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INFLUENCE OF USING HIGH VOLUME FRACTION OF SILICA FUME ON MECHANICAL AND DURABILITY PROPERTIES OF CEMENT MORTAR

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Abstract

The high pollution caused by CO_2 emission and the high level of energy consumed during cement manufacturing led the researchers to look for alternative techniques to reduce these environmental effects. One of these techniques includes reducing the content of cement in the mix by replacing it with supplementary cementitious materials such as fly ash, slag, silica fume, and so on. Many previous studies dealt with the utilizing of the high volume of supplementary cementitious materials, such as fly ash and slag. However, limited studies investigated the impact of silica fume on mortar or concrete properties in percentages of more than 30%. Thus, to produce environmentally friendly concrete, this study was performed to investigate the effect of the high replacement level of cement with silica fume on the properties of cement mortar. Six replacement proportions of silica fume (0%, 30%, 40%, 50%, 60% and 70%) were used in this paper. This paper used the flow rate, compressive strength, water absorption, bulk density and volume of permeable voids tests to test the effect of silica fume on different mortar characteristics. The results indicated that the best mixture among all other mixes was found by 50% substitution of silica fume. At this percentage, an enhancement in compressive strength of nearly 83%, 74% and 75% at 7, 28 and 56 days, respectively and an improvement in water absorption resistance by 8% compared to the control mixture were achieved.

Keywords: Bulk density, Compressive strength, High volume fraction, Silica fume.

1. Introduction

Concrete is the most used building material worldwide [1]. It can be used in various construction applications (such as dams, bridges, pavement and buildings). Cement is the major binder substance utilized in the manufacturing of concrete [2, 3]. It is anticipated that the fabrication of cement will be increased by approximately 400% relative to the production levels in 1990 as a result of the considerable expansion in the industry of construction [4].

Carbon emissions have been increased by nearly 30% in the atmosphere over the last century [5], which significantly changed the global climate [6-11] and consequently it caused serious environmental pollution and global warming [12-21]. The cement industry alone is in charge of about 5-8% of the CO_2 emissions worldwide [22-27]. Besides, the cement industry contributes to other air pollutants such as nitrogen oxide, sulphur dioxide, and carbon monoxide [28]. Furthermore, the cement industry generates about 30 million tons per year worldwide of a solid waste material called cement kiln dust [29]; and as it is known that the solid waste treatment requires proper landfills and complicated management plans [30-32]. Therefore, the cement industry has a significant impact on climate change and sustainable development [33, 34]. Additionally, cement manufacture is deemed one of the industries that require intensive energy and associated with the consuming of natural resources. In order to reduce these effects, supplementary cementitious materials (for example silica fume, limestone, fly ash, rice husk ash, and so on) are used as an alternative to cement [35, 36]. Additionally, the sludge of water and wastewater treatment plants, especially from electrocoagulation plants, was recycled in concrete [37-51]. The utilization of such substances in the manufacturing of cement has twofold profits by decreasing the negative environmental impact of cement and can reduce the volume of solid waste [52].

Silica fume (SF) is a by-product material produced during the manufacture of silicon metal in the electrical furnace [53]. SF is a non-crystalline (amorphous) silica. It has a high pozzolanic reaction when used in cement and concrete [53]. Many surveys have been made previously to study the impact of SF on various characteristics of concrete and mortar [54]. Bhanja and Sengupta [55] investigated the effect of SF (within the range of 0% to 25%) on the mechanical performance of concrete with water/binder ratios within the range between 0.26 to 0.42. Compressive and splitting tensile strength tests were executed in that study. It was demonstrated that the concrete compressive strength and tensile strength improved with increasing the SF content. Furthermore, in the same study, it was reported that the optimum replacement proportion of SF was depended on the water/ binder ratio of the mix. Mohamed [56] studied the effect of different percentages of fly ash and/or SF as cement replacement materials on the compressive strength of self-compacting concrete. It was revealed that replacing the cement with 15% SF gave higher strength than those with fly ash and without replacement mixes. A comparison between the effect of SF, fly ash and metakaolin on the mechanical and durability properties of mortar was performed by Mardani-Aghabaglou et al.[57]. It was stated that replacing the cement with 10% SF indicated higher compressive strength and lower water absorption than all other mixes. Çakır and Sofyanlı [58] investigated the influence of SF on the performance of recycled aggregate concrete (RAC). It was concluded that using 10% proportion of SF as cement replacement enhanced the mechanical and physical characteristics and significantly decrease the volumetric water absorption of RAC in comparison with plain RAC.

