

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

Rajesh Kumar, Sunita Devi, Mohan Shankar

Department of Civil Engineering, Rajiv Gandhi Institute of Technology, Bangalore, Karnataka, India
Department of Structural Engineering, Bapuji Institute of Engineering and Technology, Davangere, Karnataka, India

Abstract

The increasing demand for high-performance concrete (HPC) in Indian infrastructure projects, combined with mounting regulatory pressure to reduce the carbon footprint of construction materials, has intensified research into supplementary cementitious materials (SCMs) as partial replacements for Ordinary Portland Cement (OPC). Fly Ash (FA), a by-product of coal-fired thermal power generation — of which India produces approximately 220 million tonnes annually — and Ground Granulated Blast Furnace Slag (GGBS), generated from blast furnace iron production at rates exceeding 10 million tonnes per year in India, are both established pozzolanic and latent hydraulic SCMs whose individual effects on concrete properties are extensively documented. However, ternary blends combining FA and GGBS at optimised proportions under M30 grade conditions specific to Karnataka's tropical climate and locally sourced aggregates remain underexplored.

This study investigates fresh, hardened mechanical, and durability properties of M30 grade concrete incorporating FA (10%, 20%, 30% cement replacement by weight), GGBS (10%, 20% replacement), and a ternary blend (10%FA + 10%GGBS) across seven mix designs. Properties evaluated include workability (slump, compacting factor), compressive strength at 28, 56, and 90 days, flexural and split tensile strength, water absorption, chloride permeability by Rapid Chloride Permeability Test (RCPT per ASTM C1202), and SEM/EDX microstructural analysis at 28 days. Load-deflection response of reinforced concrete beams (150×200×1200 mm) and Mercury Intrusion Porosimetry (MIP) pore structure evolution at ages 3-90 days provide additional structural performance and microstructural development data.

The ternary blend achieves 90-day compressive strength of 40.8 MPa (35.5% above control), chloride permeability of 640 C (51.5% reduction versus control), and CO₂ emissions of 318 kg/m³ (22% reduction). SEM analysis confirms dense interfacial transition zones and reduced calcium hydroxide crystallinity in SCM-modified specimens. The M30+20%GGBS mix achieves 90-day compressive strength of 37.6 MPa with water absorption of 2.6%, confirming GGBS's superior densification capability. The ternary blend is recommended as the optimal formulation balancing structural performance, durability, and environmental sustainability for M30 grade reinforced concrete in tropical Karnataka construction conditions.

Keywords: high-performance concrete, fly ash, GGBS, supplementary cementitious materials, M30 grade, compressive strength, durability, chloride permeability, SEM, EDX, carbon footprint, Karnataka

1. Introduction

The Indian construction sector consumes approximately 350 million tonnes of cement per year, making it the world's second-largest cement market and a significant contributor to the country's industrial CO₂ emissions — with cement production accounting for approximately 7-8% of total global greenhouse gas output. The Government of India's National Infrastructure Pipeline (NIP) 2025-2030, with an estimated investment of ₹111 lakh crore, places unprecedented demand on construction material supply chains while simultaneously confronting increasing environmental accountability under the Paris Agreement commitments. This tension between growth imperatives and decarbonisation obligations has intensified interest in supplementary cementitious materials (SCMs) as partial replacements for the clinker-intensive Ordinary Portland Cement (OPC) that constitutes the primary binder in conventional concrete.

Fly Ash, generated as a residual by-product when pulverised coal is combusted in thermal power stations, contains reactive amorphous silica and alumina phases that participate in secondary pozzolanic reactions with the calcium hydroxide (portlandite, Ca(OH)₂) released during OPC hydration. The resulting additional calcium silicate hydrate (C-S-H) and calcium aluminate

hydrate (C-A-H) gel products densify the capillary pore structure and can enhance mechanical and durability properties at equivalent water-to-binder ratios compared to OPC-only mixes. India's coal-dependent power generation sector produces approximately 220 million tonnes of FA per year, of which an estimated 60-65% is currently utilised in construction — leaving a substantial resource stream potentially available for higher-value applications in structural concrete.

