EFFECT OF REPLACEMENT OF FLY ASH WITH SILICA FUME ON DURABILITY PROPERTIES OF SELF-COMPACTING CONCRETE

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ABSTRACT

The durability of self-compacting concrete (SCC) is a crucial factor in ensuring long-term structural performance, particularly in aggressive environments. This study investigates the influence of replacing fly ash with silica fume on the durability properties of SCC. Concrete mixes were prepared by partially substituting fly ash with silica fume at varying replacement levels, and their performance was assessed through water absorption and rapid chloride permeability (RCPT) testing. The results indicated that the incorporation of silica fume significantly reduces both water absorption and RCPT, demonstrating improved resistance to water ingress. This enhancement can be attributed to the densification of the microstructure and the refinement of pore distribution due to the high pozzolanic reactivity of silica fume. The findings highlight that replacing fly ash with silica fume contributes to superior durability characteristics of SCC, making it a promising material for sustainable and long-lasting concrete structures.

Key Words: Structural performance, durability, silica fume, densification

1. INTRODUCTION

Durability of concrete has emerged as one of the most important concerns in modern civil engineering practice, as it governs the long-term performance and serviceability of structures exposed to aggressive environmental conditions [1,2]. While conventional concrete is known for its strength and versatility, its porous nature and susceptibility to deterioration mechanisms such as chloride ingress, water penetration, carbonation, and sulphate attack often limit its service life [3,4]. To overcome these challenges, supplementary cementitious materials (SCMs) such as fly ash and silica fume are being increasingly used in concrete mixtures to enhance durability alongside mechanical performance [5-10]. Their incorporation not only improves microstructural characteristics but also contributes to sustainable construction by utilizing industrial by-products and reducing Portland cement consumption.

Fly ash, a finely divided by-product of coal combustion in thermal power plants, has been widely recognized as an effective SCM in concrete [11,12]. Its spherical particles enhance the workability of concrete mixes, while its pozzolanic activity gradually improves strength and durability over time. Fly ash contributes to refinement of pore structure by reacting with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) gel, thereby reducing permeability and improving resistance against aggressive ions [1,13]. However, the pozzolanic reaction of fly ash is relatively slow in the early stages of hydration, which may not provide sufficient densification during the initial curing period. This drawback necessitates the exploration of other highly reactive SCMs to complement its performance.

Silica fume, also known as micro-silica, is an ultrafine amorphous material obtained as a by-product of silicon and ferrosilicon alloy industries [9,14]. With an average particle size nearly 100 times smaller than cement grains, silica fume exhibits extremely high pozzolanic reactivity. Its incorporation into concrete leads to rapid consumption of calcium hydroxide and formation of additional C-S-H gel, significantly refining the pore structure and reducing the permeability of the hardened matrix [6,15,16]. Moreover, the filler effect of its ultrafine particles helps in packing the voids between cement grains, thereby producing a denser, more impermeable microstructure [9,14]. This directly translates into improved durability properties such as reduced water absorption, higher resistance to chloride penetration, and improved protection of embedded reinforcement against corrosion.

The combined use of fly ash and silica fume in concrete offers a synergistic effect, where the slow pozzolanic reaction of fly ash is complemented by the rapid reactivity of silica fume. Such hybrid mixes are capable of providing both improved fresh properties, as seen in self-compacting concrete (SCC), and superior long-term durability. In SCC, where flow-ability and resistance to segregation are critical, fly ash helps in improving workability due to its smooth particle shape, while silica fume contributes to cohesiveness and strength [17,18]. From a durability perspective, reducing permeability is the key to resisting water ingress and chloride attack, both of which are major causes of reinforcement corrosion and eventual deterioration of structures. Water absorption tests provide insight into the pore connectivity and resistance of concrete to moisture penetration, while rapid chloride permeability tests (RCPT) offer an assessment of its vulnerability to chloride ingress, which is particularly relevant for structures in marine environments or those exposed to de-icing salts.

Thus, incorporating silica fume and fly ash in SCC represents a promising approach to enhance durability while maintaining sustainable construction practices. By optimizing the replacement levels, a balance can be achieved between workability, strength, and durability, leading to longer service life and reduced maintenance costs of concrete structures. The present study focuses on examining the durability aspects of SCC incorporating silica fume as a partial replacement of fly ash, specifically through water absorption and rapid chloride permeability tests, to understand its potential in producing high-performance and durable concrete for modern infrastructure.

