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Strength Development Models of Concrete with Silica Fume As Fine Aggregate Replacement Material

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Strength Development Models of Concrete with Silica Fume As Fine Aggregate Replacement Material

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Abstract - An extensive experimentation was performed to study the strength development of concrete in which fine aggregate was partially replaced with silica fume. Mathematical models were developed using statistical techniques to predict the compressive strength of such concrete. Water-to-cement ratio was varied from 0.50 to 0.60 and fine aggregate replacement level ranged from 0 to 15%. Compressive strength testing was conducted at age of 7, 28, and 56 days. Results showed that compressive strength of concrete, made with silica fume as fine aggregate replacement material, was higher than the control concrete. The developed models provided a closed form estimate of compressive strength of concrete. The models would serve as useful guidelines for proportioning concrete mixes incorporating silica fume as fine aggregate replacement material. Such concrete could be used successfully in structural applications with economic and environmental advantages.

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I. INTRODUCTION

Silica Fume (SF) is generally used as a replacement of cement, as an admixture in concrete, and in manufacturing of cement. Economic and environmental considerations played a great role in advancing its usage. SF, composed of submicron particles of silicon dioxide, is produced by electric arc furnaces as a by-product waste of the production of metallic silicon or ferrosilicon alloys. SF incorporation could enhance the concrete basic properties in both the fresh and hardened states. It improves compressive strength, durability, depletion of cement alkalis, resistance to chloride and sulphate penetration, and continued micro structural development through a long-term hydration and pozzolanic reaction (Lam et al., 1998; Zain et al., 1999; Nassif et al., 2003; Demirboga and Gul, 2006; Gonen and Yazicioglu, 2007; Sata et al., 2007; Yazici, 2008).

The literature is rich with standard codes of practice, guidelines, and predication models to estimate the compressive strength of SF concrete. The majority used SF as a mineral admixture or as a cement replacement material (Slanicka, 1991; Babu and Prakash, 1995; Gutierrez and Canovas, 1996; Duval and Kadri, 1998; Papadakis et al., 2002; Bhanja and Sengupta, 2003; Zelic et al., 2004; Holland, 2005; Bhikshma et al., 2009).

In spite of the wealth of information available in the existing literature on compressive strength predication of SF concrete, no studies have reported on the direct role of SF as fine aggregate (sand) replacement material, and guidelines to predict the compressive strength of such concrete at any replacement level are not yet available. This aspect has been investigated in this research based on work conducted by Ismeik [2010]. Statistical techniques were used to provide mathematical models to estimate the compressive strength of concrete when fine aggregate was replaced partially by SF.

II. EXPERIMENTAL PROCEDURE

a) Materials

Ordinary Portland cement (C) type I, conforming to ASTM C150, was used with properties listed in Table 1. Properties of SF, conforming to ASTM C1240, are shown in Table 2. Aggregate conforming to ASTM C33 was used. Fine aggregate (FA) with a 4.75-mm maximum size was used while the coarse aggregate (CA) used had a 16.6 mm nominal size. Physical properties of aggregate are listed in Table 3 with grading shown in Figure 1. Absorption and specific gravity tests were performed for fine and coarse aggregate according to ASTM C127 and ASTM C128 specifications, respectively. Tap water (W) needed for the mix design was adjusted based on the absorption of aggregate.

Table 1 : Properties of ordinary Portland cement

Property	Value
Fineness (90-µm sieve)	8.3
Specific surface (m^2/kg)	281
Normal consistency (%)	28
Vicat setting time (min)	
Initial	145
Final	260
Specific gravity	3.15

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Table 2 : Properties of silica fume

Property	Value
SiO_2 Content (%)	90
Surface Area (m^2/kg)	20,000
Specific gravity	2.2
Unit weight (kg/m^3)	245
Fineness (45-µm sieve)	5.1

