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ARTICLE

Enhancing Concrete Properties Using Silica Fume: Optimized Mix Design

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ABSTRACT

In the current work concrete mixes containing (7.0-33.11) weight % silica fume as fractional substitution of cement with water/cement ratio (0.42-0.48) were formulated conferring to an implemented two factorial central composite design. The samples were water cured for 7, 28, 56, and 90 days. The samples were tested for compressive strength and density. The experimental results approved that compressive strength and density increase with age and with rising silica fume content up to 11.9 wt. %. Response surface analysis results for samples cured for 28 days confirmed that silica fume concrete with developed compressive strength (53.42 MPa) could be prepared by incorporation of 11.9 wt. % silica fume as a substituent for cement using a 0.42 water/cement ratio. An intensification in compressive strength and density (up to 39.3% and 2.6%) respectively was recorded for silica fume concrete mixes in contrast to Portland cement concrete. Overall, the research findings revealed that silica fume concretes prepared with appropriate silica fume content and water/cement ratio exhibited superior strength and density features candidate them to be used effectively in civil engineering structural applications.

Keywords: Silica fume; Silica fume-cement concrete; Response Surface Methodology; Density; Compressive strength; Optimization; Modeling

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1. Introduction

During the last decade, fly ash, granulated blast furnace slag, metakaolin, and silica fume paid a lot of attention and were used widely as supplementary cementitious materials that replace cement [1]. Silica fume is a by-product of the production process of silicon metal and ferrosilicon alloys. SF compose primarily of pure silica in nanocrystalline form. It has a very high content of amorphous silicon dioxide and consists of very fine spherical particles. Silica fume can be used as an additive that is added separately at the concrete mixer or else incorporated into cement during its manufacturing. The concrete composite containing silica fume is a durable construction material. It can be used in numerous applications where durability may be of concern. The durability of concrete is improved by the addition of silica fume due to the permeability reduction, and pore structure refining, lessening the diffusion of harmful ions, and dropping the content of calcium hydroxide which leads to an increase in the sulfate attack resistance [2].

The durability enhancement will also upgrade the ability to protect the embedded steel from corrosion in silica fume concrete [3]. The mechanism involved is due primarily to the high pozzolanic reaction linked with improvement in the interfacial transition zone.

The reaction of water and Portland cement (the hydration process) resulted in the formation of two chemical compounds: Free lime or Calcium Hydroxide (CH), which is a by-product that acts as a filler or discharging out of inferior concrete, and Calcium Silicate Hydrate (CSH), which is the agent responsible for the strength-producing crystallization. Additional CSH is produced from the reaction between the silica fume and the CH (the pozzolanic reaction) that occupy the voids around hydrated cement particles leading to densifying the microstructure of concrete and improving its mechanical strength [4]. However, it was reported that an optimum of about 10% to 15% of silica fume could be replaced in concrete mixes [5-9].

The reaction between CH and SiO_2 is a pozzolanic reaction. The reaction is presented in Equation (1):

$$3Ca(OH)_2 + 2[SiO_2] = [3(CaO).2(SiO_2).3(H_2O)] \quad (1)$$

The pozzolanic reaction of silica fume that proceeds through the consumption of CH has been reported to take place according to the following stoichiometric equation [5]:

$$S + 1.1CH + 2.8H = C_{1.1}SH_{3.9} \quad (2)$$

The bleeding and segregation of concrete are effectively eliminated owing restriction of the mobility of water within concrete due to the high surface area of silica fume particles.

2. Materials

Ordinary Portland cement (OPC) confirming to Iraqi Specifications No. 5, (1984), natural sand passing through a 2.36 mm sieve, gravel passing through a 20 mm sieve, silica fume (SF) purchased from a local market and tap water was used as raw materials in the study. The silica fume sample specifications are shown in **Table 1**. The mix proportion (1:2:4) was used for concrete in the study.

Table 1. The silica fume sample specifications.

Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3
%	90.03	0.91	1.24	0.51	1.64	0.98	0.39	0.46
LOI	2.32							
Specific gravity	2.14							

3. Methodology

Response surface methodology (RSM) was used in this study, it is a statistical means that sightsees the correlations between several descriptive variables and one or more response variables by means of fitting design and analysis of experiments in an empirical way [10]. The two-level factorial design has been applied to elucidate the significant input variables (SF content and w/c ratio) and to optimize and model their effects on some SF-cement concrete hardened properties. The specific and interactive effects of the two variables X1 (silica fume content wt. %) and X2 (w/c ratio) on compressive strength were studied through 10 experimental runs. A polynomial model design is fitted to evaluate the effect of each independent variable on the response. It is represented in Equation (3):

$$Y = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 11x12 + \beta 22x22 + \beta 12x1x2 \quad (3)$$

The response (Y) is correlated to the set of regression coefficients (β): The model intercept is (β0), β1, β2 are linear terms, β12 is the interaction term, and β11, and β22, are quadratic coefficient terms. The regression and graphical analysis of the data were carried out using the software portable statgraphics centurion 15.2.11.0.exe.

The experimental mix design and the experimental results of the average values of compressive strength for the control and SFC samples cured for 7, 28, 56, and 90 days are displayed in **Table 2**.

Table 2. Experimental design and experimental results of average compressive strength.

xp. No.	Silica fume content wt. (%)	W/C	Average compressive strength (MPa)							
			7 days		28 days		56 days		90 days	
			C	SFC	C	SFC	C	SFC	C	SFC
1	15	0.43	25.42	37.51	37.83	48.60	40.11	53.80	41.69	55.12
2	22.5	0.45	24.02	31.23	35.11	40.12	37.05	45.61	38.89	46.98
3	30	0.43	25.42	29.42	37.83	39.31	40.11	43.22	41.69	45.07
4	11.9	0.45	24.02	39.51	35.11	50.33	37.05	52.65	38.89	53.88
5	33.11	0.45	24.02	27.22	35.11	36.32	37.05	40.45	38.89	41.03
6	15.0	0.47	22.11	34.43	33.24	44.52	35.23	47.18	36.17	48.76
7	22.5	0.48	21.04	30.43	31.13	37.84	33.98	44.23	35.54	45.78
8	30	0.47	22.11	28.28	33.24	36.91	35.23	41.54	36.17	42.79
9	22.5	0.42	26.21	32.17	38.88	42.24	41.02	48.44	41.99	49.89
10	22.5	0.45	24.02	31.55	35.11	40.12	37.05	45.65	38.89	46.88
11	7	0.45	24.02	36.22	35.11	46.34	37.05	50.09	38.89	51. 67

C: Control composites, SFC: Cement-silica fume Concrete composites.

4. The properties investigated

The dried 150*150*150 mm cubes of plain concrete and SF-concrete cured for 28 days were used for testing the bulk density. The methodology employed to test the density included the accurate measurement of the cube's weight and volume. The density values of the SF-concrete were taken as the average result of three tests.

A machine for mechanical strength testing model 50-C23C02 with a 2000 KN load capacity was used to test the 150*150*150 mm concrete cubes for compressive strength. The load at a constant rate was applied to the SF-concrete specimen until the specimen failed. The average of three test results for the failure load was documented and was reserved as the compressive strength of the tested cubes.

5. Results and discussion

One of the utmost central constraints in the design of concrete assemblies is compressive strength. It represents the capability of concrete to bear the loads tending to size reduction. The silica fume concrete samples (SFC) prepared at different ages (7, 28, 56, and 90 days) according to the experimental design were tested for compressive strength. Control samples (C) were prepared and tested for compressive strength for comparison purposes. **Table 2** shows the average experimental results of compressive strength.

It is obvious to note that the values of compressive strength increase with curing age and vary with water/cement ratio and silica fume content in the concrete mix. The variation of compressive strength for control and silica fume concrete samples of similar water/cement ratio cured for different periods is shown in **Figure 1**. The compressive strength seemed to rise with increasing the age of the samples. Also, the compressive strength rises with increasing silica fume content in the concrete mix up to a specified certain level. The compressive strength increases up to 11.9 wt. % of silica fume in the concrete mix then a dramatic decline was observed with increasing silica fume content. A similar trend was reported by other researchers [6,11]. Nevertheless, compressive strength values of the mixes containing silica fume are of developed compressive strength related to the reference samples.

