



Mechanical Behavior of Hardened Concrete with Variation Silica Fume and the Water Cement Ratio w/c

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ABSTRACT

This research examines the combined effect of silica fume (SF) percentage and water-cement (w/c) ratio on the performance of hardened concrete. The experiment used eight concrete mixes consisting of SF percentage of 0%, 7%, 13%, and 18% at two ratios of w/c: 0.4 and 0.5. The mechanical performance of each mix was determined in terms of compressive strength, tensile strength, and density after curing. It is found that the inclusion of silica fume improves the performance of concrete mix until its maximum content of 13%. At 13% content of SF and w/c ratio of 0.4, maximum compressive strength (24.85 MPa) and tensile strength (4.0 MPa) can be obtained owing to its contribution to enhanced microstructure through pozzolanic reaction and filler action. However, increase in w/c ratio to 0.5 reduces the strength values due to increased porosity. The ANOVA test showed that both SF percentage and w/c ratio have significant effect on mechanical performance ($p < 0.01$), but the latter is a more influential parameter.

KEYWORDS: Silica Fume, Water Cement Ratio, Compressive Strength, Tensile Strength, ANOVA

1. INTRODUCTION

The rising need for more durable and sustainable construction materials has spurred significant investigations into the addition of supplementary cementitious materials (SCMs) as part replacements for cement [1]. Of these materials, silica fume has proved to be among the most useful additives owing to its effectiveness in improving the mechanical strength and durability of concrete, thus minimizing the adverse effect on the environment resulting from the manufacturing process of cement. Silica fume owes its unique qualities to the fineness of its particles and pozzolanic activity that allows it to create C-S-H [2]. Numerous studies have confirmed that the incorporation of silica fume improves compressive strength, reduces permeability, and enhances resistance to aggressive environmental conditions [3, 4].

Water to cement (w/c) ratio is an important factor in determining strength and durability properties of concrete. The empirical equation proposed by Duff A. Abrams reveals that there exists an inverse relation between compressive strength and water-to-cement (w/c) ratio because the latter affects directly the porous structure of concrete and its microstructure [5]. Small values of water-to-cement (w/c) ratio mean lower volume of pores and thus better properties of the material; larger values lead to increased porosity and

deterioration of mechanical properties. However, the effect of water-to-cement (w/c) ratio is not straightforward when silica fume is used [6].

A substantial body of research has investigated the influence of silica fume on concrete properties. Early studies reported that moderate replacement levels (typically 10–15%) lead to significant improvements in compressive and tensile strengths due to enhanced bonding and reduced microcracking [7, 8]. More recent investigations have emphasized the role of silica fume in refining the interfacial transition zone (ITZ) and improving durability characteristics, including resistance to chloride ingress and chemical attack [9–11]. In addition, contemporary studies have explored the performance of silica fume in advanced concrete systems. Tak et al. [12] demonstrated that silica fume significantly enhances compressive strength in conventional concrete, while Haider et al. [13] reported improved mechanical and durability properties when silica fume is combined with other SCMs in recycled aggregate concrete. Similarly, Fode et al. [14] highlighted the importance of optimizing silica fume dosage to achieve superior mechanical performance and durability in modern cementitious composites.

On the other hand, numerous research works have been conducted in terms of w/c ratio, showing that the increase in

its value results in higher porosity and lower strength, while the decrease leads to increased density of hardened concrete [15, 16]. Nevertheless, existing investigations have mostly focused on the effect of silica fume content or w/c ratio separately; the impact of their combined use has hardly been explored. It should also be noted that the combination of experimentation with statistical analysis, which would include the ANOVA technique, has not yet become commonplace. This can prevent engineers from creating an optimal strategy for designing concrete mixtures.

In light of the discussion above, this paper will attempt to investigate the mechanical characteristics of concrete that has already hardened. Specifically, this study involves an examination of varying percentages of silica fume in relation to the w/c ratio to determine the ideal values for each of these components. In addition to the experimental method used in conducting the research, a statistical analysis is intended to validate results and ascertain the relevance of each component in terms of its contribution to the mixture.

2. MATERIALS AND METHODS

2.1 Materials

The experiment involved the use of conventional materials for concrete, such as OPC, fine aggregates, coarse aggregates, drinking water, and silica fume as supplementary cementing materials. All these materials have been selected in such a manner that they can be repeatedly used under identical conditions.

