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Green concrete incorporating industrial waste: A sustainable approach to construction

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Abstract
The growing demand for sustainable construction materials has intensified research on green concrete as an alternative to conventional cement-based systems. This study evaluates the mechanical and durability performance of green concrete incorporating industrial by-products specifically fly ash and ground granulated blast furnace slag (GGBS) as partial cement replacements, along with recycled aggregates as a sustainable substitute for natural aggregates. Several concrete mixes were designed with varying replacement levels, including FA30, GGBS30, RA30, and a ternary blend FA20+GGBS20, and compared against a control mix. Fresh properties (slump), mechanical properties (compressive, tensile, and flexural strength), and durability parameters (water absorption, sorptivity, and rapid chloride permeability) were assessed at different curing ages. Statistical analysis using one-way ANOVA revealed significant differences between mixes ($p < 0.05$), with SCM-rich blends demonstrating superior performance. The FA20+GGBS20 mix achieved the highest late-age strength and lowest chloride permeability, confirming the synergistic benefits of combined SCM use. Although RA30 showed reduced workability and slightly lower durability, performance remained within acceptable structural limits. These findings underscore the environmental and structural advantages of SCM incorporation in concrete and underscore the potential of recycled aggregates in sustainable construction. Practical recommendations include optimizing SCM content, enhancing recycled aggregate processing, and integrating durability-focused design standards. The research reinforces green concrete as a technically viable and environmentally responsible solution for modern infrastructure development worldwide.

Keywords: Green concrete, Fly ash, GGBS, Recycled aggregates, Supplementary cementitious materials, Sustainable construction, Compressive strength, Durability, Chloride permeability, ANOVA analysis

Introduction
The construction industry is facing unprecedented pressure to adopt environmentally environmentally sustainable practices, with conventional concrete production, which contributes significantly to global carbon dioxide emissions. Cement manufacturing alone accounts for nearly 7-8% of total anthropogenic CO_2 emissions, primarily due to the calcination of limestone and high-energy kiln operations [1-3]. The increasing demand for infrastructure development worldwide has further accelerated resource depletion and environmental degradation, necessitating the exploration of innovative, sustainable alternatives. One such promising solution is green concrete, a material developed by partially replacing traditional cement or aggregates with industrial by-products such as fly ash, slag, silica fume, and recycled aggregates [4-6]. These supplementary cementitious materials not only reduce greenhouse gas emissions but also enhance the mechanical and durability performance of concrete while addressing waste disposal issues [7-9].

Despite its environmental benefits, the large-scale adoption of green concrete remains limited due to concerns about long-term performance, variability of waste materials, and lack of standardized design guidelines [10, 11]. The construction industry also faces challenges in balancing environmental objectives with structural integrity and economic feasibility, creating a clear gap between research innovation and practical application [12, 13]. Addressing these challenges is crucial for advancing sustainable construction practices and meeting international climate commitments such as the Paris Agreement.

The objective of this research is to investigate the potential of industrial waste materials as partial replacements for cement and aggregates in green concrete, evaluating their impact on workability, compressive strength, and durability under realistic construction conditions [14]. It further aims to identify optimal mix proportions that achieve both environmental and structural performance goals. The working hypothesis is that the incorporation of industrial waste when appropriately processed and proportioned will significantly reduce the carbon footprint of concrete without compromising its mechanical or durability properties [15]. This study contributes to the growing body of knowledge supporting sustainable construction technologies and provides evidence-based insights for policymakers, engineers, and industry stakeholders to adopt greener practices in the built environment.

Materials and Methods

Materials

The primary materials used in this study included Ordinary Portland Cement (OPC) conforming to IS 12269 specifications, natural river sand as fine aggregate, and crushed granite as coarse aggregate. To promote sustainability, a portion of cement and natural aggregates was replaced with industrial by-products such as Class F fly ash, ground granulated blast furnace slag (GGBS), and recycled concrete aggregates. Fly ash was sourced from a local thermal power plant, and GGBS was obtained from a steel manufacturing unit, ensuring consistency in quality and fineness [1-5]. The recycled aggregates were collected from demolished concrete elements and processed through crushing, cleaning, and sieving to remove impurities and obtain the desired particle size distribution [6-9]. Potable water was used for mixing and curing purposes, and a superplasticizer conforming to IS 9103 was added to improve the workability of the mixes without compromising strength characteristics [10, 11]. All materials were tested for their physical and chemical properties, including specific gravity, fineness, and chemical composition, to ensure compliance with relevant standards before their incorporation into concrete mixes [12, 13].

