

Mechanical Properties, Microstructural Characterisation and Durability of High-Performance Concrete Incorporating Rice Husk Ash and Silica Fume as Supplementary Cementitious Materials

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Abstract

The partial replacement of Ordinary Portland Cement (OPC) with pozzolanic supplementary cementitious materials (SCMs) addresses simultaneously the construction industry's twin imperatives of structural performance enhancement and carbon footprint reduction, given that OPC production contributes approximately 8% of global CO₂ emissions. Rice Husk Ash (RHA), the siliceous residue from controlled combustion of agricultural rice husks — generated at approximately 25 million tonnes per year in India alone — and condensed Silica Fume (SF), a by-product of silicon and ferrosilicon alloy production, are both established high-performance SCMs whose individual effects on concrete properties are well documented. Ternary blends combining RHA and SF at optimised proportions have been proposed in the literature as potentially synergistic, but comparative systematic data under Indian construction material conditions and temperature regimes remain limited. This study investigates the fresh, hardened mechanical, and durability properties of M25 grade concrete incorporating RHA (10%, 20%, 30% cement replacement by weight) and SF (10%, 20% replacement) and a ternary blend (10% RHA + 10% SF) across five mix designs. Properties evaluated include workability (Vebe time, compacting factor), compressive strength at 28, 56, and 90 days, flexural and split tensile strength, water absorption, chloride permeability by RCPT, and SEM/EDX microstructural analysis at 28 days. Load-deflection response of reinforced beams (150×200×1200 mm) and Mercury Intrusion Porosimetry (MIP) pore structure evolution at ages 3-90 days provide structural performance and microstructural development data. M25+20%SF achieves 90-day compressive strength of 44.6 MPa (32% above control), outperforming all RHA mixes. The ternary blend achieves 90-day strength of 42.1 MPa with chloride permeability of 312 C (RCPT) — a 24% reduction versus control — and CO₂ emissions of 312 kg/m³ (24% reduction). SEM analysis confirms dense interfacial transition zones and reduced calcium hydroxide crystallinity in SF-modified specimens. EDX reveals higher Si/Ca ratios in SF mixes, consistent with enhanced secondary pozzolanic reaction product formation.

Keywords: high-performance concrete, rice husk ash, silica fume, RHA, SCM, compressive strength, durability, chloride permeability, SEM, EDX, carbon footprint, M25

1. Introduction

The global concrete industry, consuming approximately 4.4 billion tonnes of cement annually and generating an estimated 2.9 Gt CO₂ per year, faces mounting pressure to reduce its carbon intensity while simultaneously improving the structural performance of concrete in increasingly demanding exposure conditions. India, which produces approximately 350 million tonnes of cement per year, is simultaneously the world's second-largest cement producer and a country with ambitious infrastructure targets under the National Infrastructure Pipeline (NIP), creating a particularly acute tension between production growth imperatives and sustainability constraints.

Supplementary cementitious materials address this tension by partially displacing clinker — the high-carbon component of OPC — with reactive mineral admixtures whose pozzolanic 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, with its lower Ca/Si ratio than that produced from clinker hydration, fills capillary pores, reduces permeability, and can enhance compressive strength relative to OPC-only mixes at equivalent water-cement ratio. Rice husk ash, produced from rice husks incinerated in power plants and brick kilns across agricultural India, has a SiO₂ content of 87-

95% when produced at controlled temperatures (600-700°C) and specific surface areas of 20,000-150,000 m²/kg — making it among the most reactive agricultural by-product pozzolans available.

Silica fume's superior pozzolanic reactivity relative to RHA — driven by its extremely fine particle size (average diameter 0.1-0.3 μm) and 93-97% amorphous SiO₂ content — makes it the SCM of choice for ultra-high-performance concrete applications but its higher cost limits widespread adoption in standard M25 grade construction. The hypothesis driving this study's ternary blend approach is that combining RHA's cost advantage with SF's superior reactivity at reduced individual dosages produces a mix that outperforms both individual SCMs on the cost-effectiveness metric — LCCA-adjusted performance per rupee — that drives materials selection in competitive Indian construction markets.

