Pergamon

Cement and Concrete Research 30 (2000) 593–597

CEMENT AND CONCRETE RESEARCH

Toughness characterization of steel fiber-reinforced concrete by JSCE approach

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

[a]Faculty in Civil Engineering, Sri Jayachamarajendra College of Engineering, Mysore, Karnataka, PIN 570 006, India
[b]Department of Civil Engineering, Indian Institute of Technology, Kharagpur, PIN 721 302, India

Received 4 December 1998; accepted 7 January 2000

Abstract

The objective of the present investigation is to study the toughness of steel fiber-reinforced concrete (SFRC) based on the Japan Society of Civil Engineers (JSCE) approach. Two aspect ratios of fiber and two different concrete strengths are considered. The toughness factor as measured by the JSCE approach is reported and there is a good correlation between the fiber-reinforcing index and the calculated toughness factor. It is observed that this approach is quite simple and any suitable deflection measuring technique can be employed. Though this method raises some concerns, the advantages are significant. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Toughness; Flexural toughness factor; Steel fiber-reinforced concrete; Deflection

1. Introduction

The addition of steel fibers significantly improves many of the engineering properties of mortar and concrete, notably impact strength and toughness [1,2]. The enhanced performance of fiber-reinforced concrete compared to its unreinforced counterpart comes from its improved capacity to absorb energy during fracture. While a plain unreinforced matrix fails in a brittle manner at the occurrence of cracking stresses, the ductile fibers in fiber-reinforced concrete continue to carry stresses well beyond matrix cracking, which helps maintain structural integrity and cohesiveness in the material. Further, if properly designed, fibers undergo a pullout process, and the frictional work needed for pullout leads to a significantly improved energy absorption capability. This energy absorption attribute of SFRC is often termed Toughness.

The importance of fiber geometry and matrix strength on the toughness characteristics of SFRC has been clearly established by earlier researchers [3–8]. However, as pointed out by Balaguru et al. [4], a great deal of earlier research was conducted with straight, undeformed fibers, which are now rarely used in field applications. In addition, most investigators have used unrealistically high fiber volume fractions with little relevance to the quantities used in the field. In many studies, the deflections were measured without accounting for extraneous deformations, as reported by Gopalaratnam et al. [9], and Banthia and Trottier [5–7].

2. Techniques for toughness measurements

The most common method to measure toughness is to use the load–deflection curve obtained using a simply supported beam loaded at the third points (four-point bending) [10]. The two widely used standard test methods are the ASTM C 1018 standard test method and the Japan Society of Civil Engineerrs (JSCE) standard SF-4 method.

2.1. ASTM C 1018 standard test method

The ASTM C 1018 [11] standard method is based on determining the amount of energy required first to deflect and crack an FRC beam loaded at its third points, and then to further deflect the beam out to selected multiples of the first-crack deflection. Toughness indexes I_5, I_{10}, I_{20}, I_{30}, etc., are then calculated by taking the ratios of the energy absorbed to a certain multiple of first-crack deflection and

* Corresponding author. Tel.: +91-0821-512568 (O), +91-0821-541253 (R); fax: +91-0821-515770.

E-mail address: nataraja96@yahoo.com (M.C. Nataraja).

0008-8846/00/$ – see front matter
PII: S0008-8846(00)00212-X

the energy consumed up to the occurrence of first crack. Expressed in general terms.

$$I_N = \text{Energy absorbed up to a certain multiple of first} - \text{crack deflection/Energy absorbed up to the first crack}$$

The subscript N in these indexes are based on the elasto-plastic analogy such that, for a perfectly elasto-plastic material, the index I_N would have a value equal to N. Here, the given FRC is compared with a conceptual material that behaves in an ideally elasto-plastic manner. Implicitly, the scheme also assumes that plain concrete is ideally brittle and, hence, the various toughness indexes in its case assume a constant value of 1.

2.2. JSCE standard SF-4 method

In this technique [12], the area under the load–deflection plot up to a deflection of span/150 is obtained. From this measure of flexural toughness, a flexural toughness factor (FT) is calculated. It may be noted that FT has the unit of stress such that its value indicates, in a way, the post-matrix cracking residual strength of the material when loaded to a deflection of span/150. The chosen deflection of span/150 for its calculation is purely arbitrary and is not based on serviceability considerations. According to Banthia and Trottier [5,7], there are many concerns with the ASTM C 1018 and JSCE test methods. These are briefly discussed below.

