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Modeling of concrete containing steel fibers: toughness and mechanical properties

Ismail H. Cagatay*[1] and Riza Dincer[2]

[1]*University of Cukurova, Civil Engineering Department, Adana, Turkey*
[2]*University of Cukurova, Vocational School of Adana, Adana, Turkey*

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Abstract. In this study, effect of steel fibers on toughness and some mechanical properties of concrete were investigated. Hooked-end steel fibers were used in concrete samples with three volume fractions (v_f) of 0.5%, 0.75% and 1% and for two aspect ratios (*l/d*) of 45 and 65. Compressive and flexural tensile strength and modulus of elasticity of concrete were determined for cylindrical, cubic and prismatic samples at the age of 7 and 28 days. The stress-strain curves of standard cylindrical specimens were studied to determine the effect of steel fibers on toughness of steel-fiber-reinforced concrete (SFRC). In addition, the relationship between compressive strength and the flexural tensile strength of SFRC were reported. Finally, a simple model was proposed to generate the stress-strain curves for SFRC based on strains corresponding to the peak compressive strength and 60% of peak compressive stress. The proposed model was shown to provide results in good correlation with the experimental results.

Keywords: fiber reinforcement, toughness, mechanical properties, compressive strength, flexural strength.

1. Introduction

Plain concrete is a brittle material which has a relatively high compressive strength but low tensile strength. The addition of steel fibers, on the other hand, can improve the flexural strength of the concrete (ACI Committee 544 1982 and ACI Committee 1990). It has been shown by many researches (Barros and Figueiras 1999, Ezeldin and Balaguru 1992, Nataraja *et al*. 2000, Shah and Batson 1987, Bencardino *et al.* 2008) that the addition of steel fibers improves concrete properties such as tension, compression, shear, flexural strength, ductility, impact resistance and first cracking strength. Moreover, some authors concluded that it is possible to obtain comparable performances in terms of ultimate strength by using steel fibers as shear reinforcement in adequate dosage instead of stirrups (Cucchiara *et al.* 2004).

However, many researchers (Naaman and Reinhardt 1996, Armelin and Helene 1995) hold the view that steel fibers do not have a significant influence on the compressive behavior of concrete due to the small volume of fiber in concrete, Balaguru and Shah 1992 and Nataraja *et al.* 1999 reported that considerable increase in strain at peak stress and the toughness of the materials has been observed.

The main contribution of the steel fibers to concrete is that it improves toughness or energy absorption capacity. The toughness or energy absorption capacity can be determined from the area

* Corresponding author, Associated Professor, E-mail: hcagatay@cukurova.edu.tr

under the stress-strain curve of concrete samples in compression. This property is influenced by composition parameters of concrete (volume fractions v_f, aspect ratio, fiber geometry, fiber length etc.) and loading velocity. Experimental studies show that toughness or energy absorption capacity is influenced by volume fractions and aspect ratio. A combination of these two effects is used in the form of reinforcing index, RI (=weight fraction × aspect ratio) which is described in terms of weight fraction w_f (Vellore *et al.* 1991).

The most common method to measure toughness is the use of the load-deflection curve obtained using a simply-supported beam loaded at three points. ASTM C 1018 1989 or TS 10515 1992 is based on determining the amount of energy.

Toughness is also defined as a measure of the ability of the material to absorb energy during deformation and estimated as the area under the stress-strain curve of the material under compression (Nataraja *et al.* 1999). The stress-strain behavior of the material in compression is required to design and analyze structures using steel-fiber-reinforced concrete for compression. While the compressive strength is used for the strength calculation of the structural components, the stress-strain curve is needed to evaluate the toughness of the material for consideration of ductility.

Many researchers (Carreira and Chu 1985, Fanella and Naaman 1985) proposed analytical models to predict the complete stress-strain curve of SFRC taking into account the fiber shape, volume fraction and fiber geometry. Fanella and Naaman (1985) proposed a model for the fiber-reinforced mortar. In the model different sets of constants are used for each descending branches of the curve for the same ascending branch. Nataraja *et al.* (1999) proposed an analytical model to generate both the ascending and descending portions of the stress-strain curve of SFRC. In their study round crimped steel fibers were used.

In this paper, an extensive experimental work has been done for the toughness, compressive and flexural tensile strength, and modulus of elasticity of SFRCs for 7 and 28 days. Three volume fractions of 0.5%, 0.75% and 1.0% and two aspect ratios of 45 and 65 of hooked-end steel fibers were used. In addition, the effects of steel fibers on stress-strain curve of SFRCs for 7 and 28 days were reported and a simple model was proposed to generate the stress-strain curve for a SFRC based on strain corresponding to the peak compressive strength and 60% of peak compressive stress.

