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Stress–strain curves for steel-fiber reinforced concrete under compression

M.C. Nataraja [*,1], N. Dhang, A.P. Gupta

Department of Civil Engineering, Indian Institute of Technology, Kharagpur, 721 302, India

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Abstract

Steel-fiber reinforced concrete is increasingly being used day by day as a structural material. The complete stress–strain curve of the material in compression is needed for the analysis and design of structures. In this experimental investigation, an attempt has been made to generate the complete stress–strain curve experimentally for steel-fiber reinforced concrete for compressive strength ranging from 30 to 50 MPa. Round crimped fibers with three volume fractions of 0.5%, 0.75% and 1.0% (39, 59, and 78 kg/m^3) and for two aspect ratios of 55 and 82 are considered. The effect of fiber addition to concrete on some of the major parameters namely peak stress, strain at peak stress, the toughness of concrete and the nature of the stress–strain curve is studied. A simple analytical model is proposed to generate both the ascending and descending portions of the stress–strain curve. There exists a good correlation between the experimental results and those calculated based on the analytical model. Equations are also proposed to quantify the effect of fiber on compressive strength, strain at peak stress and the toughness of concrete in terms of fiber reinforcing parameter.

Keywords: Stress–strain curves; Steel–fiber reinforced concrete; Crimped fiber; Compression; Toughness; Fiber content; Fiber length; Aspect ratio; Fiber reinforcing index; Normalisation; Composite; Analytical model

1. Introduction

Use of steel-fiber reinforced concrete has steadily increased during the last 25 years. Considerable developments have taken place in the field of steel-fiber reinforced concrete as reported by Bentur and Mindess [1]. The current field of application of steel-fiber reinforced concrete include highway and airfield pavements, hydraulic structures, tunnel linings etc.(e.g. Refs. [2–4]). As noted by ACI committee 544, the composite has potential for many more applications, specially, in the area of structural elements. A number of researchers are evaluating the possibility of using steel-fiber reinforced concrete for structural applications. Strength and ductility are among the important factors to be considered in the design of seismic resistant reinforced concrete structures. Under seismic condition, the structure may be subjected to large deformations.

The addition of steel-fibers significantly improves many of the engineering properties of mortar and concrete, notably impact strength and toughness. Flexural strength, fatigue strength, tensile strength and the ability to resist cracking and spalling are also enhanced. To design and analyze structures using steel-fiber reinforced concrete for compression, the stress–strain behavior of the material in compression is needed. 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.

Considerable work has been done on the mechanical properties of fiber reinforced concrete. The effect of addition of steel-fibers on compressive strength ranges from negligible to marginal and sometimes up to 25% as reported by Balaguru and Shah [5]. Considerable increase in strain at peak stress and the toughness of the material has been observed. Toughness is a measure of the ability of the material to absorb energy during deformation estimated using the area under the stress–

[*] Corresponding author.
E-mail address: nata@civil.iitkgp.ernet.in (M.C. Nataraja)
[1] Faculty in Civil Engineering, Sri Jayachamarajendra College of Engineering, Mysore, 570006, India. Presently working as a research scholar at IIT, Kharagpur-721 302.

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strain curves (e.g. Ref. [5]). A number of empirical expression for the stress–strain diagram of plain concrete have been proposed by Wee et al. [6], Carreira and Chu [7], Wang et al. [8], Popovics [9], Desayi and Krishnan [10], and Hognestad et al. [11]. However, they cannot represent the behavior of steel-fiber reinforced concrete. The main drawback of these equations is that the effect of fibers has not been accounted for in the parameter given as constant in the proposed equations.

Fanella and Naaman [12] proposed an analytical model to predict the complete stress–strain curve of fiber reinforced mortar taking into account the fiber shape, volume fraction and fiber geometry. To model various descending branches of the curve for the same ascending branch, four different sets of constants are used for each branch. These constants were to be determined using the characteristics of the curve such as modulus of elasticity and empirical relationships obtained using the experimental curves. To evaluate these constants the boundary conditions as described in their paper are needed. In particular, the constants are related to the peak-stress (compressive strength) and strain, to the stress and strain at 45% of the peak stress (elastic modulus), to the stress and strain at the inflection point and to the stress and strain of an arbitrary point taken at the tail end of the descending branch. In their investigation, that point was taken at a strain of 0.0154.

