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Role of water–binder ratio on the strength development in mortars incorporated with silica fume

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Abstract

An experimental investigation on the variation of compressive strength, with water–binder (w/b) ratios in mortars incorporated with silica fume, has been reported. The w/b ratios varied between 0.35 and 0.50 at a constant increment of 0.05. The silica fume content varied from 0% to 30%. The strength development with w/b ratio has been studied at different ages of 3, 7, 28 and 90 days. Abrams' generalized water–cement (w/c) ratio law has been verified for mortars with silica fume at all the ages. From the test results, it has been observed that, in plain cement mortars, the strength of mortar decreases as the w/b ratio increases at any age of mortar. However, the mortar mixes containing silica fume did not follow the same variation as has been observed in plain cement mortars. At early ages of 3 and 7 days, the strength of mortars with silica fume decreases with w/b ratio up to 0.45. Between w/b ratio 0.45 and 0.50, the strength has been observed to increase with w/b ratio. However, at the ages of 28 and 90 days, the strengths of mortars at w/b ratios of 0.35, 0.40 and 0.50 were observed to be more or less the same. But, at w/b ratio of 0.45, the strength has been observed to be the lowest at any silica fume content. At w/b ratio of 0.50, the influence of silica fume (>27.5%) was pronounced significantly at later ages. Moreover, it has been observed that the variation of strength with w/b ratio could not comply with the Abrams' generalized w/c ratio law in mortars containing silica fume.

Keywords: Age; Mortar; Silica fume; Strength; Water–binder ratio

1. Introduction

Abram's law pronounces the importance of water–cement (w/c) ratio on the strength of concrete [9–11]. According to Abram's generalization law, the compressive strength of concrete varies inversely with w/c ratio. Information on the influence of w/c ratio on the strength of mortar is very limited. Currie and Sinha [5] reported that the largest single most important factor affecting the compressive strength of mortar appeared to be the w/c ratio, and the relationship between compressive strength and w/c ratio seemed to be unaffected by the use of different sands and sand grading. Rao [12] reported that the high-strength mortars obey Abrams' generalized law with w/c ratio greater than 0.40. A generalized variation of compressive strength with w/c ratio for mortars ranging from very low strength to very high strength has been proposed for practical use. The properties of cement-based materials are primarily affected by the w/c ratio, chemical composition, microstructure and pore geometry of the cementitious materials, properties of aggregates, cement–aggregate ratio and properties of cement–aggregate interfacial zone.

When siliceous by-products are introduced, they change the behavior of cementitious composites significantly. It has been reported that silica fume accelerates both C_3S and C_3A hydration during the first few hours [1]. The compressive strength of cement paste containing silica fume decreases as the silica fume content increases at low water–cementitious materials ratios of 0.25, but plain cement paste exhibited highest strength and greater strength development after 28 days [6]. At higher water–cementitious materials ratio of 0.45, the paste with 30% addition of silica fume exhibited highest strength between 1 and 180 days. In mortars, sand acts as a sink for crystallized $Ca(OH)_2$. Hydration proceeds faster in pastes with silica fume, regarding both $Ca(OH)_2$ and non-evaporable water contents, whereas the hydration reaction in mortars with silica fume terminate earlier. Modification of the pattern of crystallization and degree of

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Table 1
Physical properties of cement

Property	Result
Fineness of cement (%)	2.65
Normal consistency (%)	31.5
Setting times (min)	
(a) Initial	135
(b) Final	335
Specific gravity	3.168
Compressive strength (N/mm^2)	
(a) At 3 days	21.06
(b) At 7 days	30.14
(c) At 28 days	48.74

orientation of CH crystals due to silica fume has been observed at the aggregate surface during the first few days of cement hydration [7]. Cong et al. [4] reported that silica fume mortars exhibit lower compressive strength at the age of 3 days and higher strengths at 7 and 28 days than the ordinary mortars and superplasticized mortars. Mak and Torii [8] observed that, at the early ages of 3 and 7 days, the non-evaporable water content seems to be higher with silica fume than that found in plain Portland cement concrete. After 28 days, the non-evaporable water content continuous to increase significantly in plain cement concrete. The following three mechanisms, namely: (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 [2,3,6], are believed to be responsible for the strength development of concrete and mortars containing silica fume.

