COMPARISON OF FLEXURAL TOUGHNESS PARAMETERS FOR FIBRE REINFORCED CONCRETE FROM NOTCHED AND UNNOTCHED BEAM TESTS

SUJATHA JOSE, RAVINDRA GETTU

Abstract

This paper discusses the comparison of the flexural toughness parameters of fibre reinforced concrete (FRC) obtained from unnotched and notched beam tests. Results obtained from tests on a 40 MPa strength concrete reinforced with different dosages of hooked-ended steel, polypropylene and glass fibres have been used to correlate toughness parameters obtained from the two test methods. It was observed that for steel and polymer fibre reinforced concrete, good correlation existed between the unnotched beam test parameters ($f_{e,150}$ and $f_{e,300}$) and notched beam test parameters (f_{R1} and f_{R3}). This enables the use of the *fib Model Code 2010* for the design of FRC structural elements at both serviceability and ultimate limit states, even when only unnotched beam test data is available.

Keywords: Fibre reinforced concrete, flexural toughness, glass fibres, hooked ended steel fibres, notched beam test, polypropylene fibres, unnotched beam test.

1. INTRODUCTION

There are various guidelines and standards for the characterization of flexural toughness of fibre reinforced concrete (FRC); these approaches are generally based on either a two-point loading test on an unnotched specimen or a centre-point loading test on a notched specimen. Unnotched specimens have been used in the ASTM C1609[1], JSCE SF4[2] and ICI-TC/01[3], and notched specimens in EN14651:2005 (E)[4] and RILEM TC 162-TDF[5] recommendations. Since both types of tests are used in practice, it would be useful to have correlations between the parameters obtained from either method. There have been studies correlating parameters from notched beam tests with tests on panels, especially of steel fibre concrete. However, few studies have extended such correlations to concretes with different types of fibres (hooked ended steel, macro polypropylene and glass) involving tests on unnotched specimens. The present work focuses on correlations between toughness parameters of concrete with different dosages of hooked-ended steel, polypropylene and glass fibres, obtained from both notched and unnotched beam tests. Such correlations would be useful if the results from one specific test method could be used to derive the parameters of the other test method. The details of the notched beam test and its results for all the fibre types are published by the same authors before and would be referring to them[6]. As *fib Model Code 2010*[7] provides design guidelines for the design of FRC structural elements at both serviceability and ultimate limit states based on the flexural toughness parameters determined from notched beam tests according to EN 14651, the correlation could enable the use of the *fib Model Code 2010* even when only unnotched beam test data is available.

2. EXPERIMENTAL PROGRAMME

The setup adopted for the unnotched beam loaded at thirds (four-point bend) tests followed JSCE SF4 and ICI-TC/FRC 01.1 specifications, and the three-point bend (on the centrally loaded notched beam) tests (3PBT) follow EN14651, as shown in Figures 1 and 2, respectively. In the notched beam test, a 25 mm deep notch was cut at mid-span, across which the crack mouth opening (CMOD) was monitored. Both types of tests were performed in a closed-loop servo-controlled, Controls testing system, and the control and data acquisition were done through a Controls Advantest interface. In both the test methods, the prism is loaded such that the direction of casting was perpendicular to the loading direction. Both the tests were displacement controlled, where the notched beam test was performed at defined CMOD rates and the unnotched beam test was run at defined deflection rates. Both tests were performed initially by increasing the load at a constant rate of 100 N/s up to about 40% of the estimated peak load, and then by changing to CMOD or deflection control. The deflection of the specimen was taken as the average of the measurements of the two LVDTs (of 10 mm range), fixed to the neutral axis by means of a rod, which in turn was held by a yoke on either side of the specimen (see Figure 1). For both the tests, the time to peak in all cases was 2-3 minutes. The unnotched beam test was performed up to a deflection of 3 mm and the time taken for the entire test for the concretes with steel, polymer and glass fibres were about 30, 45 and 60 minutes, respectively. Flexural toughness parameters from the load-CMOD curves of the notched beam test are the limit of proportionality (LOP) and residual flexural strength at different CMOD (0.5, 1.5, 2.5 and 3.5 mm). The parameters from the unnotched beam test are flexural strength and equivalent flexural strength derived from the load-deflection curves, based on JSCE SF4.