Ezeldin and Balaguru [13] have proposed an analytical expression for generating the stress–strain curve of SFRC based on the expression proposed by Carreira and Chu [7] for uniaxial compression of plain concrete. This expression involves a material parameter β, which is to be evaluated from the physical property of the stress–strain curve. The equation proposed to determine the parameter β is for hooked steel-fibers. Here, β is a dimensionless parameter, which depends on the shape of the stress–strain diagram. The equation proposed by Desayi and Krishnan [10] is a particular case of the equation proposed by Carreira and Chu [7] in which $\beta = 2$. Another particular case was proposed by Tulin and Gerstle [14] for $\beta = 3$. Similar equations were used by Popovics [9] for the ascending branch.

In the present study, an extensive experimental work has been carried out to study the stress–strain behavior of steel-fiber reinforced concrete with compressive strength ranging from 30 to 50 MPa. Crimped steel-fibers were used in this study. Three fiber volume fractions and two aspect ratios were studied. The influence of fiber addition on peak stress, strain at peak stress, the toughness of concrete and the nature of the stress–strain curve were investigated. Analytical expression similar to Ezeldin and Balaguru [13] was proposed, which generates the complete stress–strain curves for concrete reinforced with crimped steel-fibers.

2. Experimental programme

The experimental programme was designed to evaluate the toughness and to study the stress–strain behavior under compression of steel-fiber reinforced concrete using crimped steel-fibers.

2.1. Materials and mix proportions

Following materials were used in the present investigation: 53 grade ordinary portland cement conforming to IS:12269-1987 [15] with a 28-days compressive strength of 57 MPa, natural river sand, crushed stone aggregate of maximum size 20 mm, tap water for mixing and curing and a super-plasticizing admixture. The sand had fineness modulus of 2.3, bulk specific gravity (SSD) of 2.61. The steel-fibers used in this investigation were crimped along the length (undulated) having a tensile strength of 550 MPa. Two types of fibers with average lengths of 27.5 and 41 mm were investigated. Their equivalent aspect ratios were 55 and 82.

14 series of concrete mixes were used in this investigation. Two mix proportions for grade M20 and M30 were designed based on the provisions of IS:10262-1982 [16], keeping in mind the guidelines mentioned in Ref. [3]. The mixes M1–M7, for M20 grade of concrete consist of 397 kg of cement, 562 kg of fine aggregate and 1152 kg of coarse aggregate per cubic meter of concrete. While, for the mixes M8–M14, designed for M30 grade, the corresponding values are 517, 493 and 1122 kg, respectively. Here, M20 and M30 concretes are designed for a targeted compressive strength of 28 and 40 MPa at 28 days, respectively. However, the actual compressive strength of the tested cylinders is slightly higher. M20 concrete has resulted in compressive strength up to 30 MPa, while M30 concrete resulted in compressive strength up to 50 MPa depending on the quantity of the fiber. Other details on mix proportions are presented in Table 1.

2.2. Mixing, casting and curing

The dry cement and aggregates were mixed for 1 min in a 0.06 m^3 laboratory mixer. The mixing continued for further 1 min while about 80% of water were added. The mixing was continued for another 1 min and the fibers were then fed continuously to the mixer for a period of 2–3 min. Finally, the remaining water along with super plasticizer was added and the mixing was continued for an additional 2 min.

For each mix, total of 5 cylinders, 150×300 mm were cast. After 24 h, the specimens were demoulded

Table 1
Details of mixes considered

Grade of concrete mix	Mix designation	Water/cement ratio	Fiber content (kg/m^3)	Fiber length (mm)	Aspect ratio (l/d)	Super-plasticizer[a] (%)
M20	M1	0.49	–	–	–	–
	M2	0.49	39	27.5	55	–
	M3	0.49	58	27.5	55	–
	M4	0.49	78	27.5	55	–
	M5	0.49	39	41	82	–
	M6	0.49	58	41	82	–
	M7	0.49	78	41	82	–
M30	M8	0.38	–	–	–	0.75
	M9	0.38	39	27.5	55	0.75
	M10	0.38	58	27.5	55	0.75
	M11	0.38	78	27.5	55	0.75
	M12	0.38	39	41	82	0.75
	M13	0.38	58	41	82	0.75
	M14	0.38	78	41	82	0.75

[a] Percentage by weight of cement, d = diameter of the fiber, 0.5 mm.

and cured under water until testing as per IS:516-1959 [17].

