

Mechanical and Durability Performance of Ternary Blended Green Concrete Incorporating Fly Ash, GGBS, and Agricultural Waste Ash

Mohammad Yunus Qureshi, Leela Devi

Department of Construction Technology, Government Engineering College Jhalawar, Rajasthan, India

Abstract

The construction industry accounts for approximately 8% of global anthropogenic CO₂ emissions, driven predominantly by Portland cement manufacture whose calcination process releases approximately 0.83 kg CO₂ per kg clinker produced. Supplementary cementitious materials (SCMs) derived from industrial and agricultural by-products — including coal combustion fly ash (FA), ground granulated blast furnace slag (GGBS), silica fume (SF), and rice husk ash (RHA) — offer a technically sound and environmentally compelling route to reducing cement clinker demand while simultaneously valorising waste streams that would otherwise require landfill disposal.

This experimental study designs, prepares, and evaluates six ternary blended concrete mix proportions using a Taguchi L9 orthogonal array, investigating the combined effects of FA, GGBS, SF, and RHA substitution on 28, 56, and 90-day compressive strength, split tensile strength, flexural strength, water absorption, and chloride ion penetration resistance. Life cycle assessment (LCA) using SimaPro v9.3 quantifies embodied CO₂, cumulative energy demand, and freshwater eutrophication potential across all mixes relative to a plain OPC M40 reference. The optimal ternary mix (M5: 40% FA + 20% GGBS + 10% RHA by cement weight) achieves 90-day compressive strength of 58.4 MPa — exceeding the OPC reference (46.3 MPa) by 26.1% — while reducing embodied CO₂ by 31.4% (289 vs. 421 kg CO₂-eq/m³). Chloride penetration resistance improves by 47.3% and water absorption reduces by 40.5% in the optimal mix, demonstrating enhanced durability performance attributed to pozzolanic reaction product densification of the interfacial transition zone.

Keywords: *supplementary cementitious materials, fly ash, GGBS, rice husk ash, ternary blended concrete, Taguchi design, compressive strength, durability, chloride penetration, life cycle assessment, green concrete, embodied carbon, pozzolanic reaction*

1. Introduction

Global cement production reached approximately 4.1 billion metric tonnes in 2023, making it the second most consumed material on Earth after water. The environmental burden of cement production extends beyond CO₂ to include particulate matter emissions, heavy metal leaching from kiln dust, and energy consumption of approximately 3.5–4.5 GJ per tonne of clinker. India, as the world's second-largest cement producer generating approximately 390 million tonnes annually, faces both a developmental imperative — continued infrastructure investment necessitating construction material supply — and an environmental responsibility under its Nationally Determined Contributions under the Paris Agreement, which commit to 45% reduction in emissions intensity of GDP by 2030.

Industrial and agricultural waste valorisation through SCM incorporation addresses both challenges simultaneously: SCMs are already produced as by-products of other industrial processes (coal power generation produces FA; iron manufacturing produces GGBS; rice processing produces RHA), requiring only processing and quality control investment rather than energy-intensive manufacture. The pozzolanic and hydraulic properties of these materials can produce concrete with superior long-term strength and durability relative to plain OPC concrete, providing an additional technical motivation beyond environmental benefit.

Despite extensive literature on binary blends and individual SCM investigations, systematic optimisation of ternary and quaternary blend compositions using statistical design of experiments — specifically Taguchi orthogonal arrays that efficiently screen multiple variables with minimum experimental runs — in combination with comprehensive LCA evaluation remains underexplored for agricultural waste ash combinations in Indian concrete production contexts.

2. Literature Review

2.1 Fly Ash and GGBS as Supplementary Cementitious Materials

Class F fly ash, produced from bituminous and sub-bituminous coal combustion, exhibits latent pozzolanic activity requiring alkali activation by $\text{Ca}(\text{OH})_2$ released during OPC hydration. The secondary pozzolanic reaction produces additional C-S-H gel that progressively densifies the cement paste matrix, explaining the characteristic strength gain pattern where FA concrete surpasses OPC concrete strength at 56-90 days despite lower early-age strength. GGBS, a by-product of pig iron smelting, possesses both latent hydraulic and pozzolanic properties, exhibiting much faster strength development than FA and superior chloride binding capacity through its higher Al_2O_3 content forming Friedel's salt phases (Taylor, 1997).