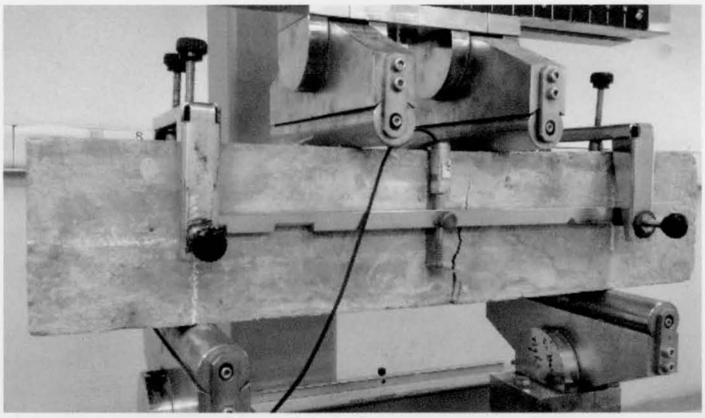

Figure 1: Setup of unnotched beam test (4PBT).

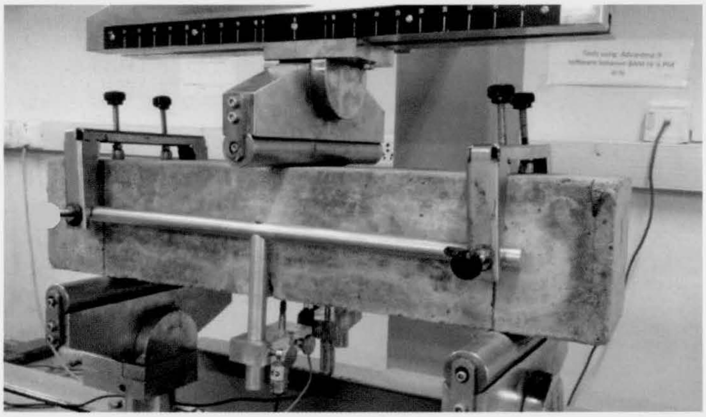

Figure 2: Setup of notched beam test (3PBT).

The residual flexural tensile strength, f_{Rj}, which is an estimate of the flexural strength retained by FRC after cracking up to a particular crack width, is calculated from the load-CMOD curve corresponding to CMOD=CMODj (j= 1,2,3,4) for CMOD values of 0.5, 1.5, 2.5 and 3.5 mm (Figure 3), as per EN 14651:2005 (E)[4]; see details in Jose et al.[6]. The toughness parameter obtained from the unnotched beam test is the equivalent flexural strength ($f_{e,n}$) based on the load-deflection curves, as recommended by ASTM C1609[1], JSCE SF4[2] and ICI-TC/FRC 01.1[3]. The mean flexural strength (f_{ct}) is found by using the peak load, and the two equivalent flexural strengths, $f_{e,300}$ and $f_{e,150}$, are computed from the average load $P_{e,n}$, which is the ratio of $T_{e,n}/\delta_n$ as shown in the Figure 4, where $T_{e,n}$ is the area under the load-deflection curve upto the deflection $\delta_n = l_s/n$, and ls is the span between the supports, which is 450 mm, and n = 150 and 300 for the parameters $f_{e,150}$ and $f_{e,300}$, respectively.

$$f_{(R,j)} = \frac{3F_j l}{2bh_{sp}^2}$$

$$P_{(e,n)} = \frac{T_{(e,n)}}{\delta_n} \qquad f_{(e,n)} = \frac{P_{e,n} \times l_s}{bd^2}$$

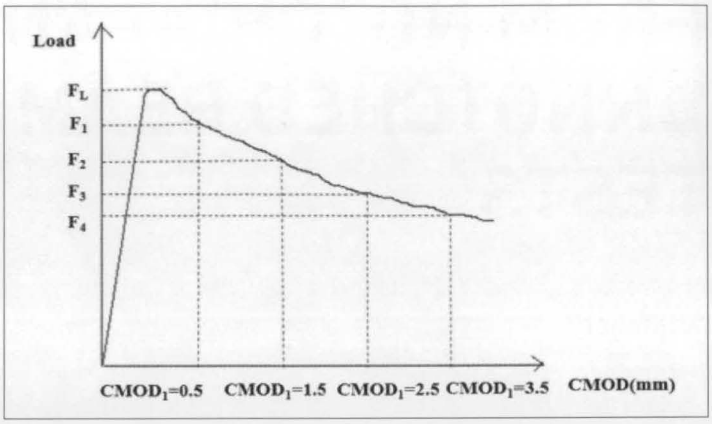

Figure 3: Estimation of residual flexural strengths f_{R1}, f_{R2}, f_{R3} and f_{R4} (notched beam test-EN14651).

