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MODELING FOR THE EVALUATION OF STRENGTH AND TOUGHNESS OF HIGH-PERFORMANCE FIBER REINFORCED CONCRETE

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Abstract

This paper presents the multivariate linear models for the evaluation of compressive, flexural and splitting tensile strengths, and toughness ratio of high-performance steel fiber reinforced concrete (HPSFRC). In this study, 44 series of concrete mixes with varying silica fume replacement and fiber dosage (V_f = 0.0, 0.5, 1.0 and 1.5%) were considered. Test results indicated that addition of fibers into silica fume concrete improves the compressive strength moderately and tensile strengths significantly. Based on the test results of 144 specimens, multivariate linear regression models were developed for the prediction of 28-day strength and toughness properties of HPSFRC and the absolute variations obtained are 1.09%, 2.36%, and 3.36% for compressive, flexural, and splitting tensile strengths, respectively. The validity of the proposed models was verified with the test data of earlier researchers. The proposed models were shown to provide results in good correlation with experimental results. The predicted values were also analyzed at significance level of 0.05.

Keywords: High-performance steel fiber reinforced concrete; Fiber reinforcing index; Compressive strength; Tensile strengths; Toughness; Modeling

1. Introduction

Concrete fiber composites have been found more economical for use in Airport and Highway Pavements, Bridge Decks, Erosion resistance Structures, slope stabilization, Refractory Concrete, Earthquake Resistance Structures and Explosive Resistance Structures [1, 2]. To increase the fracture resistance of cementitious materials, fibers are frequently added, thus forming a composite material. In the design of concrete structures the two important properties required

Nomenclatures

f_{cf}	Compressive strength of HPSFRC, MPa
f_{rf}	Flexural strength of HPSFRC, MPa
f_{spf}	Splitting tensile strength of HPSFRC, MPa
RI	Fiber reinforcing index
r	Regression coefficient
s	Standard error of the estimate
TR	Toughness ratio
V_f	Steel fiber volume fraction in percent by volume of concrete
w_f	Weight fraction = (density of fiber/ density of fibrous concrete)*V_f.

Abbreviations

SFRC	Steel fiber reinforced concrete
HPSFRC	High-performance steel fiber reinforced concrete

are: compressive strength and tensile strengths (modulus of rupture/ splitting tensile strength). The compressive strength is specified for structural applications while flexural strength is specified for pavement applications. In certain applications, toughness parameters may be specified [2].

Earlier researchers [3-13] were developed empirical expressions/ models for the prediction of strength of SFRC using limited variables and date sets. In this paper, data sets containing test results of 144 specimens (44 input records) from experimental investigation was considered for developing the mathematical models to evaluate the 28-day strength properties of high-performance steel fiber reinforced concrete (HPSFRC) mixes, and then verified for the validation of the models based on the test results of the earlier researchers. Analyzing the data sets using statistical methods, unknown coefficients (called regression coefficients) were determined, and multivariate linear (MLR) regression models were developed which give relationship between 28-day strengths (compressive, flexural and splitting tensile strengths) (dependent variables) and the influencing independent parameters (maximum 8 variables) involved in the concrete mix design of HPSFRC. To verify the performance of the proposed mathematical models, collected test data of earlier researchers have been used and models have been validated with an absolute variation of 1.5 percent (mean) for compressive strength. The predicted values were analyzed at 95% confidence level and the proposed models were found to predict the strengths quite accurately.

Research significance

Some methodology adopted for a mathematical model was taken into account for developing the multiple linear models to predict 28-day compressive, flexural and splitting tensile strengths of SFRC, which may serve as the useful tools in the civil engineering optimization problems such as optimization of concrete mixtures, and structural design of SFRC. In certain applications toughness property is needed. Experimental data was statistically analyzed for developing mathematical models considering more influencing factors which are not considered by the earlier researchers, and also the models were verified for its performance/ suitability.