Ordinary Portland Cement (Type I) satisfying Iraqi Specification No. 5/1984 [17] was employed as the basic binding material. The cement exhibited desirable physical and chemical properties, like the fineness of texture and desirable properties regarding the development of strength. The fine aggregate was in the form of river sand that had a light brown appearance and belonged to Zone II according to IS:383-1970 standards. It had a clean appearance and appropriate grain size distribution. Crushed natural gravel having a maximum nominal size of 20 mm served as the coarse aggregate, as per Iraqi Specification No. 45/1984 [17]. The aggregates chosen were due to their strengths, durability, and capability of creating mechanical interlock within the concrete composite. The silica fume was used as mineral admixtures in which silica fume acted as a partial substitution of cement by weight according to ASTM C1240 [18]. The unique characteristics of the silica fume are that the particles consist of silica (less than 1 μm), significant surface area, and higher percentage of amorphous silicon dioxide. Due to the nature of silica fume, the material can act as a pozzolan and filler on a microscopic scale.

Water free from hazardous substances was used during mixing and curing. Water was chosen taking into account the effect it has during the process of hydration and strength development. The materials involved in the mix preparation and the procedures adopted are as follows in **Figure 1** below.



Figure 1. Material of Mix Concrete

2.2 Mix Design and Experimental Variables

The experiment was intended to assess the joint effect of the amount of silica fume and the water–cement (w/c) ratio on the mechanical characteristics of hardened concrete. Two w/c ratios (0.4 and 0.5) were chosen for experimentation because they symbolized relatively small and medium water

quantities, respectively, typically adopted in structural concrete.

Initially, a series of trial mixes were tested in order to determine an optimal control mix that possesses sufficient workability and strength. There were three trial mixes prepared, whose characteristics were assessed by

compressive strength tests after 7 and 28 days. Trial mixes' test results are given in **Table 1**. Mix 2 was chosen as the

control mix, as it provided better compressive strength at 28 days along with acceptable workability.

Table 1. Trial Mix Proportions and Strength Results

Mix Sym.	Cement kg/m ³	Fine kg/m ³	Course kg/m ³	Water kg/m ³	$f'c$ 7 days	days $f'c$ 28
1	394	788	1174	138	17.632	19.48
2	350	822	1193	123	16.713	21.20
3	370	807	1165	130	19.03	20.50

After the reference mix was selected, silica fume was added as an alternate ingredient for the cement at four different percentages: 0%, 7%, 13%, and 18%. This percentage range was selected to consider the positive and negative impacts of the increased dosage of silica fume.

In turn, for each percentage of silica fume used, two water-to-cement ratio mixes were taken, giving eight mixes in total, from M1 to M8 as presented in **Table 2**.

Table 2. Concrete Mix Matrix

Mix. Symbol	Variable Silica Fume (SF%)	Variable Water Cement Ratio (W/C)
M1	0.0	0.4
M2	7.0	0.4
M3	13.0	0.4
M4	18.0	0.4
M5	0.0	0.5
M6	7.0	0.5
M7	13.0	0.5
M8	18.0	0.5

2.3 Mixing Procedure

Concrete mixing involved following a laboratory standard for the consistent mixing of concrete. Initially, all dry ingredients, such as cement, silica fume, fine aggregate, and coarse aggregate, were mixed until a homogenous mix of all these ingredients was attained. Water was then slowly added to the dry mixture as continued mixing ensured the adequate mixing of cementitious materials. The process involved great care in avoiding particle agglomeration for silica fume at high replacement percentages.

2.4 Specimen Preparation and Casting

The cylindrical molds of dimensions 100 mm diameter and 200 mm height were utilized for specimen manufacturing. Prior to filling the molds with concrete, the molds were oiled internally for easy removal of the specimens upon hardening.

The concrete was cast layer by layer into the molds, which were manually compacted in order to expel entrapped air within the layers. The specimens' consistency was maintained during the process of compaction. A total of sixteen specimens were manufactured for the two test types, namely compressive strength and splitting tensile strength tests. **Figure 2** illustrates the procedure followed in the casting process.



Figure 2. The Mixture of Concrete and the Mold

2.5 Curing Regime

After the casting process, the specimens were kept undisturbed for a period of 24 hours in a laboratory environment. Afterwards, the specimens were taken out from the molds and placed inside a water curing tank at normal laboratory temperatures.

The specimens underwent the curing process for two periods of time. These were 7 days and 28 days. The method of continuous water curing was employed to guarantee total hydration of the specimens.

3. RESULTS AND DISCUSSION

An extensive series of tests was performed to investigate the physical properties of fresh and hardened concrete mixes. The scope of the investigation was set up to study the effects of SF content and w/c ratio on the workability, density, compressive strength, and splitting tensile strength.