Table 3 : Physical properties of aggregate

Property	Fine aggregate	Coarse aggregate
Specific gravity	2.46	2.75
Specific gravity (SSD)	2.50	2.78
Apparent relative density	2.56	2.83
Los Angeles abrasion (%)	N/A	20.50
Absorption (%)	1.62	1.05
Fineness modulus	2.73	6.53
Voids (%)	36.7	38.1
Unit weight (kg/m^3)	1705	1617

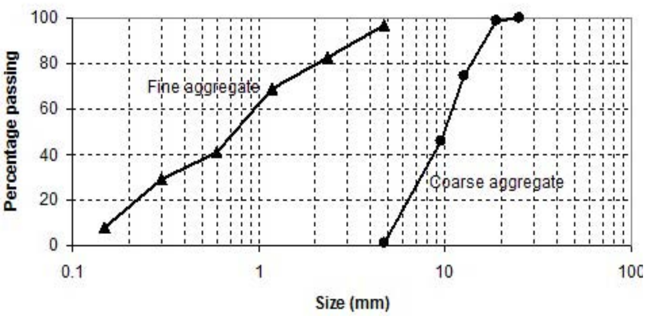

Figure 1 : Grain size distribution of aggregates

b) Mix proportions

Concrete mix proportions are summarized in Table 4. Three series of tests designated as series I (mix A, B, C, and D), series II (mix E, F, G, and H), and series III (mix I, J, K, and L) were prepared with three water-to-cement (W/C) ratios of 0.50, 0.55, and 0.60, respectively. In each series, the replacement level (R) of fine aggregate with silica fume, was 0, 5, 10, and 15% by weight. The cement content (C) varied from 384 to 400 kg/m^3. The cementitious materials content (CM = C + SF) varied between 385 and 450 kg/m^3 resulting in four water-to-cementitious materials (W/CM) ratios of 0.50, 0.48, 0.46, and 0.44 for test series I, of 0.55, 0.53, 0.51, and 0.49 for test series II, and of 0.60, 0.58, 0.55, and 0.53 for test series III.

c) Preparation and casting of test specimens

All experiments were conducted in a laboratory under a controlled environment and were properly monitored. Specimens used were standard cylinders of 150 x 300 mm. Concrete mixes were made in a power-driven 90-liter revolving type drum mixer conforming to ASTM C192. The dry constituents were mixed in the rotating mixer with a speed of 40 rpm. The standardized mixing procedure was as follows: cement, fine aggregate and SF were mixed first; then water and coarse aggregate were added. The overall mixing time was about 4 minutes. The time, sequence, and method of adding the aggregate and SF for each batch remained unchanged and simulated good field practice. Concrete casting was performed according to ASTM C192.

Table 4 : Concrete mix proportions and experimental results

Series	Mix	W/C	R	P	W/CM	Weight (kg/m^3)						Compressive strength (MPa)		
						SF	C	CM	W	FA	CA	f_{sf}^{7}	f_{sf}^{28}	f_{sf}^{56}
I	A	0.50	0	0.000	0.50	0	400	400	200	340	1360	19.67	31.95	33.81
	B		5	0.041	0.48	17	400	417	200	323	1359	27.04	35.11	39.62
	C		10	0.078	0.46	34	400	433	200	306	1358	25.56	34.92	39.52
	D		15	0.113	0.44	51	399	450	200	288	1357	25.38	34.46	37.49
II	E	0.55	0	0.000	0.55	0	392	392	216	333	1334	17.84	26.39	30.04
	F		5	0.041	0.53	17	391	409	216	317	1333	21.97	32.88	37.21
	G		10	0.078	0.51	33	391	425	215	300	1332	21.50	32.60	38.18
	H		15	0.113	0.49	50	391	441	215	283	1331	21.23	30.46	33.71
III	I	0.60	0	0.000	0.60	0	385	385	231	327	1308	14.37	21.88	27.13
	J		5	0.041	0.58	16	384	401	231	310	1307	17.02	27.31	30.37
	K		10	0.078	0.55	31	384	417	231	294	1306	19.03	28.89	32.46
	L		15	0.113	0.53	49	384	433	230	277	1305	18.57	27.14	31.49

W/C = water-to-cement ratio, R = silica fume replacement level of fine aggregate, P = silica fume-to-cementitious materials ratio (SF/CM), W/CM = water-to-cementitious materials ratio, SF = silica fume, C = cement, CM = cementitious materials (SF+C), W = water, FA = fine aggregate, CA = coarse aggregate. f_{sf}^{7}, f_{sf}^{28} and f_{sf}^{56} = compressive strengths of concrete at 7, 28, and 56 day, respectively.