2. Materials and Methods

The works presented in this paper is a part of the research work carried out at Anna University-Chennai, India.

2.1. Materials

Ordinary Portland cement-53 grade satisfying the requirements of IS: 12269-1987 and silica fume (Grade 920-D) in powder form contained 88.7% of SiO_2, having specific surface area of 23000 m^2/kg, and specific gravity of 2.25 were used. Fine aggregate (locally available river sand) passing 4.75 mm IS sieve, conforming to grading zone-II of IS: 383-1978 was used. It has fineness modulus of 2.65, specific gravity of 2.63, and water absorption of 0.98% @ 24 hrs. Coarse aggregate (crushed blue granite stone) with 12.5 mm maximum size, conforming to IS: 383-1978 was used. Its properties are: specific gravity=2.70; fineness modulus=6.0; water absorption=0.65% @24 hrs. Superplasticizer (sulphonated naphthalene formaldehyde - SNF) conforming to ASTM Type F (ASTM C494) was used. Specific gravity of SNF=1.20±0.05. Steel fibers (crimped type) conforming to ASTM A820- 2001 has been used. Its properties are: diameter=0.45 mm; length=36 mm; aspect ratio, l/d=80; ultimate tensile strength, f_u=910 MPa and elastic modulus, E_{sf}=200 GPa. Photo of crimped steel fibers is shown in Fig. 1.

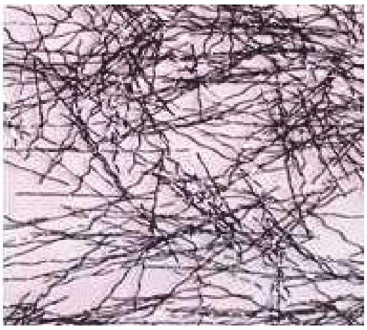

Fig. 1. A Photo of Crimped Steel Fibers (Rounded) (Aspect Ratio= 80).

2.2. Mixture proportions and test specimens

Mixtures were proportioned using guidelines and specifications given in ACI 211.4R-1993, recommended guidelines of ACI 544-1993, and guide lines of IS: 10262-1982. Mixture proportions used in the test program are summarized in Table 1. In this study, steel fiber up to 1.5% volume fraction was chosen, is based on the literature review and most of the researchers [1, 3, 4, 6, 8-11] have used steel fibers up to V_f =1.5%. Earlier researchers have observed that fiber volume fraction more than 1.5% in concrete mix has caused problems, such as workability, balling effect and non-uniform fiber distribution. For each water-cementitious materials ratio three fiber volume fractions, V_f = 0.5, 1.0 and 1.5% by volume of concrete

Table 1. Mix Proportions for HPSFRC (Data for 1 m³).