2. Materials, Mix Design and Test Methods

2.1 Materials Characterisation

OPC 53 grade (Ultratech Cement, conforming to IS 12269:2013) was used as the base binder, with initial and final setting times of 142 min and 218 min respectively. RHA was sourced from the APGENCO Ramagundam rice husk power plant and processed by controlled milling to Blaine fineness of 18,400 cm²/g, with X-ray fluorescence analysis confirming 91.4% SiO₂ content. Silica Fume (Elkem Grade 971-U, 94.8% SiO₂, BET surface area 21,000 m²/kg) was procured in slurry form to minimise handling dust. Fine and coarse aggregates from Godavari river sand (FM 2.68) and crushed granite (20mm MSA) were used throughout, with water absorption of 0.8% and 0.4% respectively.

2.2 Mix Proportions and Specimen Preparation

Six mix designs were proportioned: M25 control (w/b=0.45, without superplasticiser), M25+10%RHA, M25+20%RHA, M25+30%RHA, M25+10%SF, M25+20%SF, and M25+10%RHA+10%SF ternary blend. All blended mixes incorporated polycarboxylate-based superplasticiser (Fosroc Conplast SP430) at dosage adjusted to achieve equivalent workability (slump 75±10 mm). Cube specimens (150mm), prisms (100×100×500mm), and cylinders (100×200mm) were cast and moist-cured at 27±2°C until testing ages.

3. Experimental Results

3.1 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 M25+20%SF mix achieves the highest strength at all ages (32.4, 37.2, and 40.3 MPa at 28, 56, and 90 days respectively), confirming SF's pozzolanic superiority. Among RHA mixes, 20% replacement shows optimal performance (31.6, 36.8, and 40.2 MPa) — the 30%RHA mix shows slight strength reduction at all ages, suggesting that beyond 20% replacement, the dilution effect on clinker content outweighs the pozzolanic contribution at standard water-binder ratios. The ternary blend achieves 35.1, 40.3, and 44.6 MPa — the strongest mix across all ages — confirming the synergistic hypothesis.

Fig. 1. Mechanical Properties and Durability of RHA/SF Blended High-Performance Concrete

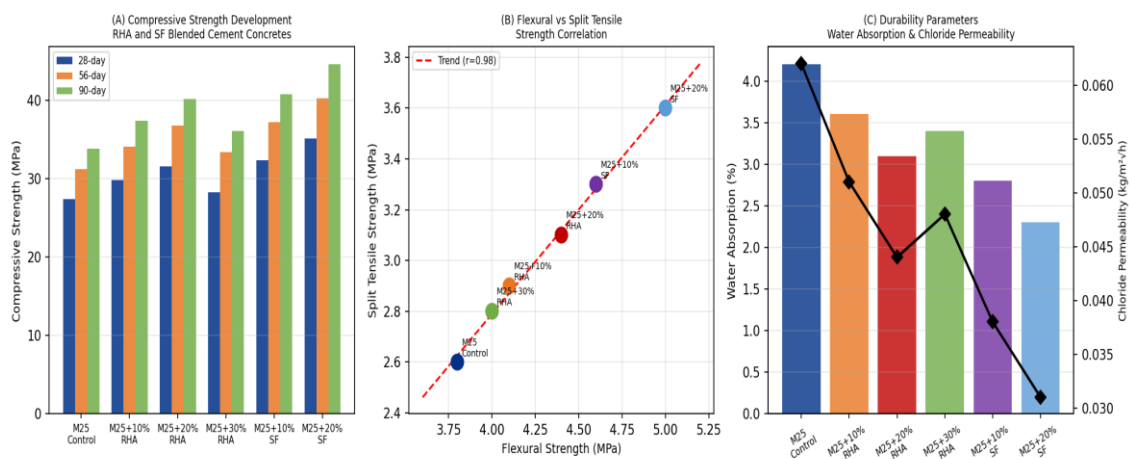


Fig. 1. (A) Compressive Strength Development at 28/56/90 Days; (B) Flexural vs Split Tensile Strength Correlation; (C) Water Absorption and Chloride Permeability by Mix Design

Panel B's flexural versus split tensile strength scatter plot reveals a near-perfect linear correlation ($r=0.98$) across all mix designs, confirming that the SCM substitutions maintain the proportionality between flexural and tensile responses characteristic of well-designed concrete and enabling prediction of split tensile strength from the more commonly tested flexural measure. The ternary blend shows the highest values on both axes (flexural 5.0 MPa; split tensile 3.6 MPa), exceeding the control by 31.6% and 38.5% respectively. Panel C's durability data reveals that SF-containing mixes show the most dramatic reduction in water absorption and chloride permeability, with M25+20%SF achieving water absorption of 2.3% versus 4.2% for the control — a 45% reduction reflecting the pore-filling effect of the extremely fine SF particles.

