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Combined effect of silica fume and steel fiber on the splitting tensile strength of high-strength concrete

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Abstract

This paper presents the influence of adding steel fibers and incorporation of silica fume on the mechanical properties of high-strength concrete. The variables investigated are steel fiber volume fraction (0 to 1.5%), silica fume replacement (5 and 10%) and water-to-binder ratio (0.25, 0.30, 0.35 and 0.40). The influence of fiber content in terms of fiber reinforcing index on the compressive and splitting tensile strengths of high-strength steel fiber reinforce concrete (HSFRC) is presented. The addition of crimped steel fiber into high-strength concrete improves splitting tensile strength significantly. Based on the test data, using regression analysis, empirical expression to predict 28-day tensile strength of HSFRC in terms of fiber reinforcing index was developed and the absolute variation and integral absolute error (IAE) obtained are 3.1% and 3.3, respectively. The relationship between splitting tensile and compressive strength of SFRC was reported with regression coefficient, r = 0.86 and IAE value determined is 10.9. The experimental values of previous researchers were compared with the values predicted by the model and found to predict the values quite accurately.

Keywords: *High-strength concrete, Splitting tensile strength, Silica fume, Steel fiber reinforcing index, High-strength fiber reinforced concrete, Modeling.*

1. Introduction

The axial tensile (pull) test is difficult to conduct free of eccentricity and is further complicated to secondary stresses induced during the testing. Moreover, the stress concentration near the gripping assembly may result in premature failure [1]. These difficulties rise to use of indirect tensile tests (modulus of rupture and split tension tests). Normally, tensile strength derived from the flexural tension (modulus of rupture) test is higher than that assessed from the direct tension test made on concrete from the same batch, which was explained by Neville (1995) [1]. Another indirect test method is splitting tension test (called as Brazilian test). The Brazilian test normally gives consistent results that lies between those based on the other two test methods. This test is a simple way of testing concrete under tension and the equipment used is the compressive strength testing machine. Moreover, the same size of concrete cylinder specimen can be used for both the splitting tensile strength test and compressive strength test.

The use of silica fume in high-strength concrete has shown significant improvement attained on the interfacial zone of cement paste-aggregate, which increases the bond strength [2].

Fibers are needed in HSC/ HPC whenever its intrinsic brittleness represents a limitation for its use. The use of fibers in concrete has gained momentum in the infrastructural and industrial applications such as industrial floors, pavements and overlays, marine structures, repair and rehabilitation and retrofitting of structures, earthquake resistant structures and slope stabilization. Balaguru and Shah (1992) [3] and ACI 544.1R- 1996 [4] have reported that the addition of steel fibers in concrete matrix improves many of engineering properties of concrete especially tensile strength, impact and thermal shock, toughness and ductility. The combined use of superplasticizer, and supplementary cementing materials such as silica fume which is a most valuable and widely used mineral admixture having pozzolanic reaction and filler effect, which will in turn improve the interface of the materials, thereby enhancing the strength and durability of the concrete, can lead to economical high-performance concrete.

Earlier researchers [5, 6, 7] have developed empirical equations for the prediction of 28-day tensile strength of HSFRC as a function of fiber reinforcing index (RI), and also only a few studies exist on the splitting tensile strength of high-strength steel fiber reinforced concrete incorporating silica fume. In all the equations only a particular w/cm ratio with varying fiber content was used. However, rather absolute strength values have been dealt with in all the models and thus are valid for a particular water-binder (w/b) ratio and specimen parameter considered. Also, in their expressions, contribution of

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matrix and fiber reinforcing index or fiber volume fraction were only considered and fiber-matrix interaction term was not considered. The fiber bond matrix parameter is considered in this investigation. Ramadoss (2008) [8] has considered non-dimensional parameter for developing mathematical model for predicting 28-day compressing strength of HPFRC. The relationship between 28-day splitting tensile strengths ratio (f_{spf}/f_{sp}) (non-dimensional parameter) and fiber reinforcing index (RI) at any water-to-cementitious materials (w/cm) ratio is quite limited. Where, f_{spf} is splitting tensile strength of HSFRC; f_{sp} is splitting tensile strength of nonfibrous concrete.

