

# CHARACTERISTICS OF SILICA-FUME CONCRETE

By Safwan A. Khedr,<sup>1</sup> Member, ASCE, and Mohamed Nagib Abou-Zeid<sup>2</sup>

**ABSTRACT:** Proper introduction of silica fume in concrete improves both the mechanical and durability characteristics of the concrete. This paper presents the results of research effort conducted at the American University in Cairo using Egyptian silica fume in concrete. The program investigated various characteristics of silica-fume concrete. It emphasized the effect of silica fume on workability level and its maintenance of fresh concrete; strength development, strength optimization and elastic modulus of hardened concrete; and chemical and mechanical durability of mortar. The experimental program comprised six levels of silica-fume contents (as partial replacement of cement by weight) at 0% (control mix), 5%, 10%, 15%, 20%, and 25%, with and without superplasticizer. It also included two mixes with 15% silica fume added to cement in normal concrete. Durability of silica-fume mortar was tested in chemical environments of sulfate compounds, ammonium nitrate, calcium chloride, and various kinds of acids. It was found that there was an optimal value of silica-fume content at which concrete strength improved significantly. Due to the slow development of pozzolanic effect, there was a drop in early strength up to seven days and late significant gains up to 56 days upon introducing silica fume to concrete. Elastic modulus, toughness, and steel-concrete bond increased at the optimum silica-fume content in concrete. Silica-fume mortar exhibited significant improvement in durability against chemical attacks of most salts and acids. The improvement was moderate in the case of sulfate compounds. Mechanical erosion resistance increased moderately in silica-fume concrete.

## INTRODUCTION

Condensed silica fume is a relatively new member in the family of pozzolans that are introduced to react with the free lime in the concrete matrix and consequently improve its performance. Silica fume, sometimes called microsilica or silica dust, is a byproduct of manufacturing silicon or ferro-silicon alloys. The fume is condensed on filters mounted at the exit of escaping gases during the manufacturing process as part of the environmental protection provision. Silica fume has a high content of silicon dioxide (85–97%). It consists of very fine spherical glassy siliceous particles. Approximately 800,000 t/yr are produced in the western world. In Egypt, it amounts to more than 12,000 t annually.

Condensed silica fume has been classified as a pozzolan by the American Concrete Institute (ACI) Committee 226 on cementitious materials (ACI 1987). ASTM C 618 recognizes three classes of pozzolan; N, F, and C. Silica fume is somewhat closer to the N class. However, particular provision is needed to identify appropriate classification of silica fume.

The superfineness of silica fume (specific surface area 15,000–20,000 m<sup>2</sup>/kg compared to 200–500 m<sup>2</sup>/kg for cement) and the high content of silica dioxide enhance pozzolanic action. Yet this fineness and slow nature of pozzolanic effect also imposes some problems in the development of concrete durability and strength.

<sup>1</sup>Assoc. Prof., Constr. Engrg., The American Univ. in Cairo, P.O. Box 2511, Cairo, Egypt.

<sup>2</sup>PhD Res. Engr., Civ. Engrg. Dept., Univ. of Kansas, Lawrence, KS 66045.

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The new pozzolan (silica fume) has attracted the attention of many researchers. Research has been conducted in various parts of the world (e.g. Norway, Canada, United States, Japan) to study various aspects of using silica fume in concrete and mortar. However, the technical data and information is far from complete, especially with silica-fume concrete being a promising material with many potential applications in the construction industry.

There are issues related to mix design and structural design regarding the new material that need more elaboration or have little available technical literature. Some of these issues follow.

1. The type and dosage of superplasticizer needed to produce and maintain reasonable workability and enhance the strength of concrete with silica fume must be addressed. The high fineness of the silica fume that partially replaces or is added to cement hinders the workability of concrete (Sellevold et al. 1983; Carette et al. 1983). In particular instances, the silica fume itself may work, with some additives, as a lubricating agent in the concrete and enhance its workability. Also, sustaining this workability over a reasonable length of time is of prime concern.

2. The slower development of strength associated with the introduction of silica fume in concrete should be studied. Pozzolanic action is slow by nature. Although the gain in the final strength is significant, it takes from three to seven days for the mix to start displaying portions of that gain (Maage 1986; Burge 1983). Since very fine filler (silica fume) do not exhibit significant chemical reaction during this early age and because of the associated reduction in portland cement content; it is reasonable to expect that there will be a drop in early strength development.

3. Studies are needed concerning the development and variation of compressive and flexural strength in silica-fume concrete. The main effect on strength of silica fume stems from its reaction with lime in concrete and the resulting better pore distribution in its matrix (Detwiler et al. 1989). That is, there is a need for an amount of silica fume to complete these actions. Any extra quantity of silica fume merely will be dust filler in concrete, which may be detrimental to its characteristics. Therefore, it is sensible to predict that there should be an optimal value for the content of silica fume in the concrete (as cement replacement or addition).

4. The stress-strain behavior, elastic modulus, and toughness of silica-fume concrete must be researched. A thorough understanding of the complete stress-strain curve is essential to the design of concrete structures. Very little technical literature is available on these mechanical properties of silica-fume concrete.

5. Durability of silica-fume concrete in aggressive chemical environments should be explored. Silica-fume concrete has been reported to possess lower water permeability, (ACI 1987; Gjorv et al. 1990). This nominates the silica-fume concrete for better durability properties. Nevertheless, reported research on its durability is limited. The brief data in the literature is inconclusive and there is no evidence to suggest that behavior of portland cement plus silica fume is similar to that of other pozzolans (Cohen et al. 1988).

The objective of the present research effort, which was conducted at the American University in Cairo (AUC), is to bring forward results of investigations of these issues. It is part of an on-going experimental research

program designed to study the feasibility of using silica fume in concrete in Egypt. The analyses of the results elaborate on the reasoning, comparison, and consequences of behavior of silica-fume concrete.

## EXPERIMENTAL PROGRAM

### General

The experimental program for this research was designed to study the effect of silica fume on different concrete characteristics (Fig. 1). These characteristics were divided into three categories: fresh concrete, hardened concrete, and durability of mortar.

