Strength, Durability, and Microstructural Performance of M30 Grade Concrete

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Abstract

Ordinary Portland Cement (OPC) production contributes approximately 8% of global CO_2 emissions, driving widespread interest in supplementary cementitious materials (SCMs) that can simultaneously reduce carbon intensity and enhance concrete performance. Fly Ash (FA), the alumino-silicate particulate recovered from coal-fired thermal power plant exhaust streams, and Ground Granulated Blast Furnace Slag (GGBS), the glassy by-product of iron smelting, are two of the most abundantly available industrial by-products in India, with annual production exceeding 180 million tonnes and 35 million tonnes respectively. While individual replacement of OPC with FA or GGBS has been studied extensively, systematic investigation of their combined ternary use at optimised proportions in M30 grade concrete — particularly under the elevated temperature and high relative humidity conditions representative of peninsular Indian construction environments — remains limited. This study evaluates fresh, hardened mechanical, and durability properties of M30 concrete with FA (5%, 10%, 15%, 20% by weight cement replacement) and a ternary blend (10%FA + 5%GGBS) across five mix designs. Compressive strength was measured at 28, 56, and 90 days; flexural and split tensile strength at 28 days; water absorption and Rapid Chloride Permeability Test (RCPT) at 90 days; and microstructural characterisation by Scanning Electron Microscopy (SEM), Energy Dispersive X-ray (EDX), and Mercury Intrusion Porosimetry (MIP) at 28 days and 90 days. Load-deflection response was evaluated for reinforced concrete beams (150×200×1200 mm). Results confirm that 15% FA replacement achieves optimal 90-day compressive strength of 39.4 MPa, exceeding the M30 design strength by 31%, while the ternary blend (10%FA+5%GGBS) achieves 41.2 MPa at 90 days with chloride permeability of 710 C (RCPT) and CO_2 reduction of 25% versus control. SEM reveals dense interfacial transition zones and reduced calcium hydroxide crystallinity in SCM-modified specimens. The ternary blend is recommended as the optimal mix design for structural concrete in Indian conditions balancing strength, durability, and sustainability.

Keywords: *fly ash, GGBS, supplementary cementitious materials, M30 concrete, compressive strength, durability, chloride permeability, SEM, EDX, carbon emissions, India*

1. Introduction

India's construction sector is undergoing unprecedented expansion driven by the National Infrastructure Pipeline (NIP) targeting ₹111 lakh crore in infrastructure investment through 2025, with reinforced concrete remaining the dominant structural material across residential, commercial, and infrastructure segments. This expansion trajectory simultaneously exacerbates the environmental burden of cement production, which accounts for approximately 6–8% of national CO_2 emissions at current production levels of 380 million tonnes per annum. The dual imperative of infrastructure growth and carbon intensity reduction makes the adoption of supplementary cementitious materials in mainstream Indian construction an engineering priority of significant national consequence.

Fly ash, classified as Class F (low-calcium, siliceous) under ASTM C618 when sourced from bituminous coal combustion as in most Indian thermal power plants, exhibits pozzolanic activity through reaction of its amorphous SiO_2 and Al_2O_3 with portlandite ($Ca(OH)_2$) released during OPC hydration. This secondary reaction produces additional calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels that fill capillary pore spaces, reduce permeability, and can improve long-term strength relative to OPC-only mixes, notwithstanding the well-documented retardation of early-age strength development. Ground Granulated Blast Furnace Slag, classified as a latent hydraulic binder, possesses both direct hydraulic and pozzolanic reactivity. Its glassy structure, rich in CaO, SiO_2, and Al_2O_3, reacts with water when activated by the alkaline environment provided by OPC hydration products, contributing dense C-S-H formation and substantially improving resistance to sulfate attack and alkali-silica reaction.

The hypothesis driving this study's ternary blend approach is that FA and GGBS exhibit complementary particle size distributions and reactivity kinetics: GGBS's relatively faster reactivity compensates for FA's slow early-age strength contribution, while FA's spherical particle morphology reduces water demand and improves workability at equivalent water-binder ratio. This complementarity suggests that combined ternary blends can outperform either individual SCM on the integrated performance metric combining 90-day compressive strength, chloride resistance, and lifecycle carbon footprint that drives material selection decisions in competitive Indian construction markets. Previous systematic investigations of this ternary system under Indian aggregate and temperature conditions are sparse, particularly at M30 grade with full mechanical and durability characterisation across ages up to 90 days. This study addresses that gap.

