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Development of strength with age of mortars containing silica fume

G. Appa Rao*

Department of Civil Engineering, Indian Institute of Science, Bangalore 560 012, India

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Abstract

Some experimental investigations on the development of compressive strength with age of mortar incorporated with silica fume with different water/binder (w/b) ratios have been reported. The silica fume content varied from 0% to 30% by weight of cement. Four w/b ratios, 0.35, 0.40, 0.45, and 0.50, were used. At every w/b ratio, the strength developments at 3, 7, 28, and 90 days have been observed. The highest development rate of compressive strength was observed at early ages (3 and 7 days). At w/b ratio 0.35, the highest value has been observed at 3 days with a silica fume content of 22.5%. At w/b ratios 0.35, 0.40, and 0.45, the strength increases up to an optimum content of silica fume, beyond which it decreases as the silica fume content increases. After 7 days, the strength development has been slowed down significantly at these w/b ratios. However, at w/b ratio 0.50, consistent strength development has been observed at the ages of 3, 7, 28, and 90 days. This has been dependent on the continuous availability of water content at all the ages. However, the ratios of strength of mortar at 3 and 7 days to strength at 28 days, and at 3, 7, and 28 days to strength at 90 days have been observed to be higher at w/b ratio 0.35 than those with other w/b ratios.

Keywords: Cement; Compressive strength; Mortar; Silica fume; Strength development; Water/binder ratio

1. Introduction

The addition of silica fume increases the rate of cement hydration at early hours due to release of OH^- ions and alkalis into pore fluids. This is attributable to the ability of silica fume to provide nucleating sites to hydration products like lime, calcium silicate hydrates (CSH), and ettringite [1]. When siliceous products like silica fume, flyash, and blast furnace slags are mixed with Portland cement and hydrated, they produce pore structure more discontinuous and impermeable than that of hydrated cement paste [2]. It has been reported that silica fume accelerates both C_3S and C_3A hydration during the first few hours [3]. Silica fume tends to affect the pattern of crystallization and degree of orientation of CH crystals at the aggregate surface during the first few days of cement hydration [4]. CSH formed during the hydration of cement play a significant role in influencing the characteristics of cement paste. Hydration proceeds faster in pastes with silica fume, regarding both $Ca(OH)_2$ and nonevaporable water contents at the early age of 3 and 7 days. The hydration reactions (in mortar) with silica fume terminate earlier with regard to the above two parameters. After 28 days, nonevaporable water content continues to increase significantly in plain cement concrete [5]. The nonevaporable water content decreases between 90 and 550 days [6,7]. As much as 40% of additional water requirement was observed for cement pastes containing 20–30% silica fume for obtaining standard consistency cement pastes [8]. As the silica fume content increases, false setting of cement paste was observed at 30% addition of silica fume [8]. Before demoulding of the test specimens, if the mortar is not subjected to adverse exposing conditions, the curing time of silica fume mortar is less than that of the plain cement mortar [9].

The compressive strength of cement paste containing silica fume decreases as the silica fume content increases at low water/binder (w/b) ratios (0.25). After 28 days, plain cement paste exhibits higher strength and greater strength development [7]. At a higher w/b ratio (0.45), with 30% silica fume, the pastes exhibit higher strength between 1 and 180 days than those of plain pastes. It has been reported that silica fume mortars exhibit lower

* Tel.: +91-80-309-2330.
E-mail address: gangolu@civil.iisc.evnet-in (G.A. Rao).

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compressive strength at 3 days and higher strengths at 7 and 28 days than the ordinary mortars and superplasticized mortars [10]. Three mechanisms (i) strength enhancement by pore size refinement and matrix densification, (ii) strength enhancement by reduction in content of $Ca(OH)_2$ (CH), and (iii) strength enhancement by cement paste–aggregate interfacial refinement seem to be responsible for the strength development capability of silica fume [7,11,12]. The optimum replacement of cement by silica fume seems to be 15% [13]. The 7-day strength of concrete is of the order of 86% of the 28-day strength with 28% silica fume [14], which is higher than that of plain cement concrete (60% to 70%) at a temperature of 20°C.

