SCIENTIFIC PAPER
Published: September 24, 2024
https://doi.org/10.13167/2024.29.2

Improvement of physical and mechanical properties of high-performance sand concrete with different silica fume content

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Received:
October 9, 2023

Revised:
February 21, 2024

Accepted:
April 2, 2024

Published:
September 24, 2024

Citation:
Chalah, K.; Hammas, A.; Benmounah, A.
Improvement of physical and mechanical properties of high-performance sand concrete with different silica fume content.
Advances in Civil and Architectural Engineering,
2024, 15 (29), pp. 19-32.
https://doi.org/10.13167/2024.29.2

ADVANCES IN CIVIL AND ARCHITECTURAL ENGINEERING (ISSN 2975-3848)

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Abstract:
Silica fume (SF) is widely used for the improvement of several properties of cementitious materials. For this purpose, this study investigated the effect of SF content on the mechanical and durability properties of high-performance sand concrete (HPSC). The experiment work consists of the preparation of HPSC by adding different amounts of SF (0 %, 4 %, 6 %, and 8 %) as a replacement for ordinary Portland cement at a constant water-to-cement ratio of 0,35. The compressive and flexural strengths were performed on the HPSC samples with two standardised sizes of 40 mm × 40 mm × 40 mm and 40 × 40 × 160 mm, which cured during 3, 7, and 28 d. In contrast, both water absorption and water capillary absorption analyses were conducted under a prismatic size of 40 × 40 × 160 mm and cured for 28 d. Based on the test results, the optimal amount of SF was obtained using mechanical strength analysis (6 %). The results showed that at this content of SF, the compressive strength and flexural strength increased by 6,19 and 10,03 %, respectively. In contrast, the addition of SF above this concentration slightly increased the mechanical properties. However, the lowest value of water absorption was obtained for the sample with 6 % SF content. Indeed, at this concentration of SF, the water absorption and the capillarity values of HPSC samples decreased by 8,80 and 8,57 %, respectively.

Keywords:
high-performance sand concrete; silica fume; mechanical properties; physical properties

1 Introduction

Silica fume (SF) is a fine powder obtained as a by-product of the production of silicon and ferrosilicon. SF mainly consists of spherical particles with an average diameter of 0,150 µm. Typically, this powder contains approximately 85-95 % amorphous SiO_2 [1, 2]. According to the European standard EN 13263-1 [3], the amorphous silica content must be higher than 92% to provide good reactivity to this powder. Owing to its significant properties, SF is an important additive in the cement industry, particularly in the production of Portland-SF cement (CEM II/A-D), and its addition can improve its properties. Moreover, SF is considered an essential component for manufacturing high-performance concrete (HPC) used in construction, generally for the repair of degraded structures [4-6]. Hamada et al. [7] indicated the importance of adding SF in the development of sustainable cement concrete. In this study, the authors concluded that SF addition has a significant effect on the improvement of pore size and the decrease in drying shrinkage through the pozzolanic reaction. However, compared to natural pozzolan (NP) and ground granulated blast furnace slag (GGBS), SF has a low particle size distribution and reactive silica, which explains its effects on both the filler and pozzolanic reactions.

Generally, SF is used to improve the properties of concrete, particularly its mechanical strength and durability. Hamada et al. [8] concluded that the addition of SF improved the compressive and flexural properties of concrete. However, the effect of SF on the viscosity of the mixture must also be considered. According to the study conducted by Chalah et al. [9], who analysed the rheological properties of cementitious paste with different SF content and a low water-to-cement ratio (W/C = 0,35), the consistency index of the cementitious paste increased from 15 to 20 Pa, for the sample without and with 10 % of SF addition, respectively. However, several studies have indicated that the use of NP in ordinary Portland cement (OPC) slightly decreased the workability of the mortar [10], and the addition of GGBS improved the fluidity of the cement paste [11].

Recently, several studies have investigated the effects of SF on the properties of cementitious materials. Luo et al. [12] studied the effect of the SF content on the properties of concrete in both fresh and hardened states. The studied properties were improved by increasing the compressive strength and reducing the number of capillary pores; thus, a more compact concrete was obtained compared to the control concrete. Uzbas and Aydin [13] investigated the effect of SF addition on the microstructure of ordinary concrete at a W/C ratio of 0,6. The results of this study indicated that the optimal amount of SF, which involved the densest structure, was estimated at 15 %. Moreover, Sharaky et al. [2] studied the influence of both SF and nano-silica on the compressive strength of concrete manufactured with cement contents of 300, 400, 500, and 600 kg/m^3, 0,35 to 0,70 W/C ratios, and cured for 28 d of hydration. With regard to the addition of a high amount of SF in the cement, Hanumesh et al. [14] manufactured an ordinary concrete by substituting OPC with different concentrations of SF, up to 20 %. The results of this study indicated that the optimum concentration obtained for SF addition was 10 %. In this case, the obtained concrete had the highest compressive strength on all the curing days (7, 28, 56, and 90 d). Simultaneously, Bhanja et al. [15] studied the effect of SF on the splitting-tensile strength of HPC by replacing different amounts of cement with SF from 5 % to 25 %. In this study, the W/C ratio varied from 0,26 to 0,42. The authors concluded that using recycled aggregates in cementitious materials was advantageous. Following this approach, Cakır and Sofyanlı [16] investigated the effects of incorporating SF at 5 % and 10 % to improve the properties of ordinary fluid concrete elaborated with recycled aggregates. In this study, compressive strength, tensile splitting strength, water absorption, and ultrasonic pulse velocity were investigated. On the other hand, Koting et al. [17] examined the mechanical behaviour of cementitious pastes containing 5 % and 10 % of SF as a replacement for OPC. Compressive strength tests were conducted after 1, 3, 7, and 28 d of hydration. This study was completed using a workability test in two cases with W/C ratios of 0,35 and 0,50. Campos et al. [18] investigated the effect of SF on the compressive strength of mortars, where the W/C ratio was fixed at 0,30. Hamada et al. [19] evaluated the combined effects of SF and fly ash powders on