2. MATERIALS USED

Ordinary Portland Cement (OPC), conforming to IS: 8112 specifications, was employed as the primary cementitious binder in this investigation. Class F fly ash, procured from a nearby thermal power station, was utilized as a supplementary material. This fly ash, characterized by its low calcium content and rich proportion of silica and alumina, offered excellent potential for pozzolanic reactivity. In addition, silica fume sourced from Delhi, India, was incorporated. The silica fume consisted of ultrafine amorphous silica particles with high surface area, enabling accelerated pozzolanic activity and effective pore refinement within the concrete matrix.

Table 1: Physical properties of fine aggregates

Property	**Result**
Physical Appearance	Dull grey
Fineness modulus	2.54
Water absorption (%)	1.98
Specific gravity	2.56

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For the aggregates, natural river sand passing through a 4.75 mm IS sieve was selected as fine aggregate, ensuring good grading and workability. Crushed granite with a nominal maximum size of 20 mm was adopted as coarse aggregate, chosen for its strength and durability characteristics. The physical properties of fine and coarse aggregates are presented in Table 1 and Table 2, respectively. Potable water free from deleterious salts, oils, and organic impurities was used throughout the study for both mixing and curing, ensuring proper hydration and uniform strength development in the concrete specimens.

Table 2: Physical properties of coarse aggregates

Property	**Result**
Physical Appearance	Sub-angular
Fineness modulus	6.47
Specific gravity	2.66
Water absorption (%)	1.43

3. MIXING AND CASTING

The concrete mixtures were prepared in accordance with standard self-compacting concrete (SCC) practices to ensure uniformity and homogeneity. The dry materials, including cement, fly ash, silica fume, fine aggregate, and coarse aggregate, were first blended in a pan mixer to achieve a uniform distribution of particles. This dry mixing step was followed by the gradual addition of water along with the required superplasticizer to attain the desired flow-ability and workability characteristics of SCC. Mixing was continued until a consistent, homogeneous mix with no visible segregation was obtained. Mixture proportioning is given in Table 3.

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

After preparation, the fresh SCC was immediately cast into standard cube and cylindrical moulds for testing. The cube specimens (100 mm × 100 mm × 100 mm) were cast for water absorption testing, while cylindrical specimens (100 mm diameter × 200 mm height) were cast for rapid chloride permeability testing out of which 100 mm diameter × 50 mm high discs were cut out. During casting, the mixes were placed in moulds without vibration, as SCC inherently possesses self-compaction properties. Care was taken to avoid air entrapment, ensuring dense and uniform specimens.

The moulded specimens were covered with plastic sheets to minimize moisture loss and kept undisturbed for 24 hours at ambient laboratory conditions. After demoulding, all specimens were transferred to a curing tank containing potable water and were cured at room temperature until the designated testing age. This ensured proper hydration and strength development, thereby allowing accurate evaluation of durability properties.

4. TESTING METHODS

The durability performance of the prepared self-compacting concrete (SCC) mixes was assessed using two standard tests: water absorption test and rapid chloride permeability test (RCPT). All procedures were carried out in accordance with relevant Indian Standards to ensure reliability and reproducibility of results. Besides compressive strength results of all mixtures were are taken into account.

The water absorption test was performed following the guidelines of IS: 516–1959 (Methods of Tests for Strength of Concrete). Cube specimens of size 150 mm were oven-dried at a temperature of 105 ± 5 °C until a constant mass was achieved. The dried specimens were then cooled to room temperature and weighed (W_1). Subsequently, the specimens were immersed completely in water for 48 hours. After immersion, the surface water was wiped off, and the saturated mass (W_2) was recorded. The water absorption was calculated as the percentage increase in mass relative to the oven-dry mass using the formula:

$$\text{Water Absorption (\%)} = \frac{(W2-W1)}{W1} \times 100$$

This test provides an indication of the pore structure and permeability of concrete, which directly influences durability. The resistance of concrete to chloride ion penetration was evaluated in accordance with ASTM C1202-2017, as there is no direct IS code specified for RCPT. However, this method is widely accepted in Indian research and practice. Cylindrical specimens of 100 mm diameter and 200 mm height were used, which were sliced into 50 mm thick discs after 28 days of curing. The specimens were vacuum-saturated prior to testing to ensure full pore connectivity.