2. Experimental program

2.1 Materials and mix proportions

2.1.1 Cement

The cement used was ASTM Type I normal Portland cement (NPC 42.5 MPa) with a specific gravity of 3.15 g/cm^3. Compressive strength at the age of 2, 7 and 28 days of cement was 27.8, 38.9 and 49.5 MPa, respectively. Its Blaine specific surface area was 3610 cm^2/g and its chemical compositions are given in Table 1.

2.1.2 Aggregate

Natural river aggregate was used. The absorption value of the sand used was 1.3% and its relative density at saturated surface dry condition was 2.51. The gravel was 16 mm maximum nominal size with 0.85% absorption value and its relative density was 2.66.

Table 1 Chemical composition of cement, %

Oxide composition	%
SiO_2	19.97
Al_2O_3	5.49
Fe_2O_3	4.30
CaO	62.08
MgO	2.29
SO_3	2.83
K_2O	0.88
Na_2O	0.10
Mn_2O_3	0.12

2.1.3 Steel fiber

The hooked-end steel fibers with lengths 50 mm, 60 mm, respective aspect ratios of 45, 65, and a density of 7.8 g/cm^3 were used. The axial tensile strength and modulus of elasticity were 1250 MPa, 200000 MPa, respectively.

2.2 Mixing, casting and curing

Aggregate was sieved using standard sieves and separated into three groups consisting of 0-4, 4-8 and 8-16 mm. A combination of separated aggregate was obtained with a grading that complied with requirements of TS 706 (1980) (equivalent ASTM C33). The gradations are presented in Table 2.

Three different fiber volume percentages were added to each batch of concrete as 0.50%, 0.75%, 1.00% by volume of concrete (39 kg/m^3, 58.5 kg/m^3 and 78 kg/m^3) as shown in Table 3. Plain concrete samples without steel fibers (PLAINC) were also prepared to compare the results with those with steel fibers.

The cement and aggregates were mixed for 1 min in a 0.160 m^3 mixer with horizontal axis. The mixing was continued for another 1 min and the fibers were then added continuously to the mixer

Table 2 Aggregate gradations (taking 0.25-16 mm particles as 100%)

	Particle size (mm)						
	0/0.25	0.25/0.5	0.50/1	1/2	2/4	4/8	8/16
Content %	4	4	9	14	25	16	29

Table 3 Properties of steel fiber used in various mixes

Grade of concrete mix	Fiber content (kg/m^3)	Fiber length (mm)	Aspect ratio (l/d)
PLAINC	-	-	-
SFRC11	39	50	45
SFRC12	58.5	50	45
SFRC13	78	50	45
SFRC21	39	60	65
SFRC22	58.5	60	65
SFRC23	78	60	65

Table 4 Proportions for various mixes used

Mixture materials	PLAINC $v_f = 0$	SFRC11 SFRC21 $v_f = 0.5$	SFRC12 SFRC22 $v_f = 0.75$	SFRC13 SFRC23 $v_f = 1.0$
Cement (kg)	350	350	350	350
Steel fiber (kg)	0	39	58.5	78
Water (kg)	135	135	135	135
Super-plasticizer (kg)	4.2	4.2	4.2	4.2
Fine aggregate (0-4 mm) (kg)	726.2	721.2	718.7	716.2
Coarse aggregate (4-9.5 mm) (kg)	575.0	571.0	569.0	567.0
Coarse aggregate (9.5-16 mm) (kg)	575.0	571.0	569.0	567.0

for a period of 2 min. Finally, the water along with superplasticizer was added and the mixing was continued for an additional 2 min. Cylindrical samples with 150 mm diameter and 300 mm length, cubic samples with 150 mm length and prism samples with dimensions of $150 \times 150 \times 500$ mm were cast from fresh concrete mixtures and the vibrations were induced by a table vibrator. For each mix and age (7, 28 days) a total of six cubic and cylindrical specimens for compressive strength and three prismatic specimens for flexural strength were cast. All the test specimens were demoulded after one day and then cured under water until testing at the age of 7 and 28 days in accordance with TS 3068 (1978). The mix proportions are given in Table 3 and 4.

3. Testing

Cylinders and cubes were tested after 7 and 28 days, in accordance with TS 3114 (1980) (equivalent