the mechanical and microstructural properties of sustainable concrete. They concluded that the presence of SF significantly improved the compressive strength of the studied concrete.
Based on a literature review of the effects of SF on the general properties of cementitious materials, it appears that there are few studies that explain the existing correlation between mechanical resistance, durability, and the use of an adequate quantity of SF, particularly in the case of HPSC. In addition, few studies have been conducted on the effect of adding SF to HPSC. In this study, different amounts of SF were added for the substitution of OPC to elaborate HPSC with a 0,35 W/C ratio (4 %, 6 %, and 8 % by weight of cement). Furthermore, this study aimed to clarify the relationship between the amount of SF and the properties of HPSC by evaluating the compressive strength, flexural strength, water absorption by immersion, and capillary water absorption. Thus, the optimal amount of SF that results in good mechanical and water absorption properties of HPSC was also investigated.

2 Materials and methods

2.1 Materials

OPC noted CEM I 52,5 N, conforming with the European Standard EN 197-1 [20], was used in this study (see Figure 1-a), with a blain specific surface area of 350 m^2/kg.
SF (Figure 1-b) is a grey-white powder produced during the smelting of ferrosilicon alloys and industrial silicon. It is a non-crystallised by-product with good reactivity to OPC. In this study, CONDENSIL S95 DP product based on SF, procured from “Sika Company,” with a particle size in the range of 0,02–0,28 μm and a specific surface area of 23000 m^2/kg, was used.
Crushed sand (Figure 1-c) with a fineness modulus of 2,8 and dune sand (Figure 1-d) with a fineness modulus of 1,1 were used. The bulk density and specific gravity of the dune sand were 1620 kg/m^3 and 2,60, respectively. The crushed sand was characterised by a bulk density and specific gravity of 1560 kg/m^3 and 2,55, respectively.
“Sika ViscoCrete TEMPO-12” superplasticiser supplied by the Sika company was selected for its good properties. This product was an acrylic copolymer-based organic additive (SP) with a solid content of 30 % (Figure 1-e). It should be noted that the use of the superplasticizer provides good stability for concrete fluidity.

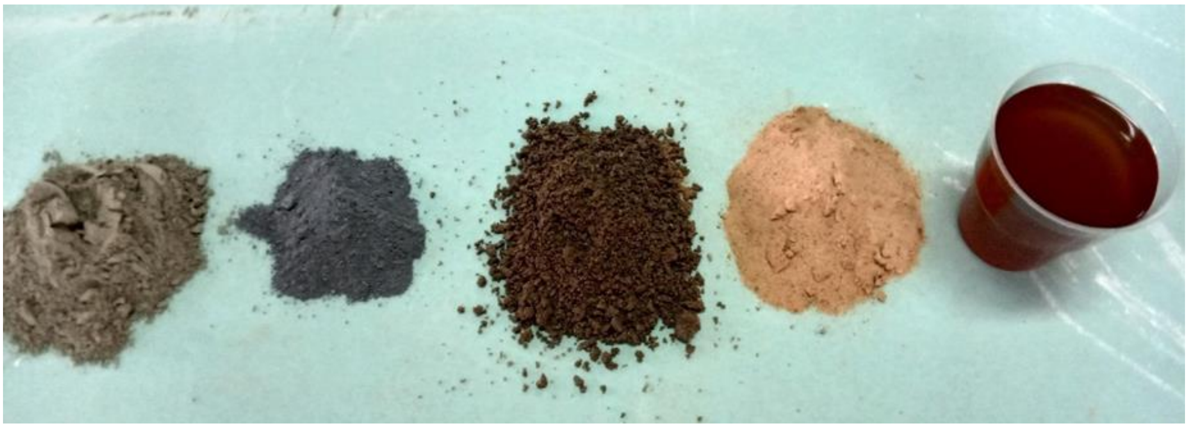

Figure 1. Raw materials used to prepare high-performance sand concrete: (a) ordinary Portland cement, (b) SF, (c) crushed sand, (d) dune sand, and (e) superplasticizer

2.2 Mixture proportions and sample preparation

The manufacturing of HPSC requires high quantities of cement, SF, and a superplasticizer. In this study, four combinations were prepared with the following notations: F0, F4, F6, and F8, for 0 %, 4 %, 6 %, and 8 % of SF by the total weight of cement, respectively. In this study, a W/C ratio of 0,35 was applied to all the prepared HPSC. Considering the low W/C ratio selected and the EN 197-1 standard [20], which limits SF addition to 10 %, the higher concentration of SF addition used was limited to 8 % by weight of cement.

The workability of the different studied mixtures was estimated from the flow spread diameter of the fresh HPSC using a mini-MBE cone (Mortiers de Béton Equivalent) [21]. In this case, the flow-spread diameter of the mixture was 20 cm. The proportions of the al mixture used are listed in Table 1.

Table 1. Mixtures proportions of HPSC (kg/m^3)

HPSC	**Composition** (kg)						**Mixtures' parameters**		
	Crushed sand	**Dune sand**	**Cement**	**SF**	**Water**	**SP**	**S:C**	**W/C**	**Spread diameter** (cm)
F0	1230	410	545	0	191	10,9	3:1	0,35	20
F4			525	22		11,5			
F6			514	33		12,1			
F8			503	44		12,7			

2.3 Test procedures

2.3.1 Compressive strength test

The compressive strength of the HPSC was determined using cubic samples of 40 × 40 × 40 mm in size. For this analysis, three specimens were tested to estimate the average values. All samples were cured for 3, 7, and 28 d before testing using an MTS criterion model 45 machine (Minneapolis, MN, USA) with a crosshead loading capacity of 300 kN (Figure 2-a). The compressive strength of the HPSC cured at different ages was determined based on EN 12390-3 [22].