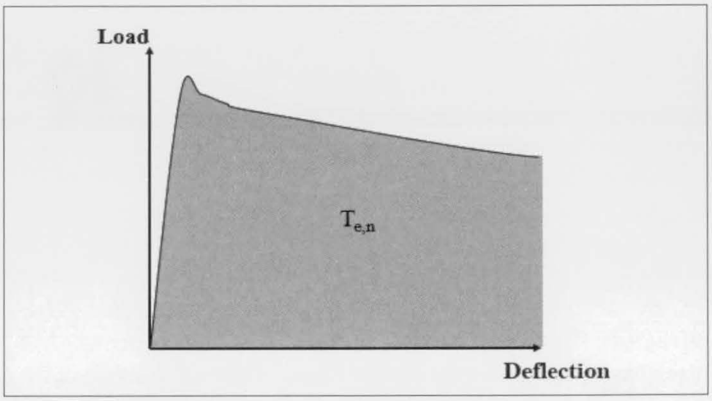

Figure 4: Determination of $f_{e,n}$ (unnotched beam test).

3. MATERIALS USED IN THE STUDY

The concrete used had a 40 MPa design compressive strength (denoted as M40), with Portland pozzolana cement (PPC), river sand (with grain size range of 0-5 mm, corresponding to Zone 2 of IS 383 (2016) and crushed granite coarse aggregates (in the fractions of 5-10 mm and 10-20 mm) and the water/cement ratio was 0.45. A polycarboxylate (PCE) based superplasticizer (with a density of 1080 kg/m^3 and solid content of 33%), was used to attain the desired workability. The nominal mix proportions for the concretes are given below in Table 1. The fibre types and dosages incorporated are given in Table 2. The mixing of the concrete was done in a forced-action vertical axis pan mixer of 250 litres capacity. The sequence of mixing was: initial dry mixing of aggregates and cement; adding of water and wet mixing for few minutes; and then addition of super-plasticizer. In the case of steel and polymer fibres, the concrete was mixed for about 3 minutes after fibre addition, whereas the mixing was limited to 45 seconds for concretes with glass fibres (as per the instructions of the manufacturer) to prevent any degradation of the fibres. Cubes of 150 × 150 × 150 mm and prisms of 150 × 150 × 700 mm were cast from all the concretes. The specimens were left in the moulds for 24 hours after casting, then demoulded and cured for the next 27 days in a mist room, after which they were tested.

Table 1: Nominal mix proportions

MATERIAL	QUANTITY (KG/M³)
Cement	380
Fine aggregate	760
5-10 mm Coarse aggregate	390
10-20 mm Coarse aggregate	700
Water content	171

Table 2: Fibre details

MATERIAL	TYPE	SPECIFIC GRAVITY* (G/CC)	LENGTH* (MM)	DIAMETER* (MM)	TENSILE STRENGTH* (MPA)	FIBRE DOSAGE (KG/M³)	VOLUME FRACTION *VF* IN %
Steel	Hooked-ended steel	7.80	60	0.75	1225	10,15,20,30,45	0.13,0.19, 0.26,0.38, 0.57
Polymer	Poly-propylene fibres	0.92	40	0.44	620	2.5, 3.75, 5	0.27,0.40,0.54
Glass	Glass	2.68	36	0.54	1700	5,10,15	0.19,0.37,0.57

* specified by the manufacturer

Table 3: Fresh properties and compressive strengths of the different mixes (from [6])

CONCRETE NOTATION	TYPE OF FIBRE	FIBRE DOSAGE (KG/M³) VOLUME FRACTION *VF* IN%	UNIT WEIGHT (KG/M³)	SLUMP (MM)	COMPRESSIVE STRENGTH (MPA) (MEAN ± STANDARD DEVIATION)		
					AT 3 DAYS	AT 7 DAYS	AT 28 DAYS
M40SF0	Steel	-	2450	90	22.3±1.2	33.7±0.5	47.1±0.3
M40SF10		10; 0.13	2450	95	22.5±0.8	34.4±0.9	48.4±0.8
M40SF15		15; 0.19	2470	95	23.5±0.7	35.6±1.5	49.2±0.6
M40SF20		20; 0.26	2490	100	26.7±0.8	36.7±1.6	50.4±1.3
M40SF30		30; 0.38	2475	110	27.9±1.3	37.3±0.7	51.5±1.7
M40SF45		45; 0.57	2490	100	28.6±0.4	38.0±0.9	52.8±0.7
M40PF0	Polymer	-	2480	90	21.1 ± 0.3	29.9 ±1.7	46.5±1.6
M40PF2.5		2.5; 0.27	2450	70	24.10±1.4	31.1 ± 0.8	46.5 ± 1.6
M40PF3.75		3.75; 0.40	2470	65	22.2± 0.6	30.4±2.6	49.3 ± 2.8
M40PF5		5; 0.54	2460	45	22.5± 0.2	31.8±0.8	47.3±3.3
M40GF0	Glass	-	2440	105	20.6 ± 1.3	27.9 ± 3.4	44.8 ± 0.5
M40GF5		5; 0.19	2430	80	22.9 ± 2.2	32.8 ± 1.9	45.8 ± 1.2
M40GF10		10; 0.37	2430	70	23.3 ± 1.7	34.5 ± 0.8	44.5 ± 1.2
M40GF15		15; 0.56	2400	60	20.7 ± 0.3	30.1 ± 2.5	46.5 ± 1.0

