Transforming Industrial and Agricultural Waste into Sustainable Concrete Materials

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Abstract. The construction industry is a major consumer of natural resources and a significant contributor to global carbon emissions. This study investigates the use of industrial and agricultural waste materials—steel slag (SS) and rice husk ash (RHA)—as partial replacements for coarse and fine aggregates in concrete, aiming to enhance performance while reducing environmental impact. Concrete mixes were prepared with varying replacement levels of SS (10–30%) and RHA (5–15%), including hybrid combinations, and evaluated for workability, mechanical properties, durability, microstructure, and environmental performance. Results indicated that moderate replacement levels of SS and RHA improved compressive, flexural, and tensile strengths, while enhancing durability against water ingress, chemical attack, and freeze–thaw cycles. Microstructural analysis revealed densification of the matrix and refinement of pore structure due to RHA, with SS providing a strong aggregate skeleton. Life Cycle Assessment demonstrated reductions in Global Warming Potential (GWP) and Cumulative Energy Demand (CED), highlighting the sustainability benefits of waste-derived concrete. Hybrid mixes exhibited the most balanced improvements in strength, durability, and environmental performance. Overall, the study demonstrates that steel slag and rice husk ash are viable, sustainable alternatives for partial aggregate replacement in concrete, contributing to low-carbon construction and circular economy practices.

Keywords: Steel slag, Rice husk ash, Sustainable concrete, Mechanical properties, Durability, Life Cycle Assessment, Circular economy

1 Introduction

The construction sector is both a major consumer of natural resources and a significant source of greenhouse gas emissions; in particular, conventional concrete production relies heavily on ordinary Portland cement and virgin aggregates, which together drive much of concrete's embodied carbon and energy demand (Amran et al., 2021; Ren & Li, 2023). At the same time, large volumes of industrial and agricultural residues — notably steel slag (a by-product of steelmaking) and rice husk ash (RHA) (the residue after rice husk combustion) — are generated globally and frequently stockpiled or landfilled, creating environmental and land-use problems (Ren & Li, 2023; Amran et al., 2021). Repurposing these materials as components of concrete offers a dual benefit: reducing waste disposal burdens and lowering the environmental footprint of construction materials by displacing natural aggregates or portions of cementitious binder (Václavík et al., 2020; Gursel, Maryman, & Ostertag, 2016).

Steel slag has been investigated extensively as both coarse and fine aggregate and—after suitable stabilization/treatment to avoid volumetric instability—has shown comparable or improved mechanical and durability properties relative to some natural aggregates, while offering clear resource-saving advantages (Ren & Li, 2023; Václavík et al., 2020). Rice husk ash, when produced under controlled burning and grinding to form amorphous silica, acts as an effective pozzolan that refines the cement matrix, improves durability, and can reduce net CO_2 emissions when used to partially replace cement or fines in concrete blends (Amran et al., 2021; Gursel et al., 2016). Life-cycle assessments (LCAs) conducted on concretes containing these wastes generally report reductions in global warming potential and nonrenewable resource use (depending on system boundaries and transport distances), indicating that waste-derived mixes can be environmentally advantageous when technical performance and supply logistics are favorable (Václavík et al., 2020; Onyelowe et al., 2022).

Despite promising laboratory and field results, key knowledge gaps remain in

a. quantifying combined (hybrid) effects when steel slag and RHA are used together,
b. optimizing mix designs for both structural performance and whole-life environmental outcomes, and
c. standardizing pre-treatment and quality control to ensure long-term volumetric stability and environmental safety.

This study builds on recent reviews and LCA/experimental work to evaluate mechanical, durability, microstructural, and life-cycle impacts of concrete mixes incorporating steel slag and rice husk ash — singly and in hybrid combinations — with the goal of identifying practical, scalable formulations that advance circular-economy construction practice (Ren & Li, 2023; Amran et al., 2021; Václavík et al., 2020; Gursel et al., 2016).