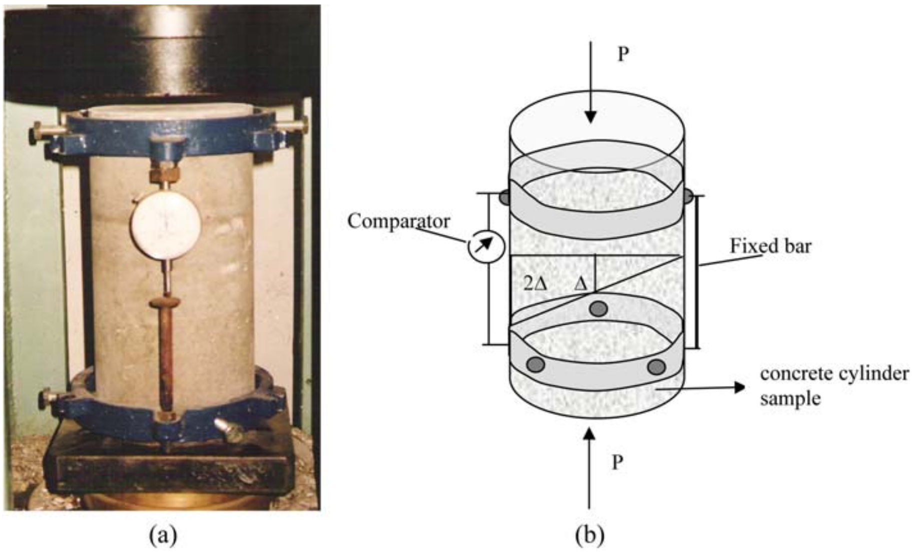

Fig. 1 Testing a concrete cylinder in compression: (a) concrete cylinder sample and (b) measurement of strains with a comparator

Fig. 2 Testing a concrete prism in flexure

ASTM C39). The tests were conducted in the 2000-kN compression testing machine. Before testing, all the cylinders were capped to ensure parallel loading faces according to TS 3068 (1978) (equivalent ASTM C617). The strains were measured with a comparator by hand operation. Deformations were taken approximately at every 0.00004 mm increment. The flexural tests were conducted the prisms at third points over a simply supported span of 450 mm in accordance with TS 3284 (1979) (equivalent ASTM C78). The test apparatus for compressive strength and flexural strength are shown in Figs. 1 and 2, respectively. The modulus of elasticity of the concrete samples were determined as the slope of the straight line that connects the origin to a given stress, 0.40 f'_c , for the stress-strain curves of the samples.

4. Results and discussions

The test results of compressive strength and flexural strength of cubic and cylindrical specimens and modulus of elasticity at the age of 7 and 28 days were presented in Table 5. The relative values were also given in the Table 5. Experimental and theoretical results of the stress-strain properties of the specimens for 7 and 28 days were also presented in Table 6 and 7. All the results were base on the average results of three samples.

4.1 Mechanical properties

4.1.1 Compressive strength

It can be seen from the results in Table 5 that, the compressive strength at 28 days of all the cylindrical and cubic samples with steel fiber content were found greater than those of control sample (PLAINC). Increase in compressive strength, is maximum for fibers having higher volume fraction and for higher aspect ratios. The increasing in average compressive strength of the

Table 5 Mechanical properties of steel-fiber reinforced concrete

Mixture code	v_f (%)	Compressive strength (MPa)								Flexural strength (MPa)				Modulus of elasticity (GPa)			
		7 days				28 days				7 days		28 days		7 days		28 days	
		Cube	(%)	Cylinder	(%)	Cube	(%)	Cylinder	(%)		(%)		(%)		(%)		(%)
PLAINC	-	50.9	100	30.2	100	59.9	100	41.2	100	4.1	100	5.1	100	32.8	100	30.5	100
SFRC11	0.5	56.5	111	28.2	93	65.9	110	43.1	105	4.5	110	4.7	92	39.2	120	30.8	101
SFRC12	0.75	60.9	120	34.9	116	66.1	110	48.2	117	5.6	137	7.4	145	36.9	113	32.3	106
SFRC13	1.0	50.6	99	39.7	131	62.7	105	45.9	111	6.1	149	7.6	149	33.0	101	34.2	112
SFRC21	0.5	50.0	98	35.4	117	61.5	103	46.7	113	4.9	120	6.0	118	27.4	84	35.7	117
SFRC22	0.75	51.3	101	38.6	128	61.4	103	46.3	112	7.4	180	7.0	137	27.4	84	36.9	121
SFRC23	1.0	55.7	109	43.9	145	68.8	115	52.5	127	7.2	176	8.9	175	31.2	95	32.3	106

cylindrical samples at 28 days was found about 11% and 18% for SFRC11-13 (i.e. SFRC11, SFRC12, and SFRC13) and SFRC21-23 samples, respectively. The highest compressive strength of cylindrical samples was obtained from the sample with 1% steel fiber content and higher aspect ratio (SFRC23), which is greater 27% than those of PLAINC.

The ratios of the compressive strength of the cylindrical samples to the cubic samples at 28 days were also found as 0.71 and 0.76 for the specimens of SFRC11-13 and SFRC21-23, respectively, while this ratio was 0.69 for PLAINC.