Empirical expression to predict 28-day splitting tensile strength of HSFRC in terms of fiber reinforcing index for a wide range of w/cm ratios has been developed. This paper presents the investigation on the splitting tensile and compressive strength properties of HSC with w/cm ratio ranging from 0.25 to 0.4, and studies the incorporation of silica fume (5 to 10%) by mass and effect of addition of crimped steel fibers (fiber volume fraction, V_f = 0.5, 1 and 1.5%) on improving these properties. The proposed model was shown to provide good correlation with the test results, and predicted the test data of earlier researches quite accurately.

2. Experimental Program

2.1. Material properties and mix proportions

Ordinary Portland cement-53 grade complying with the requirements of IS: 12269- 1987, and condensed silica fume (SF) contained 88.7% of SiO_2, 1.8% of loss on ignition at 975^{o}C and 0.9% of carbon content conforming to ASTM C1240-1999 were used. Specific gravity of SF = 2.25; bulk density = 670 kg/m^3; fineness on BET = 23 m^2/gm. Fine aggregate (river sand) conforming to grading zone-II of IS: 383-1978 was used. It has fineness modulus of 2.65 and specific gravity of 2.63. Coarse aggregate (crushed granite stone) with 12.5 mm maximum size, conforming to IS: 383-1978 was used. It has specific gravity of 2.70 and fineness modulus of 6.0. Superplasticizer of sulphonated naphthalene formaldehyde condensate as HRWR admixture conforming to ASTM Type F (ASTM C494) and IS: 9103-1999 was used. Crimped steel fibers conforming to ASTM A820-2001 was used. Physical properties of steel fiber are given in Table 1.

Table 1 Physical properties of crimped steel fiber

Geometry and properties	Value
Fiber diameter, d (mm)	0.45
Fiber length, l (mm)	36
Aspect ratio, l/d	80
Ultimate tensile strength, f_u (MPa)	910
Elastic modulus, E_f (GPa)	200

Mixtures were proportioned using guidelines and specifications given in ACI 211.4R-1993 [9], and recommended guidelines of ACI 544.3R-1993 [10]. Mixture proportions used in the test program are summarized in Table 2. This aspect of work has been carried our elsewhere [8]. For each water-cementitious materials ratio, 6 fibrous concrete mixes were prepared with three fiber volume fractions, V_f = 0.5, 1.0 and 1.5% (39, 78 and 117.5 kg/m^3, respectively). Slump value obtained is 75 ± 25 mm for silica fume concrete mixes and VeBe value is 12 ± 3 sec for fibrous concrete mixes. For each mix at least six 150 Ø x 300 mm cylinders were prepared. Specimens were cast, water cured at 27±2 ^{o}C and tested at 28 days.

Table 2 Mix proportions for HSFRC (Data for 1 m^3)

Mix Designation	W/Cm	C, kg	FA, kg	CA, kg	SF, kg	W, kg	SP, kg	Steel fiber, V_f(%)
FC1-0	0.4	416	691	1088	22	175	7.66	0
FC1-0.5	0.4	416	687	1079	22	175	7.66	0.5
FC1-1	0.4	416	682	1071	22	175	7.66	1
FC1-1.5	0.4	416	678	1062	22	175	7.66	1.5
FC1*-0	0.4	394.2	691	1088	43.8	175	7.66	0
FC1*-0.5	0.4	394.2	687	1079	43.8	175	7.66	0.5
FC1*-1	0.4	394.2	682	1071	43.8	175	7.66	1
FC1*-1.5	0.4	394.2	678	1062	43.8	175	7.66	1.5
FC2-0	0.35	461.7	664	1088	24.3	170	9.72	0
FC2*-0	0.35	437.4	664	1088	48.6	170	9.72	0
FC3-0	0.3	522.5	624	1088	27.5	165	13.75	0
FC3*-0	0.3	495	624	1088	55	165	13.75	0
FC4-0	0.25	608	562	1088	32	160	17.60	0
FC4*-0	0.25	576	562	1088	64	160	17.60	0

In mix designation FC1 to FC4 and FC1* to FC4*, silica fume replacement is 5 and 10%, respectively by weight of cementitious materials (Cm).

