

Influence of Silica Fume on High Strength Lightweight Concrete

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Abstract—The main objective of this paper is to determine the isolated effect of silica fume on tensile, compressive and flexure strengths on high strength lightweight concrete. Many experiments were carried out by replacing cement with different percentages of silica fume at different constant water-binder ratio keeping other mix design variables constant. The silica fume was replaced by 0%, 5%, 10%, 15%, 20% and 25% for a water-binder ratios ranging from 0.26 to 0.42. For all mixes, split tensile, compressive and flexure strengths were determined at 28 days. The results showed that the tensile, compressive and flexure strengths increased with silica fume incorporation but the optimum replacement percentage is not constant because it depends on the water–cementitious material (w/cm) ratio of the mix. Based on the results, a relationship between split tensile, compressive and flexure strengths of silica fume concrete was developed using statistical methods.

Keywords—Silica fume, Lightweight, High strength concrete, and Strength.

I. INTRODUCTION

THE American Concrete Institute (ACI) defines silica fume as “very fine non-crystalline silica produced in electric arc furnaces as a by-product of the production of elemental silicon or alloys containing silicon”. The use of silica fume (SF) for production of high performance concretes is very common. Many extensive experiments were carried out by many researches around the world indicated that the usage of silica fume in concrete increases the concrete strengths, modulus of elasticity, chemical and abrasion resistance, in addition to enhancing durability, corrosion protection and mechanical properties. But there is not a clear, unique conclusion regarding the optimum silica fume replacement percentages, although some of the researchers have reported different replacement levels [1, 2 and 3].

Bhanjaa and Sengupta [4, 5 and 6] studied the effect of silica fume on the tensile and compressive strength of high-performance concrete (HPC); they developed mathematical model using statistical methods to predict the 28-day compressive strength of silica fume concrete with water-to-cementitious material (w/cm) ratios ranging from 0.3 to 0.42 and silica fume replacement percentages from 5 to 30.

Song et al. [7] based on a microstructure model predicted a procedure for the diffusivity of high strength concrete by considering water-to-binder ratio, silica fume replacement ratio, and degree of hydration as major influencing factors. They concluded that diffusivity of concrete can be reduced by adding Silica fume which makes the microstructure of concrete denser. Mazloom et al. [8] investigated the effects of binder systems containing different levels of silica fume on fresh and mechanical properties of high-strength concrete. The properties evaluated were: development of compressive strength; secant modulus of elasticity; strain due to creep, shrinkage, swelling and moisture movement. Other researchers [9, 10 and 11] studied the effect of high temperature on the performance of lightweight concrete with silica fume in terms of compressive and splitting tensile strengths, weight loss and mechanical properties.

Some researchers such as Ganesh Babu and Saradhi Babu [12] and González-Fonteboa and Martínez-Abella [13] used expanded polystyrene (EPS) beads and demolition waste as lightweight aggregate with silica fume. The formers studied the strength and the durability performance of EPS concretes. The mixes were designed by using the efficiency of silica fume at the different percentages. The resulting concretes were seen to have densities varying from 1500 to 2000 kg/m³, with the corresponding strengths varying from 10 to 21 MPa. The rate of strength gain for these concretes shows that an increase in the percentage of silica fume increases the 7-day strength. While [13] carried out experiments to determine the density, water absorption, grading, shape index, flakiness index and fragmentation resistance. Rao [14] did some experimental investigations on the influence of silica fume on various properties of cement pastes and mortars. The properties included specific gravity, normal consistency of cement, air content and workability of mortar with different silica fume contents. The test results show that the silica fume changes the behavior of cement pastes and mortars significantly.

Chen and Liu [15] investigated the mechanical properties of expanded polystyrene (EPS) concrete. They showed that EPS concrete with a density of 800–1800 kg/m³ and a compressive strength of 10–25 MPa can be made by partially replacing coarse and fine aggregate by EPS beads. Fine silica fume greatly improved the bond between the EPS beads and cement paste and increased the compressive strength of EPS concrete. In addition, adding steel fiber significantly improved the drying shrinkage. Roy et al. [16] dealt with the mix design and mechanical properties of very lightweight concrete made of expanded polystyrene (EPS) spheres and very high

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performance matrix. Based on experimental data obtained on different EPS concrete, it is shown that the lower the inclusion size, the higher the compressive strength of the hardened concrete. Babua et al. [17] studied the mechanical properties of expanded polystyrene (EPS) concretes containing fly ash and compared the results with those in literature on concretes containing OPC alone as the binder.