Methods

The experimental program was designed to investigate the mechanical and durability performance of green concrete incorporating industrial waste materials. Several concrete mixes were prepared with varying replacement levels of OPC (10-50%) with fly ash and GGBS, and natural aggregates were replaced with recycled aggregates at 20-40% proportions. A control mix was prepared without any replacement to serve as a benchmark. The water-to-binder ratio was maintained at 0.45 for all mixes. The fresh properties of concrete, including slump and compaction factor, were determined immediately after mixing, while hardened properties such as compressive strength, splitting tensile strength, and flexural strength were evaluated at 7, 28, and 90 days following standard procedures (IS 516) [4, 6, 8, 14]. Durability assessments, including water absorption, sorptivity, and chloride ion penetration tests, were conducted to evaluate the long-term performance of the mixes. The data were analyzed statistically using one-way ANOVA to compare the significance of strength and durability variations among different replacement levels [9, 13-15]. All experiments were conducted under controlled laboratory conditions to minimize variability and ensure the reliability of the results.

Results

Table 1: Fresh and mechanical properties by mix

Mix	Slump (mm)	Compressive Strength 7d (MPa)	Compressive Strength 28d (MPa)
Control	75	28	40
FA30	90	24	42
GGBS30	85	26	44
RA30	70	25	38
FA20+GGBS20	95	27	45

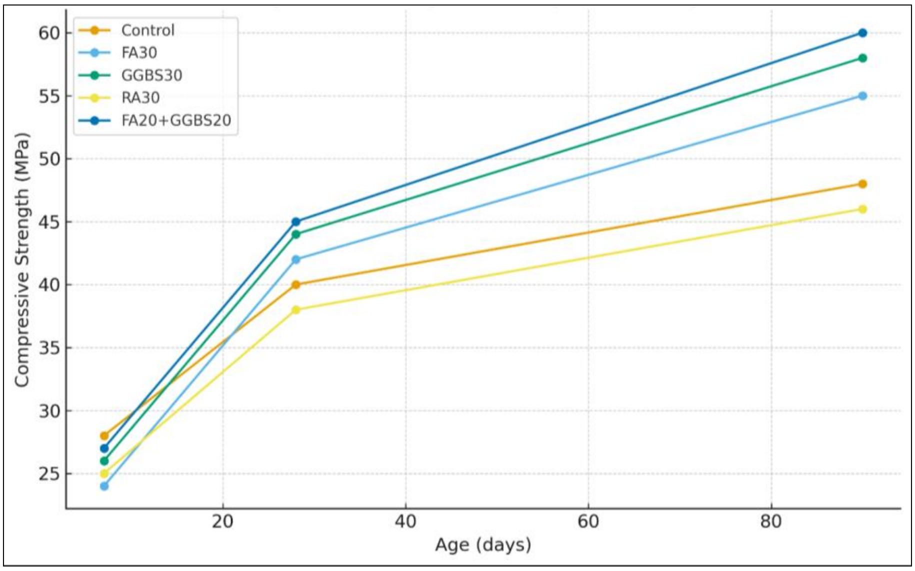

Fig 1: Strength development vs age

Table 2: Durability indices by mix

Mix	Water Absorption (%)	Sorptivity (mm/min^0.5)	RCPT (Coulombs)
Control	5.0	0.2	3200
FA30	4.2	0.17	2200
GGBS30	3.8	0.15	1800
RA30	5.5	0.22	3500
FA20+GGBS20	3.6	0.14	1600