4. RESULTS AND DISCUSSION

The fresh properties of M40 grade concrete mix for plain as well as steel, polymer and glass fibre reinforced concrete for the different mixes are given in Table 3. The details of the mixes and other details have been published elsewhere by the same authors[6]. Note that in the mix designation, M40 denotes the concrete grades, SF, PF and GF denotes the use of steel, polymer and glass fibres, and the number at the end denotes the fibre dosage in kg/m^3. It can be seen that the unit weight of fresh concrete is in the range of 2430 – 2490 kg/m^3, indicating that all the mixes attained uniform degrees of compaction. The super-plasticizer dosage, by weight of cementitious materials, was increased (e.g., from 0.19% in the plain concrete to 0.3% for 30 kg/m^3 of steel fibres, 0.75% for 5 kg/m^3 of polymer fibres and to 0.8% for 15 kg/m^3 of glass fibres) in order to obtain a slump of 100±20 mm for concretes with steel, 60±20 mm for polymer and 70±20 mm for glass fibres. The mean uniaxial compressive strength values along with the standard deviations for concretes with different fibre types and volume fractions are given in Table 3. The results indicate that incorporation of steel fibres resulted in a slight increase in the compressive strength compared to plain concrete, from 3% to 12% for the fibre dosages of 10 kg/m^3 to 45 kg/m^3. However, the results also indicate that the increase in compressive strength is not significant due to the addition of polypropylene and glass fibres, for the dosages considered here.

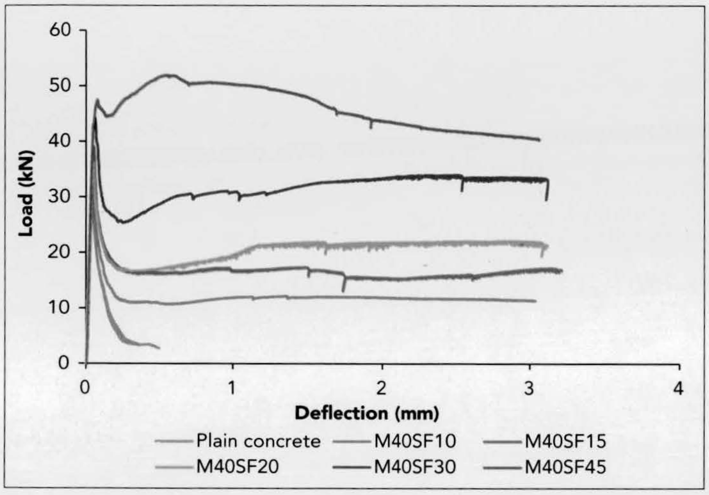

Figure 5: Typical load-deflection curves- of M40SF mixes.

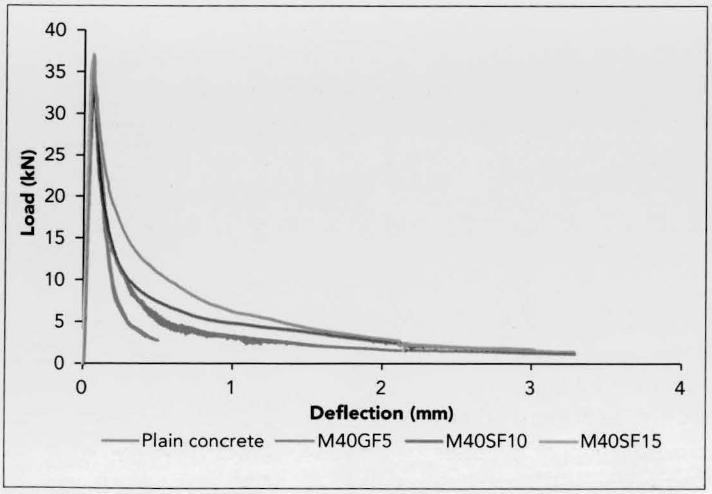

Figure 6: Typical load-deflection curves of M40PF mixes.

