EFFECT OF REPLACEMENT OF FLY ASH WITH SILICA FUME IN MINERAL ADMIXTURE BASED SELF-COMPACTING CONCRETE

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ABSTRACT

The present study investigates the influence of partially replacing fly ash with silica fume in mineral admixture–based self-compacting concrete on its mechanical properties. Fly ash is widely used in concrete for its pozzolanic activity and sustainability benefits, while silica fume, with its ultra-fine particle size and high silica content, is known to enhance strength and impermeability. In this work, concrete mixes were prepared with a fixed total mineral admixture content, where varying proportions of fly ash were substituted with silica fume. Compressive strength, split tensile strength, and flexural strength tests were conducted at different curing ages. The results demonstrated that partial replacement of fly ash with silica fume significantly improved early-age strength. The study highlights the potential of an optimized fly ash–silica fume combination for producing high-performance and durable concrete while promoting the sustainable use of industrial by-products.

Key Words: Silica fume, fly ash, concrete, srength

1. INTRODUCTION

Concrete is the most widely used construction material across the world due to its versatility, strength, and durability [1,2]. However, the increasing demand for cement has raised environmental concerns, particularly because cement production is energy-intensive and contributes significantly to global carbon dioxide emissions [3,4]. As a result, the use of supplementary cementitious materials (SCMs) has become an important strategy for producing sustainable and high-performance concrete [5-7]. Among these SCMs, fly ash and silica fume have gained substantial attention due to their ability to enhance both the mechanical and durability properties of concrete while utilizing industrial by-products that would otherwise contribute to environmental pollution [8-10].

Fly ash is a fine, powdery material obtained as a by-product from coal-fired thermal power plants. Classified primarily into Class F and Class C based on its chemical composition, fly ash consists largely of silica, alumina, and unburned carbon [9,11]. When incorporated into concrete, fly ash participates in pozzolanic reactions with calcium hydroxide released during cement hydration, forming additional calcium silicate hydrate (C-S-H) gel [9]. This secondary C-S-H contributes to strength gain over time and improves workability, resistance to sulphate attack, and reduction of heat of hydration. However, its relatively slow reaction rate often results in lower early-age strength compared to ordinary Portland cement concrete.

Silica fume, on the other hand, is an ultrafine powder collected as a by-product during the production of silicon or ferrosilicon alloys in electric arc furnaces [8,10]. With particle sizes about 100 times smaller than those of cement grains and a silica content exceeding 85%, silica fume is highly reactive [12,13]. It has extremely fine particles that fill voids within the cement paste matrix, reducing its permeability and refining the microstructure. The pozzolanic reactivity of silica fume is much faster than that of fly ash, resulting in significant improvements in early-age strength, abrasion resistance, and chloride ion penetration resistance. However, excessive silica fume content may reduce workability and increase water demand, requiring careful mix design [14,15].

In modern concrete technology, combining different mineral admixtures can lead to a synergistic effect, balancing the advantages and limitations of each. By partially replacing fly ash with silica fume, it is possible to maintain the sustainability benefits of using industrial by-products while enhancing early-age performance and long-term durability. Such a combination can optimize pore structure, control micro-cracks, and improve resistance against aggressive environmental conditions. Therefore, studying the effect of replacing fly ash with silica fume in mineral admixture-based concrete is crucial for developing mixes that meet the dual objectives of environmental sustainability and structural performance.

2. MATERIALS USED

The primary binder in this study was Ordinary Portland Cement (OPC) conforming to IS: 8112 specifications. Fly ash, obtained from a local thermal power plant, was classified as low-calcium Class F, with a high silica and alumina content suitable for pozzolanic activity. Silica fume was sourced from Delhi, India. It consisted of ultrafine, amorphous silica particles. Natural river sand passing through a 4.75 mm sieve was used as fine aggregate, while crushed granite with a nominal size of 20 mm served as coarse aggregate. Properties are given in Table 1 and Table 2 respectively. Potable water free from impurities was used for mixing and curing to ensure consistent hydration and strength development.