3.1 Workability Behavior

The workability of the fresh concrete mixtures, evaluated through the slump test, is illustrated in **Figure 3**. All mixtures exhibited slump values within the range of 8–10 cm, indicating moderate consistency suitable for structural applications.



Figure 3. Slump Test

3.2 Density Characteristics

The density of the hardened mortar samples was calculated according to BS 1015: Part 10 (1999)[19]. As indicated from the data provided in **Table 3** and shown in **Figure 4**, the density of the hardened concrete samples falls into a relatively narrow interval ranging from 2360 kg/m³ to 2520 kg/m³; thus, the presence of silica fume in the composition of concrete samples did not affect the bulk density while having a noticeable effect on the internal structure and properties of the material. As can be seen from **Table 3**, the greatest density values were recorded for the control sample (M1), while samples containing silica fume were

characterized by somewhat smaller density values, as shown in **Figure 4**, where it is observed a small decrease in the density followed by small variations with increasing content of the additive. The reason for the decrease in density is related to the lower specific gravity of silica fume than that of Portland cement.

Nevertheless, this variation in density is limited in all mixes, implying that the incorporation of silica fume has no significant impact on the mass-volume ratio of the concrete. On the contrary, silica fume seems to be mainly affecting the concrete microstructure. Due to the fine nature of silica fume, it works as filler material for the cementitious matrix,

taking up void volume and improving particle packing. This causes densification of pores and reduction of capillary void interconnectivity, thus improving the durability and mechanical performance of concrete without affecting its bulk density. Indeed, according to **Figure 4**, there is no distinct trend of density with silica fume content, which implies that density is not a controlling factor for developing concrete strength. In other words, changes in mechanical

properties can be attributed to microstructural densification due to increased C–S–H formation.

In summary, from the results obtained above, it can be noted that although silica fume affects the density of the concrete to a very small extent, its effect on the performance of the concrete is mainly achieved through the processes of refining the microstructure. This conclusion is supported by several previous studies [20].

Table 3. Test Results of Compressive Strength and Splitting Tensile Strength

Mix. Symbol	Variable Silica Fume (SF%)	Variable Water Cement Ratio (W/C)	Test Results		Density kg/m ³
			f _c (MPa)	f _t (MPa)	
M1	0.0	0.4	21.2	3.5	2520
M2	7.0		22.725	3.7	2380
M3	13.0		24.85	4.00	2430
M4	18.0		19.24	2.9	2400
M5	0.0	0.5	19.0	3.2	2500
M6	7.0		20.5	3.4	2360
M7	13.0		22.5	3.7	2390
M8	18.0		17.5	2.7	2400

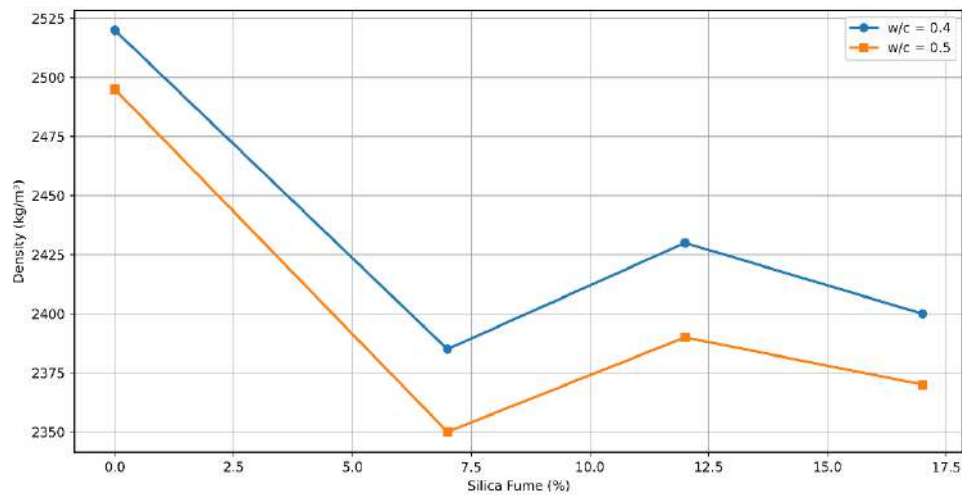


Figure 4. Density Variation with Silica Fume Content

3.3 Compressive Strength Response

Compressive strength of cylindrical concrete samples was determined using ASTM C39/C39M-05[21]. As shown in Figures 5 and 6, the compressive strengths of samples show clear non-linear variation depending on the use of silica fume in the mix. There is an increase in the values until a maximum of 24.85 MPa when 13% of silica fume is used (water-to-cement ratio 0.4). After that, there is a decline in strength. The reason for this phenomenon can be attributed

to the effect of densification due to the pozzolanic reaction and packing efficiency and workability-related problems as the silica fume quantity increases[22].

