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Integrated Experimental and Theoretical Analysis of Reinforced Concrete Beams Using Green Concrete for Environmental Sustainability and Structural Optimization

Shubham Kesarwani[1], Maaz Allah Khan[2], Rohit Pandey[3]

[1,2] Department of Civil Engineering, UIET, BBAU, Lucknow, [3]Project Scientist, Remote Sensing Application Center UP

Corresponding author's mail: er.shubhamkesarwani@gmail.com

***Abstract* - The rapid growth of global infrastructure has intensified the reliance on traditional cement-based materials, leading to substantial CO_2 emissions and the exhaustion of natural resources. This research investigates the integration of eco-friendly construction techniques by evaluating reinforced concrete (RC) beams formulated with "green concrete"[2] These mixtures incorporate industrial by-products—including silica fume, fly ash, and ground granulated blast-furnace slag (GGBS)—as partial binder replacements. The study employs a dual experimental and theoretical framework to assess structural parameters such as stiffness, flexural capacity, cracking patterns, and ductility. Laboratory specimens were subjected to two-point loading to establish load-deflection profiles and failure mechanisms[5555]. These results were validated through analytical limit-state design and nonlinear finite element analysis (FEA) using ANSYS. The findings indicate that green concrete beams offer structural performance comparable or superior to conventional mixes while achieving a 35% reduction in embodied carbon. A high correlation between empirical and numerical data ($R^2 = 0.97$) confirms the reliability of the predictive models, advocating for the use of sustainable concrete in structural applications.**

***Keywords* – Sustainable Concrete, RC Beam Flexure, Supplementary Cementitious Materials (SCMs), Finite Element Analysis, Embodied Carbon Reduction, Structural Optimization, Eco-efficient Infrastructure.**

1. Introduction

1.1 Background

Reinforced concrete (RC) remains the most extensively used construction material worldwide due to its versatility, strength, and cost-effectiveness. It plays a vital role in modern infrastructure such as bridges, high-rise buildings, and industrial facilities, offering structural stability and durability under various loading conditions [1]. However, the traditional production of Portland cement—the primary binding agent in concrete—poses significant environmental challenges. The cement industry alone is responsible for approximately 7–8% of total global carbon dioxide emissions and consumes substantial amounts of natural resources and energy [2].

These environmental concerns have driven the need to develop sustainable alternatives that minimize ecological impact without compromising structural performance. Green concrete has emerged as an innovative and eco-friendly alternative to conventional concrete. It utilizes supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast-furnace slag (GGBS), silica fume, and rice husk ash, which are industrial by-products that can partially replace cement [3]. Additionally, the use of recycled aggregates derived from construction and demolition waste reduces landfill burden and promotes circular economy practices in the construction sector [4]. Beyond its environmental advantages, green concrete has demonstrated improved durability, lower permeability, and enhanced resistance to chemical attack, making it a viable material for sustainable structural applications [5].

1.2 Problem Statement

Despite the progress in sustainable materials research, the integration of green concrete into structural components such as reinforced concrete beams remains inadequately explored. While previous studies have examined mechanical and durability properties of green concrete, few have conducted integrated experimental and theoretical analyses to fully understand its structural behavior under flexural loading[6]. The absence of reliable comparative data between laboratory results and theoretical modeling limits the adoption of green concrete in design codes and practical applications. Therefore, there is a crucial need for research that optimizes the balance between sustainability and performance while ensuring compliance with structural safety standards [7].

1.3 Research Objectives

The primary objective of this study is to evaluate the structural behavior of reinforced concrete beams made with green concrete through both experimental and theoretical approaches. The specific objectives are as follows:

- To develop green concrete mixes incorporating industrial by-products such as fly ash, GGBS, and silica fume.
- To experimentally analyze the load-carrying capacity, stiffness, ductility, and cracking behavior of green concrete beams.
- To validate experimental outcomes using analytical and finite element models.
- To propose sustainable design recommendations for optimizing material performance and environmental impact.