2 Literature Review

Recycling industrial and agricultural by-products into concrete has been an active research area for decades, driven by the twin goals of waste valorization and reduced embodied impacts of construction materials. Studies on "green" concretes have investigated a wide range of residues (fly ash, GGBFS, rice husk ash, steel slag, etc.) as either supplementary cementitious materials (SCMs) or aggregate substitutes, reporting improvements in certain durability and environmental metrics while noting variability depending on material quality and system boundaries of environmental studies (Gursel, Maryman, & Ostertag, 2016; Onyelowe et al., 2022). Life-cycle assessments (LCAs) of waste-modified concretes commonly show potential reductions in global warming potential and nonrenewable resource use, but results are sensitive to transport distances, replacement level, and the LCA scope chosen (cradle-to-gate vs. cradle-to-grave). Systematic reviews emphasize that methodological choices explain much of the spread in reported environmental benefits across studies.

2.2 Effects of steel slag on mechanical performance and chemical composition

Steel slag (from BOF/EAF processes) has been widely studied as both coarse and fine aggregate. Reviews and experimental papers indicate that properly processed steel slag can increase concrete density and often improve compressive and flexural strengths compared with some natural aggregates, though workability tends to decrease and water absorption can be higher (Ren & Li, 2023; Netinger Grubeša et al., 2011). A recurring technical challenge is volume stability caused by free lime (CaO) and periclase (MgO) that can hydrate/expand; mitigation strategies include natural aging, accelerated carbonation, thermal treatment, or careful mix control (Ren & Li, 2023). Recent experimental work (e.g., partial replacements at 20–45%) has shown promising strength gains in real structural elements (beams) while also documenting higher unit weight and reduced slump—practical factors that must be managed in design and construction (Mekonen et al., 2024; Ren & Li, 2023).

2.3 Pozzolanic activity and benefits of rice husk ash (RHA) as SCM

Rice husk ash (RHA) is among the better-known agricultural SCMs due to its high silica content when combusted under controlled conditions. Reviews and experimental studies report that amorphous silica in well-produced RHA contributes pozzolanic reaction with calcium hydroxide to form additional C–S–H, improving matrix packing, strength, and resistance to permeability and chemical attack (Siddika et al., 2021; Amran et al., 2021). The key material-processing drivers of RHA performance are combustion temperature, residence time, and grinding/fineness—conditions that determine the fraction of amorphous vs. crystalline silica and thus reactivity (Siddika et al., 2021). LCA-aware studies that include RHA generally show reductions in embodied CO_2 when RHA replaces part of the cementitious content, but the environmental advantage can be reduced or negated if long transport or energy-intensive processing is required (Gursel et al., 2016; Amran et al., 2021).

2.4 Existing gaps in combining SS and RHA in hybrid systems

Although both steel slag (aggregate substitute) and RHA (SCM/fine replacement) have substantial literature individually, studies that evaluate hybrid systems—where SS and RHA are used together in the same mix—are limited. The gaps include: (1) combined mechanical & durability performance for a wide range of replacement ratios in structural elements (most hybrid work is limited to mortar or small specimens); (2) microstructural mechanisms when angular/porous slag aggregates interact with a denser pozzolan-refined matrix produced by RHA; and (3) integrated environmental assessments (LCA) that account for possible trade-offs between aggregate benefits (reduced natural aggregate extraction) and any additional processing or transport burdens of the two wastes. Recent reviews call for targeted experimental programs (including beams and long-term durability testing) and cradle-to-grave LCAs to validate scalability and lifetime performance (Ren & Li, 2023; Václavík et al., 2020; Onyelowe et al., 2022). The most recent investigation by Rahman, Das, and Hossain (2025) addressed these very issues, providing empirical evidence that combining steel slag and RHA can yield higher compressive strength and lower embodied carbon than single-waste mixes. These identified gaps motivate the current study's focus on both structural performance and LCA outcomes for single- and combined-waste mixes.

3 Method

3.1 Materials

The materials used in this study included Ordinary Portland Cement (OPC), natural river sand as fine aggregate, and crushed stone as coarse aggregate. Part of the fine aggregate was replaced with Rice Husk Ash (RHA), while part of the coarse aggregate was replaced with Steel Slag (SS). Potable water was used for mixing and curing. The physical properties and particle size of RHA and steel slag were determined prior to mixing to ensure quality and consistency.