2.3.2 Flexural strength test

Flexural strength tests were conducted for prismatic cementitious specimens (40 × 40 × 160 mm) based on EN 12390-5 [23] after 3, 7, and 28 d (Figure 2-b). All the samples were tested using an MTS machine (criterion model 45, Minneapolis, MN, USA) with a crosshead loading capacity of 50 kN. The top of the testing machine was equipped with a steel roller, and the bottom was equipped with two rollers. Thus, the flexural strength for three-point bending was calculated as indicated in the test standard.

2.3.3 Water absorption test

The water absorption test was performed using the immersion method according to the ASTM C642 standard [24] on prismatic specimens measuring 40 × 40 × 160 mm. The test was achieved on the specimens cured for 28 d of hydration age (Figure 2-c). The average value was obtained from three measurements performed on three specimens for each mixture. First, the samples were oven-dried at a temperature of 50 °C until their dry masses were obtained (Md). The increase in the mass of the HPSC samples resulting from the absorption of water over 48 h was estimated (Mw). Finally, water absorption was calculated using the total immersion method, as indicated in the ASTM C642 standard.

2.3.4 Capillary water absorption test

The capillary water absorption was evaluated on prismatic specimens measuring 40 × 40 × 160 mm, which were cured for 28 d of hydration age (Figure 2-d). Measurements were performed based on the EN 480-5 standard [25]. During this test, the face down was used in contact with water in a tray, and the temperature was 20 ± 2 °C. Three samples for the capillarity test were prepared for each HPSC mixture, and the average value was calculated from three measurements.

Water uptake was measured by weighing the specimens at different intervals: 10 min, 90 min, 4 h, 1 d, 4 d, 7 d, and 14 d. The test consisted of measuring the mass of capillary water at specific time intervals. Capillary water absorption was determined based on the equation shown in the EN 480-5 standard.

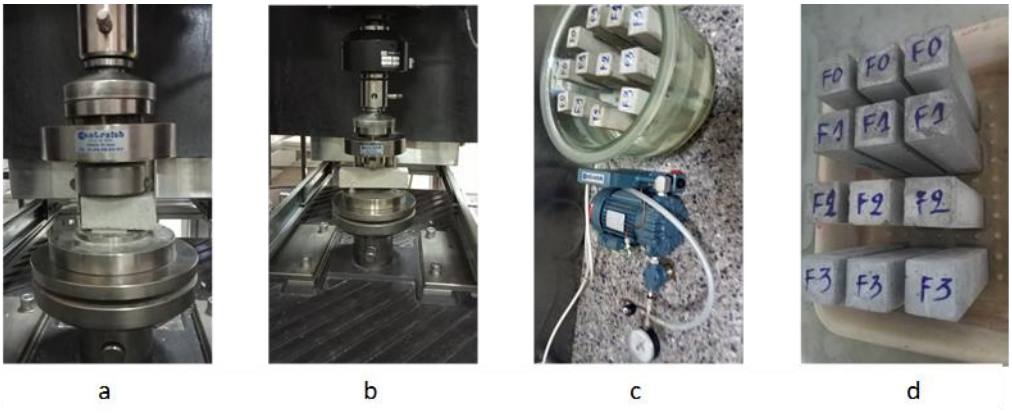

Figure 2. Photographs of the tests (a) compressive strength test, (b) flexural strength test, (c) water absorption test, and (d) capillary water absorption test

3 Results

3.1 Compressive strength

The compressive strengths of the HPSC samples cured at different hydration ages are listed in Table 2. The results indicate that the compressive strength of HPSC increased by increasing different amounts of SF from 4 to 8 % after 28 d of hydration, which is in accordance with Tak et al. (2023) [26]. According to Lee et al. [27] and Koting et al. [17], the compressive strength of cementitious grout containing SF increased with increasing SF concentration and hydration age. They indicated that this improvement was mainly owing to the supplementary CSH produced in the presence of water, amorphous silica, and calcium hydroxide. However, at early hydration ages, particularly after 3 and 7 d of hydration, the compressive strength of the reference sample (F0) was greater than that of all HPSC samples with SF additions (F4, F6, and F8), as shown in Figure 3-a. This result was confirmed by Umar et al. [28], who indicated that the compressive strength of concrete with SF was lower than that of concrete without SF after a curing age of 3 d.

Figure 3-b shows the development of the compressive resistance as a function of the SF content. The compressive strength of the HPSC without SF (F0) is considered a reference value (0 %). The improvement in this property for the samples cured after 28 d of hydration age was 2,19 %, 6,19 %, and 7,22% for 4,00 %, 6,00 % and 8,00 % of SF addition, respectively. However, the concrete exhibited a decline in compressive strength after 3 d of curing. The decreases in compressive strength were 3,75 %, 5,68 %, and 6,94 %, with the addition of 4 %, 6 %, and 8 % of SF, respectively. Moreover, there was no significant difference in compressive strength between the samples of HPSC with 6 % and 8 % of SF addition cured after 28 d of hydration age.

Similar study was conducted by Nagrockiene et al. [29], who added SF as replacement addition of OPC with different amounts (2,5 to 10,0 %) and 0,47 of W/C ratio. The authors indicated that the compressive strength of samples cured at 28 d of hydration age increased slightly from 10,1 to 13,4 % when the amount of SF increased from 7,5 to 10,0 % compared to the sample without SF. Koting et al. [17] observed that at 28 d of hydration age, the samples based of cement mixed with SF increased strongly in compressive strength from 26 to 30 % for samples with adding SF amounts of 5 % and 10 %, respectively.