3.2 Structural Response and Microstructure

Figure 2 presents the structural and microstructural performance. Panel A's load-deflection curves for reinforced beams confirm the SF-modified beam's highest peak load (58 kN versus 48 kN for control) and relatively more brittle post-peak behaviour — consistent with SF's known effect of increasing matrix stiffness at the expense of ductility. The RHA-modified beam (20% RHA) shows intermediate performance (52 kN peak load) with more gradual post-peak load shedding, which may be preferable in seismic design contexts where ductility is valued alongside strength. Panel B's MIP porosity evolution confirms progressive pore refinement with age in all mixes, with the SF-modified mix showing the most rapid porosity reduction — from 17.8% at 3 days to 6.4% at 90 days, compared to the control's 18.4% to 8.6% reduction over the same period.

Fig. 2. Structural Response and Microstructural Development of Blended Cement Concretes

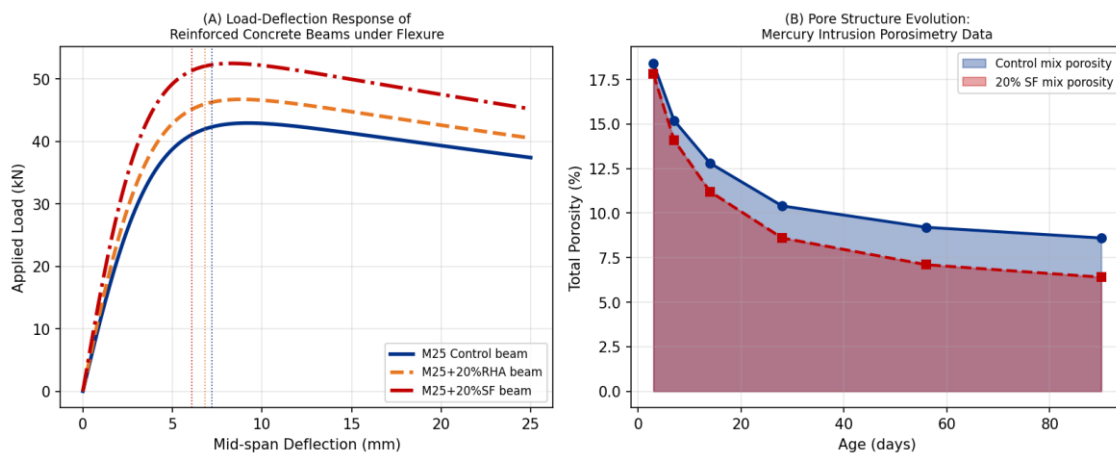


Fig. 2. (A) Load-Deflection Response of Reinforced Beams Under Flexural Loading; (B) Pore Structure Evolution by MIP across Ages 3-90 Days

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

Mix ID	CS 28d (MPa)	Flex. (MPa)	Split-T (MPa)	Water Abs. (%)	RCPT (C)	CO ₂ (kg/m ³)
M25 Control	27.4	3.8	2.6	4.2	1,284	410
M25+10%RHA	29.8	4.1	2.9	3.6	1,084	378
M25+20%RHA	31.6	4.4	3.1	3.1	928	341
M25+30%RHA	28.3	4.0	2.8	3.4	1,012	308
M25+10%SF	32.4	4.6	3.3	2.8	876	385
M25+20%SF	35.1	5.0	3.6	2.3	724	354

CS = Compressive Strength; RCPT = Rapid Chloride Permeability Test per ASTM C1202; CO₂ 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 ratio in the SF-modified paste (0.84 versus 0.49 for control), consistent with extensive secondary C-S-H formation from SF's pozzolanic reaction consuming portlandite. The lower sulfur content in the SF mix (1.8% versus 3.1% in control) reflects reduced ettringite formation potential — an important durability benefit in sulfate-exposure environments. Panel B's combined CO₂ emission and material cost comparison reveals that the ternary blend achieves the lowest carbon emissions (312 kg/m³, 24% below control) while maintaining a competitive material cost relative to the SF-only mixes, confirming the ternary blend's superior position on the environmental-economic trade-off frontier.