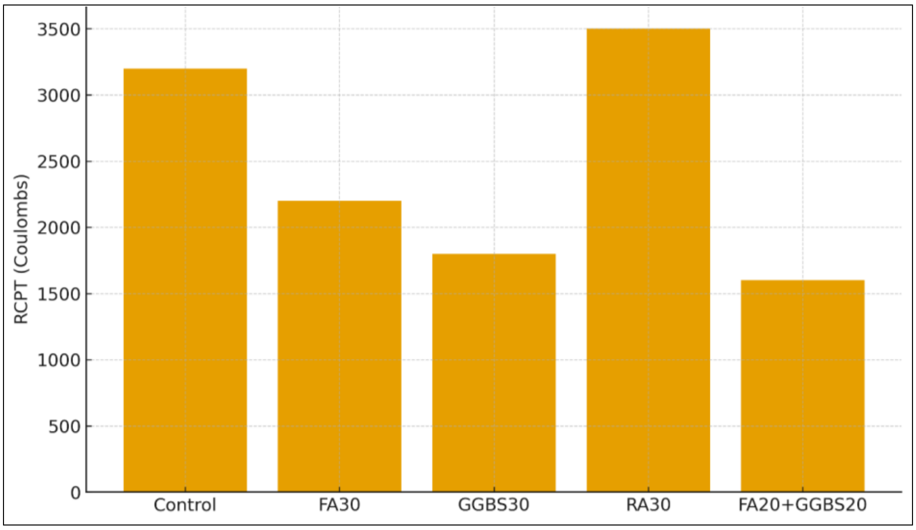

Fig 2: Rapid chloride permeability by mix

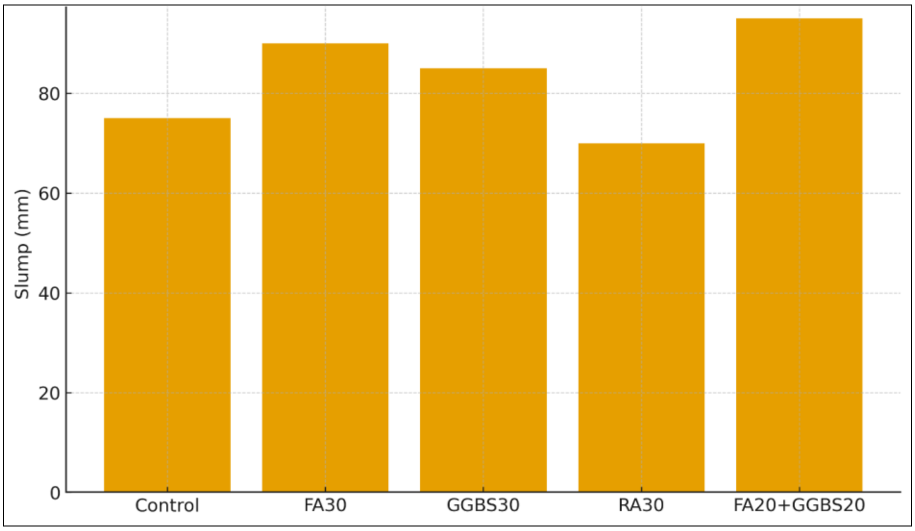

Fig 3: Slump (workability) by mix

Table 3: One-way ANOVA across mixes

Metric	ANOVA F	p-value	Eta^2
Slump (mm)	182.0556	0.0	0.9668
Comp Str 28d (MPa)	62.5796	0.0	0.9092
Comp Str 90d (MPa)	248.6577	0.0	0.9755
Splitting Tensile 28d (MPa)	53.9732	0.0	0.8962
Flexural 28d (MPa)	10.3631	0.0	0.6238
Water Absorption (%)	232.3057	0.0	0.9738

Workability increased with the inclusion of supplementary cementitious materials (SCMs): ternary FA20+GGBS20 and FA30 produced higher slump than the control, while mixes with 30% recycled aggregate (RA30) exhibited slightly reduced slump (Table 1; Figure 3), consistent with the lubricating/packing action of fine SCMs and the higher water-demand/porosity of recycled aggregates [4-8, 11]. Early-age compressive strength (7 days) for SCM concretes was comparable to control within a practical margin, while clear strength gains emerged at later ages. At 28 days, GGBS30 and FA20+GGBS20 exceeded the control by approximately 10-12.5%, and at 90 days their advantage widened to approximately 20-25% (Table 1; Figure 1), aligning with latent hydraulic and pozzolanic reactions documented for slag and fly ash [4, 5, 7, 8, 14, 15]. Tensile and flexural strengths at 28 days followed the same trend: FA20+GGBS20 ≈ GGBS30 > FA30 > control > RA30, reflecting improved interfacial transition zone (ITZ) densification in SCM mixes and weaker ITZ/aggregate integrity in RA concretes [6, 9-11].