SF was used in the literature as a cement replacement material within the range (5-30%) [59-61]. Limited studies were conducted with higher replacement ratios (more than 30%). This is owing to the high initial cost of SF as compared with ordinary Portland cement (OPC). However, it was reported previously [62] that though the cost of SF concrete was more than OPC concrete, the environmental assessment indicated that the CO_2 emission was reduced significantly after replacing cement with SF. Additionally, it was stated in the same work [62] that the extended service life and long term benefits might overcome the high initial cost of SF. Therefore, in order to produce environmentally and clean concrete as well as to add some data to the open literature about the impact of high volume fraction of SF on mortar properties, this experimental study is performed. It aims to examine the consequence of the high replacement level of cement with SF (30%-70%) on some mechanical and durability properties of cement mortar. The investigated properties were the flow rate, compressive strength, bulk density, water absorption, and volume of permeable voids.

2. Materials and methodology

2.1. Materials

2.1.1. Binder materials

The materials utilized in the production of mortar were cement and SF. The cement used in this investigation was lime cement (Type CEM II/A-L 42.5R). The fineness and chemical composition of cement (Table 1) conform to the Iraqi standards NO.5 [63]. The initial and final setting times of the cement are shown in Table 2. The SF was purchased from BASF (Baden Aniline and Soda Factory) company. The fineness and chemical properties of SF (which is conformed to ASTM C1240 [64]) are illustrated in Table 1. The properties of SF are adopted from Mozan and Khalil [65]. Where the same materials were used in this study.

Table 1. The fineness and chemical composition of cement and SF.

Oxide	Cement	SF
CaO %	62.1	0.65
SiO_2 %	22.1	90.2
Al_2O_3 %	4.2	0.24
Fe_2O_3 %	3.9	2.4
MgO %	3.3	0.41
SO_3 %	1.9	0.4
L.O.I.	3.1	3.33
Blaine Fineness (m^2/kg)	3600	21000

Table 2. The physical specification of cement.

Property	Value
Initial setting time (min)	105
Final setting time (min)	150

The fineness of the binder materials has a considerable effect on the mechanical performance of the mortar and concrete. Shubbar et al. [66] stated that the compressive strength obtained is increased with the increasing of the fineness of the binder materials. As observed from Table 1 that the SF has higher fineness than the cement, thus it is expected that the presence of the SF would improve the performance of the mortar during the hydration reaction.

2.1.2. Sand

Natural sand was used that graduated to comply with the Iraqi standard NO.45 [67] requirements, the grading of the natural sand is shown in Table 3.

Table 3. The grading of the natural sand.

Sieve opening, mm	Accumulative passing, %
10	100
4.75	100
2.36	100
1.18	75
0.60	36
0.3	23.5
0.15	2.5

2.1.3. Superplasticizer

Superplasticizer called Glenium 54 conforms to ASTM C494 Type A and F [68] was used as a workability adjuster.

2.1.4. Water

Tap water (City of Babylon) was used during this investigation.

2.2. Methodology

The mix proportions for all mixes were 1:2.75 (cement + SF: sand) and the water/binder ratio was fixed as 0.485. Six replacement proportions of SF by weight of cement were used: 0%, 30%, 40%, 50%, 60% and 70%. The mixes details are presented in Table 4.

Table 4. Mix proportion details of the mortar prepared with different proportions of Cement and SF.

Mix symbol	Cement (g)	SF (g)	SF (%)	Sand (g)	Water (g)	Superplasticizer, % of cement
0SF	500	0	0	1375	242	0
30SF	350	150	30	1375	242	0.75
40SF	300	200	40	1375	242	1.05
50SF	250	250	50	1375	242	1.5
60SF	200	300	60	1375	242	2.1
70SF	150	350	70	1375	242	2.5

The procedures provided by ASTM C109 [69] for mixing and compaction were followed for all mixes. The SF was added together with cement and sand, while the superplasticizer was mixed with the mixing water before adding. The flow rate of fresh mortar was measured immediately after mixing as described in ASTM C1437 [70]. The compressive strength, water absorption, bulk density and volume of permeable voids tests were performed for the hardened mortars. The detailed procedures of ASTM C642

[71] were taken into account for measuring the water absorption, bulk density, and volume of permeable voids using Eqs. (1), (2) and (3), respectively:

$$A = \frac{B-C}{B} \times 100 \quad (1)$$

$$G = \frac{C}{D-F} \times 1000 \quad (2)$$

$$V = \frac{D-C}{D-F} \times 100 \quad (3)$$

where,

A : water absorption after immersion (%).