Cm = C+ SF = cement + silica fume.

V_f denotes steel fiber volume fraction in percent in volume of concrete.

In each w/cm ratio of mix, four fiber volume fractions (V_f = 0, 0.5, 1.0, and 1.5%) are used.

2.2. Compressive strength

Compressive strength tests were performed according to ASTM C39-1992 [11] standards using 150 mm diameter cylinders without capping, loaded uniaxially. Each strength value was an average strength of there specimens. 28-day compressive strength of plain concrete (high-strength concrete) is presented in Table 3. Compressive strength of high-strength concrete without SF content (HSC1-HSC4) obtained is in the range of 44.06 - 67.72 MPa. 28-day compressive strength gain of silica fume concrete obtained at 5% and 10% silica fume replacement with w/cm ratio = 0.4 are 6.31% and 16.65%, respectively, to that of plain concrete (HSC). Compressive strength values ranging from 46.9 to 80.4 MPa obtained for HSFRC mixes at 28-day are given in Table 4. Fig. 1 shows the effect of fiber reinforcing index (RI) on compressive strength of concrete at 10% silica fume replacement.

Table 3 Compressive and splitting tensile strengths of control concrete (HSC)

Mix designation	w/cm ratio	C, kg	SF, kg	28-day compressive strength, f'_c (MPa)	28-day split tensile strength, f_{sp} (MPa)
HSC1	0.4	438	0	44.06	3.54
HSC2	0.35	486	0	51.02	4.02
HSC3	0.3	550	0	58.51	4.37
HSC4	0.25	640	0	67.72	4.83

Table 4 28-day compressive strength and splitting tensile strength of steel fiber reinforced concrete and silica fume concrete, their ratios and percent variations

Mix Designation	w/cm ratio	RI	f'_{cf} (MPa)	f_{spf} (MPa)	f_{spf} / f_{sp}	Predicted by the model % error in f_{spf}
FC1-0	0.4	0	46.85	3.88	1	0.00
FC1-0.5		1.29	48.94	4.97	1.281	6.82
FC1-1		2.58	52.00	5.60	1.443	3.883
FC1-1.5		3.88	52.68	6.04	1.556	-1.65
FC1*-0		0	52.56	4.38	1	0.00
FC1*-0.5		1.29	54.77	5.48	1.251	4.56
FC1*-1		2.58	56.01	6.37	1.454	4.61
FC1*-1.5		3.88	57.40	6.83	1.559	-1.48
FC2-0	0.35	0	52.69	4.41	1	0.00
FC2-0.5		1.29	55.64	5.69	1.290	7.49
FC2-1		2.58	57.85	6.31	1.431	3.05
FC2-1.5		3.88	58.23	6.67	1.512	-4.62
FC2*-0		0	55.85	4.75	1	0.00
FC2*-0.5		1.29	59.65	5.94	1.25	4.55
FC2*-1		2.58	61.05	6.65	1.4	0.91
FC2*-1.5		3.88	61.44	7.26	1.528	-3.53
FC3-0	0.3	0	60.10	4.86	1	0.00
FC3-0.5		1.29	62.81	6.35	1.307	8.64
FC3-1		2.58	64.01	6.73	1.385	-0.18
FC3-1.5		3.88	64.56	7.15	1.471	-7.56
FC3*-0		0	63.86	5.12	1	0.00
FC3*-0.5		1.29	67.12	6.35	1.24	3.76
FC3*-1		2.58	68.91	7.18	1.402	1.08
FC3*-1.5		3.88	69.67	7.71	1.506	-5.08
FC4-0	0.25	0	71.64	5.15	1	0.00
FC4-0.5		1.29	74.15	6.58	1.278	6.58
FC4-1		2.58	75.65	7.51	1.458	4.87
FC4-1.5		3.88	76.09	7.95	1.544	-2.51
FC4*-0		0	74.87	5.62	1.000	0.00
FC4*-0.5		1.29	77.42	6.95	1.237	3.48
FC4*-1		2.58	79.96	8.05	1.432	3.15
FC4*-1.5		3.88	80.41	8.48	1.509	-4.87

