring the impact of eco-friendly marketing on consumer behavior in Bangladesh. International Journal of Economic and Environmental Sustainability, 1(1).