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Effect of curing procedures on properties of silica fume concrete

Houssam A. Toutanji [b,*], Ziad Bayasi [a]

[a]Department of Civil Engineering, San Diego State University, San Diego, CA 92182, USA

[b]Department of Civil and Environmental Engineering, University of Alabama in Huntsville, Huntsville, AL 35899, USA

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Abstract

The effect of curing procedure on hardened silica fume concrete is reported. The silica fume contents were 10%, 15%, 20%, and 30% by weight of cement. The aggregate to cementitious material ratios (cement + silica fume) ranged from 1.0 to 3.8. Three different curing methods were used: steam, moist, and air curing. Mechanical properties such as compressive strength, permeability, and permeable voids were determined. Steam curing was found to enhance the properties of silica fume concrete, whereas air curing exhibited adverse effects as compared to moist curing. Enhancement in the mechanical properties of silica fume concrete caused by steam curing was manifested by strength increase and permeability and permeable void volume decrease.

Keywords: Curing procedure; Moist curing; Steam curing; Air curing; Silica fume; Compressive strength; Flexural strength; Permeability

It is well documented that the use of silica fume as a partial replacement for cement in combination with superplasticizers provides a significant increase in the strength of concrete [1–3]. The water reduction of fresh concrete and the formation of a more densely compacted matrix at the interfacial zone are believed to be the main causes for this improved strength, permeability, and durability.

The action of silica fume in concrete is physiochemical. The physical phase of this action is in the refinement of the void system of cement paste and particularly the transition zone. The chemical phase consists of the pozzolanic reaction, which transforms the weak calcium hydroxide [$Ca(OH)_2$] crystals into the strong calcium silicate hydrate (CSH) gel. The results of these actions of silica fume provide significant improvements in compressive and flexural strengths, as well as dramatic improvements in durability and impermeability [4–7]. Utilization of methods of curing for silica fume concrete requires consideration. Curing affects the properties of plain and silica fume concrete by altering cement hydration and pozzolanic reaction.

Bentur et al. [8] reported that the strength of silica fume concrete is greater than that of silica fume paste. They attributed it to the change in the role of aggregate in the concrete. In cement concrete, the aggregate functions as an inert filler, but, due to the presence of the weak interfacial zone, composite concrete is weaker than cement paste. A similar conclusion made by Toutanji and El-Korchi [9] was that the increase in compressive strength of mortar containing silica fume, as a partial replacement for cement, greatly contributes to strengthening the bond between the cement paste and aggregate. They reported that partial replacement of cement by silica fume and the addition of superplasticizer increase the strength of mortar but have no influence on the strength of cement paste. Their results were verified by statistical analysis using hypothesis testing at a 95% confidence level.

On the other hand, some researchers have reported that the increase in concrete strength is due, in great part, to a higher quality of the cement paste matrix. Cong et al. [10] found that the replacement of cement by silica fume (up to 18%) and the addition of superplasticizer increase the strength of cement paste. Darwin et al. [11] found that the strengths of both cement paste and mortar increase when 15% of the cement is replaced by silica fume. However, the ratio of the strength of mortar to the strength of cement paste is lower for the materials containing silica fume, which indicates that using silica fume enhances the strength of mortar more than it does to that of cement paste.

ACI Committee 234 [12] concluded that silica fume does not improve the 7-day compressive strength of concrete when cured at 50°F (10°C). However, when cured under temperatures exceeding 68°F (20°C), the 7-day compressive strength tends to improve significantly [13]. It was also indicated that the pozzolanic reaction is, in general, very tem-

* Corresponding author. Tel.: 205-890-6370; Fax: 205-890-6724; E-mail: toutanji@ebs330.eb.uah.edu.

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perature sensitive. With continuation of moisture curing, the rate in tensile and flexural strength increase of silica fume concrete is observed to be higher at later ages as compared to plain concrete.