### Mix Design

There are three techniques for incorporating silica fume relative to cement in the concrete mix: addition to cement, partial replacement of cement by equal weight of silica fume, and partial replacement of cement by less weight of silica fume. The first technique is used when special concrete with high strength is required. When the purpose is to save cement content, the second technique is used, which usually results in higher quality concrete. Since concrete yields higher quality with 1:1 replacement, it is possible to use silica fume to reduce the cost for comparable quality by reducing the cement content and replacing it with a lesser amount of silica fume; this describes the third technique.

The experimental program included two sets of concrete mixes prepared using the second technique with cement content of  $420 \text{ kg/m}^3$ . Each set had six mixes at six different percentages of 1:1 partial replacement of cement. The silica fume dosages were 0% (control mix), 5%, 10%, 15%, 20%, and 25% of cement (Table 1). One set was prepared with water/(cement + silica fume) ratio of 0.3 with superplasticizer (sodium naphthalene sulfonate) of  $12.6 \text{ L/m}^3$ . The other set entailed water/(cement + silica fume)  $[w/(c + s)]$  ratio of 0.57 without the use of superplasticizer. A high-strength mix

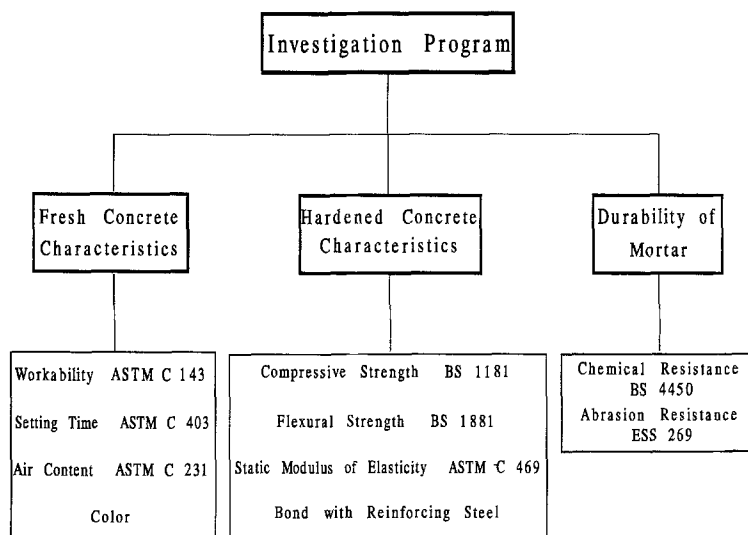


FIG. 1. Silica-Fume Concrete Investigation Scheme

**TABLE 1. Proportions of Concrete Mixes**

Mix (1)	Cement (kg/m <sup>2</sup> ) (2)	Silica fume (kg/m <sup>2</sup> ) (3)	Water (L/m <sup>3</sup> ) (4)	Super- plasticizer (L/m <sup>3</sup> ) (5)	Fine aggregate (kg/m <sup>3</sup> ) (6)	Coarse aggregate (kg/m <sup>3</sup> ) (7)
(a) First Set I						
Ia	420	0	125	12.6	695	1,245
Ib	399	21	125	12.6	695	1,245
Ic	378	42	125	12.6	695	1,245
Id	357	63	125	12.6	695	1,245
Ie	336	84	125	12.6	695	1,245
If	315	105	125	12.6	695	1,245
(b) Second Set II						
IIa	420	0	240	0	650	1,030
IIb	399	21	240	0	650	1,030
IIc	378	42	240	0	650	1,030
IId	357	63	240	0	650	1,030
IIe	336	84	240	0	650	1,030
IIIf	315	105	240	0	650	1,030
(c) Mix III						
III	420	63	145	14.5	695	1,245

designed according to the first technique was also included in the program. It involved adding 15% of silica fume (by weight of cement).

### Materials

All constituent materials used in the program were from local sources in Egypt. Periodical control tests were carried out to assure uniformity of supply throughout the experimental program.

Type I portland cement was used in all mixes. The cement had the following measured properties: (1) Normal consistency = 26%–26.5%; (2) initial setting time = 2.5–2.65 h; (3) final setting time = 3.0–3.6 h; (4) fineness = 323–342 m<sup>2</sup>/kg; 3-day mortar cube strength = 221–230 kg/cm<sup>2</sup>; 7-day mortar cube strength = 290–294 kg/cm<sup>2</sup>.

The fine aggregate was a natural silicious sand with 2.67 bulk specific gravity, 0.7% absorption, and fineness modulus of 2.52. Crushed dolomite was used as coarse aggregate with bulk specific gravity of 2.68, apparent specific gravity of 2.80, water absorption of 1.6%, and Los Angeles abrasion value of 24.7%. The nominal maximum size was 19 mm.

A superplasticizer of sodium naphthalene sulfonate was used in mixes I and III, and in mortar. It complied with ASTM C 494 type F. This admixture was found to give the advantage as a water reducer without significant change in setting time or air entrainment. Therefore, it served the particular purpose of maintaining workability of silica-fume concrete at the same  $w/(c + s)$  ratio.

The silica fume used in this experimental program was obtained from a ferrosilicon manufacturing plant at Edfu, in southern Egypt. It was produced as a byproduct of a Soderberg electrical processing. The silica fume was condensed through glass-fiber composite filters mounted at the exit of exhaust gases as a measure of environmental protection and as a cleaning

TABLE 2. Chemical and Physical Characteristics of Silica Fume and Different Mineral Admixtures