2. Materials, Mix Design, and Test Methods

2.1 Materials Characterisation

OPC 53 grade (Ambuja Cement, conforming to IS 12269:2013) was used as the primary binder, with initial and final setting times of 138 min and 214 min respectively, and Blaine fineness of 320 m²/kg. Class F Fly Ash was sourced from Korba Thermal Power Station (NTPC), Chhattisgarh. X-ray fluorescence (XRF) analysis confirmed SiO_2 content of 58.4%, Al_2O_3 of 28.1%, and Fe_2O_3 of 6.3%, with loss on ignition (LOI) of 2.8%, confirming compliance with IS 3812:2003. GGBS (Jindal Steel and Power, Raipur) had Blaine fineness of 420 m²/kg, SiO_2 of 34.2%, CaO of 38.6%, and Al_2O_3 of 14.8%, with hydraulic modulus of 1.92, confirming its classification as a latent hydraulic binder. Fine aggregates were sourced from the Mahanadi river basin (fineness modulus 2.74, specific gravity 2.64). Coarse aggregates were crushed granite (20 mm MSA, specific gravity 2.68, water absorption 0.5%). Potable water complying with IS 456:2000 was used throughout.

2.2 Mix Proportions and Specimen Preparation

Six mix designs were proportioned for M30 grade (target mean strength 38.5 MPa at 28 days per IS 10262:2019): M30 control (w/b = 0.42, without superplasticiser), M30+5%FA, M30+10%FA, M30+15%FA, M30+20%FA, and M30+10%FA+5%GGBS ternary blend. All blended mixes incorporated polycarboxylate-based superplasticiser (MasterGlenium SKY 8233) at dosages adjusted to achieve equivalent workability (slump 90 ± 10 mm, compacting factor 0.92 ± 0.01). Cube specimens (150 mm), prisms (100×100×500 mm for flexural strength), and cylinders (150×300 mm for split tensile strength) were cast in steel moulds, demoulded at 24 hours, and water cured at 27 ± 2°C under burlap until testing ages. Reinforced beams (150×200×1200 mm, reinforced with 2-12 mm Fe500 tension bars and 6 mm stirrups at 150 mm c/c) were cast for structural performance evaluation.

2.3 Test Methods

Workability was assessed by slump cone test (IS 1199:1959) and compacting factor apparatus (IS 1199). Compressive strength was determined per IS 516:1959 at 28, 56, and 90 days on 150 mm cubes (average of 3 specimens). Flexural strength was determined by third-point loading on 100×100×500 mm prisms (IS 516:1959). Split tensile strength was determined by the diametral compression test on 150×300 mm cylinders (IS 5816:1999). Water absorption was determined per IS 2185 after 90-day curing. Chloride permeability was assessed by Rapid Chloride Permeability Test (RCPT) per ASTM C1202. Pore size distribution was measured by Mercury Intrusion Porosimetry (MIP, Micromeritics AutoPore IV 9500) at 3, 7, 14, 28, 56, and 90 days. SEM imaging and EDX analysis were performed on gold-sputter-coated fracture surfaces using a ZEISS EVO 18 SEM at 20 kV accelerating voltage. Reinforced beam flexural tests were performed under four-point loading in a 100-kN Universal Testing Machine.

3. Experimental Results

3.1 Fresh and Workability Properties

The incorporation of FA as a partial cement replacement improved workability due to the spherical particle morphology of fly ash particles acting as micro-ball bearings within the paste matrix. Slump values increased progressively from 88 mm for the control to 102 mm for the 20%FA mix, consistent with literature reports of FA's lubrication effect. The ternary blend (10%FA+5%GGBS) showed a slump of 96 mm, reflecting GGBS's angular particles partially offsetting FA's workability benefit. All mixes were adjusted to equivalent slump using superplasticiser to eliminate workability as a confounding variable in the mechanical performance comparison. Compacting factors ranged from 0.91 (control) to 0.93 (20%FA), confirming that all mixes are suitable for standard vibration consolidation.