2.3. Testing

All cylinders were tested according to ASTM C-39 standards after 28 days. The test was conducted in a 3000 kN compression testing machine with a rate of loading controller. Before testing, the cylinder was capped with a hard plaster on the cast face to ensure parallel loading faces of the test specimens and constant height for all cylinders. A compressometer equipped with three dial gauges available in the laboratory was used to record the deformation over the middle half of the cylinder. In the present study, many trial tests were conducted initially to have control on operation of the machine. The load was applied at a very slow rate and an initial load of about 50 kN was applied and released. The testing head was lowered slowly to bring it in contact with the specimen. At this stage, the dial gauges were set to zero. Load was increased slowly by adjusting the lever and controlling the oil flow simultaneously. Deformations were taken approximately at every 50 kN load increment. The testing was performed with the help of technical assistants to control the whole testing process. There was no difficulty in recording the load and deformation readings manually. Load indicating needle of the machine gauge was moving slowly during the loading stage (ascending). However, the movement was rather faster in the unloading (descending) stage. Efforts were made to take as many readings as possible, to get a considerable length of post-peak portion of the stress–strain curve. In the descending portion, readings were taken at random intervals. Strains and corresponding stresses were calculated and the average readings are reported. Variations in readings among the gauges were not significant.

3. Experimental results and analysis

The shape of the uniaxial stress–strain curve is strongly affected by the testing conditions such as stiffness of the testing machine, size and shape of the specimen, loading rate etc. and concrete characteristics such as water/cement ratio, aggregate type, type of fiber, etc. However, careful attention was given at all stages to avoid variations in the casting, testing and in instrumentation.

4. Observations and discussions

All results are presented in Table 2. Discussions are based on the average results of three or more samples. A deviation of about 8–10% was observed in compressive strength results of few samples, specially, in the higher volume fraction of steel-fiber.

The addition of fibers increased the strain corresponding to the peak stress. The strain capacity and the elastic deformation capability of the concrete matrix in the prefailure zone are increased considerably with the inclusion of steel-fibers. Increase in peak strain, is maximum for fibers having higher volume fraction and for higher aspect ratios. Both ascending and descending portion of the stress–strain curves are affected by the addition of steel-fibers. However, the significant effect is noticed in the descending portion of the stress–strain curve. The slope of the descending part of the stress–strain curve, decreases with increase in fiber content at a constant aspect ratio and with increase in aspect ratio for constant volume fraction (fiber content).

The area under the stress–strain curve is a measure of toughness of the material. Researchers have used different definitions for the toughness using the area under

Table 2
Experimental and calculating results

Mix designation	From experiments				From proposed equations			
	f'_{cf} (1)	ε_{of} (2)	TR (3)	RI (4)	f'_{cf} (5)	ε_{of} (6)	TR1 (7)	TR2 (8)
M1	29.42	0.0025	–	0	29.42	0.0025	0.6	–
M2	36.03	0.003	0.73	0.9	31.36	0.003	0.69	0.48
M3	33.48	0.0033	0.76	1.33	32.29	0.0033	0.73	0.6
M4	38.48	0.0035	0.72	1.79	33.29	0.0036	0.78	0.68
M5	32.83	0.0032	0.77	1.34	32.31	0.0033	0.73	0.6
M6	36.31	0.0039	0.78	1.98	33.7	0.0037	0.79	0.71
M7	34.7	0.0044	0.79	2.67	35.19	0.0041	0.86	0.78
M8	43.01	0.0027	–	0	43.01	0.0027	0.55	–
M9	45.84	0.0031	0.66	0.9	44.95	0.0032	0.64	0.54
M10	41.59	0.0033	0.69	1.33	45.88	0.0035	0.68	0.64
M11	46.97	0.0034	0.75	1.79	46.88	0.0038	0.73	0.7
M12	45.65	0.0035	0.71	1.34	45.9	0.0035	0.68	0.64
M13	46.12	0.0035	0.72	1.98	47.29	0.0039	0.74	0.72
M14	49.23	0.0039	0.77	2.67	48.78	0.0043	0.81	0.77

