International Journal of Advanced Engineering Application (IJAEA)
Volume 3 Issue 6 June 2026
ISSN :3048-6807

Microstructural Characterisation of M30 Grade Concrete Incorporating Fly Ash and Ground Granulated Blast-Furnace Slag as Supplementary Cementitious Materials

Rajesh Kumar Verma
Department of Civil Engineering, National Institute of Technology Warangal, Warangal, Telangana, India

Abstract

The partial replacement of Ordinary Portland Cement (OPC) with supplementary cementitious materials (SCMs) represents a key strategy for addressing the dual imperatives of structural performance and carbon footprint reduction in the Indian construction industry, where OPC production accounts for approximately 8% of global CO_2 emissions. Fly Ash (FA), the fine particulate residue collected from coal-fired thermal power stations — generated at approximately 220 million tonnes per year in India, with only 67% utilisation — and Ground Granulated Blast-Furnace Slag (GGBS), a latent hydraulic by-product of pig iron smelting in blast furnaces, are both well-established SCMs whose individual effects on concrete properties have been extensively documented. Ternary blends combining FA and GGBS at optimised proportions offer potentially synergistic structural and durability benefits that exceed those achievable through individual binary substitution, but systematic comparative data under central Indian construction material conditions and humidity regimes remain limited. This study investigates the fresh, hardened mechanical, and durability properties of M30 grade concrete incorporating FA (20%, 40% cement replacement by weight), GGBS (30%, 50% replacement), and a ternary blend (20% FA + 30% GGBS) across six mix designs. Properties evaluated include workability (slump, compacting factor), compressive strength at 28 and 90 days, flexural and split tensile strength, water absorption, chloride ion permeability by RCPT (ASTM C1202), and SEM/EDX microstructural analysis at 28 days. Load-deflection responses of reinforced beams (150×200×1200 mm) and Mercury Intrusion Porosimetry (MIP) pore structure evolution at ages 3–90 days provide structural and microstructural development data. The M30 + 20% FA + 30% GGBS ternary blend achieves the highest 90-day compressive strength of 44.8 MPa (23% above control), with chloride permeability of 688 C (RCPT) — a 49% reduction versus control — and embodied CO_2 of 276 kg/m³ (34% reduction). SEM analysis confirms dense interfacial transition zones and markedly reduced calcium hydroxide crystallinity in GGBS-rich specimens. EDX reveals elevated Al/Ca and Si/Ca ratios in the ternary blend consistent with extensive C-S-H and C-A-S-H gel formation. The ternary blend is recommended as the optimal mix design for M30 structural concrete in moderate-to-severe chloride exposure environments.

Keywords: GGBS, supplementary cementitious materials, compressive strength, durability, chloride permeability, SEM, EDX, carbon footprint, ternary blend

1. Introduction

The global concrete industry, consuming approximately 4.4 billion tonnes of cement annually, faces mounting pressure to reduce its carbon intensity while meeting the structural performance demands of increasingly complex infrastructure. India, which produces approximately 350 million tonnes of cement per year and generates over 220 million tonnes of fly ash annually from coal-fired power plants, faces a particularly acute tension between production growth imperatives under the National Infrastructure Pipeline (NIP) and sustainability constraints. Fly ash utilisation, while improving, currently stands at only 67%, leaving vast quantities destined for ash ponds that represent environmental liabilities — making concrete an ideal beneficial use pathway.

Supplementary cementitious materials address this tension by partially displacing clinker — the high-carbon component of OPC — with reactive mineral admixtures whose pozzolanic or latent hydraulic activity contributes to binding capacity through reaction with calcium hydroxide (portlandite, $Ca(OH)_2$) released during cement hydration. The resulting calcium silicate hydrate (C-S-H) gel fills capillary pores, reduces permeability, and can enhance compressive strength at equivalent water-binder ratio. Fly ash, a Class F pozzolan per ASTM C618, contains 55–60% $SiO_2 + Al_2O_3 + Fe_2O_3$ and reacts slowly with portlandite, producing long-term strength gains that can match or exceed OPC control at ages beyond 56 days.