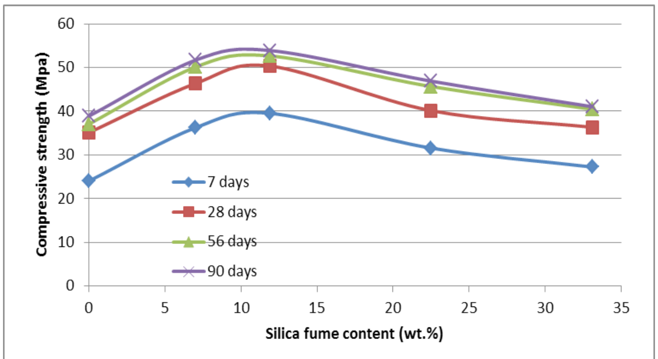


Figure 1. Compressive strength for control and silica fume concrete samples (w/c = 0.45) cured for different periods.

In a comparison of the mixes of optimum compressive strength (containing 11.9 wt. % silica fume) cured at different ages with the control mixes, it can be pointed out that the two mixes showed a more development in compressive strength in the first week, after which the % of developing decreases. The percent gain in compressive strength for concrete mixes comprising silica fume as a substituent to cement with age 7, 14, 21, and 28 days were 39.21, 30.24, 29.63 and 29.31 respectively.

The experimental results were analyzed to inspect the impact of silica fume content on bulk density of the silica fume concrete mixes. It is obvious to note that all mixes were of higher density compared to the control samples. An optimum increase in density of 2.64% was recorded for the mix containing 11.9 wt. % silica fume as shown in **Figure 2**.

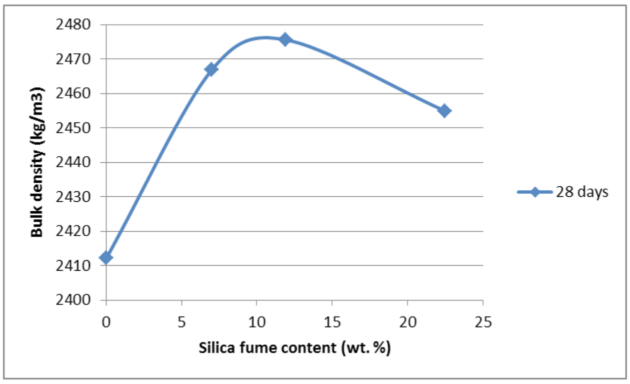


Figure 2. Bulk density versus silica fume strength content for hardened concrete mixes.

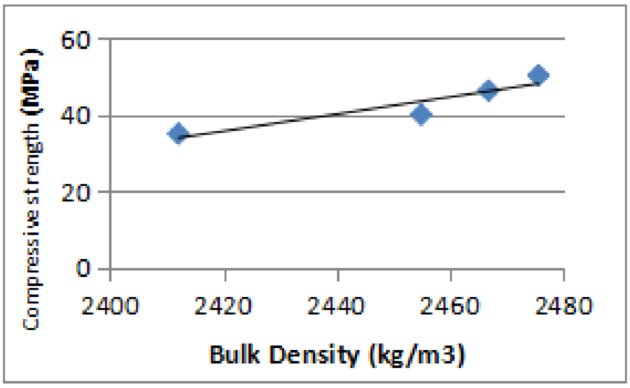


Figure 3. Correlation of compressive and bulk density.

The reasons for the developed strength and density of the prepared silica fume concrete compared to control samples may be attributed to the additional CSH that occupies many of the voids around hydrated cement particles. Also, to fill the spaces between mixed grains with the fine silica fume particles. The additional CSH resulting from the Pozzolanic reaction arises between silica fume and the Calcium Hydroxide, and the mix spaces filled by the small size silica fume particles result in lessening the size of the individual openings and cavities in the mix.