Note: (1) Peak compressive stress in MPa. (2) Strain corresponding to peak stress. (3) Toughness ratio based on experimental results, TR = area(OABC)/(f'_{cf} × 0.015). (4) Reinforcing index, RI = $w_f \times l/d$, where, w_f is the weight fraction of fibers. (5) Peak stress in MPa from the proposed equation (1). (6) Strain corresponding to peak stress from proposed equation (2). (7) Toughness ratio from the proposed equation (3). (8) Toughness ratio based on analytical curves for the experimental results using equation (4). Items in columns (5)–(8) will be discussed later.

the curve. Fanella and Naaman [12] have defined the toughness of FRC as the ratio of toughness of the fiber reinforced matrix to that of the unreinforced control matrix. The toughness of the specimen was computed up to a strain of 0.0154, though the specimens still had significant resistance left. Here, this ratio is greater than unity. It can also be defined as the ratio of area of the descending part, to the area of the ascending part of the stress–strain curve. Ezeldin and Balaguru [13], have proposed a rigid plastic approach to define the toughness ratio. It is observed in the present work that the area under the stress–strain curve increases with the increase in fiber content. As this area increases with respect to both volume fraction and aspect ratio (l/d), a common parameter, which combines these two effects, is used in the form of reinforcing index. However, the reinforcing index RI ($= w_f \times l/d$), is defined in terms of weight fraction w_f. Weight fraction is approximately equal to 3.2 times the volume fraction. In this paper, the toughness is measured as the total area under the stress–strain curve up to a strain of 0.015, which is five times the ultimate concrete strain of 0.003 adopted in the ACI building code. Fenella and Naaman [12], Ezeldin and Balaguru [13] have used this strain, as it is sufficient to represent the trend of the post-peak behavior. This toughness is compared to the toughness of a rigid plastic material in the form of a toughness ratio (TR) as indicated in Fig. 1.

By this approach, the toughness of the material can be easily evaluated and the results are presented in the Table 2. The toughness ratios (TR), presented in column (3) are calculated from the experimental stress–strain curves. The variation in the toughness ratio is also presented in Figs. 2 and 3. In some cases specially, in the case of higher volume fraction and aspect ratio, the toughness ratio has decreased marginally due to non-uniform distribution of the fiber during mixing. The variation of strain corresponding to peak stress with respect to volume fraction and aspect ratio is presented in Fig. 4. Normalized stress–strain curves between f_c/f'_{cf} and $\varepsilon_c/\varepsilon_{of}$ for fiber reinforced concrete are shown in Figs. 5–8. The increase of reinforcing index (RI) would yield a larger area under the stress–strain curve making a flatter descending part and a higher toughness ratio as shown in Table 2.

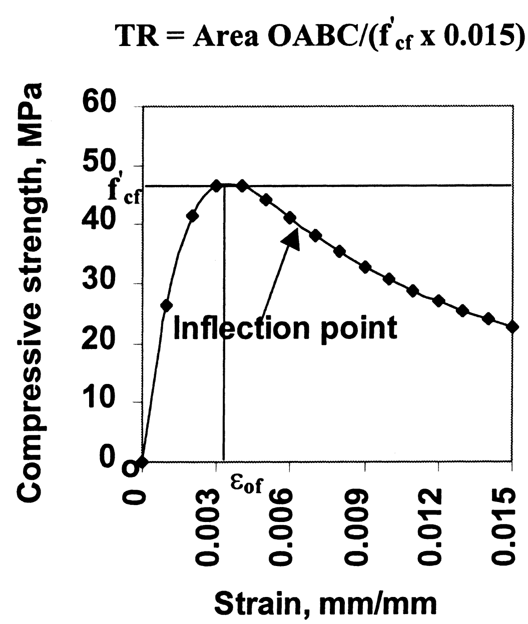

Fig. 1. Toughness ratio definition.