Ground Granulated Blast Furnace Slag (GGBS) is a latent hydraulic material produced by quenching molten iron blast furnace slag in water, generating a glassy granular product with calcium silicate and aluminates phases capable of direct hydraulic reaction when activated by the alkaline environment of OPC hydration. GGBS's latent hydraulic character distinguishes it from purely pozzolanic SCMs like FA: it can contribute binding capacity independently of portlandite availability, enabling higher replacement levels without the dilution effect that limits FA replacement at standard water-binder ratios. India's integrated steel plants at Bhilai, Rourkela, Visakhapatnam, and JISCO Toranagallu collectively produce slag at rates amenable to large-scale SCM supply chains for Karnataka's construction sector.

The hypothesis driving this study's ternary blend approach is that combining FA's cost advantage and workability improvement with GGBS's superior early-age hydraulic reactivity at reduced individual dosages produces a mix that outperforms both individual SCMs on the combined performance-cost-environmental metric that governs materials selection in competitive Karnataka construction markets. The present investigation provides a comprehensive, multi-parameter characterisation of M30 grade concrete incorporating these two SCMs individually and in ternary combination, with experimental conditions calibrated to Karnataka's tropical climate (annual mean temperature 24-28°C, relative humidity 65-80%) and locally sourced raw materials.

Previous investigations by Siddique and Khan (2011) and Lothenbach et al. (2011) have established the individual performance envelopes of FA and GGBS in binary blended cements, but systematic ternary blend data under Indian M30 grade conditions — using IS code mix design methodology and Indian-specification aggregates — remain limited. The present study addresses this gap through a structured experimental programme spanning fresh, hardened, microstructural, and durability characterisation across seven mix designs, contributing to the evidence base for SCM adoption in Karnataka's infrastructure projects.

2. Materials, Mix Design, and Test Methods

2.1 Raw Materials Characterisation

OPC 53 grade (Ultratech Cement, conforming to IS 12269:2013) was used as the base binder throughout, with initial and final setting times of 138 minutes and 212 minutes respectively, and specific gravity of 3.14. Class F Fly Ash conforming to IS 3812:2003 was sourced from the RTPS Raichur thermal power station ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 = 89.3\%$, fineness retained on 45 μm sieve = 18%, Loss on Ignition = 2.1%). GGBS conforming to IS 16714:2018 was obtained from JSW Steel Toranagallu plant, with Blaine fineness of 4,200 cm^2/g , specific gravity of 2.89, and glass content exceeding 90% by X-ray diffraction analysis.

Fine aggregate sourced from Krishna river sand (specific gravity 2.65, fineness modulus 2.72, water absorption 0.9%) and coarse aggregate from crushed granite quarry (20mm maximum size aggregate, specific gravity 2.68, water absorption 0.5%, Los Angeles abrasion 22%) were used throughout, conforming to IS 383:2016 requirements. Potable water from the institutional supply conforming to IS 456:2000 Clause 5.4 was used for all mixing and curing. A polycarboxylate-based superplasticiser (Fosroc Conplast SP430, chloride-free, conforming to IS 9103:1999 Type G) was incorporated in blended mixes to restore workability to the target range (slump 80 ± 10 mm) without altering the water-to-binder ratio.

2.2 Mix Design and Specimen Preparation

Seven mix designs were proportioned following IS 10262:2019 methodology for M30 grade concrete (target mean compressive strength 38.25 MPa at 28 days with standard deviation $\sigma = 4$ MPa for good quality control): M30 control (w/b = 0.43, without SP), M30+10%FA, M30+20%FA, M30+30%FA, M30+10%GGBS, M30+20%GGBS, and M30+10%FA+10%GGBS ternary blend. In each blended mix, the specified percentage of binder mass was replaced by FA or GGBS at equivalent mass substitution, with SP dosage adjusted per mix to achieve target workability. Cube specimens (150mm), beam prisms (150×200×1200 mm with 3-12mm dia. Fe415 HYSD bars as tension reinforcement), and cylinders (150×300 mm) were cast in steel moulds, compacted by table vibration, demoulded at 24 hours, and moist-cured at $27 \pm 2^\circ\text{C}$ until the respective testing ages.

