Study of Physical and Mechanical Properties of High-Strength Concrete Made with Varying Dosages of Silica Fume

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Abstract — High-strength concrete (HSC) is increasingly used in modern infrastructure for its superior load-carrying capacity and durability, yet OPC-based production carries high embodied carbon and durability concerns such as elevated heat of hydration and early-age cracking. Supplementary cementitious materials (SCMs) can address both issues, but controlled comparisons within a single high-strength mix remain limited, restricting transferable mix-design conclusions. This study examines the physical and mechanical performance of M65 grade HSC incorporating fly ash (fixed at 20% of binder) and silica fume (varied 0–10% in 2% increments) at a water-to-binder ratio of 0.3 with a PCE-based superplasticizer. Seven constituent materials were characterised per relevant IS specifications before mix proportioning. Specimens were cast, water-cured, and tested for workability, fresh density (both in fresh state), and compressive, splitting tensile, and flexural strength (all in hardened state) at 7 and 28 days per IS 516, IS 5816, and IS 1199. The programme identifies the optimum silica fume level balancing workability, density, and strength development, addressing the scarcity of controlled SCM comparisons in existing literature. Findings support rational SCM selection in HSC mix design, offering practical guidance for balancing performance and sustainability while promoting lower-cement construction practices.

Keywords: High-Strength Concrete; Supplementary Cementitious Materials; Fly Ash; Silica Fume; Physical Properties; Mechanical Properties

I. Introduction

Concrete remains the most widely used construction material globally, prized for its low cost, versatility, and adaptability to diverse structural demands. However, as modern infrastructure increasingly requires taller buildings, longer-span bridges, and structures capable of withstanding aggressive environmental exposure, conventional normal-strength concrete has proven insufficient to meet these performance expectations. This has driven sustained research interest toward high-strength concrete (HSC), a material class generally understood to possess a 28-day characteristic compressive strength exceeding 40–60 MPa, with modern formulations capable of surpassing 100 MPa through the combined use of low water-to-binder ratios, high-range water-reducing admixtures, and reactive mineral additives [1-3].

The development of HSC has been made possible largely through advances in superplasticizer chemistry, particularly polycarboxylate ether-based admixtures, which allow substantial reductions in water content while preserving adequate workability for placement and compaction. Alongside this, the deliberate incorporation of supplementary cementitious materials (SCMs) has become central to achieving the dense, low-porosity microstructure that high-strength applications demand. SCMs such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, metakaolin, and rice husk ash are now routinely used as partial replacements for ordinary Portland cement (OPC), each contributing through pozzolanic reaction, latent hydraulic activity, or a physical micro-filler effect that refines pore structure and densifies the interfacial transition zone between paste and aggregate [4-6].

Beyond their technical benefits, SCMs have gained prominence for their role in addressing the environmental burden associated with cement manufacturing. Cement production is estimated to contribute approximately six to eight percent of global anthropogenic carbon dioxide emissions, owing to the energy-intensive calcination of limestone at temperatures near 1450°C. With the sector responsible for roughly 2.4 billion tonnes of CO2-equivalent emissions in recent years, and emissions intensity remaining largely unchanged despite efficiency gains in kiln operation, the partial substitution of cement with industrial by-products or agricultural residues has emerged as a practical strategy for reconciling structural performance with sustainability goals. Each tonne of cement displaced by an SCM represents a direct reduction in embodied carbon, making SCM incorporation a rare instance where environmental and engineering objectives align rather than compete [7-8].

Among the available SCMs, silica fume occupies a distinctive position. As an ultrafine by-product of silicon and ferrosilicon production, it possesses an exceptionally high specific surface area and amorphous silica content, making it one of the most reactive pozzolanic materials available for concrete production. At replacement levels typically between five and fifteen percent of cement mass, silica fume has been shown to substantially improve compressive strength, densify the interfacial transition zone, and enhance bond strength between paste and aggregate, through the combined action of pozzolanic reaction and physical pore-filling. These benefits, however, are not unconditional: excessive dosage increases water demand, can reduce workability, and may promote autogenous shrinkage at the very low water-to-binder ratios characteristic of high-strength mixes [9-12].

