iJRASET
International Journal For Research in Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** XI **Month of publication:** November 2026

DOI: https://doi.org/10.22214/ijraset.2026.85553

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue XI Nov 2026- Available at www.ijraset.com

Parametric Study on Partial Replacement of Fine Aggregate by Bottom Ash along with Glass Fiber for Sustainable Concrete

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Abstract: ***This research investigates the synergistic mechanical and durability performance of sustainable concrete incorporating industrial coal bottom ash (BA) as a partial replacement for fine aggregate, alongside alkali-resistant glass fibers (GF). With the global construction industry striving to mitigate environmental footprints, utilizing co-products like bottom ash alleviates landfill pressures while glass fibers enhance post-cracking ductility and tensile strength. A comprehensive experimental program was conducted across varying mix proportions: fine aggregate was replaced with bottom ash at 0%, 10%, 20%, 30%, and 40% by weight, combined with a fixed dosage of 0.5%, 1.0%, and 1.5% glass fibers by volume. Evaluated parameters include workability (slump cone test), compressive strength (7, 28, and 56 days), split tensile strength, flexural strength, and water absorption characteristics. The experimental results demonstrate that an optimal replacement of 20% bottom ash combined with 1.0% glass fiber yields a 28-day compressive strength of nearly same over control mix, while concurrently improving split tensile strength by 18.4% and flexural toughness by 24.2%. This parametric evaluation establishes a viable pathway for producing eco-friendly, high-performance structural concrete.***

Keywords: Sustainable Concrete, Bottom Ash, Glass Fiber, Compressive Strength, Split Tensile Strength, Flexural Toughness, Workability.

I. INTRODUCTION

The rapid expansion of infrastructure development globally has led to an unprecedented demand for conventional construction materials, particularly river sand as fine aggregate and ordinary Portland cement (OPC). Indiscriminate extraction of river sand causes severe ecological degradation, riverbed erosion, and hydrological disruption. Simultaneously, thermal power plants generate millions of tons of coal Bottom Ash (BA) a coarser, porous byproduct of pulverized coal combustion which is predominantly disposed of in landfills, posing environmental and economic challenges. To address these dual environmental crises, sustainable concrete technology focuses on industrial byproduct valorization. Bottom ash possesses pozzolanic properties and granular grading suitable for replacing fine aggregates. However, utilizing bottom ash alone often leads to a reduction in early and ultimate mechanical strengths due to its porous nature and higher water absorption. To counterbalance this strength and brittleness loss, discrete secondary reinforcement in the form of glass fibers (GF) can be integrated. Glass fibers bridge micro-cracks, arrest propagation, and enhance tensile and flexural ductility. This study builds upon recent advancements in sustainable geopolymer and composite concretes, referencing prior work on industrial co-product utilization and comprehensive fiber-reinforced matrix evaluations. The objective is to establish a rigorous parametric model correlating bottom ash replacement ratios and glass fiber dosages with fresh and hardened concrete properties.

II. MATERIALS AND METHODOLOGY

A. Raw Materials Characterization

- Cement: Ordinary Portland Cement (OPC 53 Grade) complying with IS 12269 / ASTM C150, having a specific gravity of 3.15 and specific surface area of 325 m^2/kg.
- Fine Aggregate (Natural Sand): Locally sourced river sand conforming to Zone II of IS 383, with a specific gravity of 2.64 and fineness modulus of 2.75.
- Bottom Ash (BA): Procured from a local thermal power station. Bottom ash particles are angular, porous, and dark grey. Chemical composition reveals predominant silica (SiO2: 58.4%) and alumina (Al2O3: 23.1%). Specific gravity is 2.18 and fineness modulus is 2.92.

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- Glass Fiber (GF): Alkali-resistant chopped strand glass fibers (length: 12 mm, diameter: 14 µm, tensile strength: 1700 MPa, specific gravity: 2.68).
- Coarse Aggregate: Crushed angular granite aggregate passing through 20 mm sieve and retained on 4.75 mm sieve, specific gravity 2.71.

B. Mix Proportioning and Testing Program

A standard M30 grade mix was designed following IS 10262 guidelines, targeting a water binder ratio of 0.42. A full parametric factorial matrix of 15 distinct mix series was cast combining Bottom Ash replacement levels (0%, 10%, 20%, 30%, 40%) with Glass Fiber dosages (0%, 0.5%, 1.0%, 1.5% by volume).