During the test, each specimen was placed between two chambers: one containing 3% sodium chloride (NaCl) solution and the other containing 0.3 N sodium hydroxide (NaOH) solution. A potential difference of 60 V DC was applied across the specimen for 6 hours. The total charge passed through the specimen, measured in coulombs, was recorded using an automatic data acquisition system.

5. RESULTS AND DISCUSSION

The compressive strength results are shown in Table 4; where it was seen that strength got improved with substitution of silica fume. Besides, the results obtained at 28 days of curing highlight the positive influence of silica fume on the resistance of SCC against water and chloride ingress (Figure 1 and Figure 2).

Table 4: Compressive strength results of various mixtures

Mixture Designation	7-Day Compressive Strength (MPa)	28-Day Compressive Strength (MPa)
M1 (Control)	26.79	40.60
M2	28.64	43.12
M3	29.83	44.98

The water absorption results indicated a significant reduction in the mixes containing silica fume compared to the control mix. The reference mixture (M1), containing only fly ash as supplementary cementitious material, exhibited higher water absorption due to its relatively porous microstructure. In contrast, the incorporation of silica fume led to notable improvements. The M2 and M3 mixtures showed reductions of 14.6% and 13.67%, respectively, in water absorption compared to M1 at 28 days. This improvement can be attributed to the ultrafine particle size and high pozzolanic reactivity of silica fume, which refined the pore structure, reduced pore connectivity, and enhanced the overall impermeability of the matrix. The results clearly demonstrate that even partial replacement of fly ash with silica fume contributes to lowering water absorption, thereby improving resistance against moisture-induced deterioration.