The addition of silica fume beyond 11.9 wt. % in the concrete mix resulted in a decline in compressive strength and density may be ascribed to the high-water absorption of silica fume. The extra added silica fume may result in decreasing the amount of water needed for hydration [12].

An interesting positive mathematical correlation between compressive strength and density was developed (**Figure 3**) with a relatively high regression coefficient (R^2 = 0.8694). The developed relation is presented in Equation (4).

$$Y = 0.2226x-502.95 \quad (4)$$

where Y is compressive strength (MPa), and x is bulk density (kg/m^3).

The experimental results of compressive strength for silica fume concrete cured for 28 days were analyzed statistically by RSM using analysis of variance (ANOVA). This statistical tool has been used successfully for optimization and modeling the properties of concrete composites [13,14]. The results obtained from this study are shown in **Figure 4**. The estimated P-values (less than 0.05) of the factorial model reflect the model accuracy and that the operating variables are statistically significant.

The Pareto chart, normal plot of the standardized effect, response surface and contour plots are estimated from ANOVA. They are used to further justifying of the ANOVA outcomes. The variations of the mean among the high and low values of each factor are verified in the Pareto chart (**Figure 4a**). The extent of slope denotes the intensity of the effects that each factor employs. The response increases for higher levels of that factor when the slope is positive, and vice-versa [10]. The results revealed that the mean strength of fume silica concrete decreases progressively in the direction of silica fume content > water/cement ratio of the silica fume concretes.

The content of silica fume looked to play a key role in affecting the strength of the samples. The negative slope of the influence of silica fume content naked that compressive strength declines with growing silica fume content beyond a certain limit. The water/cement ratio appeared to have a significant impact on the strength of the mixes with the smallest slope line. **Figure 4b** justified the situation.

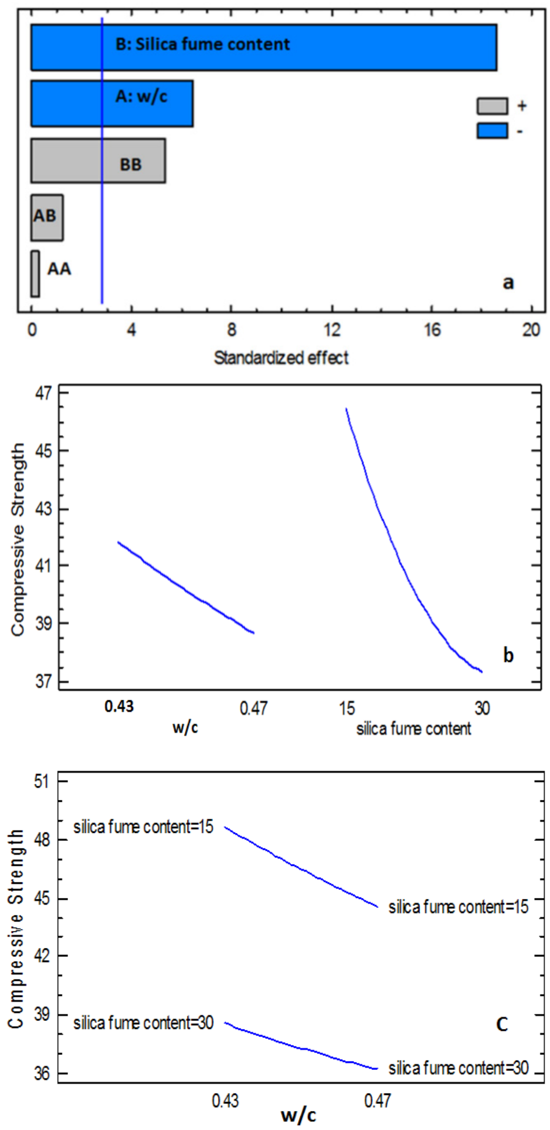
The parallel lines of the two parameters specify the lack of interaction between the parameters **Figure 4c**. The normal probability plot **Figure 4E** shows that the data are assigned normally, as most of the points are closer to the straight line. The insignificant interactions were shown by the non-elliptical nature of the contour plots of **Figure 4F**.