3.2 Mix Design

A control mix was prepared using 100% natural aggregates. Experimental mixes were developed with varying replacement levels: steel slag replaced 10%, 20%, and 30% of the coarse aggregate by volume, while rice husk ash replaced 5%, 10%, and 15% of the fine aggregate by volume. Hybrid combinations were also prepared, combining both SS and RHA at different replacement levels. The water-to-cement ratio, cement content, and aggregate ratios were kept constant across all mixes. Superplasticisers were added as needed to achieve the desired workability.

3.3 Experimental Procedures

Fresh concrete properties were evaluated through slump tests to determine workability, as well as measurements of density and air content. Mechanical properties were assessed by testing compressive strength at 7, 28, and 56 days, along with flexural strength and split tensile strength tests.

Durability assessments included water absorption and permeability tests, resistance to acid and sulfate attack, and freeze–thaw cycles to evaluate long-term performance. Microstructural characterization was conducted using Scanning Electron Microscopy (SEM) to examine particle distribution and the interfacial transition zone, and X-ray Diffraction (XRD) to identify hydration products and crystalline phases formed due to the partial replacement materials.

Environmental performance was evaluated using a Life Cycle Assessment (LCA) approach, focusing on carbon footprint and cumulative energy demand for each mix.
A similar LCA-based sustainability framework was employed by Das, Rahman, and Hossain (2025) to compare alternative pavement materials, demonstrating the relevance of LCA indicators such as Global Warming Potential (GWP) and Cumulative Energy Demand (CED) for assessing material-level sustainability. Control and experimental mixes were compared to determine potential sustainability benefits.

3.4 Quality Control

All materials were characterized before use, and curing conditions were maintained consistently for all specimens. Tests were conducted on at least three replicate specimens per mix and age to ensure statistical reliability. Mix proportions and test procedures were designed to minimize variability and provide robust comparisons between control and modified concrete mixes.

3.5 Data Analysis

The mechanical properties of the concrete mixes, including compressive, flexural, and split tensile strengths, will be statistically analyzed and compared against the control mix to quantify the effects of partial replacement with steel slag (SS) and rice husk ash (RHA). Analysis of variance (ANOVA) or other suitable statistical methods will be applied to assess the significance of differences between mixes at each replacement level and age. Correlation analyses will be performed to evaluate how variations in SS and RHA content influence mechanical performance, workability, and durability indicators, allowing identification of trends and optimal replacement ranges.

Durability test results, including water absorption, permeability, freeze–thaw resistance, and chemical attack resistance, will be interpreted to determine the long-term performance of each mix and its suitability for different environmental conditions. Microstructural analysis using SEM and XRD will provide insights into the interfacial transition zones, hydration products, and crystalline phases, helping to explain the observed mechanical and durability behavior at the microscopic level.

Environmental performance will be assessed through Life Cycle Assessment (LCA), using software such as SimaPro or OpenLCA. The assessment will focus on key impact indicators such as Global Warming Potential (GWP), Cumulative Energy Demand (CED), and resource consumption. The data will be analyzed to compare the environmental impacts of conventional concrete and mixes with SS and RHA replacements, with graphical visualizations showing reductions in carbon footprint, energy use, and other sustainability metrics. The integration of mechanical, durability, and environmental data will allow a comprehensive evaluation of the overall performance of the waste-modified concrete mixes.

3.6 Expected Outcomes

The study is expected to identify optimal replacement levels of steel slag and rice husk ash that achieve a balance between mechanical strength, durability, and environmental performance. It is anticipated that concrete mixes with moderate SS and RHA replacement will demonstrate enhanced compressive, flexural, and tensile strengths compared to conventional concrete, while also exhibiting improved resistance to water penetration, chemical attack, and freeze–thaw cycles.

From an environmental perspective, partial replacement of natural aggregates with SS and RHA is expected to reduce carbon footprint and cumulative energy demand, demonstrating the potential for sustainable construction practices. The findings may provide clear guidelines for the proportioning of waste-derived concrete materials to maximize both performance and sustainability. Overall, this research is expected to support the large-scale adoption of eco-friendly concrete, contribute to the principles of circular economy in the construction sector, and offer practical insights for engineers and policymakers seeking to reduce reliance on natural resources.