Although the literature is rich in reporting the effect of silica fume on different issues as stated above, there is not a unique conclusion regarding the optimum silica fume replacement percentages especially for lightweight high strength concrete. In this paper the isolated effect of silica fume on the tensile, compressive and flexure strengths of lightweight high strength concrete is studied by replacing cement with percentages of silica fume at different water–binder ratio, keeping other mix design variables constant. The experiments were carried out over water–binder ratios ranging from 0.26 to 0.42 and silica fume–binder ratios from 0% (control) to 25%. For all mixes, compressive, flexure and splitting tensile strengths were determined at 28 days.

II. EXPERIMENTAL PROGRAM

A. MATERIALS

The cementitious materials used were ordinary Portland cement (OPC) and silica fume (SF), their chemical properties are given in Table 1. Lightweight aggregate was adopted to achieve concrete densities less than 1850 kg/m³. The specific gravity and water absorption values of the lightweight aggregate were obtained as 2.71% and 4.2 %, respectively. Fig. 1 and 2 show the sieve analysis of fine and coarse aggregate, respectively. Portable water and superplasticiser (SP) were employed for the mixing.

B. MIX PROPORTIONS

TABLE 1
CHEMICAL PROPERTIES OF CEMENT AND SILICA FUME

Item	% by mass	
	Ordinary Portland Cement (OPC)	Silica Fume (SF)
SiO ₂	21.36	91.5
Al ₂ O ₃	5.57	0.65
Fe ₂ O ₃	3.35	0.3
CaO	62.5	0.9
Finess as Surface Area (m ² /kg)	370	16,000
Specific gravity	3.10	2.2

Details of the mix proportions for the concrete containing different levels of silica fume are given in Table 2. The control mix was cast using OPC (0% SF), while the other mixes were prepared by replacing part of the cement with silica fume at five different replacement levels on mass-for-mass basis. The percentages of SF replacements were 5%, 10%, 15%, 20% and 25%. The water-cementitious ratios used in this experiment were 0.26, 0.30, 0.34, 0.38 and 0.42.

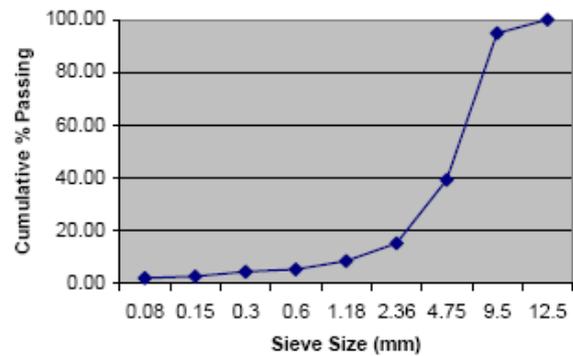


Fig. 1 Sieve Analysis for used fine aggregate

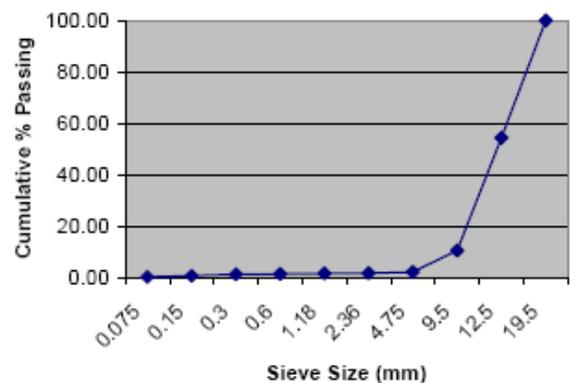


Fig. 2 Sieve Analysis for used Coarse aggregate

C. EXPERIMENTAL PROCEDURE

As stated earlier, the main objective of this paper is to determine the isolated effect of silica fume on the strengths of lightweight high strength concrete. Accordingly, other mix design variables were considered constant such as, mix proportions, the aggregate-binder, coarse-medium-fine aggregate ratio, dosage of SP, curing conditions and testing procedure. The total binder content was fixed at about 500 kg/m³ varying from 520 kg/m³ at w/cm ratio of 0.26 to 480 kg/m³ at w/cm ratio of 0.42. The mix proportion was adopted as C/FA/MA/CA= 1: 1.28: 1.45: 0.726 for all the mixes.