The test results of compressive strength of cubic and cylindrical specimens at the age of 7 days were presented in Table 5. The relative compressive strength values of SFRCs according to volume fractions v_f, and aspect ratio l/d, are also given in the Table. The results show that the effect of steel fibers on compressive strength of cylindrical samples is founded more significant at 7 days comparing to the results at 28 days. The increasing in average compressive strength of the cylindrical samples

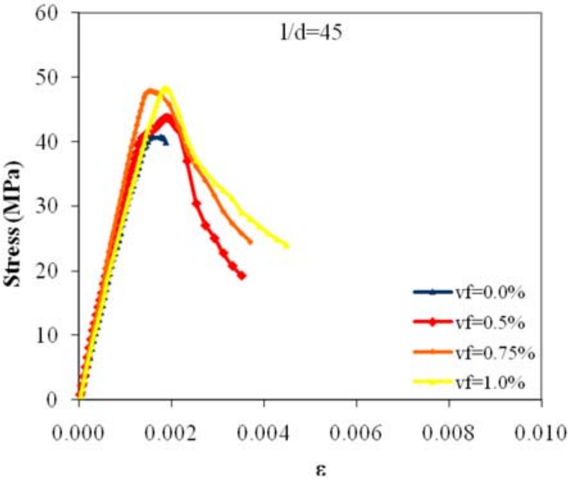

Fig. 3 Stress-strain curves for steel fiber reinforcing concrete (aspect ratio = 45, volume fractions are 0.50, 0.75 and 1.0)

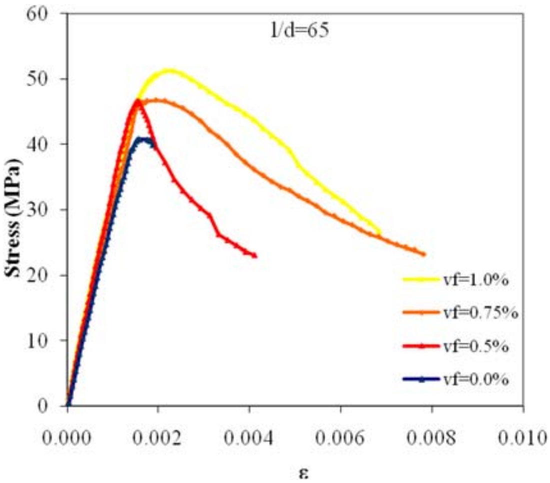

Fig. 4 Stress-strain curves for steel fiber reinforcing concrete (aspect ratio = 65, volume fractions are 0.50, 0.75 and 1.0)

was found about 13 and 30% for SFRC11-13, and SFRC21-23, respectively as seen in Table 5. The highest compressive strength value of cylindrical samples was obtained from the samples with 1% steel fiber content and higher aspect ratio (SFRC23) as 43.9 MPa, which is greater 45% than those of PLAINC.

The average ratios of the compressive strength at 7 days of the cylindrical samples to the cubic samples were found as 0.62 and 0.75 for the specimens of SFRC11-13 and SFRC21-23, respectively, while this ratio was 0.59 for plain concrete.

Figs. 3 and 4 show the stress-strain curves of cylindrical specimens for aspect ratio = 45, and 65, respectively. As seen in the figures, the addition of steel fibers increased the strain corresponding to the peak stress for both two aspect ratios 45 and 65. Increase in peak strain is maximum for fibers having higher volume fraction and for higher aspect ratios.

However, the ascending portion of the stress-strain curve is not affected significantly by the addition of steel-fibers, the descending portion of the curve is affected. The slope of the descending part of the curves decreases with the increase of the fiber content.

4.1.2 Flexural tensile strength

The flexural tensile strength values of SFRC samples at the ages of 28 days are given in Table 5. All of the flexural tensile strength values of prismatic samples of SFRC were found greater than those of control sample PLAINC, but only SFRC11. The increasing in average tensile strength at 28 days of the samples was found about 29% and 43% for SFRC11-13 and SFRC21-23, respectively. The highest tensile strength value obtained from the samples of SFRC23, which is greater 75% than the control sample.

The effect of steel fibers on tensile strength at 7 days is also more significant as the results observed in compressive strength. The increasing in average tensile strength at 7 days of the samples was found about 32% and 59% for SFRC11-13 and SFRC21-23, respectively.

The test results are also indicated that there is a strong linear relationship between the compressive

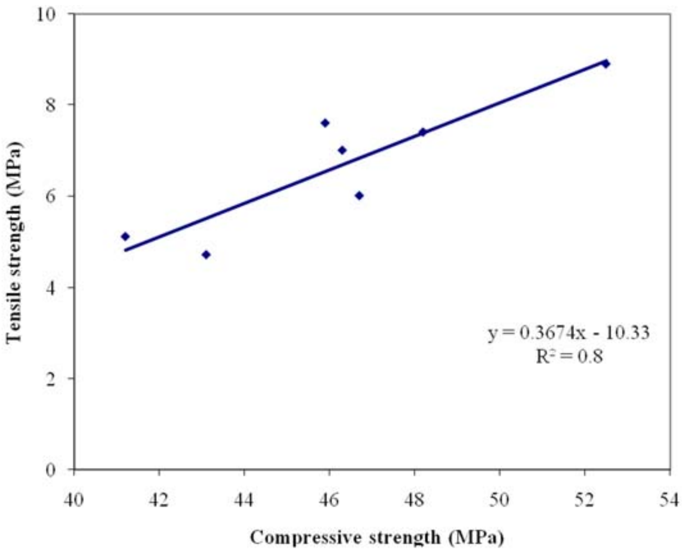

Fig. 5 Relationship between compressive strength and the flexural tensile strength

