Mechanical Properties of Steel Fiber-Reinforced Concrete

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Abstract: This paper presents the results from an experimental program and an analytical assessment of the influence of addition of fibers on mechanical properties of concrete. Models derived based on the regression analysis of 60 test data for various mechanical properties of steel fiber-reinforced concrete have been presented. The various strength properties studied are cube and cylinder compressive strength, split tensile strength, modulus of rupture and postcracking performance, modulus of elasticity, Poisson's ratio, and strain corresponding to peak compressive stress. The variables considered are grade of concrete, namely, normal strength (35 MPa), moderately high strength (65 MPa), and high-strength concrete (85 MPa), and the volume fraction of the fiber (V_f=0.0, 0.5, 1.0, and 1.5%). The strength of steel fiber-reinforced concrete predicted using the proposed models have been compared with the test data from the present study and with various other test data reported in the literature. The proposed model predicted the test data quite accurately. The study indicates that the fiber matrix interaction contributes significantly to enhancement of mechanical properties caused by the introduction of fibers, which is at variance with both existing models and formulations based on the law of mixtures.

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Introduction

In earlier studies (Ghosh et al. 1989; Agrawal et al. 1996; Gao et al. 1997; Padmarajaiah 1999; Song and Hwang 2004), the improvement in mechanical properties in concrete due to the addition of steel fibers were expressed as a function of fiber-reinforcing index ($\mathrm{RI}=V_f L_f/\phi_f$) and concrete strength. Hannant (1978) has discussed the role played by both the fiber content (V_f) and the fiber aspect ratio (L_f/ϕ_f) in the workability, and strength enhancement of steel fiber-reinforced concrete (SFRC). Hannant (1978) captured the strength contribution of the fiber in the composite through the combined influence of both factors, namely, fiber content (V_f) and the fiber aspect ratio (L_f/ϕ_f) through the RI. Most of these models (Ghosh et al. 1989; Agrawal et al. 1996; Gao et al. 1997; Padmarajaiah 1999) were developed based on the test data of a single grade of concrete. The mechanical strength properties SFRC are closely related to the fiber parameters, matrix strength, and their interaction. However, the matrix strength fiber interaction has not been considered in the earlier studies. The fiber matrix interaction is an important factor that represents the strength enhancement due to the fiber bridging action across the microcracks in the concrete matrix. The present study reports on the test data for various strength grades of SFRC (35, 65, and 85 MPa) with various fiber dosages (V_f=0, 0.5, 1.0, and 1.5%). An empirical relationship for various mechanical properties of SFRC has been proposed. The proposed model attempts to bring out the significance of fiber matrix interaction in all the strength properties.

This study reports the experimental results of the strength properties of SFRC, namely, cube and cylinder compressive strength, split tensile strength, modulus of rupture, modulus of elasticity, Poisson's ratio, and strain corresponding to peak compressive stress. Empirical relationships were developed for various strength properties based on the regression analysis of the 60 test data. It is expected that these proposed models would be helpful in assessing the strength properties of fiber-reinforced concrete based on the matrix strength and fiber-RI.

Experimental Program

Details of the standard test specimens, namely, cubes, cylinders and prisms are given in Table 1. Five specimens each were cast using each grade of concrete (35, 65, and 85 MPa) and tested. The weight of the constituent materials per 1 m^3 of concrete arrived at based on absolute volume method [IS: 10262 (BIS 1982)] for various concrete mixes is given in Table 2. Blended-type cement having a specific gravity 3.14 was used for the study. River sand (<4.75 mm) of specific gravity 2.62 was used as fine aggregate and crushed stone aggregate (<10 mm) of specific gravity 2.69 was used as the coarse aggregate. Sulphonated naphthalene polymer based superplasticizer was used for the preparation of moderately high strength (65 MPa) and high-strength concrete (85 MPa). Silica fume was used for high-strength concrete (85 MPa). The fibers used were of hooked-end type (Fig. 1) glued in bundles having a length of 30 mm and aspect ratio of 55. The fiber dosage was varied (V_f) between 0.0 and 1.5% (Table 2). All the specimens were cured in water for a period of 28 days and then tested.

The cube and cylinder specimens were tested to determine the

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Table 1. Specimens for the Assessment of Strength Properties of SFRC

Strength property	Specimen	Dimensions (mm)	Number of specimens for each mix
Cube compressive strength	Cube	150×150×150	5
Cylinder compressive strength	Cylinder	150φ×300	5
Splitting tensile strength	Cylinder	150φ×300	5
Modulus of rupture	Prism	100×100×500	5
Modulus of elasticity	Cylinder	150φ×300	5
Poisson's ratio	Cylinder	150φ×300	5
Stress–strain behavior	Cylinder	150φ×300	5

compressive strength according to IS: 516 (BIS 1959). Cylinder specimens were tested for split tensile strength according to IS: 5816 (BIS 1999). Modulus of rupture test was carried out according to IS: 516 (BIS 1959). Modulus of elasticity and Poisson's ratio of concrete were determined using the standard cylinder specimens (BIS 1959).