Cong et al. [18] reported that the strength of cement paste and concrete can be affected by 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. Hence, the dosage of SP was kept constant for all the mixes. In order to minimize variations in workability, the compaction energy was varied for obtaining proper compaction and the mixing procedure and time were kept constant for all the concrete mixes investigated.

TABLE II
MIX PROPORTIONS

w/cm Ratio	Cement (Kg/m ³)	Silica Fume (Kg/m ³)	Aggregate (Kg/m ³)			Water (Kg/m ³)	SP (%)
			Fine	Medium	Coarse		
0.26	520	0	667	756.36	378.18	135.2	3.5
	494	26					
	468	52					
	442	78					
	416	104					
	390	130					
0.30	510	0	653	740.85	370.43	153	3.5
	484.5	25.5					
	459	51					
	433.5	76.5					
	408	102					
	382.5	127.5					
0.34	500	0	640	726	363	170	3.5
	475	25					
	450	50					
	425	75					
	400	100					
	375	125					
0.38	490	0	628	711.48	355.74	186.2	3.5
	465.5	24.5					
	441	49					
	416.5	73.5					
	392	98					
	367.5	122.5					
0.42	480	0	616	698.28	349.14	201.6	3.5
	456	24					
	432	48					
	408	72					
	384	96					
	360	120					

w/cm = Water– cementitious material ratio by weight.
SP= superplasticizer.

For each mix, the following specimens were made: three (150 x150 x150) mm³ cubes for compressive strength determination; three (150 x300) mm cylinders for splitting tensile strength determination and three (100 x100 x500) mm³ beams for flexure strength determination. A symmetrical two point loading setup, with beam span of 400 mm, was used for the flexure test. All specimens were moist cured under water at room temperature until testing. Each strength value was the average of the strength of three specimens. Table 3 shows the unit weight of specimens used. They are within the lightweight ranges of 300 to 1850 kg/m³ as defined by Neville [19].

III. RESULTS AND DISCUSSIONS

A. COMPRESSIVE STRENGTH

The isolated effect of SF increases the compressive strength as shown in Fig. 3. This Fig. shows the variation of compressive strength with SF replacement percentages where the compressive strength values at different w/c ratios have been plotted for the five SF replacement percentages in addition to the control mix (0% SF). The percentages of gaining strength with respect to the control mix for w/c 0.26, 0.3, 0.34, 0.38 and 0.42 at 5%, 10%, 15%, 20% and 25% SF replacements are 15.8%, 29.1%, 35.5%, 31.5% and 31.25%, respectively.

TABLE III
UNIT WEIGHT OF SPECIMENS USED

W/C	SF (%0)	SF (%5)	SF (%10)	SF (%15)	SF (%20)	SF (%25)
0.26	1865.19	1863.70	1858.67	1861.63	1856.00	1851.85
0.30	1807.41	1799.11	1790.52	1787.26	1792.00	1775.41
0.34	1748.15	1743.70	1712.00	1709.63	1712.59	1714.37
0.38	1734.52	1728.59	1695.70	1702.81	1707.26	1698.37
0.42	1693.33	1703.11	1704	1717.33	1696.89	1703.41

The results indicate that the highest compressive strength for w/c 0.26 is 61.75 MPa at 15% SF replacement. For w/c 0.3 and 0.34; the highest is 56.23 and 52 MPa, respectively, at 20% SF replacement. While, for w/c 0.38 and 0.42; the highest is 46.15 and 40.95 MPa, respectively, at 25% SF replacement.