2.3. Concerns with the ASTM C 1018 test method

2.3.1. Measuring true specimen deflections

An accurate measurement of deflection is very important to characterize toughness of FRC. In a flexural specimen under a transverse load, however, the biggest source of error is the settlement of the specimen supports themselves, such that the measured displacement of the load points comprises not only the true displacement due to the response of the beam material to the applied stress but also those arising from seating and the downward movement of the beam as a rigid body. If not properly considered, the settlement in the supports can lead to a gross overestimation of the first-crack energy and, hence, to erroneous indexes. The calculation of toughness indexes requires an accurate assessment of the first-crack energy, which constitutes the denominator in the definition of the various indexes. In addition, it is mentioned that the identification of first-crack deflection is not so simple, due to the substantial non-linearity of load deflection curves even prior to attaining the peak load.

2.3.2. Instability after peak load

The point of peak load occurrence, however, is also the point of instability for the loading machine, which, if not stiff enough, will undergo sudden unloading and release large amount of energy. This sudden release of energy has major effects on the load–deflection curves immediately following the peak load. The problem associated with instability can be remedied by using a closed-loop servo controlled test system. The commercial laboratories, unfortunately, do not commonly use this kind of sophisticated equipment.

2.4. Concerns with the JSCE SF-4 test method

Identifying the correct occurrence location of the first crack, which is crucial and one of the main problems with the ASTM method, is not a concern with the JSCE method. Unlike the ASTM method, the instability in the load–deflection plot right after the first crack is not of major concern in the JSCE method, since the end point deflection of span/150 is too far out in the curve to be affected by the instability in the initial portion. However, there are other limitations and concerns. First of all, FTs are specimen geometry-dependent, which makes an exact correlation with the field performance of FRC rather difficult. In addition, the end point chosen on the curve at a deflection of span/150 is often criticized for being much greater than the acceptable deflection/serviceability limits. The behavior immediately following the first crack, which may be of importance in many applications, is not indicated in FT in any way. Finally, the technique may be criticized for failing to distinguish between the pre-peak and post-peak behaviors by adopting the smeared approach of using the total area under the curve to calculate FTs.

2.5. Banthia and Trottier's [5] proposed technique

In order to simplify the approach, a new method has been proposed by Banthia and Trottier [5] wherein identification of first crack is not required. The procedure according to them is as follows:

1. Obtain the load–deflection curve with accurate deflection measurements using a Yoke or similar device.
2. Locate the peak load and divide the curve into two regions: the pre-peak region (before the occurrence of the peak load) and the post-peak region (after the peak load). Note the value of the load at the peak and measure the area under the curve up to the peak load. This measure of energy is termed as pre-peak energy and denoted as E_{pre}.
3. Locate points on the curve in the post-peak region with specimen deflections equal to various fractions of the span L/m_1, L/m_2, etc. The suggested fractions are between $L/3000$ and $L/150$. Measure the areas under the curve up to these deflections, denoted as $E_{total,m}$ (measured at a deflection of L/m).
4. Subtract the pre-peak energy E_{pre} from the various values of $E_{total,m}$ to obtain the post-peak energy values to a deflection of L/m, $E_{post,m}$.

Table 1
Details of mixes considered

Mix	Mix designation	w/c ratio	Fiber content (kg/m^3)	Fiber length (mm)	Aspect ratio ($1/\varphi$)	Mix proportions per m^3 of concrete				
						C (kg)	fa (kg)	ca (kg)	w (l)	sp (%)
M20	CM1	0.49	–	–	–	397	562	1152	195	Nil
	CM2	0.49	39	27.5	55	397	562	1152	195	Nil
	CM3	0.49	58	27.5	55	397	562	1152	195	Nil
	CM4	0.49	78	27.5	55	397	562	1152	195	Nil
	CM5	0.49	39	41	82	397	562	1152	195	Nil
	CM6	0.49	58	41	82	397	562	1152	195	Nil
	CM7	0.49	78	41	82	397	562	1152	195	Nil
M30	CM8	0.38	–	–	–	517	493	1122	195	0.75
	CM9	0.38	39	27.5	55	517	493	1122	195	0.75
	CM10	0.38	58	27.5	55	517	493	1122	195	0.75
	CM11	0.38	78	27.5	55	517	493	1122	195	0.75

Note: c = cement, fa = fine aggregate, ca = coarse aggregate, w = water, sp = superplasticizer.

