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CHARACTERIZATION OF THE TOUGHNESS OF FIBER REINFORCED CONCRETES USING THE LOAD-CMOD RESPONSE

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Abstract
Engineering measures of the toughness of fiber reinforced concretes (FRC) are usually obtained from the load-deflection response of unnotched beams. The problems with this approach are avoided in part by the use of notched specimens. In the present work, toughness measures based on the load versus crack opening (CMOD) response of notched beams under three-point loading are analyzed. The influences of specimen size and fiber volume fraction (0-1%) on the load-CMOD based toughness measures are studied for a 70 MPa strength silica fume concrete. The fibers used in the work were high-strength hooked steel fibers. Tests were performed under crack opening control in a servohydraulic testing machine to get the stable post-peak response for the plain and fiber concretes. The size effect method is used to characterize the fracture parameters of the matrix. Two important conclusions are that the area under the load-CMOD curve reflects the effectiveness of the fiber and that the deflection-CMOD relation is practically independent of the specimen size and fiber content.

1 Introduction

The incorporation of fibers in concrete increases its energy absorption capacity considerably. This improves the fracture, fatigue and impact performance of the material, changing the modes of failures from brittle to ductile. For the purpose of materials engineering, characterization and structural design, the ductility of the fiber-reinforced concrete (FRC) is conventionally represented by an experimentally-determined toughness.

Several "engineering" measures of toughness have been used for characterizing FRC. These parameters are not related directly to the fracture toughness or the fracture energy. They are based on simple test configurations such as flexure, compression and tension, and are defined as the absolute energy absorbed, normalized indices related to the energy absorbed at different stages of failure, equivalent post-cracking flexural strengths or other quantities that represent the post-cracking response (cf. Gopalaratnam et al., 1995). Though these measures are intended to represent the material ductility, they depend on specimen size and geometry, test parameters and experimental setup. To avoid these problems, several toughness measures have been proposed recently based on the load versus crack opening (CMOD) response of notched specimens such as those used for determining the fracture properties of concrete (Gopalaratnam et al., 1991; Bryars et al., 1994; Jamet et al., 1995). This approach is also expected to lead to properties of a more fundamental nature and to the application of fracture mechanics principles.

The present work studies the characterization of FRC toughness based on the area under the load-CMOD curve of a notched beam tested in a closed-loop servohydraulic machine. The material used is a high strength concrete in which low volume-fractions of hooked steel fibers are incorporated.

2 Toughness of fiber reinforced concretes

The flexural configuration is the most popular test setup for characterizing FRC toughness due to its simplicity and due to its ability to simulate the loading in several practical situations. The various toughness measures derived from the flexural test and the problems associated with them have been reviewed recently by Gopalaratnam and Gettu (1995). The specimen that is commonly used is the unnotched beam subjected to four-point (or third-point) loading and tested under displacement control. Other configurations include the plate subjected to a punching load and the centrally-loaded notched beam.

Traditionally, the load-deflection response of the specimen is obtained up to prescribed deflection limits and used to calculate the toughness measures. The area under the load-deflection curve until a certain deflection (for a given specimen) is defined as toughness in the Japanese standard (JCI, 1984). The ASTM C 1018 (1992) standard specifies dimensionless indices obtained by dividing the area up to a prescribed multiple of the first-crack deflection by the area until the first-crack deflection. The ACI 544 recommendation (1988) defines an alternate toughness index that is the difference between the areas under the entire load-deflection curves of the FRC specimen and an identical specimen without fibers. One important problem with these methods is the difficulty in determining the deflection correctly, which leads to erroneous toughness values, especially when they depend on the first-crack deflection (Gopalaratnam et al., 1991; Gopalaratnam and Gettu, 1995).

Fracture mechanics based methods are also being extended to FRC. Hillerborg (1983, 1985) proposed the use of the fracture energy (RILEM, 1985) to quantify the ductility of FRC. Other related approaches have used the stress-displacement relation of the crack to characterize the failure behavior (Li et al., 1993). These methods are unattractive in practice since almost the entire load-displacement response has to be determined experimentally using a tension or bending test. This leads to several problems, two of which are important from the point of view of FRCs: (1) the considerable time and extensometry required for performing the test until the load drops to zero, and (2) the lack of practical significance of the response at large deformations. The application of other nonlinear fracture mechanics methods, such as effective crack models based on the behavior at the peak load, is not possible since it characterizes only the matrix-dominated response for most FRCs (Bryars et al., 1994).