Property (1)	Portland cement (2)	Slag (3)	Artificial Pozzolanas		
			Silica fume (4)	Fly ash (5)	Egyptian silica fume (6)
CaO (%)	60–67	32–48	0.1–0.6	3–7	0.2
SiO <sub>2</sub> (%)	17–25	28–40	86–96	40–55	97.0
Al <sub>2</sub> O <sub>3</sub> (%)	2–8	10–22	0.2–0.6	20–30	0.2
Fe <sub>2</sub> O <sub>3</sub> (%)	0–6	4.0	0.3–1.0	5–10	0.5
MgO (%)	0.1–4.0	2–16	0.3–3.5	1–4	0.5
SO <sub>3</sub> (%)	1–4	3.0	0.1–0.4	0.4–2.0	0.15
(Na <sub>2</sub> )O (%)	—	—	0.8–1.8	—	0.2
K <sub>2</sub> O (%)	0.2–1.5	3.0	1.5–3.5	1–5	0.5
C (%)	—	—	0.5–2.0	—	0.5
H <sub>2</sub> O (%)	—	0–0.8	0.3–1.0	0.2–0.8	0.5
Specific gravity	3.15	2.90	2.10–2.20	2.10	2.10
Bulk unit weight (Kg/m <sup>3</sup> )	1,200–1,400	1,000–1,200	200–400	900–1,000	350
Loss by ignition (%)	—	—	2–4	12	2.1
Specific surface area (m <sup>2</sup> /Kg)	200–500	—	15,000–20,000	200–600	16,700

process. More than 10,000 t of silica fume are produced annually in Egypt. Table 2 shows the chemical and physical properties of the silica fume used. Table 2 offers comparison with typical values of portland cement, silica fumes, and other pozzolans obtained from ACI (1987) and Sellevold (1983).

Plain and deformed steel bars were used in the pullout test. The yield and ultimate strengths of the smooth bars were 358 and 478 MPa, respectively. The yield and ultimate strengths for the deformed bars were 465 and 670 MPa, respectively.

### Testing Procedures

Relevant standard testing procedures are shown in Fig. 1. However, the following should be pointed out:

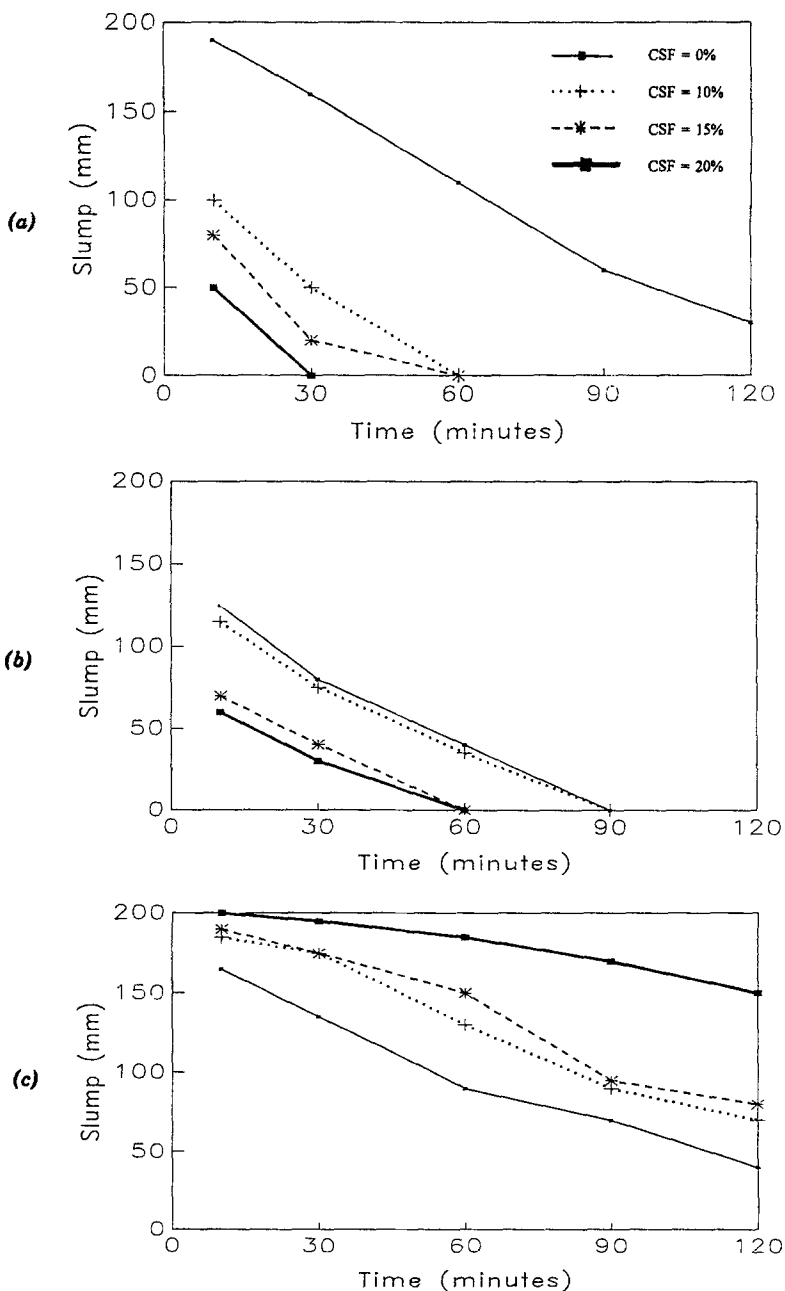
- Change of slump during the first 2 h was considered as an indication of maintenance of workability.
- Concrete cubes (15-cm sides) were cast and tested for compressive strength. The cubes were moist cured until the time of testing; 1, 3, 7, 28, 56, and 90 days. Three cubes were tested at each condition and age.
- Beams tested for flexural strength were  $50 \times 10 \times 10$  cm. A two-point testing setup with beam span of 30 cm was used for this test.
- Cylinder samples were tested for static modulus of elasticity.
- A pullout test was used to measure steel-concrete bond. Deformed and smooth bars, 12.5-mm diameter and 60-cm length, were placed in standard cylindrical concrete samples ( $15 \times 30$  cm) that were moist cured until time of test. Pullout load was recorded at the first slip.
- Chemical durability tests were performed on mortar prisms  $7 \times 7 \times 3.5$  cm cut out of mortar cubes made and cured according to ASTM C 109. Two sets of samples were tested: control mix (water:cement:sand, 0.485:1.0:2.75) and mix that contained 20% silica fume as 1:1 partial replacement of cement. No chemical admixtures were used. The samples were immersed in various chemical compounds for eight weeks. Each week, the samples were washed, oven dried, and weighed. The chemical compounds employed in these tests were saturated sodium sulfate, saturated magnesium sulfate, saturated calcium chloride, saturated ammonium nitrate, 20% nitric acid, concentrated nitric acid, 20% sulfuric acid, concentrated sulfuric acid, and 50% hydrochloric acid.
- Samples similar to those tested for chemical durability were subjected to abrasion tests according to ESS 269 for mechanical durability.