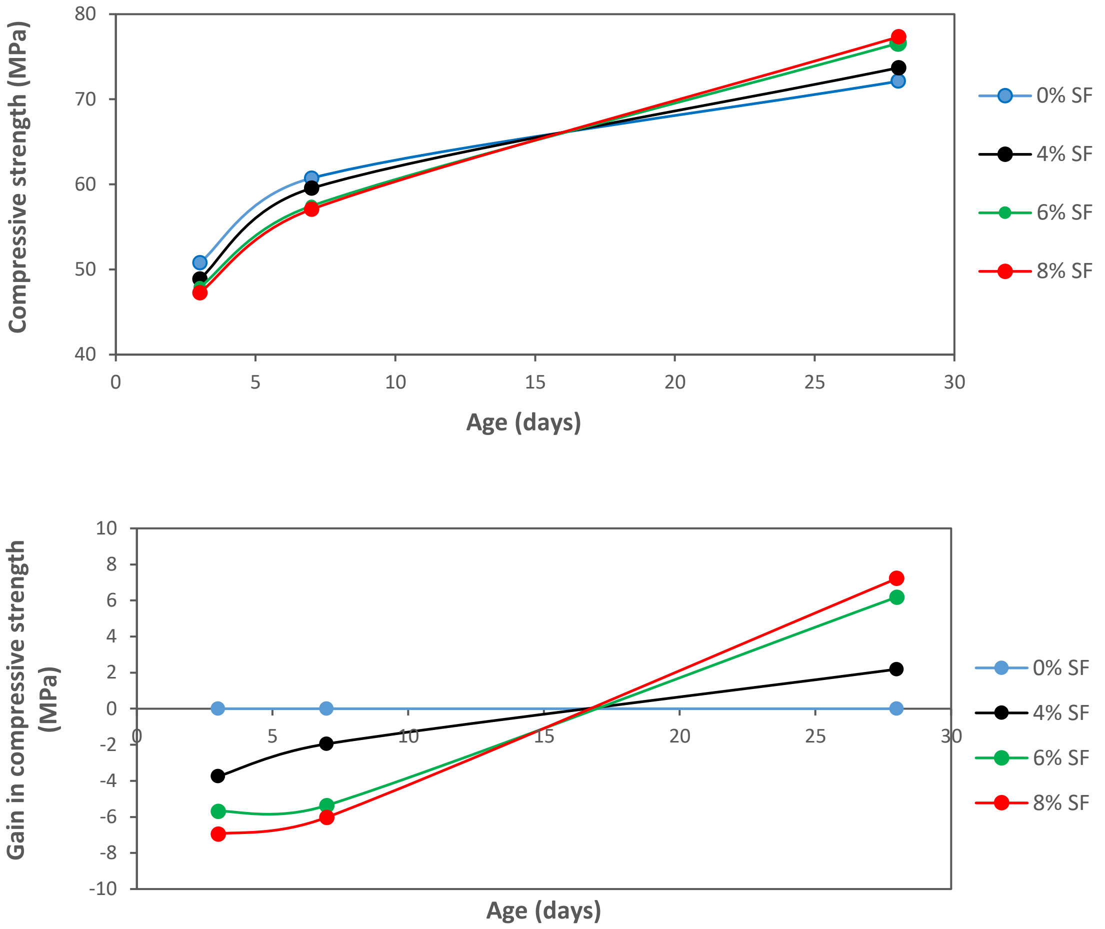

Figure 3. Compressive strength versus hydration time and SF amount: (a) development of compressive strength and (b) gain in compressive strength

Table 2. Compressive strength and flexural strength values of HPSC

Samples	Compressive strength (MPa)			Flexural strength (MPa)		
	3 days	7 days	28 days	3 days	7 days	28 days
F0	50,80 ± 0,18	60,73 ± 1,03	72,12 ± 3,45	10,81 ± 0,54	11,49 ± 0,59	12,26 ± 0,29
F4	48,89 ± 1,19	59,54 ± 1,09	73,70 ± 1,63	10,45 ± 0,06	11,3 ± 0,56	12,75 ± 0,15
F6	47,91 ± 1,09	57,47 ± 2,78	76,59 ± 2,24	9,88 ± 0,42	11,17 ± 0,45	13,49 ± 0,24
F8	47,27 ± 2,89	57,07 ± 2,16	77,33 ± 1,07	9,68 ± 0,47	10,89 ± 0,85	13,76 ± 0,32

3.2 Flexural strength

Figure 4 shows the results obtained for the flexural strength of all the mixtures cured for 3, 7, and 28 d of hydration. It is evident that the development of flexural strength followed a similar trend to the results obtained for compressive strength. The evolution of flexural strength as a function of hydration age was investigated for all the HPSC samples. The evolution curves of F4, F6, and F8 did not exhibit the same tendency as that of the control HPSC (F0). Figure 4-a clearly indicates that the F4, F6, and F8 curves remained below the reference curve (F0) at 3 d and closely matched the F0 curve at 7 d. However, after 28 d, the compressive strengths of the F4, F6, and F8 HPSC were greater than those of the reference HPSC (F0). The increase in the SF content decreased the flexural strength of the HPSC (F0) at an early age, whereas at 28 d the resistance improved.

Figure 4-b shows the evolution of flexural strength versus SF content. The resistance of the HPSC without SF (F0) was used as the reference value (0%). When 4, 6, and 8 % SF replacement cement were added, the flexural strength of HPSC improved by 3,99, 10,03, and 12,23 %, respectively. However, samples cured for 3 d of hydration ages showed a decline in flexural strength values; the values presented decreased by 3,33 %, 8,60 %, and 12,23 % in the presence of 4 %, 6 %, and 8 % of SF addition, respectively. In addition, the results showed that the F8 sample had no significant improvement in flexural strength compared to the F6 sample after 28 d of hydration.