Mix Designation	W/Cm	C kg	FA kg	CA kg	SF kg	*W* kg	SP (%)	Steel Fiber, V_f(%)
	X_1	X_2	X_3	X_4	X_5	X_6	X_7 (wt)	X_8 (wt)
FC1-0	0.4	416	691	1088	22	175	1.75	0
FC1-0.5	0.4	416	687	1079	22	175	1.75	0.5
FC1-1	0.4	416	682	1071	22	175	1.75	1
FC1-1.5	0.4	416	678	1062	22	175	1.75	1.5
FC1*-0	0.4	394.2	691	1088	43.8	175	1.75	0
FC1*-0.5	0.4	394.2	687	1079	43.8	175	1.75	0.5
FC1*-1	0.4	394.2	682	1071	43.8	175	1.75	1
FC1*-1.5	0.4	394.2	678	1062	43.8	175	1.75	1.5
FC1**-0	0.4	372.2	691	1088	65.8	175	1.75	0
FC1**-1	0.4	372.2	682	1071	65.8	175	1.75	1
FC1**-1.5	0.4	372.2	678	1062	65.8	175	1.75	1.5
FC2-0	0.35	461.7	664	1088	24.3	170	2	0
FC2-0.5	0.35	461.7	660	1079	24.3	170	2	0.5
FC2-1	0.35	461.7	655	1071	24.3	170	2	1
FC2-1.5	0.35	461.7	651	1062	24.3	170	2	1.5
FC2*-0	0.35	437.4	664	1088	48.6	170	2	0
FC2*-0.5	0.35	437.4	660	1079	48.6	170	2	0.5
FC2*-1	0.35	437.4	655	1071	48.6	170	2	1
FC2*-1.5	0.35	437.4	651	1062	48.6	170	2	1.5
FC2**-0	0.35	413.1	664	1088	72.9	170	2	0
FC2**-1	0.35	413.1	655	1071	72.9	170	2	1
FC2**-1.5	0.35	413.1	651	1062	72.9	170	2	1.5
FC3-0	0.3	522.5	624	1088	27.5	165	2.5	0
FC3-.5	0.3	522.5	620	1079	27.5	165	2.5	0.5
FC3-1	0.3	522.5	615	1071	27.5	165	2.5	1
FC3-1.5	0.3	522.5	611	1062	27.5	165	2.5	1.5
FC3*-0	0.3	495	624	1088	55	165	2.5	0
RC3*-0.5	0.3	495	620	1079	55	165	2.5	0.5
FC3*-1	0.3	495	615	1071	55	165	2.5	1
FC3*-1.5	0.3	495	611	1062	55	165	2.5	1.5
FC3**-0	0.3	467.5	624	1088	82.5	165	2.5	0
FC3**-1	0.3	467.5	615	1071	82.5	165	2.5	1
FC3**-1.5	0.3	467.5	611	1062	82.5	165	2.5	1.5
FC4-0	0.25	608	562	1088	32	160	2.75	0
FC4-0.5	0.25	608	558	1079	32	160	2.75	0.5
FC4-1	0.25	608	553	1071	32	160	2.75	1
FC4-1.5	0.25	608	549	1062	32	160	2.75	1.5
FC4*-0	0.25	576	562	1088	64	160	2.75	0
FC4*-0.5	0.25	576	558	1079	64	160	2.75	0.5
FC4*-1	0.25	576	553	1071	64	160	2.75	1
FC4*-1.5	0.25	576	549	1062	64	160	2.75	1.5
FC4**-0	0.25	544	562	1088	96	160	2.75	0
FC4**-1	0.25	544	553	1071	96	160	2.75	1
FC4**-1.5	0.25	544	549	1062	96	160	2.75	1.5

In mix designation FC1 to FC4, FC1* to FC4*, and FC1** to FC4**, silica fume replacement is 5, 10, and 15 percent respectively by weight of cementitious materials, after hyphen denotes fiber volume fraction in percent.

(39, 78 and 117.5 kg/m^3, respectively) were used. Superplasticizer with dosage range of 1.75 to 2.75% by weight of cementitious materials has been used to maintain the adequate workability of plain and fiber reinforced concrete. Slump value obtained was 75±25 mm for silica fume concrete mixes and VeBe value was 12±3 seconds for fibrous concrete mixes. Concrete was mixed using a tilting type mixer and specimens were cast using steel moulds, compacted by using table vibrator. For each mix at least three 150 mm side cubes, three 150 mm diameter cylinders and three 100×100×500 mm prisms were prepared and water cured at 27±2^{o}C until the age of testing at 28 days.

2.3. Compressive strength test

Compressive strength tests were carried out according to IS: 516-1979 standards using 150 mm cubes loaded uniaxially and performed according to ASTM C 39-1992 standards using 150 mm diameter cylinders loaded uniaxially. The tests were done in a servo- controlled compression testing machine by applying load at the rate of 14 MPa/min. Minimum of three specimens were tested to assess the average strength. Test results on 144 specimens were used for developing the mathematical models.