2. Abrams' w/c ratio law

Among all other factors influencing the strength of concrete, it was strongly believed that concrete strength was dependent on only one factor, the w/c ratio, as a first approximation. Abrams' w/c ratio law, pronounced during 1918, has been described as the most important observation of the inverse proportionality between w/c ratio and the strength of concrete. The mathematical relationship between concrete strength and w/c ratio, according to Abrams, is (Eq. (1))

$$\sigma_c = A/B^{w/c} \quad (1)$$

where σ_c = compressive strength of concrete, w/c = water–cement ratio, A and B are constants for a given material, age and test conditions. In the case of HPC, generally incorporated with supplementary cementitious materials, such as fly ash, ground granulated blast furnace slag, silica fume, etc., the Abrams' w/c ratio law is not directly applicable in such concretes [11]. Alternative augmented water–cementitious materials ratio law can be proposed for designing concrete mixes with the incorporation of cement replacement materials. In such cases, the Abrams' law can be proposed using the concept of "equivalent cement, C_{eq}" as (Eq. (2))

$$\sigma_c = A/B^{w/c,eq} \quad (2)$$

3. Experimental program

3.1. Materials

Ordinary Portland cement conforming to IS: 12269-1987 was used. The physical properties of cement are shown in Table 1. Natural river sand was used. In this study, the sand fraction passing through 1.18 mm sieve and retaining on 600 μm was adopted. The specific gravity and bulk density are 2.65 and 1584 kg/m^3, respectively. Silica fume supplied by Nava Bharat Ferro Alloy, Palvanch, Andhra Pradesh was used for this program. The chemical composition of the silica fume is shown in Table 2. The specific surface area of the silica fume is 14–16 m^2/g. Potable water was used. No high-range water-reducing agents were used in this program. At lower water–binder (w/b) ratios, the mortar seems to be slightly stiff, but at w/b ratio >0.40, no such difficulty has been observed.

3.2. Mix proportioning

Mortar mixes were designed to study the influence of w/b ratio on the compressive strength at different ages with different silica fume content. Four w/b ratios of 0.35, 0.40, 0.45 and 0.50 were used. At every w/b ratio, the silica fume content was varied from 0% to 30% by weight of cement. The cementitious material–sand ratio was 1:3 throughout. The compressive strength of mortar was observed at different ages, with different silica fume contents at different w/b ratios. For all the mortar mixes, the strength of mortar was observed at the ages of 3, 7, 28 and 90 days.

3.3. Preparation of test specimens

The test specimens were prepared using standard metallic cube mould of size 70.7 mm × 70.7 mm × 70.7 mm for compressive strength of mortar. At every age, the strength was calculated as the average of three test specimens. The specimens were experimented at room temperature of 27 ± 2°C with a relative humidity of 65%.

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 ($SiO_2 + Al_2O_3 + Fe_2O_3$)	87–90.5
Calcium oxide (CaO)	1.0–1.5
Loss on ignition	4–7

4. Test results and discussion

Fig. 1 shows the variation of compressive strength of mortar at the age of 3 days with different silica fume contents as a function of w/b ratio. At 3 days, the plain cement mortar (SF = 0%) exhibited decrease in strength with w/c ratio. This has been generally observed in Abrams' law in cement mortars (Currie and Sinha [5], Rao [12]). At 5% silica fume content, the compressive strength of mortar decreases up to w/b ratio of 0.40, but at w/b ratio of 0.5, the strength increases. In other mortar mixes containing silica fume content from 10% to 17.5%, the strength decreases very moderately up to the w/b ratio of 0.40. However, at w/b ratio of 0.50, the strength increases slightly. At the age of 3 days, it has been generally observed that the compressive strengths of mortars with w/b ratios of 0.35 and 0.40 were seemed to be greater than those with w/b ratios of 0.45 and 0.50. But, the strengths of mortars at w/b ratio of 0.50 have been observed to be greater than those with w/b ratio of 0.45. From Fig. 1, it is clear that up to w/b ratio of 0.45, all the mortar mixes exhibited decreasing strength with w/b ratio. Whereas at w/b ratio of 0.50, the strength is reversed, i.e., increasing trend has been noticed in all the mortar mixes except the plain cement mortar. Further, the mortar mixes incorporated with silica fume contents between 25% and 30% exhibited very significant compressive strength at w/b ratio of 0.50. Feldman and Cheng Yi [6] reported similar observations in cement pastes. At w/b ratio of 0.45, they observed higher compressive strength at 30% silica fume content between 1 and 180 days.