## TEST RESULTS AND ANALYSIS

### Fresh Concrete

#### Workability

Fig. 2 shows the workability maintenance for different concrete mixes over a 2-h period. Slump was the measure of workability. The involved mixes had zero, 10%, 15%, and 20% silica fume as 1:1 partial replacement of cement. Fig. 2(a) shows the relationship when  $w/(c + s)$  ratio is at the



**FIG. 2. Maintenance of Workability of Silica-Fume Concrete (1:1 Replacement): (a) Set II; (b) 0.9% Superplasticizer and  $w/(c + s) = 0.4$ ; (c) Set I**

high level of 0.57 with no superplasticizer added (set II). Fig. 2(b) represents  $w/(c + s)$  of 0.4 and normal level dose of 0.9% superplasticizer (by weight of  $[c + s]$ ), which was a trial mix tested for initial comparison. Fig. 2(c) presents the case when high dose of superplasticizer used at 3% and  $w/(c + s)$  is reduced to 0.3 (set I). When no superplasticizer was used, Fig. 2(a), the drop in the slump value with time was directly proportional to the increase of the silica-fume content. This was simply due to the large surface area introduced to the mix due to silica-fume addition.

The workability was improved upon the addition of normal dose of superplasticizer, Fig. 2(b). It is obvious that the silica-fume concrete at this superplasticizer dosage is still incapable of meeting the high workability demands; such as ready-mix concrete or pumped concrete. However, use in precast or prestressed concrete is quite possible from the workability point of view.

Fig. 2(c) shows the relationship for relatively high doses of superplasticizer. It seemed that the superplasticizer dose could have been reduced for higher silica-fume content to achieve comparable workability to the control mix. Investigation by Sellevold et al. (1983) lead to similar conclusion. However, Carrette et al. (1983) had to increase superplasticizer content for higher silica fume in order to maintain the same slump. Fig. 2(c) also illustrates that reasonable workability is maintainable during the first 2 h of concrete age. This should alleviate problems during transporting and placing silica-fume concrete.

The silica-fume concrete was observed to have more cohesiveness and no bleeding was noticed at mid and high contents of silica fume. This was considered an advantage to prevent segregation and increased consolidability. However, adequate curing was essential in order to avoid plastic shrinkage cracking, ACI (1987). Table 3 shows the setting time for the concrete mixes made with different doses of superplasticizer and silica fume. The increase of silica-fume dosage caused an extension in the setting time in the case using relatively high doses of superplasticizer. In the event of using no superplasticizer there was no significant change in the setting time due to silica-fume introduction.

The retardation of setting is primarily due to the decrease of the cement content, which is responsible for short-term setting, and the addition of the pozzolanic silica fume, which takes material, longer to act. This will also reflect on the rate of strength development.

The addition of silica-fume concrete was associated with an increase in

**TABLE 3. Initial Setting Time and Air Content of Silica-Fume Concrete**

Silica fume dosage (%) (1)	Superplasticizer dosage (%) <sup>a</sup> (2)	$w/(c + s)$ (3)	Setting time (h) (4)	Air content (%) (5)
0	3.0	0.3	5.33	3
10	3.0	0.3	6.25	4
20	3.0	0.3	6.91	4.5
0	0	0.57	4.25	1
10	0	0.57	4.00	1.5
20	0	0.57	4.08	2.5

<sup>a</sup>Percentage by weight of cement plus silica fume.

the air content (Table 3). This increase was independent of superplasticizer addition. One should note, however, that the superplasticizer itself caused a more noticeable increase in air content. It seemed that the increases in air content caused by adding superplasticizer and by the dosage level of silica fume were independent. These results were different from those obtained by Carette et al. (1983). The type of superplasticizer may be the contributing factor for the disagreement of the results.

### Concrete Color

By visual inspection, no difference in concrete color at the different concrete manufacturing stages was observed. The condensed silica-fume powder obtained in Egypt is of relatively low carbon content (0.3–0.5%). This might be the reason the product addition did not result in darker color concrete.

## Hardened Concrete

### Compressive Strength Using Superplasticizer

Fig. 3 shows the strength development of concrete made with and without silica fume as 1:1 partial replacement of cement at various silica-fume contents. The values given herein are the average compressive strength of three cubes. Superplasticizer was used at a rate of 3% and  $w/(c + s)$  of 0.3 (set I). Fig. 4 illustrates the gain of strength as a percentage compared with the control mix of zero silica-fume content.

Figs. 3 and 4 show, first, that there was significant gain in compressive strength due to silica-fume introduction. This gain was obvious beyond 7-day age. The apparent reason for that might be attributed to the pozzolanic reaction, which took relatively longer time to show effect on strength.

Second, the gain in compressive strength was significant after 7 days up to 56 days. That might lead to the possibility of adopting the 56-day compressive strength for comparison between behavior of concrete with and without silica fume.