There is a need for a simple test method that can quantify the toughness of FRC unambiguously. It is further useful if the toughness measure represents the fundamental behavior of the material during failure. Recently, methods based on fracture have been proposed with this objective. Bryars et al. (1994) modified the toughness index of Barr (Barr and Hasso, 1985) by defining it as the area under the load-CMOD curve of a notched beam up to a prescribed multiple of the CMOD at the peak load divided by the area up to the first peak. They found that this index was practically size-independent and reflected the post-crack ductility adequately. Jamet et al. (1995) studied this and other possible toughness measures, and concluded that the absolute load-CMOD area was more sensitive to the effectiveness of the fibers than normalized indices calculated at relatively small deformations.

3 Fracture response of the notched beam

The linear elastic fracture mechanics (LEFM) behavior of common notched beam geometries used in material characterization can be computed from the geometry-dependent functions available in handbooks such as Murakami (1990). Alternatively, elastic analysis can be used. The specimen used here is the centrally loaded notched beam with a span/depth ratio of 2.5 (see Fig. 1). The load-deflection and load-CMOD curves for this specimen, according to LEFM, have been obtained by finite element analysis using interface elements. These curves are plotted in Fig. 2a for unit values of modulus of elasticity (E), thickness (b) and critical stress intensity factor (K_{Ic}), and for depth $d = 100$ and notch length $a_0 = 0.275d$. It can be seen that the increase in deflection for a given drop in load is much lower than the corresponding increase in the CMOD. This is also reflected in Fig. 2b, where the relative increases in the areas under the load-deflection and load-CMOD curves after the peak are plotted with respect to the deflection and the CMOD, respectively. The areas are normalized with the areas up to the peak and the displacements are normalized with the displacements at the peak. This also suggests that the load-CMOD area is more sensitive to crack propagation than the load-deflection area. The deflection-CMOD relation is shown in Fig. 2c, where the initial part corresponds to increasing load without crack propagation ($a=a_0$, $K_I<K_{Ic}$), the kink corresponds to the peak ($a=a_0$, $K_I=K_{Ic}$) and the curve after the kink corresponds to critical crack propagation ($a>a_0$, $K_I=K_{Ic}$).