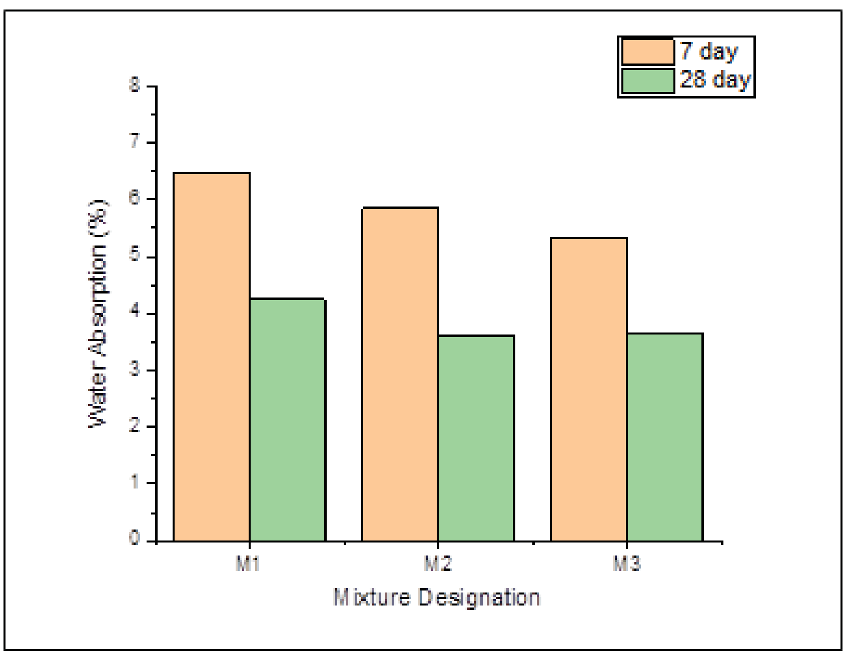

Figure : Water absorption of various mixtures

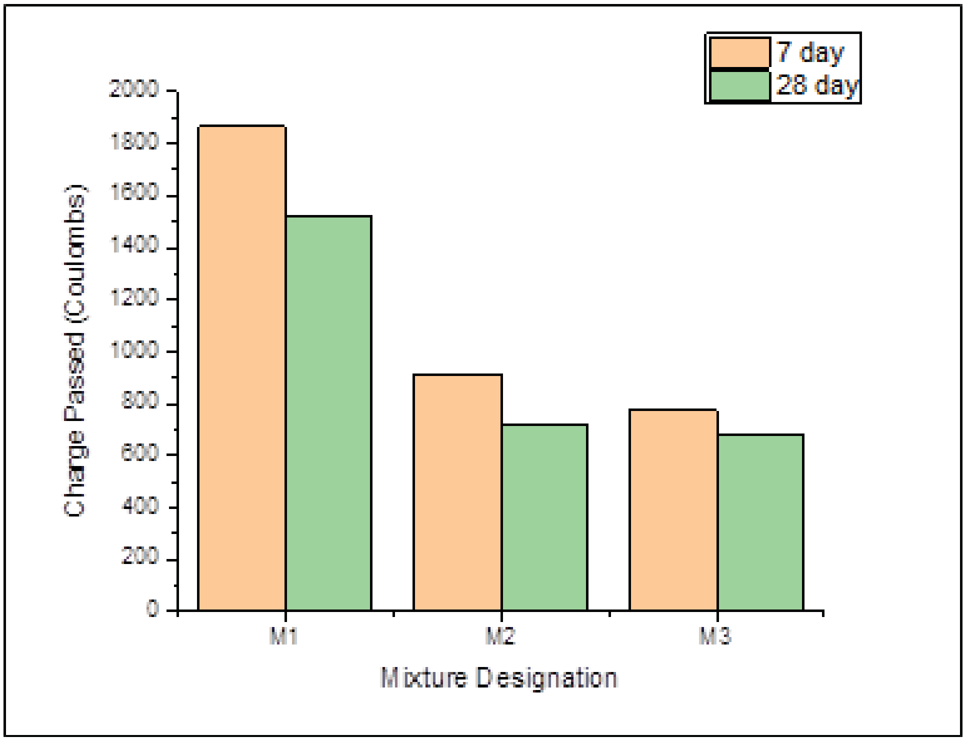

Figure : RCPT results of various SCC mixtures

The RCPT results also revealed a similar trend to that of water absorption. The charge passed through the specimens decreased significantly for mixes containing silica fume. The reduced chloride ion penetrability in M2 and M3 mixes indicates that silica fume not only refines the pore structure but also reduces the transport pathways for aggressive ions such as chlorides. This enhancement is critical for reinforced concrete structures exposed to marine or de-icing salt environments, where chloride-induced corrosion is a major durability concern. Although the reduction percentages in RCPT were not numerically specified, the observed trend was consistent with water absorption results, confirming the beneficial effect of silica fume addition.

The reduction in both water absorption and chloride permeability highlights the role of silica fume in enhancing the durability of SCC. Its filler effect and accelerated pozzolanic reaction contribute to the densification of the cementitious matrix, limiting the ingress of fluids and ions. Furthermore, the combined use of fly ash and silica fume creates a synergistic effect, where fly ash enhances workability while silica fume ensures early-age densification and long-term impermeability. The findings suggest that the replacement of fly ash with silica fume, even in moderate proportions, provides a balanced improvement in durability without compromising the sustainability benefits of fly ash utilization.

6. CONCLUSION

This study examined the durability performance of self-compacting concrete (SCC) prepared with silica fume as a partial replacement for fly ash, with a focus on water absorption and rapid chloride permeability. The results demonstrated that the incorporation of silica fume significantly improved the impermeability of SCC. At 28 days of curing, water absorption decreased by 14.6% and 13.67% in the M2 and M3 mixes, respectively, compared to the control mixture (M1). A similar decreasing trend was observed in rapid chloride permeability test (RCPT) results, further confirming the beneficial effect of silica fume in restricting the ingress of chloride ions.

The improved performance can be attributed to the ultrafine particle size and high pozzolanic reactivity of silica fume, which refined the pore structure and enhanced matrix densification. While fly ash improved workability and contributed to long-term strength development, silica fume provided early-age densification and superior resistance to permeability. Together, these materials created a synergistic effect, enhancing both fresh and hardened properties of SCC. Overall, it can be concluded that the partial replacement of fly ash with silica fume in SCC is a viable approach to producing durable, sustainable, and high-performance concrete, particularly for structures exposed to aggressive environmental conditions.

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