

Basic Properties of Concrete with Silica Fume as Supplementary Cementitious Material: Effects of Replacement Level and Particle Size

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Abstract

This study systematically investigates both the effects of replacement level and particle size of silica fume (SF) on concrete, identifying critical insights for optimising its use as a supplementary cementitious material (SCM). The key finding is that while SF significantly enhances mechanical properties, its optimal performance is contingent on two distinct factors: a specific replacement percentage for different strengths and a refined particle size for overall efficacy. Specifically, compressive strength was maximised at a 20%wt cement replacement, achieving 49.5 MPa at 56 days, whereas flexural strength peaked at a lower 10%wt replacement, showing a 40% increase over the control. This divergence underscores distinct strengthening mechanisms; compressive strength is governed by enhanced bulk hydration, while flexural strength is more sensitive to the densification of the interfacial transition zone (ITZ). Concurrently, any incorporation of SF markedly reduced workability, with slump values plummeting from 178 mm for the control mix to just 25 mm at 25%wt replacement, primarily due to its fine particle morphology. Beyond replacement level, particle size was identified as a decisive factor. Grinding SF from a median diameter of 76 μm to a finer median diameter of 47 μm profoundly improved concrete performance, leading to a 25% increase in early compressive strength and a remarkable more than 60% increase in flexural strength compared to mixes with larger, unground SF particles, despite a manageable reduction in slump. These results demonstrate that the sustainability and structural efficiency gains from using SF are not inherent but must be engineered. Ultimately, successfully balancing the often-competing demands of workability and strength requires a tailored approach that simultaneously optimises both its proportion in the mix and its physical fineness.

Keywords: Compressive strength, Flexural strength, Particle size, Silica fume, Slump.

1. Introduction

Driven by the need for sustainable construction, silica fume (SF) has emerged as an eminent supplementary cementitious material (SCM) due to its pozzolanic and micro-filling properties capable of enhancing the properties of concrete [1]. It is a by-product generated during the production of silicon and ferrosilicon alloys. It mainly consists of amorphous silicon dioxide or silica (SiO_2) exceeding 85%. Composed of ultrafine particles with an average diameter of 10-100 μm ; it is often many times finer than cement. Its primary application is as a partial replacement for Portland cement,

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typically accounting for 5-15% weight of Portland cement (%wt). Incorporating SF can improve the mechanical properties and durability of concrete through both physical and chemical mechanisms. However, the workability of concrete may be compromised with SF as SCM.

The fine particles of SF reduce concrete workability, making it harder to handle [2-4]. This occurs because its high surface area demands more water, leaving less to lubricate the mix. Additionally, its irregular, yet approximately spherical, shape can lead to increased inter-particle friction [5]. Using superplasticizers with SF can mitigate this issue and improve workability while maintaining its benefits [2,5].

Silica fume significantly improves the compressive strength of concrete, especially at early stages [6-9]. At optimal replacement levels of 10-15%wt, strength can increase by over 25%, with 28-day strength often increasing by 20-40% [8,10]. This strengthening occurs through two main mechanisms: the primary chemical mechanism consumes calcium hydroxide (CH) to form additional calcium silicate hydrate (CSH) gel, refining the microstructure and increasing the solid volume of the binding paste [8,9,11]. Secondly, the ultra-fine particles of SF fit into the spaces between cement grains, creating a denser, more impermeable microstructure [11]. In general, this bulk hydration mechanism reduces the volume of large, harmful capillary pores, hence a denser concrete product with enhanced compressive strength.

Similar improvements are observed in tensile and flexural strengths, with increases up to 26% and 16%, respectively [6,9,12-14], though the percentage increase is generally lower than that for compressive strength. The mechanism of improvement on tensile strength is through the enhanced bond between the paste and the aggregate interface, which is also known as the interfacial transition zone (ITZ). Silica fume densifies the ITZ, which is typically the weakest link in concrete, making it more homogeneous and stronger.

Beyond improving concrete strengths, SF also enhances its durability. By reducing porosity, SF makes the concrete less permeable [2,11,15]. This improves resistance to chemical threats like chloride penetration and most sulphate attacks [6,16,17], though performance against magnesium sulphate can be poor [18]. One drawback is that SF may lower freeze-thaw resistance, requiring additional measures to compensate [4,6].

