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INVESTIGATIONS ON THE TENSILE STRENGTH OF HIGH PERFORMANCE CONCRETE INCORPORATING SILICA FUME

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ABSTRACT

Though the literature is rich in reporting on silica fume concrete the technical data on tensile strength is quite limited. 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. 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 results of the present investigation indicate that silica fume incorporation results in significant improvements in the tensile strengths of concrete. It is also observed that the optimum replacement percentage, which led to maximization of strength, is not a constant one but depends on the water- cementitious material ratio of the mix. Compared to split tensile strengths, flexural strengths have exhibited greater percentage gains in strength. 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. For the present investigation transgranular failure of concrete was observed which indicate that silica fume incorporation results in significant improvements in the strength of both paste and transition zone.

Keywords: Concrete, Silica fume, Water-cementitious material ratio, Tensile strengths.

1. INTRODUCTION

Compressive strength is considered as an index to assess the overall quality of concrete and it is generally assumed that an improvement in the compressive strength results in improvement of all other properties. Hence strength investigations are generally centered on compressive strengths. Even though 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. Usually only the compressive strength of concrete is measured and the tensile strength is estimated from the compressive strength by using empirical correlation equations. But in concrete cracks can propagate very easily in tension and cracking of concrete due to its tensile stress being exceeded may cause serviceability and durability problems. Present day new generation HPC require along with improved compressive strengths high tensile strength, reduced porosity and very high durability. These special attributes are especially necessary with reference to the performance requirements of concrete for use in Nuclear Power Plant structures. These concretes almost invariably incorporate mineral admixtures for a variety of reasons such as strength, high crack resistance, low permeability, and durability factors. Silica fume has a tremendous potential in this context and it is well documented that the use of silica fume in concrete results in a significant improvement in the mechanical properties of concrete. Though 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. Bayasi and Zhou [1993] 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. 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 (Bhanja, 2001). A wide database of strength results have been created and based on the present results relationships between the 28-day tensile and compressive strengths of silica fume concrete have been proposed, 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. 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 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 (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 (Mindess and Young, 1991). Factors that affect the strength development of concrete are several, including materials used, mixture procedures, curing environment, test methods, and others. 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 (Bhanja and Sengupta, 2003). As a result the individual contribution of the different parameters on the strength of concrete has not been properly assessed. 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 to fine aggregate ratios, dosage of SP, mixing procedures, curing conditions and testing procedures constant. Since 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 (Neville, 1996) to keep the ratios constant. 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 30% silica fume dosage was adopted. According to Neville [1996] superplasticizers can affect the concrete strength even at constant water cement ratio. Cong et al. (1992) 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 superplasticizer. Hence the dosage of superplasticizer 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 (Bhanja and Sengupta, 2003). Since the SP content of all the mixes was kept constant, to minimize variations in workability, the compaction energy was varied for obtaining proper compaction (Bhanja and Sengupta, 2002). The mixing procedure and time was kept constant for all the concrete mixes investigated. 150 × 150 × 150 mm cube specimens were used for compressive strength determination. 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 set up with beam span of 400 mm was used for the flexural test. All the specimens were moist cured under water at room temperature till testing. Each strength value was the average of the strength of three specimens. Specimens were tested according to relevant Indian Standards.

Table 1 Mix Proportions

w/cm ratio	Cement (kg/m^3)	Silica fume		Aggregates (kg/m^3)		Water (kg/m^3)
		%	(kg/m^3)	Fine	Coarse	
0.26	520	0	0	667	1146	135.2
	494	5	26			
	468	10	52			
	442	15	78			
	416	20	104			
	390	25	130			
0.30	510	0	0	653	1122.5	153
	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
	475	5	25			
	450	10	50			
	425	15	75			
	400	20	100			
	375	25	125			
0.38	490	0	0	628	1078	186.2
	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
	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 superplasticizers were used

3. RESULTS AND DISCUSSIONS

For all the concrete mixes, compressive, split tensile and flexural strengths were determined at the end of 28 days. Table 2 shows the variation of compressive, split tensile and flexural strengths with silica fume replacement percentage. The results indicate that the optimum silica fume replacement percentage for maximizing the strengths is not a unique one but has varied from 15 to 25% replacement levels (Bhanja and Sengupta, 2003). Khedr and Abou Zeid (1994) reported that the optimum silica fume replacement percentage for obtaining maximum 28-day strength of concrete ranged from 10 to 20 %. It is observed that silica fume incorporation increases the split and flexural tensile strengths of concrete. A close observation of Table 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 resulted in considerable improvements in the split tensile strength with respect to control. The initial filling of the voids by silica fume significantly improves the tensile strengths but at higher levels the improvements decrease. Though the trend in strength gain is almost similar to that of compressive strength the optimum 28-day split tensile strength lies in the range of 5-10 % (Bhanja and Sengupta, 2004). The present results indicate that higher percentage replacements have no significant effect on split tensile strength of silica fume concrete.

