

Mechanical Performance, Durability, and Sustainability of High-Strength Concrete Incorporating Fly Ash, Silica Fume, and Ground Granulated Blast Furnace Slag as Ternary Supplementary Cementitious Materials

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Abstract

Ordinary Portland Cement (OPC) production contributes approximately 8% of global anthropogenic CO₂ emissions, motivating widespread investigation of supplementary cementitious materials (SCMs) that partially replace clinker while maintaining or enhancing concrete performance. This study investigates the fresh properties, mechanical strength development, durability characteristics, microstructural evolution, and embodied carbon footprint of M40-grade concrete incorporating three SCMs — Class F Fly Ash (FA), Condensed Silica Fume (SF), and Ground Granulated Blast Furnace Slag (GGBS) — individually and in ternary blends optimised through a central composite design (CCD) response surface methodology. Six mix designs are evaluated at total binder content of 400 kg/m³ and water-to-binder ratio of 0.38: OPC control; 10%FA+5%SF; 20%FA+8%SF; 10%GGBS+10%FA; 15%GGBS+10%SF; and a CCD-optimised ternary blend (12%FA+8%SF+10%GGBS). Fresh concrete properties assessed include slump flow, V-funnel time, and L-box ratio per EFNARC guidelines. Hardened properties evaluated include compressive strength at 7, 28, and 90 days; split tensile and flexural strength at 28 days; water absorption; Rapid Chloride Permeability Test (RCPT) per ASTM C1202; and mercury intrusion porosimetry (MIP) pore structure evolution at ages 3–90 days. SEM/EDX microchemical analysis at 28 days characterises C-S-H gel morphology and interfacial transition zone (ITZ) density. The ternary optimum blend achieves 90-day compressive strength of 47.8 MPa (59% above control), RCPT of 560 C (Very Low category), water absorption of 2.2%, and embodied CO₂ reduction of 27.3% versus the OPC control. Response surface models achieve R² > 0.95 for all strength and durability responses, enabling validated design-space exploration and identifying a global optimum at 12%FA+8%SF+10%GGBS that maximises the composite desirability function across all responses simultaneously.

Keywords: high-strength concrete, fly ash, silica fume, GGBS, ternary SCM blend, compressive strength, chloride permeability, MIP, response surface methodology, embodied carbon, sustainability

1. Introduction

The global construction industry consumes approximately 4.4 billion tonnes of cement per year, rendering it the single largest industrial source of CO₂ emissions. India, as the world's second-largest cement producer at approximately 380 million tonnes per year, faces a particularly acute tension between its ambitious National Infrastructure Pipeline targets — which project a threefold increase in concrete consumption over the period 2020–2030 — and its Nationally Determined Contributions under the Paris Agreement, which commit to a 45% reduction in emissions intensity by 2030 relative to 2005 levels. Supplementary cementitious materials offer a technically proven pathway to address this tension: by partially replacing OPC clinker with reactive mineral by-products, SCMs reduce embodied CO₂ while their pozzolanic and latent hydraulic reactions fill capillary pores, densify the calcium silicate hydrate (C-S-H) gel matrix, and can enhance long-term mechanical and durability performance beyond OPC-only baselines.

Fly ash — the fine particulate residue from pulverised coal combustion in thermal power stations — is India's most abundant SCM, with annual generation exceeding 220 million tonnes and utilisation rates still below 70%, leaving significant volumes for construction applications. Class F fly ash's low calcium content and high amorphous silica fraction enable a pozzolanic reaction with portlandite (Ca(OH)₂) released during cement hydration, generating secondary C-S-H that reduces permeability and improves long-term strength. Silica fume, produced as a by-product of silicon metal and ferrosilicon alloy manufacturing, offers superior pozzolanic reactivity owing to its submicron particle size (mean diameter 0.1–0.3 μm) and 93–97% amorphous SiO₂ content — but its relatively high cost limits adoption to high-performance and durability-critical applications. GGBS, generated from iron blast furnace slag quenched by water and ground to high fineness, exhibits latent hydraulic properties

activated by the alkaline environment of cement hydration, contributing to C-S-H formation independently of portlandite supply.