2. Research significance

Research efforts on the use of industrial by-products in the concrete industry have been reported during past two decades. Due to its high pozzolanic action, silica fume is considered as an efficient strength-developing additive in cement products. However, the behavior of cementitious products varies with chemical composition and the source of silica fume. Very significant information on the properties of cement pastes, mortar, and concrete using silica fume has been reported in the world. The production of silica fume in India is very limited. However, the use of Indian silica fume has been reported. Before using the new by-product, knowledge of the behavior of the cement paste and mortar/concrete is very important. The information on the influence of silica fume available in India on various properties of cementitious products (cement pastes, mortar/concrete) is negligible. The objective of this program is to study the influence of silica fume on strength development of mortar to achieve optimum w/b ratio to produce better performance at different ages. The strength development at different w/b ratio with the age of mortar with different silica fume contents was studied.

3. Experimental program

3.1. Materials

An ordinary Portland cement conforming to IS: 12269-1987 was used. Various physical and chemical properties of the cement are shown in Table 1. Silica fume produced in the manufacturing of Ferro silicon alloy with the chemical composition as given in Table 2 partially replaced the cement in the mortar mixes. Specific gravity and specific surface of the silica fume are 2.051 and 16,000 m^2/kg, respectively. Natural River sand available in the nearby stream was adopted with the fractions of sand passing through 1.18-mm sieve and retaining on 0.60 mm. The specific gravity and the bulk density of sand are 2.68 and 1584 kg/m^3, respectively. Potable water available in the laboratory was used. No water-reducing agents were used for improving the workability of mortar in this program.

Table 1
Physical and chemical properties of cement used for the program

Property	Result (%)
Loss on ignition	1.20
Insoluble residue	0.40
Total silica	21.60
Alumina	5.20
Ferric oxide	4.20
Calcium oxide	64.30
Magnesium oxide	1.20
Sulphuric anhydride	1.67
Lime saturation factor	0.91
Alumina modulus	1.24
Tricalcium silicate	51.50
Dicalcium silicate	23.15
Tricalcium aluminate	6.70
Tetracalcium aluminoferrite	12.80
Fineness	2.65
Normal consistency	31.5
Specific gravity (ratio)	3.17
Setting times (min)	
Initial	135
Final	335
Compressive strength (MPa)	
3 days	21.1
7 days	30.1
28 days	48.70

3.2. Testing procedure

Mortar mixes were designed to study the compressive strength, at different ages, with different w/b ratios. The w/b ratios of 0.35, 0.40, 0.45, and 0.50 were adopted. At each w/b ratio, silica fume content varied from 0% to 30% by weight of cement. The cementitious material-to-sand ratio was 1:3 by weight throughout. The compressive strength development in mortar, with different silica fume contents with different w/b ratios, has been studied at different ages, i.e., 3, 7, 28, and 90 days. A machine mixer was used for mixing the dry as well as wet mortar for sufficient time till a uniform mix was achieved. The test specimens were prepared using standard metallic cube mould of size $70.7 \times 70.7 \times 70.7$ mm for compressive strength of mortar. Three test specimens were prepared for obtaining average values at any age at any w/b ratio. After 24 h of casting, the specimens were immersed in water for curing for 28 days. After 28 days of water curing, the specimens were air-dried with a relative humidity of $65 \pm 5\%$ and an average temperature of 30 ± 2°C. The specimens were tested under loading control machine at a constant rate of about 0.01 MPa/s.

Table 2
Chemical composition of silica fume

Chemical compound	Result (%)
Silica (SiO_2)	84–86
Alumina oxide (Al_2O_3)	1.00
Iron oxide (Fe_2O_3)	2.0–3.5
Silica + alumina + iron oxide ($SiO_2 + Al_2O_3 + Fe_2O_3$)	87–91
Calcium oxide (CaO)	1.0–1.5
Loss on ignition	4–7

The rate of loading was maintained constant throughout the program.