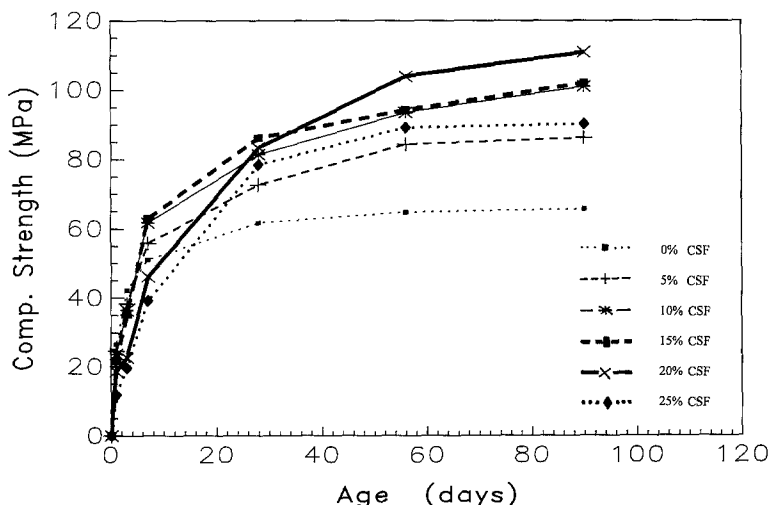
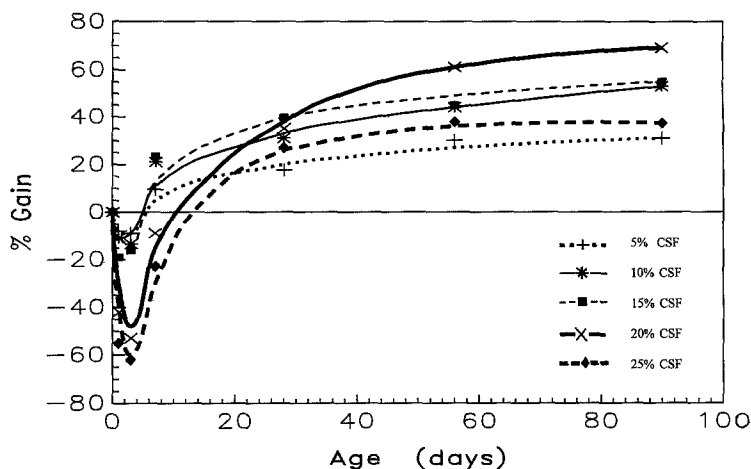


FIG. 3. Compressive Strength of Silica-Fume Concrete: Cube Testing, Set I (1:1 Replacement)



**FIG. 4. Gains in Compressive Strength of Silica-Fume Concrete Relative to Control Mix: Set I (1:1 Replacement)**

Third, the gain in strength—as shown in Fig. 4 for age 28 days and older—increased as silica-fume content increased up to about 20% replacement of cement. This could be attributed to the lime content, which is believed to be between 15% and 20% of the cement paste (Lea 1970). Considering the  $w/(c + s)$  ratio of 0.3, the corresponding value of silica-fume replacement is enough to react with the lime present in the paste and should range from 16% to 22% (of dry cement). This might explain the drop in the gain of strength, as compared to control mix, at the 25% cement replacement by silica fume where there would be extra free silica fume, which did not react with lime. Regarding 28-day strength and above, we could see that the optimum dosage of silica fume is in the range of 10% to 20%. However, this might not necessarily be the optimum dosage range for other cement types and cement contents or for the case of a different type or dosage of chemical admixtures. It was also dependent on the age at which the strength of silica-fume concrete is considered.

Fourth, there was a drop in the early strength of silica-fume concrete up to the 7th day as compared to control mix. Two rationales could be behind this observation. The pozzolanic reaction of the silica fume, which replaced portion of the cement took longer time than normal cement hydration. This would lead to a lower early strength. Second, as all the superplasticizer introduced an accelerating effect to cement hydration, and with less cement content, less acceleration effect was expected in the case of silica-fume replacement of cement. Naturally, this drop in strength was more obvious as silica-fume dosage increased.

Maage (1986) had similar observations regarding the early loss of strength of silica-fume concrete up to seven days. Carette et al. (1983) reported late development in strength for silica-fume concrete. However, they did not notice early loss of strength.

Investigation of the results obtained by Burge (1983) support the findings of optimal value of 1:1 cement silica-fume partial replacement around 20% for 28-day compressive strength. The 1-day compressive strength showed loss of strength of silica-fume concrete compared to the control mix.

### Compressive Strength without Superplasticizer

Figs. 5 and 6 show the results of compressive strength of silica-fume concrete with  $w/(c + s)$  of 0.57 and no superplasticizer used. In view of Figs. 5 and 6, the following was observed:

1. There was a significant gain in compressive strength due to silica-fume introduction. This gain was noticeable for concrete older than 3 days. However, the gain in strength then, as shown in Fig. 6, was somehow lower than the gain recorded for silica-fume concrete made with superplasticizer. Low

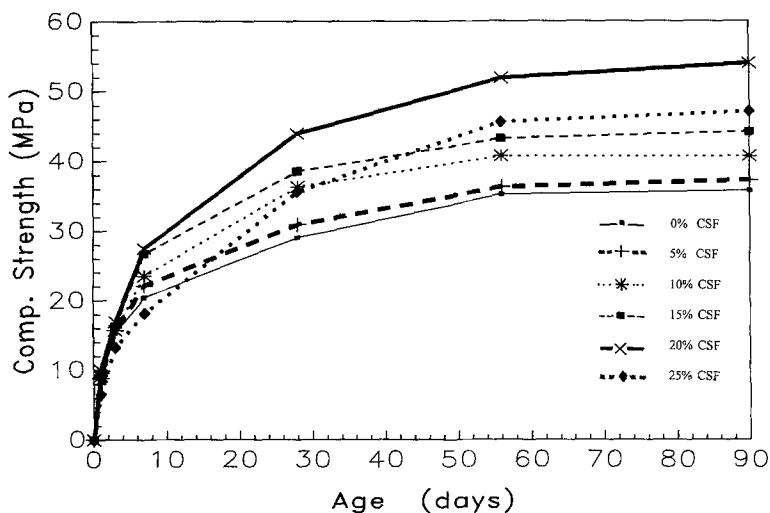


FIG. 5. Compressive Strength of Silica-Fume Concrete: Cube Testing, Set II (1:1 Replacement)

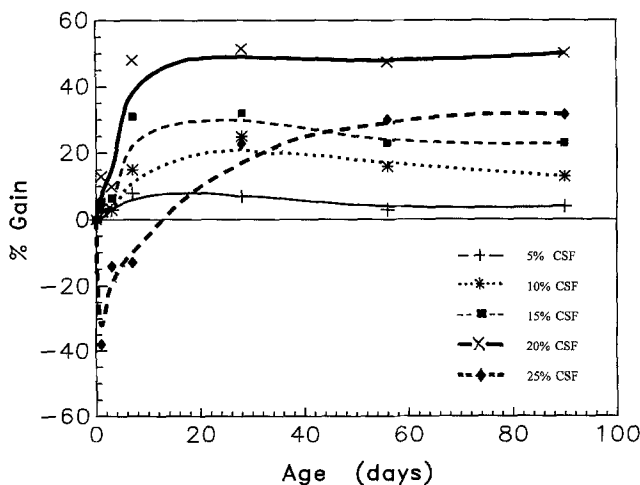


FIG. 6. Gains in Compressive Strength of Silica-Fume Concrete Relative to Control Mix: Set II (1:1 Replacement)

ratio of  $w/(c + s)$  helped to make a better use of silica fume without the detrimental effect of increasing water to maintain workability as shown in Fig. 4.