Molds were covered to prevent loss of water from evaporation. Specimens were kept for 24 hours in molds at a temperature of 23° C in the casting room; and then cured in a water tank for the specified time at a temperature of 23° ± 1° C.

d) Testing of the specimens

Compressive strength tests were performed at age of 7, 28, and 56 days. The specimens were tested in a dry state following the moist curing. Prior to compression testing, the top and bottom ends of the each specimen were capped with sulfur mortar conforming to the requirements of ASTM C617. A compression machine, conforming to ASTM C39, was used for all compression strength testing at a load rate of 0.15 MPa/s. The compressive strength of specimens was recorded as load was gradually applied until failure. The average of 3 specimens was used to report the compressive strength of each mix. High quality control requirements in terms of mixing, curing, and testing of specimens were strictly followed during the experimental phase. Tests not adhering to such requirements were rejected and repeated.

III. RESULTS AND DISCUSSION

a) Compressive strength

Compressive strength for all concrete mixes was determined at 7, 28, and 56 days of curing as shown in Table 4. Figures 2, 3, and 4 show the variation of compressive strength with SF replacement levels for test series I (W/C = 0.50), II (W/C = 0.55), and III (W/C = 0.60), respectively. Test results show that the compressive strength of concrete mixes with 5, 10, and 15% replacement levels (mix B, C, and D), (mix F, G, and H), (mix J, K, and L), were higher than their corresponding control concretes, (mix A, E, and I), respectively.

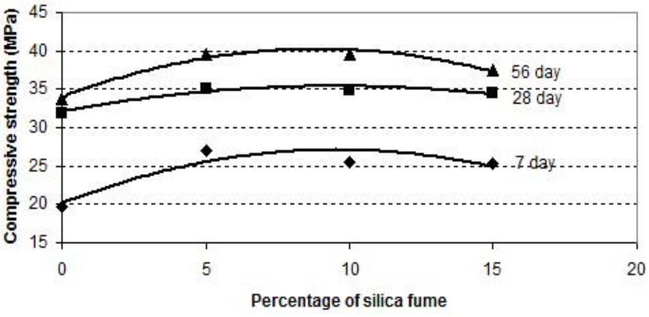

Figure 2 : Concrete compressive strength development of test series I (W/C = 0.50)

The maximum value of 28-day compressive strength was obtained as 35.11 MPa at 5% replacement level with a W/C ratio of 0.50 and W/CM ratio of 0.48 (mix B), and the minimum was obtained for the control specimens at a W/C ratio of 0.60 and W/CM ratio of 0.60 as 21.88 MPa (mix I). The maximum value of 56 - day compressive strength was obtained as 39.62 MPa at 5% replacement level with a W/C ratio of 0.50 and W/CM ratio of 0.48 (mix B), while the minimum value was 27.13 MPa obtained at the control specimens at a W/C ratio of 0.60 and W/CM ratio of 0.60 (mix I). When the W/CM ratio decreased, the compressive strength of concrete increased for all ages and replacement levels compared to the corresponding control mix. The results indicated that the strength benefits were increased as the age increased.