4. Test results and discussion

4.1. Strength

Experimentally, the compressive strengths of mortars at 3, 7, 28, and 90 days have been observed at different w/b (cement + silica fume) ratios incorporated with different silica fume contents. At 3 days, it is clearly observed that the highest value of compressive strength of 35.9 MPa was exhibited by mortar mix with 0.35 w/b ratio at 22.5% silica fume content. The deviation of the strength of mortar from mean values was less than 5% in all the mortars. At 3 days, it has been generally observed that the highest values of compressive strengths were achievable in mortar mixes with silica fume content in the range of 20% and 25%. The strength development between 7 and 28 days seems to be good in plain cement mortar at w/b ratio 0.35. However, the strength development is very significant between 3 and 7 days with silica fume mortars. At w/b ratio 0.35, the highest compressive strength was achieved in a mortar incorporated with 20% silica fume. As shown in Fig. 1, the strength development is relatively steep between 3 and 7 days with silica fume mortars, followed by between 7 and 28 days. Between 28 and 90 days, the difference in strength is not very significant. As has been shown in Fig. 1, the variation of strength between 28 and 90 days with silica fume was found to be similar at all contents of silica fume. However, it has been observed that at 5% addition of silica fume, the lowest strengths were observed at different ages. In plain cement mortars, the strength development seemed to be good at any age of mortar. At 20% silica fume the variation is very steep at early ages. This seems to be the highest strength development among the mortars at any silica fume content. Among all the mortar mixes, the lowest strength development has been achieved with 5% silica fume. After 28 days, the rate of strength development decreases with age. That means, after 28 days, increase in strength with age is very modest.

The highest value of compressive strength were 28.9 MPa (SF = 20%) at w/b ratio 0.40, 25.0 MPa (SF = 17.50%) and 28.9 MPa (SF = 22.5%) at w/b ratios 0.45 and 0.50, respectively. It has been clearly indicated that at w/b ratio 0.35, the mortar mixes exhibited much higher strength than those with other w/b ratios at the same silica fume content. Fig. 2 shows the variation of compressive strength with age (log scale) of mortar. Though the strength development at w/b ratio of 0.40 between 3 and 7 days has been observed to be lesser than that at 0.35, the strength development after 28 days seemed to be better than that at 0.35 w/b ratio. It shows that the increase in w/b ratio increases the strength development slightly after 28 days in these mixes. At 3 days, the plain cement mortar exhibited lower strength than those with silica fume. At 3 and 28 days, the highest strengths were observed with 20% silica fume contents, whereas at 7 and 90 days it is 22.5%. In general, the optimum silica fume content that has been observed to produce the highest strength at any age is almost 20%. At 3 and 7 days, the compressive strength of mortar increases as the silica fume content increases up to an optimum silica fume content, beyond which the strength of mortar decreases as the silica fume content increases. This trend has been observed in mortar mixes with w/b ratios 0.35, 0.40, and 0.45. At this age, at w/b ratio 0.50, the compressive strength of mortar consistently increases as the silica fume content increases. The same trend has also been observed at 28 and 90 days. Neglecting a small variation in the compressive strength of mortar, it has been generally observed that the optimum

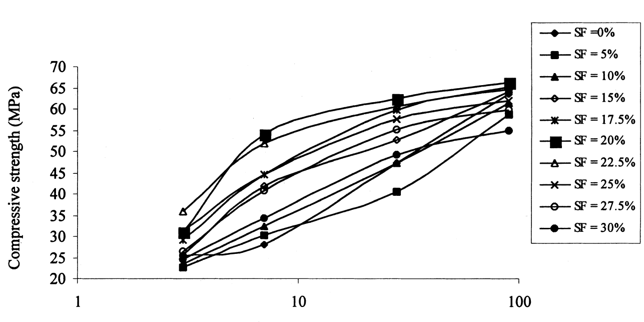

Fig. 1. Variation of compressive strength of mortar with age (log scale) at different silica fume contents at w/b ratio of 0.35.