2.4. Flexural and splitting tensile strength tests

Flexural strength (modulus of rupture) tests were conducted according to ASTM C 78-1994 using 100×100×500 mm prisms under third- point loading on a simply supported span of 400 mm. The tests were conducted in a 1000 kN closed loop hydraulically operated UTM. Samples were tested at a deformation rate of 0.1 mm/min. The Splitting tensile strength tests were conducted according to the specification of ASTM C 496-1990 using 150×300 mm cylindrical specimens. The tests were conducted in a 1000 kN closed loop hydraulically operated Universal testing machine. Three samples (minimum) were used for computing the average strength.

3. Analysis and Modeling of Concrete Strength

Compressive and tensile strengths of SFRC are considered as a function of the following 8 input parameters;

1. Water - cementitious materials ratio (W/Cm)
2. Cement (C), kg.
3. Fine aggregate (FA), kg.
4. Coarse aggregate (CA), kg.
5. Water (W).
6. Silica fume (SF), kg.
7. Super-plasticizer (SP), kg.
8. Fiber dosage, kg based on volume fraction (%).

In modeling the strength of concrete, regression analysis was carried out to establish the nature of relationship between the parameters (independent and dependent variables) involved in the mix proportioning of concrete, and hence to estimate the coefficients of linear/non-linear equations, involving independent variables.

Multivariate linear regression model

Multiple linear regression estimates the coefficients of the linear equation, involving more than one independent variable that best predict the value of the dependent variable. To predict the behavior or events more accurately, it is intended to go beyond the assumptions of ordinary linear regression techniques. The basic formulation of multiple linear regression equation is shown in Eq. (1).

$$\begin{bmatrix} \partial/\partial a_0 \\ \partial/\partial a_1 \\ \partial/\partial a_2 \\ \partial/\partial a_3 \\ \partial/\partial a_4 \\ \vdots \\ \partial/\partial a_n \end{bmatrix} \sum_{i=1}^{k} \{P_i - (a_0 + a_1 x_{1i} + a_2 x_{2i} + a_3 x_{3i} + \cdots + a_n x_{1i})\} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{Bmatrix} \qquad (1)$$

Equation (1) is solved with the input data (independent and dependent variables) by carrying out the required operations. In multiple linear regression (MLR) analysis, it is assumed that the variable y or P is related to variables x_1, x_2, x_3, . . . x_n, for which an individual value of y is defined as:

$$y = a_0 + \sum a_i\, x_i \qquad (i = 1 \text{ to } n) \qquad (2)$$

The mathematical model for predicting 28-day compressive strength is expressed by a linear equation (3) by rewriting the Equation (2) in the expanded form as:

$$y = a_0 + a_1\, x_1 + a_2\, x_2 + a_3\, x_3 + a_4\, x_4 + a_5\, x_5 + a_6\, x_6 + a_7\, x_7 + a_8\, x_8 \qquad (3)$$

where y is the estimated compressive strength/ or dependent variable, n is the number of parameters; a_o and a_i (a_1 to a_8) are the regression coefficients, (i =1 to 8), and x_1, x_2, x_3......x_8 are the independent variables.

When a regression model has estimated using the available data set, an additional data set may become necessary to test the validity of the developed model.

4. Results and Discussion

Results obtained for engineering properties from the investigation are given and discussed. Analytical evaluation for the development of models for the prediction of strength properties is carried out.

4.1. Compressive strength and toughness ratio

The variation of the compressive strength, f_{cf}, as obtained for concrete cube specimens on the effect of fiber content in terms of fiber reinforcing index is presented in Table 2. Test results in Table 2 show that the addition of steel fiber (volume fraction = 0.5 to 1.5%) in HSC matrix increases the compressive strength by about 13% which is due to the fiber matrix bond in concrete. MLR model was developed by analyzing the experimental data sets containing 8 parameters by using SPSS software. Figures 2 and 3 show the correlation of predicted values by the multivariate linear model with the experimental values and the linear probability plot of predicted strength, respectively. It was found that the predictions provided by the proposed models are in good agreement with the experimental values. Figure 4 shows the probability curve for experimental values. In Fig. 4 the curve indicates that a close agreement is existed between experimental data and prediction values.