Strength Prediction Models

Based on the regression analysis of the 60 test data, empirical models have been developed for predicting the strength properties of fiber-reinforced concrete. The proposed strength prediction models accounts for the interaction of matrix strength with fiber. The general form of the proposed strength prediction model is given by

$$f_{\mathrm{SFRC}} = A(f'_{\mathrm{cu}})^{\alpha 1} + B(f'_{\mathrm{cu}})^{\alpha 2}\mathrm{RI} + \mathrm{C\ RI} \qquad (1)$$

where f_{SFRC}=strength property (cylinder strength/split tensile strength/modulus of rupture) of the steel fiber-reinforced concrete; A, B, and C=regression coefficients; f'_{cu}=28-day cube compressive strength of the matrix (plain concrete); and RI=fiber-reinforcing index ($V_f L_f/\phi_f$). The value of $\alpha 1$ has been assumed to take a value of 0.5 or 1.0 as used in the conventional established method. The value of $\alpha 1$ in the prediction models of Poisson's ratio and strain corresponding to the peak compressive stress has been obtained by regression analysis of the test data of plain concrete having no fibers. The value of $\alpha 2$ has been assumed to take a value of 0.5 or 1.0 so as to get minimum deviation for predicted results from the corresponding test data. The first term with coefficient A represents the contribution of strength of the plain concrete or matrix. The second term with coefficient B represents the contribution of matrix strength–fiber interaction explicitly, which depends on the pullout characteristics of fiber from the matrix. The third term represents the contribution of the fiber dosage and fiber geometry. The coefficients represent the factors, namely, orientation of fiber, shape of the fiber, surface characteristics, etc., that contribute to the strength of the fiber-reinforced concrete. Hence, the coefficients of the predictive equation obtained based on the regression analysis of the test data of the present study partially characterizes the type of the fiber used. In earlier models (Taerwe 1992; Agrawal et al. 1996; Gao et al. 1997; Padmarajaiah 1999; Song and Hwang 2004) based on the law of mixtures, contribution of matrix represented by first and fibers represented by third term of Eq. (1) only was considered and the fiber matrix interaction term represented by the second term of Eq. (1) was ignored. The variation of the values of the strength properties predicted using a model consisting of only first and third terms of Eq.(1) when compared with the corresponding test result was found to be significant. The strength predictive models for various mechanical properties of SFRC accounting for the matrix strength–fiber interaction explicitly as given by the second term of Eq. (1) is found to predict the corresponding test results quite accurately. The regression models of various strength properties are presented in Table 3.

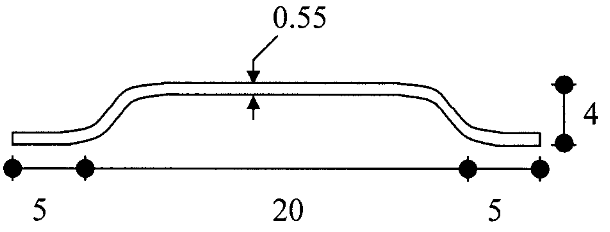

Fig. 1. Hooked-end steel fiber (all dimensions are in millimeter)

Results and Discussion

The test data of various strength properties of SFRC are presented in Fig. 2. The addition of fibers increased the various strength properties of concrete. The average strength of SFRC based on the five test data is presented in Table 4.

The average increase in cube compressive strength (f'_{cuF}) due to the addition of steel fibers (V_f=1.5%) was found to be minimal (3.65% in normal-strength concrete, 2.65% in moderately high-

Table 2. Weights of Constituent Materials for 1 m^3 Concrete

Item	Unit	Normal-strength concrete				Moderately high-strength concrete				High-strength concrete			
f'_{cu}	MPa	35	35	35	35	65	65	65	65	85	85	85	85
V_f	%	0	0.5	1	1.5	0	0.5	1	1.5	0	0.5	1	1.5
Water	kg	190	190	190	190	158	158	158	158	140	140	140	140
Cement	kg	400	400	400	400	450	450	450	450	450	450	450	450
Fine aggregate	kg	610	600	600	590	610	610	600	600	630	625	620	615
Coarse aggregate	kg	1,130	1,120	1,110	1,110	1,140	1,130	1,120	1,110	1,170	1,160	1,150	1,140
Silica fume	kg	—	—	—	—	—	—	—	—	50	50	50	50
Super plasticizer	L	—	—	—	—	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Fiber	kg	—	40	80	120	—	40	80	120	—	40	80	120
Water/(cement+silica fume)	kg	0.48	0.48	0.48	0.48	0.35	0.35	0.35	0.35	0.28	0.28	0.28	0.28

Note: Density of super plasticizer=1,200 kg/m^3 or 1.2 kg/L.

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Table 3. Strength Prediction Models for SFRC

Serial number	Property description	Prediction model
1	Cube compressive strength	$f'_{\mathrm{cuF}}=f_{\mathrm{cu}}+0.014f_{\mathrm{cu}}\mathrm{RI}+1.09\mathrm{RI}$ (MPa)
2	Cylinder compressive strength	$f'_{\mathrm{cuF}}=0.84f'_{\mathrm{cu}}+0.046f'_{\mathrm{cu}}\mathrm{RI}+1.02\mathrm{RI}$ (MPa)
3	Split tensile strength	$f_{\mathrm{spcF}}=0.63(f'_{\mathrm{cu}})^{0.5}+0.288(f'_{\mathrm{cu}})^{0.5}\mathrm{RI}+0.052\mathrm{RI}$ (MPa)
4	Modulus of rupture	$F_{\mathrm{flF}}=0.97(f'_{\mathrm{cu}})^{0.5}+0.295(f'_{\mathrm{cu}})^{0.5}\mathrm{RI}+1.117\mathrm{RI}$ (MPa)
5	Poisson's ratio	$\nu_{\mathrm{cF}}=0.01(f'_{\mathrm{cu}})^{0.167}+0.0001f'_{\mathrm{cu}}\mathrm{RI}+0.012\mathrm{RI}$
6	Modulus of elasticity	$E_{\mathrm{cF}}=4.58(f'_{\mathrm{cu}})^{0.5}+0.42(f'_{\mathrm{cu}})\mathrm{RI}+0.39\mathrm{RI}$ (GPa)
7	Strain at peak compressive stress	$\varepsilon_{\mathrm{ocF}}=[493.4(f'_{\mathrm{cu}})^{0.3943}+3.5788f'_{\mathrm{cu}}\mathrm{RI}+484.95\mathrm{RI}]\times 10^{6}$