From the variation of compressive strength with w/b ratio, it can be inferred that Abrams' w/c ratio law cannot be applicable to mortars containing higher silica fume contents at higher w/b ratios. The violation of the generalized Abrams' law in mortars containing silica fume content at early ages is due mainly to the pozzolanic reaction of silica fume and the amount of non-evaporable water content present in the mix. At the early ages of 3 and 7 days, the non-evaporable water content seems to be higher with silica fume than that found in plain Portland cement concrete. After 28 days, the non-evaporable water content continuous to increase significantly in plain cement concrete [8]. It is also interesting to note that the strength, at the age of 3 days, in mortars at w/b ratios of 0.35 and 0.50 seems to be very close to each other with silica fume contents up to 22.5%. However, the strength of mortar with higher silica fume contents from 25% to 30%, at w/b ratio of 0.50, has been observed to be very significant.

Fig. 2 shows the variation of compressive strength of mortar at the age of 7 days with w/b ratio with different silica fume contents. At 7 days, the plain cement mortar exhibited lower strengths than those with silica fume at any age. In mortar mixes containing 30% silica fume, the compressive strength gradually increases as the w/b ratio increases. This is contrary to the generally observed variation of compressive strength with w/c ratio in plain cement mortars [12]. At w/b ratio of 0.50, the highest strength was observed at 30% silica fume content. The compressive strength gradually decreases with decrease in the silica fume content at w/b ratio of 0.50. Except in few mortar mixes, the strength decreases with w/b ratio up to 0.45 at the age of 7 days. However, the highest value of compressive strength was observed in mixes with 20% silica fume content at w/b ratio of 0.35. At w/b ratio of 0.50, in general, the higher strengths were observed in mortars with silica fume between 17.5% and 22.5%. From the complex variation of the strength with w/b ratio, it is understood that both w/b ratio and the silica fume content influence the strength development of mortars. The pozzolanic reaction of silica fume at the early ages seems to be very significant factor for the violation of the general law. It could be inferred that the extent of pozzolanic reaction of silica fume might be determined by the amount of non-evaporable water content

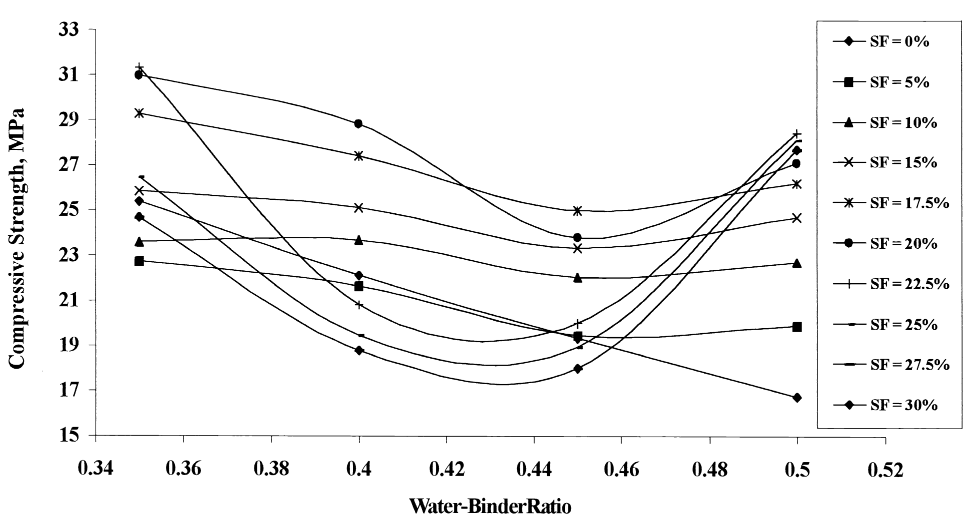

Fig. 1. Variation of compressive strength with w/b ratio in mortar mixes containing different percentages of silica fume at the age of 3 days.