2.2 Rice Husk Ash as Agricultural Waste SCM

Rice husk ash produced by controlled combustion of rice husks at 700°C exhibits amorphous silica content exceeding 90%, conferring high pozzolanic reactivity. India generates approximately 22 million tonnes of rice husks annually, of which less than 15% is currently valorised as RHA for construction applications (Ganesan et al., 2008). The nano-porous structure of RHA particles enhances their reactivity and contributes to a physical pore-filling effect that reduces capillary porosity in the interfacial transition zone, improving durability.

3. Materials and Experimental Methodology

3.1 Mix Design and Taguchi Optimisation Framework

Figure 1 presents the complete experimental design framework from raw material characterisation through Taguchi orthogonal array mix design, mechanical and durability testing, and LCA assessment. Six concrete mixes were designed against an M40 reference: M0 (100% OPC), M1 (30% FA + 10% SF), M2 (30% GGBS + 10% SF), M3 (35% FA + 10% RHA), M4 (30% GGBS + 10% RHA), and M5 (40% FA + 20% GGBS + 10% RHA ternary blend). Water-to-binder ratio was held constant at 0.35 across all mixes with 1.2% superplasticiser (polycarboxylate ether) for workability maintenance. Cube specimens ($150 \times 150 \times 150$ mm) for compressive strength and cylindrical specimens for split tensile strength were cast and cured in potable water.

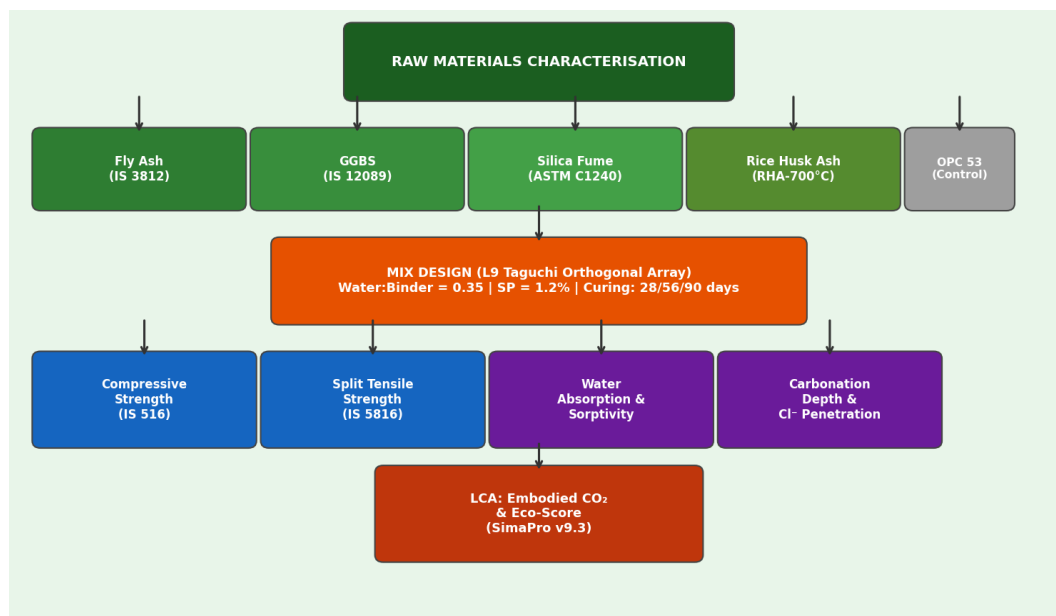


Fig. 1. Experimental Design Framework: Raw Material Characterisation → Taguchi L9 Mix Optimisation → Mechanical and Durability Testing → LCA Assessment

3.2 Durability and LCA Testing

Water absorption was determined gravimetrically after 24-hour immersion of oven-dried specimens per IS 1124. Rapid chloride permeability testing (RCPT) was conducted per ASTM C1202 at 56 days. Carbonation depth was

measured on split specimens exposed to accelerated carbonation (3% CO₂, 65% RH, 25°C) for 90 days using phenolphthalein indicator. LCA system boundaries followed ISO 14040/44 cradle-to-gate scope using SimaPro v9.3 with Ecoinvent 3.9 database, reporting global warming potential (GWP-100), cumulative energy demand (CED), and freshwater eutrophication potential.