Table 1: Physical properties of fine aggregates

Property	Result
Physical Appearance	Dull grey
Specific gravity	2.56
Fineness modulus	2.54
Water absorption (%)	1.97
Unit weight (kg/m3)	1527

Table 2: Physical properties of coarse aggregates

Property	Result
Physical Appearance	Sub-angular
Specific gravity	2.66
Fineness modulus	6.47
Water absorption (%)	1.43
Unit weight (kg/m3)	1698

3. MIXING AND CASTING

Concrete mixes were prepared with varying proportions of fly ash and silica fume while maintaining a constant total binder content as seen in Table 3. It can be seen in this table that fly ash was replaced with silica fume at 0%, 50% and 100% replacement levels. The weighed quantities of cement, mineral admixtures, fine aggregate, and coarse aggregate were first dry-mixed to ensure uniform distribution. Water was then added gradually, and the mixture was blended thoroughly using a mechanical mixer to achieve a homogeneous and workable consistency. Flow-ability properties were checked in order to meet specification of EFNARC .

Fresh concrete was placed into standard steel moulds for cube specimens (150 mm × 150 mm × 150 mm) to test compressive strength, cylindrical specimens (150 mm diameter × 300 mm height) for split tensile strength, and prism specimens (100 mm × 100 mm × 500 mm) for flexural strength. Compaction was not carried out as SCC inherently possesses self-compaction properties. After casting, the specimens were covered with wet burlap for 24 hours and subsequently cured in clean water at room temperature until the designated testing ages.

Table 3: Mix proportioning of various mixtures

Mix Designation	Cement (kg/m3)	Fly Ash (%)	W/B ratio	Coarse Aggregates (kg/m3)	Fine Aggregates (kg/m3)	Silica Fume (%)
M1 (Control)	400	20	0.40	635	955	0
M2	400	10	0.40	635	955	10
M3	400	0	0.40	635	955	20

4. TESTING METHODS

After curing, the specimens were taken out of the water tank, surface-dried, and tested for their respective properties at designated ages. Compressive strength was determined on cube specimens using a compression testing machine with a uniform loading rate until failure. The maximum load recorded was divided by the loaded area to obtain the compressive strength value. Split tensile strength was assessed on cylindrical specimens by applying a diametral compressive load. The load produced tensile stresses along the vertical diameter of the cylinder, and the failure load was used to calculate the tensile strength.

Flexural strength was evaluated on prism specimens using a two-point loading arrangement. The load was applied gradually until fracture, and the modulus of rupture was calculated based on the span length, load at failure, and specimen dimensions. All tests were conducted in accordance with relevant Indian Standard specifications to ensure reliability and accuracy of the results.

5. RESULTS AND DISCUSSION

The mechanical properties of the concrete mixes were evaluated in terms of compressive strength, split tensile strength, and flexural strength. The results are shown in Figure1, Figure 2 and Figure 3 respectively. These figures clearly indicated that the replacement of fly ash with silica fume had a significant effect on the performance of mineral admixture–based concrete. For compressive strength, the control mix (M1) containing only fly ash showed lower early-age strength compared to the modified mixes. When 10% of fly ash was replaced with silica fume (M2), the compressive strength increased by 6.2% relative to M1 at 28-day curing period. A further replacement level of 20% silica fume (M3) resulted in an even higher gain, with a 10.8% increase compared to the control mix. This improvement can be attributed to the high pozzolanic reactivity and ultra-fine particle size of silica fume, which enhanced the microstructure by reducing pore volume and accelerating the formation of additional C–S–H gel.