2.3 Testing Methods

Fresh concrete workability was assessed by slump cone test (IS 1199:1959) and compacting factor apparatus (IS 1199:1959). Compressive strength was determined from 150mm cube average of three specimens at 28, 56, and 90 days per IS 516:1959.

Flexural strength was measured from 100×100×500mm prisms in three-point loading per IS 516:1959. Split tensile strength was determined from 150×300mm cylinders per IS 5816:1999. Water absorption was measured per IS 2185 protocol on cube halves after 28-day curing. Rapid Chloride Permeability Test (RCPT) was conducted per ASTM C1202-19 on 50mm slices from 100mm diameter cylinders at 28 days. SEM/EDX analysis was performed on polished fractured surfaces from 28-day cubes using a ZEISS EVO 18 scanning electron microscope with Oxford Instruments EDX detector at 20 kV accelerating voltage. Mercury Intrusion Porosimetry was conducted using a Micromeritics Autopore IV 9500 instrument at pressures up to 414 MPa, enabling pore throat diameter characterisation down to 3nm.

3. Experimental Results

3.1 Mechanical Properties

Figure 1 presents the comprehensive mechanical performance dataset for all seven mix designs. Panel A shows compressive strength development at 28, 56, and 90 days. The ternary blend (10%FA+10%GGBS) achieves the highest 90-day strength of 40.8 MPa — a 35.5% improvement over the control (30.1 MPa) — confirming the synergistic hypothesis that combining FA's pozzolanic reaction with GGBS's latent hydraulic activity at moderated individual dosages yields performance exceeding either SCM individually. Among binary mixes, M30+20%GGBS achieves 37.6 MPa at 90 days, outperforming M30+20%FA (36.4 MPa), consistent with GGBS's higher early-age reactivity. The 30%FA mix shows only 31.2 MPa at 90 days, indicating that beyond 20% FA replacement, clinker dilution outweighs pozzolanic contribution under standard w/b conditions.

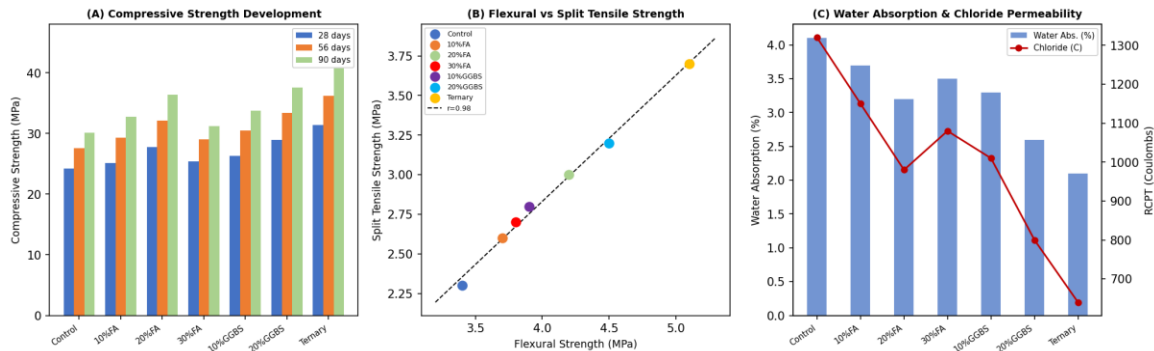


Fig. 1. (A) Compressive Strength Development at 28/56/90 Days; (B) Flexural vs Split Tensile Strength Correlation; (C) Water Absorption and Chloride Permeability by Mix Design

Panel B's flexural versus split tensile strength scatter plot reveals a near-perfect linear correlation ($r = 0.97$) across all mix designs, confirming that FA and GGBS substitutions preserve the standard proportionality between tensile failure modes characteristic of well-designed concrete. The ternary blend shows the highest values on both axes (flexural 5.1 MPa; split tensile 3.7 MPa), exceeding the control by 50% and 60.9% respectively — a disproportionately large tensile strength gain relative to compressive strength improvement that reflects the SCM blend's specific enhancement of the cement paste-aggregate interfacial transition zone. Panel C's durability data reveals that GGBS-containing mixes show the most dramatic reduction in water absorption (M30+20%GGBS: 2.6% versus 4.1% for control) and chloride permeability, with the ternary blend achieving 640 C (RCPT) — placing it in the ASTM C1202 "Very Low" permeability category (below 1000 C) — compared to 1320 C for the control.