Using SF as a partial cement replacement also lowers the carbon footprint of concrete, supporting sustainable construction [11,17,19]. This is particularly relevant as Malaysia's cement production generated approximately 22-27 million metric tons of CO₂ between 2015 and 2024 [20], underscoring the urgent need to reduce emissions by 2030 to meet the UN's Sustainable Development Goal for Sustainable Cities and Communities [21].

Existing research on SF concrete seldom explores high-percentage replacements (> 15%wt) or particle size effects. Furthermore, studies often use SF with an unreported median particle size, preventing meaningful comparison across different mix designs. These identified gaps motivate the present investigation.

2. Materials and methods

2.1. Raw materials

Ordinary Portland cement (CEM I 42.5N), compliant with MS EN 197-1:2014 [22] and supplied by Cahya Mata Cement Sdn. Bhd., with a median diameter (D_{50}) of 20 μm [23], served as the base cementitious material. Silica fume, sourced from a local ferroalloy manufacturer, was used as an SCM. It has a D_{50} of 76 μm , as shown in the scanning electron microscope (SEM) image in Figure 1. River sand with a fineness modulus of 2.35 was used as fine aggregate, which is considered fine sand. Crushed granite with a maximum size of 20 mm and a bulk density of 1520 kg/m³ was used as coarse aggregate.

2.2. Mix proportion

A starting mix proportion was first designed following the procedures by Teychenne et al. [24] for a target cube compressive strength of 35 MPa after 28 days of curing, with high workability for the fresh concrete, reflected by a slump range of 60-180 mm. Trial mixes were cast and adjusted to achieve a 28-day compressive strength of 35 MPa. The final mix proportion, based on these trials, had a cementitious material-to-fine aggregate-to-coarse aggregate ratio of 1:1.42:2.64 and a water-to-cementitious material ratio of 0.65. It is noteworthy that no superplasticizer was used in this study. Ordinary Portland cement was then replaced with SF at 5, 10, 15, 20, and 25%wt in separate concrete batches, with a control batch of concrete with no SF as SCM.

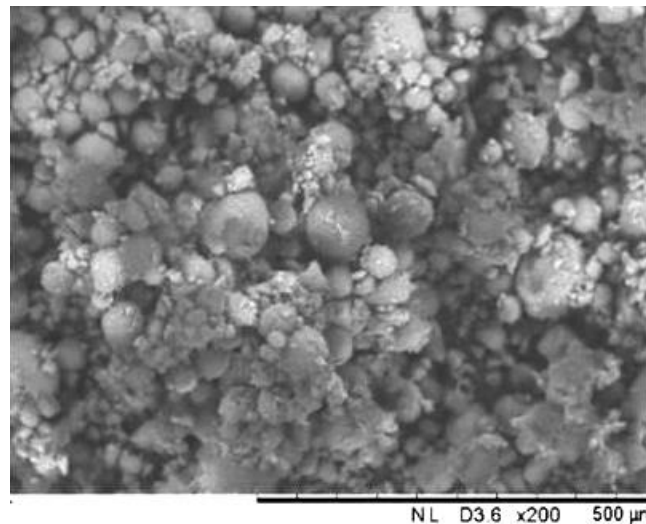


Figure 1. Scanning electron microscope image of unground silica fume ($D_{50} = 76 \mu\text{m}$)

2.3. Test programme

For compressive and flexural strength testing, 100 mm cubes and 500 mm long prisms (with a 100 mm × 100 mm cross-section) were cast in compliance with BS EN 12390-1:2021 [25] and BS EN 12390-2:2019 [26]. Prior to casting, coarse aggregates were soaked for 24 hours in potable water and then surface-dried with a lint-free cloth to achieve a saturated-surface-dry (SSD) condition. The moulds were coated with a thin layer of recycled engine oil. The workability of the fresh concrete was assessed via a slump test per BS EN 12350-2:2019 [27]. After demoulding at 24 hours, all specimens were labelled and transferred to a curing tank, where they were fully submerged in potable water at ambient temperature.