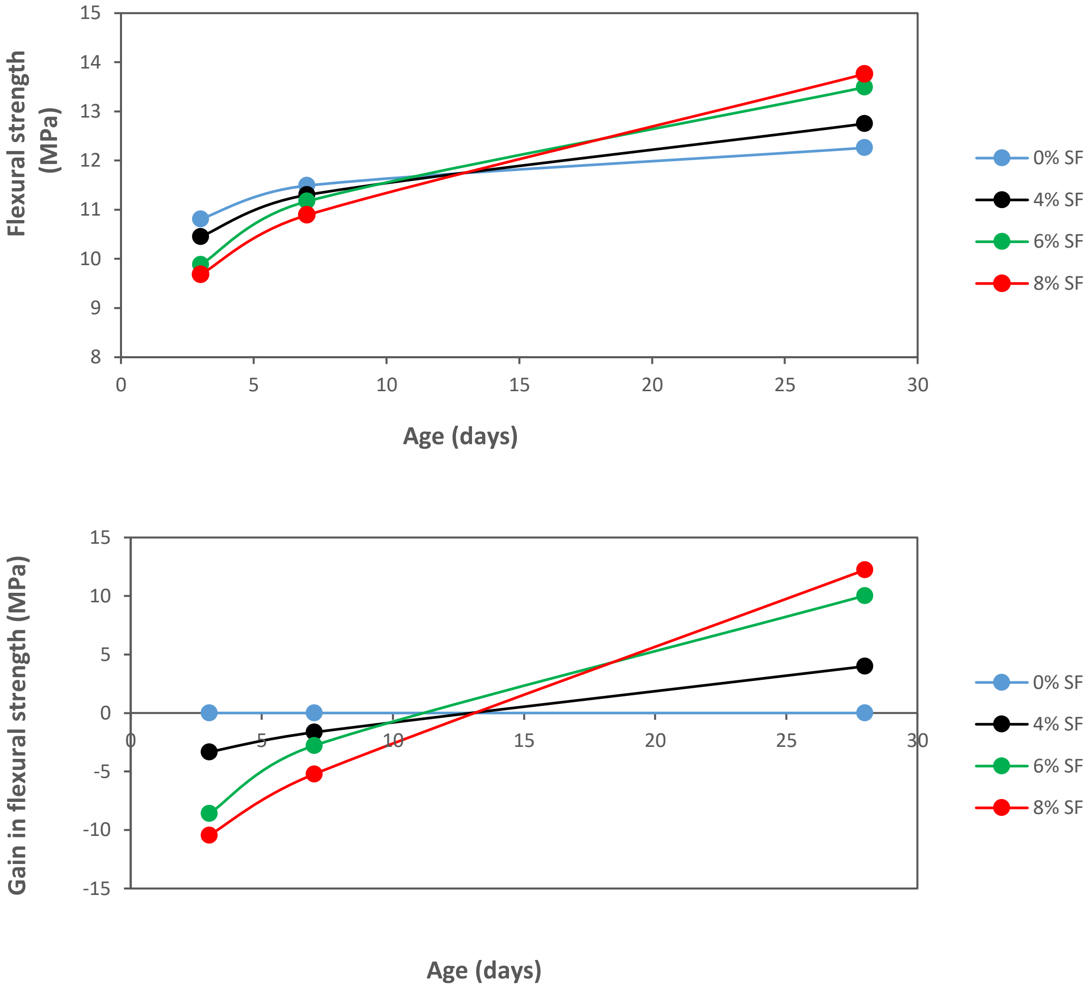

Figure 4. Flexural strength versus the hydration age and SF content: (a) development of flexural strength and (b) gain in flexural strength

Figure 5-a shows a regression analysis of the compressive strength versus SF addition for samples cured at different hydration ages. In addition, Figure 5-b shows the regression analysis of the compressive strength curves related to the different hydration ages (3, 7, and 28 d) versus the SF amounts. Regression analysis showed a linear relationship between the compressive and flexural strengths. Moreover, the evolution of the mechanical strength was inversely proportional to the increase in the quantity of SF after 3 and 7 d of hydration. These observations are consistent with those of previous studies [30, 31].