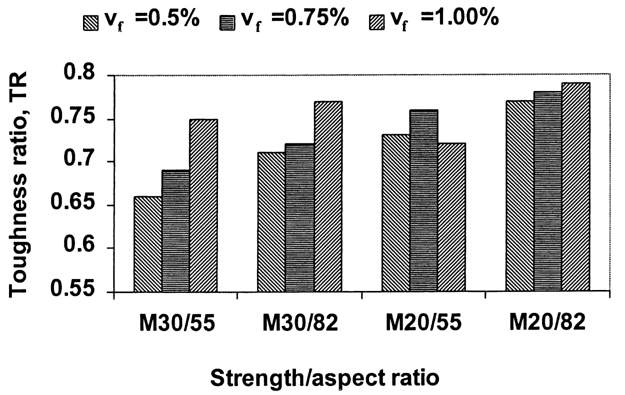

Fig. 2. Variation of toughness ratio with strength and aspect ratio for different fiber contents ($v_f = 1\%$, 78 kg/m^3).

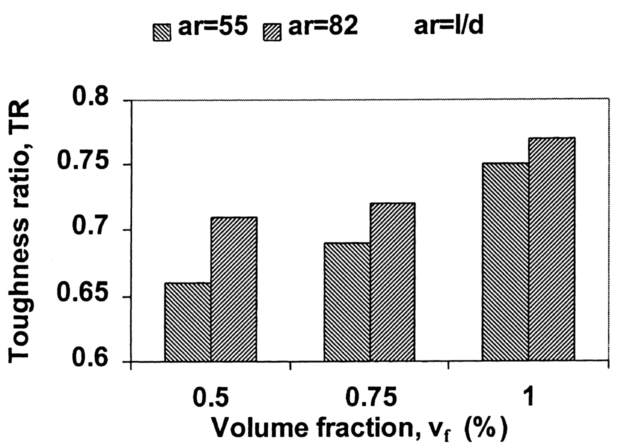

Fig. 3. Variation of toughness ratio with volume fraction for different aspect ratio for M30 concrete ($v_f = 1\%$, 78 kg/m^3).

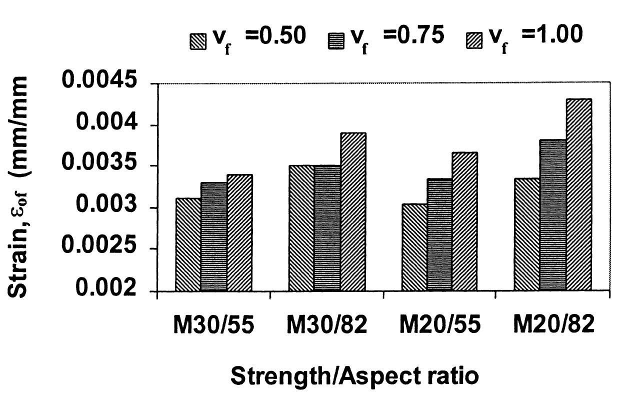

Fig. 4. Variation of strain at peak stress with respect to strength and aspect ratio for different fiber contents ($v_f = 1\%$, 78 kg/m^3).

A square fitting line analysis was performed, to establish a possible relationship between the steel–fiber reinforcing index and the parameters of the stress–strain

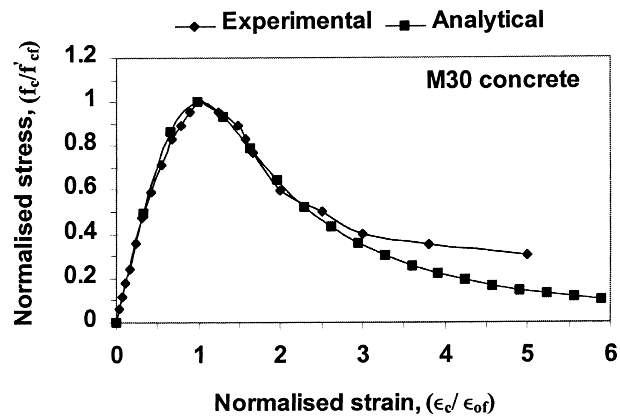

Fig. 5. Normalised stress–strain curves for steel-fiber reinforced concrete (aspect ratio = 55, volume fraction = 0.50%).