The flexural behavior of FRC mixes from unnotched beam testing was assessed by load-deflection curves derived by carrying out the bending tests as per ASTM C1609, JSCE SF4 and ICI-TC/FRC 01.01; see details in Nayar et al.[8]. The flexural response in terms of typical load-deflection curves are presented in Figures 5-7. It was observed that, the post-peak load-carrying capacity and the area under the load deflection curve have a direct relation with the fibre dosage as expected; higher dosage imparts more toughness to the concrete irrespective of the type of fibre. The load-deflection response of plain concrete captured upto 0.5 mm deflection exhibits a softening type behavior, whereas it is clear from the load-deflection curves of steel fibres (see Figure 5) that there is a gradual change from softening-type response to plastic-type response as the fibre dosage increases, especially after a deflection of 0.3 mm. For a steel fibre dosage of 10 and 15 kg/m^3 concrete, a flat post-peak response was observed, and for the dosages of 20, 30 and 45 kg/m^3, a hardening response was seen. The post-cracking behavior of PFRC as shown in the curves (see Figure 6), show that for all the dosages of polypropylene fibres there is a sudden drop in the load-deflection curve after the peak load and a flat response beyond a deflection of about 0.5 mm due to the retention of the post-cracking load carrying capacity. Moreover, it can also be seen that the load-carrying capacity increases as the dosage increases from 2.5 to 5 kg/m^3. The load-deflection curves of GFRC (Figure 7) show a sudden drop in the load-carrying capacity after the peak, for all dosages, with little load retention beyond 1.5 mm. An increase in toughness as the dosage increases is noticed only until deflection of about 1.5 mm, beyond which there is no significant improvement. Similar behavior in GFRC has also observed in previous work[8].

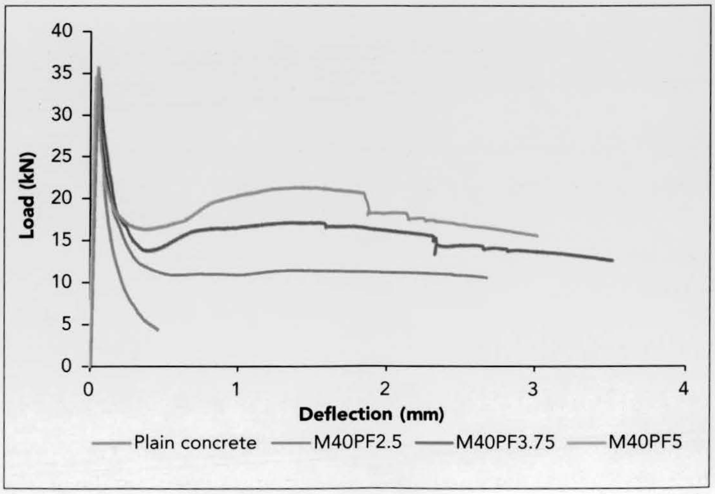

Figure 7: Typical load-deflection curves of M40GF mixes.

The toughness parameters obtained from the unnotched beam tests are presented in Table 4, and those from the notched beam tests in Table 5, in terms of mean values and coefficients of variation (COV in %). It can be seen from Table 4 that the flexural strengths of the FRC mixes are slightly higher than that of plain concrete. However, the increase does not show any clear trends or dependence on the fibre dosage or type, though the highest values were obtained with the GFRC.

Table 4: Parameters from unnotched beam tests *(mean and COV)*

FIBRE TYPE	CONCRETE	FIBRE DOSAGE IN KG/M^3; VOLUME FRACTION *VF* IN%	*FCT* (MPA)	*FE,300* (MPA)	*FE,150* (MPA)
Steel	M40SF0	-	4.46 (12)	-	-
	M40SF10	10; 0.13	4.61 (17)	1.85 (20)	1.85 (30)
	M40SF15	15; 0.19	5.21 (8)	2.51 (20)	2.59 (20)
	M40SF20	20; 0.26	5.35 (7)	2.60 (8)	2.82 (17)
	M40SF30	30; 0.38	5.59 (7)	4.21 (18)	4.61 (23)
	M40SF45	45; 0.57	6.81 (18)	5.94 (20)	6.16 (25)
Polymer	M40PF0	-	4.52 (10)		
	M40PF2.5	2.5; 0.27	4.50 (5)	1.62 (7)	1.57 (6)
	M40PF3.75	3.75; 0.40	5.20 (5)	2.16 (10)	2.19 (9)
	M40PF5	5; 0.54	5.15 (8)	2.50 (12)	2.30 (15)
Glass	M40GF0	-	4.70 (15)		
	M40GF5	5; 0.19	5.42 (9)	0.97 (13)	0.65 (15)
	M40GF10	10; 0.37	4.86 (14)	1.02 (5)	0.68 (52)
	M40GF15	15; 0.56	5.19 (5)	1.6 (19)	1.1 (28)

The equivalent flexural strengths, i.e., the $f_{e,n}$ values, reflect clearly the increase in the post-peak load-carrying capacity of all the mixes of FRC with an increase in dosage of the fibres, as expected. However, it can be seen that the hooked-ended fibres yield better toughening than the polypropylene fibres, which in turn perform better than the glass fibres. Comparison of the values of the two equivalent flexural strengths show that $f_{e,150}$ is higher than $f_{e,300}$ for all the higher dosages (≥ 15 kg/m^3) of hooked-ended steel fibres reflecting 'hardening' type response. Moreover, $f_{e,150}$ is practically equal to $f_{e,300}$ for the polypropylene fibres, reflecting a flat response. However, $f_{e,150}$ is lower than $f_{e,300}$ for all the dosages of GFRC, which reflects softening-type response.