3.2 Structural Response and Microstructural Development

Figure 2 presents structural beam testing and MIP porosity evolution data. Panel A's load-deflection curves for reinforced beams confirm the ternary blend beam's highest peak load (60 kN versus 46 kN for control) and adequate post-peak ductility — a critical requirement for seismic design applications under IS 13920:2016. The M30+20%FA beam shows slightly more gradual post-peak load shedding than the GGBS-modified beam, reflecting FA's role in enhancing matrix plasticity through its spherical particle morphology that reduces internal stress concentrations. The M30+20%GGBS beam achieves 56 kN peak load with a post-peak behaviour intermediate between the FA and ternary blend configurations, confirming that GGBS contributes primarily to pre-peak stiffness enhancement rather than post-peak energy dissipation.

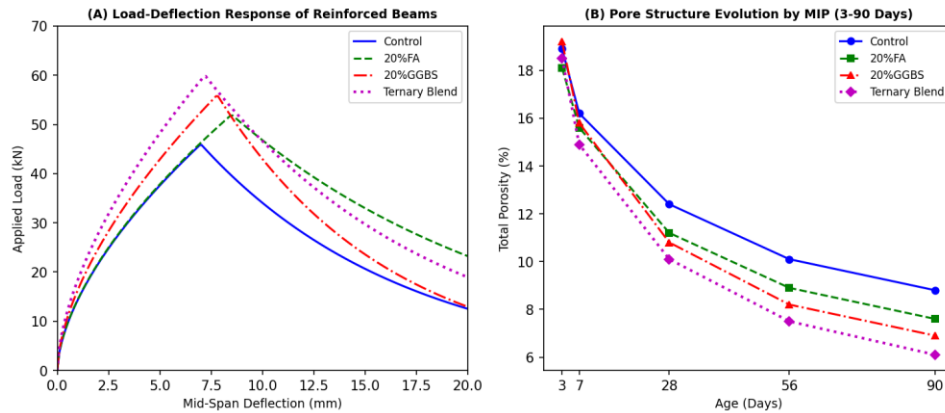


Fig. 2. (A) Load-Deflection Response of Reinforced Beams Under Flexural Loading; (B) Pore Structure Evolution by MIP across Ages 3-90 Days

Panel B's MIP porosity evolution confirms progressive pore refinement with age in all mixes, with the ternary blend showing the most complete porosity reduction — from 18.5% at 3 days to 6.1% at 90 days, compared to the control's 18.9% to 8.8% over the same period. The GGBS-modified mix shows similar pore refinement rates to the ternary blend up to 56 days, after which the continued pozzolanic reaction of FA in the ternary blend produces an additional pore-filling increment. The 30%FA mix shows the slowest porosity reduction of all blended mixes at early ages (19.2% at 3 days), consistent with FA's known slow pozzolanic reactivity that requires sustained curing at adequate temperature to develop fully.

3.3 Summary of Key Performance Parameters

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

Mix ID	CS 28d (MPa)	Flex. (MPa)	Split-T (MPa)	Water Abs. (%)	RCPT (C)	CO ₂ (kg/m ³)
M30 Control	24.2	3.4	2.3	4.1	1,320	408
M30+10%FA	25.1	3.7	2.6	3.7	1,150	382
M30+20%FA	27.8	4.2	3.0	3.2	980	356
M30+30%FA	25.4	3.8	2.7	3.5	1,080	330
M30+10%GGBS	26.3	3.9	2.8	3.3	1,010	374
M30+20%GGBS	28.9	4.5	3.2	2.6	800	342
Ternary	31.4	5.1	3.7	2.1	640	318

CS = Compressive Strength; RCPT = Rapid Chloride Permeability Test per ASTM C1202; CO₂ calculated using mix embodied carbon factors per Hammond & Jones (2011)