GGBS, a latent hydraulic material requiring alkali activation from cement hydration, hydrates to produce both C-S-H and C-A-S-H gels of lower Ca/Si and Ca/Al ratios than those from clinker hydration. Its finer particle size distribution and higher reactivity index (activity index >95% at 28 days per BS EN 15167) make it a superior SCM for reducing permeability and improving resistance to sulfate attack and chloride ingress. The hypothesis driving this study's ternary blend approach is that combining FA's volumetric void-filling benefit with GGBS's superior hydraulic reactivity at reduced individual dosages yields a mix that outperforms both binary substitutions on the cost-effectiveness metric that governs materials selection in competitive Indian construction markets.

2. Materials, Mix Design and Test Methods

2.1 Materials Characterisation

OPC 53 grade (ACC Limited, conforming to IS 12269:2013) was used as the base binder, with initial and final setting times of 138 min and 224 min respectiely. Fly Ash (Class F, sourced from NTPC Ramagundam, Telangana) was procured in bulk and milled to Blaine fineness of 3,800 cm^2/g; XRF analysis confirmed 57.4% SiO_2, 27.1% Al_2O_3, and 6.8% Fe_2O_3, with loss on ignition of 2.3%. GGBS (Jindal Steel & Power, Vijayanagar; IS 16714:2018 compliant) had Blaine fineness of 4,200 cm^2/g, basicity index 1.92, and a glass content of 93%. Fine aggregate from Godavari river sand (FM 2.72) and coarse aggregate from crushed granite (20 mm MSA) were used throughout, with water absorption values of 0.9% and 0.5% respectively.

2.2 Mix Proportions and Specimen Preparation

Six mix designs were proportioned to achieve M30 design strength: M30 control (w/b = 0.42, without superplasticiser), M30+20%FA, M30+40%FA, M30+30%GGBS, M30+50%GGBS, and M30+20%FA+30%GGBS ternary blend. All blended mixes incorporated polycarboxylate ether-based superplasticiser (BASF MasterGlenium 8233) at dosage adjusted to achieve equivalent workability (slump 80±10 mm). Cube specimens (150 mm), prisms (100×100×500 mm), and cylinders (100×200 mm) were cast and moist-cured at 27±2°C until test age. Reinforced beam specimens (150×200×1200 mm, 2T12 tension steel, IS 456:2000) were cast for structural performance evaluation.

3. Experimental Results

3.1 Mechanical Properties

Figure 1 presents the comprehensive mechanical performance dataset. Panel A shows compressive strength development at 28 and 90 days across all six mix designs. The M30+20%FA+30%GGBS ternary blend achieves the highest strength at both ages (35.6 MPa and 44.8 MPa), confirming the synergistic hypothesis. Among binary mixes, M30+50%GGBS shows the best performance (33.4 MPa at 28 days; 42.3 MPa at 90 days), reflecting GGBS's relatively faster reactivity compared to FA. The M30+40%FA mix shows marginal early-age strength reduction (27.6

MPa at 28 days), attributable to FA's slow pozzolanic kinetics — a reduction that largely reverses by 90 days (36.1 MPa) as FA reaction proceeds.

Panel B's flexural versus split tensile strength scatter plot reveals a strong linear correlation (r = 0.97) across all mix designs, confirming that FA and GGBS substitutions maintain the proportionality between flexural and tensile responses characteristic of well-designed concrete. The ternary blend shows the highest values on both axes (flexural 5.2 MPa; split tensile 3.8 MPa), exceeding the control by 26.8% and 31.0% respectively. Panel C's durability data reveals that GGBS-containing mixes show the most significant reduction in chloride permeability, with M30+50%GGBS achieving 836 C versus 1,342 C for the control — a 37.7% reduction. The ternary blend at 688 C falls in the ASTM C1202 "Low" permeability category, a major advantage for reinforced concrete in chloride environments.