2. Similar to the first set of tests, the optimum dosage range was around 20% replacement. However, the dosage of 25% did not yield as low results as in the case of silica fume with superplasticizer. The role of extra free silica fume in this case is to help fill voids. This resulted in a better pore structure, and greater degree of hydration took place at higher water  $w/(c + s)$  ratio.

3. Fig. 6 shows that there was no significant gain in strength for silica-fume concrete less than 3 days old. Here, there was no remarkable loss, relative to control mix at this early age, similar to that shown in Fig. 4 for the case of using superplasticizer.

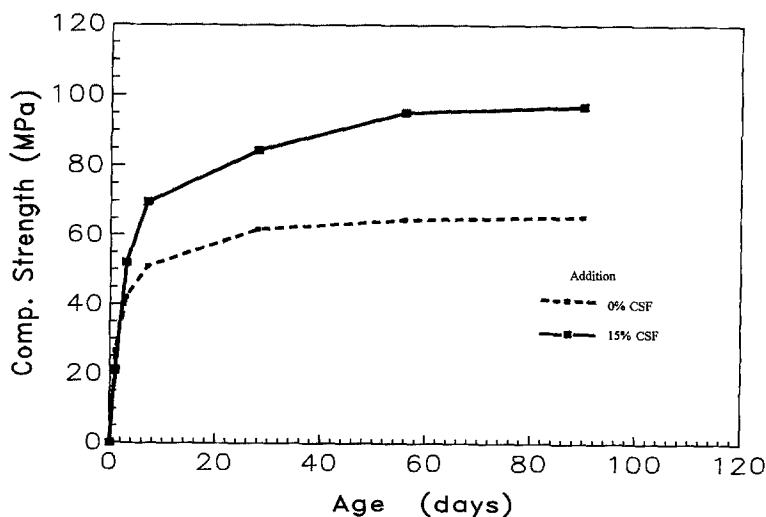
Sandvik et al. (1986) had similar observations for rates of strength development for silica-fume concrete without superplasticizer.

### *Compressive Strength of Concrete with Silica Fume Added to Cement*

The third set of mixes was prepared using the first technique of addition of silica fume. Here, the control mix was similar to that in the first set of tests;  $w/(c + s)$  of 0.3 and portland cement content of  $420 \text{ kg/cm}^3$ . The silica-fume mix had extra 15% of silica-fume powder. The test results are shown in Fig. 7.

The crushed cubes that yielded high strengths were inspected. It was observed that many of the coarse aggregates were crushed, i.e. the fracture surface took place through the aggregates. This was an indication of the high strength of the paste in the silica-fume concrete.

There was significant gain in compressive strength for the silica-fume concrete. However, the values shown in Fig. 7 indicated a similar gain of



**FIG. 7. Compressive Strength of Silica-Fume Concrete: Cube Testing Set III (1:1 Replacement)**

strength when compared with 15% replacement as shown in Fig. 3. This was due to the fact that the total amount of paste herein was more than necessary to work as a binder for aggregates in the soft composite concrete structure. Consequently, this excess of paste acted as a filler. In addition, there was more free lime that was not counteracted by pozzolanic reaction. In other words, 15% silica-fume addition seemed to be below an optimum silica-fume content.

Because the amount of portland cement in both mixes was the same, there was no serious drop in the early strength of silica-fume concrete. This lead to a principle of silica-fume addition being advantageous even when high early strength must be maintained.

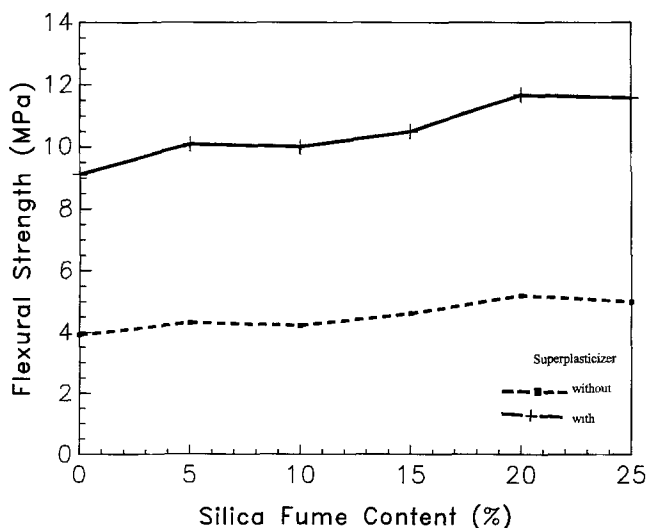
### *Flexural Strength*

Fig. 8 shows the results of the flexural strength tests. The strength levels plotted in Fig. 8 represent the average value of three beams tested after 28 days. From Fig. 8, the following could be observed:

1. Reducing the  $w/(c + s)$  ratio, when using superplasticizer, resulted in an increase in flexural strength. This increase was more significant than the increase due to introducing silica fume.
2. There was significant gain in the flexural tensile strength when silica-fume dosage increased from 5% to 20%. Again, there seemed to be an optimum silica-fume content (1:1 cement replacement) around the value 20%. Doses more than 20% replacement did not produce extra gains in the flexural strength.

It seemed that this gain was partially because silica-fume particles enhanced the concrete pore structure by filling the voids that may exist. Such voids would certainly reduce the flexural tensile stresses.

Carette et al. (1983) stated that pattern of flexural strength development of silica-fume concrete was similar to that of compressive strength. This



**FIG. 8. Flexural Strength of Silica-Fume Concrete (1:1 Replacement, 28 Days)**

supports the findings of optimum content range of silica fume that might apply to compressive and flexural strengths.