B : the mass of the wet specimen in the air after immersion (g).

C : the mass of the oven-dry specimen in the air (g).

G : dry bulk density (Mg/m^3).

D : the mass of the wet specimen in the air after boiling and immersion (g).

F : the mass of the wet specimen in water after boiling and immersion (g).

Standard 50 mm cubes were utilized for the mortar compressive strength, water absorption and bulk density tests Three test ages were considered for the compressive strength (7, 28 and 56 days) and one age (56 days) for the other tests. A number of 72 cubes (54 cubes for compressive strength test and 18 cubes for water absorption, bulk density and volume of permeable voids tests) were made for this study.

3. Results and Discussions

3.1. Flow rate

Results of flow rates of fresh mortars are presented in Fig.1.

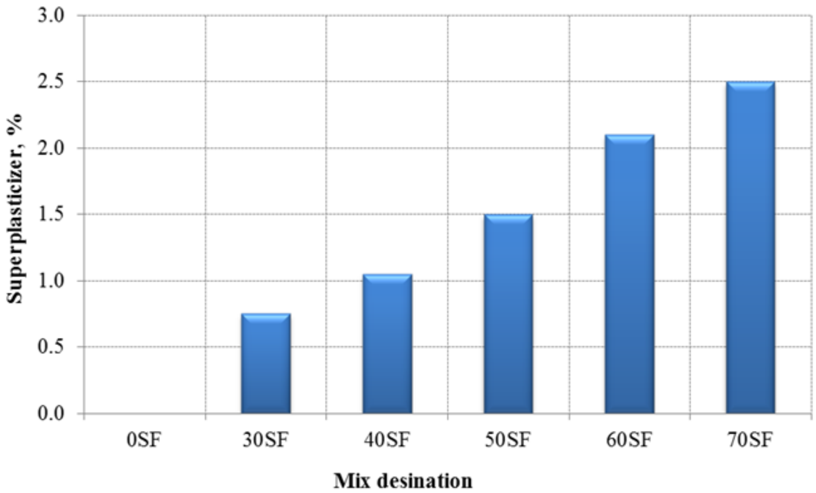

Fig. 1. Variation of Superplasticizer dosage with the content of silica fume in the Mix.

The SP dosage was varied from 0 to 2.5% of cement weight to maintain the flow rate values within the range of 200 ±20 mm. It can be shown from the figure that, for the flow to be within the specified range, the SP dosage was increased with the increase of SF content in the mix. This increase in SP demand is owing to the absorption of SP by SF particles as a result of the high surface area of SF which leads to reducing the available amount of SP in the solution [60].

3.2. Compressive strength

The results of the compressive strength of the mortars after 7, 28 and 56 days of water curing at ambient temperature are presented in Fig. 2.

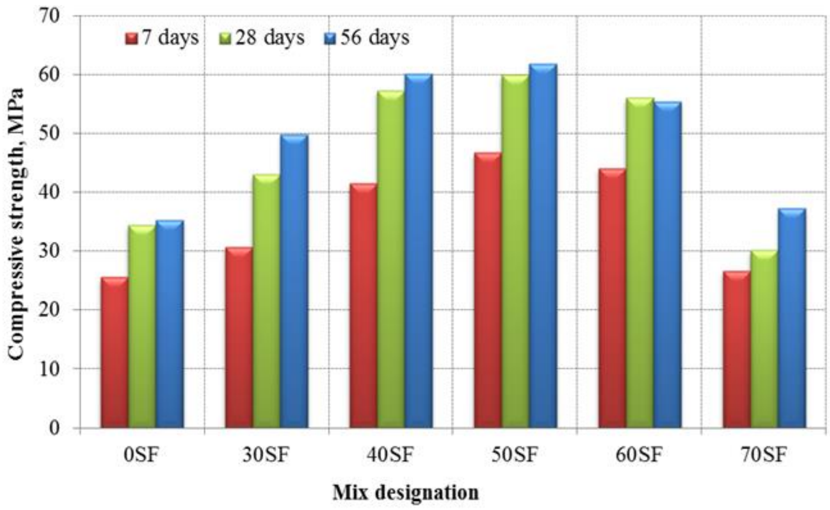

Fig. 2. Compressive strength results of mortar prepared with different proportions of cement and SF after 7, 28 and 56 days of curing.