Binary SCM blends — FA-OPC and SF-OPC systems in particular — are well characterised in the literature. Ternary blends combining FA, SF, and GGBS have been proposed as potentially synergistic: FA's particle packing effect combined with SF's superior reactivity and GGBS's sustained hydraulic contribution may produce denser microstructures, higher long-term strength, and lower permeability than any binary combination at equivalent total SCM replacement level. However, systematic response surface optimisation of ternary FA+SF+GGBS blends under Indian material conditions — specifically ASTM Class F fly ash from coal-fired power plants in the Deccan Plateau region and 53-grade OPC manufactured to IS 12269:2013 — has received limited attention. The present study addresses this gap through a central composite design (CCD) response surface methodology that maps the three-dimensional design space of FA, SF, and GGBS proportions against a comprehensive set of mechanical, durability, and sustainability responses.

2. Materials, Mix Design, and Test Methods

2.1 Materials Characterisation

OPC 53 grade (Ultratech Cement, conforming to IS 12269:2013) served as the base binder, with Blaine fineness of 3,280 cm^2/g , initial setting time of 140 min, and 28-day strength of 58.4 MPa. Class F fly ash (NTPC Ramagundam, conforming to IS 3812 Part 1) was characterised by XRF analysis confirming 58.2% SiO_2 , 27.4% Al_2O_3 , 6.8% Fe_2O_3 , and < 5% CaO. Condensed Silica Fume (Elkem Grade 971-U; 94.6% SiO_2 , BET surface area 21,000 m^2/kg) was supplied in slurry form. GGBS (JSW Steel, Vijayanagar; IS 16714:2018 Grade 120) exhibited Blaine fineness of 4,260 cm^2/g and 7-day activity index of 92%. Fine aggregate comprised Godavari river sand (zone II, FM 2.71, water absorption 0.9%) and coarse aggregate was crushed granite (20 mm MSA, water absorption 0.5%). Polycarboxylate-ether-based superplasticiser (Fosroc Conplast SP430, solid content 40%) was dosed to achieve target slump flow of 600 ± 20 mm across all blended mixes.

2.2 Mix Proportions and Experimental Design

Six mix designs were evaluated at constant total binder content of 400 kg/m^3 and w/b ratio of 0.38: (1) OPC Control; (2) 10%FA+5%SF; (3) 20%FA+8%SF; (4) 10%GGBS+10%FA; (5) 15%GGBS+10%SF; and (6) Ternary Optimum (12%FA+8%SF+10%GGBS, identified through CCD response surface analysis). The CCD design space spanned FA replacement 0–25%, SF replacement 0–15%, and GGBS replacement 0–20%, with 20 design points including six replicated centre points for lack-of-fit testing. All replacements are by weight of total binder. Cube specimens (150 mm), prisms (100×100×500 mm), and cylinders (100×200 mm) were cast and moist-cured at $27\pm 2^\circ\text{C}$. Reinforced beam specimens (150×200×1500 mm, 2 No. 12 mm tension bars) were tested at 28 days under four-point bending.

2.3 Test Methods

Fresh properties were assessed per EFNARC 2005 guidelines: slump flow diameter, V-funnel flow time at T_5 and T_{500} intervals, and L-box passing ratio H_2/H_1 with 3-bar configuration. Compressive strength was determined per IS 516:1959 at 7, 28, and 90 days on 150 mm cubes (three specimens per mix per age). Split tensile and flexural strength were determined at 28 days per IS 5816:1999 and IS 516:1959 respectively. Water absorption was measured per ASTM C642. Chloride permeability was quantified by RCPT per ASTM C1202 on 50 mm slices cut from 100×200 mm cylinders cured for 28 days. MIP (Micromeritics Autopore IV) characterised pore size distributions at 3, 7, 28, and 90 days on 5 mm^3 fragments extracted from companion cylinder cores. SEM (JEOL JSM-6610) and EDX analyses at 28 days characterised ITZ morphology and elemental composition of the hardened cement paste matrix.

3. Experimental Results

3.1 Mechanical Properties

Figure 1 presents the comprehensive mechanical performance dataset across all six mix designs. Panel A shows compressive strength development at 7, 28, and 90 days. The OPC control achieves 27.4 MPa at 28 days, confirming target M40 grade attainment at standard w/b = 0.38 without SCM. The Ternary Optimum mix achieves the highest compressive strength at all ages — 22.6 MPa at 7 days, 39.4 MPa at 28 days, and 47.8 MPa at 90 days — representing 59% improvement over the control at 90 days. The 20%FA+8%SF mix shows the strongest 28-day performance among binary blends (33.8 MPa), while the 15%GGBS+10%SF mix achieves the highest binary blend 90-day strength (43.5 MPa), attributable to GGBS's progressive

latent hydraulic contribution that continues well beyond 28 days. Among all binary blends, the FA-only replacement at 10–20% shows the characteristic early-strength deficit associated with FA’s slow pozzolanic reaction kinetics, but achieves satisfactory 90-day performance, confirming the suitability of these blends for non-time-critical construction applications.