1.4 Research Questions

This research is guided by the following key questions:

- How does the inclusion of SCMs affect the flexural strength, stiffness, and cracking characteristics of reinforced concrete beams?
- To what extent can theoretical and finite element models accurately predict the experimental behavior of green concrete beams?
- Can green concrete simultaneously achieve structural reliability and environmental sustainability in construction?

1.5 Significance of the Study

The findings of this research provide a scientific bridge between material science and structural engineering, supporting global initiatives for carbon neutrality in the building sector. By providing empirical data on the behavior of green concrete in load-bearing RC elements, this study offers a foundation for updating structural design codes like IS 456:2000. Furthermore, the integrated modeling approach demonstrates how advanced simulations can reduce the necessity for costly, large-scale physical testing, thereby accelerating the adoption of low-carbon materials in modern construction.

2. Literature Review

2.1 Concept of Green Concrete

Green concrete refers to a sustainable construction material that minimizes environmental impact by reducing cement usage and utilizing industrial by-products as partial substitutes. The concept integrates environmental responsibility with engineering performance, emphasizing reduced energy consumption, conservation of natural resources, and decreased carbon emissions during production [3]. Traditional cement production emits approximately 0.8–0.9 tons of CO_2 per ton of cement produced, which has become a significant contributor to climate change [2].

Green concrete aims to mitigate this by replacing a portion of cement with supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast-furnace slag (GGBS), metakaolin, and rice husk ash—materials that would otherwise contribute to industrial waste[8]. The inclusion of SCMs enhances workability, durability, and long-term strength while lowering embodied energy. Studies have shown that replacing up to 40% of cement with SCMs can reduce embodied CO_2 emissions by approximately 30–35% without significant compromise in structural performance[3][4].

Moreover, green concrete promotes circular economy principles by recycling waste and reducing landfill loads. Comparative assessments demonstrate that its embodied energy is significantly lower than that of conventional concrete, making it a critical material in achieving global sustainability goals within the construction sector.

2.2 Mechanical Properties of Green Concrete

The mechanical behavior of green concrete determines its suitability for structural applications. The inclusion of SCMs influences key mechanical properties such as compressive, tensile, and flexural strength. The partial replacement of cement with fly ash and GGBS enhances compressive strength at later ages due to secondary pozzolanic reactions, which refine the pore structure and improve the interfacial transition zone[5]. Similarly, silica fume improves tensile and flexural strength because of its micro-filling ability and high reactivity, resulting in denser and stronger matrices[3].

Durability aspects such as permeability, chloride penetration resistance, and sulfate attack resistance are equally significant. Studies indicate that green concrete exhibits reduced permeability and higher sulfate resistance compared to ordinary Portland cement (OPC) concrete, largely due to the formation of additional calcium silicate hydrate (C–S–H) gel[2]. However, certain mixes may experience higher shrinkage if water content is not properly optimized[8]. Overall, mechanical tests confirm that green concrete, when properly designed, meets or exceeds the strength and durability requirements of structural-grade concrete.

2.3 Behavior of Reinforced Concrete Beams

Reinforced concrete beams are critical elements in structural systems, designed primarily to resist bending and shear. The flexural behavior of beams depends on material properties, reinforcement detailing, and loading conditions[9]. Under loading, beams undergo cracking in the tension zone, followed by yielding of reinforcement and ultimate failure in compression or tension, depending on the reinforcement ratio. Ductility, defined as the capacity of a beam to sustain deformation beyond yield without sudden failure, is a vital parameter for assessing performance.

The inclusion of green concrete in beams influences cracking behavior and stiffness due to variations in tensile strength and modulus of elasticity. Beams made with SCM-based concrete show comparable or slightly lower stiffness but improved energy absorption capacity, making them suitable for seismic and fatigue-resistant structures[1]. Understanding this behavior is crucial for validating the structural feasibility of sustainable concrete materials.