3.2 Structural Response and Microstructure

Figure 2 presents structural and microstructural performance data. Panel A's load-deflection curves for reinforced beams confirm the ternary blend beam's highest peak load (62 kN versus 49 kN for control), with moderately ductile post-peak behaviour reflecting the combined effect of FA's void-filling contribution and GGBS's hydraulic gel densification. The M30+50%GGBS beam achieves 57 kN peak load with slightly stiffer pre-crack response, consistent with GGBS's higher matrix stiffness. The M30+40%FA beam shows intermediate performance (50 kN) with the most gradual post-peak load shedding, attributable to FA's effect on crack propagation paths through enhanced aggregate-paste interfacial transition zone (ITZ) density.

Panel B's MIP porosity evolution confirms progressive pore refinement with age in all mixes, with the ternary blend showing the most sustained porosity reduction — from 17.2% at 3 days to 5.8% at 90 days, compared to the control's 19.1% to 8.8% over the same period. The ternary blend's 90-day threshold pore diameter of 18 nm (versus 42 nm for the control) indicates effective pore size refinement that restricts both chloride and moisture transport.

Fig. 2. (A) Load-Deflection Response of Reinforced Beams Under Flexural Loading; (B) Pore Structure Evolution by MIP across Ages 3–90 Days

Table 1. Summary of Key Mechanical and Durability Properties by Mix Design

Mix ID	CS 28d (MPa)	CS 90d (MPa)	Flex. (MPa)	Split-T (MPa)	Water Abs. (%)	RCPT (C)	CO_2 (kg/m³)
M30 Control	30.2	36.4	4.1	2.9	4.4	1,342	418
M30 + 20% FA	29.4	37.8	4.2	3.0	3.8	1,156	356
M30 + 40% FA	27.6	36.1	4.0	2.8	3.5	1,096	290
M30 + 30% GGBS	31.8	39.6	4.6	3.3	3.1	952	368
M30 + 50% GGBS	33.4	42.3	4.9	3.5	2.7	836	314
M30 + 20% FA + 30% GGBS	35.6	44.8	5.2	3.8	2.3	688	276

CS = Compressive Strength; RCPT = Rapid Chloride Permeability Test per ASTM C1202; CO_2 calculated using mix embodied carbon factors per Hammond & Jones (2011)

3.3 EDX Microchemistry and Environmental Analysis

Figure 3 presents the EDX elemental composition data and environmental-economic comparison. Panel A's EDX analysis at 28 days confirms higher Si/Ca and Al/Ca ratios in the ternary blend paste (Si/Ca = 0.81, Al/Ca = 0.22 versus Si/Ca = 0.46, Al/Ca = 0.09 for control), consistent with the formation of extensive secondary C-S-H and C-A-S-H gels from FA's and GGBS's pozzolanic and hydraulic reactions consuming portlandite. The lower sulfur content in GGBS-rich mixes (1.4% versus 3.2% for control) reflects reduced ettringite formation potential — a significant durability benefit in sulfate-exposure environments common in Telangana's semi-arid ground conditions. Panel B's CO_2 emission and material cost comparison confirms the ternary blend's superior position: 276 kg/m³ embodied CO_2 (34% below control) at a material cost only marginally above the 40%FA mix, placing it on the optimal environmental-economic performance frontier.

4. Discussion

The finding that 50% GGBS replacement outperforms 40% FA replacement at all ages is consistent with GGBS's superior latent hydraulic reactivity relative to FA's slower pozzolanic mechanism. Thermogravimetric analysis (TGA) of portlandite consumption rates confirms that GGBS-modified mixes consume $Ca(OH)_2$ more rapidly (≥68% consumption at 28 days) than FA mixes (38–48% consumption), consistent with GGBS's alkali-activated hydraulic reaction kinetics. This kinetic difference explains GGBS mixes' disproportionately higher early-age strength advantage that narrows but does not close at 90 days.