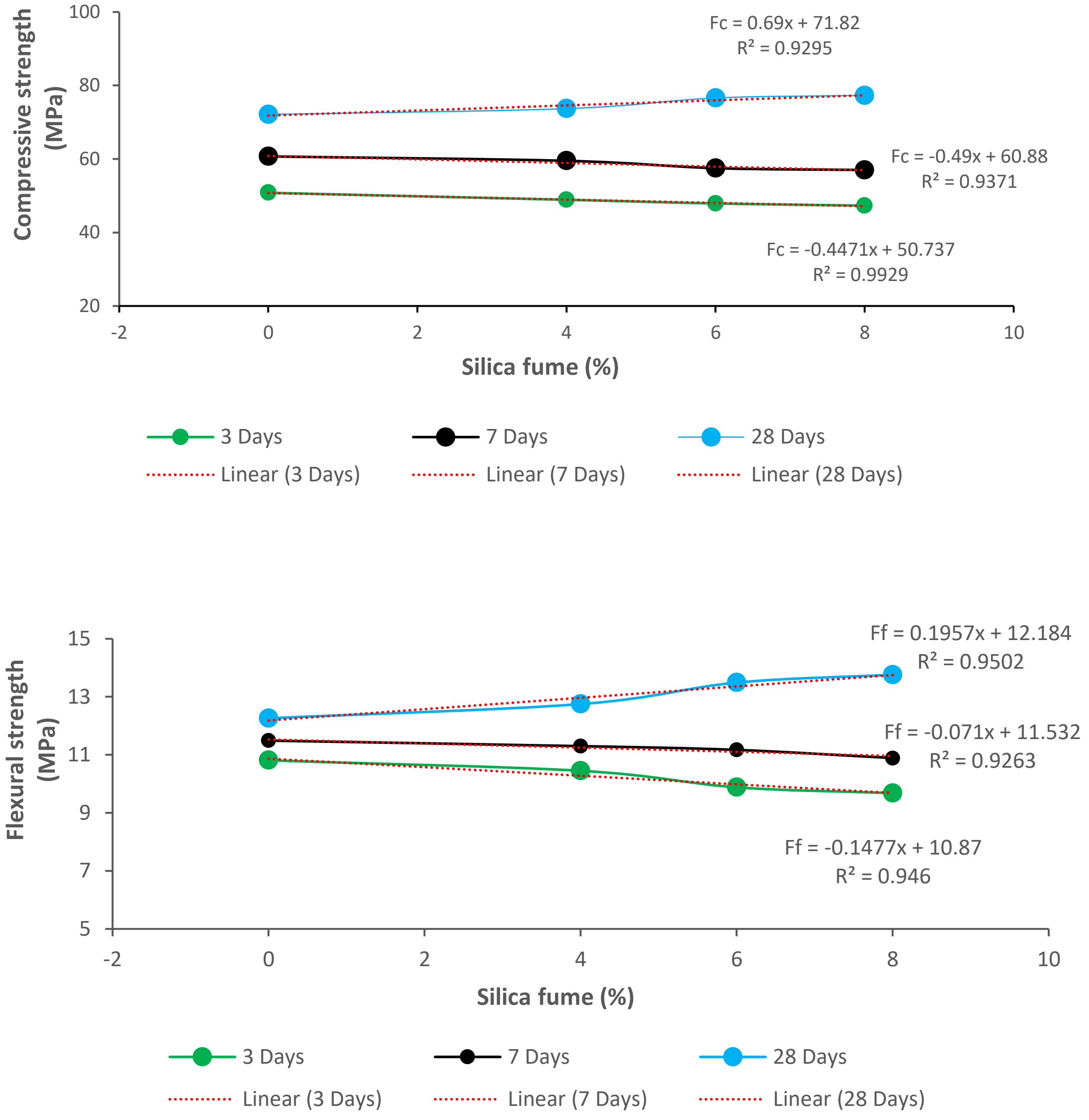

Figure 5. Regression of mechanical strength as a function of hydration age (a) in compressive strength and (b) in flexural strength

3.3 Water absorption

The effect of the SF content on the water absorption of the HPSC is shown in Figure 6-a. The addition of SF increased the resistance of HPSC to water penetration. The results also showed that water absorption was reduced by 5,28 and 8,80 % for samples with 6 and 8 % SF additions, respectively. Lee et al. [27] showed that the addition of SF to cement mortar resulted in low water absorption. This result was confirmed by Sharaky et al. [2]. SF has finer particles, which causes a denser cementitious structure [32]. Consequently, SF generally causes a decrease in pore size, which involves a reduction in water absorption [33]. According to Cakır and Sofyanlı [16], the addition of SF (10 %) in concrete manufactured with recycled aggregate significantly reduced the mass of absorbed water.

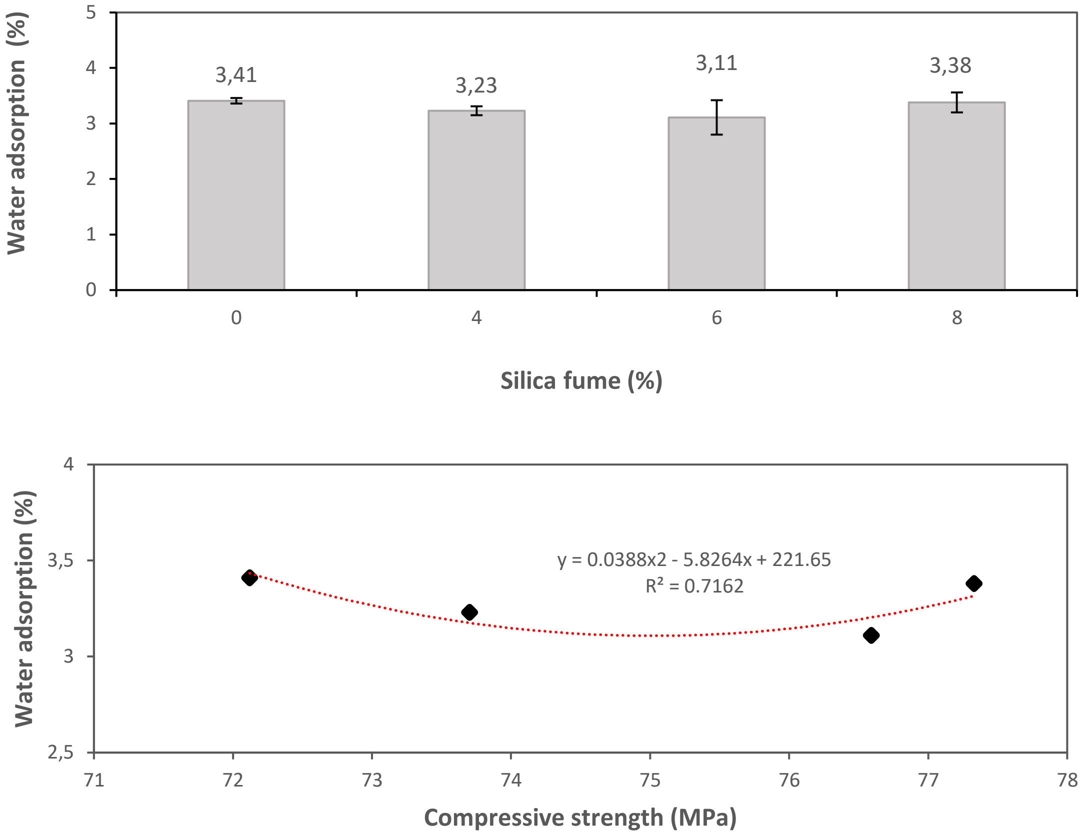

Figure 6. (a) Effect of SF on the water adsorption of samples cured for 28 d, and (b) the relationship of water absorption with compressive strength values

The relationship between the compressive strength and water absorption of the HPSC is shown in Figure 6-b, with an R-squared coefficient of 0,7162. The trend curve of the compressive strength showed a polynomial relationship with water absorption. When 6 % (F6) of SF was added, the amount of water absorbed became the lowest. Subsequently, by adding 8 % of SF contents to the mixture, the compressive strength was slightly increased, and the F8 sample absorbed a small amount of additional water.