strength concrete, and 2.59% in high-strength concrete) as shown in Table 4. The average increase in the cylinder compressive strength (f'_{cyF}) due to the addition of steel fibers ($V_f=1.5\%$) was found to be quite small at 8.33% in normal-strength concrete, 6.10% in moderately high-strength concrete, and 4.60% in high-strength concrete (Table 4). The maximum value of the standard deviation in the test results was found to be 2.5%. The small increase in the compressive strength due to the addition of steel fibers ($V_f=0-1.5\%$) of various grades of concrete is shown in Figs. 2(a and b).

Unlike concrete in compression, use of fibers, increases the split tensile strength (f_{spcF}) due to the addition of steel fibers ($V_f=1.5\%$) by 38.2% in normal-strength concrete, 41.2% in moderately high-strength concrete and 38.5% in high-strength concrete (Table 4). The variation of split tensile strength (f_{spcF}) due to the addition of steel fibers ($V_f=1.5\%$) is shown in Fig. 2(c). The increase in modulus of rupture (f_{flF}) due to the addition of steel fibers ($V_f=1.5\%$) was found to be 46.2% in normal-strength concrete, 38.8% in moderately high-strength concrete and 40.0% in high-strength concrete (Table 4). The variation of modulus of rupture (f_{flF}) due to the addition of steel fibers ($V_f=1.5\%$) is shown in Fig. 2(d). The increase in the tensile strengths, namely, split tensile strength (f_{spcF}) and the modulus of rupture (f_{flF}) due to the addition of the fibers is due to the action of fibers across the cracks in the concrete matrix. Fig. 3 shows the load displacement response of 65 MPa concrete for various fiber dosages. It is clear that the increase in fiber content enhances the tensile strength characteristics. The post-cracking response is significantly enhanced with increased fiber dosages across different concrete strength (35, 65, and 8 MPa) as seen in Fig. 4.

The variation in the Poisson's ratio of the concrete (ν_{cF}) due to the addition of steel fibers was marginal [Fig. 2(e)]. The value of Poisson's ratio was found to be varying from 0.18 to 0.22 for various grades of concrete (Table 4). Poisson's ratio of SFRC (ν_{cF}) is computed based on the observations at initial stages of loading, where the fibers do not play a significant role in the load sustenance. Thus, the addition of fibers did not show significant variation in Poisson's ratio of concrete (ν_{cF}).

The increase in modulus of elasticity (E_{cF}) due to the addition of steel fibers ($V_f=1.5\%$) was found to be 8.3% in normal-strength concrete, 9.2% in moderately high-strength concrete, and 8.2% in high-strength concrete (Table 4). The variation of modulus of elasticity (E_{cF}) due to the addition of fibers ($V_f=1.5\%$) is shown in Fig. 2(f). As these measurements for modulus of elasticity were in the linear region of the stress–strain response, the effect of fibers was not pronounced.

The increase in strain corresponding to the peak compressive stress ($\varepsilon_{\mathrm{ocF}}$) due to the addition of steel fibers ($V_f=1.5\%$) was