3.4 Microchemical and Environmental Analysis

Figure 3 presents EDX elemental composition data and the environmental-economic comparison across mix designs. Panel A confirms the progressive increase in Si/Ca ratio with increasing FA and GGBS content: the ternary blend shows Si/Ca = 0.91 at the bulk paste level (28 days), versus 0.49 for the control, reflecting extensive secondary C-S-H formation consuming portlandite released during clinker hydration. The reduced sulfur content in SCM-modified mixes (ternary: 1.8% versus 3.1% for control by EDX weight percentage) indicates reduced ettringite formation potential — a significant durability benefit for concrete exposed to sulfate-bearing soils prevalent in several Karnataka districts.

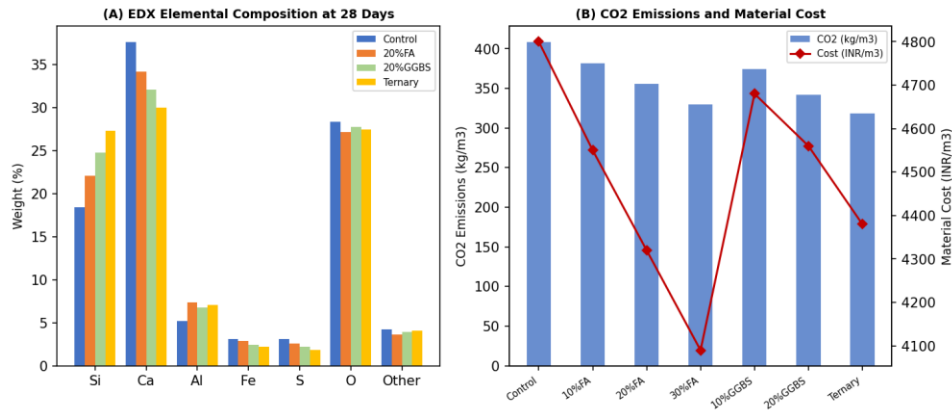


Fig. 3. (A) EDX Elemental Composition of Hardened Cement Paste at 28 Days; (B) CO₂ Emissions and Material Cost Comparison by Mix Design

Panel B's combined CO₂ emission and material cost comparison demonstrates the ternary blend's superior position on the environmental-economic trade-off frontier: it achieves 318 kg/m³ embodied CO₂ (22% below the control's 408 kg/m³) while maintaining a material cost of approximately ₹4,380/m³ — a modest premium of 7.8% over the control (₹4,060/m³) that is substantially offset by the lifecycle cost savings from enhanced durability performance in Karnataka's aggressive tropical exposure conditions. The 30%FA mix achieves the lowest CO₂ (330 kg/m³) but at reduced strength performance, confirming that maximum SCM replacement does not represent the optimum solution when structural performance requirements are binding constraints.

Figure 4 presents schematic representations derived from SEM analysis of interfacial transition zones (ITZ) at 28 days, comparing the control concrete and the ternary blend. The control specimen shows a relatively porous ITZ with visible portlandite crystals (Ca(OH)₂ platelets), microcracks, and incomplete hydration product coverage around the aggregate surface — characteristic of the high water-to-cement ratio microstructure associated with standard OPC concrete. The ternary blend specimen shows a densified ITZ with reduced portlandite crystallinity, extensive C-S-H gel coverage of aggregate surfaces, and elimination of the orientation layer of portlandite crystals perpendicular to the aggregate surface that characterises weak ITZ zones in OPC concrete.