For comparison, the mean values of parameters obtained from notched beam tests, along with the coefficients of variation (COV), of all the mixes are given in Table 5. The curves from the tests and other details have been published elsewhere by the same authors[6].

5. RELATIONSHIP BETWEEN THE PARAMETERS OF NOTCHED AND UNNOTCHED BEAM TESTS

Comparisons are made here between the residual flexural strength (f_R) from the notched beam test and equivalent flexural strength (*fen*) values from the unnotched beam test associated with a particular deflection or cracking level[9]. To facilitate the comparisons, rigid body mechanics is used to derive nominal relations between deflection and CMOD for the post-cracking regime, as $\frac{\delta}{CMOD} = 0.75$ for the unnotched beam configuration and $\frac{\delta}{CMOD} = 0.82$ for the notched beam configuration. Consequently, pairs of toughness parameters have been identified that correspond to similar CMOD values, as:

$f_{e,150}$ and $f_{R,3}$ corresponding to CMOD limits of 4 and 2.5 mm, respectively

$f_{e,300}$ and $(f_{R1}+f_{R3})/2$ corresponding to CMOD limits of 2 and 2.5 mm, respectively

In order to observe whether the correlations between the above pairs of parameters are fibre dependent, they are plotted separately for SFRC, PFRC and GFRC in Figures 8-10, respectively.

Table 5: Flexural toughness parameters (mean and COV) (from [6])

FIBRE TYPE	CONCRETE	FIBRE DOSAGE IN KG/M^3; VOLUME FRACTION *VF* IN %	*FCTF* (LOP) (MPA)	*FR,1* (MPA) CMOD=0.5 MM	*FR,2* (MPA) CMOD=1.5 MM	*FR,3* (MPA) CMOD=2.5 MM	*FR,4* (MPA) CMOD=3.5 MM	*FEQ,2* (MPA)	*FEQ,3* (MPA)
Steel	M40SF0	-	5.22 (8)	-	-	-	-	-	-
	M40SF10	10; 0.13	5.33 (8)	2.19 (8)	2.11 (10)	2.13 (11)	2.05 (14)	1.99 (16)	2.04 (13)
	M40SF15	15; 0.19	5.44 (9)	2.35 (6)	2.48 (8)	2.55 (11)	2.48 (12)	2.09 (9)	2.40 (10)
	M40SF20	20; 0.26	5.58 (4)	3.40 (16)	3.73 (15)	3.80 (10)	3.68 (8)	3.23 (18)	3.62 (13)
	M40SF30	30; 0.38	5.38 (8)	4.04 (15)	5.21 (12)	5.54 (14)	5.48 (14)	3.89 (18)	5.03 (12)
	M40SF45	45; 0.57	5.47 (8)	5.30 (15)	6.70 (18)	6.63 (23)	6.53 (21)	5.29 (16)	6.33 (19)
Polypropylene	M40PF0	-	5.0 (4)	-	-	-	-	-	-
	M40PF2.5	2.5; 0.27	5.13 (8)	1.52 (9)	1.30 (6)	1.27 (4)	1.16 (11)	1.26 (11)	1.33 (4)
	M40PF3.75	3.75; 0.40	5.06 (9)	2.00 (7)	1.92 (7)	2.01 (6)	1.90 (7)	1.66 (16)	2.05 (11)
	M40PF5	5; 0.54	5.51 (5)	2.33 (12)	2.55 (10)	2.58 (13)	2.29 (13)	2.13 (10)	2.49 (10)
Glass	M40GF0	-	5.06 (8)	0.82 (18)	-	-	-	-	-
	M40GF5	5; 0.19	5.13 (11)	1.34 (10)	0.58 (16)	0.39 (13)	0.23 (56)	1.04 (17)	0.54 (33)
	M40GF10	10; 0.37	5.47 (4)	1.80 (14)	1.13 (13)	0.70 (39)	0.57 (45)	1.48 (26)	0.95 (23)
	M40GF15	15; 0.56	5.77 (6)	2.42 (21)	1.22 (32)	0.75 (41)	0.52 (38)	2.51 (22)	1.49 (40)