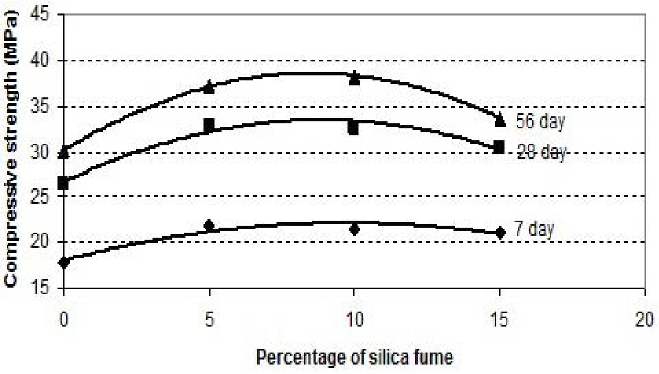

Figure 3 : Concrete compressive strength development of test series II (W/C = 0.55)

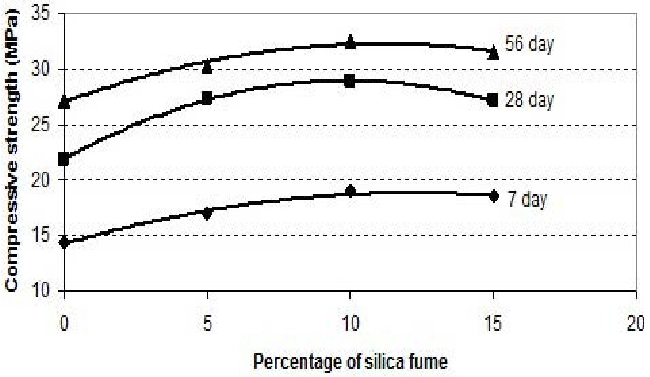

Figure 4 : Concrete compressive strength development of test series III (W/C = 0.60)

It was observed that SF incorporation in concrete, as fine aggregate replacement material, increased the strength. A close observation of Figures 2, 3, and 4 illustrated that benefits gradually decreased after about 10% level. At higher replacement levels of SF, no further increase in the compressive strength was dedicated. Generally, for all W/C ratios, 5 to 15% replacements improved the compressive strength with respect to control concrete.

b) Models development

It is considered useful to derive compressive strength development models of concrete made with SF as fine aggregate replacement material. Regression analysis was used to quantitatively correlate the compressive strength of SF fume concrete f_{sf} to a selected range of variables. The method of least squares that leads to the best fitting line of a postulated form to a set of data was used to form regression models between the dependent variable and independent variables. SPSS software was utilized to develop the strength prediction models based on the available data. Stepwise calibration procedure was then used to form the multiple linear regression models and to determine the critical and non critical influencing variables. F-test and t-test were used to verify the choice of models and critical variables with a significant level of 5%.

Statistical analysis of the results of the three series of tests produced the following 3 models with their corresponding coefficient of determination (R^2). The compressive strength of SF concrete f_{sf}^{7}, f_{sf}^{28} and f_{sf}^{56} at 7, 28, and 56 day, respectively, was determined as:

$$f_{sf}^{7} = -71.650(\mathrm{W/C}) - 6.073\mathrm{R} + 841.128\mathrm{P} + 56.892 \quad (1)$$

(R^2 = 0.938)

$$f_{sf}^{28} = -78.075(\mathrm{W/C}) - 7.897\mathrm{R} + 1080.187\mathrm{P} + 69.796 \quad (2)$$

(R^2 = 0.959)

$$f_{sf}^{56} = -72.475(\mathrm{W/C}) - 9.629\mathrm{R} + 1311.367\mathrm{P} + 70.210 \quad (3)$$

(R^2 = 0.946)

where

W/C : water-to-cement ratio by weight

R : silica fume replacement level of fine aggregate

P : silica fume-to-cementitious materials ratio by weight (SF/CM)

A more general prediction model that incorporates the testing age T, in days, could also be proposed as shown in model 4:

$$f_{sf} = -74.067(\mathrm{W/C}) - 7.866\mathrm{R} + 1077.561\mathrm{P} + 0.268\mathrm{T} + 57.505 \quad (4)$$

(R^2 =0.914)

In developing the above models the W/C ratio was used instead of W/CM ratio since most of control mixes (without silica fume) are defined with W/C ratio during the initial design stage. The effect of the addition of the silica fume to the mix is accounted for by the term silica fume-to-cementitious materials ratio P = SF/CM = SF/(C+SF). As shown in Table 4, when the cementitious materials content CM increases, the P term increases from 0 to 0.113 for each test series accounting for the silica fume contribution to strength enhancement.