The analysis of the experimental data by the software generates a second-order empirical regression model (5). The model was assessed with a high R-value of 99.06 which imitates the accurate fitness of the model to explicate the practical results.

$$\text{Compressive Strength} = 182.91 - 360.20\,W - 3.28\,S + 240.64\,W^2 + 2.83\,WS + 0.031\,S^2 \quad (5)$$

where S is the silica fume content (wt. %), W is the w/c ratio. An optimum value of compressive strength = 53.42 MPa was valued from the analysis of the model matching to 11.9 %wt. silica fume and 0.42 w/c.

The RSM approach was applied successfully for the optimization and modeling of the mix design and properties of modified concrete and mortars [22,23].



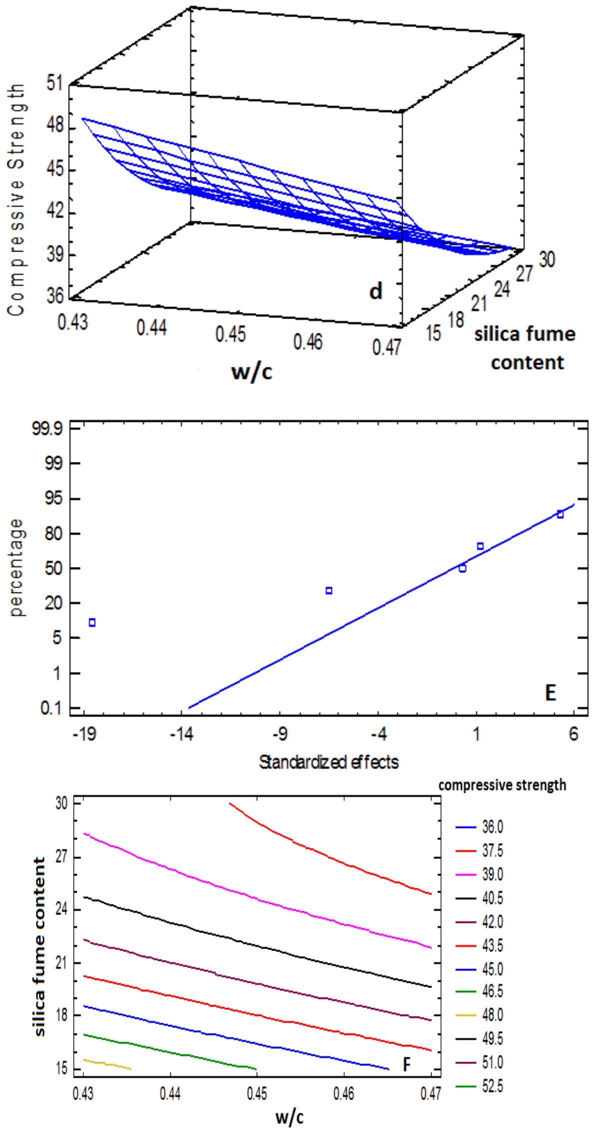


Figure 4. Pareto chart (a), standardized effects plot (b), interaction plots (c), 3-D response surface (d), Normal probability plot (E), and 2-D counter plot (F) for compressive strength.

On the other hand, the morphology of typical control concrete and SF-concrete specimens was tested by Scanning Electron Microscopy (SEM). It is well-established that for hardened plain concrete, the micro-texture visualizes that calcium silicate hydrate creates mainly around the cement grains, while calcium hydroxide deposits in the water-filled pores as illustrated in the typical SEM image of the control sample (**Figure 5** on the left). The formation of cement hydration products is obvious, the calcium hydroxide crystals are represented by the light gray irregular shape areas, while calcium silicate hydrate is signified by the dark gray areas and, the pores are implied by the black areas [24].

The SEM image of the SFC sample is shown in **Figure 5** on the right. The Figure illustrates a less porous and denser microstructure that appears as a bulk cluster. The surface is accessible for the s reaction of the binders with water increases owing to the high specific surface area of SF particles, this will hasten the cement hydration and the formation of a big quantity of hydration products. It is noted from the SEM morphological micrograph of SFC sample that most of the voids are properly filled and very dense concrete is formed.