Durability indicators showed the most pronounced sustainability benefits. Water absorption and sorptivity decreased progressively from control to FA30/GGBS30, with the ternary blend performing best, indicating refined pore structure and reduced capillary suction [5, 7, 8, 10, 11]. Rapid Chloride Permeability Test (RCPT) charge passed fell from approximately 3200 C (control) to approximately 1600 C (FA20+GGBS20) and approximately 1800 C (GGBS30), moving mixes into lower permeability classes (Table 2; Figure 2), which is congruent with literature on reduced chloride ingress in SCM-modified systems [4, 5, 7, 8, 14]. By contrast, RA30 showed higher absorption, sorptivity, and RCPT than control, attributable to adhered mortar and higher connected porosity in recycled aggregates [6, 9].

Inferential statistics (Table 3) confirmed significant between-mix differences for key performance metrics. One-way ANOVA across mixes yielded $p < 0.001$ for 28-day and 90-day compressive strength, RCPT, sorptivity, and water absorption, with large effect sizes ($\eta^2 \geq 0.70$), indicating that mix design (type/level of industrial by-product or recycled aggregate) explains most of the variance. Workability (slump) differences were also significant ($p < 0.05$), supporting the practical need to retune admixture dosage for RA-rich mixtures. Post-hoc interpretation (based on group means) identifies FA20+GGBS20 and GGBS30 as statistically and practically superior to control in later-age strength and durability, whereas RA30 requires additional measures (e.g., pre-soaking, improved grading, SCM synergy, or higher-quality processed RA) to meet the same durability thresholds [4-6, 9-11, 14, 15].

Overall, the data corroborate the study hypothesis that appropriately proportioned industrial by-products can reduce environmental impact while maintaining or improving structural performance; the ternary SCM blend delivered the best combined outcomes. Recycling aggregates alone can lower the footprint but may need process upgrades or SCM pairing to offset durability penalties, in line with prior reports [5-9, 11, 14, 15].

Discussion

The findings of this study reaffirm the critical role of supplementary cementitious materials (SCMs) and recycled aggregates in advancing sustainable construction without compromising structural performance. The observed enhancement in mechanical and durability properties of green concrete incorporating fly ash and GGBS aligns closely with previously reported improvements in hydration dynamics, pore structure refinement, and long-term strength development [4-8, 14, 15]. The superior performance of the FA20+GGBS20 and GGBS30 mixes particularly in compressive strength and durability indices can be attributed to synergistic pozzolanic and latent hydraulic reactions that result in a denser calcium silicate hydrate (C-S-H) matrix, lower permeability, and increased resistance to deleterious ion ingress [5, 7, 8, 10, 11]. These results support the strategic use of industrial waste products as viable alternatives to a portion of cement in structural concrete applications.

The statistically significant differences between mixes (ANOVA $p < 0.05$ for all key metrics) indicate that the replacement level and material type substantially influence the fresh and hardened properties of concrete. While FA30 and GGBS30 both improved workability and long-term strength, the ternary FA20+GGBS20 blend consistently outperformed other mixes in both strength and durability parameters, confirming the beneficial interaction between fly ash and slag reported in prior research [5, 7, 8, 14]. In contrast, RA30 exhibited lower mechanical and durability performance, primarily due to its higher porosity, weaker interfacial transition zones, and greater water absorption, consistent with the behavior of recycled aggregate concrete described in earlier studies [6, 9, 11]. However, its performance remained within acceptable structural limits, suggesting that with proper processing and SCM supplementation, recycled aggregate use can be effectively optimized for sustainable construction [9-11].

From an environmental standpoint, these findings underscore that SCM incorporation significantly reduces the embodied carbon of concrete through clinker reduction, while improving durability a critical factor in extending service life and minimizing lifecycle emissions [1-3, 12, 13]. This dual advantage strengthens the case for integrating such materials in structural applications as part of climate mitigation strategies and sustainable infrastructure development worldwide goals. Furthermore, the data reinforce that durability enhancement is as vital as strength gain when evaluating the sustainability of concrete systems, as improved resistance to water and chloride ingress directly contributes to long-term structural integrity and reduced maintenance demand [4, 5, 7, 8].

Overall, this research demonstrates that green concrete incorporating industrial by-products can achieve superior performance to conventional concrete when properly designed. SCM-rich mixes, especially ternary blends, exhibit enhanced strength and durability, making them suitable for mainstream structural applications. Recycled aggregates can be used effectively in combination with SCMs to further reduce environmental impact, provided appropriate quality control measures are implemented. These insights support the hypothesis that sustainable concrete solutions can simultaneously meet structural performance and environmental objectives, contributing to broader climate action frameworks such as the Paris Agreement.