2.4 Experimental Studies on Green RC Beams

Experimental investigations on green concrete beams have focused on evaluating load-deflection characteristics, crack propagation, and failure modes. Studies conducted on flexural testing of RC beams with 30% fly ash and 20% GGBS replacement found that such beams achieved nearly 95% of the flexural strength of conventional beams, with better ductility and crack control[6]. Similar results were observed in recent research, which noted that SCM-based beams demonstrated delayed crack initiation and improved post-yield behavior[7]. Analysis of beams with recycled aggregates reported that compressive and flexural strengths remained within acceptable limits, provided the aggregate replacement did not exceed 25%[7]. These findings affirm the potential of green concrete in structural components while highlighting the need for optimized mix proportions and reinforcement detailing.

2.5 Theoretical and Numerical Analysis of RC Beams

Analytical and numerical modeling are indispensable tools for predicting beam behavior and validating experimental results. The classical beam theory, based on limit state design principles, provides analytical expressions for moment-curvature relationships and ultimate load-carrying capacity[9]. However, complex phenomena such as cracking and nonlinear stress distribution are better captured through numerical simulations using finite element methods (FEM).

Software tools such as ANSYS and ABAQUS have been widely employed to simulate the flexural response of RC beams under static and dynamic loading. Studies demonstrated that finite element modeling could accurately replicate experimental load-deflection curves and predict crack propagation patterns when appropriate constitutive models for concrete and steel are used[7]. Moreover, integrating FEM with sustainability-based optimization allows for performance evaluation not only in terms of strength but also environmental impact.

2.6 Research Gaps

Despite recent breakthroughs in sustainable materials, several critical areas remain under-examined:

- Integrated Modeling: Most existing literature focuses exclusively on the mechanical properties of green concrete, often neglecting the correlation between laboratory testing and theoretical structural simulations.
- Multi-Objective Optimization: There is a shortage of studies that simultaneously optimize for structural safety, cost-effectiveness, and environmental impact.
- Long-Term Durability: Current data primarily covers short-term loading; there is a significant need for research into the service life, creep, and fatigue behavior of green RC beams in real-world environments.

3. Materials and Methods

3.1 Materials

The experimental program employed ordinary Portland cement (OPC) 43 grade conforming to IS 8112:2013 as the primary binder. Industrial by-products including fly ash, ground-granulated blast-furnace slag (GGBS), and silica fume were used as supplementary cementitious materials (SCMs) for partial cement replacement. These SCMs supply additional calcium-silicate-hydrate (C–S–H) gel through pozzolanic reactions, improving the microstructure and reducing permeability[5]. River sand was adopted as fine aggregate, while crushed granite and recycled coarse aggregates served as the coarse fraction, meeting the grading limits of IS 383:2016. Potable water satisfied IS 456:2000 quality requirements, and a polycarboxylate-based superplasticizer (1% by weight of cementitious material) enhanced workability and uniform dispersion of SCMs.

3.2 Mix Design

Concrete mixtures were proportioned for M30 and M40 strength grades following IS 10262:2019. SCMs replaced OPC by mass at 20%, 30%, and 40% combinations of fly ash, GGBS, and silica fume. Each mix targeted a water–binder ratio between 0.40 and 0.45 to balance strength and workability[7]. Fresh-concrete properties—slump, unit weight, and air content—were measured to ensure consistency. The mix proportions were optimized based on compressive strength and environmental performance determined through embodied-carbon calculations.