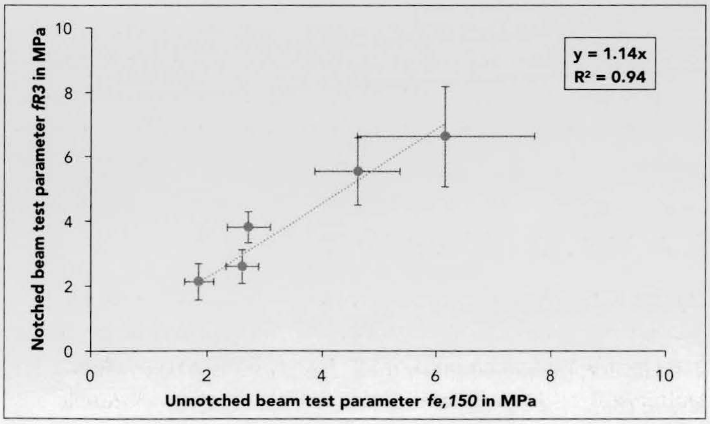

Figure 8 (a): Correlation between unnotched beam test parameters $f_{e,150}$ and notched beam test parameters f_{R3} (SFRC).

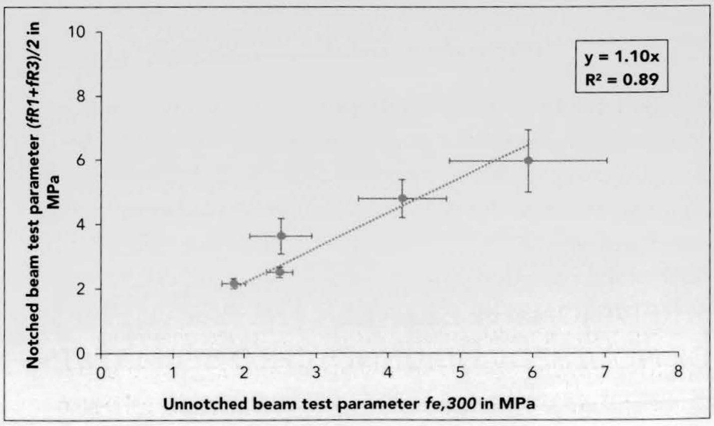

Figure 8 (b): Correlation between unnotched beam test parameter $f_{e,300}$ and notched beam test parameter $(f_{R1}+f_{R3})/2$(SFRC).

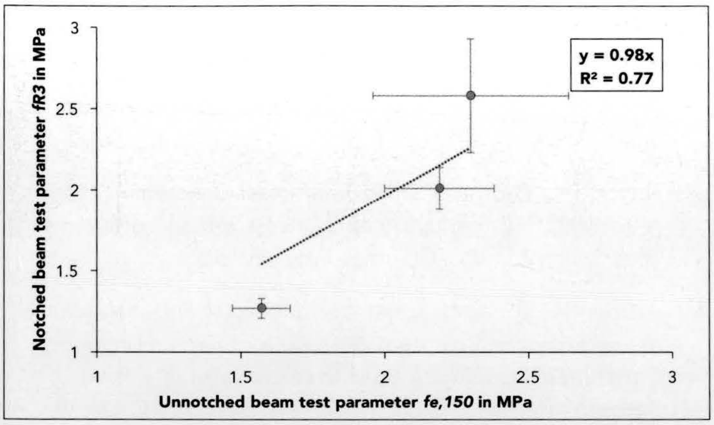

Figure 9 (a): Correlation between unnotched beam test parameters f_{e150} and notched beam test parameters f_{R3}(PFRC).

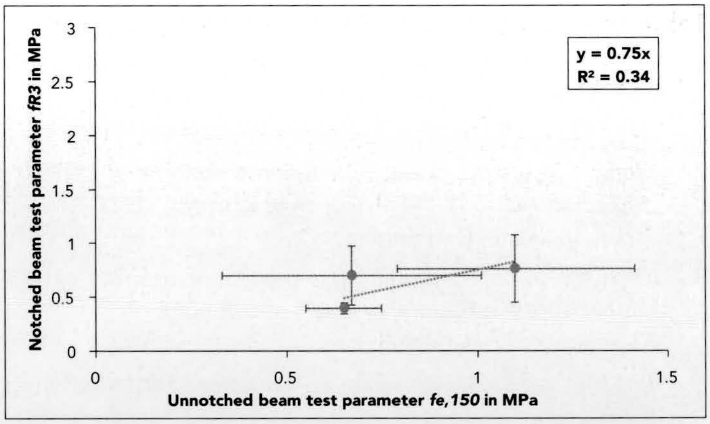

Figure 10 (a): Correlation between unnotched beam test parameters $f_{e,150}$ and notched beam test parameters f_{R3}(GFRC).