In general, in a comparison with the control mixture (0% SF), it can be observed that substitution the cement with up to 70% SF enhanced the compressive strength property for all considered ages, except 70% replacement at 28 days which reduces the strength by about 13%. This enhancement in the compressive strength could be a result of the strengthening of the aggregate-paste bond [72] and chemical reaction between SF and calcium hydroxide which produces an additional C-S-H gel that thickens the microstructure and leads finally to strength enhancement [73]. At all curing ages, the maximum enhancement was recorded for mixtures with 50% SF. The improvements related to the control mix were 83%, 74% and 75% at 7, 28, and 56 days, respectively. Although it decreased the compressive strength at the age of 28 days, the mixture with 70% proportion of SF awarded minimum strength increasing than other SF mixtures at 7 and 56 days (about 4%, and 6%, respectively) compared to control mixture.

It can be seen also from Fig. 2 that the development of strength for replacement range of 30%-50% continue approximately in a similar manner at early and later ages. Other meaning, the low content of cement did not have a high effect on the rate of the pozzolanic reaction of the SF. However, beyond 50% substitution of SF (for the 60%-70% replacement levels), the compressive strength of mortar mixtures for all considered ages (7, 28 and 56 days) tended to decrease from its highest value. This behaviour could be attributed to the low content of calcium hydroxide (which represents the main component that reacts with SF in the pozzolanic reaction) in the matrix as a result of the decreasing of cement content that leads finally a part of SF to act as a filler [74].

3.3. Water absorption

The water absorption results of mortars incorporated different proportions of SF as a replacement to cement after 56 days are presented in Fig. 3.

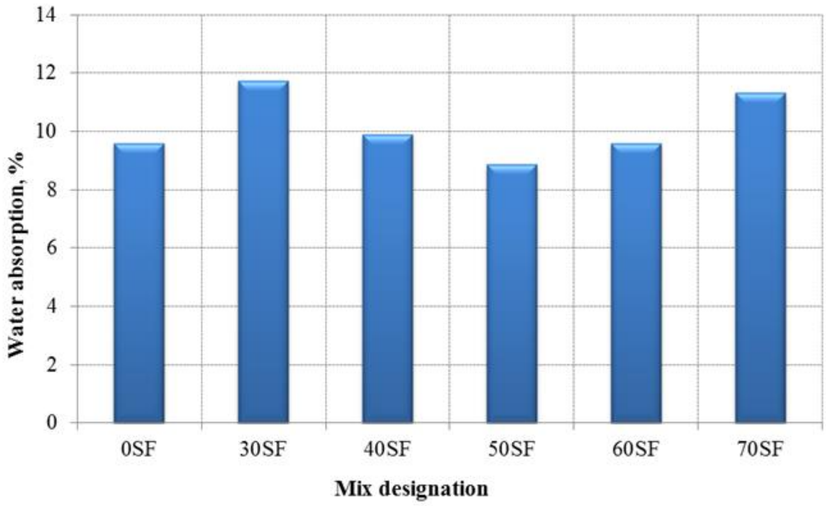

Fig. 3. Water absorption results of mortar prepared with different proportions of cement and SF after 56 days of curing.

Water absorption is considered as one of the main mechanisms (in addition to the diffusion and permeability) by which the transporting of the aggressive agents into the concrete is affected [75]. So, producing concrete with law water absorption is necessary to increase the service life of the concrete. As cleared from Fig. 3 that the mixtures with 30%, 40% and 70% SF have shown higher water absorption rate than that of the control mixture with about 22%, 3% and 18%, respectively. The results also indicated that the mixture with 60% SF has almost the same water absorption relative to the control mixtures. Additionally, Fig. 3 reveals that the mixture with 50% SF reduced the water absorption rate by about 8% relative to the control mixture. These findings were harmonious with the enhancement in the compressive strength gained for the mixture with 50% SF.

3.4. Bulk density

Figure 4 presents the bulk density results for mortars prepared with different proportions of SF as a replacement to cement after 56 days.

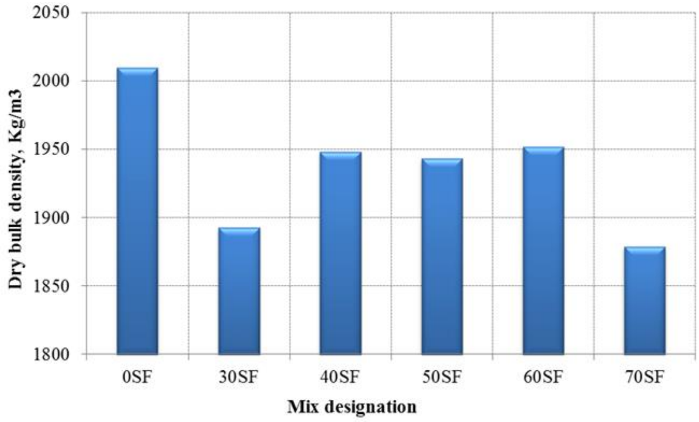

Fig. 4. Dry bulk density of mortar prepared with different proportions of cement and SF after 56 days of curing.