These results show that the optimum SF replacement percentages for obtaining maximum 28 day compressive strength of lightweight high strength concrete ranges from 15% to 25% depending on the w/c ratio of the mix. The optimum percentage of SF replacement increases with the increase of w/c ratio. On the other hand, Kheder and Abou Zied [2] reported that this range is from 10% to 20% for ordinary concrete.

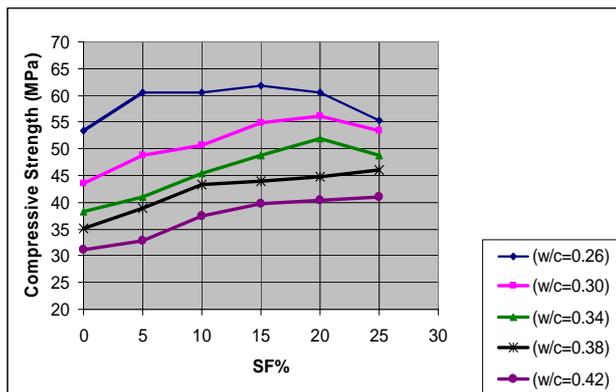


Fig. 3 Relationship between 28 day compressive strength and percentage replacement of silica fume

B. SPLIT TENSILE STRENGTH

Fig. 4 shows the variation of split tensile strength with the SF replacement percentages at different w/c ratios. The trend in the strength gain is almost similar to that in compressive strength. The percentages of gaining strength with respect to the control mix for w/c 0.26, 0.3, 0.34, 0.38 and 0.42 at 5%, 10%, 15%, 20% and 25% SF replacements are 26.9%, 22.29%, 28.43%, 27.7% and 39.07%, respectively.

The results show that the optimum SF replacement percentage for obtaining maximum 28 day split tensile strength of lightweight high strength concrete is almost a unique where it is noted 15% for w/c 0.26 and 0.30, and 20% for w/c 0.34, 0.38 and 0.42. Bhanja and Sengupta [4] reported that this range is from 5% to 10% for ordinary high strength concrete.

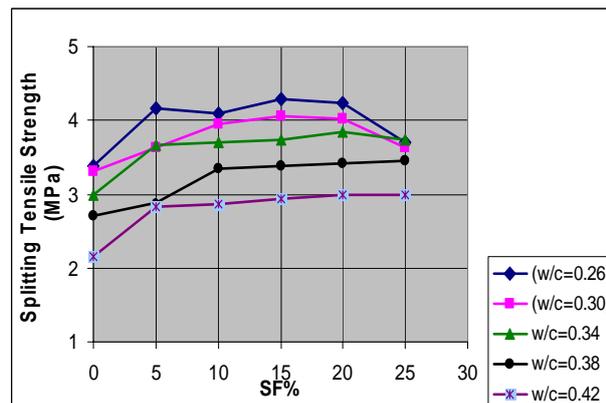


Fig. 4 Relationship between 28 day split tensile strength and percentage replacement of silica fume

C. FLEXURE STRENGTH

Fig. 5 shows the variation of split flexure strength with the SF replacement percentages at different w/c ratios. There is an obvious gain in flexural strength due to SF replacement. This strength increase is better compared with the compressive and tensile strengths for lightweight high strength concrete. The percentages of gaining strength with respect to the control mix for w/c 0.26, 0.3, 0.34, 0.38 and 0.42 at 5%, 10%, 15%, 20% and 25% SF replacements are 32.4%, 44.4%, 46.5%, 28.4% and 23.5%, respectively.

The results show that the optimum SF replacement percentage for obtaining maximum 28 day flexural strength of lightweight high strength concrete is depending on the w/c ratio. The optimum percentage is 15% for w/c 0.26, 20% for w/c 0.3 and 0.34, and 25% for w/c 0.38 and 0.42. The optimum percentage of SF replacement increases with the increase of w/c ratio as the case for compressive strength.

IV. STATISTICAL RELATIONSHIPS

A. Relationship between split tensile and compressive strength

The compressive strength of concrete is usually measured for the purpose of quality control. The tensile strength is estimated from the compressive strength by using empirical correlation equations. The results of lightweight high strength concrete mixes are analyzed statistically by performing regression analysis. Fig.6 (a), (b), (c), (d), (e) and (f) show the relationship between the 28 day split tensile and compressive

strengths for SF replacement percentages 0%, 5%, 10%, 15%, 20% and 25%, respectively.