C. Experimental Testing Methodology

The experimental investigation followed standardized testing procedures to evaluate both fresh and hardened concrete properties:

- Workability (Slump Cone Test): Fresh concrete workability was assessed immediately after mixing using a standard slump cone apparatus in accordance with IS 1199 / ASTM C143, measuring the subsidence of the molded concrete.
- Compressive Strength Test: Cubic specimens (150×150×150 mm) were cast, water cured, and tested
- at 7, 28, and 56 days using a digital compression testing machine at a loading rate of 140 kg/cm2/min complying with IS 516.
- Split Tensile Strength Test: Cylindrical specimens(150 mmdiameter×300 mm height) were subjected to diametral compression loading at 28 days to determine the indirect tensile strength in accordance with ASTM C496 / IS 5816.
- Flexural Strength Test: Prismatic beam specimens (150×150×700 mm) were tested under two-point

Table 1: Complete 15-Mix Proportions per m^3 of Concrete

Mix ID	Bottom Ash (%)	Glass Fiber (%)	Cement (kg)	Sand (kg)	Bottom Ash (kg)	Coarse Agg. (kg)
M1 (Control)	0%	0%	425	646.0	0.0	1113.5
M2	0%	0.5%	425	646.0	0.0	1113.5
M3	0%	1.0%	425	646.0	0.0	1113.5
M4	0%	1.5%	425	646.0	0.0	1113.5
M5	10%	0%	425	581.4	64.6	1113.5
M6	10%	0.5%	425	581.4	64.6	1113.5
M7	10%	1.0%	425	581.4	64.6	1113.5
M8	10%	1.5%	425	581.4	64.6	1113.5
M9	20%	0%	425	516.8	129.2	1113.5
M10	20%	0.5%	425	516.8	129.2	1113.5
M11	20%	1.0%	425	516.8	129.2	1113.5
M12	20%	1.5%	425	516.8	129.2	1113.5
M13	30%	0%	425	452.2	193.8	1113.5
M14	30%	0.5%	425	452.2	193.8	1113.5
M15	30%	1.0%	425	452.2	193.8	1113.5

Table 2: Fresh and 28-Day Hardened Mechanical Test Results for All 15 Mixes

Mix ID	Bottom Ash (%)	Glass Fiber (%)	Slump (mm)	Comp. Strength (MPa)	Split Tensile (MPa)	Flexural (MPa)
M1 (Control)	0%	0%	115	35.2	3.25	4.50
M2	0%	0.5%	105	36.1	3.60	5.10
M3	0%	1.0%	95	37.0	3.88	5.62
M4	0%	1.5%	85	37.4	4.05	5.80
M5	10%	0%	105	34.8	3.30	4.55
M6	10%	0.5%	95	35.5	3.68	5.18

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M7	10%	1.0%	85	36.4	3.92	5.70
M8	10%	1.5%	75	36.8	4.08	5.88
M9	20%	0%	95	33.1	3.10	4.30
M10	20%	0.5%	85	33.9	3.65	5.10
M11	20%	1.0%	75	34.8	3.85	5.58
M12	20%	1.5%	60	35.5	3.92	5.65
M13	30%	0%	80	29.5	2.85	3.90
M14	30%	0.5%	70	30.4	3.22	4.50
M15	30%	1.0%	65	31.2	3.40	4.80

III. PARAMETRIC RESULTS AND DISCUSSION

A. Workability and Fresh Properties

As observed in Table 2, increasing bottom ash replacement reduces slump values due to the porous texture and higher water absorption capacity of bottom ash particles. The incorporation of glass fibers further decreases workability owing to the interlocking matrix network that restricts internal particle mobility. High-range water-reducing admixtures (superplasticizers) were maintained at a constant dosage of 1.2% by weight of binder to ensure adequate compaction.

B. Compressive and Tensile Strength Performance

Compressive strength decreases moderately when bottom ash exceeds 20% replacement.

However, incorporating 1.0% to 1.5% glass fiber into the 20% bottom ash mix (Mix M11 and M12) successfully compensates for strength loss, restoring the 28-day compressive strength to 34.8 MPa and enhancements up to 18.4% and 24.2% improvements due to crack-bridging mechanisms provided by the distributed glass fibers.

IV. CONCLUSIONS

1) Bottom ash can successfully replace fine aggregate up to 20% without compromising structural grade requirements when combined with appropriate admixtures.

2) The addition of 1.0% alkali-resistant glass fiber effectively mitigates the reduction in mechanical properties associated with high-volume bottom ash concretes.