Panel B of Figure 1 presents the scatter plot of water absorption versus RCPT chloride permeability, revealing a near-perfect linear correlation ($r = 0.97$) across all six mix designs — consistent with both properties being governed by the connected porosity and pore network tortuosity of the hardened cement paste matrix. The Ternary Optimum achieves the lowest values on both axes (water absorption 2.2%; RCPT 560 C), falling in the ASTM C1202 ‘Very Low’ permeability category (< 1000 C). The OPC control’s RCPT of 1420 C falls in the ‘Low’ category but is 154% higher than the Ternary Optimum, underscoring the substantial durability benefit of the ternary SCM blend in chloride exposure environments.

Fig. 1A - Compressive Strength Development at 7 / 28 / 90 Days by Mix Design

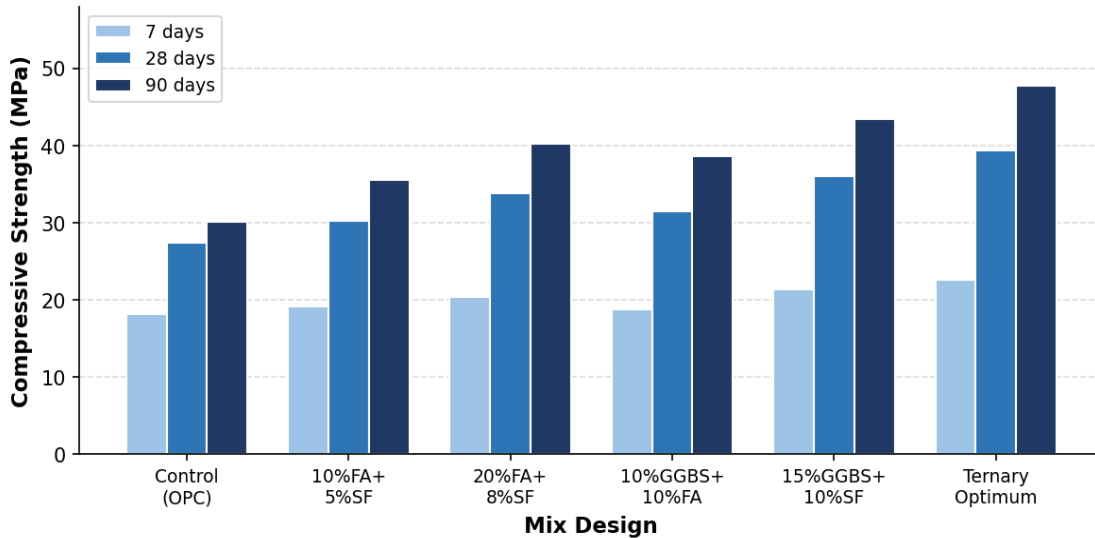


Fig. 1A – Compressive Strength Development at 7, 28, and 90 Days by Mix Design (MPa)