f'_{cf} = 150 Ø x 300mm cylinder compressive strength (MPa) of HSFRC.
f_{spf} represents splitting tensile strength of HSFRC, f_{sp} refers to the strength of SF concrete.
Fiber reinforcing index (RI) = w_f *(l/d) and average density of HSFRC = 2415 kg/m^3
Weight fraction (w_f) = (density of fiber/ density of fibrous concrete)*V_f
Aspect ratio = (l/d)

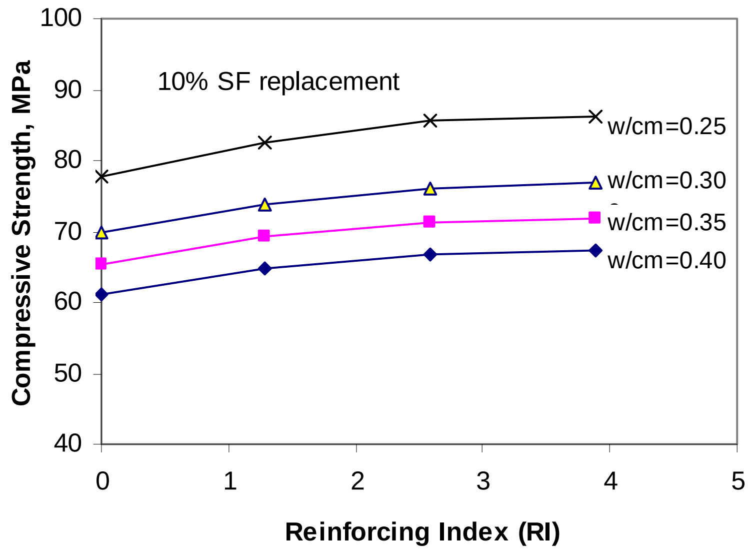

Fig. 1 Effect of fiber reinforcing index on compressive strength (10% silica fume replacement)

2.3. Splitting tensile strength

Splitting tensile tests were conducted according to ASTM C496-1990 [12] using 150 x 300 mm cylindrical specimens. The tests were conducted in a 1000 kN closed loop hydraulically operated Universal testing machine. Plywood pieces (as packing material) of size 25 x 3 mm were placed on both loading and reaction faces of specimens before testing. Three samples were used for computing the average strength.

3. Results and Statistical Modeling

3.1. Splitting tensile strength

The average percentage gains in silica fume concrete with respect to control concrete (plain concrete) at different water-cementitious materials ratios are determined as 9.4% and 18.9% at 5% and 10% replacement levels, respectively. 28-day splitting tensile strength of plain concrete (high-strength concrete) is given in Table 3. Table 4 presents the variation of the splitting tensile strength (f_{spf}) of HSFRC on the effect of fiber content in terms of fiber reinforcing index (RI). Fig. 2 shows the relationship between splitting tensile strength (f_{spf}) and fiber reinforcing index (RI) of HSFRC. It is observed from the test results given in Table 4 that there is a significant improvement in splitting tensile strength due to increase in fiber content from 0 to 1.5% (RI = 0 to 3.88) for all the mixes and the variation is 24-56 percent over reference concrete (silica fume concrete). An increase in strength of 55.94% for 1.5% fiber content (RI = 3.88) and 45.4% for 1% fiber content (RI = 2.58) of concrete was obtained, revealing that pull-out effect of fibers and ductility of fiber reinforced concrete have improved considerably. Percentage increase in splitting tensile strength for different fiber volume fractions of concrete mixes with w/cm ratios ranging from 0.25 to 0.40 is shown in Fig. 3. The similar improvement in strength trend has also been seen from the test results of SFRC at 5% SF replacement at all fiber volume fractions.