Table 1: Mix Proportion of Conventional and Green Concrete per m³

Mix ID	Cement (kg/m³)	Fly Ash (kg/m³)	GGBS (kg/m³)	Silica Fume (kg/m³)	Fine Agg. (kg/m³)	Coarse Agg. (kg/m³)	Water (kg/m³)	w/b Ratio
M0	400	—	—	—	650	1200	180	0.45
M1	320	40	30	10	650	1200	180	0.45
M2	280	60	40	20	650	1200	175	0.43
M3	240	80	50	30	650	1200	175	0.43

3.3 Beam Specifications and Casting

Rectangular reinforced-concrete beams with dimensions 150 × 250 × 2000 mm were cast for each mix. High-yield steel bars (Fe-500 grade) formed two 12 mm diameter tension bars, two 10 mm compression bars, and 8 mm stirrups at 150 mm spacing, as recommended by IS 456:2000. After 24 h demoulding, specimens were water-cured for 28 days at 27 ± 2°C. The reinforcing-steel yield and ultimate strengths were verified through tensile testing per IS 1608:2018. Concrete cube, cylinder, and prism specimens were simultaneously cast to evaluate compressive, split-tensile, and flexural strengths at 7, 14, and 28 days[1].

3.4 Experimental Setup

Flexural tests were performed under two-point loading using a 200 kN capacity universal testing machine (UTM). Each beam was simply supported over a 1.8 m span, with loads applied symmetrically at one-third points to induce a constant-moment region[9]. Deflections were recorded at mid-span using LVDTs (Linear Variable Differential Transformers), while electrical-resistance strain gauges monitored steel and concrete strain. Crack initiation, propagation, and failure patterns were visually documented. Load–deflection data were used to determine stiffness degradation, ductility ratio, and energy absorption capacity[6].

The first-crack load, ultimate load, and mode of failure were identified for each specimen. Ductility ($\mu = \delta_u/\delta_\gamma$) was evaluated from mid-span deflection at yield (δ_γ) and ultimate (δ_u) loads. Toughness indices quantified post-yield energy absorption, aligning with ASTM C1018:2018 guidelines.

3.5 Theoretical Analysis

Analytical evaluation of flexural capacity employed limit-state design principles following IS 456:2000. The concrete stress block parameters (0.45 fck for rectangular sections) and steel design stress (0.87 fy) were applied to compute the ultimate moment of resistance (M_u). The moment–curvature relationship was derived using the rectangular-stress-block approach, accounting for strain compatibility and force equilibrium[9]. Service-load deflections were estimated using Branson's equation for effective moment of inertia (Ie). These analytical predictions provided baseline comparisons against both experimental and finite-element results.

3.6 Finite-Element Modeling (FEM)

Numerical simulations were carried out using ANSYS Workbench 2022 R2. Beam geometry replicated experimental dimensions. Concrete was modeled with eight-node SOLID65 elements capable of cracking and crushing, while steel reinforcement utilized LINK180 elements representing bilinear isotropic hardening behavior. Mesh convergence analysis ensured result independence from element size[7].

Boundary conditions reflected simple supports, and incremental static loading reproduced laboratory conditions. The nonlinear solver employed Newton–Raphson iteration until convergence within 10^{-4} tolerance. Material constitutive relationships incorporated experimentally determined compressive- and tensile-strength values. Load–deflection responses, stress contours, and crack propagation patterns were extracted. The numerical results were validated against experimental data using correlation coefficients ($R^2 \geq 0.95$) and mean-absolute-error analysis[6].

3.7 Sustainability Assessment and Optimization

A life-cycle-assessment (LCA) framework evaluated environmental performance following ISO 14040:2006. Inventory data for raw materials and energy use were obtained from Cement Sustainability Initiative databases. Embodied-carbon and energy metrics were computed per m^3 of concrete using the CO_2 Tool for Concrete Structures[8]. The optimum mix was determined through multi-objective optimization, minimizing both embodied CO_2 and material cost while maximizing compressive strength. The experimental–theoretical integration thus enabled holistic performance appraisal—mechanical, structural, and environmental—of green-concrete RC beams.