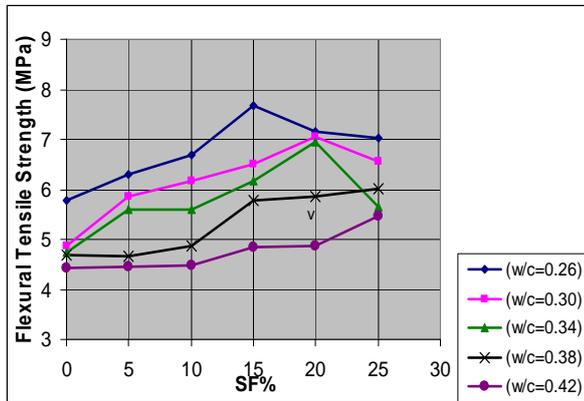


Fig. 5 Relationship between 28 day flexure strength and percentage replacement of silica fume

The empirical correlation equations for SF replacement percentages 0%, 5%, 10%, 15%, 20% and 25%, are (1), (2), (3), (4), (5) and (6), respectively, shown below:

$$f_{sp} = -0.0041 f_c^2 + 0.4 f_c - 6.3 \quad (1)$$

$$f_{sp} = -0.00075 f_c^2 + 0.12 f_c - 0.28 \quad (2)$$

$$f_{sp} = -0.0029 f_c^2 + 0.34 f_c - 5.8 \quad (3)$$

$$f_{sp} = -0.002 f_c^2 + 0.27 f_c - 4.4 \quad (4)$$

$$f_{sp} = -0.0014 f_c^2 + 0.2 f_c - 2.8 \quad (5)$$

$$f_{sp} = -0.0058 f_c^2 + 0.6 f_c - 12 \quad (6)$$

Where f_{sp} and f_c denote the 28 day split tensile and compressive strengths of concrete, expressed in MPa, respectively.

B. Relationship between flexure and compressive strength

Fig.7 (a), (b), (c), (d), (e) and (f) show the relationship between the 28 day flexure and compressive strengths for SF replacement percentages 0%, 5%, 10%, 15%, 20% and 25%, respectively.

The empirical correlation equations for SF replacement percentages 0%, 5%, 10%, 15%, 20% and 25%, are (7), (8), (9), (10), (11) and (12), respectively, shown below:

$$f_{fl} = 0.0043 f_c^2 + 0.61 f_c - 14 \quad (7)$$

$$f_{fl} = -0.003 f_c^2 + 0.46 f_c - 9.3 \quad (8)$$

$$f_{fl} = 0.0072 f_c^2 - 0.52 f_c + 14 \quad (9)$$

$$f_{fl} = 0.02 f_c^2 - 1.5 f_c + 32 \quad (10)$$

$$f_{fl} = 0.023 f_c^2 - 1.6 f_c + 31 \quad (11)$$

$$f_{fl} = 0.0073 f_c^2 - 0.61 f_c + 18 \quad (12)$$

Where f_{fl} and f_c denote the 28 day flexure and compressive strengths of concrete, expressed in MPa, respectively.

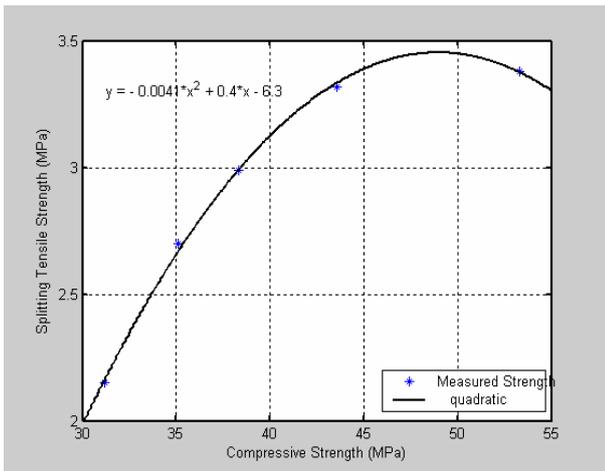
V. CONCLUSION

In this paper the isolated effect of silica fume on tensile, compressive and flexure strengths on high strength lightweight concrete was studied by carrying out many experiments. The silica fume was replaced by 0%, 5%, 10%, 15%, 20% and 25% for water-binder ratios 0.26, 0.3, 0.34, 0.38 and 0.42. The following conclusions can be derived:

