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Influence of silica fume on long-term strength of mortars containing different aggregate fractions

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Abstract

An experimental investigation on the influence of high-strength cement with silica fume on long-term strength of mortar is reported. The effect of aggregate size and specific surface of aggregate on the variation of compressive strength has been studied. It has been observed that the early strength development was very significant with the addition of silica fume in mortars. It was also found that the size of the aggregate and its specific surface play a very significant role on the strength of the mortar. The strength of mortar increases initially and then gradually decreases as the grain size and the specific surface of aggregate increases. The modulus of elasticity increases as the compressive strength of the mortar increases. Significant strength losses have been observed in both silica fume and non-silica fume mortars at the age of 180 days.

Keywords: Aggregate; Elastic moduli; Fineness modulus; Mortar; Silica fume; Surface area

1. Introduction

When silica fume is incorporated, the rate of cement hydration increases at the early hours due to the release of OH^- ions and alkalis into the pore fluid [1]. The increased rate of hydration may be attributable to the ability of silica fume to provide nucleating sites to precipitating hydration products like lime, C–S–H, and ettringite. It has been reported that the pozzolanic reaction of silica fume is very significant and the non-evaporable water content decreases between 90 and 550 days at low water/binder ratios with the addition of silica fume [2,3]. The presence of sand in mortars acts as a sink for crystallized $Ca(OH)_2$ and lowers the permeability of the cement paste [3]. It has been generally reported [4–6,19,20] that the strength development in the cement composites incorporated with silica fume is due mainly to the pore size refinement and matrix densification, reduction of $Ca(OH)_2$ content, and strong cement paste–aggregate interfacial bond. The formation of dense C–S–H gel and more homogeneous product at the interfacial zone leads to the rapid strength development of mortar at the early ages [7–10,14,15]. This has been due mainly to the nucleation of CH crystals around silica fume particles around the aggregate [13]. The increase in curing temperature at early hours results in very significant strength development with silica fume [8,12]. The pore structure of cement paste depends on the aggregate content and the amount of pores in silica fume cementitious product increases as the aggregate content increases [11]. Using scanning electron microscope (SEM) and X-ray diffraction techniques, the formations of CH and ettringite have been observed [14,16,17] in the transition zone. The thickness of this zone seems to be function of the size and shape of the sand particles. During the last two decades, few controversial reports [18,21–30] have evolved and expressed concern over the strength retrogression of high-strength cementitious products. In this study, an effort is made to investigate the influence of silica fume, size of sand particles, and its specific surface on the long-term strength of mortar using high-strength cement.

2. Research significance

During the last two decades, the concept of high-performance cementitious materials has been on the rise. Applica-

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Table 1
Physical properties of cement

Property of cement	Result
Fineness, %	2.9
Standard consistency, %	31.80
Setting times	
(a) Initial (min)	125
(b) Final (min)	305
Specific gravity	3.12
Compressive strength, MPa	
(a) At 3 days	23.00
(b) At 7 days	34.50
(c) At 28 days	52.50

tion of high-strength cementitious products for the field applications is increasing rapidly. Moreover, incorporation of high range water reducing (HRWR) agents and use of pozzolanic materials like pulverized fuel ash and silica fume are proven to be useful with low water/cementitious materials ratio. Field engineers, academicians, and scientists in the research laboratories have found the long-term strength reduction in mortar/concrete with the addition of silica fume. The information on the effect of silica fume on the long-term strength of mortar is limited. The influence of grain size of sand particles on the strength of mortar is negligible. In this study, the influence of these parameters has been studied on the long-term strength of mortar.

3. Experimental program

3.1. Materials

3.1.1. Cement

Ordinary Portland cement was used with the properties shown in Table 1.

3.1.2. Silica fume

Silica fume with a specific surface of 14–16 m^2/g and specific gravity of 2.05 was used for the program. The chemical composition of silica fume is shown in Table 2. Silica fume was used as cement replacement material at 10 wt.% of cement throughout the program.

3.1.3. Fine aggregate

The fine aggregate was non-porous quartzite from the River Swarnamukhi, Tirupathi, AP, India. The natural sand was sieved through different sieves to obtain required particle size fractions. The cement/fine aggregate ratio was maintained at 1:3 in each of the mortar mixes. The ratios of different size fractions are presented in Tables 3 and 4.