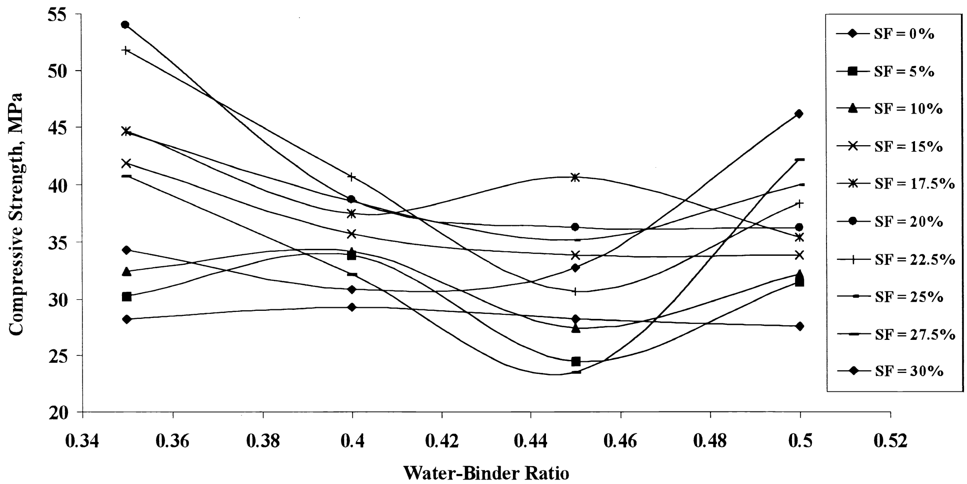

Fig. 2. Variation of compressive strength with w/b ratio in mortar mixes containing different percentages of silica fume at the age of 7 days.

at any age of mortar. If the amount of water is sufficient for reaction between $Ca(OH)_2$ and water to form calcium silicate hydrates (CSH), the silica fume reaction with $Ca(OH)_2$ continues even at later ages of mortar. This process of chemical reaction leads to modification of microstructure of the cement paste. As a result of this, the mortar matrix becomes more impermeable, and the interfacial zone between aggregate and mortar seems to be very strong in composites containing silica fume.

Fig. 3 shows the variation of compressive strength of mortar with w/b ratio at the age of 28 days with different silica fume contents. The strength of mortar has been low in mortars with silica fume contents of 27.5% and 30% at w/b ratio of 0.35. But, the strength significantly increases with w/b ratio, from w/b ratio greater than or equal to 0.40. However, in other mortar mixes, the strength decreases very moderately with w/b ratio, except at w/b ratio of 0.45. In plain cement mortars, the strength decreases as the w/b ratio increases. At w/b ratio of 0.35, the strength has been observed to be lesser in mortar with silica fume content of 5% than that of the plain cement mortar. However, at w/b ratio of 0.50, the strength of plain cement mortar, at the age of 28 days, has been observed to be the lowest among other mortars with silica fume. At 90 days, as shown in Fig. 4, the plain cement mortar performed better than most of the mixes with silica fume content at w/b ratios of 0.35 and 0.40. However, at w/b ratio of 0.50, the lowest and the highest strengths were observed with silica fume contents of 0% and 30%, respectively. Other mixes exhibited intermediate values. The strength of mortar, at w/b ratio of 0.50, increases as the silica fume content increases. At w/b ratio of 0.45, the mortar mixes show lowest strength values in general. Except that, the strength of mortars seemed to be more or less similar values at different w/b ratios. However, mortar mixes with silica fume content of 27.55% and 30% gradually increases with w/b ratio even at the age of 90 days. The observations show that as the w/b ratio increases, the long-term strength development has been observed to be very positive and consistent with 27.5% and 30% silica fume contents.