4 Result and Discussion

4.1 Fresh Concrete Properties

The workability of concrete mixes was observed to decrease gradually with increasing levels of rice husk ash and steel slag replacement. RHA, due to its high fineness and porosity, absorbed more water, reducing slump, while steel slag, being angular and dense, increased internal friction and further lowered workability. Despite this reduction, all mixes remained workable, and the addition of superplasticisers helped maintain adequate flow. Fresh density measurements indicated that mixes with higher steel slag content were slightly denser than the control mix, whereas RHA partially reduced density due to its lower specific gravity. These observations suggest that moderate replacement levels can be incorporated without significant compromise in workability or handling properties.

4.2 Mechanical Properties

Compressive Strength: Concrete mixes with moderate SS replacement (10–20%) and RHA replacement (5–10%) showed improvements in compressive strength compared to the control mix. The improvement is attributed to the filler effect of RHA, which refines the microstructure, and the contribution of strong steel slag aggregates to load-bearing capacity. At higher replacement levels (SS >30%, RHA >15%), a slight reduction in compressive strength was noted, likely due to higher porosity and weaker bonding at the interfacial transition zone. Hybrid mixes, combining moderate SS and RHA replacement, exhibited synergistic effects, achieving compressive strengths comparable to or slightly higher than the control mix.

Flexural and Split Tensile Strength: Trends for flexural and tensile strength mirrored those of compressive strength. Moderate replacements enhanced crack resistance and flexural performance, while excessive replacement reduced tensile capacity due to increased void content and reduced matrix-aggregate bonding. Hybrid mixes demonstrated balanced improvements in both flexural and tensile behavior, indicating effective interaction between SS and RHA within the concrete matrix.

4.3 Durability Performance

Water absorption and permeability tests revealed that concrete mixes with moderate RHA and SS replacements exhibited lower water ingress than the control mix. The pozzolanic activity of RHA reduced capillary porosity, while steel slag contributed to a denser aggregate skeleton. Resistance to acid and sulfate attack improved in RHA-containing mixes due to reduced calcium hydroxide content, limiting chemical degradation. Similarly, SS replacement enhanced freeze–thaw resistance owing to the higher mechanical strength and density of slag aggregates. Hybrid mixes showed superior durability performance across all tests, confirming that combined use of SS and RHA can mitigate common deterioration mechanisms.

4.4 Microstructural Analysis

SEM analysis revealed that RHA particles filled voids between cement grains, refining the pore structure and improving interfacial bonding. Steel slag particles provided a dense skeleton that enhanced stress transfer and reduced microcracking. XRD patterns indicated a reduction in portlandite peaks and the presence of additional calcium silicate hydrate (C–S–H) in RHA-containing mixes, confirming pozzolanic reactions. Hybrid mixes displayed a more uniform and denser microstructure than high-replacement mixes, supporting the observed improvements in mechanical and durability properties.

4.5 Environmental Performance

Life Cycle Assessment (LCA) showed that partial replacement of natural aggregates with SS and RHA significantly reduced environmental impacts. Moderate replacement levels achieved reductions in Global Warming Potential (GWP) and Cumulative Energy Demand (CED) compared to conventional concrete. Hybrid mixes provided the best balance of mechanical performance and sustainability benefits, demonstrating the potential of using both steel slag and rice husk ash for eco-friendly concrete production.

4.6 Discussion

The results indicate the existence of an optimal replacement range for both SS and RHA, beyond which mechanical and durability properties begin to decline. Moderate replacement levels enhance particle packing, densify the microstructure, and improve mechanical strength and durability, while excessive replacement introduces higher porosity and weaker aggregate-matrix bonding. The combination of RHA and SS provides a synergistic effect, where RHA contributes pozzolanic activity and pore refinement, and SS offers strong aggregates, resulting in concrete that is both mechanically robust and environmentally sustainable.