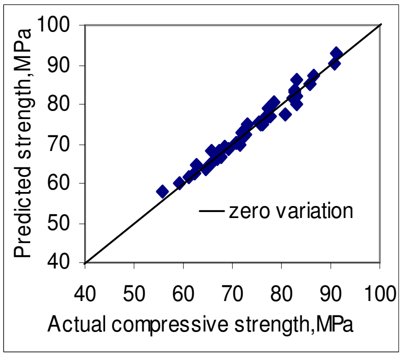

Fig. 2. Correlation of Experimental Strength with Predicted Strength, f_{cf}.

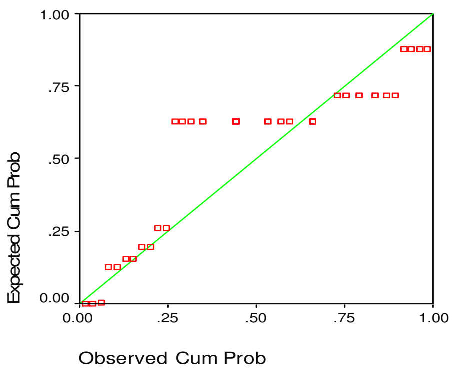

Fig. 3. Linear Probability of Predicted Compressive Strength.

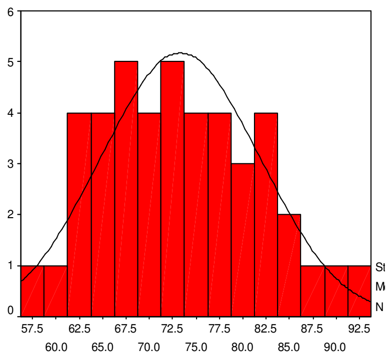

Fig. 4. Probability Curve for Experimental Values, f_{cf}.

Table 2 shows the experimental values and the absolute variation based on the predicted values by the multiple linear regression models. To see the performance of prediction, another MLR model was also developed by analyzing the experimental data sets containing 5 parameters by using SPSS software. Table 3 presents the statistical models (Equations for compressive strength) developed, and the statistical data of models indicate the accuracy of the prediction equations.

It was observed that both models perform equally to predict the values accurately and a close agreement has been obtained between the test results and prediction results. The absolute variations obtained are 1.09 percent and 1.503 percent (mean) for model-I and model-II, respectively. The predicted values were also analyzed at significance level of 0.05 and absolute error range obtained are 2.29- 0.018 for linear model-I. F-test for two sample of variance was conducted on the predicted values. F calculated and F critical one-tail obtained are closure to one another. It is observed from the F-test that there is no significant variation between the values predicted by the models. At 95% confident level the absolute variation range for model is 0.798±0.181. The validity of the proposed model was examined with the data sets of earlier researchers [3, 7, 10, 14], and observed that MLR model predicts the values quite accurately. Figure 5 shows the comparison of predicted results with the experimental results of previous researchers [3, 7, 10, 14]. The equations were found to give good correlation with experimental values. The validity of the models was investigated by examining the relevant statistical coefficients [15].

In the results presented in this paper, the toughness is measured as the total area under stress-strain curve up to a strain of 0.015 mm/mm, which is five times the ultimate concrete strain of 0.003 mm/mm as adopted in the ACI building code for concrete structures (ACI 318-1995). The toughness ratios calculated from experiment observations is varying in the range of 0.2038 - 0.6789 for the SFRC with 10% silica fume replacement. Figure 6 shows the correlation of predicted values by the multivariate linear model (Table 3) with the experimental toughness values. The standard error of the estimate, *s*, and RMS error have been obtained as 0.1318 and 0.1123, respectively. A close agreement has been obtained between the experimental and predicted values. The validity of the model was investigated by examining the relevant statistical coefficients [15].