Table 6 Experimental (Exp.) and theoretical (Eq.) results of stress-strain curves (at 7 days)

Mix 28 days	RI (1)	f_{cof} (2) Exp.	f_{cof} (2) Eq.	ε_{cof} (3) Exp.	ε_{cof} (3) Eq.	ε_{cuf} (4) Exp.	ε_{cuf} (4) Eq.	TR (5) Exp.	TR (5) Eq.	A_{cf} (6) Exp.	A_{cf} (6) Eq.
PLAINC	0	30.2	30.2	0.0010	0.0010	0.0015	0.0015	-	-	0.0158	0.0192
SFRC11	0.73*	28.2	34.2	0.0010	0.0014	0.0035	0.0035	0.68	0.66	0.0727	0.0991
SFRC12	1.09	34.9	36.0	0.0013	0.0015	0.0051	0.0045	0.70	0.70	0.1255	0.1380
SFRC13	1.46	39.7	36.1	0.0016	0.0017	0.0055	0.0045	0.72	0.73	0.1545	0.1789
SFRC21	1.06	35.4	38.2	0.0017	0.0015	0.0042	0.0056	0.70	0.70	0.1053	0.1345
SFRC22	1.57	38.6	38.8	0.0020	0.0018	0.0060	0.0059	0.72	0.73	0.1713	0.1907
SFRC23	2.11	43.9	41.7	0.0024	0.0021	0.0075	0.0074	0.73	0.72	0.2554	0.2499

Note: (1) Reinforcing index (*w_f = 39/2400 × (l/d = 45)). (2) Peak compressive strength. (3) Strain corresponding to peak stress. (4) Strain corresponding to 60% of peak stress. (5) Toughness ratio. (6) Area under the stress-strain curve up to a strain corresponding to 60% of peak stress.

Table 7 Experimental (Exp.) and theoretical (Eq.) results of stress-strain curves (at 28 days)

Mix 28 days	RI (1)	f_{cof} (2) Exp.	f_{cof} (2) Eq.	ε_{cof} (3) Exp.	ε_{cof} (3) Eq.	ε_{cuf} (4) Exp.	ε_{cuf} (4) Eq.	TR (5) Exp.	TR (5) Eq.	A_{cf} (6) Exp.	A_{cf} (6) Eq.
PLAINC	0	41.2	41.2	0.0015	0.0015	0.0015	0.0015	-	-	0.0403	0.0309
SFRC11	0.73*	43.1	44.5	0.0015	0.0016	0.0023	0.0027	0.63	0.62	0.0641	0.0805
SFRC12	1.09	48.2	46.1	0.0017	0.0016	0.0031	0.0033	0.66	0.66	0.0955	0.1046
SFRC13	1.46	45.9	47.8	0.0016	0.0016	0.0035	0.0040	0.68	0.68	0.1078	0.1301
SFRC21	1.06	46.7	46.0	0.0016	0.0016	0.0030	0.0033	0.65	0.65	0.0929	0.1025
SFRC22	1.57	46.3	48.3	0.0015	0.0017	0.0049	0.0042	0.68	0.69	0.1673	0.1374
SFRC23	2.11	52.5	50.7	0.0019	0.0017	0.0052	0.0051	0.70	0.69	0.1940	0.1741

Note: (1) Reinforcing index (*w_f = 39/2400 × (l/d = 45)). (2) Peak compressive strength. (3) Strain corresponding to peak stress. (4) Strain corresponding to 60% of peak stress. (5) Toughness ratio. (6) Area under the stress-strain curve up to a strain corresponding to 60% of peak stress.

strength and tensile strength of SFRC at 28 days as seen in Fig. 5. The compressive strength and flexural strength results were obtained from the cylindrical and prismatic samples, respectively.

A linear fitting regression analysis was performed to establish a possible relationship between compressive and flexural strengths obtained from the experimental results. These equations calculated the effect of fibers on the compressive and flexural behavior of the fiber-reinforced concrete which depends on the reinforcing index. Results obtained from these equations and experimental results are presented to compare in Table 6 and 7. Proposed equations for flexural strength and compressive strength between 40-50 MPa are given below.