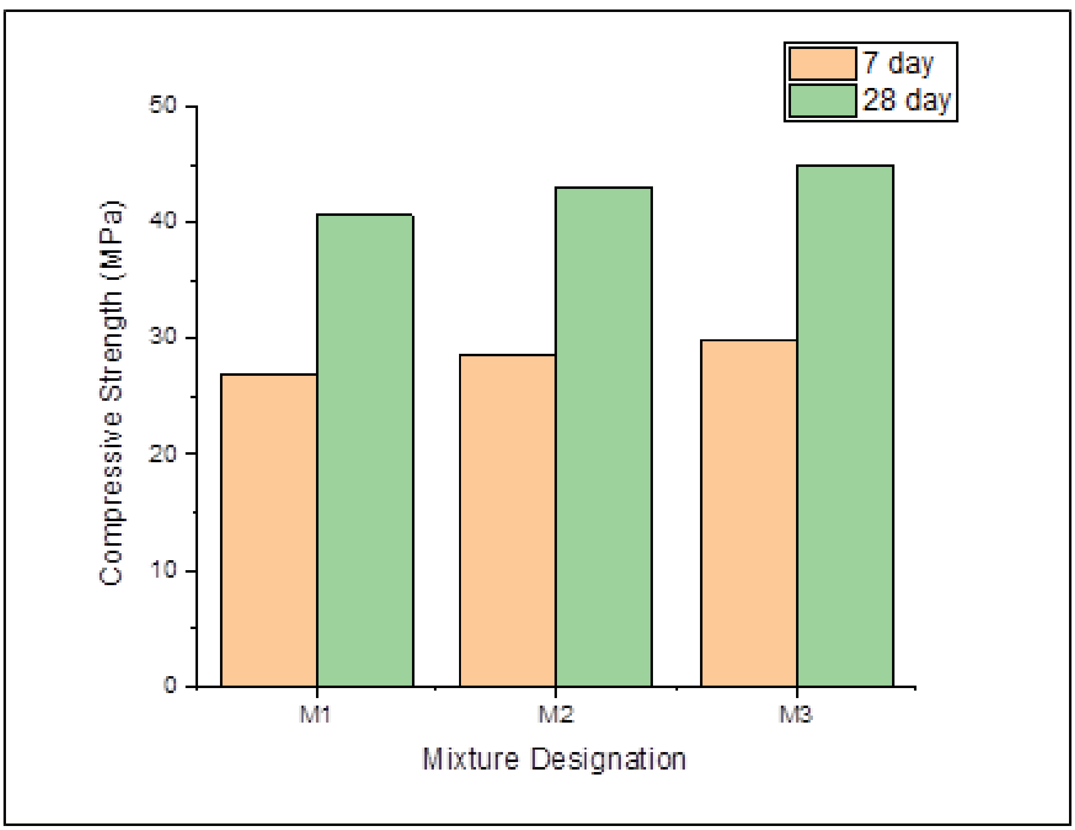

Figure : Compressive strength of various mixes

In terms of split tensile strength, both M2 and M3 mixes exhibited higher values than M1. The increase in tensile strength was consistent with the compressive strength results, reflecting the contribution of silica fume in improving bond characteristics between the matrix and aggregates. The denser and more refined matrix provided by silica fume reduced micro-crack propagation, thereby enhancing the tensile resistance. Flexural strength followed a similar trend, with M2 and M3 mixes outperforming the control mix. The improvement was more pronounced in M3, which demonstrated superior crack resistance and load-carrying capacity under bending. The enhanced flexural performance may be linked to the improved interfacial transition zone and better stress distribution within the matrix due to the filler and pozzolanic effects of silica fume.

