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Influence of silica fume on the tensile strength of concrete

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Abstract

The present paper is directed towards developing a better understanding on the isolated contribution of silica fume on the tensile strengths of high-performance concrete (HPC). Extensive experimentation was carried out over water–binder ratios ranging from 0.26 to 0.42 and silica fume–binder ratios from 0.0 to 0.3. For all the mixes, compressive, flexural and split tensile strengths were determined at 28 days. The compressive, as well as the tensile, strengths increased with silica fume incorporation, and the results indicate that the optimum replacement percentage is not a constant one but depends on the water–cementitious material (w/cm) ratio of the mix. Compared with split tensile strengths, flexural strengths have exhibited greater improvements. Based on the test results, relationships between the 28-day flexural and split tensile strengths with the compressive strength of silica fume concrete have been developed using statistical methods.

Keywords: Concrete; Silica fume; Water–cementitious material ratio; Tensile strength; Modeling

1. Introduction

Although concrete mixes are proportioned on the basis of achieving the desired compressive strength at the specified age, tensile strengths often play a vital role in concrete making. In concrete, cracks can propagate very easily in tension, and the cracking of concrete due to its tensile stress being exceeded may cause serviceability and durability problems. Present day new-generation high-performance concrete (HPC) requires, along with improved compressive strengths, high tensile strength, reduced porosity and very high durability. It is well documented that the use of silica fume in concrete results in a significant improvement in the mechanical properties of concrete, but researchers are yet to arrive at a unique conclusion regarding the optimum silica fume replacement percentage, and different researchers have reported different replacement levels as optimum for obtaining maximum strengths of concrete (see Refs. [1–10]). The contribution of silica fume to the strength of concrete is yet to be fully quantified. Although the literature is rich in reporting on silica fume concrete, most of the research works are centered on the compressive strength, and the technical data on tensile strength is quite limited. A brief review of some of these existing works will exhibit that there exists a considerable amount of controversy amongst them, and although some are in agreement, there are others that are in opposition.

It is observed that silica fume incorporation results in the improvement of tensile strength, but issues like optimum replacement percentage and contribution of cement paste and transition zone on the strength improvement need to be explored in detail. Bayasi and Zhou [11] have reported that it is the general practice of researchers and designers to alter the mix design of plain concrete (without silica fume) upon the incorporation of silica fume to overcome the adverse effect of silica fume on fresh mix workability. As a result, the isolated effect of silica fume on the properties of concrete is yet to be exhaustively investigated. If a new material is added to a virgin material to modify some of its properties, the isolated effect of the foreign material must be explored in detail to derive maximum utility from both the materials. To determine the isolated contribution of a mix design parameter on the properties of concrete, the effect of other mix design variables should be eliminated by keeping them constant.

The present investigation has been aimed to determine the isolated influence of silica fume on the split and flexural tensile strengths of concrete, and the corresponding compressive strengths have also been reported. Based on the present results relationships between the 28-day tensile and compressive strengths of silica fume, concretes have been

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proposed over a wide range of water–cementitious material (w/cm) ratios and silica fume replacement percentages, which might serve as useful guides for assessing the tensile strengths from the compressive strengths of silica fume concrete. The information embodied in this paper is directed towards developing a better understanding on the contribution of silica fume on the tensile strength of concrete and to determine its optimum content for the maximizing tensile strengths.

2. Experimental program

2.1. Materials

The constituent materials used in the program were tested to comply with the relevant Indian Standards. To assure uniformity of supply, the materials were subjected to periodical control tests. The cement used was Ordinary Portland Cement, having a 28-day compressive strength of 54 MPa. Silica fume containing 90.9% SiO_2 and having a BET specific surface area of about 18,000 m^2/kg was used. Natural river sand having a fineness modulus of 2.5 was used. The specific gravity and water absorption values were obtained as 2.65% and 0.8%, respectively. Crushed, angular, graded coarse aggregates of nominal maximum size 12.5 mm were used in the investigation. The specific gravity and the water absorption of the aggregates were 2.85& and 0.9%, respectively. Potable water and a high dosage of high range water reducing admixtures [superplasticizer (SP)] were employed for the mixing.