Compressive strength for cylindrical specimens:

$$f_{cof} = f_{co} + 5.4599\ (\mathrm{RI})\ (7\ \text{days})\ (r = 0.86)$$
$$f_{cof} = f_{co} + 4.5007\ (\mathrm{RI})\ (28\ \text{days})\ (r = 0.88) \quad (1)$$

where f_{co} and f_{cof} are the compressive strength (MPa) of plain and fiber-reinforced concrete, respectively, and RI is the reinforcing index ($w_f \times l/d$).

Flexural strength:

$$f'_{sw} = f_{sw} + 1.4641\,(\mathrm{RI})\,(7\ \text{days})\,(r = 0.89)$$
$$f'_{sw} = f_{sw} + 1.4979\,(\mathrm{RI})\,(28\ \text{days})\,(r = 0.84) \tag{2}$$

where f_{sw} and f'_{sw} are the flexural strength (MPa) of plain and fiber-reinforced concrete, respectively.

4.1.3 Modulus of elasticity

The experimental findings indicate that low value and smaller aspect ratio of fiber content has a little effect on modulus of elasticity but improve remarkable for higher aspect ratio and fiber content. The increasing in average value of modulus of elasticity of the cylindrical samples at 28th days was found about 6.3% and 14.6% for SFRC11-13 and SFRC21-23, respectively.

4.2 Toughness

A comparator was used to determine the strain and deformation characteristics of concrete specimens over the mid-region of the cylinder. Deformations were recorded at approximately every 25 kN-load increment and subsequently the corresponding strain and stress values were calculated.

In the present work, a model of stress-strain curve was proposed as seen in Fig. 6. Toughness was measured as the total area under the stress-strain curve up to a strain corresponding to 60% of peak stress. This value of strain was taken due to the reading recorded at 50% decrease of peak stress on the compression testing machine with limited strain capacity. On the other hand, the strains corresponding to 60% of peak stress are found greater than the strains corresponding to the ultimate strength which is accepted as 0.003 in many building code.

Modeled stress-strain curves for SFRC with aspect ratios of 45 and 65 for 28 days were given in Figs. 7 and 8, respectively. The addition of steel fibers increased the strain corresponding to the peak stress both at 7 and 28 days. Increase in peak strain is maximum for fibers having higher

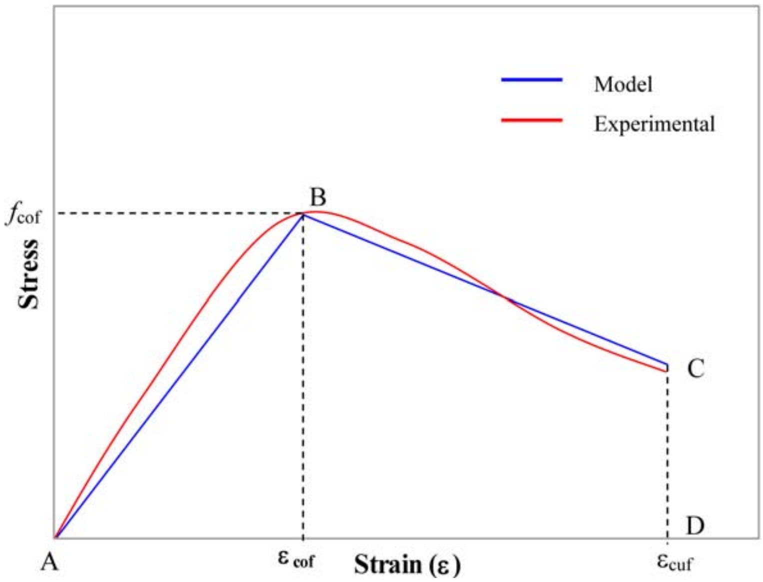

Fig. 6 Experimental and proposed model for stress-strain curves of steel-fiber reinforced concrete

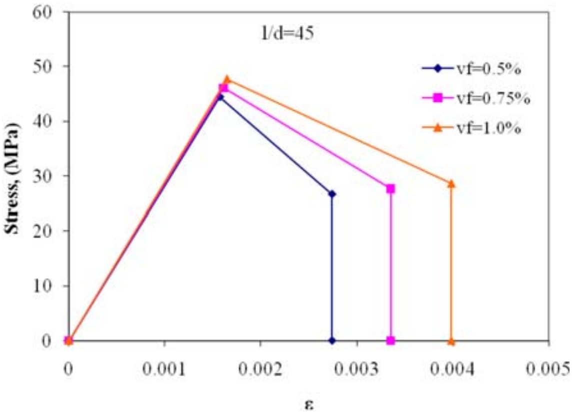

Fig. 7 Modeled stress-strain curves for steel fiber reinforcing concrete (aspect ratio = 45, volume fractions are 0.50, 0.75 and 1.0)