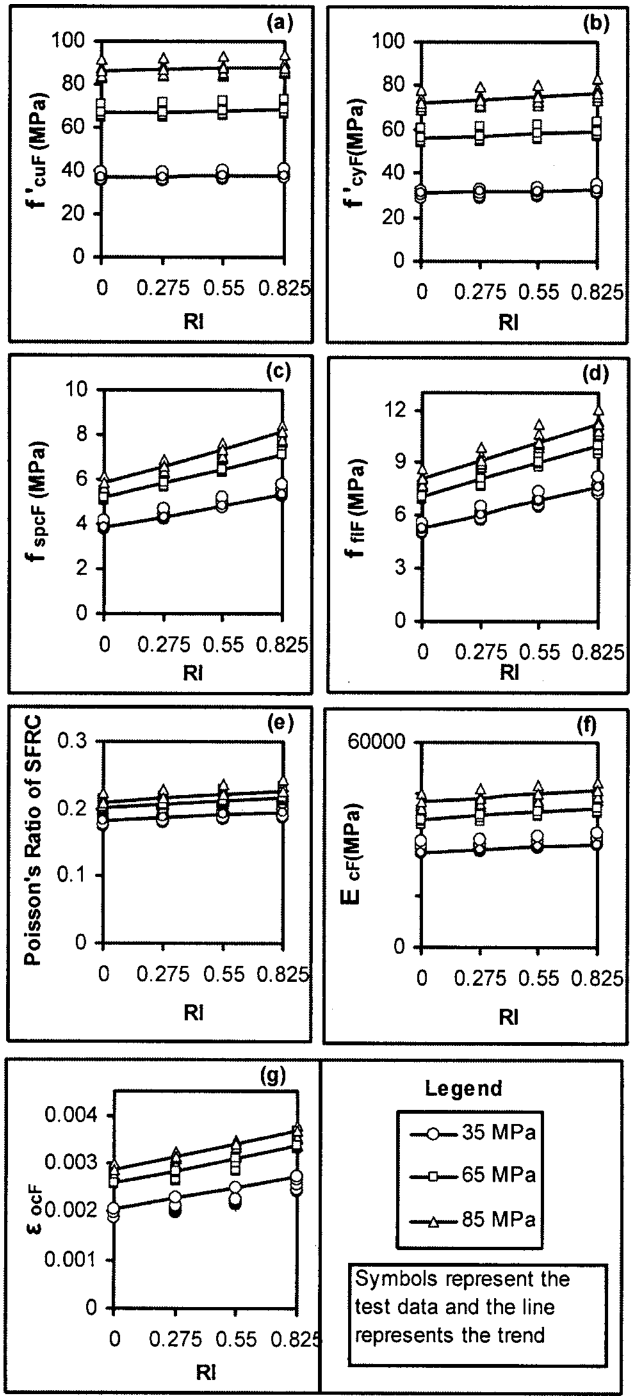

Fig. 2. Effect of reinforcing index of fiber on various strength properties of SFRC

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Table 4. Comparison of Experimental Results with the Strength Results Predicted Using the Proposed Models

		35 MPa Grade			65 MPa Grade			85 MPa Grade		
Property	RI	Experiment	Model	(4)/(3)[a]	Experiment	Model	(7)/(6)[a]	Experiment	Model	(10)/(9)[a]
f'_{cuF} (MPa)	0.000	36.6	36.6	1.00	66.6	66.6	1.00	86.1	86.1	1.00
	0.275	37.0	37.0	1.00	67.1	67.2	1.00	86.5	86.7	1.00
	0.550	37.5	37.5	1.00	67.5	67.7	1.00	87.0	87.3	1.00
	0.825	37.9	37.9	1.00	68.4	68.3	1.00	88.3	88.0	1.00
f'_{cyF} (MPa)	0.000	29.8	30.7	1.03	56.0	55.8	1.00	72.4	72.2	1.00
	0.275	30.5	31.4	1.03	57.0	57.0	1.00	73.6	73.5	1.00
	0.550	31.2	32.1	1.03	57.8	58.1	1.01	74.8	74.9	1.00
	0.825	32.3	32.9	1.02	59.4	59.2	1.00	77.0	76.3	0.99
F'_{spcF} (MPa)	0.000	3.93	3.82	0.97	5.19	5.16	0.99	5.76	5.86	1.02
	0.275	4.37	4.32	0.99	5.81	5.82	1.00	6.48	6.61	1.02
	0.550	4.87	4.81	0.99	6.49	6.48	1.00	7.20	7.36	1.02
	0.825	5.43	5.30	0.98	7.33	7.14	0.97	7.98	8.11	1.02
f_{flF} (MPa)	0.000	5.20	5.27	1.01	7.20	7.11	0.99	8.00	8.08	1.01
	0.275	6.00	6.07	1.01	8.00	8.08	1.01	9.20	9.14	0.99
	0.550	6.80	6.86	1.01	9.20	9.05	0.98	10.40	10.20	0.98
	0.825	7.60	7.66	1.01	10.00	10.01	1.00	11.20	11.26	1.01
ν_{cF}	0.000	0.182	0.181	0.99	0.201	0.201	1.00	0.210	0.209	0.99
	0.275	0.186	0.186	1.00	0.204	0.206	1.01	0.215	0.215	1.00
	0.550	0.191	0.190	0.99	0.213	0.211	0.99	0.221	0.221	1.00
	0.825	0.195	0.195	1.00	0.219	0.216	0.98	0.228	0.227	0.99
E_{cF} (GPa)	0.000	28.7	27.7	0.97	37.5	37.4	1.00	41.7	42.5	1.02
	0.275	29.4	28.5	0.97	38.6	38.4	1.00	43.0	43.7	1.02
	0.550	30.2	29.3	0.97	39.8	39.5	0.99	44.0	44.9	1.02
	0.825	31.1	30.1	0.97	41.0	40.6	0.99	45.1	46.1	1.02
ε_{ocF}	0.000	1.9×10^{-3}	2.0×10^{-3}	1.06	2.6×10^{-3}	2.58	0.97	2.8×10^{-3}	2.8×10^{-3}	1.01
	0.275	2.0×10^{-3}	2.2×10^{-3}	1.08	2.7×10^{-3}	2.78	1.02	3.0×10^{-3}	3.0×10^{-3}	1.02
	0.550	2.2×10^{-3}	2.3×10^{-3}	1.08	2.9×10^{-3}	2.98	1.02	3.2×10^{-3}	3.2×10^{-3}	1.01
	0.825	2.5×10^{-3}	2.5×10^{-3}	1.02	3.4×10^{-3}	3.19	0.93	3.5×10^{-3}	3.5×10^{-3}	0.99

[a] Numbers in parentheses represent the corresponding values in the columns.

found to be 29.5% in normal-strength concrete, 29.4% in moderately high-strength concrete, and 27.0% in high-strength concrete (Table 4). The variation in the strain corresponding to the peak compressive stress (ε_{ocF}) due to the addition of steel fibers (V_f=1.5%) for the various grades of concrete is shown in Fig. 2(g). The increase in strain corresponding to compressive strength is due to the confinement effect induced by the distributed steel fibers in a concrete matrix.