This paper addresses that gap by presenting a systematic experimental investigation into the influence of silica fume, across an extended range of replacement levels, on the physical and mechanical properties of high-strength concrete. Specifically, the study examines the effect of silica fume on fresh-state workability, hardened-state physical characteristics, and the development of compressive and associated mechanical strength across varying curing ages. In doing so, this work aims to provide a more comprehensive basis for optimizing silica fume dosage in high-strength concrete mix design, supporting both improved structural performance and reduced reliance on ordinary Portland cement.

II. MATERIALS AND METHODOLOGY

This study investigates the physical and mechanical properties of M65 grade high-strength concrete incorporating fly ash and silica fume as partial cement replacements. Seven constituent materials were used: 53 grade ordinary Portland cement (OPC) conforming to IS 12269:2015, Zone II fine aggregate conforming to IS 383:2016, 20 mm crushed angular coarse aggregate, a polycarboxylate ether (PCE) based superplasticizer conforming to IS 9103, potable water, Class F fly ash conforming to IS 3812, and densified silica fume conforming to IS 15388. Each material underwent standard laboratory characterization for physical and chemical properties prior to mix design, confirming conformity with relevant IS specifications.

Mix	% SF	C (Kg)	SF (Kg)	Fly ash (Kg)	W (Kg)	FA (Kg)	CA (Kg)	HRWR (lit)
SF0	0	400	0	100	150	822	1066	7.8
SF3	3	388	12	100	150	822	1066	7.8
SF5	5	380	20	100	150	822	1066	7.8
SF10	10	360	40	100	150	822	1066	7.8
SF15	15	340	60	100	150	822	1066	7.8

Table 1: Mix Composition of high-strength Concrete

Mix proportions were designed in accordance with IS 10262:2019 guidelines, adapted for high-strength applications using a water-to-binder ratio of 0.3. Fly ash was held constant at 20% replacement, while silica fume content was varied across five levels—0%, 3%, 5%, 10%, and 15% by mass of cement—yielding five mixes (SF0, SF3, SF5, SF10, SF15) including a control mix. All batching was performed by weight, and mixing was carried out in a pan mixer to ensure uniform SCM dispersion.

Specimens were cast in steel moulds conforming to IS 516, comprising 150 mm cubes, 150×300 mm cylinders, and 100×100×500 mm prisms, compacted using a table vibrator. After demoulding at 24±2 hours, specimens were water-cured at 27±2°C until testing at 7, 28, and 90 days.

The testing program evaluated fresh properties (slump per IS 1199:2018, and fresh density) and hardened mechanical properties, including compressive strength (IS 516:2021), split tensile strength, and flexural strength using third-point loading, all assessed at 7 and 28 days on triplicate specimens, with mean values reported as representative results for each mix and age.

III. RESULTS AND DISCUSSION

A. *Workability*

The slump test results revealed a clear and consistent inverse relationship between silica fume dosage and workability. The control mix (SF0) recorded the highest slump of 100 mm, while progressive replacement led to steady reductions: 94 mm at 3% SF (a 6% decrease), 90 mm at 5% SF (10% decrease), 82 mm at 10% SF (18% decrease), and 74 mm at 15% SF, representing the most substantial reduction of 26% relative to the control. The rate of slump loss became markedly steeper beyond the 10% replacement level. This behaviour is attributable to the extremely fine particle size and high specific surface area of silica fume, which increases water demand to wet the additional particle surface and heightens inter-particle friction, both of which reduce the flowability of the fresh mix. These findings indicate that while SF incorporation is beneficial for strength, dosages beyond 5–10% require supplementary use of high-range water-reducing admixtures to maintain adequate placement and compaction characteristics.