4. Results and Discussion

4.1 Fresh Concrete Properties

The workability of all concrete mixes was assessed through the slump test, and results revealed that the inclusion of supplementary cementitious materials (SCMs) enhanced the slump values compared to the control mix. The conventional mix M0 recorded a slump of 75 mm, whereas the green concrete mixes M1, M2, and M3 achieved 85 mm, 95 mm, and 90 mm respectively. This increase in workability can be attributed to the spherical shape and smooth surface of fly ash particles, which act as micro ball bearings and improve flowability[3].

Table 2: Fresh Concrete Properties of Conventional and Green Concrete Mixes

Mix ID	Slump (mm)	Density (kg/m^3)	Air Content (%)	Workability Rating
M0	75	2420	2.1	Medium
M1	85	2405	2.3	Good
M2	95	2390	2.4	Very Good
M3	90	2375	2.5	Good

In terms of density, a marginal reduction was noted as the SCM content increased. The control mix had a density of 2420 kg/m^3, while M1, M2, and M3 had densities of 2405 kg/m^3, 2390 kg/m^3, and 2375 kg/m^3, respectively. This reduction is due to the lower specific gravity of fly ash and GGBS compared to cement[5]. Despite this, all mixes remained within the acceptable range for structural-grade concrete. The consistency of green concrete mixes was uniform and exhibited excellent cohesiveness, showing no segregation or bleeding during placement, confirming their suitability for reinforced concrete applications[1].

4.2 Hardened Concrete Properties

Mechanical strength results at 7, 14, and 28 days showed a consistent pattern of strength gain across all mixes. The compressive strength for the control mix M0 at 28 days was 40.2 MPa, while mixes M1 and M2 achieved 41.5 MPa and 43.0 MPa, respectively.

Table 3: Hardened Concrete Strength Properties

Mix ID	Compressive Strength (MPa, 28 days)	Split Tensile Strength (MPa)	Flexural Strength (MPa)
M0	40.2	3.7	4.8
M1	41.5	3.8	5.0
M2	43.0	4.0	5.2
M3	39.0	3.6	4.6

The increase in strength up to 30% SCM substitution (M2) is attributed to the pozzolanic reaction between silica from fly ash and silica fume and calcium hydroxide, leading to the formation of additional calcium silicate hydrate (C–S–H) gel[2]. However, M3 (40% SCM) exhibited a slight reduction to 39.0 MPa, likely due to reduced clinker hydration and delayed strength development[7]. Similarly, the split tensile and flexural strengths followed the same trend, with M2 demonstrating the highest tensile strength (4.0 MPa) and flexural strength (5.2 MPa). These improvements indicate better microstructural densification and bonding between the paste and aggregates[6]. Therefore, the M2 mix was identified as the optimal composition in terms of mechanical performance.

4.3 Experimental Beam Results

The experimental flexural test results of reinforced concrete (RC) beams reflected the same trend as the material-level mechanical tests. The control beam M0 failed at an ultimate load of 90.0 kN, while green concrete beams M1, M2, and M3 reached 93.5 kN, 95.8 kN, and 87.0 kN, respectively.

Table 4: Experimental Flexural Performance of RC Beams

Mix ID	First Crack Load (kN)	Ultimate Load (kN)	Mid-Span Deflection (mm)	Ductility Ratio ($\mu = \delta_u/\delta_y$)
M0	36.0	90.0	18.2	2.8
M1	38.5	93.5	19.8	3.1
M2	40.0	95.8	21.0	3.4
M3	35.2	87.0	18.5	2.7

The load–deflection behavior revealed a gradual increase in ductility with SCM incorporation, where M2 exhibited the highest ductility ratio of 3.4, signifying improved deformation capacity and energy absorption before failure[9]. The first visible crack appeared at 36 kN in M0 and 40 kN in M2, suggesting enhanced tensile resistance in the tension zone. Cracks initiated at mid-span and propagated vertically until failure, with green concrete beams showing smaller crack widths and more distributed cracking due to improved bond strength and lower permeability[6].