Both the flexural and the compressive strength gains are presented in Fig. 9 at concrete age of 28 days. In Fig. 9, the gain in both flexural and compressive strength are shown when comparing silica-fume concrete with control normal concrete with no silica fume.

There was a gain in flexural tensile strength due to silica-fume introduction. Such a gain was always lower than that of the compressive strength, with only one exception at a 5% dosage. The initial filling of voids at this dose level by silica fume improved the tensile strength more than the compressive strength.

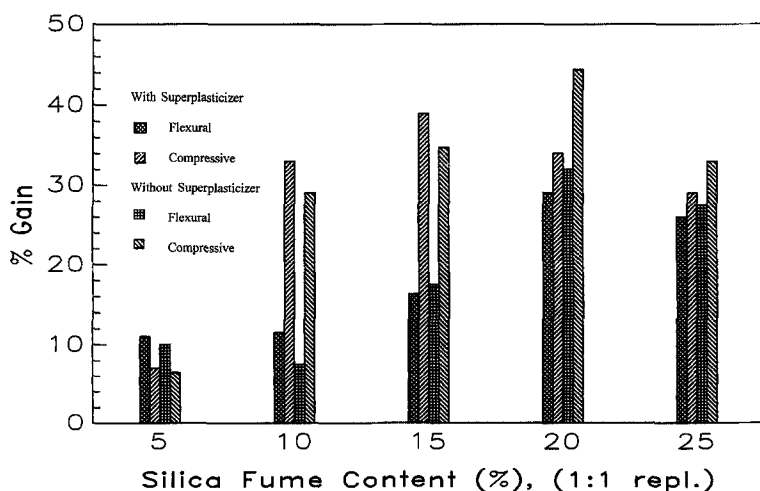
The optimum dosage for tensile strength was somehow close to that of the compressive strength. The dosage range between 15% to 20% yielded the highest value for strength when used as a cement replacement.

### *Modulus of Elasticity*

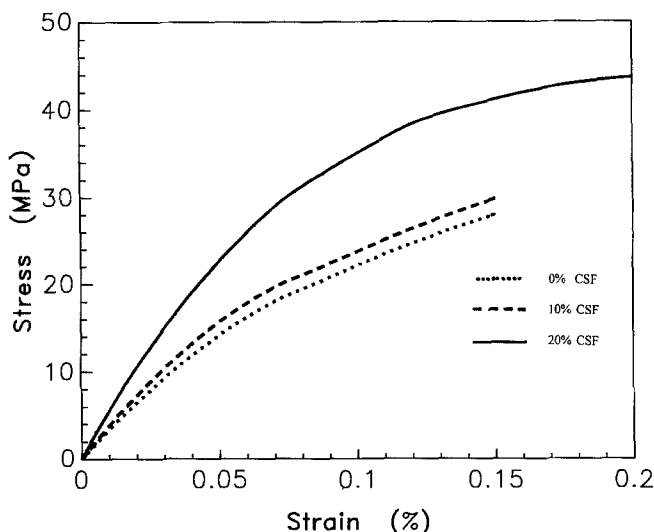
The static modulus of elasticity of concrete was measured for compression loading. The stress-strain curves are plotted in Fig. 10 for 0%, 10%, and 20% silica-fume concrete.

The addition of silica fume increased the modulus of elasticity. This increase was higher at the lower stress level, which was in the range of working stresses on structural members. The increase in the modulus of elasticity was more significant in the case of 20% silica fume. This might be considered an optimum dosage of silica fume. The ultimate strain at failure was of the same order for both normal and silica-fume concrete. Galeota et al. (1989) had similar observations in their study.

The areas under the curves in Fig. 10 indicated the toughness of these concretes per unit volume. Each curve in Fig. 10 represents results of testing three samples. Toughness was noticed to be higher for concrete with silica fume. The increase in toughness was about 115% for silica-fume content of 20%.



**FIG. 9. Gains in Compressive and Flexural Strengths at 28 Days**



**FIG. 10. Stress-Strain Curves for Silica-Fume Concrete: Set I (1:1 Replacement)**

#### *Bond with Steel Reinforcement*

The results of the pullout test indicated improved concrete-steel bond. Stresses at first slip were measured to be 3.39, 3.71, and 3.79 MPa at silica-fume contents of 0%, 10%, and 20%, respectively. The corresponding cube compressive strengths were 48.4, 54.7, and 62.5 MPa, respectively. Gjorv et al. (1990) observed the improvement in steel-concrete bond in silica-fume concrete. They attributed this improvement to reduced accumulations of free water at the interface, reduced preferential orientation of CH crystals at steel-paste transition zone, and densification of the transition zone due to pozzolanic reaction.

#### **Concrete Durability: Chemical**

Accelerated chemical durability testing was performed by subjecting silica-fume mortar prisms to aggressive chemicals. Remaining weight of samples after chemical attack was considered a measure of chemical durability. Aggressive chemicals were divided into the following categories: (1) sulfate compounds; (2) other salts; and (3) acids. Table 4 shows test results.

#### *Sulfate Attack*

Table 4 shows the remaining weight in the mortar specimens during 8 weeks of testing. There was no degradation in the case of silica-fume mortar. In the case of control mix, there was a slight loss in weight. The testing period was relatively short to cause serious deterioration. However, the observed trend showed that silica-fume concrete would have a better resistance against sodium- and magnesium-sulfate attacks.

Yamato et al. (1989) observed similar behavior for silica-fume concrete under sodium sulfate action. Cohen et al. (1988) found that introducing silica fume to type I cement concrete enhanced its resistance to sodium sulfate to be comparable to that of type V cement. However, they reported that silica fume was extremely deleterious to concrete attacked by magnesium sulfate.