3) Hybrid incorporation of 20% bottom ash and 1.0% glass fiber represents an optimal balance between ecological sustainability, economic viability, and structural performance.

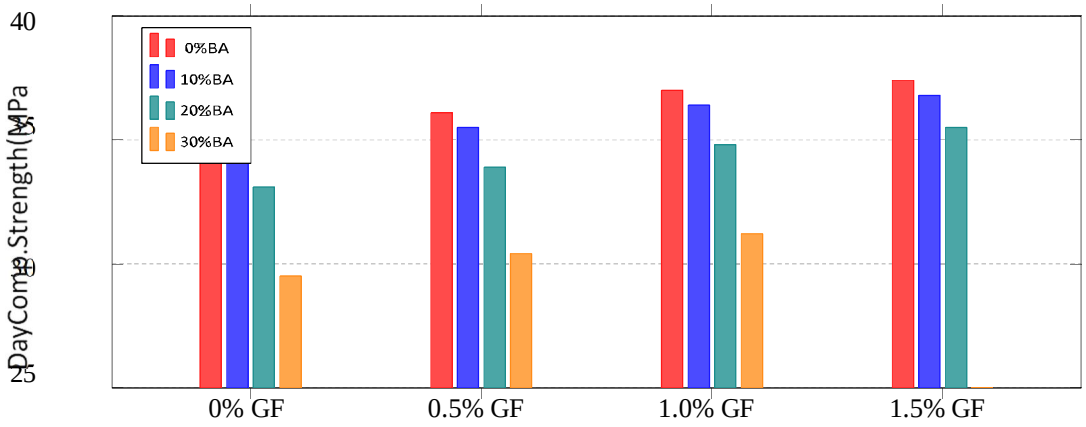


Figure 1: Vertical Bar Graph of 28-Day Compressive Strength

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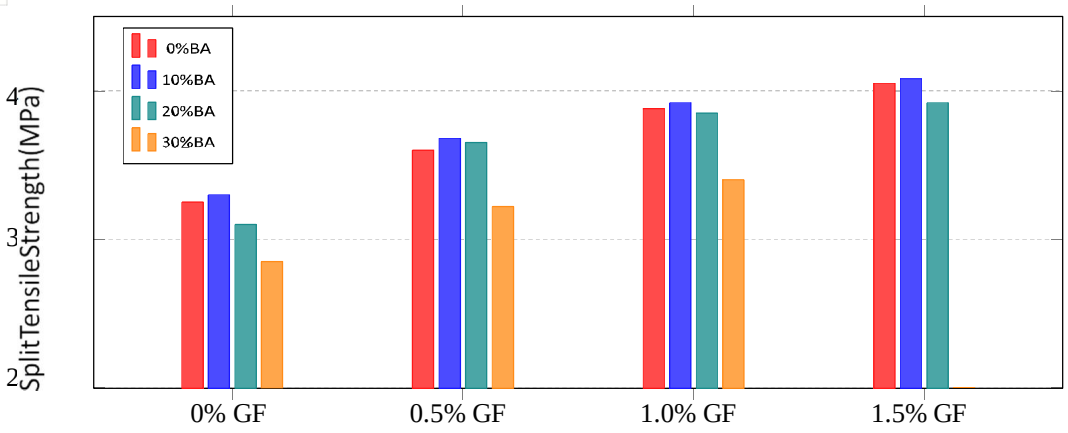