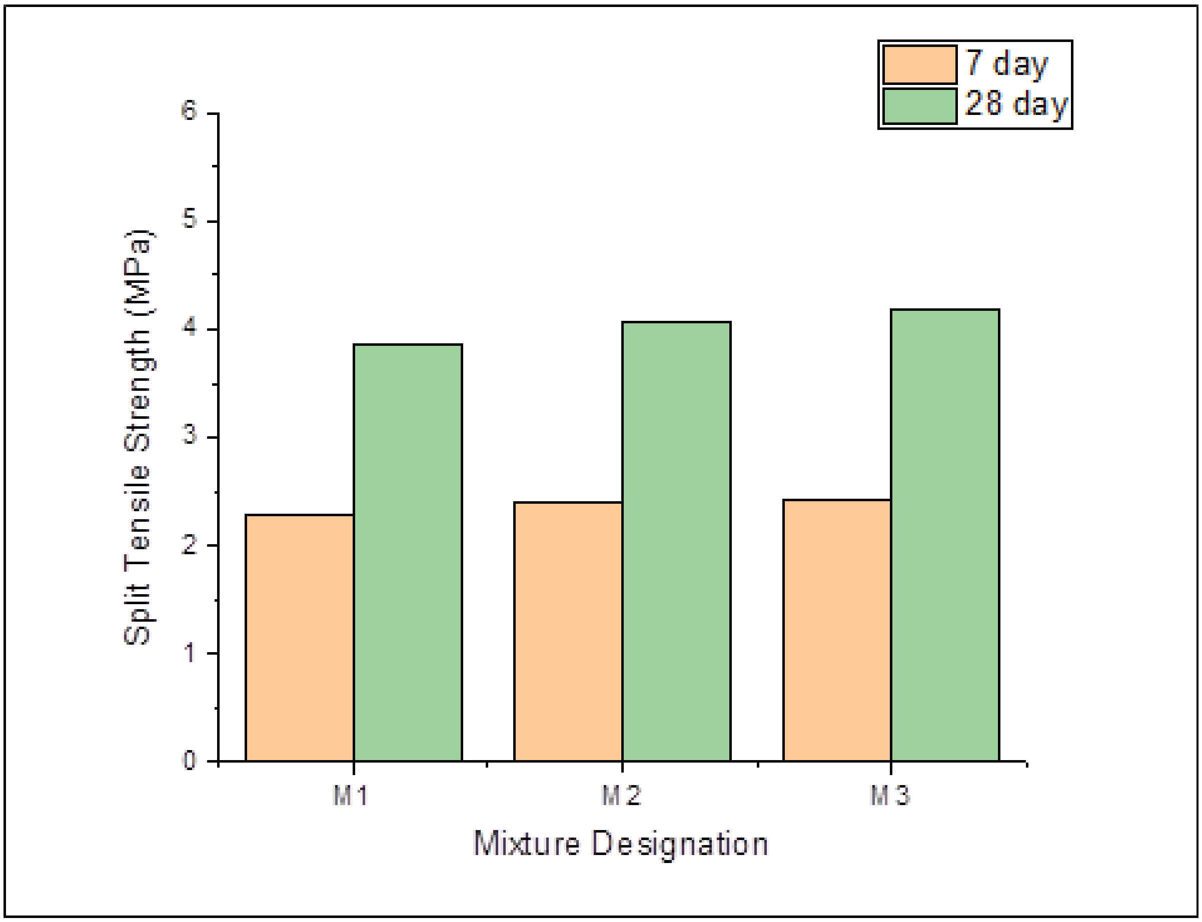

Figure : Split tensile strength of various mixes

Overall, the results confirm that partial replacement of fly ash with silica fume leads to concrete with higher strength and better structural performance. However, the increment in strength between M2 and M3 suggests that while higher silica fume content improves performance, an optimum replacement level must be identified to balance workability, cost, and strength development.