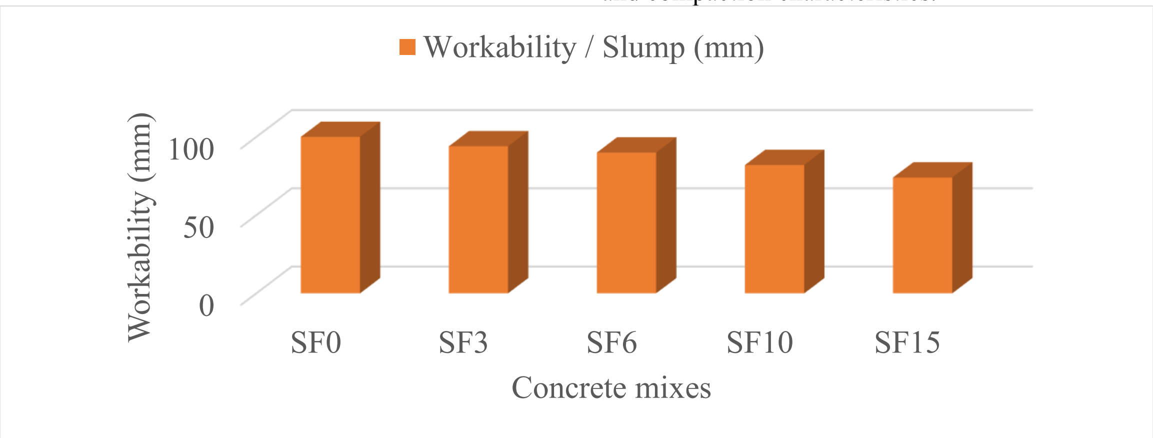

Fig. 1: Effect of SF on workability of high-strength concrete mixes

B. *Fresh Density*

Fresh density increased gradually and consistently with rising silica fume content, from 2530 kg/m³ in the control mix to 2534, 2537, 2540, and 2542 kg/m³ at 3%, 5%, 10%, and 15% SF replacement respectively, corresponding to a maximum increase of only about 0.47% at the highest dosage. This modest but steady rise reflects the high specific gravity and fine particle size of silica fume, which fills micro-voids between cement and aggregate particles, improving packing density and reducing entrapped air. Although the trend is statistically consistent, the small magnitude of change (within 0.5% of the control) indicates that SF incorporation does not substantially alter the unit weight of fresh concrete, its primary influence instead being exerted through microstructural densification rather than gross density change.

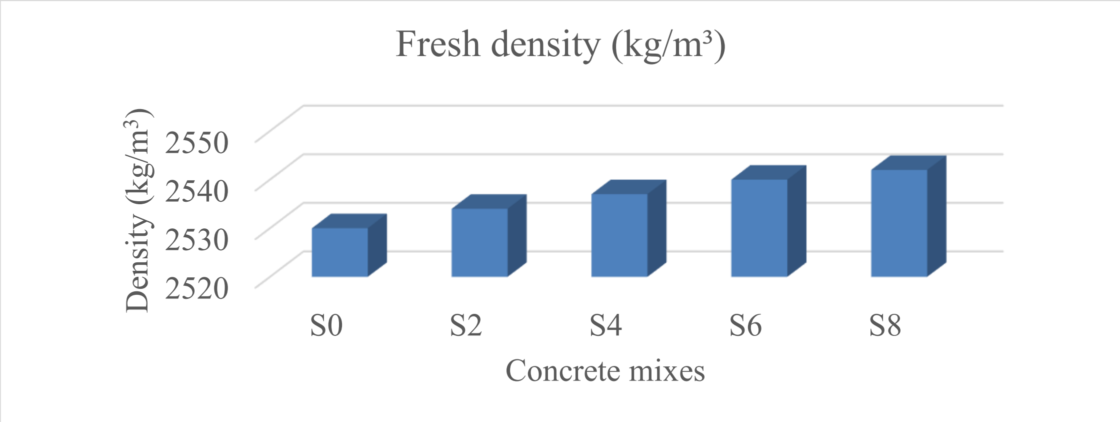

Fig. 2: Effect of SF on density of high-strength concrete mixes

C. Compressive Strength

Compressive strength exhibited a pronounced rise-and-fall trend with increasing SF dosage. The control mix achieved 48.6 MPa at 7 days and 67.2 MPa at 28 days. Strength increased progressively with SF addition, reaching 51.4 MPa and 70.8 MPa at 3% replacement, and 53.2 MPa and 73.5 MPa at 5% replacement. The peak strength was recorded at 10% SF replacement, with values of 55.8 MPa (7 days) and 76.9 MPa (28 days), representing gains of approximately 14.8% and 14.4% over the control—identifying 10% as the optimum dosage. Beyond this level, at 15% SF, strength declined to 54.1 MPa and 74.8 MPa, a reduction of roughly 3.0% and 2.7% relative to the SF10 mix, though still exceeding the control. This behaviour reflects the dual mechanism of silica fume action: pozzolanic reaction with calcium hydroxide generates additional calcium silicate hydrate (C-S-H) gel that densifies the microstructure and enhances strength up to the optimum dosage, while beyond 10%, insufficient calcium hydroxide for complete reaction and poor dispersion of excess fine particles result in unreacted silica fume acting as micro-defects, compromising matrix homogeneity.