It was found that the replacing of cement with different percentages of SF reduces the bulk density of mortar mixes with disproportionate rates. The lowest density of about 6.5% relative to the control mixture was given by 70% replacement. However, replacing the cement by 30%, 40%, 50% and 60% of with SF caused a reduction in the dry bulk density by about 5.8%, 3%, 3.3% and 2.9%, respectively, in comparison to the control mix. The varying in the density of hardened concrete or mortar are govern by the cement and water contents, the density of aggregate, and the entrapped air or entrained air voids [75]. Therefore, accordingly, replacing the cement with a material with lower specific gravity than cement such as SF can reduce the density of the hardened mortar.

3.5. Volume of permeable voids

The results of permeable pore space (voids) volume for the mortar incorporated different proportions of SF are given in Fig. 5.

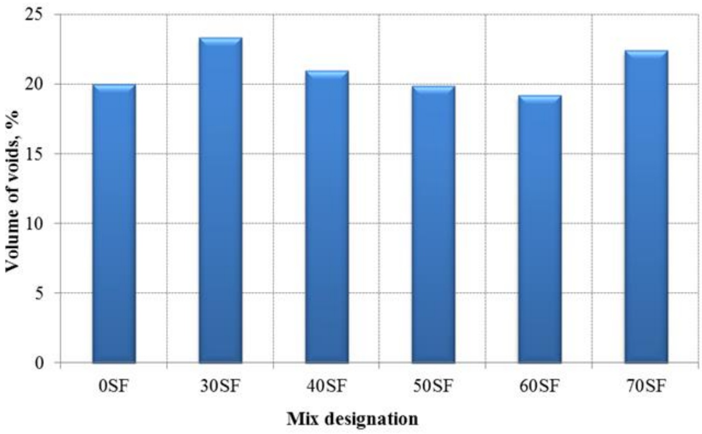

Fig. 5. Volume percent of permeable voids of mortar prepared with different proportions of cement and SF after 56 days of curing.

Results indicated that the higher the SF in the mix up to 60%, the lower the volume of permeable voids. This behaviour is attributed to the filling influence and the pozzolanic reaction of the SF [76]. However, there was no significant decreasing in the volume of permeable voids in comparison with the control mix, where, only 4% was the decreasing rate of the voids volume at 60% replacement of SF, which was the maximum improvement. On the other hand, replacing the cement with 70 % SF led to increase the voids volume by 12% related to the control specimen.

4. Conclusions

This study was conducted with the aim of investigating the impact of using a high volume fraction of SF on some properties of cement mortar. Based on the results of the present study, the following conclusions are noticed:

- The SF increases the superplasticizer demand in the fresh mortar. The higher the SF content in the mix, the higher the SP amount required to maintain the specified flow rate.
- High replacement level of cement with SF up to 50% can significantly enhance the compressive strength of mortar at earlier (7 days) and later ages (28 and 56 days). The optimum enhancement was achieved for the mixture with 50% SF. Where, the increasing rates of compressive strength are 83%, 74% and 75% at 7, 28, and 56 days, respectively in comparison to the control sample.
- Using higher proportions of SF up to 70% increases the water absorption rate of the cement mortar, except the mixture with 50% SF that indicated a lower water absorption rate by about 8% relative to the control mix.
- Replacing the cement with 70% of SF decreased the bulk density of cement mortar by 6.5% related to those mixtures without SF.
- There is no significant enhancement in the volume of permeable pores percent after incorporating a high amount of SF in mortar mixes. The farthest amendment is realized at 60% SF replacement (about 4%) in comparison to the reference sample.
- It can be concluded from this experimental investigation that it is possible to manufacture a green mortar in which the cement can be replaced with 50% SF with a significant improvement in the mechanical properties and water absorption resistance.

Abbreviations

BASF	Baden Aniline and Soda Factory
OPC	Ordinary Portland cement
RAC	Recycled aggregate concrete
SF	Silica fume
SP	Superplasticizer

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