5. Calculate the post-crack strength (PCS_m) in the post-peak region at the various deflections. The PCS_m at a deflection of L/m, is defined as Eq. (1):

$$PCS_m = \frac{(E_{post,m})L}{\left(\frac{L}{M} - \delta_{peak}\right)bh^2}. \quad (1)$$

2.6. Comparison of JSCE SF-4 method with Banthia and Trottier's [5] method

The JSCE SF-4 equation for flexural toughness is given by Eq. (2):

$$FT = \frac{A_{(L/150)}L}{(L/150)bh^2}. \quad (2)$$

Comparing the above two equations, for a deflection of $L/150$, it is observed that the terms $E_{post,m}$ and $A_{(L/150)}$ in the numerator represents the area under the load–deflection curves. The only difference is that the term $E_{post,m}$ does not include a small portion of the pre-peak area. This pre-peak area is negligible compared to the total area up to $L/150$. In the same way, the terms in the denominator, $L/M-\delta_{peak}$ and $L/150$ are almost the same except for a small difference of δ_{peak}, which is small, compared to $L/150$ (which is 2.67 mm in case of a 400-mm span). Thus, FT values and PCS values for a deflection of $L/150$ are almost same. In fact, for the usual range of deflections from $L/150$ to $L/300$ based on the serviceability consideration, the differences between the two values given by the equations are negligible. Banthia and Trottier's [5] formula is a slight modification of the JSCE formula. The real difference in the two values given by the above equations occurs for the region, which immediately follows the post-peak. If one is interested in the total energy of the material, the JSCE TF is quite meaningful. Another advantage of the JSCE method is that the value of toughness factor is not affected much by the deflection measuring techniques as observed in the present investigation (Table 2). This has also been observed by other investigators [5,7]. Consequently, even by employing a simple deflection measuring technique, one can find the JSCE toughness factor. The experimentation needed for this test is very simple.

2.7. Need for the present study

Although the JSCE method raises many concerns, the advantages of the method are such that it should not be simply ruled out. The method is simple and FT can be determined easily by using any deflection measuring

Table 2
Toughness and FT based on different deflection measuring techniques

Mix and sample no.	Deflection measurement technique	Flexural toughness (N m)	Average (N m)	FT (MPa)	Average (MPa)
CM9-1	Cross head movement	20.43	21.09	3.06	3.16
	Bottom of specimen	20.38		3.06	
	Net deflection	22.46		3.37	
CM9-2	Cross head movement	14.91	15.60	2.24	2.34
	Bottom of specimen	15.92		2.39	
	Net deflection	15.98		2.40	
CM9-3	Cross head movement	13.55	14.23	2.03	2.14
	Bottom of specimen	14.91		2.24	
	Net deflection	–		–	
Average values of three samples			16.92		2.55

Table 3
Average toughness and FT based on cross head movement for M20 mix

Mix designation	Fiber-reinforcing index RI = $w_f(1/\varphi)$	Average flexural toughness (N m)	Average FT (MPa)
CM1	0	–	–
CM2	0.9*	9.81	1.47
CM3	1.33	9.56	1.43
CM4	1.79	12.21	1.83
CM5	1.34	11.91	1.79
CM6	1.98	10.78	1.62
CM7	2.67	15.30	2.30

* w = 39/2400 = 0.0163; l/φ = 55. Hence, RI = 0.9.

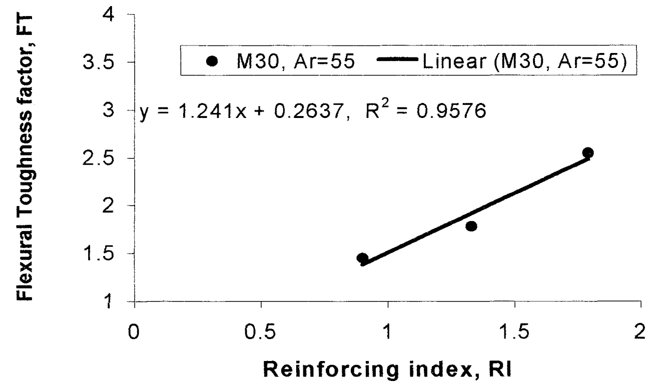

Fig. 2. FT vs. RI, M30.