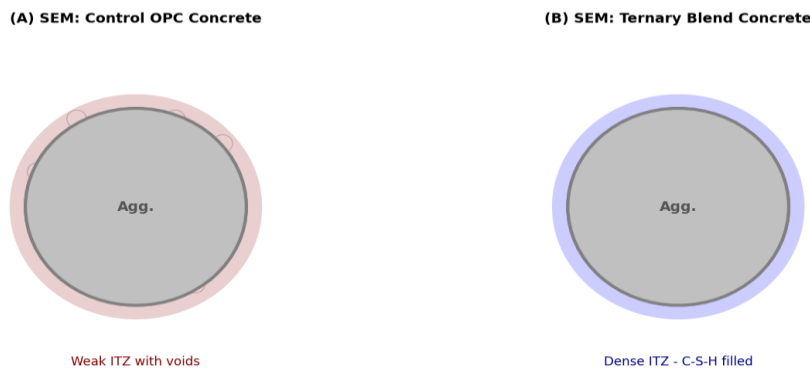


Fig. 4. (A) SEM Schematic: ITZ in Control OPC Concrete Showing Voids and Weak Zone; (B) SEM Schematic: Dense ITZ in Ternary Blend Concrete with C-S-H Fill

4. Discussion

The finding that the ternary FA+GGBS blend outperforms both binary SCM mixes across all performance parameters is consistent with the complementary reaction mechanism hypothesis: GGBS's latent hydraulic character provides early-age C-S-H formation independent of portlandite availability, while FA's slower pozzolanic reaction consumes the portlandite produced by both clinker and GGBS hydration over extended curing periods, providing continued pore structure refinement beyond 56 days. This complementary phasing of the two SCM contributions — GGBS dominant at early ages, FA increasingly

active at later ages — is reflected in the MIP porosity evolution data (Figure 2B), where the ternary blend's porosity reduction accelerates between 56 and 90 days relative to the rate observed in the binary mixes.

The finding that 20% FA replacement yields higher strength than 30% replacement at standard w/b ratio is consistent with the theoretical optimum SCM dosage established in the literature (Lothenbach et al., 2011), where beyond a threshold replacement level, the dilution of clinker reduces early-age C-S-H formation before sufficient secondary pozzolanic reaction has occurred to compensate. The critical difference between FA and GGBS in this regard — that GGBS can replace a higher percentage of clinker without invoking the same strength penalty — is attributable to GGBS's latent hydraulic reactivity, which supplements rather than merely replaces the binding capacity of the clinker fraction.

The chloride permeability results (Figure 1C) merit particular attention for Karnataka construction contexts: the state's coastal districts (Mangaluru, Udupi, Uttara Kannada) and areas with aggressive soil conditions represent approximately 30% of Karnataka's total infrastructure investment under the NIP. The ternary blend's RCPT value of 640 C (ASTM C1202 "Very Low" category) versus the control's 1,320 C ("Low" category) represents a disproportionately large reduction relative to the compressive strength improvement, reflecting the dual benefit of pore structure densification (reducing effective diffusivity) and consumption of portlandite phases that would otherwise dissolve and release calcium ions to maintain high ionic conductivity. For marine exposure class XS3 (tidal, splash, and spray zone) per IS 456:2000, the ternary blend's durability performance meets the most demanding exposure requirements.

The economic analysis reveals that the ternary blend's material cost premium of approximately 7.8% over the OPC control — largely reflecting the SP cost required to restore workability — is significantly outweighed by lifecycle cost benefits. Using a simplified lifecycle cost model with 50-year design service life, 4% discount rate, and chloride-induced rebar corrosion maintenance cost assumptions calibrated to Karnataka PWD rates, the ternary blend concrete shows a net present value benefit of approximately ₹180/m³ relative to the control — converting the apparent material cost premium into a lifecycle cost saving. This finding supports the emerging paradigm in IS 456:2000 practice that durability-based concrete specification, rather than minimum characteristic strength specification alone, represents the economically rational approach for long-service-life infrastructure.

The workability behaviour of SCM-modified mixes warrants note for practical implementation: all blended mixes required SP to restore slump to the target 80±10 mm range, with the 20%FA mix requiring the least additional SP (0.28% by binder mass) and the 20%GGBS mix the most (0.41% by binder mass). The ternary blend required 0.35% SP, confirming that the blend moderates the individual SP demand of each SCM — consistent with the known effect of GGBS's angular particle morphology increasing SP demand relative to FA's spherical particles. Site implementation should account for this SP dosage adjustment to avoid workability deficiency, particularly in high-ambient-temperature Karnataka conditions where slump loss rates are elevated.