Research on the effect of silica fume on the mechanical properties of concrete is still evolving. Curing effects on normal concrete have been studied extensively, and results have been established [14]; however, the effect of different curing procedures on silica fume concrete still needs more research. The purpose of the research reported here is to improve our understanding of the mechanism by which silica fume interacts with concrete and to shed light on the effectiveness of silica fume in improving the properties of hardened concrete under various curing procedures and conditions.

1. Experimental program

ASTM type I Portland cement was used in this research. The pertinent physical and chemical properties of the silica fume used are listed in Table 1 [15]. Naphthalene formaldehyde sulfonate base superplasticizer was used [16]. The aggregates were natural river sand and gravel. The gravel was pea stone, with a maximum size of 9 mm, dry rodded unit weight of 100 lb/ft^3, and a moisture content of 2%. The sand was regular concrete sand, with a fineness modulus of 2.58, dry specific gravity of 2.64, and moisture content of 6%.

Mixtures were batched using a conventional drum mixer. Three methods of curing were used: (1) conventional (moist curing at 23°C), (2) steam curing, and (3) air curing. For the first step in all three methods, all specimens except those with 30% silica fume and 5% superplasticizer were kept in their molds and covered with plastic sheets for 24 h. The specimens with 30% silica fume and 5% superplasticizer were kept in the covered molds for 3 days because they remained relatively soft before 3 days of age. This step preserves water within the specimens and prevents plastic shrinkage cracking. After this first step, the specimens for moist curing were cured at 73°F (23°C) with 100% humidity for 7 days. The specimens for steam curing were cured at 175°F (80°C) for 3 days in a container over water. After curing, the specimens for moist and steam curing were kept in a laboratory environment until testing age (35 days for compression and flexure and 45 days for permeability). For the third curing method, specimens were air cured in the laboratory environment at about 73°F (23°C) and humidity ranges between 10% and 30% until testing age.

Fresh concrete mixture properties were determined using (1) the slump test for workability in accordance with ASTM C143 [17] and (2) air content using the pressure method in accordance with ASTM C231 [18]. For each silica fume concrete mix, the following specimens were constructed:

A. Two 100 × 200-mm cylindrical specimens for the rapid chloride permeability test were made. Two slices were obtained from the mid-section of these two specimens. These slices were used for the permeability test according to AASHTO T277 specification [19]. The average permeability of the two tests was considered representative for the mix. In the case when the results of the two slices were not within 15% of one another, the test was repeated for two additional tests.
B. The remainder of the specimens described in part (A) is used to conduct the permeable voids according to ASTM C642 [20].
C. Three 100 × 100 × 350-mm prismatic specimens for flexural testing were made and tested in accordance with ASTM C78 [21].
D. Three 150 × 300-mm cylindrical specimens for compression testing were made and tested in accordance with ASTM C39 [22].

The experimental program for studying the effects of curing procedure on silica fume concrete is shown in Table 2. Selected mixes with variable silica fume-to-binder (binder = cement + silica fume) and aggregate-to-binder ratios were cured conventionally (in moisture), in steam,

Table 1
Chemical and physical properties of silica fume

Chemical composition	
Chemical compound	Percent of total weight
SiO_2	96.5
CaO	1.40
Fe_2O_3	0.15
MgO	0.20
Al_2O_3	0.15
K_2O	0.04
Na_2O	0.20
Physical properties	
Specific gravity = 2.3	
Bulk density = 225 kg/m^3	
Specific surface = 20,000 m^2/kg	
Average particle size = 0.14 mm	

Table 2
Design mix of silica fume concrete, ratios by weight

Mix no.	Curing	SF/B	AG/B
1	Steam	0.10	3.8
2	Moist	0.10	3.8
3	Air	0.10	3.8
4	Steam	0.15	2.9
5	Moist	0.15	2.9
6	Air	0.15	2.9
7	Steam	0.20	2.0
8	Moist	0.20	2.0
9	Air	0.20	2.0
10	Steam	0.30	1.0
11	Moist	0.30	1.0
12	Air	0.30	1.0

Note: W/B = 0.41, G/S = 1.0, and SP/B = 0.01 for all mixtures, where AG = aggregate, B = binder (silica fume + cement), G = gravel, S = sand, SF = silica fume, SP = superplasticizer, and W = water.