Fig. 2. Variation of compressive strength of mortar with age (log scale) at different silica fume contents at w/b ratio of 0.40.

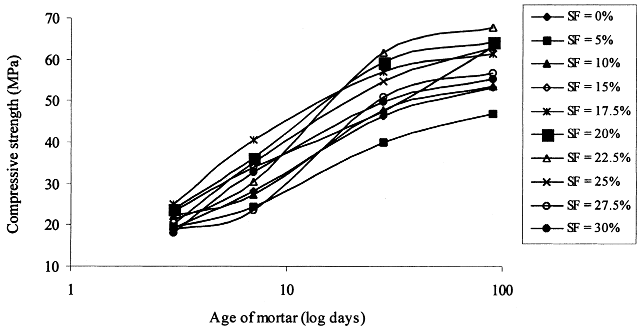

Fig. 3. Variation of compressive strength of mortar with age (log scale) at different silica fume contents at w/b ratio of 0.45.

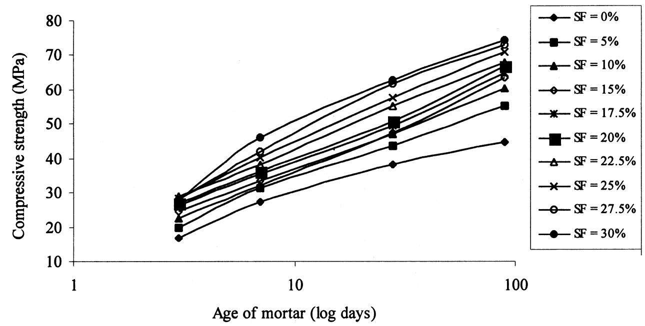

Fig. 4. Variation of compressive strength of mortar with age (log scale) at different silica fume contents at w/b ratio of 0.50.

silica fume content for achieving highest strength was 20% at w/b ratios 0.35, 0.40, and 0.45.

Figs. 3 and 4 show the variation of compressive strength with the age (log scale) of mortar at w/b ratios 0.45 and 0.50 with different silica fume contents. At w/b ratio 0.45, the highest strengths were observed with 17.5% silica fume content at 3 and 7 days, whereas at 28 and 90 days, the higher values were observed at 22.5% silica fume content. However, the consistent strength developments have been observed, at any age, in mortars at w/b ratio 0.50. The strength increases as the silica fume content increases even at the later ages. After 28 days, the strength development is consistent with age. The strength of mortar also increases as the silica fume content increases at all ages.

If the silica fume content is increased, obviously it requires more water for proper mixing and hydration of the cementitious material. The development of strength with silica fume is fast during the early ages of 3 and 7 days due to the pozzolanic action of silica fume. Since nonevaporable water content increases at higher w/b ratios, the development of strength continues even at the later ages. This is the reason why the optimum silica fume content increases as the w/b ratio increases, to produce highest strength. Hence, the pozzolanic reactions of the silica fume continue even in the later ages with the availability of sufficient nonevaporable water content in the mortars, whereas, at lower w/b ratios, a large amount of unhydrated cementitious material remains even after a longer duration. However, at higher w/b ratios ≥ 0.50, the addition of silica fume may consume larger quantity of $Ca(OH)_2$ formed during the cement hydration. Feldman and Cheng Yi [7] reported similar observations on Portland cement pastes containing silica fume contents of 0%, 20%, and 30% at water/cementitious material ratios of 0.25 and 0.45. At the early ages, 3 and 7 days, with lower w/b ratios, the nonevaporable water content seems to be higher with silica fume than that found in plain Portland cementitious products [5]. Whereas in mortar mixes with higher w/b ratios, the nonevaporable water content is sufficient for continuous hydration or pozzolanic reaction of silica fume even at the later ages of composites. However, with w/b ratio 0.50, the mortar mixes containing increasing nonevaporable water contents exhibited consistent strength development as the silica fume content increases. The nonavailability of nonevaporable water contents led to the strength retrogression in concrete and mortars as reported by several researchers [15–18]. The water content should be selected to achieve continuous hydration of the product. The concrete technologist should consider this factor while designing the products for various practical uses. The present study shows that the strength, efficiency, and increase in the strength of mortar have been observed to be very good with lower w/b ratios at early