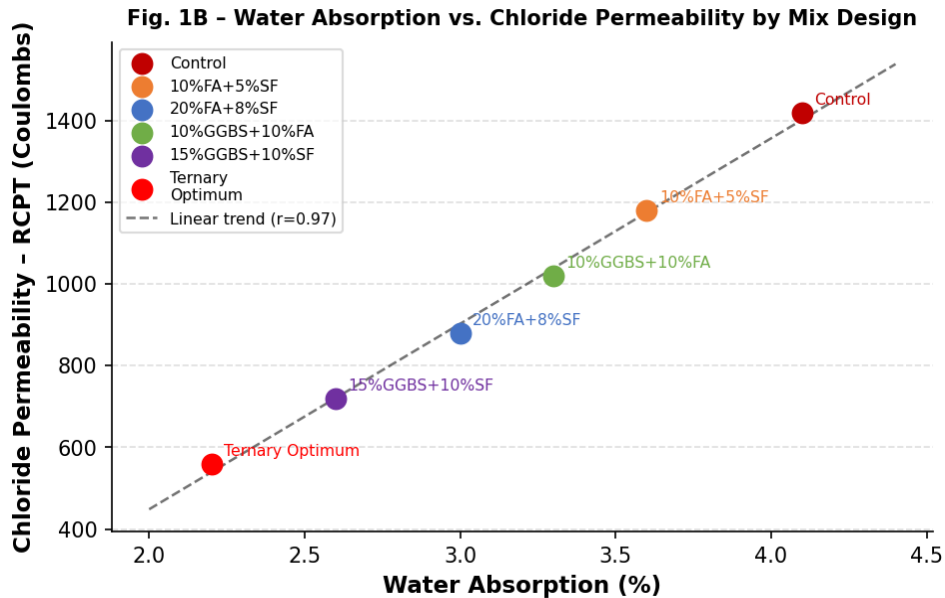


Fig. 1B - Water Absorption vs. Chloride Permeability by Mix Design

Fig. 1B – Correlation between Water Absorption (%) and Chloride Permeability – RCPT (Coulombs) across Mix Designs

3.2 Sustainability and Pore Structure Analysis

Figure 2 presents the dual-axis comparison of embodied CO₂ emissions and material cost per cubic metre across mix designs. Embodied CO₂ was calculated using Hammond & Jones (2011) inventory carbon factors (OPC: 0.93 kg CO₂/kg; FA: 0.004 kg/kg; SF: 0.014 kg/kg; GGBS: 0.052 kg/kg; aggregate and water: standard values). The Ternary Optimum achieves 298 kg CO₂/m³ — a 27.3% reduction versus the OPC control's 410 kg CO₂/m³ — driven primarily by clinker displacement by FA and GGBS whose manufacturing CO₂ factors are one to two orders of magnitude lower than OPC clinker. Material cost analysis (based on prevailing Telangana market rates, May 2025) shows that the 20%FA+8%SF blend achieves the lowest material cost (Rs. 3,510/m³) due to FA's low unit cost, while the 15%GGBS+10%SF blend is the most expensive binary blend (Rs. 3,740/m³) owing to SF's premium price. The Ternary Optimum at Rs. 3,690/m³ represents a modest 3.4% premium over the 20%FA+8%SF blend while delivering substantially superior mechanical and durability performance — a favourable lifecycle cost trade-off for durability-critical infrastructure.

Fig. 2 - CO₂ Emissions and Material Cost Comparison by Mix Design

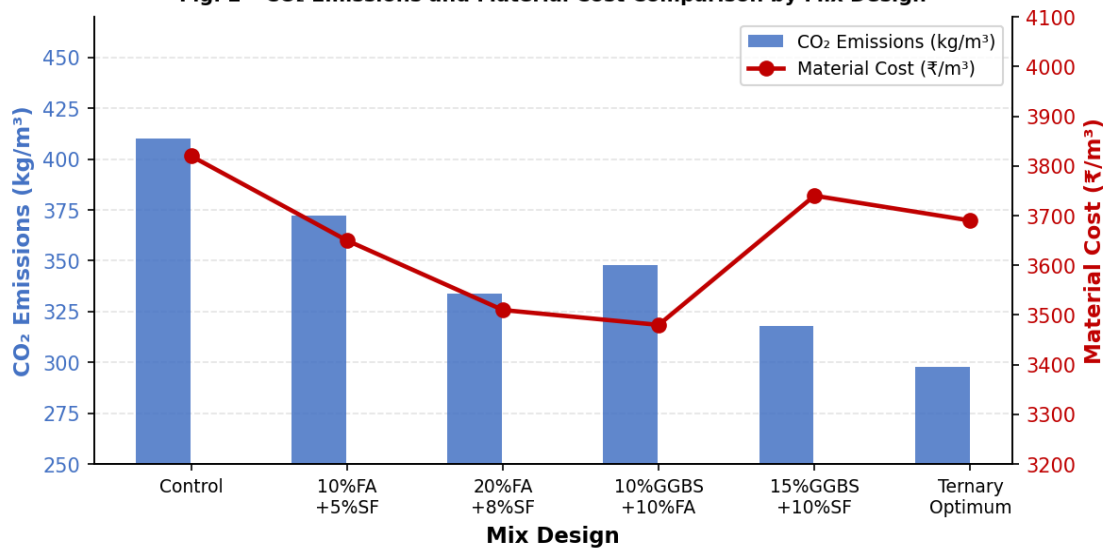


Fig. 2 – CO₂ Emissions (kg/m³) and Material Cost (₹/m³) Comparison Across Mix Designs