Two series of mortar mixes were made. Series I consisted of 14 mortar mixes with plain Portland cement mortar as reference mix, along with silica fume cement mortar at water/cementitious materials ratio of 0.417. Series II mortar mixes consisted of eight mixes, four plain mortar mixes, and four silica fume mortar mixes. The water/cementitious materials ratio was 0.5 in Series II mortar mixes. Tables 3 and 4 show the mix proportions of various mortar mixes. Cube specimens of size 70.7 mm were used for the determination of compressive strength of mortar. The strength was calculated as the average of strength on three cube specimens. In each mix, the fineness modulus and specific surface of aggregates were changed to distinguish the effect of the aggregate size, specific surface, and fineness modulus on the strength of mortars with and without silica fume. The surface area of the aggregates was calculated by assuming that all the sand particles as spherical. The surface area $=(6/\rho d_{mean})$, where ρ is the density of aggregate (2.65 for quartzite) and d_{mean} the mean diameter of the aggregate fraction.

The cube specimens were demoulded after 24 h and cured for 28 days in water. Subsequently, the specimens were exposed for the laboratory environment at 27 ± 3°C and relative humidity of 60 ± 5% for 180 days. The test results are shown in Tables 5 and 6. In obtaining the modulus of elasticity according to ASTM C 469-94, cylindrical specimens 100 mm in diameter and 200 mm in height were cast and the stress–strain relations were drawn. The curing conditions were the same as that for cube specimens.

4. Test results and discussion

Tables 5 and 6 show the test results of the program for Series I and II mortar mixes, respectively. In Series I mortars, the strength was observed at different ages of 7, 28, and 180 days. While in Series-II mortars, the strength was observed at the age of 1 day. Fig. 1 shows the variation of compressive strength at 28 days for the two series of mortar mixes with size of aggregate. From the observations, it was clear that the compressive strength initially increases and then gradually decreases as the grain size of sand increases. For all the mortar mixes, with and without silica fume, it is apparent that the highest strength values were achieved with grain sizes between 1.5 and 2.0 mm. It is also clear that the silica fume mortars are ahead of the plain cement mortars in compression at 28 days. At early days of curing, i.e. at 1 day and 7 days, the development of strength in silica fume mortars is very significant. This has been possible due mainly to the pozzolanic action of silica fume [1–6].

Table 2
Chemical composition of silica fume

Chemical compound	Result (%)
Silica (SiO_2)	86.00
Alumina oxide (Al_2O_3)	1.0 (max)
Iron oxide	2.0–3.5
Silica + alumina + iron oxide ($SiO_2 + Al_2O_3 + Fe_2O_3$)	87.00–91.00
Calcium oxide (CaO)	1.0–1.5
Loss on ignition	4.0–7.0

Table 3
Mix proportions and preliminary properties of Series I (W/C = 0.417) mortars

Mix designation	Ratios of grain size fractions in the mix				Average grain size, mm	Fineness modulus	Specific surface, m^2/kg
	4.75–2.36 mm	2.36–1.18 mm	1.18–0.60 mm	0.60–0.30 mm			
MPC I	1	0	0	0	3.55	5.0	0.637
MSF I	1	0	0	0	3.55	5.0	0.637
MPC II	0	1	0	0	1.71	4.0	1.273
MSF II	0	1	0	0	1.71	4.0	1.273
MPC III	0	0	1	0	0.89	3.0	2.544
MSF III	0	0	1	0	0.89	3.0	2.544
MPC IV	0	0	0	1	0.45	2.0	5.03
MSF IV	0	0	0	1	0.45	2.0	5.03
MPC V	1	1	1	1	1.65	3.50	1.372
MSF V	1	1	1	1	1.65	3.50	1.372
MPC VI	0	4	1	1	1.364	3.50	1.662
MSF VI	0	4	1	1	1.364	3.50	1.662
MPC VII	0	2	1	1	1.19	3.25	1.903
MSF VII	0	2	1	1	1.19	3.25	1.903

Table 4
Mix proportioning and preliminary properties of Series II (W/C = 0.50) mortars

Mix designation	Ratios of grain size fractions in the mix				Average grain size, mm	Fineness modulus	Specific surface, m^2/kg
	4.75–2.36 mm	2.36–1.18 mm	1.18–0.60 mm	0.60–0.30 mm			
PCM I	1	0	0	0	3.55	5.0	0.637
SFM I	1	0	0	0	3.55	5.0	0.637
PCM II	0	1	0	0	1.71	4.0	1.273
SFM II	0	1	0	0	1.71	4.0	1.273
PCM III	0	0	1	0	0.89	3.0	2.544
SFM III	0	0	1	0	0.89	3.0	2.544
PCM IV	0	0	0	1	0.45	2.0	5.03
SFM IV	0	0	0	1	0.45	2.0	5.03