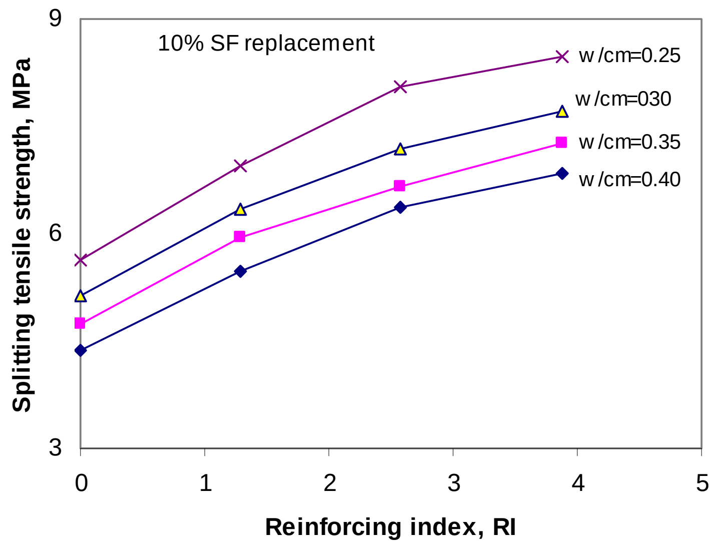

Fig. 2 Relationship between splitting tensile strength (f_{spf}) and fiber reinforcing index (RI)

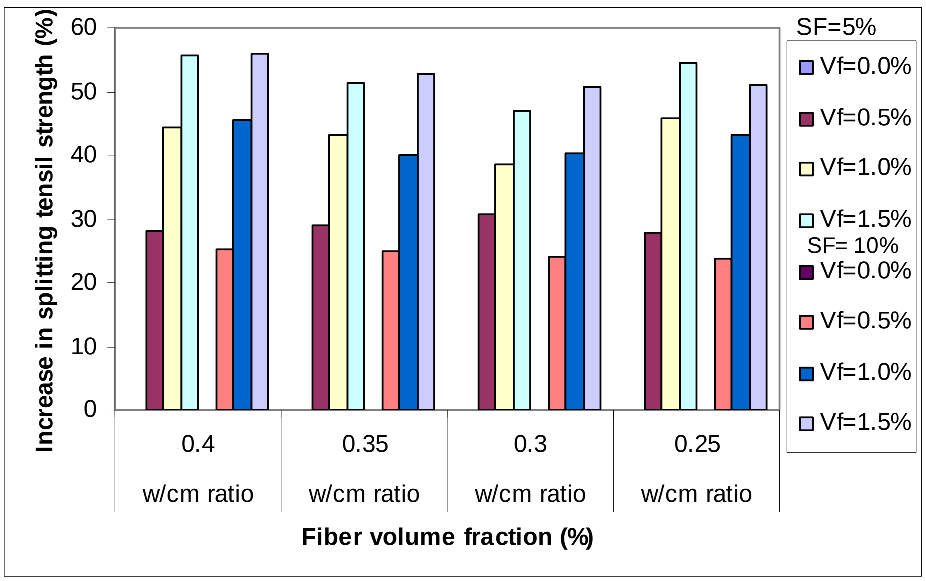

Fig. 3 Percentage increase in splitting tensile strength for different fiber volume fractions (RI = 0 to 3.88)

3.2. Relation between splitting tensile strength and compressive strength of SFRC

On correlation of test data, an empirical relation between 28-day splitting tensile and compressive strengths of steel fiber reinforced concrete with correlation coefficient, r = 0.86, is obtained as:

$$f_{spf} = 0.12\, f'_{cf}{}^{0.952} \qquad (1)$$

where f_{spf} = Splitting tensile strength of HSFRC, MPa;

f'_{cf} = compressive strength of HSFRC, MPa

In order to further evaluate the deviation between actual data points and prediction values, the integral absolute error (IAE) is employed, which is given as:

$$IAE = \frac{\Sigma(Q-P)}{\Sigma Q} x100\ \% \qquad (2)$$

where, Q is the actual strength and P is the predicted value.