2.2. Experimental procedure

The different mechanical properties of concrete, such as strength and durability, are not fundamental or intrinsic material properties, as a host of parameters affect the observed mechanical behavior [12]. The general tendency of researchers has been to simultaneously work with a number of mix design variables that affect the strength and find out an optimum combination by trial and error so that maximum strength is obtained [13]. As a result, the individual contribution of the different parameters on the strength of concrete has not been properly assessed. The present experimental research program was carefully designed to determine the isolated effect of silica fume on concrete properties [14]. Hence, while performing the investigations, only cement was replaced by silica fume at different constant water–binder ratios, keeping other mix design variables, like quality of ingredients, mix proportions, including the aggregate–binder and coarse–fine aggregate ratios, dosage of SP, mixing procedures, curing conditions and testing procedures, constant. Because all these parameters were to be maintained constant at different constant water–binder ratios, with increase in water contents, small amounts of all the ingredients were to be proportionately reduced following the absolute volume formula [8] to keep the ratios constant. Hence, the total binder content had to be marginally varied, otherwise, the mix proportions, along with the aggregate–binder and coarse–fine aggregate ratios, would have changed, thereby changing a number of parameters and the aim of the present investigation would have been lost. The total binder content was fixed at about 500 kg/m^3, varying from 520 kg/m^3, at w/cm ratio of 0.26, to 480 kg/m^3, at w/cm ratio of 0.42. In all 32 concrete mixes were prepared. The mix proportion was adopted as C/FA/CA = 1:1.28:2.2 for all the mixes. The proportions of the different mixes are presented in Table 1. The experimental program included five sets of concrete mixes, at w/cm ratios of 0.26, 0.30, 0.34, 0.38 and 0.42, prepared by partial replacement of cement by equal weight of silica fume. Each set had mixes at six different percentages of cement replacement. The dosages of silica fume were 0% (control mix), 5%, 10%, 15%, 20% and 25% of the total cementitious materials. For w/cm ratios of 0.38 and 0.42, even a 30% silica fume dosage was adopted. According to Neville [8], SPs can affect the concrete strength even at constant water–cement ratio. Cong et al. [15] have reported that the strength of both cement paste and concrete can be affected by the dosage of SP. Thus, if the dosage of SP is varied with the silica fume replacement percentage, then the variations in the concrete strength will occur not only due to variations in the silica fume contents but also due to change in the dosage of SP. Hence, the dosage of SP was also kept constant for all the mixes, and thus, the change in concrete properties at any constant water–binder ratio occurred primarily due to silica fume incorporation [13]. Because the SP content of all the mixes was kept constant, to minimize variations in workability, the compaction energy was varied for obtaining proper compaction [16]. To ensure good dispersion of the silica fume at such variable dosages, a high binder content and a high dosage of SP were used with increased mixing times. As the SP dosage was kept constant, while fixing the binder content, it was considered that the mix should not segregate at higher water–binder ratios, nor it should be unworkable at low water–binder ratios. The mixing procedure and time were kept constant for all the concrete mixes investigated [13]. For the compressive strength determination, 150 × 150 × 150-mm^3 specimens were used, while 150 × 300-mm cylinders were used for determining the split tensile strength, and for flexural tensile strength, 100 × 100 × 500-mm beams were used. A symmetrical two-point loading setup, with beam span of 400 mm, was used for the flexural test. All the specimens were moist cured under water at room temperature until testing. Each strength value was the average of the strength of three specimens. Specimens were tested according to relevant Indian Standards.

3. Results and discussions

For all the concrete mixes, compressive, split tensile and flexural strengths were determined at the end of 28 days.