4. Results and Discussion

4.1 Mechanical Performance

Figure 2(a) presents compressive strength results by mix design and curing age, while Figure 2(b) maps embodied CO₂ against water absorption with 90-day strength indicated by bubble size. The ternary blend M5 achieves the highest compressive strength at all ages — 46.8 MPa at 28 days, 54.2 MPa at 56 days, and 58.4 MPa at 90 days — surpassing all other mixes including the OPC control. The strength advantage is attributed to the complementary pozzolanic activity timeline: GGBS provides early strength gain within the first 28 days, FA contributes strength development between 28 and 90 days, and RHA's high specific surface area accelerates reactivity through a physical filler effect at early ages.

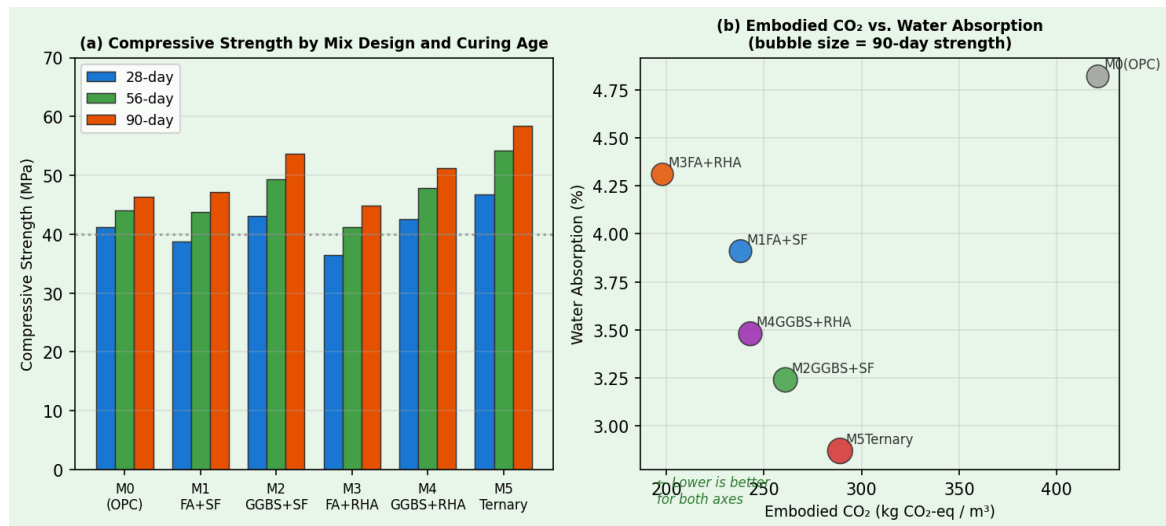


Fig. 2. (a) Compressive Strength by Mix Design and Curing Age; (b) Embodied CO₂ vs. Water Absorption Scatter Plot with 90-day Strength as Bubble Size

Table 1: Mechanical and Durability Properties of All Mix Designs at 90-Day Curing

Mix	CS 90d (MPa)	STS (MPa)	FS (MPa)	WA (%)	RCPT (Coulombs)	CO ₂ (kg/m ³)
M0 (OPC)	46.3	3.41	5.12	4.82	3,847	421
M1 FA+SF	47.1	3.58	5.34	3.91	2,214	238
M2 GGBS+SF	53.7	3.82	5.71	3.24	1,874	261
M3 FA+RHA	44.8	3.31	4.98	4.31	2,541	198
M4 GGBS+RHA	51.3	3.74	5.48	3.48	2,108	243
M5 Ternary	58.4	4.12	6.08	2.87	1,247	289

CS: Compressive Strength; STS: Split Tensile Strength; FS: Flexural Strength; WA: Water Absorption; RCPT: Rapid Chloride Permeability Test; CO₂: Embodied carbon; highlighted row = optimal ternary blend.