Correlation of values predicted by the empirical relation (Eq. (1)) with the experimental splitting tensile strengths (MPa) of HSFRC is shown in Fig. 4. The model is examined with the predictions of previous researchers [5, 7, 13 - 18], in which the integral absolute error obtained is 12.87% indicating that the prediction model performs very well with the experimental data.

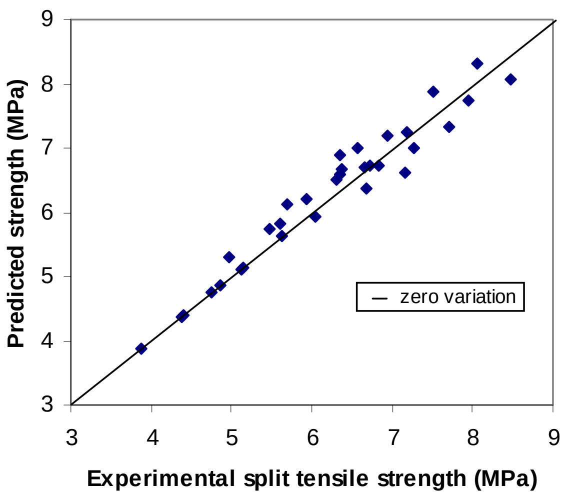

Fig. 4 Correlation of predicted values with the experimental splitting tensile strengths (MPa)

The IAE values of the empirical expressions of previous researchers/ ACI are also presented in Table 5. Compared with large IAE values of empirical expressions shown in Table 5 except the value of 10.7 for Xu and Shi (2009) [18], it is only 10.9 for Eq. (1), suggesting better reliability and accuracy of the proposed correlation equation. It can be seen from the Table 5 that the IAE values of the empirical relations except that of Xu and Shi (2009) [18] which is for SFRC, are between 25% and 30%, which verifies the inapplicability of these empirical expressions to SFRC. The absolute percent variation and standard deviation of errors have been obtained using the empirical relation (Eq. (1)) as 12 and 0.44, respectively, which reveal the significance of the prediction equation comparing to the empirical expressions of the earlier researchers.

Table 5 Empirical relation between splitting tensile strength and compressive strength of high-strength concrete and SFRC and corresponding IAE

Code of practice/ researcher	Empirical relation	Predicted strength (ave.error)	Standard deviation	IAE
ACI-363R-92 (1992)	$f_{sp} = 0.59\,(f'_c)^{0.5}$ for $f'_c < 85MPa$	1.56	0.925	25.07
ACI-318-95 (1995)	$f_{sp} = 0.56\,(f'_c)^{0.5}$ for $f'_c < 83MPa$	1.79	0.951	28.73
Ahmed and Shah (1985)	$f_{sp} = 0.46\,(f'_c)^{0.55}$ for $f'_c < 84MPa$	1.74	0.932	27.98
Wafa and Ashour (1992)	$f_{sp} = 0.58\sqrt{f'_c}$	1.63	0.935	26.27
Rashid et al. (2002)	$f_{sp} = 0.47(f'_c)^{0.56}$ for $f'_c < 120MPa$	1.46	0.900	23.48
Hueste et al.(2004)	$f_{spc} = 0.55\sqrt{f'_c}$	1.87	0.954	30.00
Thomas and Ramasamy (2007)	$f_{spc} = 0.57\sqrt{f'_c}$ for $30 < f'_c < 75MPa$	1.71	0.946	27.48
Xu and Shi (2009)	$f_{spf} = 0.21(f'_{cf})^{0.83}$	0.67	0.555	10.70
Author	$f_{spf} = 0.12(f'_{cf})^{0.952}$	0.68	0.44	10.96

Earlier researchers [8, 18] have developed expressions for modulus of rupture (flexural tensile strength) of steel fiber reinforced concrete (SFRC) as function of splitting tensile strength based on the statistical analysis of test results, as given below.