Compressive strength test was conducted after 7, 28, 56 and 90 days of curing in accordance with BS EN 12390-3:2019 [28], whereas and flexural strength test was conducted after 7 and 28 days of curing in accordance with BS EN 12390-5:2019 [29]. Prior to testing, specimens were removed from the curing tank and surface-dried for a minimum of two hours. The compressive strength was determined from the average result of three cubes tested in a compression machine. The flexural strength was calculated from the maximum load applied in a two-point loading test on prisms, again averaged from three specimens.

Following the determination of the optimal SF proportion, the material was subjected to a 90-minute grinding process in a stainless-steel ball mill equipped with grinding balls of 100 mm diameter or less, to achieve a D_{50} of 47 μm . The morphology of the ground SF is presented in Figure 2. To investigate the effect of particle size, a second batch of concrete with the same mix proportion was

cast using the ground SF at the predetermined optimum level. Its fresh property (workability) and mechanical properties (7- and 28-day compressive and flexural strengths) were then evaluated.

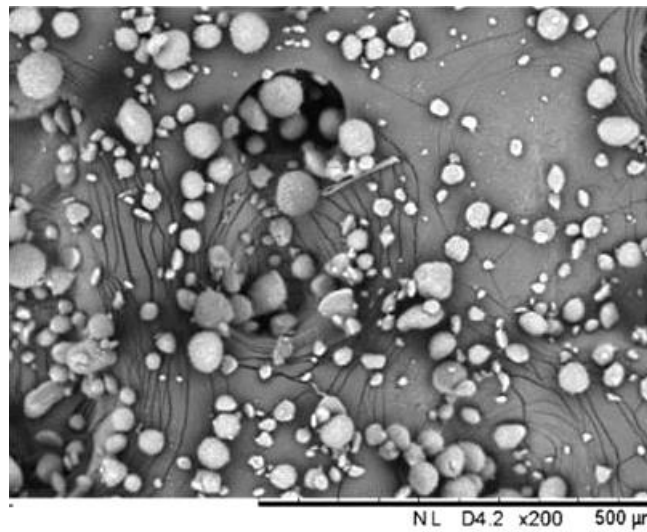


Figure 2. Scanning electron microscope image of ground silica fume ($D_{50} = 47 \mu\text{m}$)

3. Results and discussion

3.1. Workability

As a standard method for evaluating fresh concrete, the slump test assesses consistency by measuring the mixture's deformation under its own weight. The resulting slump value is a key indicator of workability, confirming the concrete's suitability for specific applications and placement methods. This property is also intrinsically linked to the eventual strength development of the hardened concrete. The effect of SF content as SCM on concrete workability is presented in Figure 3.

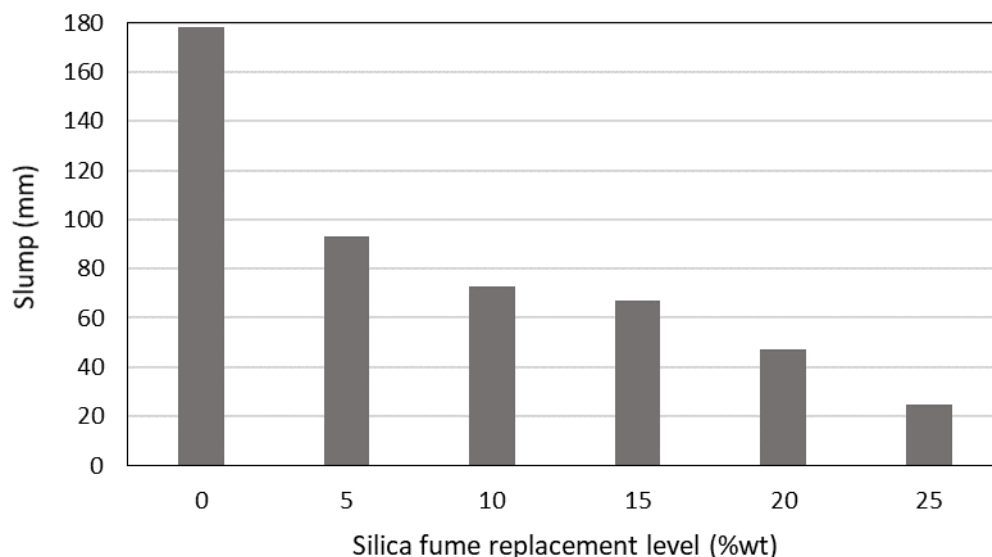


Figure 3. Effect of silica fume replacement level on workability of concrete measured with slump test