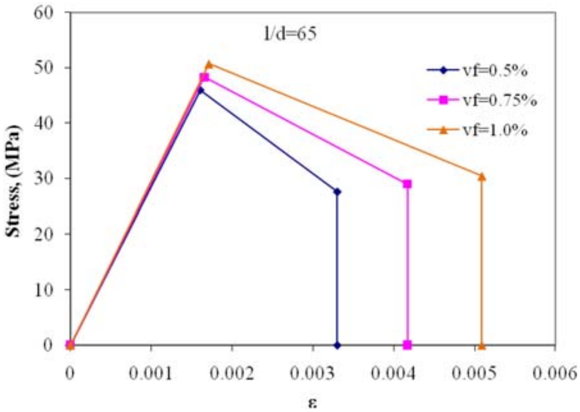

Fig. 8 Modeled stress-strain curves for steel fiber reinforcing concrete (aspect ratio = 65, volume fractions are 0.50, 0.75 and 1.0)

volume fraction and for higher aspect ratios.

However, the ascending portion of the stress-strain curve is not affected significantly by the addition of steel-fibers, the descending portion of the curve is affected. The slope of the descending part of the curves decreases with the increase of the fiber content. The strain corresponding to the 60% of peak stress for SFRC23 is greater about 2.4 times than those of PLAINC at the age of 28 days. This effect is also seen for the same samples at the age of 7 days.

Equations which were calculated based on a simple model of the stress-strain curve are given below and effects of the reinforcing index on strain and toughness are shown in Figs. 9-12.

Strain corresponding to peak stress:

$$\varepsilon_{cof} = \varepsilon_{co} + 0.0005\ (\mathrm{RI})\ (7\ \text{days})\ (r = 0.87)$$
$$\varepsilon_{cof} = \varepsilon_{co} + 0.0001\ (\mathrm{RI})\ (28\ \text{days})\ (r = 0.65) \quad (3)$$

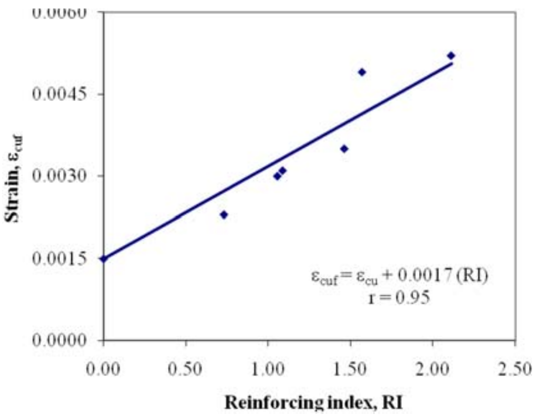

Fig. 9 Effect of reinforcing index on strain corresponding to 60% of peak stress (at 28 days)

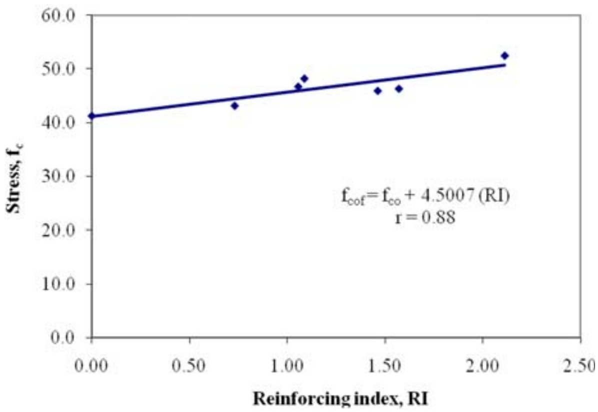

Fig. 10 Effect of reinforcing index on peak stress (at 28 days)

where ε_{co} and ε_{cof} are the strains corresponding to the peak stress for plain and SFRC, respectively, and RI is the reinforcing index.

Strain corresponding to 60% of peak stress:

$$\varepsilon_{cuf} = \varepsilon_{cu} + 0.0028\ (\text{RI})\ (7\ \text{days})\ (r = 0.92)$$
$$\varepsilon_{cuf} = \varepsilon_{cu} + 0.0017\ (\text{RI})\ (28\ \text{days})\ (r = 0.95) \quad (4)$$

where ε_{cu} and ε_{cuf} are the strains corresponding to 60% of peak stress for plain and SFRC, respectively.