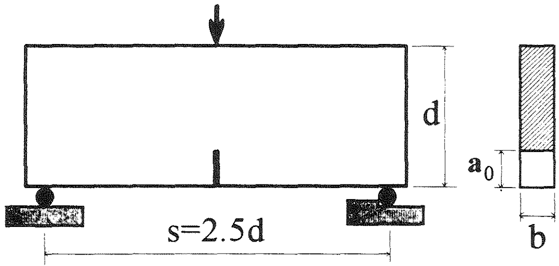

Fig. 1. Notched beam geometry

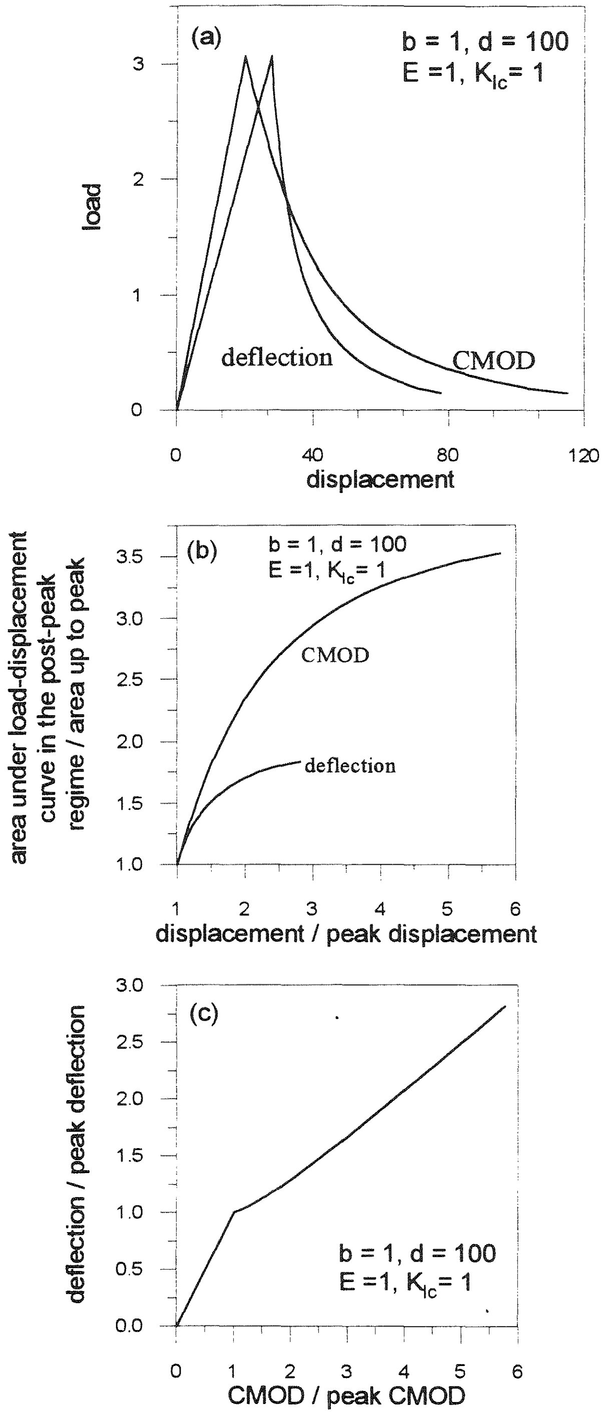

Fig. 2. (a) Theoretical LEFM load-deflection and load-CMOD curves, (b) Evolution of areas under the LEFM load-deflection and load-CMOD curves, (c) Evolution of the LEFM deflection-CMOD relation with crack propagation

Tests in this study were conducted on a concrete with a composition of cement:sand:gravel:microsilica:water equal to 1:1.32:2.2:0.1:0.42, by weight. ASTM Type I (Spanish Type 45-A) cement, crushed limestone aggregates and silica fume slurry were used. DRAMIX® ZC 30/.50 collated hooked steel fibers (tensile strength of 2000 MPa, 0.8-1.0% elongation, 30 mm length and 0.5 mm diameter) were incorporated in the concrete. The unreinforced concrete is hereafter denoted as HSC-0.0, and the concretes with 40 kg/m^3 (volume fraction, V_f, of approximately 0.5%) and 80 kg/m^3 (V_f = 1%) of fibers as HSC-0.5 and HSC-1.0, respectively. Different amounts (8-20 lit./m^3) of super-plasticizer were used in the three concretes since the addition of fibers decreased the workability. The compressive strength was obtained using 150×300 mm cylinders and was observed to decrease due to the addition of fibers, which may be attributed to the increase in air content. The mean values of the 21-day strength were HSC-0.0: 73 MPa, HSC-0.5: 66 MPa and HSC-1.0: 64 MPa.

Beams of three different sizes, three specimens in each size, were cast from each of the concretes. The specimens were geometrically similar (Fig. 1), with b = 90 mm and d = 90, 180 and 320 mm. The notches were cut with a diamond disc saw. The tests were performed at the age of 25-28 days in a closed-loop INSTRON servo-hydraulic system at constant CMOD rates, which were chosen to give peak loads in the HSC-0.0 specimens at approximately 3 minutes. The CMOD was measured with a clip gage mounted across the crack mouth. The midspan deflection was measured on the tensile face with an LVDT fixed to a yoke resting above the supports on the compressive face. Typical load-CMOD and load-deflection curves of the three concretes are shown in Figs. 3a-c and 4a-c. The size effect method of Bažant and linear regression (RILEM, 1990) were used to determine the fracture parameters of the plain concrete HSC-0.0. The values obtained were K_{Ic} = 36.1 MPa-mm$^{0.5}$ and c_f = 30.6 mm.

The plots of deflection versus CMOD for all the specimens tested are presented in Fig. 5. This shows an approximately unique relation, which is practically linear in the post-peak regime as for LEFM (see Fig. 2c). This trend suggests that toughness measures determined on the basis of CMOD can be compared to those based on deflection, for all practical purposes, using a simple relation. Therefore, the following discussion will focus only on the load-CMOD response and its utilization for the calculation of toughness measures, especially since the measurement of CMOD is more straightforward and less prone to errors than the deflection.