A consistent separation between the curves corresponding to w/c = 0.4 and 0.5 is observed, confirming the dominant influence of the water–cement ratio on strength development. Lower w/c ratio mixtures achieve superior performance due to reduced capillary porosity and improved matrix continuity.



Figure 5. Compressive Strength

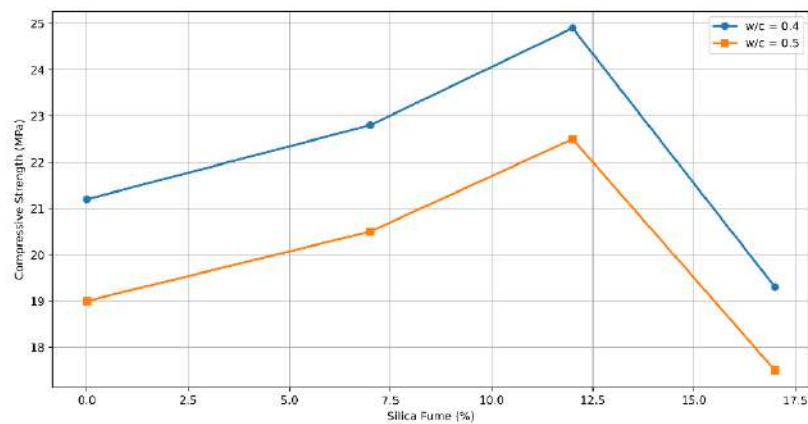


Figure 6. Compressive Strength Variation with Silica Fume Content

In summary, the findings demonstrate the optimal silica fume proportioning point and also shed light on the interdependence between the silica fume ratio and the water-cement ratio regarding compressive strength development.

3.4 Splitting Tensile Strength Response

Splitting tensile strength for concrete specimens was evaluated based on ASTM C496-86 [23]. It is evident from Figure 7 that there is a similar trend in the splitting tensile strength values that follow the same pattern as the compressive strength. This response shows a nonlinear variation with silica fume content, where the highest value is recorded at 4.0 MPa when the silica fume content is 13% SF.

The improvement in strength for silica fume content below 18% occurs because of the refinement of interfacial transition zone (ITZ) and improved particle packing efficiency, thus increasing the stress transmission capacity. On the other hand, the decrease in strength for silica fume content above 18% can be linked to the negative consequences of decreased workability that result in lower internal cohesion between particles. Similar trends have been observed in concrete containing silica fume [24]. Moreover, the distinction between the graphs for w/c = 0.4 and 0.5 clearly demonstrates the significance of the water-cement ratio. It is evident that a lower value of w/c leads to greater tensile strength because the level of porosity is minimized. In general, the findings demonstrate the optimal amount of silica fume (~13%).