However, the strength development at the early age is more likely due to a nucleation effect: CSH formed from OPC tends to precipitate on small SF particles, allowing a further dissolution of OPC in the liquid phase. Some researchers concluded that the increase in the strength with the addition of silica fume results in the improved interfacial zone between cement paste and aggregate, which is more impermeable and compact with the silica fume [7–17]. Percentage compressive strength loss in various mortar mixes is shown in Tables 5 and 6, respectively, in Series I and II mortar mixes.

In Fig. 2, it has been observed that as the specific surface of aggregate increases, the strength increases up to

Table 5
Test results on compressive strength, modulus of elasticity, and strength loss in Series I mortar mixes

Mix designation	Compressive strength, MPa			Modulus of elasticity, GPa	Strength loss, MPa	Percent strength loss
	7 days	28 days	180 days			
MPC I	18.00	28.00	38.20	1.54	− 10.20	− 36.42
MSF I	28.20	36.80	46.00	1.55	− 9.20	− 25.00
MPC II	44.00	54.20	50.00	3.6	4.20	7.73
MSF II	48.00	59.23	56.00	2.11	3.23	5.45
MPC III	39.60	44.60	44.00	3.44	0.60	1.35
MSF III	41.80	50.20	48.00	3.64	2.20	4.38
MPC IV	21.25	35.20	42.00	0.88	− 6.80	− 19.32
MSF IV	26.60	40.60	39.00	2.86	1.60	3.94
MPC V	48.60	50.70	50.00	2.90	0.70	1.38
MSF V	50.20	60.70	52.00	4.20	8.70	14.33
MPC VI	31.13	53.20	50.00	3.0	3.20	6.02
MSF VI	39.33	58.20	58.00	3.69	0.20	0.34
MPC VII	30.60	48.00	43.00	2.53	5.0	10.42
MSF VII	36.00	56.00	50.00	2.70	6.0	10.71

Table 6
Test results on compressive strength, modulus of elasticity, and strength loss in Series II mortar mixes

Mix designation	Compressive strength, MPa				Modulus of elasticity, GPa	Strength loss, MPa	Percent strength loss
	1 Day	7 Days	28 Days	180 Days			
PCM I	8.60	24.00	39.20	34.80	5.94	4.40	11.22
SFM I	11.60	25.40	41.20	38.00	3.44	3.20	7.78
PCM II	12.20	22.40	40.00	39.00	3.75	1.0	2.50
SFM II	13.60	25.60	43.60	41.00	1.20	2.60	6.05
PCM III	10.80	16.70	29.20	30.20	2.50	− 1.0	− 3.40
SFM III	16.80	20.40	39.00	40.40	1.85	− 1.4	− 3.59
PCM IV	6.85	17.20	30.00	29.20	0.50	0.80	2.70
SFM IV	12.30	23.20	36.52	35.60	1.06	3.92	2.52

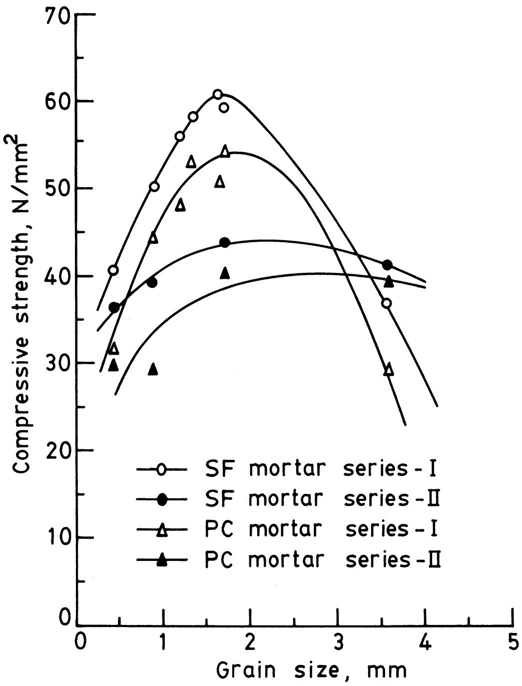

Fig. 1. Variation of compressive strength with grain size of sand particles in mortar.