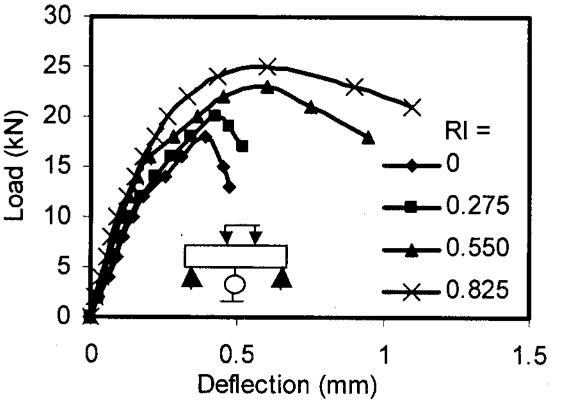

Fig. 3. Load deflection response in SFRC prism (65 MPa concrete)

Comparison of Predicted and Experimental Results

The predicted value of the various strength properties of SFRC has been compared with the experimental results of the present study (Table 4) and also with the test data reported in the litera-

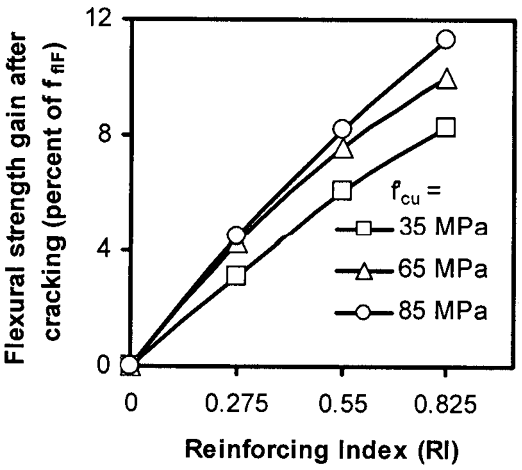

Fig. 4. Postcracking strength enhancements in SFRC with different fiber contents for different concrete mixes

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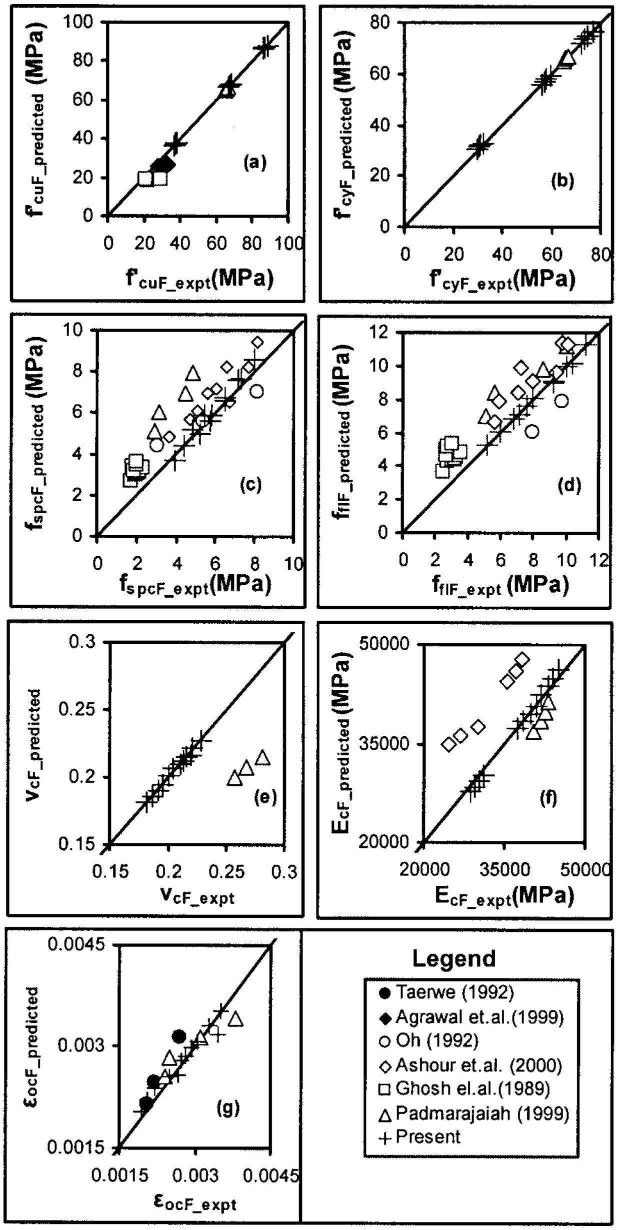

Fig. 5. Comparison of test data of the present study and test data reported in the literature with the predicted data using the proposed models

ture (Agrawal et al. 1996; Ashour et al. 2000; Gao et al. 1997; Ghosh et al. 1989; Hueste et al. 2004; Irvani 1996; Oh 1992; Padmarajaiah 1999; Song and Hwang 2004; Taerwe 1992). Fig. 5 shows the comparison for the different response quantities.

Compressive Strength

Average values of the test results of the compressive strengths (f'_{cuF} and f'_{cyF}) have been compared with the corresponding predicted strength. The comparison indicates that the proposed compressive strength model predicts the cube compressive strength and cylinder compressive strength of the present test program and that reported in earlier literature quite accurately [Figs. 5(a and b)].

Tensile Strength

Figs. 5(c and d) compare the test data of tensile strength of SFRC, namely, split tensile strength and modulus of rupture from the present test results with the corresponding predictions from models (Table 3). The proposed models predicted the experimental results of the present study quite accurately. However, scatter was seen in the predicted data of test results reported in the literature (Figs. 5(c and d)). A higher magnitude has been predicted for the tensile strength of SFRC reported in the literature. The variation in the tensile strengths of SFRC reported by various investigators may be due to the difference in degree of compaction, mix proportions, loading rate in the test procedure, aggregate to fiber length scales etc.