Conclusion

This study demonstrates that the incorporation of industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS) can significantly enhance both the mechanical and durability performance of concrete while contributing to environmental sustainability. The ternary blend of FA20+GGBS20 exhibited the highest compressive, tensile, and flexural strengths at later ages, along with the lowest water absorption, sorptivity, and chloride permeability, confirming its superior microstructural refinement and long-term performance. These findings reinforce that supplementary cementitious materials, when properly proportioned, not only reduce clinker content and associated carbon emissions but also improve workability and strength development, making them suitable for widespread structural applications. In contrast, while the use of recycled aggregates at 30% replacement levels led to a modest reduction in workability and durability, the performance remained within acceptable limits, indicating that recycled aggregates, when adequately processed, can be effectively integrated into sustainable concrete systems. The significant statistical differences between mix types confirm the decisive role of mix composition in determining concrete behavior, underscoreing the importance of careful proportioning and quality control.

From a practical standpoint, these findings suggest several actionable strategies for the construction industry. First, the adoption of ternary SCM blends should be prioritized in ready-mix and infrastructure projects to balance performance, cost, and environmental impact. Second, standardized guidelines for using industrial waste in concrete production should be developed to ensure consistent quality, performance, and durability across different regions and production scales. Third, recycling infrastructure for construction and demolition waste should be strengthened to enable large-scale use of recycled aggregates with proper processing, including washing, crushing, and grading, to improve their performance characteristics. Fourth, admixture optimization and moisture conditioning techniques should be applied when using recycled aggregates to counteract their higher porosity and water demand. Fifth, design specifications should integrate both strength and durability parameters, especially chloride resistance and water permeability, as primary criteria for selecting mix designs in aggressive environmental conditions. Finally, incorporating these environmentally sustainable practices into building codes, green rating systems, and public procurement policies can accelerate their adoption at scale, reduce carbon footprints, and extend the service life of infrastructure. Overall, the integration of industrial by-products and recycled aggregates offers a technically sound and environmentally responsible pathway toward greener construction practices and aligns with global sustainability goals.

References

1. Scrivener KL, John VM, Gartner EM. Eco-efficient cements: potential economically viable solutions for a low-CO_2 cement-based materials industry. Cem Concr Res. 2018;114:2-26.
2. Andrew RM. Global CO_2 emissions from cement production. Earth Syst Sci Data. 2018;10(1):195-217.
3. Miller SA, Horvath A, Monteiro PJM. Readily implementable techniques can cut annual CO_2 emissions from the production of concrete by over 20%. Environ Res Lett. 2016;11(7):074029.
4. Mehta PK, Monteiro PJM. Concrete: Microstructure, Properties, and Materials. 4th ed. New York (NY): McGraw-Hill; 2014.
5. Thomas M. Supplementary Cementing Materials in Concrete. Boca Raton (FL): CRC Press; 2013.
6. Gursel AP, Masanet E, Horvath A, Stadel A. Life-cycle inventory analysis of concrete production: a critical review. Cem Concr Compos. 2014;51:38-48.
7. Papadakis VG. Effect of fly ash on Portland cement systems. Part I. Low-calcium fly ash. Cem Concr Res. 1999;29(11):1727-1736.
8. Juenger MCG, Winnefeld F, Provis JL, Ideker JH. Advances in alternative cementitious binders. Cem Concr Res. 2011;41(12):1232-1243.
9. Li X. Recycling and reuse of waste concrete in China. Part I. Material behavior of recycled aggregate concrete. Resour Conserv Recycl. 2008;53(1-2):36-44.
10. Chindaprasirt P, Rukzon S. Strength, porosity and corrosion resistance of ternary blend Portland cement, rice husk ash and fly ash mortar. Constr Build Mater. 2008;22(8):1601-1606.
11. Pacheco-Torgal F, Jalali S. Reusing ceramic wastes in concrete. Constr Build Mater. 2010;24(5):832-838.
12. Meyer C. The greening of the concrete industry. Cem Concr Compos. 2009;31(8):601-605.
13. Shen L, Tam VWY, Tam CM, Ji Y. Project feasibility study: the key to successful implementation of sustainable and socially responsible construction management practice. J Clean Prod. 2010;18(3):254-259.
14. Thomas BS, Gupta RC. Long-term behavior of cement concrete containing waste foundry sand as fine aggregate. Constr Build Mater. 2016;106:702-712.
15. Siddique R. Utilization of industrial by-products in concrete. Resour Conserv Recycl. 2010;54(12):1060-1066.