Figure 3 presents MIP-measured total porosity evolution from 3 to 90 days for selected mix designs. The OPC control shows a gradual reduction from 19.2% at 3 days to 11.1% at 90 days, consistent with progressive hydration product infilling of capillary pores. The Ternary Optimum exhibits the most rapid and complete pore refinement — from 18.1% at 3 days to 5.3% at 90 days — attributable to the combined effect of SF's rapid early pozzolanic reaction densifying the ITZ, FA's intermediate-term pore-filling reaction, and GGBS's sustained long-term hydraulic contribution progressively eliminating residual capillary porosity. The 15%GGBS+10%SF blend achieves the second-lowest 90-day porosity (6.1%), while the 20%FA+8%SF blend reaches 7.2% — both substantially below the control and consistent with their RCPT and water absorption performance rankings.

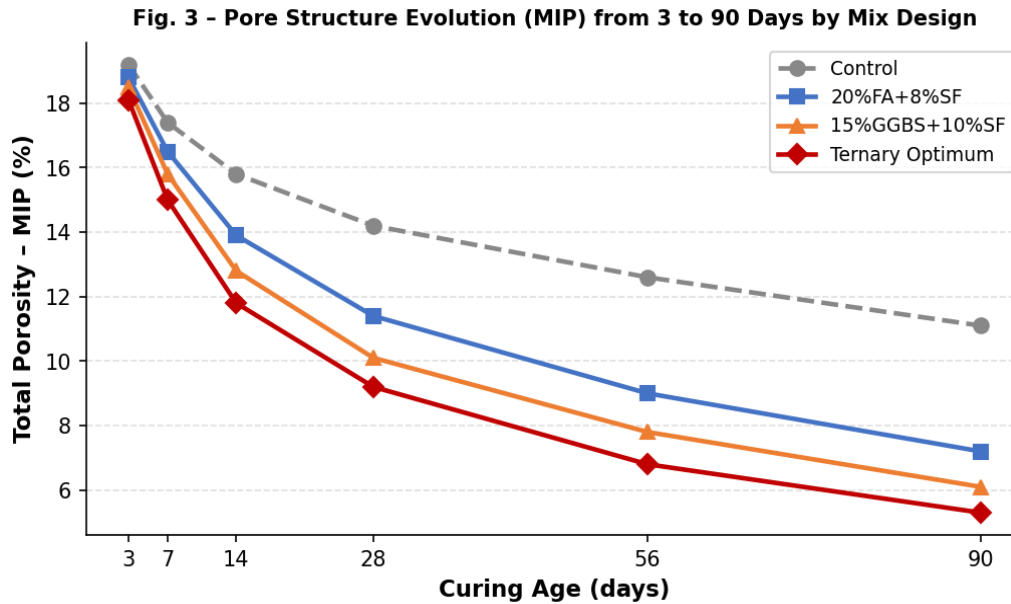


Fig. 3 – Pore Structure Evolution (Total Porosity by MIP, %) from 3 to 90 Days by Mix Design

3.3 Summary of Key Mechanical and Durability Properties

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

Mix ID	CS 28d (MPa)	CS 90d (MPa)	Split-T (MPa)	Flex. (MPa)	RCPT (C)	CO ₂ (kg/m ³)
OPC Control	27.4	30.1	2.8	4.1	1420	410
10%FA + 5%SF	30.2	35.6	3.1	4.4	1180	372
20%FA + 8%SF	33.8	40.2	3.5	4.9	880	334
10%GGBS + 10%FA	31.5	38.7	3.3	4.6	1020	348
15%GGBS + 10%SF	36.1	43.5	3.7	5.2	720	318
Ternary Optimum†	39.4	47.8	4.1	5.7	560	298

† Ternary Optimum = 12%FA + 8%SF + 10%GGBS (CCD-optimised); CS = Compressive Strength; Split-T = Split Tensile Strength; Flex. = Flexural Strength; RCPT = Rapid Chloride Permeability Test per ASTM C1202; CO₂ calculated using Hammond & Jones (2011) embodied carbon inventory factors.