Hueste et al. (2004) developed models for the tensile strength of the plain concrete based on the statistical analysis of various test data and the models are given by

$$f_{\mathrm{spc}} = 0.55\sqrt{f'_{\mathrm{cy}}} \quad \text{for } 40\text{ MPa} < f'_{\mathrm{cy}} < 90\text{ MPa} \tag{2}$$

$$f_{\mathrm{fl}} = 0.83\sqrt{f'_{\mathrm{cy}}} \quad \text{for } 40\text{ MPa} < f'_{\mathrm{cy}} < 90\text{ MPa} \tag{3}$$

The equivalent strength prediction models developed in the present study are given by

$$f_{\mathrm{spc}} = 0.63\sqrt{0.83 f'_{\mathrm{cy}}} = 0.57\sqrt{f'_{\mathrm{cy}}} \quad \text{for } 30\text{ MPa} < f'_{\mathrm{cy}} < 75\text{ MPa} \tag{4}$$

$$f_{\mathrm{fl}} = 0.87\sqrt{0.83 f'_{\mathrm{cy}}} = 0.79\sqrt{f'_{\mathrm{cy}}} \quad \text{for } 30\text{ MPa} < f'_{\mathrm{cy}} < 75\text{ MPa} \tag{5}$$

The comparison of the coefficients in Eqs. (2) and (3) with Eqs. (4) and (5) shows that the proposed models show good agreement with the models proposed by Hueste et al. (2004) for plain concrete.

Poisson's Ratio

Fig. 5(e) compares the Poisson's ratio of SFRC test results with the corresponding value predicted using models reported in Table 3. Fig. 5(e) indicates that the proposed model predicts the Poisson's ratio accurately. The literature reporting on the Poisson's ratio of the concrete is limited. The value of Poisson's ratio of 65 MPa grade concrete reported by Padmarajaiah (1999) was 0.26 for plain concrete and 0.31 for fiber-reinforced concrete, which is slightly higher than the predicted value. This variation may be due to the difference in the aggregate proportion, aggregate size and variation in the rate of loading.

Modulus of Elasticity

The predicted value of the modulus of elasticity of SFRC has been compared with the experimental results and is presented in Fig. 5(f). The proposed model (Table 4) predicted the test results accurately. The model proposed by Irvani (1996) for the modulus of elasticity of the plain concrete [Eq. (6)] is in good agreement with the model proposed in this study [Eq. (7)]

$$E_c = 0.82 \times 4.7\sqrt{f'_{\mathrm{cy}}} = 3.8\sqrt{f'_{\mathrm{cy}}}\ (\mathrm{GPa}) \quad \text{for } 55\text{ MPa} < f'_{\mathrm{cy}} < 125\text{ MPa} \tag{6}$$

Table 5. Contribution of Individual Terms in Strength Properties in Eq. (1)

Strength property	RI	$A(f'_{\mathrm{cuF}})^{\alpha 1}$	$B(f'_{\mathrm{cuF}})^{\alpha 2}$ (RI)	$[100(4)]/[(4)+(6)]^{\mathrm{a}}$	C (RI)	$[100(6)]/[(4)+(6)]^{\mathrm{a}}$
f'_{cuF} (MPa)	0.000	36.6	0.0	0	0.0	0
	0.275	36.6	0.1	32	0.3	68
	0.550	36.6	0.3	32	0.6	68
	0.825	36.6	0.4	32	0.9	68
f'_{cyF} (MPa)	0.000	30.6	0.0	0	0.0	0
	0.275	30.6	0.5	62	0.3	38
	0.550	30.6	0.9	62	0.6	38
	0.825	30.6	1.4	62	0.8	38
f'_{spcF} (MPa)	0.000	3.82	0.00	0	0.00	0
	0.275	3.82	0.48	97	0.01	3
	0.550	3.82	0.96	97	0.03	3
	0.825	3.82	1.44	97	0.04	3
f_{flF}(MPa)	0.000	5.27	0.00	0	0.00	0
	0.275	5.27	0.49	62	0.31	38
	0.550	5.27	0.98	62	0.61	38
	0.825	5.27	1.47	62	0.92	38
ν_{cF}	0.000	0.182	0.000	0	0.000	0
	0.275	0.182	0.001	23	0.003	77
	0.550	0.182	0.002	23	0.007	77
	0.825	0.182	0.003	23	0.010	77
E_{cF} (GPa)	0.000	27.7	0	0	0	0
	0.275	27.7	0.7	87	0.1	13
	0.550	27.7	1.4	87	0.2	13
	0.825	27.7	2.1	87	0.3	13
$\varepsilon_{\mathrm{ocF}}$	0.000	2.04×10^{-3}	0.00	0	0.00	0
	0.275	2.04×10^{-3}	3.79×10^{-5}	22	1.33×10^{-4}	78
	0.550	2.04×10^{-3}	7.57×10^{-5}	22	2.67×10^{-4}	78
	0.825	2.04×10^{-3}	1.14×10^{-4}	22	4.00×10^{-4}	78

Note: Columns (5) and (7) represent the contribution percentage in the increase of each strength property due to the addition of fibers of the second and third terms of Eq. (1), respectively.