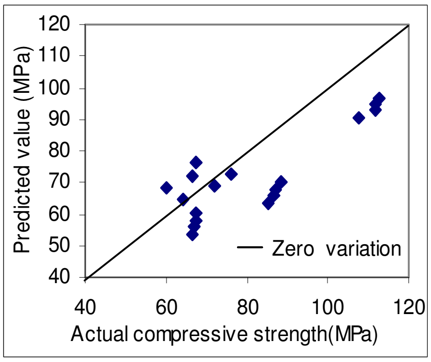

Fig. 5. Comparison of Predicted, f_{cf} with Experimental Results of Earlier Researchers.

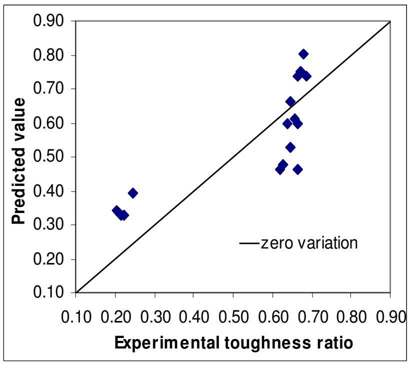

Fig. 6. Correlation of Predictions with the Experimental Results of Toughness Ratio.

4.2. Flexural and splitting tensile strengths

Table 2 presents the variation of the flexural (modulus of rupture) and splitting tensile strengths on the effect of fiber content in terms of fiber reinforcing index, RI. It is observed from the test results (Table 2) that there is a significant improvement in flexural strength with increasing the steel fiber content from 0.5 to 1.5 percent for all the mixes, varying from 16 to 38 percent to that of plain concrete (SF concrete). The improvement in splitting tensile strength of SFRC was about 56% at 1.5% fiber volume fraction compared to plain concrete matrix. The significant improvements in tensile strengths are mainly due to fiber-matrix interaction as a result of randomly oriented fibers, in the transverse direction of load after the first crack occurs in beams/ cylinders. Table 2 shows the predicted values of flexural and splitting tensile strengths by the multivariate linear models (Table 3). It was found that the predictions provided by the proposed models are in good agreement with the experimental values.

Table 2. 28-day Compressive and Tensile Strengths of HPSFRC and Strength Variation (%).