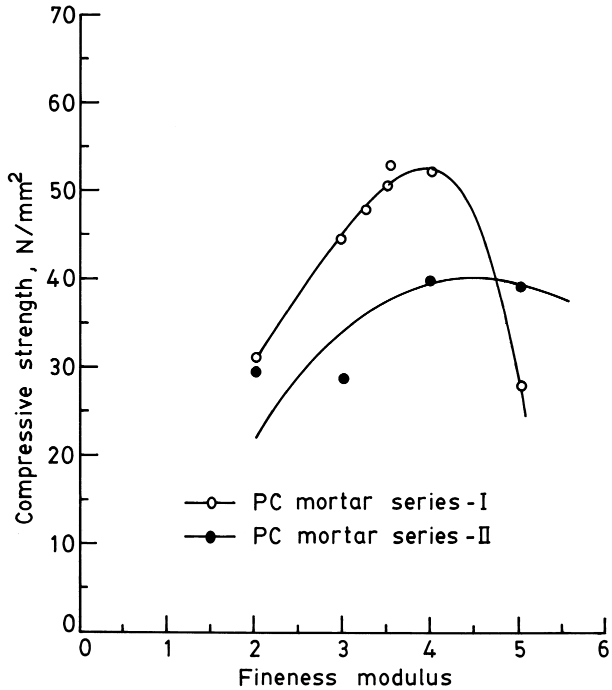

Fig. 3. Variation of compressive strength with fineness modulus of sand particles in mortar.

certain value and then gradually decreases as the specific surface of sand particles increases. It is a known fact that the specific surface of sand particles increases with decrease in the grain size. As the specific surface increases, the water demand is obviously greater. As a result, the cement and silica fume binder was supplied

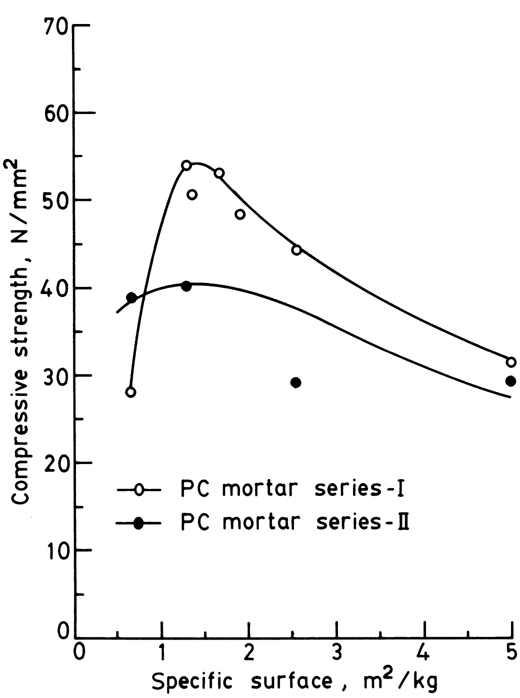

Fig. 2. Variation of compressive strength with specific surface of aggregate.

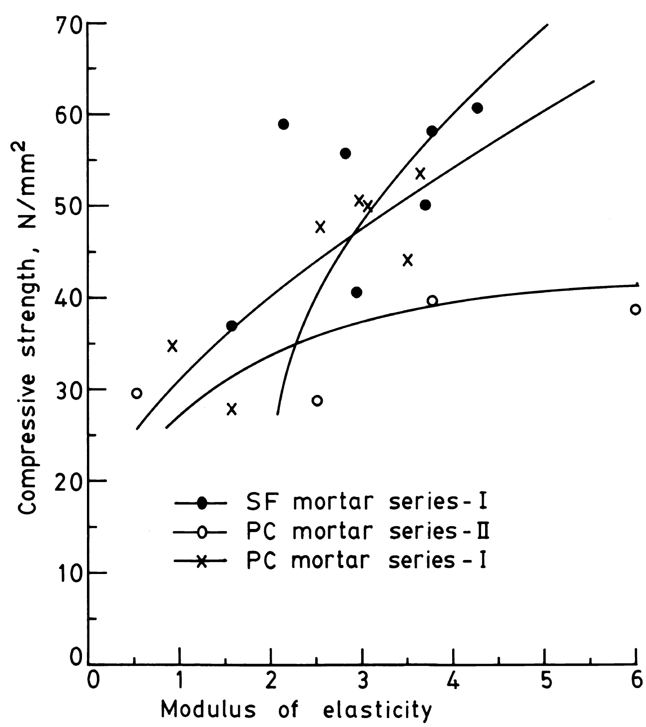

Fig. 4. Variation of modulus of elasticity with compressive strength of mortar.