Table 3
Ratio of compressive strength (MPa) at different ages with reference to 28 and 90 days with silica fume at w/b ratio of 0.35

Mix designation	Silica fume content (%)	Ratio of strength at 3 and 7 days to strength at 28 days		Ratio of strength at 3, 7, and 28 days to strength at 90 days		
		3/28	7/28	3/90	7/90	28/90
HSFM-1	0.0	0.54	0.60	0.40	0.45	0.75
HSFM-2	5.0	0.56	0.75	0.39	0.51	0.69
HSFM-3	10.0	0.50	0.69	0.38	0.53	0.77
HSFM-4	15.0	0.49	0.79	0.40	0.65	0.83
HSFM-5	17.5	0.49	0.75	0.45	0.69	0.92
HSFM-6	20.0	0.50	0.88	0.47	0.82	0.93
HSFM-7	22.5	0.59	0.86	0.56	0.80	0.94
HSFM-8	25.0	0.54	0.77	0.51	0.72	0.93
HSFM-9	27.5	0.48	0.74	0.45	0.68	0.93
HSFM-10	30.0	0.50	0.70	0.45	0.62	0.90

Table 4
Ratio of compressive strength (MPa) at different ages with reference to 28 and 90 days with silica fume at w/b ratio of 0.40

Mix designation	Ratio of strength at 3 and 7 days to strength at 28 days		Ratio of strength at 3, 7, and 28 days to strength at 90 days		
	3/28	7/28	3/90	7/90	28/90
HSFM-1	0.46	0.61	0.34	0.45	0.73
HSFM-2	0.47	0.74	0.35	0.55	0.74
HSFM-3	0.50	0.72	0.37	0.54	0.75
HSFM-4	0.49	0.70	0.41	0.55	0.79
HSFM-5	0.51	0.70	0.41	0.55	0.79
HSFM-6	0.53	0.71	0.42	0.57	0.8
HSFM-7	0.44	0.80	0.33	0.59	0.74
HSFM-8	0.43	0.80	0.35	0.65	0.81
HSFM-9	0.47	0.78	0.35	0.58	0.74
HSFM-10	0.50	0.82	0.38	0.63	0.77

ages, but that higher w/b ratios exhibit consistent performance at later ages. For producing high-performance mortars, the w/b ratio seemed to be greater than 0.45 at higher silica fume contents.

4.2. Discussion

Ratios of strengths at 3 and 7 days to strength at 28 days, and at 3, 7, 28 days to strength at 90 days are shown in Tables 3–6 at different w/b ratios. At w/b ratio 0.35, the ratio of strength at 3 days to strength at 28 days in plain cement mortar was 0.54. In mortar mix HSFM-7 (SF = 22.5%), the ratio is 0.59 which is the highest. In all other mixes, the ratio seems to be about 0.50. At w/b ratio 0.40, the ratio of strength at 3 and 28 days ranges between 0.43 and 0.53. It is in between 0.34 and 0.49 at w/b ratio 0.45, whereas at w/b ratio 0.50, it is 0.43 to 0.50. In general, the ratio of strength at 3 days to strength at 28 days ranges between 45% and 53%. The ratio of strength at 7 to strength at 28 days ranges between 60% and 88% at w/b ratio 0.35. However, it ranges between 60% and 80% at w/b ratio 0.40, between 60% and 70% at w/b ratio 0.45, and between 68% and 74% at w/b ratio 0.50. Sabir [14] reported that the 7-day strength of silica fume concrete was observed to be 86% of the 28-day strength. The ratios of strengths of 3 to 90 days are about 38% to 56% at w/b ratio 0.35, 34% to 42% at w/b ratio 0.40, 32% to 41% at w/b ratio 0.45, and 38% to 41% at w/b ratio 0.50. At 7 and 90 days, it is 45% to 50%. Between 7 and 90 days, the strength ratios are 50% to 80% at w/b ratio 0.35, 45% to 63% at w/b ratio 0.40, 41% to 59% at w/b ratio 0.45, and 53% to 62% at w/b ratio 0.50. Whereas, for the strength at 28 and at 90 days, the ratios range between 75% and 94% at w/b ratio 0.35, 73% to 80% at w/b ratio 0.40, 81% to 93% at w/b ratio 0.45, 75% to 85% at w/b ratio 0.50. Tables 3–6 show the ratios of strength of 3 and 7 days to 28 days, and of 3, 7, and 28 days to that of 90 days at different w/b ratios.