3.4 Capillary water absorption

Table 3 lists the results of capillary water absorption in terms of time for the different specimens cured for 28 d of hydration age. Based on the experimental results of the capillary water investigation, it can be observed from Figure 7 that the weight of the capillary water of the specimens with SF was lower than that of the samples without SF (F0). Similar to the results obtained for the water absorption test, the capillary water absorption values of HPSC specimens decreased with SF contents, particularly for specimens with concentrations higher than 6% of SF. From the results indicated in Figure 7-a, it can be observed that capillary water absorption decreased by 4,93, 8,57, and 0,26 % for samples with SF additions of 4, 6, and 8 %, respectively. According to the Cakır & Sofyanlı [16] results, the capillarity coefficient values of concrete containing the recycled aggregate decreased significantly in the presence of SF.

The relationship between the results obtained for compressive strength and capillary water absorption is shown in Figure 7-b. The results indicated that the same tendency was observed in the results of the absorption test by immersion. Certainly, lower capillary absorption values were obtained for the samples with a SF of 6 % (F6). In addition, the compressive strength showed a polynomial relationship with capillary water absorption. In contrast, the addition of 8% of SF contents has negative effect on the capillary water absorption properties.

Table 3. Capillary water absorption values

Time ($min^{0,5}$)	**Capillary water absorption** (kg/m^3)			
	F0	F4	F6	F8
3,16	0,08	0,12	0,14	0,14
9,48	0,35	0,45	0,55	0,62
15,50	0,52	0,66	0,71	0,84
37,94	1,43	1,59	1,56	1,67
75,89	2,57	2,50	2,48	2,50
100,39	3,01	2,95	2,87	2,95
141,98	3,84	3,66	3,52	3,85

During hydration, the addition of SF reduced the size of capillary pores through a chemical reaction with calcium hydroxide ($Ca(OH)_2$) which involved the formation of calcium silicate hydrate (CSH). Consequently, the increase in the compressive strength values in this case was mainly owing to the structural density and high development of CSH. The average particle size of SF is approximately 0,15 µm, which is 100 times finer than cement powder.

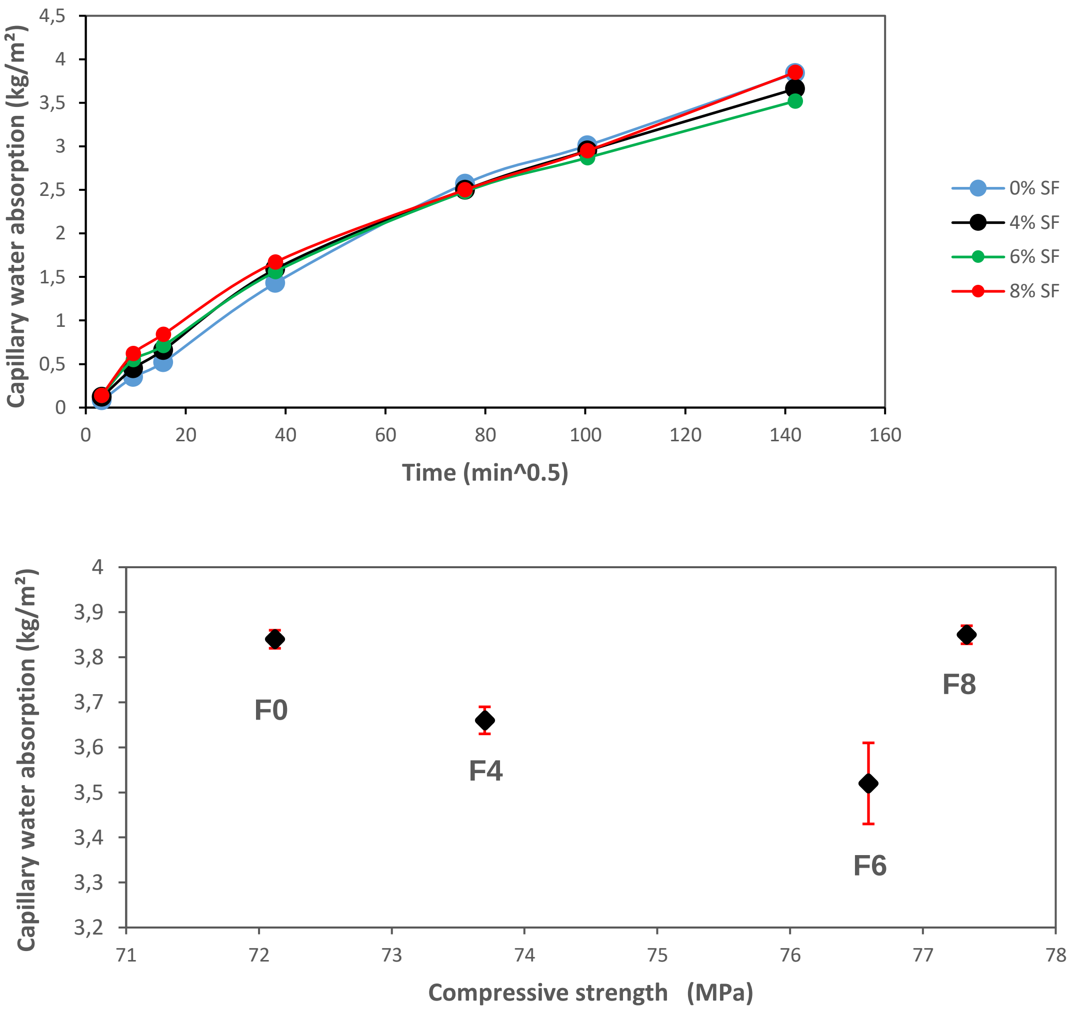

Figure 7. Effect of SF on capillary water absorption (a) kinetic of absorption and (b) relationship between absorption and compressive strength