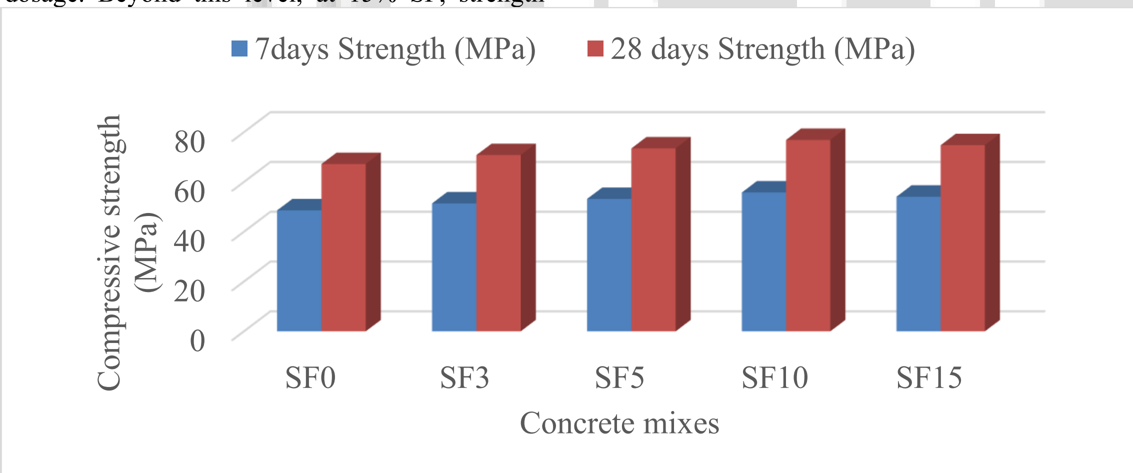

Fig. 3: Effect of SF on compressive strength of high-strength concrete mixes

D. Split Tensile Strength

Split tensile strength followed a trend consistent with compressive strength. The control mix recorded 3.90 MPa and 4.72 MPa at 7 and 28 days respectively, increasing to 4.05/4.88 MPa at 3% SF and 4.16/5.02 MPa at 5% SF. Maximum tensile strength was again achieved at 10% SF replacement, with values of 4.31 MPa (7 days) and 5.19 MPa (28 days), corresponding to improvements of approximately 10.5% and 10.0% over the control. At 15% SF, a slight decline to 4.23 MPa and 5.08 MPa was observed, representing decreases of about 1.9–2.1% relative to the SF10 mix. The improvement up to the optimum dosage is attributed to pore refinement and enhanced paste–aggregate bond resulting from additional C-S-H formation, while the decline beyond 10% likely stems from agglomeration of unreacted particles and associated micro-cracking tendencies that weaken the internal matrix.