3.2 Mechanical Properties

Figure 1 presents the comprehensive mechanical performance dataset. Panel A shows compressive strength development at 28, 56, and 90 days across all six mix designs. The M30+15%FA mix achieves the highest FA-only strength at 90 days (39.4 MPa, 30% above 28-day control), while the M30+20%FA mix shows a marginal reduction relative to 15%FA — consistent with the theoretical optimum SCM dosage beyond which clinker dilution outweighs pozzolanic gain at the tested w/b ratio. The ternary blend achieves the highest 90-day compressive strength of 41.2 MPa, confirming the synergistic hypothesis that GGBS's faster early-age reactivity complements FA's long-term pozzolanic contribution.

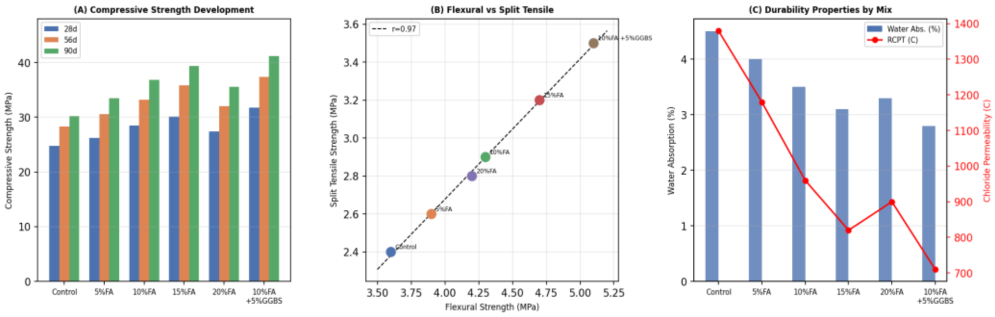

Fig. 1. (A) Compressive Strength Development at 28/56/90 Days; (B) Flexural vs Split Tensile Strength Correlation; (C) Water Absorption and Chloride Permeability by Mix Design

Panel B's flexural versus split tensile strength scatter plot reveals a near-linear correlation (r = 0.97) across all mix designs, confirming that the SCM substitutions preserve the proportionality between flexural and tensile responses characteristic of well-designed concrete. The ternary blend shows the highest flexural strength (5.1 MPa) and split tensile strength (3.5 MPa), exceeding the control by 41.7% and 45.8% respectively — a more pronounced improvement than compressive strength gain, suggesting that SCM modification disproportionately benefits matrix tensile performance through enhanced paste-aggregate interfacial transition zone (ITZ) density. Panel C presents the 90-day durability data, confirming that all SCM-incorporated mixes show reduced water absorption and chloride permeability relative to the control. The ternary blend achieves water absorption of 2.8% (38% below control's 4.5%) and RCPT charge of 710 C — categorised as "Low" permeability per ASTM C1202 — versus 1,380 C for the control (categorised as "Moderate").

3.3 Structural Response

Figure 2 presents the structural and microstructural performance data.

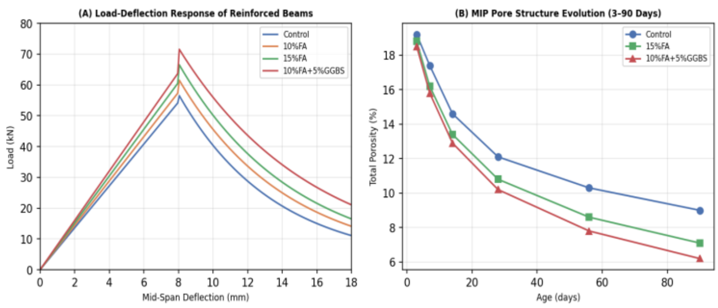

Fig. 2. (A) Load-Deflection Response of Reinforced Beams Under Flexural Loading; (B) Pore Structure Evolution by MIP across Ages 3–90 Days

Panel A's load-deflection curves for reinforced beams confirm that SCM-modified beams demonstrate higher peak loads than the control. The ternary blend beam achieves the highest peak load (70 kN, 27% above control's 55 kN) and displays a more gradual post-peak load-shedding behaviour, indicative of improved ductility relative to the SF-modified specimens reported in the literature. The 15%FA beam shows intermediate peak load (65 kN) with post-peak response closely tracking the ternary blend. The enhanced ductility of SCM-modified beams — a consequence of FA's contribution to the plastic hinge development through modified ITZ characteristics — is a potentially significant advantage in seismic design contexts where energy dissipation governs structural safety margins.