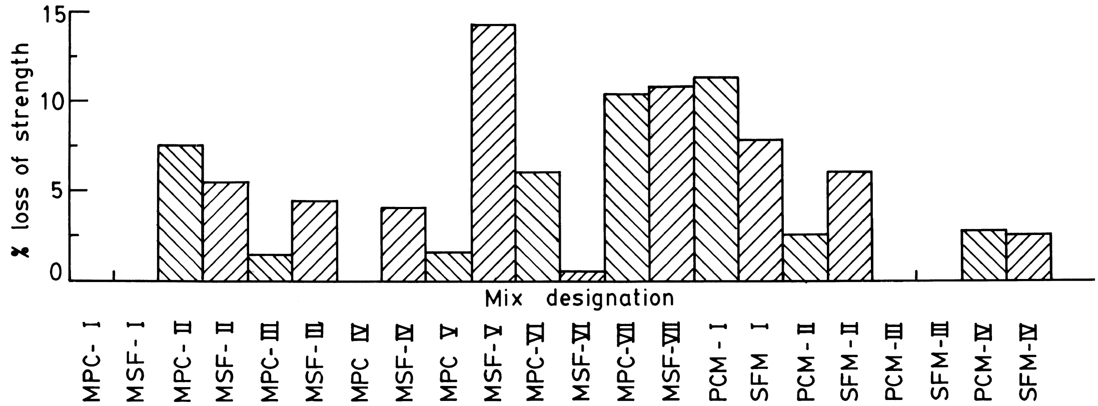

Fig. 5. Percentage strength loss in different mortar mixes.

with insufficient water for complete hydration, which thus lead to a weaker bond between cement paste and grain surface. In the case of larger sand particles, which results in lesser specific surface, the excess water around the sand particles increases the porosity and the interfacial bond between cement paste and aggregate surface becomes weak. One more reason regarding this is that the smaller sand particles are nearly of spherical in shape. The increased smooth surface of sand particles reduces the aggregate interlocking, whereas, this effect is very significant in the case of larger sand particles. It has been observed that as the fineness modulus of sand increases, the strength increases initially up to certain value and then decreases gradually. This trend has been shown in Fig. 3 for both the mortar mixes in Series I and II. The variation of modulus of elasticity of mortar with the compressive strength has been shown in Fig. 4. It has been observed that the highest compressive strengths achieved using sand with fineness modulus in the range between 3 and 4. The modulus of elasticity of mortar increases as the strength increases.

The test results on the long-term strength of mortar show a negative effect after 28 days curing on mortars, with and without silica fume. It has been observed that strength retrogression was noticed in most of the mortar mixes. Very few results have been published on the influence of temperature and relative humidity on the strength of mortars. However, extreme drying causes significant drop in the strength. In addition, severe strength reduction may be possible when the specimens are interrupted during the first few hours after casting. In the present case, the ratio of drying surface area to volume of test specimen is quite high and the drying effect seems to be significant. Recently, the loss of strength due to drying effect has been explained by few researches [21,23,24,26]. Various mortar mixes with percentage strength losses are shown in Fig. 5. From the observations made on various mortar mixes, it has been observed that the strength loss seems to be similar in all the mortar mixes, with and without silica fume, and this has been due mainly to the drying effect.

5. Conclusions

The following conclusions may be drawn from the experimental test results:

1. The grain sizes of sand particles influence the strength of mortar. The compressive strength increases gradually and then decreases as the size of sand particles increased. The highest strength was observed with grain sizes between 1.50 and 2.0 mm.
2. The addition of silica fume has significant influence on the early strength development of mortar.
3. In mixes with larger size grains, fractured surfaces revealed that crack have crossed the grains, whereas cracks could not propagate across the grains with smaller size.
4. The increase in specific surface of aggregate results in the increase in strength, initially, then gradually decreases.
5. Similar trend was observed with the fineness modulus of aggregate on strength of mortar. The highest strength was achieved with fineness modulus in the range 3–4.
6. The strength loss was observed in mortar mixes, with and without silica fume. This may be due mainly to drying effect.

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