technique and as such, the determination of first crack is not needed. The technique is sometimes criticized for the chosen deflection of span/150, as it is considered excessive for many applications. Since this deflection is purely arbitrary and not based on serviceability considerations, any other suitable limit can be used based on the serviceability requirements, and the method can still be used. The size of the specimen recommended for this testing is 100 × 100 mm in cross-section with an effective span of 300 mm (L/d = 3). However, the Indian code of practice, IS:516 [13], for flexural testing suggests 100 × 100 × 500 mm with an effective span of 400 mm (L/d = 4). Hence, an experimental study was carried out using 500-mm length prisms to determine FT based on the JSCE approach. It is observed that there exists a good correlation of this FT with the fiber-reinforcing index, which is defined as the product of weight fraction (w_f) and the aspect ratio ($1/\varphi$) of the fibers, where, φ is the fiber diameter.

3. Experimental program

3.1. Materials and mix proportions

Materials consisted of 53 grade ordinary Portland cement with a 28-day compressive strength of 57 MPa, natural river sand, crushed stone aggregate of maximum size 20 mm, tap water for mixing and curing and a superplasticizing admixture. The steel fibers used in this investigation were crimped along the length (undulated) having a breaking strength of 550 MPa. Two fibers with average lengths of 27.5 and 41 mm were investigated. Their equivalent aspect ratios were 55 and 82. A total of 11 concrete mixes were used in this investigation. The mix proportions for M20 and M30 were arrived at based on the code provisions of IS:10262-1982 [14], keeping in mind the guidelines mentioned in an ACI Committee 544 report [2]. The details of the mix proportions are presented in Table 1.

Ingredients were mixed in a laboratory mixer and cured under laboratory conditions. Workability of all mixes was quite satisfactory. For each mix, three, 100 × 100 × 500 mm prisms were cast.

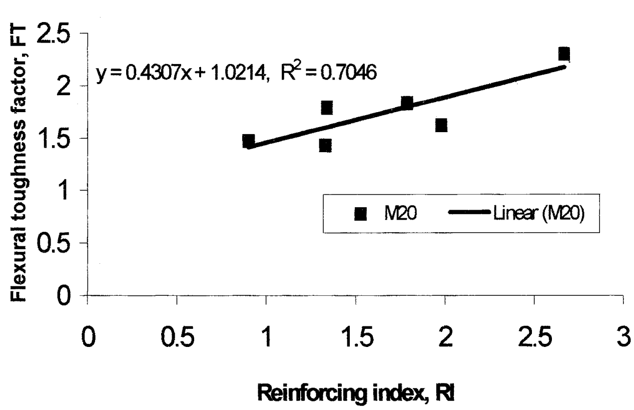

Fig. 1. FT vs. RI, M20.

3.2. Testing

All prisms were tested for flexural strength after 28 days. A 50-kN floor mounted Instron materials test system was used. No special care was taken to eliminate the extraneous support settlements from the gross deflections. This order of error does not have much influence on FT. The applied load and deflection data were recorded manually. Deflections were measured at the bottom of the specimen near the center and also at the end and the center of the specimen at the neutral axis level. Central deflections at the bottom and the difference between end

Table 4
Average toughness and FT based on different deflection measuring techniques

Mix designation	Fiber-reinforcing index RI = $w_f(1/\varphi)$	Average flexural toughness (N m)	Average FT (MPa)	Remarks
CM8	–	–	–	–
CM9	0.9	9.67	1.45	Average of eight values
CM10	1.33	11.88	1.78	Average of seven values
CM11	1.79	16.92	2.55	Average of five values

Table 5
Comparison of JSCE FT and the PCS results

Sample	JSCE FT (MPa)	PCS (PCS_{150}) (MPa)	Reference
A	5.34	5.37	[5]
B	4.00	4.01	[5]
Plain Mix-I	–	–	[7]
F1-I	5.67	5.70	[7]
F2-I	3.61	3.62	[7]
F3-I	2.80	2.71	[7]
F4-I	4.91	4.69	[7]
Plain Mix-II	–	–	[7]
F1-II	5.11	5.12	[7]
F2-II	3.22	3.21	[7]
F3-II	2.64	2.60	[7]
4-II	4.00	4.01	[7]

and central deflections along the neutral axis are considered for the calculation of toughness factors. Deflections were recorded beyond $L/150$.