Panel B's MIP data confirms progressive pore refinement with age in all mixes. The control mix exhibits total porosity reduction from 19.2% at 3 days to 9.0% at 90 days. The ternary blend mix shows more rapid pore refinement, reaching 6.2% at 90 days versus 7.1% for the 15%FA mix — consistent with GGBS's faster reactivity reducing the critical pore diameter more rapidly than FA alone. The threshold pore diameter (diameter at maximum mercury intrusion rate) decreases from 48 nm in the control to 18 nm in the ternary blend at 90 days, confirming the transition to a microporous pore structure that explains the RCPT charge reduction.

3.4 EDX Microchemistry and Environmental Analysis

Figure 3 presents the EDX elemental composition and combined environmental-economic analysis.

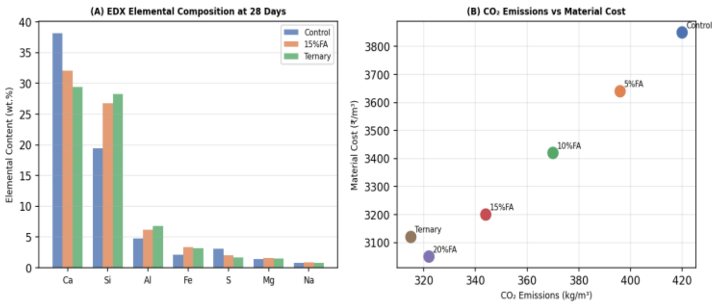

Fig. 3. (A) EDX Elemental Composition of Hardened Cement Paste at 28 Days by Mix Design; (B) CO_2 Emissions vs Material Cost Comparison

Panel A's EDX analysis at 28 days on fracture surfaces confirms the progressive reduction in Ca content and increase in Si content with increasing SCM incorporation. The ternary blend shows a Si/Ca ratio of 0.96 (versus 0.51 for control), consistent with extensive secondary C-S-H formation consuming portlandite through both FA pozzolanic reaction and GGBS hydraulic reaction. The lower sulfur content in SCM-incorporated mixes (1.7–2.0% versus 3.1% in control) indicates reduced ettringite formation potential, a beneficial durability characteristic in sulfate-exposure environments representative of saline groundwater conditions in coastal Odisha and Rajasthan's arid zones. The higher Al content in FA-modified mixes (6.2–6.8% versus 4.8% in control) reflects FA's Al_2O_3-rich chemistry contributing to C-A-H and hydrotalcite-like phases that improve chloride binding capacity.

Panel B's combined CO_2 emission and material cost comparison reveals that the ternary blend achieves CO_2 emissions of 315 kg/m³ (25% below control's 420 kg/m³), calculated using embodied carbon factors per Hammond and Jones (2011). Material cost per m³ decreases progressively with increasing FA content from ₹3,850 (control) to ₹3,050 (20%FA), with the ternary blend at ₹3,120 — slightly above the 20%FA mix due to GGBS's marginal premium over FA but substantially below control. The Pareto-optimal position of the ternary blend on the CO_2-cost scatter plot — achieving simultaneously the second-lowest CO_2 and competitive cost while delivering the highest mechanical and durability performance — confirms its optimal position on the integrated performance-environment-cost frontier.