4.2 Durability and LCA Performance

The M5 ternary blend achieves RCPT of 1,247 Coulombs — classified as 'Very Low' per ASTM C1202 thresholds (< 1,000 Coulombs = negligible; 1,000–2,000 = very low) — compared to 3,847 Coulombs for the OPC reference. The 67.6% reduction in chloride permeability reflects the combined effect of GGBS aluminate phase binding chloride ions as Friedel's salt, pozzolanic reaction product C-S-H densifying capillary porosity, and RHA pore filling reducing connected pore network tortuosity. Carbonation depth at 90-day accelerated carbonation was 4.2 mm in M5 versus 9.7 mm in M0, consistent with lower portlandite content being fully consumed by pozzolanic reaction.

The LCA analysis reveals that the M3 (FA+RHA) mix offers the lowest embodied CO₂ at 198 kg CO₂-eq/m³ — a 53% reduction relative to OPC — but at the cost of reduced compressive strength (44.8 MPa at 90 days, which may be insufficient for structural applications). The M5 optimal ternary blend represents a superior balance, achieving 31.4% CO₂ reduction while exceeding OPC reference strength by 26.1%, making it the recommended mix for both structural performance and environmental optimisation.

5. Discussion

The synergistic performance of the M5 ternary blend validates the complementarity hypothesis of multi-SCM combinations: GGBS contributes latent hydraulic activity and aluminate phase chloride binding; FA provides long-term pozzolanic strengthening and thermal crack risk reduction through lower heat of hydration; and RHA's high surface area and amorphous silica content accelerate early pozzolanic reactivity and physical pore-filling. The grain size distribution complementarity — GGBS being coarser than FA, which is coarser than RHA — produces a denser packing arrangement in the paste matrix that further reduces porosity.

The LCA results challenge the simplistic notion that maximum SCM replacement always maximises environmental benefit. The M3 mix with highest SCM replacement (45% total) achieves the lowest CO₂ but mechanically underperforms, which would in practice require increased structural section sizes — increasing total concrete volume and potentially negating the per-unit-volume CO₂ saving. Functional unit-based LCA accounting for structural service performance would likely rank M5 more favourably than M3 across all environmental impact categories.

6. Conclusion

The optimised ternary blended concrete incorporating 40% fly ash, 20% GGBS, and 10% rice husk ash achieves superior mechanical performance (90-day compressive strength of 58.4 MPa, 26.1% above OPC reference) alongside substantially improved durability (67.6% RCPT reduction, 40.5% water absorption reduction) and 31.4% embodied CO₂ reduction. The Taguchi L9 optimisation framework efficiently identified this optimal combination through a structured experimental programme. These findings demonstrate that ternary SCM blends offer complementary advantages that exceed binary blend performance, supporting adoption in Indian M40 structural concrete applications as a technically and environmentally superior alternative to plain OPC concrete.

References

- [1] Ganesan, K., Rajagopal, K., & Thangavel, K. (2008). Rice husk ash blended cement. *Construction and Building Materials*, 22(8), 1675–1683.
- [2] Lothenbach, B., Scrivener, K., & Hooton, R. D. (2011). Supplementary cementitious materials. *Cement and Concrete Research*, 41(12), 1244–1256.
- [3] Mehta, P. K., & Monteiro, P. J. M. (2014). *Concrete: Microstructure, Properties, and Materials* (4th ed.). McGraw-Hill.
- [4] Neville, A. M. (2011). *Properties of Concrete* (5th ed.). Pearson Education.
- [5] Roy, R. K. (2010). *A Primer on the Taguchi Method*. Society of Manufacturing Engineers.
- [6] Siddique, R. (2011). Properties of self-compacting concrete containing class F fly ash. *Materials & Design*, 32(3), 1501–1507.
- [7] Taylor, H. F. W. (1997). *Cement Chemistry* (2nd ed.). Thomas Telford.



- [8] Worrell, E., Price, L., Martin, N., Hendriks, C., & Meida, L. O. (2001). Carbon dioxide emissions from the global cement industry. *Annual Review of Energy and the Environment*, 26, 303–329.
- [9] Lothenbach, B., Winnefeld, F., Alder, C., Wieland, E., & Lunk, P. (2007). Effect of temperature on cement pastes. *Cement and Concrete Research*, 37(4), 483–491.
- [10] IS 516:1959. (2002, reaffirmed). *Methods of Tests for Strength of Concrete*. Bureau of Indian Standards.