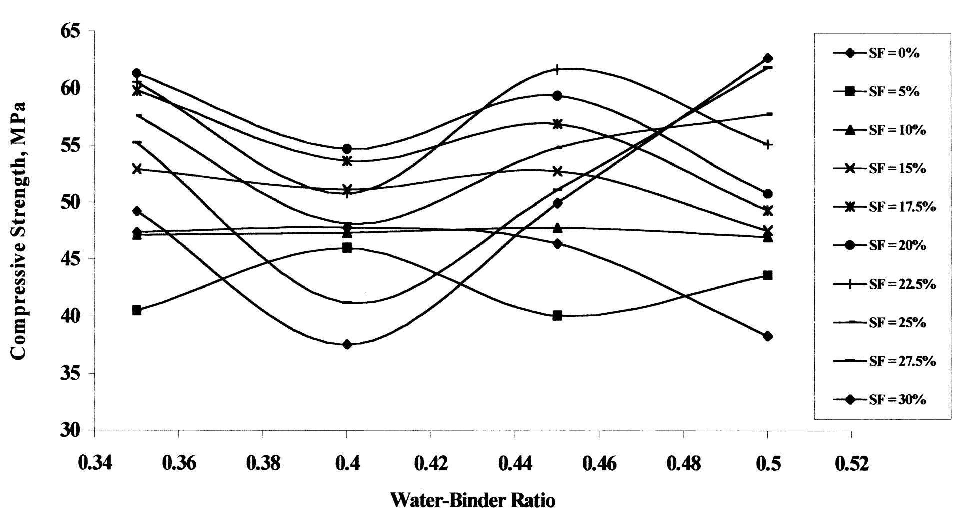

Fig. 3. Variation of compressive strength with w/b ratio in mortar mixes containing different percentages of silica fume at the age of 28 days.

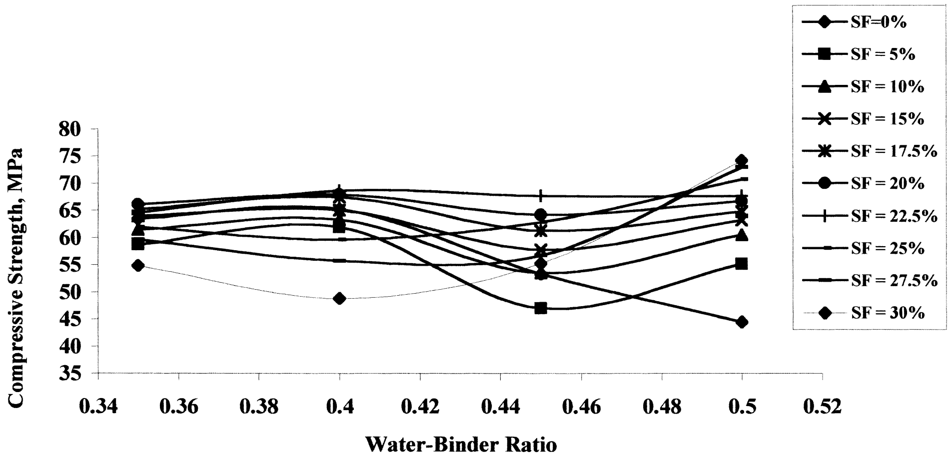

Fig. 4. Variation of compressive strength of mortars at the age of 90 days with water–binder ratio at different silica fume contents.

It can be observed in Figs. 1–4, the w/b ratio of 0.45 seems to be the transition point, from which the deviation of the general variation of strength with w/b ratio took place. At higher silica fume contents, the strength of mortars increases as the w/b ratio increases. At this juncture, it is worth to mention that the Abrams' generalized w/c ratio law cannot be applicable to mortar mixes containing silica fume contents. In other words, the variation of the compressive strength of mortars containing silica fume did not comply with the generally observed Abrams' w/c ratio law in plain cement mortars. This is mainly responsible for the pozzolanic reaction of the silica fume, which continue even at the later ages also at higher w/b ratios with higher silica fume contents.

5. Conclusion

From the test results, it can be concluded that plain cement mortars obey generalized Abrams' law at any age of mortar. However, the silica fume accelerates the strength development due to its pozzolanic reaction at an early age. As a result, the compressive strength of mortars with silica fume did not comply with the generally exhibited Abrams' w/c ratio in plain cement mortars. Further, it has been observed that at higher w/b ratio with higher silica fume contents, the mortar mixes exhibited better strength than those at lower w/b ratio at 28 and 90 days. In mortar mixes at w/b ratio >0.45, in general, the strength of mortar with silica fume increases as the w/b ratio increases. At w/b ratio of 0.50, the consistent strength development has been observed at 90 days. The strength increases as the silica fume content increases.

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