Mix Designation	w/cm	RI	150 mm cube strength	Predicted by the models (MLRM)		Tensile strengths			
				Model-I	Model-II	Flexural	Predicted	Split tensile	Predicted
		l/d = 80	f_{cf} MPa	Absolute Error,%	Absolute Error,%	f_{rf} MPa	MPa	f_{spf} MPa	MPa
FC1-0	0.4	0	55.62	1.47	2.34	5.61	5.65	3.88	4.04
FC1-0.5	0.4	1.29	59.28	1.45	0.88	6.68	6.41	4.97	4.86
FC1-1	0.4	2.58	62.2	0.82	0.16	7.17	7.17	5.60	5.68
FC1-1.5	0.4	3.88	62.85	0.73	1.73	7.46	7.93	6.04	6.51
FC1*-0	0.4	0	61.03	0.27	0.51	6.21	6.07	4.38	4.40
FC1*-0.5	0.4	1.29	64.75	0.34	1.01	7.15	6.83	5.48	5.22
FC1*-1	0.4	2.58	66.85	0.15	0.91	7.73	7.59	6.37	6.04
FC1*-1.5	0.4	3.88	67.38	0.12	0.79	8.19	8.36	6.83	6.87
FC1**-0	0.4	0	65.73	1.26	0.57	-		-	
FC1**-1	0.4	2.58	71.58	1.17	2.02	-		-	
FC1**-1.5	0.4	3.88	72.15	1.18	0.37	-		-	
FC2-0	0.35	0	62.32	0.27	0.11	6.28	6.49	4.41	4.50
FC2-0.5	0.35	1.29	65.43	0.27	0.80	7.32	7.25	5.69	5.32
FC2-1	0.35	2.58	67.72	0.27	0.89	7.88	8.01	6.31	6.14
FC2-1.5	0.35	3.88	68.36	0.19	0.70	8.44	8.77	6.67	6.97
FC2*-0	0.35	0	66.87	0.72	0.45	6.75	6.96	4.75	4.90
FC2*-0.5	0.35	1.29	69.23	0.56	0.61	8.06	7.72	5.94	5.72
FC2*-1	0.35	2.58	71.4	0.68	0.58	8.54	8.48	6.65	6.54
FC2*-1.5	0.35	3.88	71.96	0.69	1.09	9.15	9.25	7.26	7.37
FC2**-0	0.35	0	71.15	0.90	0.73	-		-	
FC2**-1	0.35	2.58	76.2	0.02	1.38	-		-	
FC2**-1.5	0.35	3.88	77.48	0.74	0.44	-		-	
FC3-0	0.3	0	65.8	1.17	2.24	7.31	7.29	4.86	4.99
FC3-0.5	0.3	1.29	70.6	0.02	0.37	8.48	8.05	6.35	5.81
FC3-1	0.3	2.58	72.41	0.50	0.02	9.05	8.81	6.73	6.63
FC3-1.5	0.3	3.88	72.94	0.53	1.72	9.58	9.58	7.15	7.46
FC3*-0	0.3	0	72.75	1.14	0.19	7.40	7.83	5.12	5.45
FC3*-0.5	0.3	1.29	75.87	0.61	1.12	8.76	8.59	6.35	6.27
FC3*-1	0.3	2.58	76.96	0.59	0.01	9.32	9.34	7.18	7.09
FC3*-1.5	0.3	3.88	77.29	0.82	1.89	10.13	10.11	7.71	7.92
FC3**-0	0.3	0	77.8	1.55	0.72	-		-	
FC3**-1	0.3	2.58	82.38	0.20	0.91	-		-	
FC3**-1.5	0.3	3.88	82.86	0.11	0.84	-		-	
FC4-0	0.25	0	75.21	0.44	0.24	7.80	8.03	5.15	5.53
FC4-0.5	0.25	1.29	80.74	2.33	3.09	9.11	8.79	6.58	6.35
FC4-1	0.25	2.58	82.97	2.27	3.12	9.62	9.54	7.51	7.17
FC4-1.5	0.25	3.88	83.03	1.77	0.95	10.16	10.31	7.95	8.00
FC4*-0	0.25	0	78.54	1.62	2.17	8.02	8.65	5.62	6.06
FC4*-0.5	0.25	1.29	82.83	0.98	0.08	9.58	9.41	6.95	6.88
FC4*-1	0.25	2.58	85.91	0.19	0.80	10.36	10.17	8.05	7.70
FC4*-1.5	0.25	3.88	86.47	0.19	0.87	11.06	10.93	8.48	8.53
FC4**-0	0.25	0	83.26	2.30	2.71	-	-	-	
FC4**-1	0.25	2.58	90.74	0.76	0.37	-	-	-	
FC4**-1.5	0.25	3.88	91.29	0.77	1.31	-	-	-	

	Model-I	Model-II
Mean	0.798	1.018
Standard deviation	0.619	0.809
At significance level of 5%, confidence interval	0.181	0.239

Fiber reinforcing index (RI) = w_f *(l/d) and
average unit weight of HPSFRC = 2415 kg/m^3, and w_f = weight fraction

Table 3 presents the statistical models (Equations for flexural and splitting tensile strengths) developed, and the statistical data of models indicate the accuracy of the prediction equations. The absolute variations obtained are 2.362 percent and 3.363 percent (mean) for flexural strength and splitting tensile strength prediction models, respectively. The standard error of the estimate (s) and RMS error have been obtained as 0.268 and 0.246, respectively, for flexural strength prediction model, and the corresponding values of 0.274 and 0.251, respectively, obtained for splitting tensile strength prediction model. The proposed models for the prediction of flexural and splitting tensile strengths (Table 3) were validated with the test data of earlier researchers [3, 10, 14]. Figure 7 shows the comparison of predicted flexural strength values with the experimental data of previous researchers [3, 10, 14]. Figure 8 shows the comparison of predicted splitting tensile strength values with the experimental results of previous researchers [3, 10, 14]. The equations were found to give good correlation with experimental values. A close agreement has been found between the experimental and predicted values for both the proposed models. The validity of the models was investigated by examining the relevant statistical coefficients [15].