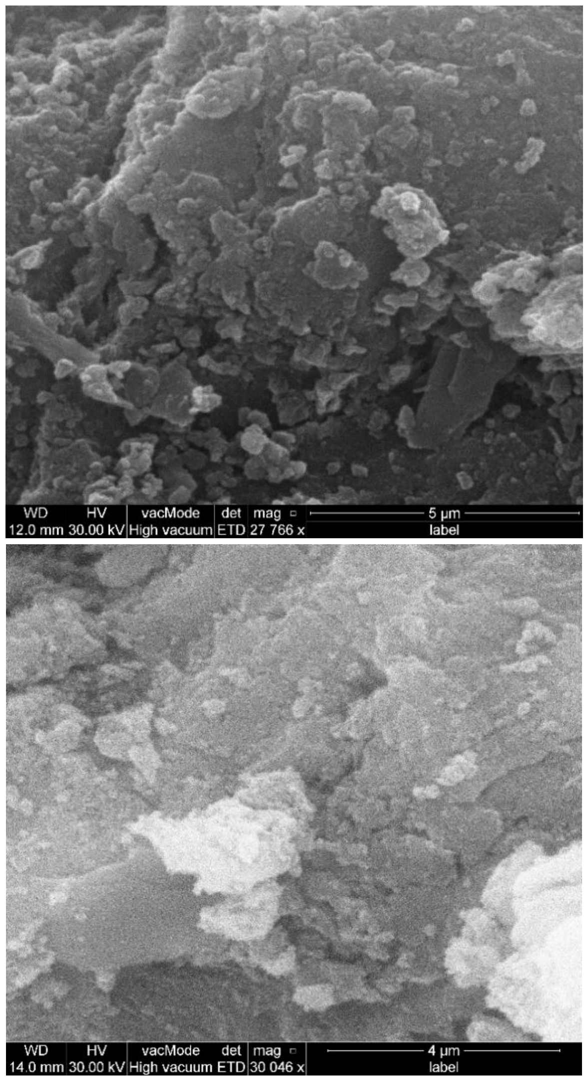


Figure 5. SEM micrographs, the control sample (left), and the SFC sample (right).

It was reported that the amount of $Ca(OH)_2$ was lessened by the addition of mineral admixtures to cement. The addition of silica fume to cement paste results in the production of amorphous CSH gel with a low proportion of Ca/Si and high density. Consequently, the amount of $Ca(OH)_2$, which is detrimental to concrete in terms of structural strength declines [25]. The dense microstructure modified by the incorporation of SF leads to building materials with higher density and mechanical strength.

6. Conclusions

The cement content in PCC could be minimized fruitfully by fractional substitution with silica fume. The approach will contribute to developing concrete properties, conserving energy and protecting the environment from the extensive emissions from cement industry as well as minimizing the pollution impact of the industrial by-product silica fume by recycling it in concrete as value-added material for structural applications in building construction. Concretes with developed properties could be produced using an appropriate silica fume content (11.9 wt. %) and 0.42 w/c ratio. On another hand, RSM can be used successfully to fix the optimal content of silica fume and w/c ratio employed to have cement-silica fume concrete composites with optimum compressive strength, and generate the relevant prediction models for strength properties of cement-silica fume concrete composites.

Author Contributions

Conception and design of the study: Ammar Ali Abed and Ibtisam Kamal.

Investigation: Ammar Ali Abed.

Methodology: Ammar Ali Abed and Ibtisam Kamal.

Study administration: Ammar Ali Abed, Ibtisam Kamal, and Alireza Mojtahedi.

Analysis and interpretation of data: Ammar Ali Abed.

Software: Ammar Ali Abed.

Supervision: Ibtisam Kamal.

Writing—original draft: Ammar Ali Abed.

Writing—review & editing: Ibtisam Kamal and Alireza Mojtahedi.

Conflict of Interest

There is no conflict of interest.

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