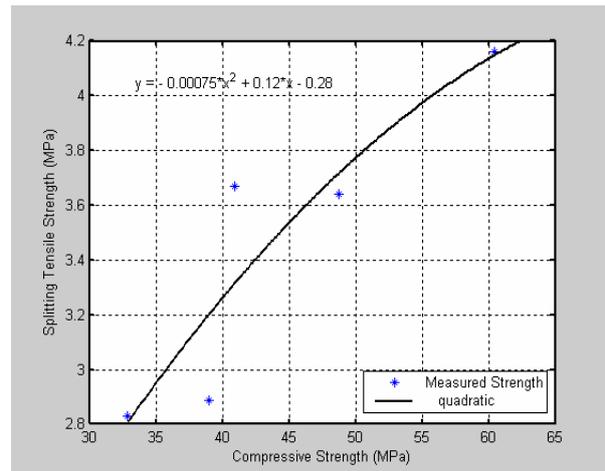
1. The isolated effect of SF increases the compressive, splitting tensile and flexure strengths. The highest increase has been found in the flexure strength.
2. The trend in the strength gain due to SF replacement in compressive strength is almost similar to that in split tensile strength for lightweight high strength concrete.
3. The optimum SF replacement percentages for obtaining maximum 28 day compressive and flexure strengths of lightweight high strength concrete ranges from 15% to 25% depending on the w/c ratio of the mix. The optimum percentage of SF replacement increases with the increase of w/c ratio. This percentage is almost a unique for tensile strength where it is noted 15% for w/c 0.26 and 0.30, and 20% for w/c 0.34, 0.38 and 0.42.
4. Relationships between split tensile and compressive strength and between flexure and compressive strength were developed using empirical correlation equations for five different SF replacement percentages in addition to the control mix.

ACKNOWLEDGMENT

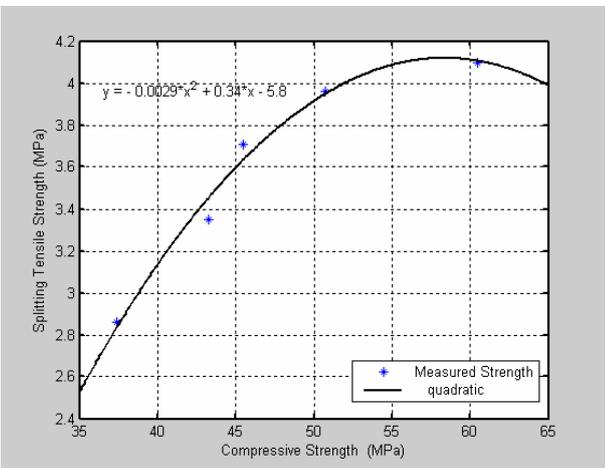
A special thanks for Mohammad Kharabsheh, Hussein Malkawi and Ahmad Gharaibeh for their efforts in performing the laboratory experiments.



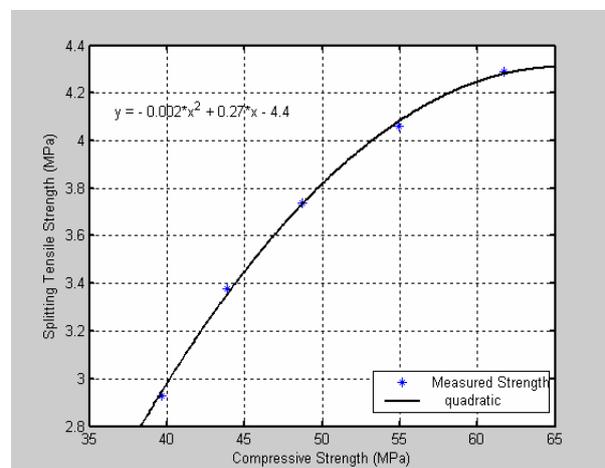
(a)