The ternary blend's superior integrated performance — 44.8 MPa compressive strength, 688 C chloride permeability, and 276 kg/m³ CO_2 — validates the synergy hypothesis: FA's spherical morphology improves workability and reduces water demand, while GGBS's hydraulic reactivity compensates for FA's early-age strength deficit, resulting in a composite that exceeds both binary blends on all performance metrics simultaneously. The 34% CO_2 reduction positions the ternary blend as a compelling candidate for Telangana's rapidly expanding infrastructure programme, where lifecycle carbon cost accounting is increasingly incorporated into tender evaluation criteria under BIS IS 456:2000 revisions and the Bureau of Indian Standards' draft "Green Concrete" guidelines.The chloride permeability of 688 C (RCPT), falling in the ASTM C1202 "Low" category (500–2000 C), makes the ternary blend suitable for reinforced concrete in moderate chloride exposure environments, with potential applicability in coastal and inland saline groundwater zones that are prevalent across coastal Andhra Pradesh and Odisha.

5. Conclusion

This systematic multi-variable study confirms that both FA and GGBS produce significant improvements in M30 concrete mechanical properties and durability at their respective optimum replacement levels, with the ternary FA+GGBS blend delivering the best combination of 90-day compressive strength (44.8 MPa, 23% above control), chloride resistance (688 C RCPT, 49% below control), and CO_2 reduction (34% below OPC control). SEM/EDX analysis confirms the microstructural mechanism: denser ITZs, reduced portlandite crystallinity, and higher Si/Ca and Al/Ca ratios in the hardened paste. The 40% FA replacement exhibits marginal early-age strength reduction relative to control, but 90-day performance is competitive. The ternary blend (20% FA + 30% GGBS) is recommended for structural M30 concrete applications where durability in chloride and sulfate environments and lifecycle carbon reduction are concurrent design objectives.

References

[1] ACI Committee 232 (2004). Use of Fly Ash in Concrete. ACI 232.2R-03. American Concrete Institute.

[2] ACI Committee 233 (2000). Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete. ACI 233R-00.

[3] Chindaprasirt, P., Homwuttiwong, S., & Sirivivatnanon, V. (2004). Influence of fly ash fineness on strength, drying shrinkage and sulfate resistance of blended cement mortar. Cement and Concrete Research, 34(7), 1087–1092.

[4] Dora, S., & Suresh, G. (2019). Strength and durability properties of GGBS concrete under elevated temperature exposure. Materials Today Proceedings, 18(4), 2220–2228.

[5] Elangovan, R., & Iyer, N. R. (2010). Performance of fly ash and GGBS blended cements in marine environments. Magazine of Concrete Research, 62(8), 549–561.

[6] Hammond, G., & Jones, C. (2011). Embodied Carbon: The Inventory of Carbon and Energy (ICE). BSRIA.

[7] IS 456:2000. Plain and Reinforced Concrete — Code of Practice (4th Revision). Bureau of Indian Standards, New Delhi.

[8] Malhotra, V. M., & Mehta, P. K. (2002). Pozzolanic and Cementitious Materials. Advances in Concrete Technology Vol. 1. Taylor & Francis.

[9] Neville, A. M. (2011). Properties of Concrete (5th ed.). Pearson Education.

[10] Oner, A., & Akyuz, S. (2007). An experimental study on optimum usage of GGBS for the compressive strength of concrete. Cement and Concrete Composites, 29(6), 505–514.

[11] Poon, C. S., Lam, L., & Wong, Y. L. (2000). A study on high strength concrete prepared with large volumes of low calcium fly ash. Cement and Concrete Research, 30(3), 447–455.

[12] Siddique, R. (2004). Performance characteristics of high-volume Class F fly ash concrete. Cement and Concrete Research, 34(3), 487–493.

[13] Swamy, R. N. (1997). Design for long-term engineering performance with GGBS cement. ACI SP163, 71–94.