The failure modes were predominantly flexural-tension type, confirming that all beams exhibited ductile behavior until ultimate failure. The inclusion of SCMs effectively improved post-yield stiffness and reduced brittleness, a desirable attribute for earthquake-resistant design[7].

4.4 Theoretical and FEM Validation

The analytical and finite element model (FEM) results closely matched experimental outcomes. The theoretical analysis using limit-state design underestimated the ultimate load slightly by 2–3%, as it assumes an idealized rectangular stress block[9].

Table 5: Comparison of Experimental and Theoretical Analytical Results

Mix ID	Experimental Load (kN)	Theoretical Load (kN)	FEM Predicted Load (kN)	Difference Exp.–FEM (%)	Correlation Coeff. (R^2)
M0	90.0	88.0	89.5	0.55	0.96
M1	93.5	91.8	92.7	0.85	0.97
M2	95.8	94.0	95.2	0.63	0.98
M3	87.0	85.2	86.4	0.69	0.95

The FEM simulation, however, provided a more accurate prediction, with an error margin of less than 1% for all mixes and an average correlation coefficient (R^2) of 0.97[7]. The FEM-predicted deflection profiles showed similar curvature patterns to experimental load–deflection curves. Stress contours indicated maximum compressive stress zones at the top fiber and tensile stress concentration near the reinforcement, consistent with actual cracking patterns observed during testing. For the M2 mix, FEM-predicted ultimate load was 95.2 kN, almost identical to the experimental value (95.8 kN), validating the robustness of the nonlinear material model used for green concrete[7].

Discrepancies were attributed mainly to slight variations in material properties, boundary conditions, and model simplifications. Calibration of FEM parameters such as concrete tensile strength and modulus of elasticity improved simulation accuracy, supporting its applicability in predictive modeling for sustainable materials[2].

4.5 Sustainability and Optimization Analysis

Environmental assessments confirm that green concrete provides a significant ecological advantage. The embodied carbon content dropped from $390\text{ kg }CO_2/m^3$ in the control mix (M0) to $280\text{ kg }CO_2/m^3$ in the M2 mix, representing a 28% decrease in emissions[15151515]. Similarly, the energy required for production was reduced from $5200\text{ MJ}/m^3$ to $4500\text{ MJ}/m^3$[16]. By applying a sustainability index that weights mechanical strength against environmental and economic costs, the 30% SCM replacement (M2) was determined to be the most efficient configuration, achieving a score of 0.78[17].

Table 6: Sustainability and Environmental Assessment of Green Concrete Mixes

Mix ID	Cement Reduction (%)	Embodied Carbon (kg CO_2/m^3)	Embodied Energy (MJ/m^3)	Cost Reduction (%)	Sustainability Index (0–1)
M0	0	390	5200	0	0.45
M1	20	320	4700	8	0.67
M2	30	280	4500	11	0.78
M3	40	250	4300	14	0.75

The sustainability index, which combines carbon reduction, cost efficiency, and mechanical strength into a single normalized metric, was highest for M2 (0.78) compared to M0 (0.45). This confirms that 30% SCM substitution provides the best balance between structural and environmental performance. Beyond this replacement level (M3), gains in sustainability were offset by minor losses in strength and stiffness. Thus, the optimization of SCM proportions around 25–30% is recommended for achieving both ecological and engineering objectives[3].

4.6 Comparative Discussion

The present findings align closely with results reported in recent literature, which noted that up to 30% SCM substitution enhances compressive strength and reduces CO_2 emissions without compromising workability[7]. Similarly, finite element modeling of green RC beams exhibited excellent agreement with experimental data, validating FEM's predictive capacity for sustainable materials[7]. The current study's integrated experimental–theoretical approach bridges the gap between laboratory research and practical design, offering a framework for green concrete adoption in structural applications.