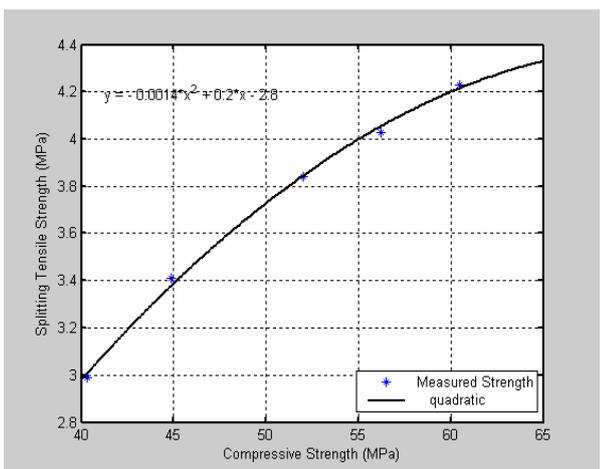
(b)



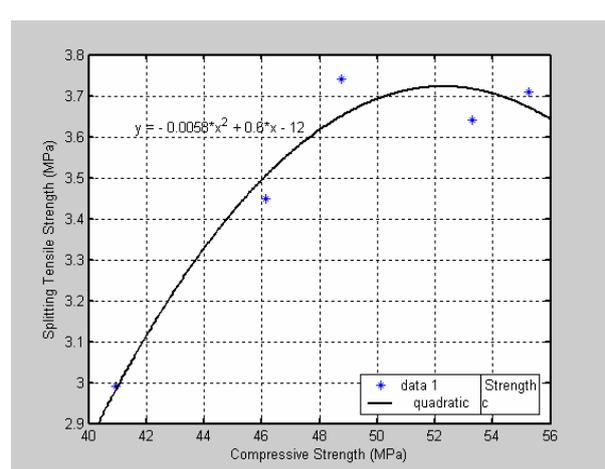
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(d)

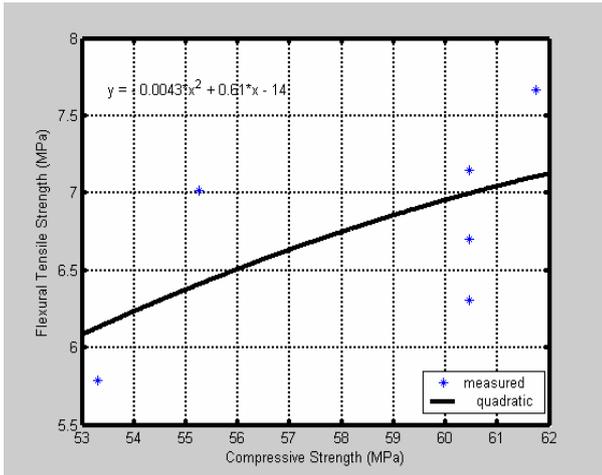


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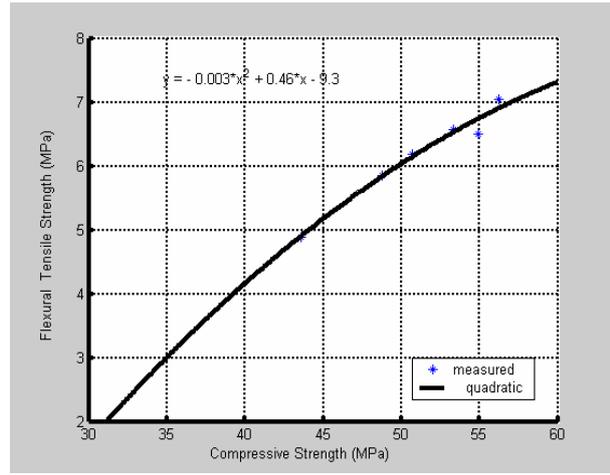


(f)