$f_{rf} = 1.321\, f_{spf}$ (Ramadoss, 2008)

$f_{rf} = 1.63\,(f_{spf})^{0.89}$ (Xu and Shi, 2009)

where f_{rf} = modulus of rupture of HSFRC, MPa; f_{spf} = Splitting tensile strength of HSFRC, MPa.

The average shear stress, τ_{cf}, for beams in which steel fibers were added, is given as recommended by ACI Committee 544-1993 based on splitting tensile strength as:

$$\tau_{cf} = \frac{2}{3} f'_t \left(\frac{d}{a}\right)^{1/4}$$

where f'_t = splitting tensile strength; d = effective depth of a beam; a = shear span; equal to distance from the point of application of load to the face of the support when concentrated loads acting.

The empirical expressions developed by the earlier researchers can be used for predicting the modulus of rupture and shear stress of SFRC based on the splitting tensile strength values obtained experimentally.

3.3. Strength prediction model

Table 4 presents the splitting tensile strength ratios of fiber reinforced concrete and silica fume concrete. Figure 5 shows splitting tensile strength ratios (f_{spf} / f_{sp}) as a function of fiber reinforcing index (RI) of the HSFRC. These ratios can be utilized for the development of the generalized expressions, which are free from the influence of varying w/cm ratios and specimen parameters, for predicting the splitting tensile strength. The validity of the model was investigated by examining relevant statistical coefficients [19].

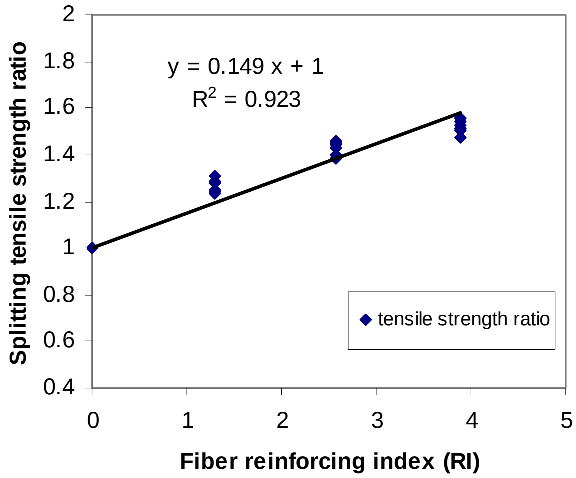

Fig. 5 Relationship between splitting tensile strength ratio (f_{spf}/f_{sp}) and fiber reinforcing index (RI)

Based on the test data, using the regression analysis, the splitting tensile strength ratio (f_{spf}/f_{sp}) of HSFRC and silica fume concrete may be predicted in terms of fiber reinforcing index, RI as follows:

$$f_{spf} / f_{sp} = 1 + 0.150\,(RI) \tag{3}$$

where f_{spf} = Splitting tensile strength of HSFRC, MPa;

f_{sp} = Splitting tensile strength of silica fume concrete, MPa and RI = fiber reinforcing index

The values of the correlation coefficient (r) and the standard error of estimate (s) have been obtained as 0.96 and 0.274, respectively. The IAE value and average absolute variation in percent have been obtained as 3.28 and 3.09, respectively. The standard deviation of errors obtained for the proposed model is 0.172. The above statistical parameters indicate the significance of the proposed model in predicting the test data quite accurately. The absolute variation in percent predicted by the mathematical model (Eq. (3)) is given in Table 4.

Eq. (3) if expanded for f_{spf} (the splitting tensile strength of HSFRC), the second term with coefficient (= 0.15* f_{sp} * RI) represents the contribution of matrix strength-fiber interaction explicitly, which depends upon the pullout/ bond characteristics of fibers in matrix. The above Eq. (3) is written for evaluating the splitting tensile strength of HSFRC in MPa as:

$$f_{spf} = f_{sp} + (0.15 f_{sp} * RI) \tag{4}$$

In the earlier studies, the contribution of matrix represented by the first term and RI of Eq. (4) was only considered and fiber-matrix interaction term represented by the second term was ignored. The proposed model was shown to provide good correlation with the test results.