Table 5 : Statistical comparison between actual and predicated strength values

	f_{sf}	Model 4	Deviation
Unit	MPa	MPa	%
Min	14.370	14.941	-4.0
Max	39.620	41.237	-4.1
Median	29.465	28.088	4.7
Mean	28.449	28.452	0.0
Range	25.250	26.296	-4.1
Std. Deviation	6.935	6.630	4.4
Coef. of Variation	0.243	0.233	4.1
R^2	1.000	0.914	-4.0

To have a more precise investigation of model 4, a comparison between the actual and predicated compressive strength values was plotted. As seen in Figure 5, there existed an excellent agreement between the actual and predicted compressive strength values. This demonstrated that model 4 could be used reliably to predicate the compressive strength of concrete made with silica fume as a partial replacement of fine aggregate.

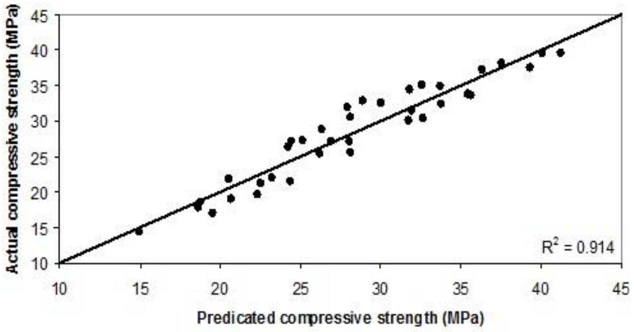

Figure 5 : Comparison between actual and predicated compressive strength values

A comparison in terms of the statistical parameters (Min, Max, Median, Mean, Range, Standard Deviation, and Coefficient of Variation) of the actual and predicated compressive strength results is believed to be useful. As seen in Table 5, the statistical parameters of model 4 are relatively close to the distribution parameters of actual strength values within a 5% deviation. Thus, model 4 produces reliable and accurate predication values and could be used conveniently to estimate the compressive strength of concrete with silica fume used as fine aggregate replacement material.

c) Applications

The strength of conventional concrete can generally be estimated with good accuracy based on strength charts or by experience if mix proportions, age, and curing conditions are known. However, when SF is used as fine aggregate replacement material the exact nature of strength development becomes complicated as such charts or experience would be no longer applicable.

The proposed four models are capable to provide a quick solution for strength estimation of mixes where fine aggregate is partially replaced with SF. With these models, strength of silica fume concrete at a particular age can be estimated over a range of replacement levels and W/C ratios. The suggested models would be of value in the design process of such concrete mixes where specific target strength needs to be achieved at a certain age or can be used to modify any basic concrete mix so that the concretes with and without silica fume have similar strengths.

IV. Conclusions

Extensive experimentation was performed to study the strength development of concrete made with silica fume as fine aggregate replacement material over a range of W/C ratios varying from 0.50 to 0.60, silica fume replacement levels ranging from 0 to 15%, and testing age of 7, 28, and 56 days.

Compressive strength of concrete, made with silica fume as fine aggregate replacement material, was higher than the control concrete at all ages. Compressive strength continued to increase with age for all silica fume replacement levels. The compressive strength increased as fine aggregate replacement level increased. This increase was maximum at a replacement level of about 10%.

On the basis of regression analysis of the experimental results, statistical models were developed to estimate the 7, 28, and 56 day compressive strength of concrete. The proposed models could serve as a useful tool for optimizing and predicting the strength of silica fume concrete over a range of replacement levels and W/C ratios. The suggested prediction models could be used to modify any basic concrete mix so that the concretes with and without silica fume would have similar strengths.

Silica fume can be used as a partial fine aggregate replacement material in concrete and such concrete can be used conveniently in structural applications with economical and environmental benefits. Short term economical advantages lie in the fact that utilization of waste product and saving of fine aggregate resources would reduce the cost of concrete production. Long term environmental advantages would be a reduction of environmental problems and hazards related to improper disposal of silica fume.

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