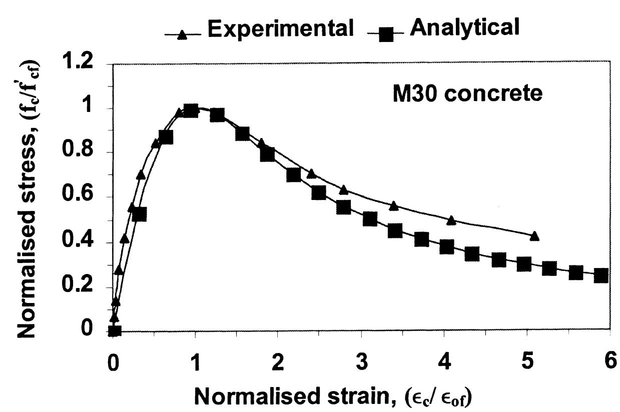

Fig. 6. Normalised stress–strain curves for steel-fiber reinforced concrete (aspect ratio = 55, volume fraction = 0.75%).

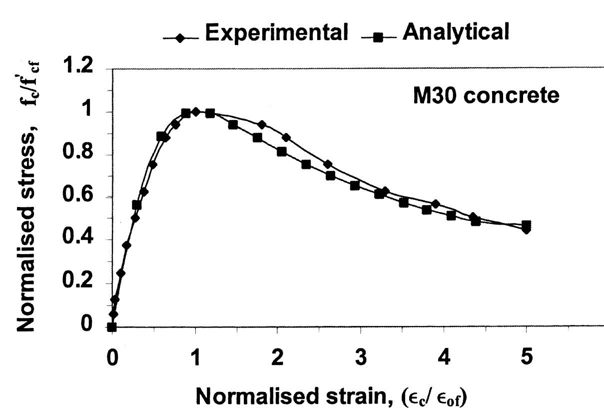

Fig. 7. Normalised stress–strain curves for steel-fiber reinforced concrete (aspect ratio = 55, volume fraction = 1.0%).

curve, i.e. the peak compressive strength, the corresponding peak strain and the toughness of the concrete. These equations are obtained using the regression

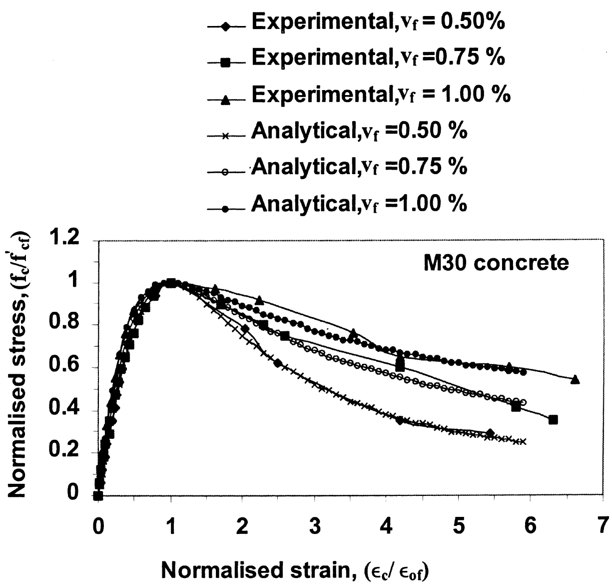

Fig. 8. Analytical and experimental normalised stress–strain curves for steel-fiber reinforced concrete (aspect ratio = 82).

analysis performed using the experimental results. All these equations very well quantify the effect of fibers on the compression behavior of the fiber reinforced concrete. Results of these equations are presented in Table 2 (columns 5–7) which are based on Eqs. (1)–(3). Additionally the stress–strain curves based on Eq. (4) are worked upon to compute toughness ratio (TR2) which is presented in column 8 of Table 2. In using Eq. (4), the value of β is obtained from Eqs. (5a)–(5c). Different proposed equations, for concrete strength up to 50 MPa are given below.