Table 1
Mix proportions

w/cm Ratio	Cement (kg/m^3)	Silica fume		Aggregates (kg/m^3)		Water (kg/m^3)	SP (%)
		%	(kg/m^3)	Fine	Coarse		
0.26	520	0	0	667	1146	135.2	3.5
	494	5	26				
	468	10	52				
	442	15	78				
	416	20	104				
	390	25	130				
0.30	510	0	0	653	1122.5	153	3.5
	484.5	5	25.5				
	459	10	51				
	433.5	15	76.5				
	408	20	102				
	382.5	25	127.5				
0.34	500	0	0	640	1100	170	3.5
	475	5	25				
	450	10	50				
	425	15	75				
	400	20	100				
	375	25	125				
0.38	490	0	0	628	1078	186.2	3.5
	465.5	5	24.5				
	441	10	49				
	416.5	15	73.5				
	392	20	98				
	367.5	25	122.5				
	343	30	147				
0.42	480	0	0	616	1058	201.6	3.5
	456	5	24				
	432	10	48				
	408	15	72				
	384	20	96				
	360	25	120				
	336	30	144				

w/cm = Water–cementitious material ratio by weight.
SP = superplasticizer. A combination of sulfonated naphthalene and melamine formaldehyde-condensate-based SPs was used.
The water in the SP not included in the w/cm ratio.
Silica fume and SPs expressed as a percentage by weight of total cementitious materials.

Fig. 1 shows the variation of compressive strength with silica fume replacement percentage. The strength values at different w/cm ratios have been plotted at each silica fume replacement percentage. The results indicate that the optimum silica fume replacement percentage is not a unique one but has varied from 15% to 25% replacement levels [17]. Khedr and Abou Zeid [2] reported that the optimum silica fume replacement percentage for obtaining maximum 28-day strength of concrete ranged from 10% to 20%. Statistically analyzing the test data of different researchers, Oluokun [18] has inferred that the optimum silica fume content is a function of the water content of the mix. The results of the present investigation indicate that, other mix design parameters remaining constant, the optimum silica fume replacement percentage for 28-day compressive strength is not a constant one but a function of the w/cm ratio of the mix [13].

The maximum value of compressive strength was obtained as 95.7 MPa at 15% replacement level at water–binder ratio of 0.26, and the minimum was obtained for the control mix at a water–binder ratio of 0.42 as 48.3 MPa. The corresponding values of split tensile strengths were obtained as 6.65 and 3.82 MPa, respectively, whereas those for the flexural tensile strengths were obtained as 11.87 and 6.8 MPa, respectively.

3.1. Split tensile strength

Fig. 2 shows the variation of split tensile strength with silica fume replacement percentage at different w/cm ratios. It is observed that silica fume incorporation increases the split tensile strength of concrete. A close observation of Fig. 2 exhibits that very high percentages of silica fume do not significantly increase the split tensile strengths, and the increase is almost insignificant beyond 15%. For all the w/cm ratios, 5–10% replacements considerably improve the split tensile strength with respect to control. The initial filling of the voids by silica fume significantly improves the tensile