The results demonstrate an inverse relationship between SF replacement level and slump value as depicted in Figure 3. The control mix (0%wt SF) achieved a collapsed slump of 178 mm, denoting high workability. The incorporation of SF significantly reduced workability; a 5%wt replacement resulted in a slump of 93 mm, which is a 48% decrease. Further increases in SF content to 10%wt and 15%wt led to continued decreases in slump to 73 mm and 61 mm, representing reductions of 59% and 66%, respectively, but still within the high workability range.

Workability loss was most severe at the highest replacement levels. Mixes with 20%wt and 25%wt SF replacement levels exhibited a significant decline in slump. The 20%wt SF replacement level mix achieved a slump of 47 mm, which is a 74% reduction; categorising it as a medium workability mix. This was further reduced to just 25 mm (an 86% decrease) at the 25%wt SF replacement level, categorising it as a low workability mix.

The loss of slump in concrete incorporating SF as SCM, as previously mentioned, is commonly caused by two key factors: the smaller particle size of SF compared to cement [2-4] and its irregular, though approximately spherical, shape that increases inter-particle friction [5]. However, in this investigation, the SF particles were larger than the cement particles. Therefore, the results are more likely explained by the second factor, which is the particle morphology and its effect on friction.

3.2. Compressive strength

Compressive strength defines the maximum stress concrete can withstand before failure, serving as a critical metric for structural safety and durability. This strength is primarily governed by the degree of cement hydration and the properties of the constituent materials. Consequently, investigating the effect of SF as an SCM on compressive strength is essential.

The development of compressive strength with respect to SF replacement level and curing age is presented in Figure 4. The results demonstrate a complex relationship between SF content and strength gain, revealing both an optimal replacement level and a clear influence of curing time.

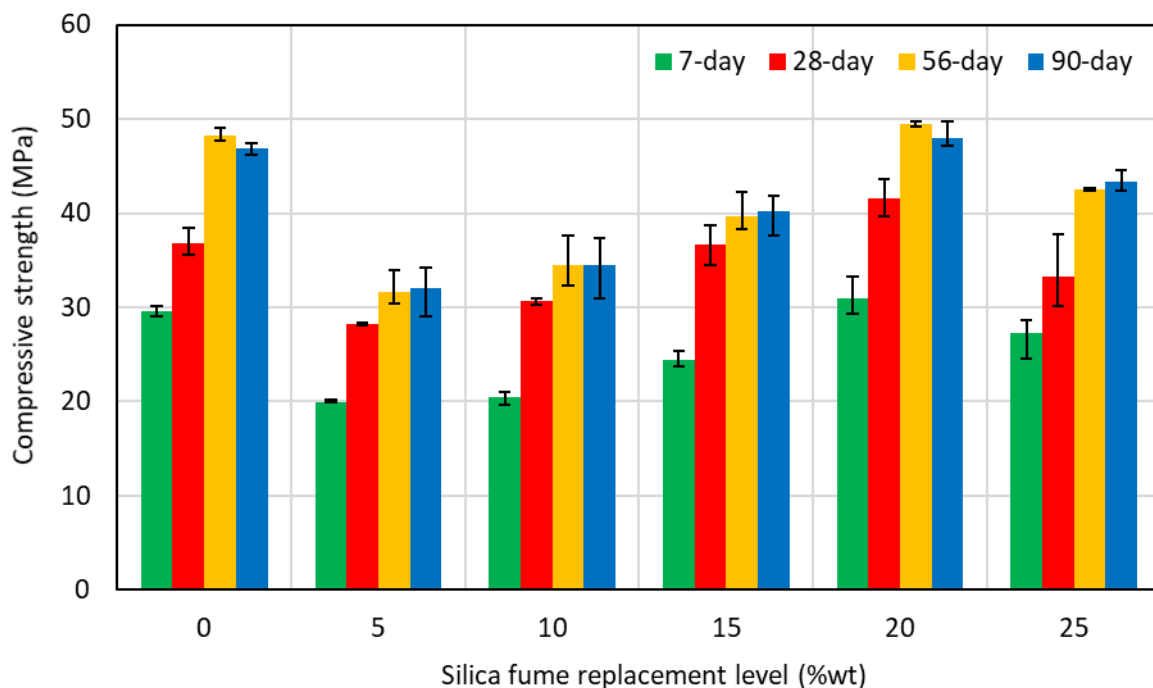


Figure 4. Effect of silica fume replacement level on concrete compressive strength