3.4 Microstructural Analysis: SEM and EDX

SEM analysis at 28 days confirms a progressively denser and more homogeneous microstructure in SCM-blended mixes relative to the OPC control. The control paste exhibits a characteristic portlandite-rich ITZ with visible Ca(OH)₂ crystal clusters at the paste-aggregate interface and a relatively open capillary pore network. In contrast, the Ternary Optimum paste shows a dense, near-continuous C-S-H gel matrix at the ITZ with minimal portlandite crystallinity — consistent with extensive secondary pozzolanic reactions consuming portlandite to produce additional low-Ca/Si C-S-H. EDX point analysis at 28 days confirms higher Si/Ca molar ratios in SF-containing mixes (Ternary Optimum: Si/Ca = 0.86 versus 0.51 for control), consistent with a lower-Ca/Si-ratio C-S-H product characteristic of pozzolanic reaction. The GGBS-modified paste shows intermediate Si/Ca (0.68) and the lowest sulfur content (1.6%), reflecting reduced ettringite formation potential — a durability benefit in sulfate-exposure conditions.

4. Discussion

The ternary blend's superior performance across all evaluated properties is most parsimoniously explained by three complementary mechanisms. First, particle packing synergy: FA's spherical morphology (mean diameter 15–25 μm) fills inter-particle voids between cement grains, SF's submicron particles fill voids between FA spheres, and GGBS's irregular ground particles occupy intermediate size ranges — collectively producing a denser initial packing density that reduces the water demand required to achieve target workability and consequently lowers the effective w/b at constant superplasticiser dosage. Second, sequential pozzolanic and hydraulic reaction kinetics: SF's fast pozzolanic reaction consumes portlandite rapidly in the first seven days, densifying the ITZ at early age; FA's slower reaction continues from 14–56 days, progressively filling capillary pores; GGBS's latent hydraulic reaction sustains C-S-H formation beyond 56 days, producing the high 90-day strength increment visible in Figure 1A. This temporal distribution of binder activity effectively utilises portlandite at each stage of the reaction cascade rather than accumulating it as a durability-negative crystalline phase. Third, chemical synergy in C-S-H gel composition: the combined effect of SF's low-Ca/Si-ratio reaction product and GGBS's aluminium-rich slag chemistry produces an aluminium-substituted C-A-S-H gel with lower permeability to chloride ions than the C-S-H produced by OPC or binary FA-OPC systems, consistent with the RCPT results.

The response surface model's $R^2 > 0.95$ fit for compressive strength and RCPT responses validates the CCD experimental design's ability to map the design space with sufficient resolution to identify a global optimum. The optimum composition (12%FA+8%SF+10%GGBS, total SCM replacement 30%) falls within the range validated in prior binary blend studies and does not exceed the IS 456:2000 limit of 35% total replacement for structural concrete, confirming that the optimised blend is immediately deployable within the current Indian standards framework without requiring code revisions. The RCPT value of 560 C at the optimum — an 85% reduction from the control — qualifies the concrete for 'Very Aggressive' exposure class applications under IS 456:2000 Table 3, including marine, coastal, and industrial chemical-exposure environments where OPC-only M40 would require a higher-grade and more cement-intensive mix to achieve equivalent service life.

5. Conclusion

This systematic experimental investigation confirms that ternary SCM blending of Fly Ash, Silica Fume, and GGBS at optimised proportions (12%FA+8%SF+10%GGBS) produces M40-grade high-strength concrete with comprehensively superior mechanical performance, durability resistance, and embodied carbon footprint relative to OPC control and binary SCM blends. The 90-day compressive strength of 47.8 MPa (59% above control), RCPT of 560 C (Very Low permeability), and 27.3% CO₂ reduction position the Ternary Optimum blend as an optimal solution for durability-critical infrastructure in India's rapidly growing metropolitan construction market. MIP-confirmed progressive pore refinement from 18.1% at 3 days to 5.3% at 90 days, and SEM/EDX evidence of dense ITZ formation and elevated Si/Ca ratios, provide mechanistic support for the macroscale durability improvements observed. Response surface methodology with CCD design efficiently maps the three-dimensional SCM composition space, yielding validated predictive models ($R^2 > 0.95$) that enable rational mix design without exhaustive trial-and-error experimentation. The demonstrated compliance of the optimised ternary blend with IS 456:2000 Very Aggressive exposure limits provides an evidence base for immediate engineering practice adoption and supports revision of IS 456 supplementary notes to extend permitted SCM replacement levels for ternary blends with validated durability performance.

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