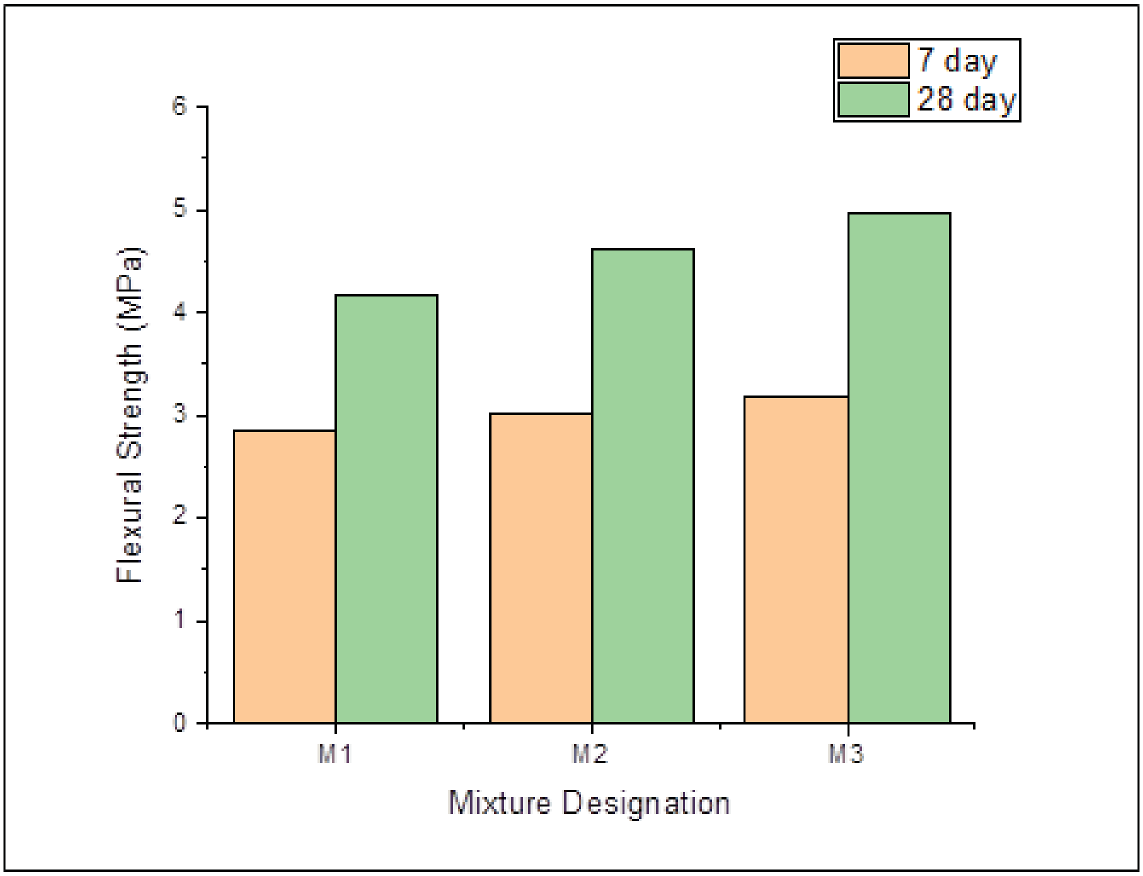

Figure : Flexural strength of various mixes.

6. CONCLUSION

This study examined the effect of partially replacing fly ash with silica fume in mineral admixture–based concrete, focusing on compressive, split tensile, and flexural strengths. The findings demonstrated that the inclusion of silica fume significantly enhanced the overall performance of concrete compared to mixes containing only fly ash. The compressive strength results showed an increase of 6.2% for M2 and 10.8% for M3 over the control mix, confirming the positive influence of silica fume on strength development. Improvements were also observed in split tensile and flexural strength, indicating a denser matrix, refined pore structure, and stronger interfacial transition zone.

The study highlights that silica fume, due to its ultrafine size and high pozzolanic reactivity, not only contributes to early strength gain but also enhances 28-day strength properties by reducing crack propagation and improving resistance under tensile and flexural stresses. Overall, the partial substitution of fly ash with silica fume can be considered a sustainable and effective approach to producing high-performance self-compacting concrete. This strategy not only utilizes industrial by-products efficiently but also contributes toward developing durable and environmentally friendly construction materials suitable for modern infrastructure demands.

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