It can be seen in Figure 4 that the control mix attained a compressive strength of 29.6 MPa at 7 days of curing. Notably, at 20%wt SF replacement level, the concrete batch exhibited the highest early-age strength, measuring 31.0 MPa, which is an increase of 4.5% compared to the control. In contrast, at 5%wt SF replacement level, the concrete showed the lowest 7-day strength value of 20.0 MPa, approximately 32% lower than the control. A similar reduction in early-age strength was observed in the 10%wt and 15%wt SF replacement levels, which registered 20.5 MPa (31% decrease) and 24.5 MPa (17% decrease), respectively. This pattern of early-age strength can be attributed to the cement dilution effect at lower SF replacement levels (< 20%wt), which slows the pozzolanic reaction. A 20%wt SF replacement level restored early strength to a level exceeding the control, which aligns with previous studies [6-9]. However, increasing the replacement to 25%wt reintroduced the cement dilution effect, reducing early-strength once more.

By the 28th day, all concrete batches exhibited substantial compressive strength development from the 7-day compressive strength. The 20%wt SF replacement level batch showed a notable development of 34%, reaching 41.5 MPa compared to its 7-day strength, and exceeded the control mix (36.8 MPa) by 13%. The 25%wt SF replacement level batch also developed significantly, rising from 27.2 MPa to 31.2 MPa, which is a gain of 15%. Similarly, the 5%wt, 10%wt, and 15%wt replacement level batches demonstrated strength developments of 42%, 50%, and 49%, respectively, reflecting a delayed yet considerable strength development beyond early ages. The cement dilution effect, as previously described for early-age strengths, was also observed here at the 5%wt, 10%wt, and 25%wt SF replacement levels.

The longer-term strength development trends had become more pronounced by the 56th day. The control mix strength developed to 48.3 MPa, representing a 31% gain from its 28-day strength and a 63% development from 7 days. The 20%wt SF replacement level batch continued to demonstrate the highest performance among all batches, reaching a peak strength of 49.5 MPa, which is 19% higher than its 28-day strength and 2.5% above the control mix. Meanwhile, the 10%wt and 15%wt SF replacement level batches showed more modest gains, achieving strengths of 34.4 MPa and 39.7 MPa, respectively. Despite these improvements, the 5%wt replacement level batch exhibited the lowest compressive strength overall at 31.7 MPa. The cement dilution effect at longer-term strengths occurs at SF replacement levels similar to those observed at early ages.

At the final curing age of 90 days, all concrete batches showed no significant development in compressive strength compared to the 56-day strength. This indicates that concrete incorporating SF as SCM does not exhibit further strength development beyond 56 days.

In terms of overall performance, the 20%wt SF replacement level demonstrated consistent strength development at all curing ages, where its compressive strength surpassed that of the control mix. It achieved the highest strength at 28 and 56 days of curing and sustained one of the greatest strength gains from early to mid-term curing. In contrast to previous studies, which reported optimal replacement levels of about 10-15%wt SF replacement level [6-9], the findings of this investigation may be attributed to the larger particle size of the SF used. The larger particle size of SF requires a higher replacement level to supply enough surface area for the pozzolanic reaction with CH. This reaction produces additional CSH gel that refines the pore structure and increases the paste's solid volume, thereby explaining the higher optimal SF replacement level observed.

3.3. Flexural strength

Flexural strength, defined as the maximum tensile stress under bending, was determined using a two-point loading test on concrete prisms. Results for 7 and 28 days of curing are reported in this study, as shown in Figure 5. After 7 days of curing, strength results for most concrete batches showed minimal deviation from the control value of 3.45 MPa. The 10%wt SF replacement batch significantly outperformed the others, achieving a flexural strength of 4.58 MPa (a 33% increase compared with the control). A 15%wt SF replacement level also yielded a higher strength of 3.91 MPa, showing a 13%

improvement. This improvement is attributed to the densification of the interfacial transition zone (ITZ). By strengthening this typically weak interface between the paste and aggregate, SF produces a more homogeneous and robust microstructure.