4 Discussion

In general, SF substitutes for OPC in concrete formulations as a mineral additive to produce high-performance cementitious materials. SF is an ultrafine material composed of round particles with an average diameter of 0,15 µm. They are approximately 100 times smaller than average cement particles [34]. Therefore, it is possible to optimise the granular stacking and improve the adhesion of various constituents of concrete, which strongly affects the mechanical properties, such as the compressive and flexural strengths. However, these advantages are mainly related to the amount of SF added to the OPC, because excessive use of SF negatively affects the properties of the cementitious material. SF occupies not only the vacuum created by cement particles but also the spaces between them, thus creating new micropores. Recently, Campos et al. [18] confirmed that the addition of SF as a partial replacement for OPC improved the density by filling small cavities in the cement structure, thereby improving the compressive strength.

When SF partially substitutes cement, initially, there is no reaction with calcium hydroxide, and it remains inert. Thus, this effect reduces the heat related to cement hydration, which explains the low mechanical resistance at an early hydration age [35-37]. Once the OPC and water start reacting with each other, the primary chemical reactions produce CSH and calcium hydroxide, also known as free portlandite. However, calcium hydroxide is not available in the early stages, and its presence is usually noticed after 7 d of hydration [28]. In addition, using a superplasticiser can delay the setting of cement and, consequently, its hardening. These phenomena explain why the addition of SF to the mixture reduces the mechanical strength at an early stage of hydration. However, the presence of SF improved the compressive and flexural strengths of the HPSC cured for 28 d of hydration. Thus, a large amount of SiO_2 reacted with $Ca(OH)_2$ in a secondary hydration reaction to produce more CSH gels, which filled the pores in the cement structure [38].

Moreover, the incorporation of SF into cementitious mixtures improves the adhesion of cement to aggregates [17]. Indeed, the presence of ultrafine particles such as SF limits the water content around the aggregates and generates more CSH. Therefore, the CSH gel adheres better to the surface, creating a stronger cementitious product.

Figure 8 shows a general overview of both the pozzolanic and filler effects when SF is added to OPC. The pozzolanic reaction that occurred between SF and $Ca(OH)_2$ led to an increase in the amount of CSH formed in the many vacancies around the hydrated cement particles, which filled the pores. This additional CSH provides HPSC with improved compressive and flexural strengths and a denser cementitious matrix. The use of SFs to obtain compact cementitious structures limits the penetration of water into the material, which is directly related to its durability.

Regarding water absorption by immersion and capillarity, the optimum amount of SF adequate for the studied HPSC was 6 %. For this purpose, Sharaky et al. [2] showed that the maximum amount of added SF is 5 %, and by adding 10 %, the samples cured for 28 d showed a decrease in compressive strength, but still remained higher than that of the control mixture. Bhanja et al. [15] concluded that the optimum splitting-tensile strength was achieved for the 28-day hydration concrete at replacement levels in the range of 5-10 %. In another study conducted by Hanumesh et al. [14], the optimal amount of SF added to concrete was estimated at 10 %, and the W/C ratio was fixed at 0,45. In addition, Koting et al. [17] noted that using 5 % SF in OPC was an adequate amount to increase the paste’s performance. Based on the results obtained by Cakır and Sofyanlı [16], the recycled aggregate concretes incorporating 10 % of SF showed better performance. Contrary to the cited studies, Uzbas and Aydin [13] concluded that the optimal content was 15 %, whereas the standard limited its use to 10 %. This was probably owing to the use of a large W/C ratio.

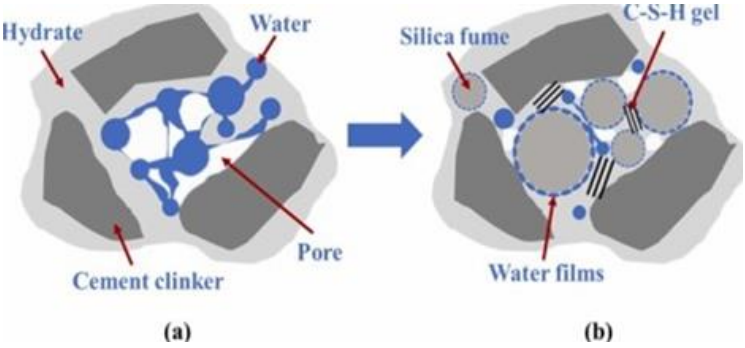

Figure 8. Microstructure of cement paste: (a) without SF and (b) with SF [12]

5 Conclusion

Based on the results obtained in this study, the following conclusions can be drawn:

1. The compressive and flexural strengths of the samples containing SF were significantly higher than those of the reference sample (F0). In contrast, the addition of SF to the mixture had a negative effect on the mechanical properties of concrete at an early age of hydration.
2. The addition of SF improved the mechanical properties of the HPSC after 28 d of hydration. Indeed, an optimal amount of SF was obtained at 6 % by weight of cement, which involved an increase in both compressive and flexural strengths of 6,19% and 10,03%, respectively. However, the addition of SF at concentrations greater than 6% had no significant effect on the mechanical properties of HPSC samples.
3. Based on the water adsorption results, it appears that SF increased the resistance of the HPSC to water penetration at 28 d of curing. The addition of SF at 6 % by weight to cement reduced the water diffusion inside the cementitious structure. Moreover, for the analyses of total absorption and capillarity, the water reductions obtained were 8,80 and 8,57 %, respectively. Moreover, the maximum reduction in absorbed water was achieved at an SF of 6,00 %.
4. According to the different results obtained for the compressive strength, flexural strength, and water absorption of manufactured HPSC with a low W/C ratio of 0,35; the adequate amount of SF for HPSC was estimated at 6,00 %.

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