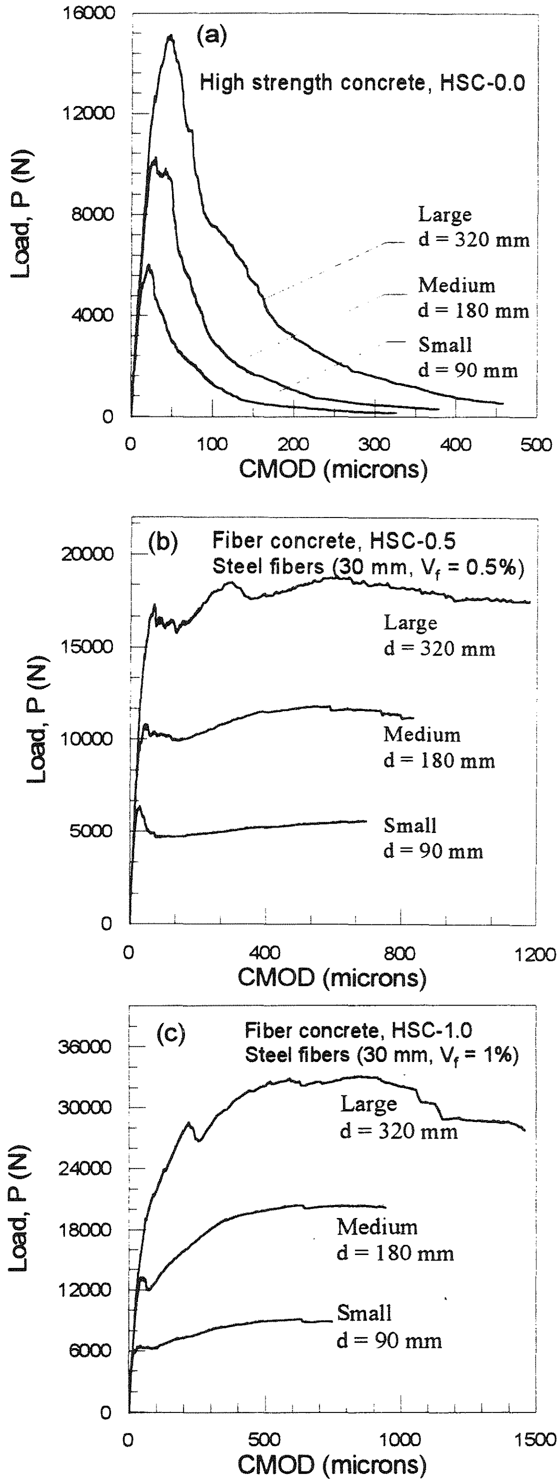

Fig. 3. Typical load-CMOD curves for concrete (a) without fibers, (b) with 0.5% fibers, and (c) with 1.0% fibers