Compressive strength:

$$f'_{cf} = f_c + 2.1604\,(\mathrm{RI}), \quad (r = 0.76), \quad \text{for strength up to 50 MPa,} \tag{1}$$

where f_c and f'_{cf} are the compressive strength of plain and fiber reinforced concrete, respectively in MPa.

Strain corresponding to peak stress:

$$\varepsilon_{of} = \varepsilon_o + 0.0006\,\mathrm{RI}, \quad (r = 0.94), \quad \text{for strength up to 50 MPa,} \tag{2}$$

where ε_o and ε_{of} are the strain corresponding to the peak stress for plain and fiber reinforced concrete, respectively.

Toughness ratio:

$$\mathrm{TR_{cf}} = \mathrm{TR_c} + 0.0978\,\mathrm{RI}, \quad (r = 0.85), \quad \text{for strength up to 50 MPa,} \tag{3}$$

where $\mathrm{TR_c}$ and $\mathrm{TR_{cf}}$ are the toughness of plain and fiber reinforced concrete, respectively.

5. Analytical expression to predict the complete stress–strain curve for fiber reinforced concrete

All empirical equations available in the literature have been reviewed and the expression proposed by Carreira and Chu [7] for uniaxial compression of plain concrete was used as a basis to obtain an equation applicable to normal strength fiber reinforced concrete. Ezeldin and Balaguru [13] have also used the same expression. The expression is of the form:

$$\frac{f_c}{f'_{cf}} = \frac{\beta(\varepsilon_c/\varepsilon_{of})}{\beta - 1 + (\varepsilon_c/\varepsilon_{of})^{\beta}}. \tag{4}$$

f'_{cf} is the compressive strength of fiber concrete and ε_{of} is the corresponding peak strain; f_c, ε_c are the stress and strain values on the curve, respectively and β is the material parameter that depends on the shape of the stress–strain diagram. To use Eq. (4) to generate the stress–strain curve for a given value of compressive strength of fiber concrete, f'_{cf}, only the value of ε_{of} and β are needed.

Usually in practice, when using fibers, the fiber content, length and diameter are known, which can be combined to define the reinforcing index as mentioned earlier. In addition, it has been noticed in the present experimental investigation and by other researchers that fibers have more effective contribution on the compressive stress–strain curve in the descending branch. Hence, using the experimental results, a best fitting statistical analysis was performed to obtain a relationship between the parameter β and the reinforcing index, RI, of the fiber-reinforced concrete based on the physical property of the stress–strain curve, which is the slope of the inflection point at the descending segment (see Fig. 1). This slope is represented by E_i. The following equations were found to best describe the relationship for the crimped fibers, for compressive strength up to 50 MPa.

$$\beta = 0.001E_i + 0.5811, \quad (r = 0.96), \tag{5a}$$

$$E_i = 1930\,\mathrm{RI}^{(-0.7406)}, \quad (r = 0.97), \tag{5b}$$

$$\beta = 0.5811 + 1.93\,\mathrm{RI}^{(-0.7406)}. \tag{5c}$$

The above equations can be used for reinforcing index up to 3 for a crimped fiber.

However, for plain concrete, the value of β can be calculated by using the expression proposed by Carreira and Chu [7], which is given by,

$$\beta = \left(\frac{f'_c}{32.4}\right)^3 + 1.55, \tag{6}$$

where, f'_c is the compressive strength of plain concrete in MPa. Here again, β is dimensionless. However, this expression was obtained as a function of f'_c, as the descending branch defined by parameter β has a strong dependence on f'_c as reported by Carreira and Chu [7]. However, β is dimensionless.

The strain corresponding to the peak stress of fiber reinforced concrete is usually larger compared to the plain concrete. The proposed equation (2), can be used to estimate the strain value for concrete reinforced with crimped fibers, using a value of 0.002 for ε_o which has been widely accepted as a constant for plain and reinforced concrete (International recommendations, CEB/FIP).