Table 3
Test results of silica fume concrete

Mix type	Mix no.	Curing procedure	Rapid chloride permeability at 45 days (coulombs)	Permeable voids at 45 days (%)	Compressive strength at 35 days (MPa)	Flexural strength at 35 days (MPa)
SF = 10%	1	Steam	875	8.8	44.48	4.21
AG = 3.8	2	Moist	841	12.6	38.90	5.79
	3	Air	2894	15.3	33.66	2.90
SF = 15%	4	Steam	744	10.0	47.31	4.97
AG = 2.9	5	Moist	951	19.0	41.86	4.28
	6	Air	1084	16.0	39.03	4.76
SF = 20%	7	Steam	582	14.8	46.34	4.55
AG = 2.0	8	Moist	1024	18.3	41.17	4.62
	9	Air	1243	23.0	39.52	3.66
SF = 30%	10	Steam	133	22.6	46.34	3.52
AG = 1.0	11	Moist	580	28.5	44.41	2.69
	12	Air	1761	31.0	32.41	1.72

Note: AG, aggregate-to-binder ratio; SF, silica fume-to-binder ratio.

and in air. The effects of these curing conditions on compressive strength, flexural strength, and permeability are discussed in the following section.

2. Experimental results

2.1. Compressive and flexural strength

Test results of the effect of curing on the properties of silica fume concrete are presented in Table 3. For each silica fume content, the aggregate-to-binder (silica fume + Portland cement) ratio was selected so that the mix possessed acceptable workability. For mixes containing a silica fume content of 30% (mixes 10, 11, and 12), the superplasticizer-to-binder ratio was increased to 5% to enhance the workability of the mix. Thus, aggregate-to-binder ratios were 3.8, 2.9, 2.0, and 1.0 for silica fume contents of 10%, 15%, 20%, and 30%, respectively.

Fig. 1 shows the compressive strength of concrete with different silica fume contents at different curing conditions. Steam curing yielded the highest compressive strength as compared to both moist and air curing for all mixtures. Under steam and moist curing, the compressive strength of concrete was practically unaffected by increasing the silica fume content beyond 10%, with the exception of the specimens with 30% silica fume exposed to moist curing. Specimens with silica fume of 30% and exposed to moist curing exhibited significant increase in strength as compared to specimens with lower silica fume content under the same curing environments. Air curing had detrimental effect on the strength, particularly on specimens with silica fume of 10% and 30%.

Fig. 2 shows the flexural strength of concrete mixes of different silica fume contents under different curing conditions. With the addition of silica fume beyond 15%, the flexural strength was significantly decreased, regardless of curing condition. Because of the scattered data, it was difficult to interpret which of the two curings, steam or moist curing, had a more pronounced effect on the flexural strength of silica fume concrete. However, it seems that specimens with lower silica fume content of 10% and exposed to moist curing exhibited higher flexural strength as compared to those exposed to steam and air curing. On the other hand, specimens exposed to steam curing with 15% silica fume exhibited higher strength than those exposed to air and moist curing. Results show that the effect of curing on flexural strength is not the same as that on compressive strength in silica fume concrete. This may be attributed to the fact that flexural strength is more sensitive to microcracks as compared to compressive strength. The addition of silica fume to the cement matrix may result in microshrinkage cracking, which could have a more prominent