Table 3. Statistical Models for the Strength Parameters.

Engineering parameter	Statistical equation	Regression coeff. (r)	Stand. Error	RMS Error
Compressive strength (model-I)	$-35562.4x_1 - 14.979x_2 - 17.853x_3 - 19.211x_4 - 14.81x_5 + 308.847x_6 + 3.7253x_7 - 6.1708x_8$	0.993	1.111	1.005
Compressive strength (model-II)	$-49.8246x_1 + 0.0616x_2 + 0.2259x_5 + 0.2704x_6 + 0.0564x_8$	0.988	1.375	1.295
Modulus of rupture	$-30.0628x_1 - 0.00354x_2 + 0.01592x_5 + 0.1074x_6 + 0.01944x_8$	0.982	0.268	0.246
Splitting tensile strength	$-12.0588x_1 + 0.00103x_2 + 0.01763x_5 + 0.04599x_6 + 0.02101x_8$	0.976	0.274	0.251
Toughness ratio	$0.04677x_1 - 3.3\times10^{11}x_2 + 2.95\times10^{12}x_5 - 0.00028x_6 + 0.00346x_8$	0.982	0.132	0.112

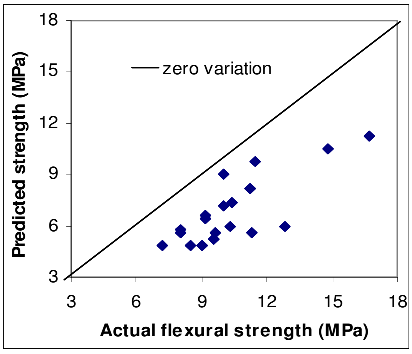

Fig. 7. Comparison of Predictions with the Experimental Results, f_{rf} of Earlier Researchers

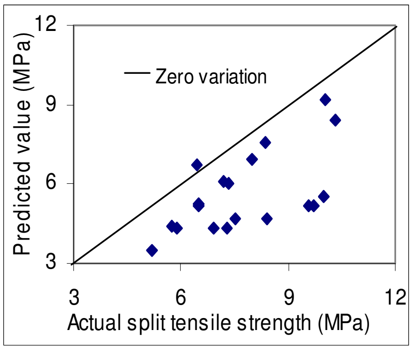

Fig. 8. Comparison of Predictions with the Experimental Results, f_{spf} of Earlier Researchers

5. Conclusions

Based on the investigation, following observations can be drawn.

- The addition of steel fibers up to 1.5% volume fraction (RI=3.88) in concrete matrix results in an increase of 13% in the compressive strength, 38% in the flexural strength and 56% in the splitting tensile strength.
- It was observed that the performance of MLR model in predicting the 28-day compressive/ tensile strengths of HPFRC is quite accurate. The proposed models were found to provide results in good correlation with the experimental results, where 95% of the estimated values are within ±2.5% of the actual values.
- Prediction of strength and toughness ratio by multivariate linear regression models was found to be adequate and this approach can easily be adopted due to its explicit nature of equations containing multi variables influencing the strength of HPFRC.
- The applicability of the statistical models was verified with the test data of earlier researchers and found to give good correlations with experimental data, and absolute variation obtained is 1.5% (mean) for compressive strength model, and absolute variations obtained are 2.362 percent and 3.363 percent for flexural and splitting tensile strength prediction models, respectively.

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