5. Sources of error and accuracy

The deviation of the strength of individual specimens from the mean of three specimens has been very small. The possible sources of errors may be due to nonuniform compaction of the mortar in all of the test specimens, difference in the rate of loading, eccentric loading, nonuniform dimensions of the specimens, nonuniform distribution of silica fume in the cement. Adopting standard specimens could minimize the above possible sources of errors. The uniformity of the cement and silica fume mixer is very important. The dry mixing of the cement and silica fume was carried out for about 2–3 min before the sand was

Table 5
Ratio of compressive strength (MPa) at different ages with reference to 28 and 90 days with silica fume at w/b ratio of 0.45

Mix designation	Ratio of strength at 3 and 7 days to strength at 28 days		Ratio of strength at 3, 7, and 28 days to strength at 90 days		
	3/28	7/28	3/90	7/90	28/90
HSFM-1	0.42	0.61	0.36	0.53	0.87
HSFM-2	0.49	0.61	0.41	0.52	0.85
HSFM-3	0.46	0.57	0.41	0.51	0.89
HSFM-4	0.44	0.64	0.40	0.59	0.91
HSFM-5	0.44	0.71	0.41	0.66	0.93
HSFM-6	0.40	0.61	0.37	0.57	0.93
HSFM-7	0.34	0.50	0.31	0.45	0.91
HSFM-8	0.36	0.46	0.32	0.40	0.81
HSFM-9	0.37	0.46	0.33	0.41	0.90
HSFM-10	0.36	0.45	0.33	0.41	0.90

Table 6
Ratio of compressive strength (MPa) at different ages with reference to 28 and 90 days with silica fume at w/b ratio of 0.50

	Ratio of strength at 3 and 7 days to strength at 28 days		Ratio of strength at 3, 7, and 28 days to strength at 90 days		
Mix designation	3/28	7/28	3/90	7/90	28/90
HSFM-1	0.43	0.71	0.38	0.62	0.86
HSFM-2	0.46	0.72	0.36	0.57	0.79
HSFM-3	0.48	0.68	0.38	0.53	0.78
HSFM-4	0.52	0.70	0.39	0.53	0.75
HSFM-5	0.53	0.72	0.40	0.55	0.76
HSFM-6	0.53	0.71	0.41	0.54	0.76
HSFM-7	0.53	0.70	0.43	0.57	0.81
HSFM-8	0.49	0.69	0.40	0.57	0.82
HSFM-9	0.45	0.68	0.39	0.58	0.85
HSFM-10	0.44	0.74	0.37	0.62	0.85

poured into the machine mixer. Adopting a large number of test specimens for obtaining better average strength could compensate the possible errors. This eliminates the errors and then the accuracy could be high. However, care has been taken to avoid all such errors while experimenting with the present program.