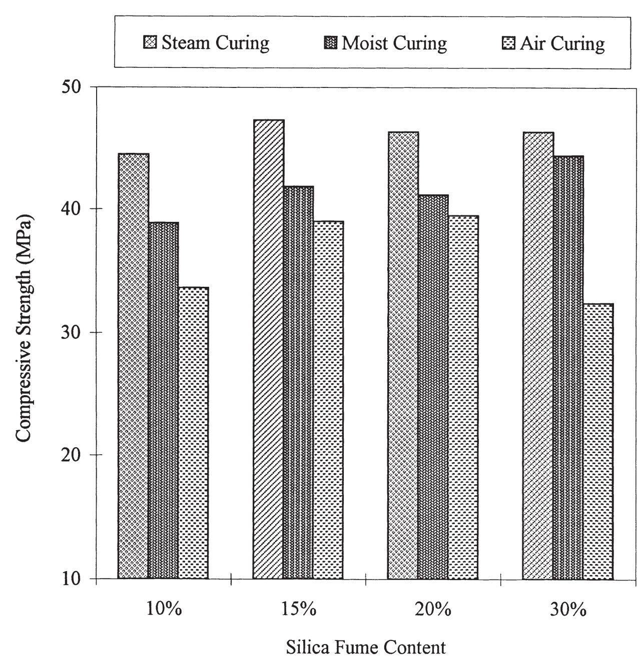

Fig. 1. Effect of various curing procedures on the compressive strength of silica fume concrete.

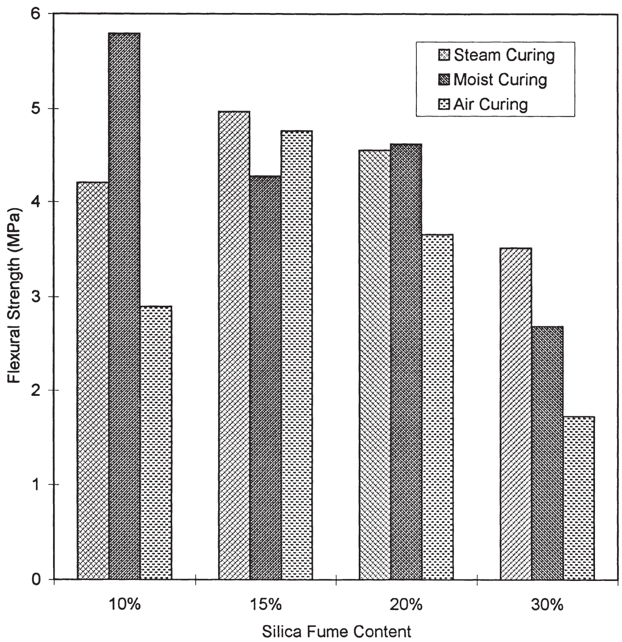

Fig. 2. Effect of various curing procedures on the flexural strength of silica fume concrete.

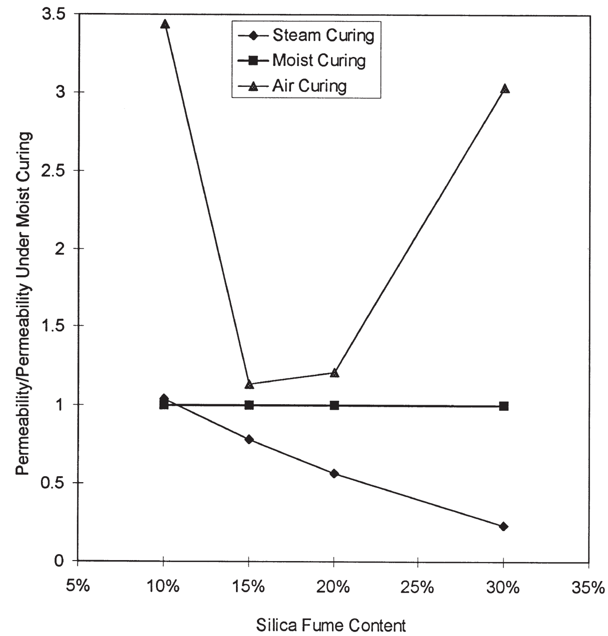

Fig. 3. Effects of curing procedures on the normalized permeability of concrete with different silica fume contents.

effect on the flexural strength as compared to compressive strength.