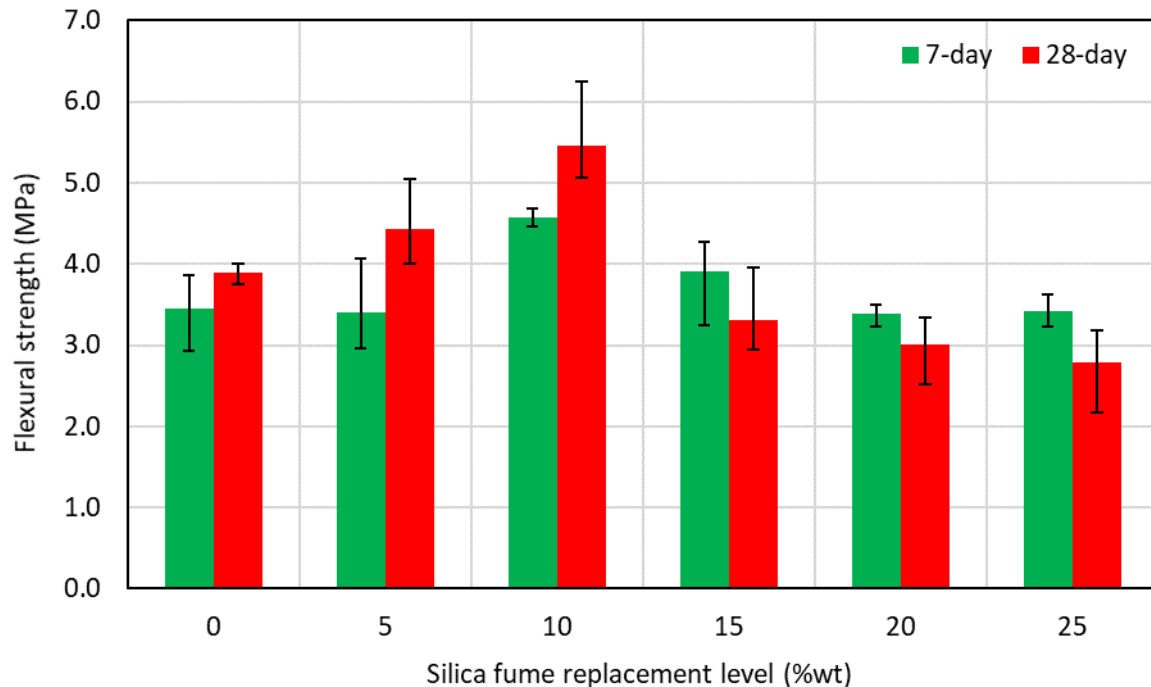


Figure 5. Effect of silica fume replacement level on concrete flexural strength

The 28-day curing period revealed a more pronounced trend in flexural strength development. The control mix exhibited a moderate strength development of 13%, reaching 3.89 MPa. In contrast, the optimal performance was observed at the 10%wt SF replacement level, which attained a peak strength of 5.46 MPa, signifying a 40% advantage over the control and a 19% increase from its own 7-day strength. The 5%wt SF replacement level batch also showed significant development, increasing 30% from its 7-day strength to a value 30% higher than the control. Similar to early-age strength, this improvement is attributed to the densification of the ITZ. However, higher replacement levels proved detrimental due to the cement dilution effect. Flexural strength reductions were recorded for 15%wt (-15%), 20%wt (-23%), and 25%wt (-28%) SF replacement level batches compared to the control.

Consistent with the literature [6,9,12-14], the optimal flexural strength was achieved at a 10%wt SF replacement level, within the effective 5-15%wt range. At optimal SF replacement levels, it produces a more homogeneous and robust microstructure by densifying the ITZ, which strengthens the weak paste-aggregate interface.