6. Conclusions

From the test results, it can be concluded that during the early ages, 3 and 7 days, strength of mortars with silica fume, in general, has been significantly high at any w/b ratio. The rate of strength development between 3 and 7 days was the highest. At w/b ratios 0.35, 0.40, and 0.45, the optimum silica fume contents for achieving highest compressive strength range between 17.5% and 22.5%. The optimum silica fume content increases with w/b ratio at any age. At w/b ratio 0.50, the strength of mortar continuously increases with all silica fume contents. The strength development after 28 days has been very moderate at w/b ratios 0.35 and 0.40 and relatively better at 0.45. However, it has been very good and consistent at w/b ratio 0.50 at any age with all silica fume contents. The ratios of compressive strengths at 3 and 7 days to strength at 28 days and at 3, 7, and 28 days to that of 90 days have been observed to be higher at w/b ratio 0.35 than those with other w/b ratios.

References

[1] J.A. Larbi, A.L.A. Fraay, J.M.J.M. Bijen, The chemistry of the pore fluid of silica fume-blended cement systems, Cem. Concr. Res. 20 (4) (1990) 506–516.

[2] Z. Bayasi, J. Zhou, Properties of silica fume concrete and mortar, ACI Mater. J. 90 (4) (1993) 349–356.

[3] H. Cheng Yi, R.F. Feldman, Hydration reactions in Portland cement–silica fume blends, Cem. Concr. Res. 15 (1985) 585–592.

[4] J.A. Larbi, J.M.J.M. Bijen, Orientation of calcium hydroxide at the Portland cement paste–aggregate interface in mortars in the presence of silica fume — A contribution, Cem. Concr. Res. 20 (1990) 461–470.

[5] S.L. Mak, K. Torii, Strength development of high strength concretes with and without silica fume under the influence of high hydration temperatures, Cem. Concr. Res. 25 (8) (1995) 1791–1802.

[6] M.H. Zhang, O.E. Gjorv, Effect of silica fume on cement hydration in low porosity cement pastes, Cem. Concr. Res. 21 (5) (1991) 800–808.

[7] R.F. Feldman, H. Cheng Yi, Properties of Portland cement silica fume pastes: II. Mechanical properties, Cem. Concr. Res. 15 (1985) 943–952.

[8] G.A. Rao, P.S. Chandra Sekhar, Preliminary investigations on silica fume–cement blends, Proceedings of National Seminar on High Performance Concrete, Bangalore, India, February (1996), pp. 3.10–3.17.

[9] M.S. Khan, M.E. Ayers, Curing requirements of silica fume and fly ash mortars, Cem. Concr. Res. 23 (1993) 1480–1490.

[10] X. Cong, S. Gong, D. Darwin, S.L. McCabe, Role of silica fume in compressive strength of cement paste, mortar, and concrete, ACI Mater. J. 89 (4) (1992) 375–387.

[11] M.D. Cohen, M. Klitsikas, Mechanisms of hydration and strength developments in Portland cement composites containing silica fume particles, Indian Concr. J. 60 (11) (1986) 296–299 (November).

[12] M.D. Cohen, A look at silica fume and its actions in Portland cement concrete, Indian Concr. J. 64 (9) (1990) 429–438 (September).

[13] Y. Yogendran, B.W. Langan, M.N. Haque, M.A. Ward, Silica fume in high-strength concrete, ACI Mater. J. 84 (1987) 124–129.

[14] B.B. Sabir, High-strength condensed silica fume concrete, Mag. Concr. Res. 47 (172) (1995) 219–226.

[15] F.D. Larrard, P.C. Aitcin, Apparent strength retrogression of silica fume concrete, ACI Mater. J. 90 (6) (1993) 581–585.

[16] F.D. Larrard, J.L. Bostvironnois, On long-term strength losses of silica fume high-strength concretes, Mag. Concr. Res. 43 (155) (1991) 109–119.

[17] B. Persson, Long-term effect of silica fume on the principal properties of low-temperature cured ceramics, Cem. Concr. Res. 27 (11) (1997) 1667–1680.

[18] P.C. Aitcin, P. Laplante, Long-term compressive strength of silica fume concrete, J. Mater. Civ. Eng. 6 (3) (1990) 357–375.