[a] Numbers in the brackets/parentheses represent the corresponding values in the column.

$$E_c = 4.6\sqrt{0.83 f'_{\mathrm{cy}}} = 4.2\sqrt{f'_{\mathrm{cy}}}\ \text{(GPa)} \quad \text{for } 30\ \text{MPa} < f'_{\mathrm{cy}} < 75\ \text{MPa} \tag{7}$$

The comparison of the predicted strength and test results of the present study and that reported in the literature has been presented in Fig. 5(f). The modulus of elasticity reported by Ashour et al. (2000) was the secant modulus evaluated at a stress level of $0.5f'_{\mathrm{cyF}}$. The proposed model for predicting the modulus of elasticity (Table 3) developed based on the stress-strain response up to $0.4f'_{\mathrm{cyF}}$ predicted slightly higher magnitude compared with the test results reported by Ashour et al. (2000).

Strain at Peak Compressive Stress

The strain at peak compressive stress predicted using proposed regression model (Table 4) has been compared with the corresponding experimental results and presented in Fig. 5(g). The comparison indicated that proposed model predicts the experimental data quite accurately.

Contribution of Fiber–Matrix Interaction

To bring out the contribution of fiber–matrix interaction term in Eq. (1), the generalized form of the prediction model, the individual contribution of the various terms are computed and compared (Tables 5 and 6). The second and third term in Eq. (1) represents the effect of matrix strength to fiber interaction. The percentage contribution of the second term of Eq. (1) in the total increase in the strength property of SFRC of 35 and 85 MPa grade due to the addition of fibers is presented in Column 5 of Tables 5 and 6, respectively. Similarly, the contribution of third term of Eq. (1) is presented in Column 7 of Tables 5 and 6. The contribution of the fiber–matrix interaction term [second term in Eq. (1)] varies for various strength properties. The comparison of the contribution of individual terms indicated that the contribution of the fiber–matrix interaction term is significant in computing the increased benefits due to the addition of fibers in concrete matrix.

The prediction models for mechanical properties of SFRC reported have been presented in Table 7. The average value of the ratio of predicted results to the test results of the present study and standard deviation of this ratio is also presented in Table 7. The average value of the ratio of the predicted strength to test result is an indication of the performance of the model and the standard deviation is indicative of the scatter in the computed ratio. The cube compressive strength and the cylinder compressive strength predicted using the earlier models (Agrawal et al. 1996; Padmarajaiah 1999; Song and Hwang 2004) was also found to be in good agreement with the test data of the present study (Table 7). The tensile strengths, namely, split tensile strength and

Table 6. Contribution of Individual Terms in Strength Properties of SFRC in Eq. (1) (85 MPa)

Strength property	RI	$A(f'_{\mathrm{cuF}})^{\alpha 1}$	$B(f'_{\mathrm{cuF}})^{\alpha 2}$ (RI)	$[100(4)]/[(4)+(6)]^{c}$	C (RI)	$[100(6)]/[(4)+(6)]^{c}$
f'_{cuF} (MPa)	0.000	86.1	0.0	0	0.0	0
	0.275	86.1	0.3	52	0.3	48
	0.550	86.1	0.6	52	0.6	48
	0.825	86.1	0.9	52	0.9	48
f'_{cyF} (MPa)	0.000	72.1	0.0	0	0.0	0
	0.275	72.1	1.1	80	0.2	20
	0.550	72.1	2.2	80	0.5	20
	0.825	72.1	3.3	80	0.8	20
f'_{spcF} (MPa)	0.000	5.86	0.00	0	0.00	0
	0.275	5.86	0.74	98	0.01	2
	0.550	5.86	1.47	98	0.03	2
	0.825	5.86	2.21	98	0.04	2
f_{flF} (MPa)	0.000	8.08	0.00	0	0.00	0
	0.275	8.08	0.75	71	0.31	29
	0.550	8.08	1.50	71	0.61	29
	0.825	8.08	2.25	71	0.92	29
ν_{cF}	0.000	0.209	0.000	0	0.000	0
	0.275	0.209	0.002	41	0.003	59
	0.550	0.209	0.004	41	0.006	59
	0.825	0.209	0.007	41	0.010	59
E_{cF} (GPa)	0.000	42.5	0.0	0	0.0	0
	0.275	42.5	1.0	91	0.1	9
	0.550	42.5	2.1	91	0.2	9
	0.825	42.5	3.2	91	0.3	9
$\varepsilon_{\mathrm{ocF}}$	0.000	2.86×10^{-3}	0.00	0	0.00	0
	0.275	2.86×10^{-3}	8.90×10^{-5}	40	1.33×10^{-4}	60
	0.550	2.86×10^{-3}	1.78×10^{-5}	40	2.67×10^{-4}	60
	0.825	2.86×10^{-3}	2.67×10^{-4}	40	4.00×10^{-4}	60

Note: Columns (5) and (7) represent the contribution percentage in the increase of each strength property due to the addition of fibers of the second and third terms of Eq. (1), respectively.

[c] Numbers in the brackets/parentheses represent the corresponding values in the column.