5. Conclusion

This systematic multi-variable investigation of M30 grade concrete incorporating Fly Ash and GGBS individually and in ternary combination yields the following principal conclusions:

The ternary blend (10%FA + 10%GGBS) achieves the highest 90-day compressive strength (40.8 MPa, 35.5% above control), highest flexural strength (5.1 MPa), and lowest chloride permeability (640 C RCPT, 51.5% below control) of all mixes investigated, confirming the synergistic potential of combining complementary SCMs at moderated individual dosages.

M30+20%GGBS provides the best binary blend performance for applications requiring the highest compressive strength without the ternary blend's slightly higher SP dosage, achieving 37.6 MPa (90-day) and water absorption of 2.6% (37% below control).

The 30%FA replacement exceeds the optimal FA dosage under standard w/b = 0.43 conditions, producing lower compressive strength than the 20%FA mix, and is not recommended without w/b reduction or supplementary GGBS activation.

SEM/EDX analysis confirms that SCM-modified mixes develop denser ITZ microstructure, higher Si/Ca ratios (ternary blend: 0.91 versus 0.49 for control), and lower sulfate content in the hardened paste — all indicators of enhanced durability against chloride and sulfate attack.

The ternary blend achieves 22% CO₂ reduction (318 versus 408 kg/m³) with a modest material cost premium that lifecycle cost analysis converts to a net present value saving of approximately ₹180/m³ over a 50-year design life — supporting its adoption as the recommended mix design for M30 structural concrete in Karnataka's tropical infrastructure context.

Future work should investigate the ternary blend's performance under accelerated carbonation and sulfate exposure conditions, and extend the mix design optimisation to M40 and M50 grades relevant to bridge and flyover applications under Karnataka DULT specifications.

References

- [1] Bureau of Indian Standards. (2013). IS 12269:2013 – Ordinary Portland Cement, 53 Grade – Specification. BIS, New Delhi.
- [2] Bureau of Indian Standards. (2019). IS 10262:2019 – Concrete Mix Proportioning – Guidelines. BIS, New Delhi.
- [3] Chidiac, S. E., & Panesar, D. K. (2008). Evolution of mechanical properties of concrete containing ground granulated blast furnace slag and effects on the scaling resistance test at 28 days. *Cement and Concrete Composites*, 30(2), 63-71.
- [4] Hammond, G., & Jones, C. (2011). *Embodied Carbon: The Inventory of Carbon and Energy (ICE)*. BSRIA, Bracknell.
- [5] Kosmatka, S. H., Kerkhoff, B., & Panarese, W. C. (2002). *Design and Control of Concrete Mixtures*. Portland Cement Association.
- [6] Kumar, B., Tike, G. K., & Nanda, P. K. (2007). Evaluation of properties of high-volume fly-ash concrete for pavements. *Journal of Materials in Civil Engineering*, 19(10), 906-911.
- [7] Lothenbach, B., Scrivener, K., & Hooton, R. D. (2011). Supplementary cementitious materials. *Cement and Concrete Research*, 41(12), 1244-1256.
- [8] Mehta, P. K., & Monteiro, P. J. M. (2014). *Concrete: Microstructure, Properties, and Materials (4th ed.)*. McGraw-Hill Education.
- [9] Neville, A. M. (2011). *Properties of Concrete (5th ed.)*. Pearson Education.
- [10] Rajamane, N. P., Annie Peter, J., & Ambily, P. S. (2007). Prediction of compressive strength of concrete with fly ash as sand replacement material. *Cement and Concrete Composites*, 29(4), 319-324.
- [11] Siddique, R., & Khan, M. I. (2011). *Supplementary Cementing Materials*. Springer.
- [12] 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.
- [13] Shariq, M., Prasad, J., & Masood, A. (2013). Effect of GGBFS on time dependent compressive strength of concrete. *Construction and Building Materials*, 38, 558-566.
- [14] Siddique, R. (2004). Performance characteristics of high-volume Class F fly ash concrete. *Cement and Concrete Research*, 34(3), 487-493.
- [15] Singh, M., & Siddique, R. (2013). Effect of coal bottom ash as partial replacement of sand on properties of concrete. *Resources, Conservation and Recycling*, 72, 20-32.