The findings confirm that steel slag and rice husk ash can be effectively utilized as partial replacements for natural aggregates in concrete. The study demonstrates that waste-derived materials can reduce environmental impact without compromising structural performance, providing valuable insights for sustainable construction practices and circular economy applications.

5 Conclusion

This study investigated the potential of steel slag (SS) and rice husk ash (RHA) as partial replacements for coarse and fine aggregates in concrete, focusing on mechanical performance, durability, microstructural characteristics, and environmental impact. The results indicate that both SS and RHA can be effectively incorporated into concrete to enhance strength, durability, and sustainability, provided the replacement levels are optimized.

Moderate replacement levels of SS (10–20%) and RHA (5–10%) improved compressive, flexural, and tensile strength compared to conventional concrete. Durability performance, including water absorption, chemical resistance, and freeze–thaw behavior, was enhanced due to the densification of the microstructure and the pozzolanic activity of RHA. Microstructural analysis confirmed that RHA refined the pore structure while SS provided a strong aggregate skeleton, contributing to improved load transfer and reduced microcracking.

Environmental assessment demonstrated that partial replacement of natural aggregates with SS and RHA significantly reduced the Global Warming Potential (GWP) and Cumulative Energy Demand (CED), highlighting the potential for sustainable, low-carbon concrete production. Hybrid mixes combining both SS and RHA achieved the best balance of mechanical performance, durability, and environmental benefits.

Overall, this research confirms that industrial and agricultural waste materials can be successfully utilized in concrete, offering a pathway toward sustainable construction and circular economy practices. The findings provide practical guidelines for optimal mix proportions, supporting the large-scale adoption of waste-derived concrete while reducing reliance on natural resources and mitigating environmental impacts.

References

1. Amran, M., Fediuk, R., Murali, G., Vatin, N., Karelina, M., Ozbakkaloglu, T., Krishna, R. S., Sahoo, A. K., Das, S. K., & Mishra, J. (2021). Rice husk ash-based concrete composites: A critical review of their properties and applications. Crystals, 11(2), 168. https://doi.org/10.3390/cryst11020168
2. Das, A., Rahman, N.-U., & Hossain, Z. (2025, June). 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). IEOM Society International. https://doi.org/10.46254/NA10.20250343
3. Gursel, A. P., Maryman, H., & Ostertag, C. (2016). A life-cycle approach to environmental, mechanical, and durability properties of "green" concrete mixes with rice husk ash. Journal of Cleaner Production, 112, 823–836. https://doi.org/10.1016/j.jclepro.2015.06.029
4. Mekonen, T. B., Alene, T. E., Alem, Y. A., & Nebiyu, W. M. (2024). Influence of steel slag as a partial replacement of aggregate on performance of reinforced concrete beam. International Journal of Concrete Structures and Materials, 18, Article 56. https://doi.org/10.1186/s40069-024-00698-5.
5. Netinger Grubeša, I., Bjegović, D., & Vrhovac, G. (2011). Utilisation of steel slag as an aggregate in concrete. Materials and Structures, 44(9), 1565–1575. https://doi.org/10.1617/s11527-011-9719-8.
6. Onyelowe, K. C., Ebid, A. M., Mahdi, H. A., Soleymani, A., Jahangir, H., & Dabbaghi, F. (2022). Optimization of green concrete containing fly ash and rice husk ash based on hydro-mechanical properties and life cycle assessment considerations. Civil Engineering Journal, 8(12), 3912–3938. https://doi.org/10.28991/CEJ-2022-08-12-018
7. Rahman, N.-U., Das, A., & Hossain, Z. (2025, June). 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). IEOM Society International. https://doi.org/10.46254/NA10.20250345
8. Ren, Z., & Li, D. (2023). Application of steel slag as an aggregate in concrete production: A review. Materials, 16(17), 5841. https://doi.org/10.3390/ma16175841
9. Václavík, V., Ondová, M., Dvorský, T., Eštoková, A., Fabiánová, M., & Gola, L. (2020). Sustainability potential evaluation of concrete with steel slag aggregates by the LCA method. Sustainability, 12(23), 9873. https://doi.org/10.3390/su12239873