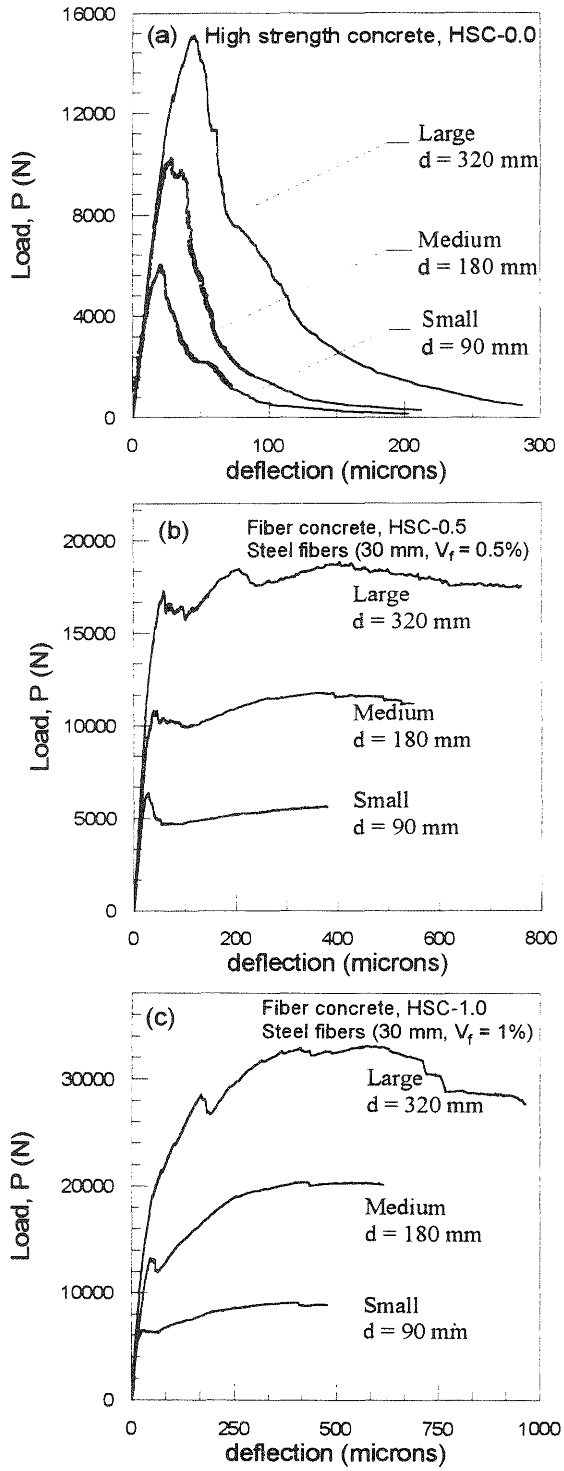

Fig. 4. Typical load-deflection curves for concrete (a) without fibers, (b) with 0.5% fibers, and (c) with 1.0% fibers