Table 7. Comparison of Results of the Present Study with the Predicted Results Using Strength Models Reported Earlier

			Predicted strength	
Property	Investigator	Predicted model	Average	Standard deviation
f'_{cuF} (MPa)	Agrawal et al. (1996)	$f'_{\mathrm{cuF}}=f'_{\mathrm{cu}}+0.106(\mathrm{RI})-2.65\times 10^{-5}(\mathrm{RI})^{2}+2.28\times 10^{-6}(\mathrm{RI})^{3}$	0.99	0.01
	Padmarajaiah (1999)	$f'_{\mathrm{cuF}}=f'_{\mathrm{cu}}+1.998(\mathrm{RI})$	1.00	0.00
f'_{cyF} (MPa)	Song and Hwang (2004)	$f'_{\mathrm{cyF}}=f'_{\mathrm{cy}}+15.12(V_f)-4.17(V_f)^{2}$	0.97	0.02
	Padmarajaiah (1999)	$f'_{\mathrm{cyF}}=f'_{\mathrm{cy}}+2.274(\mathrm{RI})$	0.99	0.01
f'_{spcF} (MPa)	Ghosh et al. (1989)	$f_{\mathrm{spcF}}=0.11f'_{\mathrm{cu}}(1-V_f)+0.573(\mathrm{RI})+0.571$	1.29	0.25
	Padmarajaiah (1999)	$f_{\mathrm{spcF}}=(f'_{\mathrm{cu}})^{0.5}/3+1.918(\mathrm{RI})$	0.57	0.04
f_{flF} (MPa)	Ghosh et al. (1989)	$f_{\mathrm{flF}}=0.15f'_{\mathrm{cu}}(1-V_f)+0.79(\mathrm{RI})$	1.17	0.24
	Padmarajaiah (1999)	$f_{\mathrm{flF}}=f_{\mathrm{flF}}+4.419(\mathrm{RI})$	1.05	0.05
ν_{cF}	Gao et al. (1997)	$\nu_{\mathrm{cF}}=\nu_c[1-0.172(\mathrm{RI})]$	0.90	0.08
	Padmarajaiah (1999)	$\nu_{\mathrm{cF}}=\nu_c+0.03704(\mathrm{RI})$	1.04	0.03
E_{cf} (GPa)	Gao et al. (1997)	$E_{\mathrm{cF}}=E_c[1+0.173(\mathrm{RI})]$	1.03	0.02
	Padmarajaiah (1999)	$E_{\mathrm{cF}}=E_c+2440.2(\mathrm{RI})$	0.99	0.01
$\varepsilon_{\mathrm{ocF}}$	Taerwe (1992)	$\varepsilon_{\mathrm{ocF}}=\varepsilon_{\mathrm{oc}}+0.0115f'_{\mathrm{cyF}}$	0.89	0.10
	Padmarajaiah (1999)	$\varepsilon_{\mathrm{ocF}}=\varepsilon_{\mathrm{oc}}+1.15\times 10^{-3}(\mathrm{RI})$	1.07	0.06

modulus of rupture predicted using the existing models (Padmarajaiah 1999; Ghosh et al. 1989) showed some scatter (Table 7). The variation in the predictions of tensile strength of SFRC may be because these models have been developed based on test results of a single grade of concrete. The predicted values of Poisson's ratio, modulus of elasticity, and strain corresponding to peak compressive stress using the existing models showed deviation up to 10% (Table 7). The proposed models given in Table 4 accounting for the fiber-matrix interaction for predicting the strength properties of SFRC predicted the test results quite accurately.

Conclusions

Based on the present study, following conclusions are drawn:

- The maximum increase in the compressive strength, modulus of elasticity, and Poisson's ration due to the addition of steel fibers was found to be quite small (less than 10%) in various grades of concrete (35, 65, and 85 MPa).
- The maximum increase in the tensile strength, namely, split tensile strength and modulus of rupture due to the addition of steel fibers, was found to be about 40% in various grades of concrete (35, 65, and 85 MPa) and is the primary justification for using fibers in concrete. The post-cracking response is significantly enhanced with fiber dosages across the different concrete grades.
- The maximum increase in the strain corresponding to the peak compressive strength was found to be about 30% in various grades of concrete (35, 65, and 85 MPa). Enhanced peak strain capacity is another significant benefit derived from the use of fibers.
- The proposed empirical models derived based on the regression analysis of 60 test data of the present study predicted the strength properties of the steel fiber-reinforced concrete quite accurately. Thus, the proposed strength prediction models can be used for the assessment of the strength properties of SFRC based on the grade of concrete and fiber-RI.
- The comparison of the contribution of individual terms indicated that the contribution of the fiber–matrix interaction term is significant in computing the increased benefits due to the addition of fibers in concrete matrix. This term has not been considered in earlier models reported in the literature and does not appear in the prediction models based on law of mixtures.

It is expected that the prediction models proposed in this study would be useful to compute the mechanical strength properties of SFRC, which are the input parameters for flexure and shear design or analysis methods of SFRC structures.

Notation

The following symbols are used in this paper:

E_c, E_{cF} = modulus of elasticity of plain concrete and fiber-reinforced concrete, respectively;

f'_{cu}, f'_{cuF} = cube compressive strength of plain concrete and fiber-reinforced concrete, respectively;

f'_{cy}, f'_{cyF} = cylinder compressive strength of plain concrete and fiber-reinforced concrete, respectively;

f_{fl}, f_{flF} = modulus of rupture of plain concrete and fiber-reinforced concrete, respectively;

f_{spc}, f_{spcF} = split tensile strength of plain concrete and fiber-reinforced concrete, respectively;

L_f = length of the fiber;

RI = reinforcing index of fiber $(V_f L_f / \phi_f)$;

V_f = volume fraction of the fiber;

$\varepsilon_{oc}, \varepsilon_{ocF}$ = strain corresponding to peak compressive stress of plain concrete and fiber-reinforced concrete, respectively;

ν_c, ν_{cF} = Poisson's ratio of plain concrete and fiber-reinforced concrete, respectively;

ϕ = diameter; and

ϕ_f = diameter of the fiber.

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