2.2. Permeability

Fig. 3 illustrates the effects of curing on the permeability of silica fume concrete. The test results are presented using the "normalized property." The normalized property of a mix is the value of that property divided by the same property of another mix that has the same mix proportions. Fig. 3 shows that steam curing decreases the permeability of silica fume concrete. The effect of steam curing becomes more significant as silica fume content increases. On the other hand, air curing increases the permeability of silica fume concrete. The difference between air curing and moist curing (the conventional curing) decreases with increasing silica fume content up to 20%. However, at silica fume content of 30%, the difference in permeability between air curing and moist curing increases significantly. This sudden change in permeability in concrete with 30% silica fume is due to extensive shrinkage cracking, which develops due to air curing.

In a similar manner, Fig. 4 shows the effect of curing on the volume of permeable voids of silica fume concrete. The test results were also presented using the "normalized property." The results show that steam curing decreases the volume of permeable voids compared to moist curing. On the other hand, air curing increases the volume of permeable voids as compared with moist curing.

3. Conclusions

This study was conducted to assess the effects of three curing conditions on hardened silica fume concrete. The measured properties were compressive strength, flexural strength, and rapid chloride permeability. The curing methods were moist, steam, and air curing. These specific conclusions can be drawn from the results of this study:

1. Specimens under steam curing experienced the highest compressive strength as compared to both moist and air curing for all mixtures. Under steam and moist curing, the compressive strength of concrete was

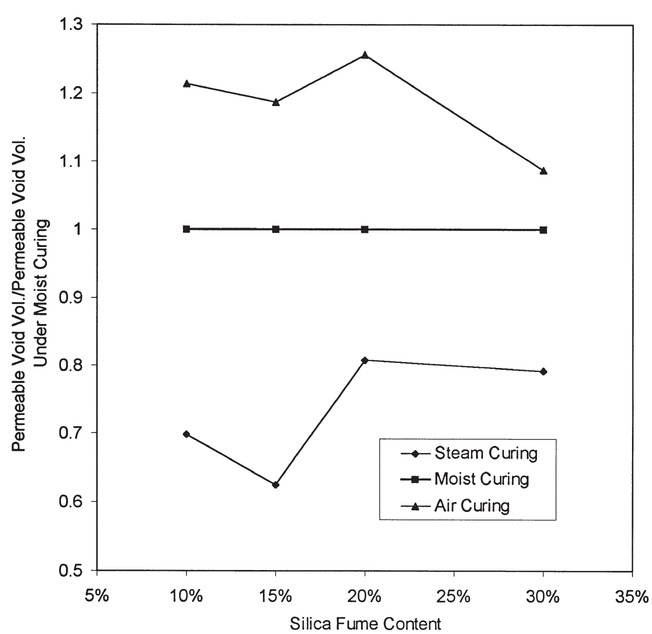

Fig. 4. Effects of curing procedures on the normalized volume of permeable voids of concrete with different silica fume contents.

practically unaffected by increasing the silica fume content beyond 10%, with the exception of the specimens with 30% silica fume exposed to moist curing.

2. With the addition of silica fume beyond 15%, the flexural strength was significantly decreased, regardless of the curing conditions. It was difficult to interpret which of the two curings, steam or moist curing, had a more pronounced effect on the flexural strength of silica fume concrete. Results show that the effect of curing on flexural strength is not the same as that on compressive strength in silica fume concrete.
3. As compared to moist curing, steam curing decreased permeability of silica fume concrete whereas air curing increased permeability. The change of permeability caused by curing is strongly dependent on the silica fume content of the mix. However, concrete with 30% silica fume content exposed to air curing experienced a significant increase in permeability. This is attributed to the extensive shrinkage cracking, which develops due to air curing.

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