Toughness ratio:

The toughness ratio is determined as, TR = Area ABCD/($f_{cof} \times \varepsilon_{cuf}$), where f_{cof} and ε_{cuf} are the peak stress and the strain corresponding to the stress of 60% of peak stress, respectively, as seen in Fig. 6. A second order fitting line was performed to establish a possible relationship between the reinforcing index and the toughness ratio. The toughness ratio for SFRC samples at the age of 7 and 28 days were given in below.

$$TR_{cf} = 0.5 + 0.274\ (\text{RI}) - 0.0803\ (\text{RI})^2\ (7\ \text{days})\ (r = 0.99)$$
$$TR_{cf} = 0.5 + 0.199\ (\text{RI}) - 0.0508\ (\text{RI})^2\ (28\ \text{days})\ (r = 0.99) \quad (5)$$

where TR_{cf} is the toughness ratio for fiber reinforced concrete. The effect of the reinforcing index on toughness ratio at 28 days is shown in Fig. 11. The toughness ratio increases as the reinforcing index is increased. The more the reinforcing index is, the more the toughness ratio was. However, this relationship is not linear.

Toughness was also measured as the total area under the stress-strain curve up to strain corresponding to 60% of peak stress. The area under the stress-strain curve up to strain corresponding to 60% of peak stress

$$A_{cf} = A_c + 0.1016\ (\text{RI})\ (7\ \text{days})\ (r = 0.98)$$
$$A_{cf} = A_c + 0.0678\ (\text{RI})\ (28\ \text{days})\ (r = 0.93) \quad (6)$$

where A_c is the area under the stress-strain curve up to strain corresponding to 60% of peak stress of the PLAINC.

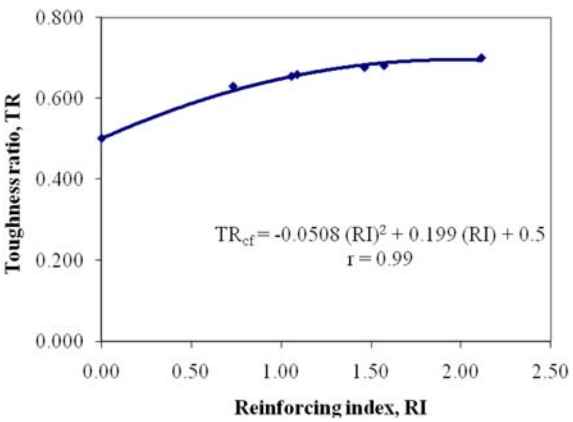

Fig. 11 Effect of reinforcing index on toughness ratio (at 28 days)

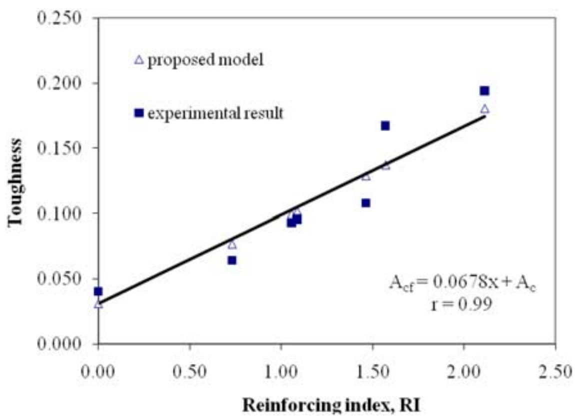

Fig. 12 Effect of reinforcing index on toughness (at 28 days)

Effect of reinforcing index on toughness under stress-strain curve up to strain corresponding to 60% of peak stress at the age of 28 days is given in Fig. 12. The test results are indicated that there is a strong linear relationship between toughness and reinforcing index at 28 days as shown in Fig. 12.

5. Conclusions

The concluding remarks can be made from this study.

1. There is a strong linear relationship between toughness and reinforcing index at 28 days. The more the reinforcing index is, the more the toughness ratio was.
2. The increasing in compressive strength depends on the volume fractions, aspect ratios as well as the age of the concrete. For the same volume contents, the specimens with higher aspect ratio and fiber content showed better mechanical properties under all mechanical strength. Increase in compressive strength, is maximum for fibers having higher volume fraction and for higher aspect ratios.
3. The effect of steel fibers on compressive strength of cylindrical samples is founded more significant at 7 days comparing to the results at 28 days. Compared to plain concrete (PLAINC), the concrete cylinder sample of %1 fiber content and higher aspect ratio (SFRC23) caused a 27% and 45% increase in the compressive strength at 28 days and 7 days, respectively.
4. Steel fibers significantly improve the tensile strength of SFRC. The increasing in average tensile strength at 28 days of the samples was found about 29% and 43% for SFRC11-13 and SFRC21-23, respectively. The highest tensile strength value obtained from the samples of SFRC23 is greater 75% than the control.
5. Although the strain corresponding to the peak stress only slightly improves with the addition of fibers, the strain corresponding to 60% of peak stress increases considerably.
6. There is a strong linear relationship between the compressive strength and tensile strength of SFRC at 28 days.
7. A simple model was proposed to generate the stress-strain curve for steel-fiber-reinforced concrete containing hooked-end fibers based on the strain corresponding to the peak compressive strength and 60% of peak compressive stress. The proposed equations provide a good correlation between the predicted and the experimental results.

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