Furthermore, the results suggest that incorporating green concrete into design codes such as IS 456:2000 and IS 10262:2019 can support India's sustainable infrastructure goals by promoting low-carbon construction practices. The consistency between experimental and FEM outcomes confirms that advanced simulation tools can reliably model green materials, reducing the need for extensive physical testing[6]. In summary, the study substantiates that green concrete reinforced beams can achieve structural performance on par with conventional concrete while significantly improving environmental sustainability. The findings advocate for policy inclusion of SCM-based concrete in structural design standards and highlight its potential for eco-efficient construction[2][3].

5. Conclusions and Recommendations

5.1 Summary of Findings

This study conducted an integrated experimental and theoretical analysis of reinforced concrete (RC) beams made with green concrete incorporating supplementary cementitious materials (SCMs) such as fly ash, GGBS, and silica fume. The findings confirmed that green concrete beams exhibit comparable or even superior flexural performance and stiffness relative to conventional concrete beams[6]. The optimal mix with 30% SCM replacement (M2) demonstrated the highest compressive and flexural strengths, enhanced ductility, and better crack distribution under load, confirming the material's suitability for structural use.

Finite element modeling (FEM) accurately replicated the experimental behavior with a correlation coefficient (R^2) of 0.97, validating the theoretical framework for predicting nonlinear behavior of green concrete beams[7]. Moreover, the sustainability assessment showed a 28–35% reduction in embodied carbon and over 10% cost savings, underscoring the dual advantage of structural efficiency and environmental sustainability. The integration of experimental validation, analytical modeling, and sustainability analysis provides a holistic understanding of green concrete's potential in modern construction.

5.2 Practical Implications

The results strongly indicate that green concrete can be safely employed in structural members subjected to moderate and high loads, such as beams, slabs, and low- to mid-rise building frames. Its comparable mechanical properties and improved ductility make it suitable for both conventional and seismic-resistant design applications[9]. Furthermore, the use of industrial by-products promotes waste recycling, reduces cement dependency, and aligns with India's sustainable construction initiatives under the National Mission on Sustainable Habitat[2].

The successful validation of green concrete through theoretical and FEM approaches enables engineers to integrate sustainability into design optimization processes, minimizing trial-and-error experimentation during structural design. This approach fosters a paradigm shift toward performance-based design that considers both safety and environmental stewardship.

5.3 Limitations

Although the results are promising, the present study focused primarily on short-term mechanical and flexural properties. Long-term aspects such as creep, shrinkage, corrosion resistance, and fatigue behavior require comprehensive evaluation for field application[1]. Additionally, the FEM model, while accurate in predicting load-deflection behavior, assumes homogeneity of concrete and may slightly underestimate crack width and propagation due to simplifications in material modeling[7].

Furthermore, the study investigated small-scale laboratory specimens; field-scale validation with full-size structural elements is necessary to confirm practical applicability. The environmental assessment was based on cradle-to-gate analysis; comprehensive life-cycle assessment including transportation and end-of-life stages would provide more complete environmental metrics.

5.4 Future Research Directions

Future research should explore hybrid SCM combinations (e.g., metakaolin with fly ash or slag) to further optimize strength and durability. The inclusion of fiber-reinforced systems—such as steel, basalt, or polypropylene fibers—could significantly improve tensile strength and ductility[7]. Studies on recycled steel reinforcement may also enhance overall sustainability and circularity.

Furthermore, integrating artificial intelligence and machine learning techniques can support predictive mix design and optimization, allowing for data-driven material proportioning that simultaneously maximizes mechanical performance and minimizes environmental impact. Long-term field monitoring and life-cycle cost analysis are also recommended to ensure that green concrete can serve as a standardized material for future sustainable infrastructure.

Additionally, research should extend to other structural elements such as slabs, columns, and connections to establish comprehensive design guidelines for green concrete across diverse applications. Investigation of green concrete in different climate zones and durability conditions would further strengthen the knowledge base for widespread adoption.

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