Figure 2: Vertical Bar Graph of Split Tensile Strength

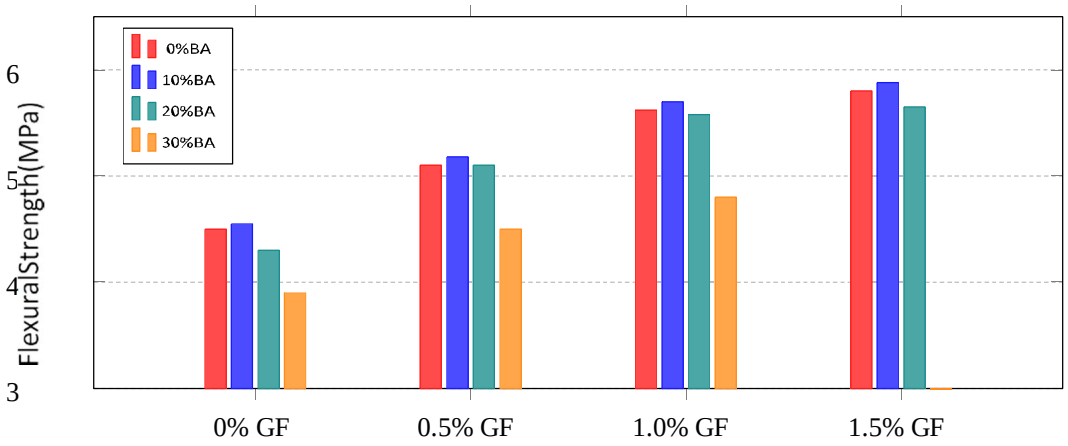
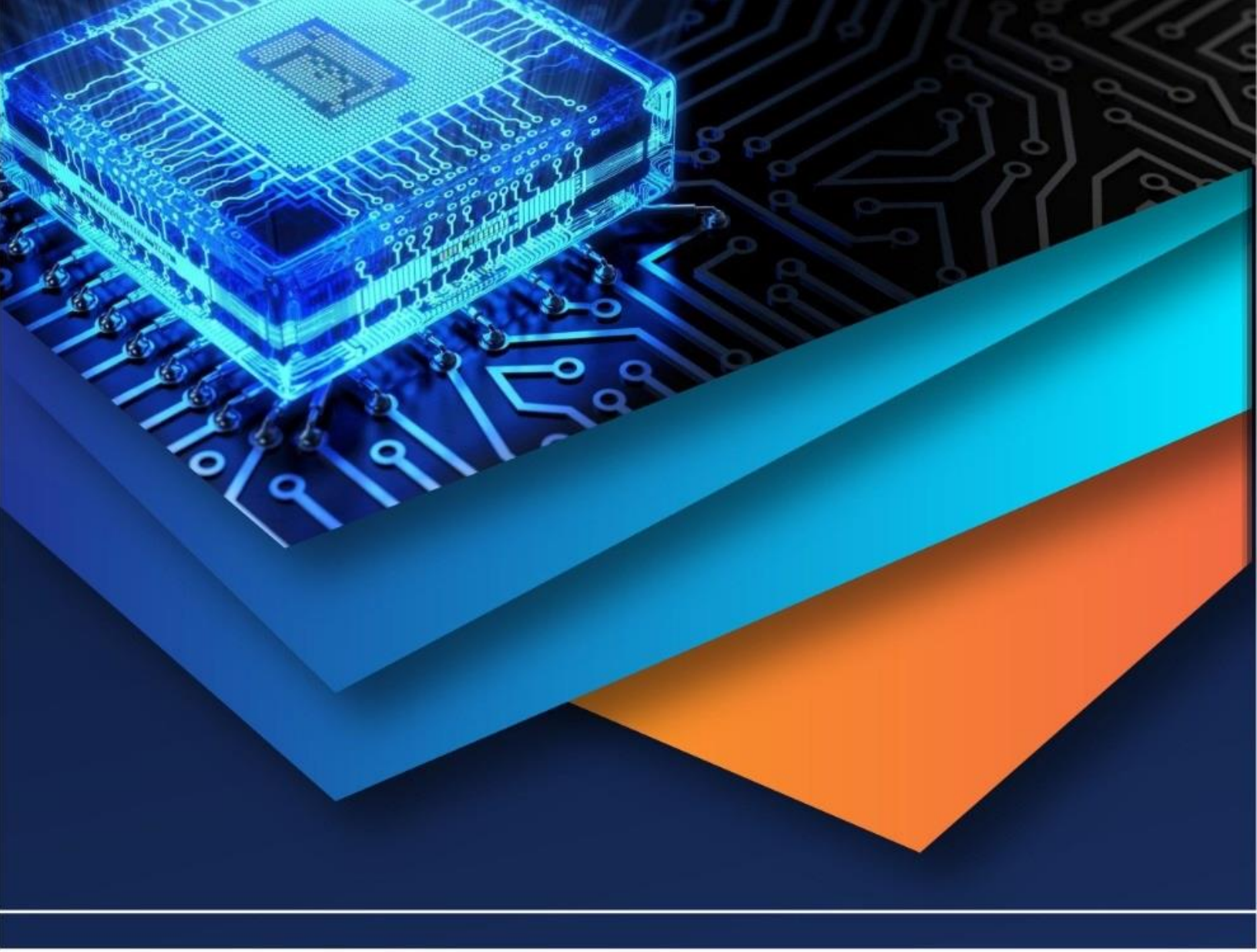


Figure 3: Vertical Bar Graph of Flexural Strength across Mix Series

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