Table 2 28-day compressive and tensile strength results

w/cm	Silica Fume	Compressive Strength (MPa)	Split Tensile Strength (MPa)	Flexural Strength (MPa)
0.26	0	81.9	5.19	8.91
	5	91.7	6.37	9.79
	10	93.0	6.34	10.33
	15	95.7	6.65	11.87
	20	93.9	6.51	11.07
	25	88.3	5.75	10.97
0.30	0	67.4	5.05	7.47
	5	75.4	5.61	9.03
	10	79.1	6.06	9.55
	15	84.2	6.27	10.0
	20	87.6	6.25	10.93
	25	82.8	5.59	10.27
0.34	0	59.3	4.53	7.35
	5	64.3	5.63	8.77
	10	72.0	5.71	8.86
	15	76.3	5.75	9.8
	20	81.3	6.01	10.87
	25	78.5	5.80	8.73
0.38	0	54.5	4.10	7.17
	5	60.2	4.53	7.18
	10	66.5	5.12	7.6
	15	67.6	5.21	9.0
	20	69.3	5.23	9.07
	25	71.4	5.26	9.4
	30	67.4	4.90	7.93
0.42	0	48.3	3.82	6.8
	5	50.8	4.39	6.85
	10	57.5	4.46	6.93
	15	60.7	4.50	7.42
	20	62.7	4.55	7.48
	25	63.7	4.53	8.32
	30	51.1	4.34	6.77

Silica fume seems to have a more pronounced effect on the flexural strength than the split tensile strength. For flexural strengths, even very high percentages of silica fume significantly improve the strengths. The gains in split tensile strengths are higher than the flexural strengths at lower replacement levels. But a steady increase in the flexural strength is observed with increase in silica fume replacement percentage and the gains are higher than those of split tension at higher replacement levels. Maximum gains in split tensile strength was about 33% whereas up to 50% improvements in flexural strengths were obtained due to silica fume incorporation.

Strength of concrete is governed by the strength of cement paste, strength of transition zone and strength of aggregates. Silica fume incorporation results in significant improvements in the strength of both paste and transition zone. Bhanja and Sengupta (2003) have reported that out of a total silica fume content of 33.33% by weight of cement responsible for improving the strength of concrete, 14.53% contributed to the pozzolanic action and the rest i.e. 18.8% contributed to the physical effect, which indicates that the amount of silica fume contributing to the physical effect is comparable or even more significant than the amount contributing to the pozzolanic effect. For the present investigation transgranular failure of concrete was observed which justify the above statements. As the effect of pore filling, resulting in pore refinement, is more pronounced on the flexural tensile strength, the present results, which indicate relatively higher gains in flexural strengths than split tensile strengths, emphasize the significance of the physical effect of silica fume in 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. [1995] as 1.5. As per ACI the ratio should range from 1.4 to 1.6. Zheng et al. (2001) reviewing works of previous researchers have reported that flexural tensile strength is generally 35% higher than split tensile strength. However for the present results on silica fume concrete, flexural strength values seem to be about 60 % higher than the corresponding split tensile values.

Empirical formulae connecting the tensile (f_t) and compressive (f_c) are generally of the following form-

$$f_t = \left(f_c\right)^n$$

where k and n are coefficients. Analyzing the present strength results of 32 concrete mixes statistically by performing regression analysis the following relationships relating the 28-day split and flexural tensile strengths with compressive strengths of silica fume concrete have been obtained as follows-

$$f_{sp} = 0.25(f_c)^{0.72}\,MPa ------(1)$$

$$f_{fl} = 0.28(f_c)^{0.8}\,MPa ------(2)$$

where f_{sp}, f_{fl} and f_c denote the split tensile, flexural and compressive strengths of concrete expressed in MPa respectively.

3 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 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 15-25 %.
3. Both the split and flexural tensile strengths at 28 days follow almost the same trend as the 28-day compressive strength. 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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