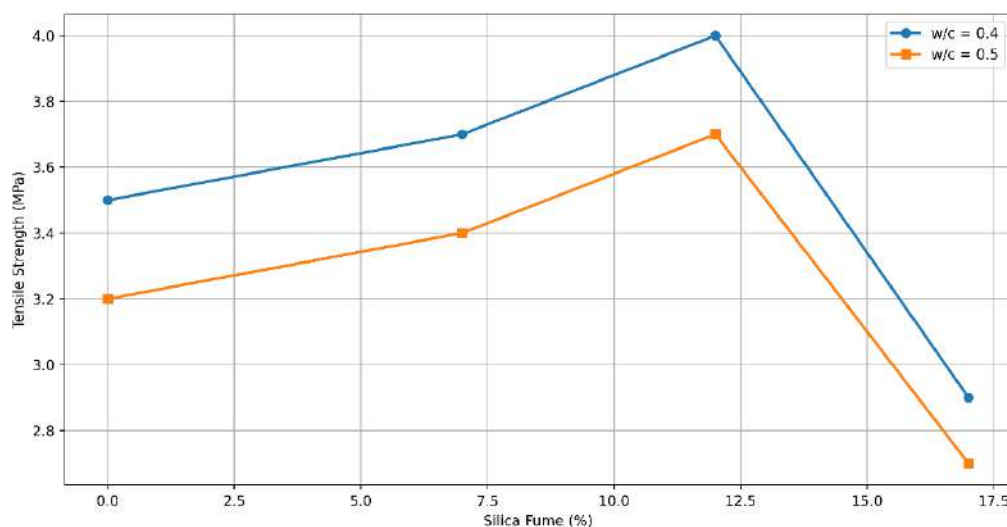


Figure 7. Tensile Strength Variation with Silica Fume Content

3.5 Statistical Validation and Interpretation

In order to prove the reliability of the test results and estimate the impact of SF dosage and w/c ratio on the mechanical characteristics of concrete, an analysis of variance (ANOVA) [25] was carried out. The ANOVA technique is frequently used in cementitious materials research to estimate the importance of mixture components

and their contribution to the variability in mechanical behavior. ANOVA was carried out at a 95% confidence interval ($\alpha = 0.05$). The ANOVA data for compressive and splitting tensile strengths are presented in Tables 4 and 5, respectively. In both cases, SF dosage and w/c ratio proved to be highly important ($p < 0.01$).

Table 4. ANOVA Results for Compressive Strength

Source of Variation	DF	F-value	p-value	Significance
Silica Fume (SF)	3	284.36	0.00035	Highly Significant
W/C Ratio	1	253.61	0.00054	Highly Significant

Table 5. ANOVA Results for Splitting Tensile Strength

Source of Variation	DF	F-value	p-value	Significance
Silica Fume (SF)	3	313.00	0.00030	Highly Significant
W/C Ratio	1	121.00	0.00161	Highly Significant

It is evident from the statistical findings that both silica fume percentage and water-to-cement ratio significantly affect the mechanical properties of concrete. The higher F values obtained for the w/c ratio, as shown in Table 4, confirm that it plays a pivotal role in regulating compressive strength by affecting the porosity and continuity of the matrix. This finding corroborates earlier statistical studies on cement-based materials, which revealed water content to be an important parameter that determines strength variability [26].

However, silica fume shows greater influence on tensile strength compared to metakaolin, evidenced by the increased F-value shown in Table 5. This is because silica fumes are more effective in the refinement of ITZ and the bonding process within the matrix. The same conclusion has also been drawn from previous ANOVA and Taguchi methods, where silica fume showed greater improvement in

tensile properties because of denser microstructure and efficient packing of particles [27].

In addition, the statistical results correlate well with the non-linear relationship established through experimentation (Figures 6 and 7), whereby the strength rises until the silica fume content reaches an optimum value (~13%) after which the strength begins to decline. This has been illustrated through statistical analysis, wherein it is suggested that increased silica fume content can cause lower levels of workability and dispersion, thus leading to poor mechanical properties.

The ANOVA results suggest a joint non-linear relationship between silica fume content and water-to-cement ratio, underscoring the need for optimizing both simultaneously. The current study provides convincing statistical evidence for the observations made experimentally and corroborates

other recent studies using statistical methods for predicting performance in modified cementitious materials.

4. CONCLUSION

The present research work has been conducted systematically with an objective to understand the joint effect of silica fume content and w/c ratio on the mechanical properties of hardened concrete specimens. The results of the study reveal the significance of both the factors for controlling the behavior of concrete specimens. The use of silica fume as cementitious material has been found to greatly improve the mechanical properties of the hardened concrete specimens. A silica fume content of about 13% has been determined to be the optimal content since the highest values of compressive strength and splitting tensile strength have been achieved at that percentage value. It has been seen that the combination of both the reactions leads to the production of C–S–H, which makes concrete microstructure denser and finer.

It was found that the water-cement ratio is the most important variable that determines the performance of the material in terms of its mechanical strength. The decrease in the water-cement ratio (from 0.5 to 0.4) significantly improves the mechanical properties mainly because of the lower porosity of the matrix and its higher density. An increase in the content of silica fume up to 18% led to a decrease in performance indicators due to a reduction in workability, particle agglomeration, and poor compacting. This indicates the importance of optimizing the mixed composition, ensuring satisfaction of mechanical requirements, as well as providing sufficient workability.

Taking into account the results obtained due to the ANOVA analysis, it is possible to state that not only the amount of silica fume, but also the water-cement ratio has a considerable influence on mechanical properties of the material; at the same time, the latter one has the strongest influence on these parameters. Thus, considering all the obtained results, it is possible to claim that the most efficient mixture ratio is 13% of silica fume and water–cement ratio of 0.4.

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