Eq. (4) can be used to generate the complete stress–strain curve for different β values in a normalized manner. The β can be found from the knowledge of reinforcing index based on the established relation from Eqs. (5a)–(5c). The descending part of the stress–strain curve is effected by the β value. As the value of β decreases, the area under the stress–strain curve increases, which means the curve becomes flatter as shown in Fig. 9. Figs. 5–8 show that there is a good correlation between the experimentally measured stress–strain curves with the analytical curves. The analytical curves are obtained by using Eqs. (2), (5a), (5b), (5c) and (4) depending on the compressive strength of the fiber concrete. For straight fibers and end hooked fibers the equations proposed by Ezeldin and Balaguru [13] may be used.

It has been pointed out by Carrasquillo et al. [18] that the shape of the experimentally drawn stress–strain curve is effected by the length of the strain gauges. As suggested by Ezeldin and Balaguru [13], a correction factor may be introduced in the equation to generate the analytical curves for the middle third or the full length strain measurements. Fanella and Naaman [12] have considered the deformation of the whole length of the cylinder whereas, Ezeldin and Balaguru [13] have considered the middle half of the cylinder for measuring the strain.

The sensitivity of the model to the variation in peak strain has been studied by generating set of curves using different critical values of strain. It has been observed that the variation in the stress–strain parameters and the shape of the stress–strain curve is very marginal and is within the acceptable limits. An increase of peak strain by 25% has caused a reduction of about 10% in the value of β which is equivalent to about 5% increase in the reinforcing index for the type of fiber used. The variation in peak strain due to changes in curing condition is usually within ±10% as reported by Ezeldin and Balaguru [13], which has a negligible effect on the shape of the stress–strain curve indicating the acceptable sensitivity of the proposed model to variation in peak strain.

Thus, the proposed model can be used to obtain the complete stress–strain curve of steel-fiber reinforced concrete containing crimped fiber. The parameters needed are the reinforcing index RI, which is usually known in practice, the peak compressive strength of the fiber reinforced concrete f'_{cf} and the corresponding strain ε_{of}. Knowing the compressive strength of the plain concrete, f_c and the reinforcing index, RI, all required parameters of the stress–strain curve of the steel-fiber reinforced concrete can be evaluated using the proposed equations.

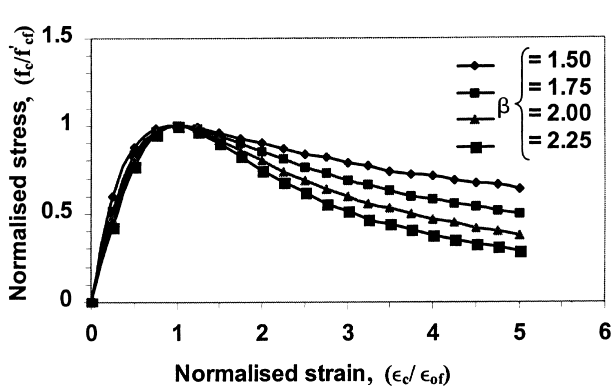

Fig. 9. Effect of β on the stress–strain curves for steel-fiber reinforced concrete.

6. Conclusions

Based on the above experimental study, following conclusions can be drawn regarding the compression behavior of steel-fiber reinforced concrete;

1. Addition of crimped steel-fibers to concrete increases the toughness considerably. The increase in toughness is directly proportional to the reinforcing index. Increase in toughness is marginally higher for lower grade of concrete compared to higher grade of concrete. A marginal increase in compressive strength, strain at peak stress is also observed. This increase is directly proportional to the reinforcing index.
2. An analytical expression is proposed to generate the complete stress–strain curve for a steel-fiber reinforced concrete containing crimped fibers based on the parameter β and the strain corresponding to the peak compressive strength.
3. The proposed equation to determine the value of β is valid for crimped steel-fiber with reinforcing index value ranging from 0.9 to 2.7.
4. The proposed expression provides a good correlation between the predicted and the experimental results. The toughness ratio calculated, from the stress–strain curves based on the predicted equations, matches with those calculated from the experimental stress–strain curves, within an acceptable limit of error.
5. The proposed equations (1), (2) and (3) can be used to estimate the parameters of steel-fiber reinforced concrete as a function of reinforcing index, knowing the respective parameters of the unreinforced concrete.

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