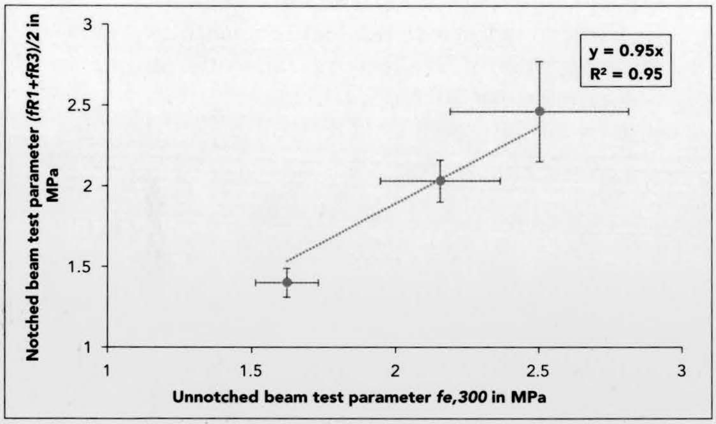

Figure 9 (b): Correlation between unnotched beam test parameter $f_{e,300}$ and notched beam test parameter $(f_{R1}+f_{R3})/2$(PFRC).

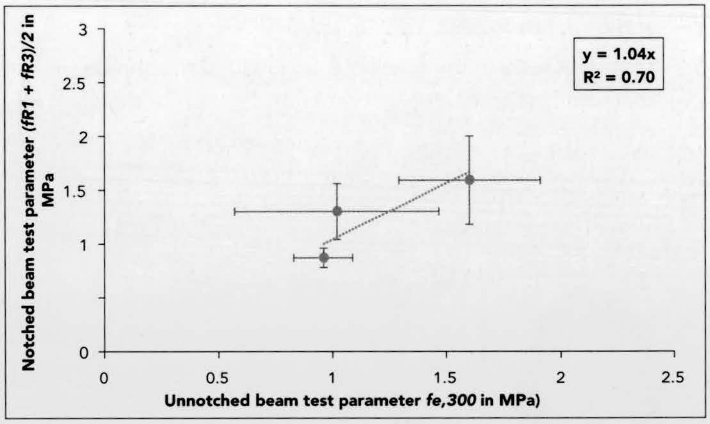

Figure 10 (b): Correlation between unnotched beam test parameter $f_{e,300}$ and notched beam test parameter $(f_{R1}+f_{R3})/2$(GFRC).

The relationships represented in Figures 8-10 show that good correlations existed between the unnotched and notched beam test parameters for different dosages (upto a V_f of 0.6%) of SFRC and PFRC, whereas a less R^2 value was observed for GFRC, probably due to the higher variability of the toughness parameters for GFRC. The correlation equations show that the relationships are fibre dependent as there is slight variation in the slope of the equations for SFRC, PFRC and GFRC. It is noted that the correlations could be affected by the type of fibres.

6. CONCLUSIONS

The post-cracking flexural behaviour of steel, polypropylene and glass fibre reinforced concrete was assessed using four-point bending tests on unnotched specimens. The study demonstrates that the toughness parameters obtained can be correlated with those from tests of notched beams (EN14651). Further, the specific conclusions from this work are:

- From the analysis of the test results, it was observed that for steel and polymer fibre reinforced concrete, good correlation existed between the unnotched beam test parameters ($f_{e,150}$ *and* $f_{e,300}$) and notched beam test parameters (f_{R1} *and* f_{R3}) and linear relationship that existed between the parameters are fibre dependent. This enables the use of the *fib Model Code 2010* for the design of FRC structural elements at both serviceability and ultimate limit states, even when only unnotched beam test data is available.
- The scatter in the flexural toughness parameters obtained for both unnotched and notched beam testing shows that polypropylene fibre reinforced concrete exhibited least scatter compared to that of steel and glass fibre reinforced concrete, with GFRC with highest scatter, irrespective of the type of test.

7. ACKNOWLEDGEMENTS

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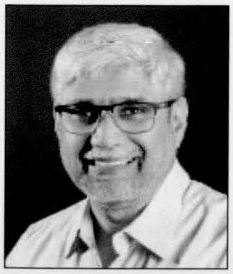
SUJATHA JOSE holds a B.Tech. degree in Civil Engineering from National Institute of Technology (NIT) Calicut, a Masters degree in Construction Engineering and Management from College of Engineering, Guindy, Anna University and is pursuing her Ph.D. degree at Building Technology and Construction Management Division, Indian Institute of Technology (IIT) Madras. Her research interests include fiber reinforced concrete, special concretes, sustainability and durability in concrete.



RAVINDRA GETTU is a Professor of Civil Engineering at the Indian Institute of Technology (IIT) Madras. His current research interests are in fiber reinforced concrete, the effective use of chemical admixtures, self-compacting concrete, sustainability, housing and the mechanical characterization of construction materials. He is currently the President of The Reunion Internationale des Laboratories et Experts des Materiaux, Systemes de Construction et Ouvrages (RILEM), the International Union of Laboratories and Experts in Construction Materials, Systems and Structures.