3.4. Comparison of test results of previous researchers

Yao et al. (2003) [20] have obtained splitting tensile strength improvement for FRC using steel-hooked end fiber at volume fraction, v_f = 0.5%, is 10.1% compared to control concrete. Chen and Liu (2005) [21] have obtained tensile strength improvement for FRC with 9.1% silica fume replacement using steel-crimped fiber at v_f = 1%, is 23.9% compared to reference concrete. Sivakumar and Santhanam (2007) [22] have obtained splitting tensile strength improvement for FRC with 7% SF replacement using steel-hooked fibers at v_f = 0.5%, is 26.8% compared to control concrete. Altun et al. (2007) [23] have obtained splitting tensile strength improvement for FRC with v_f = 0.76%, is 54.3% compared to plain concrete. Wafa and Ashour (1992) [5], Nataraja et al. (2001) [6], Thomas and Ramasamy (2007) [7] have obtained tensile strength improvement for SFRC, are 55.7%, 35% and 41.2%,respectively compared to reference concrete. The values obtained experimentally are comparable with the reported results of the researchers, and the maximum improvement in splitting tensile strength obtained in this investigation with 10% SF replacement using crimped fiber (V_f = 1.5%) is 56%.

3.5. Validation of the model with the experimental values of previous researchers

The performance of the proposed model was assessed with the splitting tensile strength results obtained by the earlier researchers, and found to predict the strengths in good agreement with the actual values. A comparison between the experimental results obtained by Wafa and Ashour 1992 [5]; Nataraja et al. 2001 [6]; Thomas and Ramasamy 2007 [7]; Koksal et al. 2008 [24] and those predicted by the present model (Eq. 4) is shown in Fig. 6.

The average absolute variation and IAE value obtained for the predicted values of the test data of the earlier researchers by the proposed model (Eq. (4)) are 5.24% and 6.22, respectively. It was observed form the predictions and the Fig. 6 that the proposed model performs very well for different types of fibers and aspect ratios.

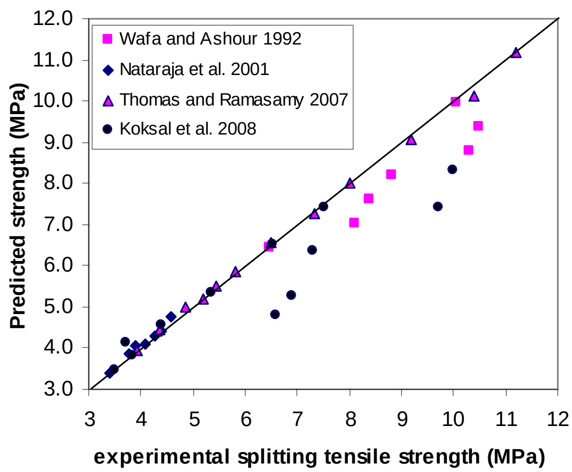

Fig. 6 Comparison of predicted strengths with the actual splitting tensile strengths (MPa) of earlier researchers

4. Conclusions

Based on the experimental study on high-strength steel fiber reinforced concrete, the following conclusions are drawn.

1) The average percentage gains in the splitting tensile strength of silica fume concrete with respect to control were obtained as 9.4% and 18.9% at 5% and 10% SF replacement, respectively.

2) The addition of steel fibers by 1.5% volume fraction (RI=3.88) results in an increase of 56% in the splitting tensile strength compared with concrete matrix.

3) The relation between 28-day splitting tensile strength and compression strength of SFRC was developed, and found to give good predictions with the test data of earlier researchers.

4) Splitting tensile strength prediction model was found to predict the test values quite accurately and the IAE value/ absolute percent variation were within 3.5%.

5. Abbreviation

HSFRC = high-strength steel fiber reinforced concrete
f_{spf} = splitting tensile strength of HSFRC, MPa
f_{sp} = splitting tensile strength of SF concrete , MPa
f'_{cf} = cylinder compressive strength of HSFRC, MPa
l/d = aspect ratio of fiber
RI = fiber reinforcing index.
IAE = integral absolute error

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