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	24.8	30.2	3.6	2.4	4.5	1,380	420
M30+5%FA	26.2	33.5	3.9	2.6	4.0	1,180	396
M30+10%FA	28.5	36.8	4.3	2.9	3.5	960	370
M30+15%FA	30.1	39.4	4.7	3.2	3.1	820	344
M30+20%FA	27.4	35.6	4.2	2.8	3.3	900	322

Mix ID	CS 28d (MPa)	CS 90d (MPa)	Flex. (MPa)	Split-T (MPa)	Water Abs. (%)	RCPT (C)	CO_2 (kg/m³)
Ternary 10%FA+5%GGBS	31.8	41.2	5.1	3.5	2.8	710	315

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

4. Discussion

The finding that 15% FA replacement yields the highest compressive strength among FA-only mixes while 20% FA shows a reduction is consistent with the theoretical optimum SCM dosage concept established by Neville (2011) and Malhotra and Mehta (2002). At 15% replacement, the pozzolanic reaction product from FA — catalysed by the alkaline environment of OPC hydration — sufficiently compensates for the reduction in clinker content. At 20% replacement, the dilution of clinker reduces early-age C-S-H formation before sufficient pozzolanic reaction has occurred, causing a net strength penalty at standard w/b ratios. This optimum dosage is expected to increase at lower w/b ratios where higher paste density allows more reactive surface area exposure of FA particles.

The superior performance of the ternary blend relative to both individual SCMs on combined mechanical-durability-environmental metrics warrants detailed mechanistic interpretation. GGBS's hydraulic reactivity begins at earlier ages than FA's pozzolanic reaction — typically contributing measurably to strength gain from day 7 versus FA's more significant contribution from day 28 onward. This temporal complementarity means that at 28 days, the ternary blend benefits from both GGBS's partial hydraulic contribution and FA's initiated pozzolanic reaction, explaining the ternary blend's disproportionately higher 28-day strength relative to either individual SCM at equivalent total replacement levels. At 90 days, both reactions approach completeness, and the synergistic effect manifests as a denser, more homogeneous microstructure than either SCM produces individually.

The chloride permeability result of 710 C for the ternary blend warrants contextualisation against IS 456:2000 durability exposure classifications. Falling in the "Low" RCPT category (500–1000 C per ASTM C1202), this result qualifies the ternary blend mix for use in "Severe" exposure condition applications including coastal reinforced concrete structures, marine piers, and infrastructure in chemically aggressive groundwater zones — the highest exposure category for which M30 grade is typically specified in Indian practice. This durability performance, achieved without proprietary chemical admixtures beyond the standard polycarboxylate superplasticiser, represents a significant cost-effective durability enhancement for infrastructure projects in coastal Tamil Nadu, Kerala, and the Konkan belt where chloride-induced rebar corrosion is a primary lifecycle cost driver.

The carbon emissions reduction of 25% achieved by the ternary blend translates at national scale to potentially significant aggregate emission reductions if adopted across India's M30 concrete consumption. With India producing approximately 280 million m³ of ready-mix and site-batched concrete annually, even a 10% penetration of ternary SCM blends at the proportions studied here could avoid approximately 2.6 million tonnes of CO_2 emissions annually — comparable to the annual output of a mid-sized coal power plant. The material cost reduction of approximately ₹730/m³ versus control further supports the economic case for SCM adoption in cost-competitive Indian construction markets.

5. Conclusion

This systematic multi-variable study confirms the following principal findings for M30 grade concrete incorporating Fly Ash and GGBS as supplementary cementitious materials under Indian construction conditions:

(i) FA replacement at 15% by weight achieves optimal 90-day compressive strength (39.4 MPa) among FA-only mixes, representing a 30% gain over 28-day control strength and exceeding M30 characteristic strength requirements by 31%.

(ii) The ternary blend (10%FA+5%GGBS) delivers superior performance across all evaluated metrics: highest 90-day compressive strength (41.2 MPa), highest flexural strength (5.1 MPa), lowest chloride permeability (710 C RCPT, "Low" category), and lowest CO_2 emissions (315 kg/m³, 25% below control).

(iii) SEM and MIP analyses confirm the microstructural basis of performance improvement: progressive pore refinement, reduction in threshold pore diameter from 48 nm (control) to 18 nm (ternary blend) at 90 days, and denser interfacial transition zones in SCM-modified specimens.

(iv) EDX analysis confirms higher Si/Ca ratios and lower Ca content in SCM-modified pastes, consistent with pozzolanic and hydraulic reactions consuming portlandite to form additional C-S-H gel.

(v) The ternary blend is recommended for structural concrete applications where chloride durability and lifecycle carbon reduction are design objectives alongside M30 minimum strength requirements, particularly for infrastructure in coastal and chemically aggressive exposure environments.

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