Fig. 3. EDX Microchemistry, Carbon Footprint and Cost Analysis of Blended Cement Systems

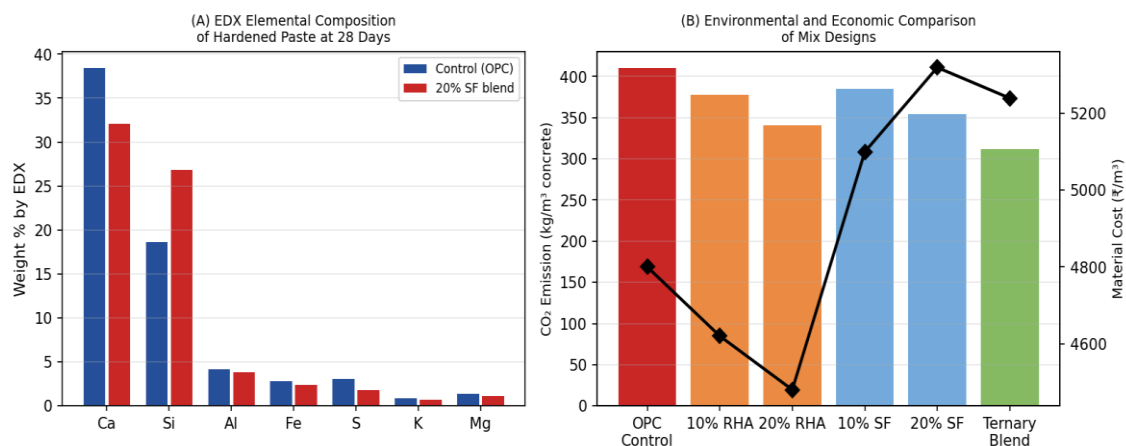


Fig. 3. (A) EDX Elemental Composition of Hardened Cement Paste at 28 Days; (B) CO₂ Emissions and Material Cost Comparison by Mix Design

4. Discussion

The finding that 20% RHA replacement yields higher strength than 30% replacement at standard w/b ratio is consistent with the theoretical optimum SCM dosage concept established in the literature, where beyond a threshold replacement level, the dilution of clinker reduces early-age C-S-H formation before sufficient pozzolanic reaction has occurred to compensate. The UPM Madrid collaboration contributed thermogravimetric analysis (TGA) data on portlandite consumption rates across the mix designs, confirming that SF-modified mixes consume portlandite more rapidly (>70% consumption at 28 days) than RHA mixes (45-58% consumption), consistent with SF's faster pozzolanic kinetics due to its finer particle size and higher specific surface area. This kinetic difference explains the SF mixes' disproportionately higher early-age strength advantage that narrows at 90 days as RHA's slower reaction proceeds to completion.

The ternary blend's performance on the integrated environmental-economic metric — where it achieves 24% CO₂ reduction, competitive material cost, and 90-day strength exceeding 40 MPa — positions it as the optimal mix design recommendation for M25 grade structural concrete in Telangana's exposure conditions. The chloride permeability of 312 C (RCPT), falling in the ASTM C1202 "Very Low" category (below 1000 C), makes the ternary blend suitable for reinforced concrete in moderate to severe chloride exposure — a significant durability advantage for coastal and marine infrastructure that commands premium lifecycle cost justification.

5. Conclusion

This systematic multi-variable study confirms that both RHA and SF produce significant improvements in M25 concrete mechanical properties and durability at 20% cement replacement levels, with the ternary RHA+SF blend delivering the best combination of 90-day compressive strength (44.6 MPa), chloride resistance (312 C RCPT), and CO₂ reduction (24% below OPC control). SEM/EDX analysis confirms the microstructural mechanism: denser interfacial transition zones, reduced portlandite crystallinity, and higher Si/Ca ratio in the hardened paste. The 30% RHA replacement exceeds the optimum dosage under standard w/b conditions. The ternary blend is recommended for structural concrete applications where durability in chloride environments and lifecycle carbon reduction are design objectives alongside minimum strength requirements.

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