3.4. Effect of particle size of silica fume

A divergence was observed between the optimal SF replacement levels for compressive strength (20%wt) and flexural strength (10%wt). This inconsistency is potentially due to the larger particle size of the unground SF ($D_{50} = 76 \mu\text{m}$), as noted previously. Given the predominant importance of compressive strength, the 20%wt SF replacement level was deemed optimal and was therefore used to study the effect of SF particle size. Two SF particle sizes were used: an unground variant with a D_{50} of 76 μm and a ground variant with a D_{50} of 47 μm . The effect of SF particle size on the workability

(slump) and mechanical properties (compressive and flexural strength) of concrete is summarised in Table 1.

As expected, a smaller SF particle size resulted in a lower slump due to its greater specific surface area. The increased surface area demands more water to coat the particles, effectively reducing the free water content that provides lubrication. Consequently, reducing the SF particle size from 76 μm to 47 μm caused a significant 26% slump decrease, from 47 mm to 35 mm.

Table 1. Test results on the effect of SF particle size at 20%wt SF replacement level

Test parameter	Particle size (D_{50}) of SF	
	76 μm	47 μm
Slump	47 mm	35 mm
7-day compressive strength	31.0 MPa	38.9 MPa
28-day compressive strength	41.5 MPa	45.5 MPa
7-day flexural strength	3.39 MPa	5.52 MPa
28-day flexural strength	3.01 MPa	5.15 MPa

The batch incorporating smaller SF particles exhibited significantly higher compressive strength at both 7 and 28 days of curing, as shown in Table 1. At 7 days, its strength reached 38.9 MPa, approximately 25% greater than that of the batch with a larger SF particle size (31.0 MPa). This trend continued at 28 days, where the smaller SF particle size batch achieved 45.5 MPa compared to 41.5 MPa for the larger SF particle size batch, reflecting a 10% improvement. These results indicate that the reduced SF particle size enhanced the pozzolanic reactivity, leading to more efficient hydration and accelerated strength development.

A further distinction in flexural strength is evident, as shown in Table 1. The smaller SF particle size batch demonstrated significantly higher strength, with a 63% improvement at 7 days (5.52 MPa) and a 71% improvement at 28 days (5.15 MPa) over the batch with larger SF particle size.

It is noteworthy that the enhancement in flexural strength was more pronounced than the corresponding increase in compressive strength with the use of a smaller SF particle size. Although a reduction in slump was observed, the values remained within the medium workability range of 30–60 mm. These findings highlight the need for further investigation to establish the optimal SF content in relation to particle size for achieving balanced concrete performance.

4. Conclusion

This investigation demonstrated that the use of SF as SCM significantly affects the workability and mechanical performance of concrete, with both replacement level and particle size playing critical roles. The incorporation of SF reduced workability, with slump values decreasing as replacement levels increased. At 20%wt SF replacement level, workability fell to the medium range, while 25%wt SF replacement level produced low workability.

Compressive strength results indicated that the optimal SF replacement level was 20%wt, yielding superior performance at all curing ages and surpassing the control batch at both 28 and 56 days. In contrast, flexural strength was maximised at 10%wt SF replacement level, consistent with literature values. This divergence highlights the differing mechanisms by which SF influences bulk hydration and the interfacial transition zone. Therefore, to meet structural compressive-strength requirements, replacement of binder with 20%wt of SF is recommended; to optimise flexural performance, 10%wt SF replacement is ideal.

Particle size of SF was found to be a decisive factor. Concrete incorporating a smaller SF particle size ($D_{50} = 47 \mu\text{m}$) exhibited substantially higher compressive and flexural strengths

compared to the concrete batch with a larger particle size ($D_{50} = 76 \mu\text{m}$), despite a modest loss in workability. The improvement was more pronounced for flexural strength, suggesting that finer SF more effectively enhances the pozzolanic reaction and densifies the microstructure of concrete.

Overall, the findings confirm that both replacement level and particle size govern the performance of concrete containing SF as SCM. While 20%wt SF replacement level with finer particles produced the highest compressive strength, optimal design requires balancing particle size, replacement level, and workability to achieve the desired concrete performance. Further research is recommended to refine these parameters and establish comprehensive guidelines for SF utilisation in concrete.

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Conflict of Interest

We declare no conflict regarding the publication of the study.

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