4. Experimental results and discussion

Load–deflection curves were obtained beyond span/150, so that toughness could be calculated up to a deflection of span/150. Toughness factors were expressed as a function of the fiber-reinforcing index. It was observed that there exists a good correlation between FT with the fiber-reinforcing index.

From Table 2, it can be observed that FT is almost independent of the type of deflection measuring technique. The results are presented for one typical mix consisting of three samples. Here, the net deflection is the difference between the center and end deflections measured along the neutral axis. In this net deflection, it is assumed that the error in deflection measurements is at a minimum as reported in Ref. [9]. From Table 3, it can be seen that the flexural toughness and FT increase as the fiber volume fraction is increased for a given aspect ratio. It also increases as the aspect ratio is increased, for a given volume fraction. To combine the effect of both volume fraction and aspect ratio, the fiber-reinforcing index is introduced ($RI = w_f(1/\varphi)$). It can be seen from Figs. 1 and 2 that there exists a good correlation between FT and RI. The FT increases as the strength of the matrix is increased as observed for the M30 concrete shown in Table 4. Again, the TF increases with volume fraction. Here, the TF is calculated as an average of the values obtained from different measuring techniques. From Table 5, it is observed that the JSCE toughness factor and the PCS as calculated based on Banthia and Trottier's [5] formula are almost the same at $L/150$. Banthia and Trottier's [5] approach is a slight modification of the JSCE approach as explained earlier. For this comparison, results are taken from Refs. [5] and [7].

5. Conclusions

The characterization of flexural toughness based on the JSCE approach is very simple and is independent of the type of deflection measuring technique. No sophisticated instrumentation is required to determine the toughness factor. The determination of first crack, which is very difficult to identify, is not required in this method. The flexural toughness factor calculated using this approach has good correlation with the fiber-reinforcing index.

References

[1] ACI Committee 544, ACI 544.IR-82, state-of-the-art report on fiber reinforced concrete, Concr Int 5 (1982) 9–30.
[2] ACI Committee 544, Guide for specifying, mixing, placing, and finishing steel fiber reinforced concrete, ACI Mater J 90 (1) (1993) 94–101.
[3] P. Soroushian, Z. Bayasi, Fiber type effects on the performance of steel fiber reinforced concrete, ACI Mater J 88 (2) (1991) 129–134.
[4] P. Balaguru, R. Narahari, M. Patel, Flexural toughness of steel fiber reinforced concrete, ACI Mater J 89 (6) (1992) 541–546.
[5] N. Banthia, J.F. Trottier, Test methods for flexural toughness characterisation of fiber reinforced concrete: Some concerns and proposition, ACI Mater J 92 (1) (1995) 48–57.
[6] N. Banthia, J.F. Trottier, Concrete reinforced with deformed steel fibers: Part II. Toughness characterisation, ACI Mater J 92 (3) (1995) 146–154.
[7] J.F. Trottier, N. Banthia, Toughness characterisation of steel fiber reinforced concrete, ASCE J Mater Civ Eng 6 (2) (1994) 264–289.
[8] L. Chen, S. Mindess, D.R. Morgan, Specimen geometry and toughness of steel fiber reinforced concrete, ASCE J Mater Civ Eng 6 (4) (1994) 529–541.
[9] V.S. Gopalaratnam, S.P. Shah, G.B. Batson, M.E. Crisswell, V. Wecharatna, M. Wecharatna, Fracture toughness of fiber reinforced concrete, ACI Mater J 88 (4) (1991) 339–353.
[10] ACI Committee 544, Measurement of properties of fiber reinforced concrete, ACI Mater J 85 (6) (1988) 583–589.
[11] ASTM C 1018, Standard Test Methods for Flexural Toughness and First Crack Strength of Fiber Reinforced Concrete (Using Beam with Third Point Loading), ASTM, V 4.02, pp. 637–644.
[12] JSCE Standard SF-4, Method of Test for Flexural Strength and Flexural Toughness of Fiber Reinforced Concrete, 1984, pp. 58–66.
[13] IS:516-1959, Methods of Test for Strength of Concrete, Bureau of Indian Standards (BIS), India.
[14] IS:10262-1982, Recommended Guidelines for Concrete Mix Design, Bureau of Indian Standards (BIS), India.