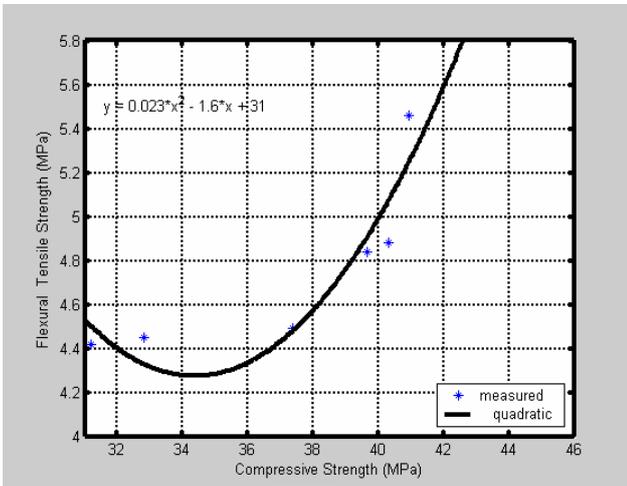
Fig. 6 Relationships between the 28 day split tensile and compressive strengths for SF replacement percentages (a) 0%, (b) 5%, (c) 10%, (d)15%, (e) 20% and (f) 25%.



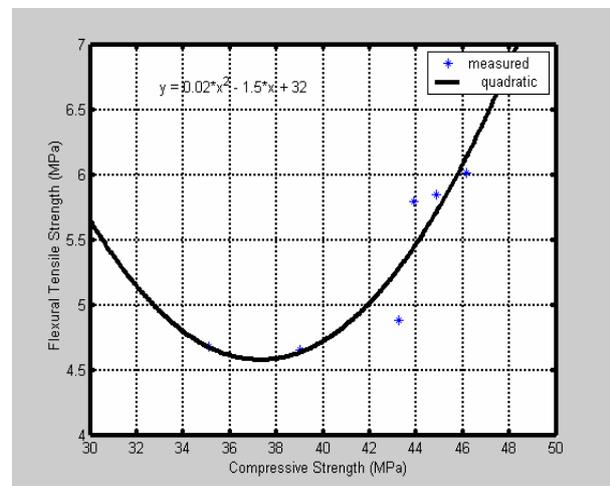
(a)



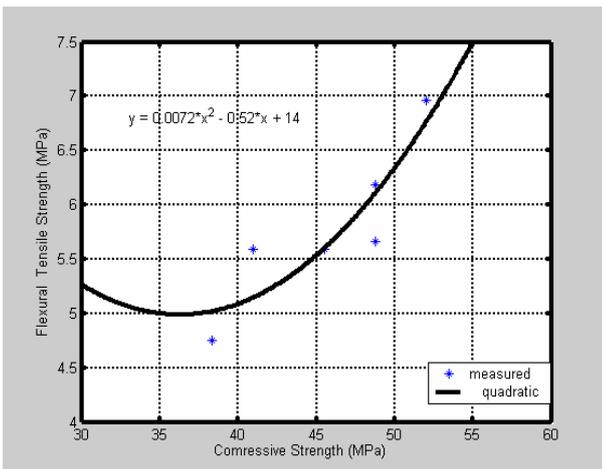
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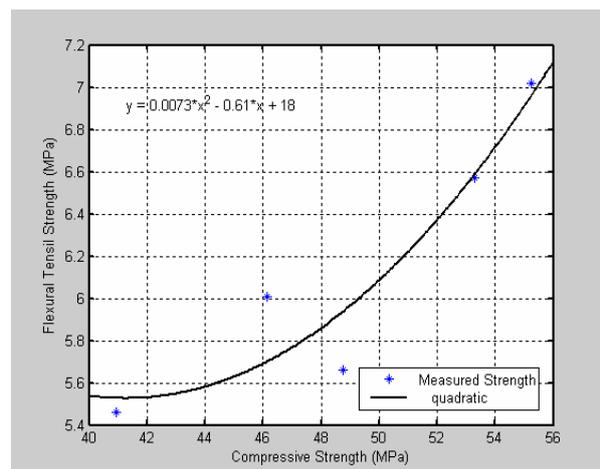
(c)



(d)



(e)



(f)

Fig. 7 Relationships between the 28 day compressive and Flexure strengths for SF replacement percentages (a) 0%, (b) 5%, (c) 10%, (d) 15%, (e) 20% and (f) 25%.

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