**TABLE 4. Chemical Durability of Silica-Fume Mortar (Percent Weight Remaining after Chemical Aggression)**

(1)	Week							
	1 (2)	2 (3)	3 (4)	4 (5)	5 (6)	6 (7)	7 (8)	8 (9)
<i>(a) Saturated Sulfates</i>								
Sodium—control	100	100	99	99	98	98	97	96
Sodium—SFM <sup>a</sup>	100	100	100	100	100	100	100	100
Magnesium—control	100	99	98	97	97	96	95	94
Magnesium—SFM <sup>a</sup>	100	100	100	100	100	100	100	100
<i>(b) Saturated Ammonium Nitrate</i>								
Control	100	98	96	95	81	— <sup>b</sup>	—	—
SFM <sup>a</sup>	100	98	96	95	95	95	95	95
<i>(c) Saturated Calcium Chloride</i>								
Control	100	95	82	— <sup>b</sup>	—	—	—	—
SFM <sup>a</sup>	100	99	95	89	88	88	87	87 <sup>c</sup>
<i>(d) Nitric Acids</i>								
Concentrated—control	97	92	51	32	30	29	28	27
Concentrated—SFM <sup>a</sup>	99	99	89	68	64	61	58	55
20%—control	95	88	73	57	55	53	52	— <sup>b</sup>
20%—SFM <sup>a</sup>	97	92	92	92	92	91	91	91
<i>(e) Sulfuric Acids</i>								
Concentrated—control	99	97	95	95	93	91	90	89
Concentrated—SFM <sup>a</sup>	99	98	96	96	94	93	92	91
20%—control	93	86	79	73	71	69	68	67
20%—SFM <sup>a</sup>	97	90	83	82	82	81	81	81
<i>(f) Hydrochloric Acid</i>								
50%—control	94	88	84	80	40	56	43	31
50%—SFM <sup>a</sup>	98	92	88	85	84	83	83	83

<sup>a</sup>SFM: Silica-fume mortar.<sup>b</sup>Disintegration.<sup>c</sup>Partial rupture.

### *Other Salts Attack*

Ammonium nitrate is a common ingredient in some industries, especially in fertilizer processing, and calcium chloride has been used for a long time as a concrete accelerator as well as being one of the salts that exist in seawater. Table 4 shows the remaining weight during the test period for these two salts. There was a significant improvement in the resistance of mortar due to silica-fume introduction. It was noticed that cracks started to appear in the control specimens made without silica fume after two weeks of immersion. These cracks ended with complete disintegration after five weeks for the ammonium nitrate specimen and three weeks for calcium chloride.

The observed rupture indicated that expansive compounds were formed due to the reaction between the lime and the aggressive solutions. These

reactions were reduced in the case of silica-fume mortar due to the reduction of the harmful lime content in the matrix.

### *Acid Attack*

Mortar specimens were subjected to nitric acid, sulfuric acid, and hydrochloric acid. The nitric and sulfuric acid were in two forms: concentrated and 20% concentration. The hydrochloric acid was of 50% concentration. Table 4 shows the sustained weight for mortar with and without silica fume. Nitric acid is one of the most aggressive chemicals to concrete. The silica-fume mortar specimens offered better resistance to deterioration by nitric acids than portland-cement mortar. By examining the surface of the two specimens, a softening scratchable surface developed only on the surface of the control specimen. Also change of color of the control mortar specimen was observed.

Sulfuric acid exists in many industries as well as being one of the major reasons of corrosion of concrete in sewage works. The effect of sulfuric acid on the mortar specimens is shown in Table 4. Less deterioration effect was noticed in the case of silica-fume mortar. However, this effect was not as drastic as was observed in the case of nitric acid due to the active nature of the sulfuric acid that reacts not only with the lime but with other components in the concrete matrix such as tricalcium aluminate.

Hydrochloric acid is a common chemical existing in industry, e.g. food industry. Table 4 shows the remaining weight due to 50% hydrochloric acid attack. A weight loss of 70% was recorded for ordinary mortar while only 17% was recorded for silica-fume mortar. Change of color and weaker surface structure developed noticeably when scratched in the ordinary mortar. Such development was less noticeable in silica-fume mortar.

From these tests, it could be observed that silica fume greatly enhances the concrete durability in aggressive chemical environments. This enhancement could be attributed to the following factors.

First, silica fume reacted with the lime present in the paste matrix. Consequently, it reduced lime presence in its free format. Lime is considered one of the harmful compounds as it reacts with many chemicals causing concrete degradation.

Second, silica-fume mortar had a better pore structure with greater impermeability than ordinary mortar. This would slow down the penetration of water and chemicals into mortar.

Third, tricalcium aluminate is thought to be harmful in reaction with aggressive chemical environments. As silica fume partially replaced cement, the total amount of tricalcium aluminate was less in the concrete matrix. This decrease in tricalcium aluminate content might contribute to better concrete durability.

### **Concrete Durability: Abrasion Resistance**

When mortar cubes were tested for abrasion, the results showed average abrasion in control mortar of 21.5%, but it was 18.5% for silica-fume mortar. This shows a 14% improvement in abrasion resistance due to the introduction of silica fume. Berra et al. (1989) also observed improvement of erosion resistance for silica-fume mortar.

### **CONCLUSIONS**

Results indicated general superior performance of silica-fume concrete and mortar with 1:1 cement replacement, compared to respective control

concrete and mortar that incorporates type I cement and the same mix proportions. The silica fume presented herein as a mineral admixture is employed to produce concrete of special characteristics or to produce less expensive concrete of comparable characteristics, as silica fume is less expensive than cement. On the basis of the experimental results of this research, the following main conclusions are inferred:

It is preferable to use superplasticizer when introducing silica fume to concrete in order to keep the water ratio at acceptable levels and obtain reasonable and maintainable workability. Sodium naphthalene sulfonate is found effective with no side effects.

Compressive strength of silica-fume concrete is significantly improved up to 56 days. However, there is a drop in the early strength in normal (without accelerators) mix design.

The 56-day compressive strength might be more suitable to indicate the effect of silica-fume on the characteristics concrete.

Flexural strength is improved upon introduction of silica fume in concrete.

There is an optimum content of silica fume between 15% to 20% (1:1 partial cement replacement) at which maximum strengths are obtained.

Elastic modulus, toughness, and steel-concrete bond increase for silica-fume concrete.

Silica-fume mortar show amelioration in chemical resistance against the attack of all acids and salts involved in this research. Relatively minor improvements are observed against sulfate compounds.

Abrasion resistance of silica-fume mortar is slightly higher than the control mix.

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