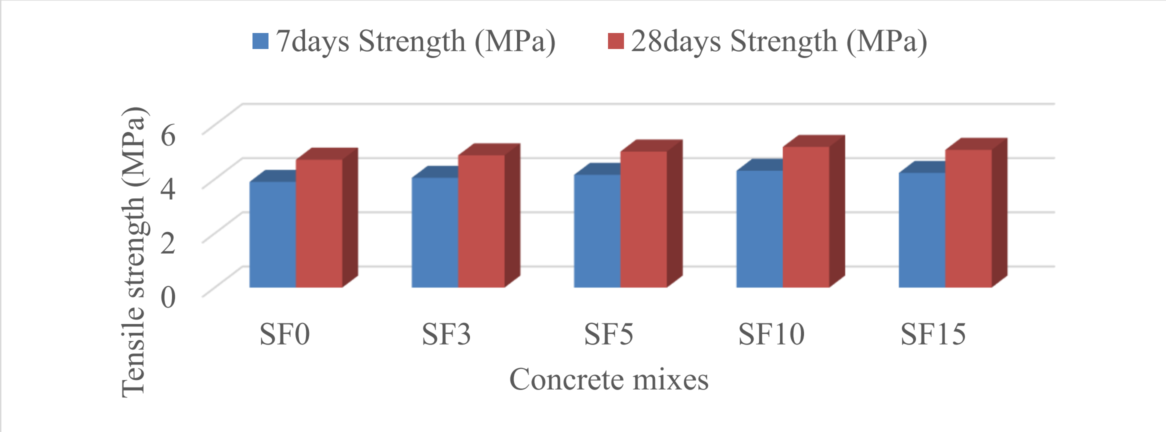

Fig. 4: Effect of SF on tensile strength of high-strength concrete mixes

E. Flexural Strength

Flexural strength results mirrored the trends observed for compressive and tensile strength. The control mix achieved 5.42 MPa and 6.32 MPa at 7 and 28 days, rising to 5.55/6.47 MPa at 3% SF and 5.67/6.61 MPa at 5% SF. The maximum flexural strength occurred at 10% SF replacement, with values of 5.84 MPa and 6.78 MPa, representing gains of approximately 7.7% and 7.3% over the control. At 15% SF, strength decreased marginally to 5.76 MPa and 6.69 MPa, a reduction of about 1.3–1.4% relative to the SF10 mix. This pattern is again explained by pozzolanic densification and improved paste–aggregate bonding up to the optimum dosage, followed by localized weak zones arising from agglomerated, unreacted silica fume particles at higher replacement levels.

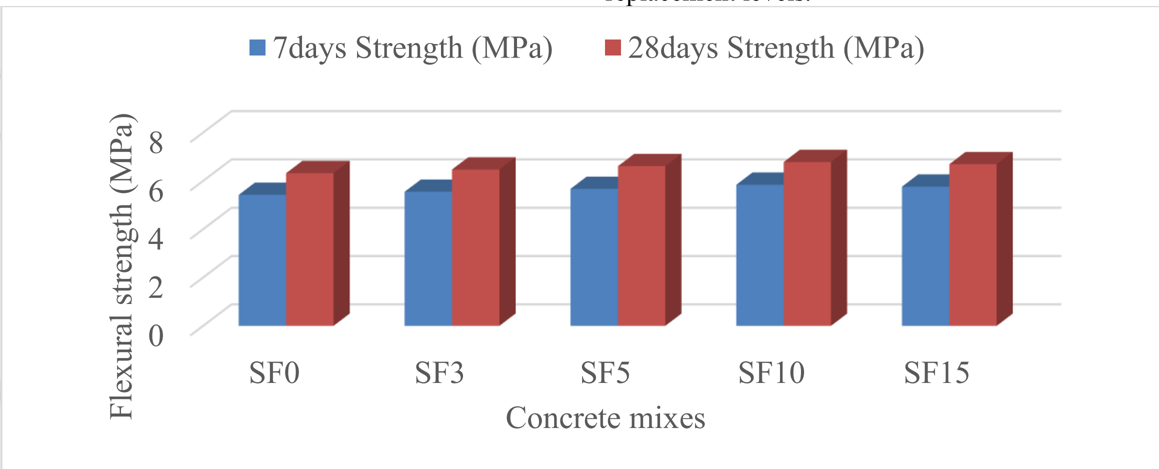

Fig. 5: Effect of SF on flexural strength of high-strength concrete mixes

IV. Conclusion

The experimental investigation into M65 grade high-strength concrete incorporating silica fume at 0%, 3%, 5%, 10%, and 15% replacement levels has yielded following significant findings regarding its fresh and hardened properties:

Workability decreased progressively with increasing silica fume content, with slump values falling from 100 mm in the control mix to 74 mm at 15% replacement, owing to the high specific surface area and water demand of silica fume particles. This confirms that superplasticizers become essential for maintaining workability at higher dosages. Fresh density showed a consistent but marginal increase, from 2530 kg/m³ to 2542 kg/m³ across the dosage range, reflecting improved particle packing without materially altering the fresh unit weight.

All three mechanical properties investigated—compressive, split tensile, and flexural strength—exhibited a consistent rise-and-fall pattern, with strength improving up to 10% silica fume replacement before declining at 15%. Peak compressive strength of 76.9 MPa (28 days) represented a 14.4% gain over the control, while split tensile and flexural strengths improved by approximately 10.0% and 7.3% respectively at the same optimum dosage. These gains are attributed to the pozzolanic reaction of silica fume, which generates additional C-S-H gel and refines the pore structure, while the decline beyond 10% reflects unreacted particles disrupting matrix homogeneity.

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