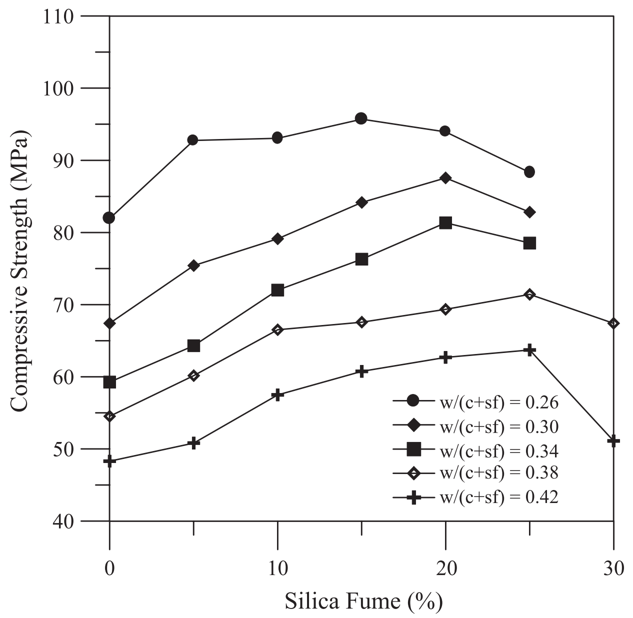

Fig. 1. Relationship between 28-day compressive strength and percentage replacement of silica fume.

strengths, but at higher levels, the improvements decrease. On computing the percentage gains in split tensile strengths of silica fume concrete with respect to control at the different water–binder ratios, the values of the average gains at 5%, 10%, 15%, 20% and 25% replacement levels are obtained as 16.7%, 22%, 25%, 25.7% and 19.3%, respectively [14]. Although the trend in strength gain is almost similar with that of compressive strength, the optimum 28-day split tensile strength lies in the range of 5–10%.

3.1.1. Relationship between split tensile and compressive strength

Usually, only the compressive strength of concrete is measured for the purpose of quality control. The tensile strengths are estimated from the compressive strength by using empirical correlation equations. Analyzing the present strength results of 32 concrete mixes, statistically by performing regression analysis, the following relationship between the 28-day split tensile and compressive strengths of silica fume concrete has been obtained, as expressed in Eq. (1):

$$f_{sp} = 0.248(f_c)^{0.717}\text{MPa} \tag{1}$$

where f_{sp} and f_c denote the 28-day split tensile and compressive strengths of concrete, expressed in MPa, respectively. The value of the correlation coefficient (r) and standard error of the estimate (s) has been obtained as .94 and 0.02, respectively.

3.2. Flexural tensile strength

Fig. 3 shows the variation of flexural tensile strength with silica fume replacement percentage at different w/cm ratios. Silica fume seems to have a more pronounced effect on the flexural strength than the split tensile strength does. For flexural strengths, even very high percentages of silica fume significantly improve the strengths. The average percentage gains in the flexural tensile strengths of silica fume concrete with respect to control at the different water–binder ratios are computed as 10.2%, 14.5%, 27%, 31% and 26.6% at 5, 10, 15, 20 and 25 percentage replacement levels, respectively [14]. The gains in split tensile strengths are

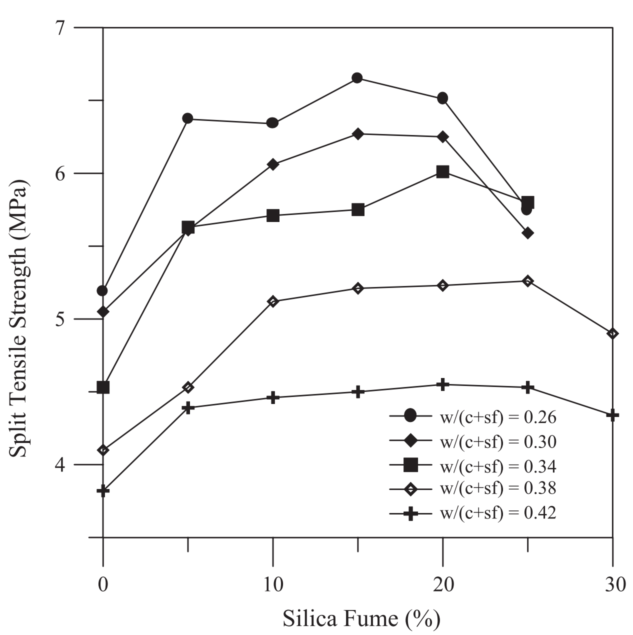

Fig. 2. Relationship between 28-day split tensile strength and percentage replacement of silica fume.

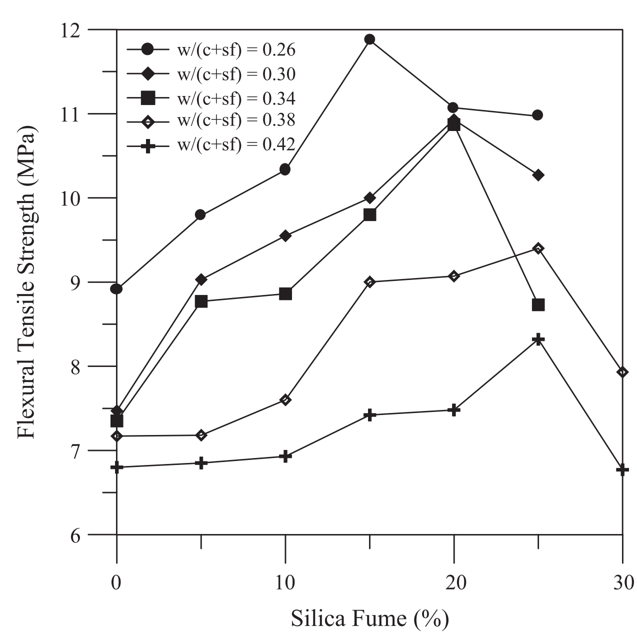

Fig. 3. Relationship between 28-day flexural tensile strength and percentage replacement of silica fume.

higher than the flexural strengths at lower replacement levels. But a steady increase in the flexural strength is observed with increase in the silica fume replacement percentage, and the gains are higher than those of split tension at higher replacement levels.

The flexural strengths almost follow the same trend as the 28-day compressive strength does. The results of the present investigation indicate that the optimum silica fume replacement percentage for 28-day flexural tensile strength is not a constant one but a function of the water cementitious material ratio of the mix and has been found to range from 15% to 25%.

3.2.1. Relationship between flexural and compressive strength

Cetin and Carrasquillo [9] have observed that no single equation seems to represent the modulus of elasticity or flexural tensile strength of HPCs with sufficient accuracy, and measured values should be used instead of predicted ones. Analyzing the present test results statistically, the relationship between the 28-day flexural and compressive strengths has been obtained as

$$f_{fl} = 0.275(f_c)^{0.81}\,\text{MPa} \tag{2}$$

where f_{fl} and f_c denote the flexural and compressive strengths of concrete expressed, in MPa, respectively. The value of the correlation coefficient (r) and standard error of the estimate (s) has been obtained as .93 and 0.03, respectively.

3.3. Ratio between the flexural and split tensile strengths of silica fume concrete

For the present investigation, the average ratio between the flexural and split tensile strengths of silica fume concrete has been obtained as 1.65. The ratio between flexural and split tensile strength was obtained by Zhou et al. [6] as 1.5. As per ACI, the ratio should range from 1.4 to 1.6. Zheng et al. [19], reviewing works of previous researchers, have reported that flexural tensile strength is generally 35% higher than split tensile strength.

4. Conclusions

Extensive experimentation was carried out to determine the isolated effect of silica fume on the tensile strength of concrete at water–binder ratios ranging from 0.26 to 0.42 and cement replacements of 0% to 30%. The following conclusions can be derived from the present investigation:

1. The results of the present investigation indicate that, other mix design parameters remaining constant, silica fume incorporation in concrete results in significant improvements in the tensile strengths of concrete, along with the compressive strengths.
2. The optimum silica fume replacement percentages for tensile strengths have been found to be a function of w/cm ratio of the mix. The optimum 28-day split tensile strength has been obtained in the range of 5–10% silica fume replacement level, whereas the value for flexural strength ranged from 15% to 25%.
3. Both the split and flexural tensile strengths at 28 days follow almost the same trend as the 28-day compressive strength does. Increase in split tensile strength beyond 15% silica fume replacement is almost insignificant, whereas sizeable gains in flexural tensile strength have occurred even up to 25% replacements.

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