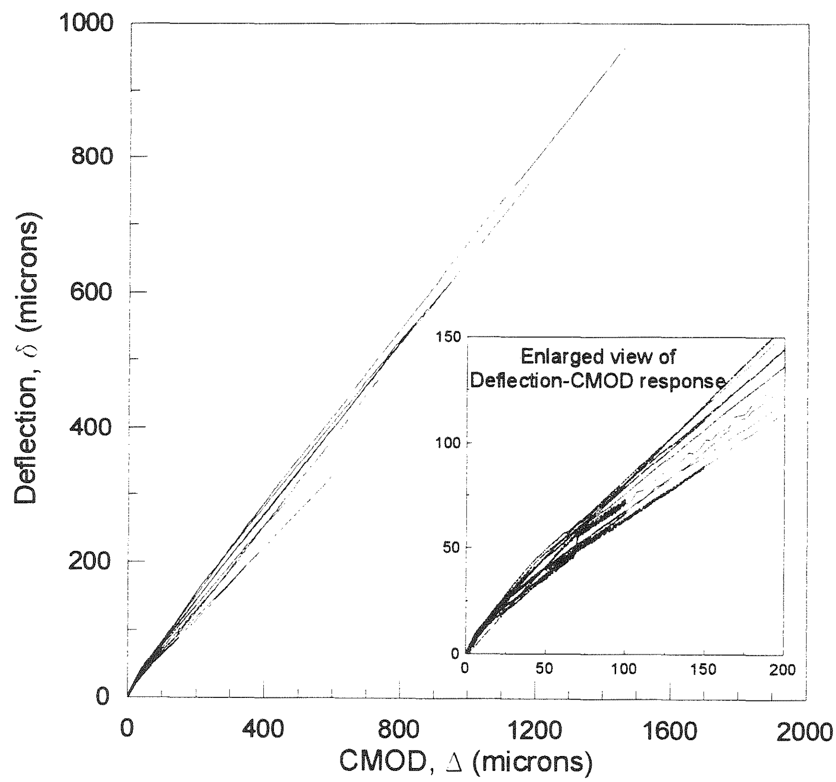

Fig. 5. Typical deflection-CMOD responses of all the concretes

4 Toughness based on the load-CMOD response

The typical evolution of the area under the load-CMOD curves of the different concretes is shown by Figs. 6a-c. These curves demonstrate the post-crack load carrying capacity and the energy absorbed during the cracking of the different specimens. Obviously, much more energy is absorbed during the cracking of the FRC specimens than in the unreinforced ones. The initial parts of the curves are almost identical implying that the matrix-dominated response of the concrete is not affected by these fiber volumes. The shape of the curve also indicates the type of failure behavior: a decreasing slope and a final plateau indicate softening-type behavior (as in LEFM; see Fig. 2b); a linearly increasing curve indicates plastic-type behavior; and a monotonically increasing slope indicates hardening-type behavior. It is clear that there is an increasing tendency towards hardening-type behavior with an increase in fiber volume and an increase in specimen size. It can be concluded that even a low volume fraction (0.5%) of steel fibers is sufficent to increase the ductility of high strength concrete significantly. Since the area under the load-CMOD

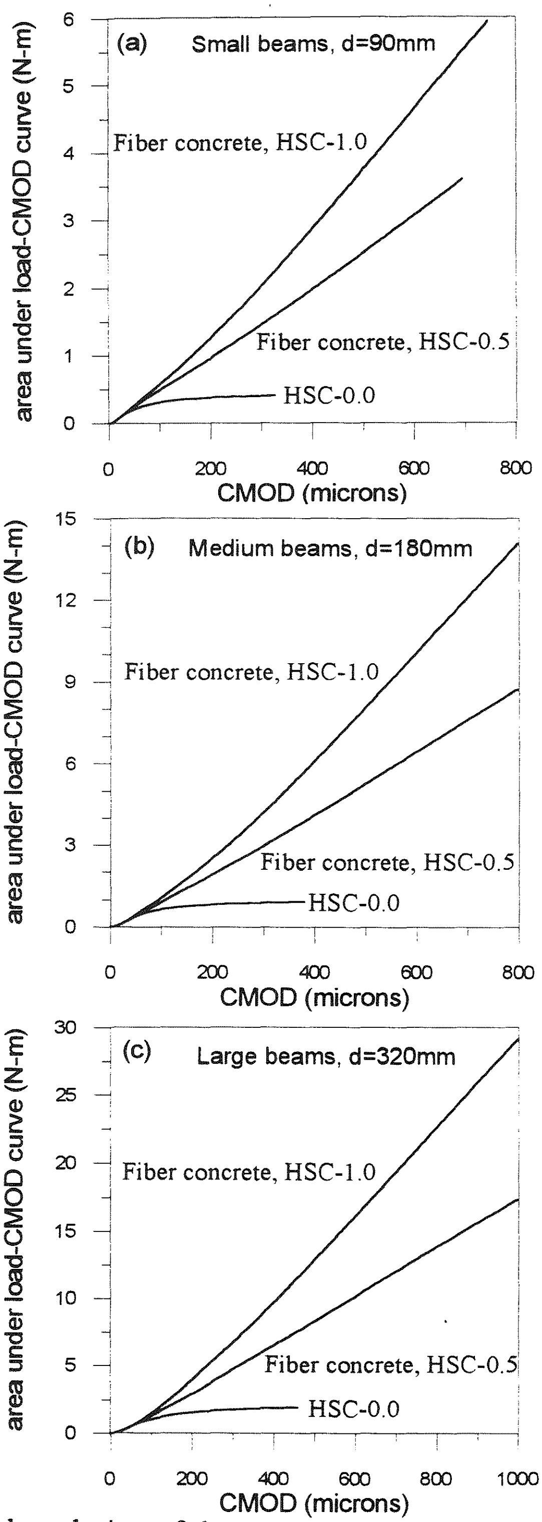

Fig. 6. Typical evolution of the area under the load-CMOD curve for (a) small, (b) medium, and (c) large beams

high strength concrete significantly. Since the area under the load-CMOD curve reflects the effectiveness of the fibers adequately, the definition of toughness measures based on this aspect of the behavior is promising.

Table 1. Average toughness values for different concretes based on load-CMOD area

Material	d (mm)	T_n^A = area until CMOD limit d/n (N-m)				$T_n^E = T_n^A$ / ligament area (N/mm)			
		n=2000	n=1000	n=500	n=250	n=2000	n=1000	n=500	n=250
HSC-0.0	90	0.195	0.301	0.379	---	0.033	0.051	0.065	---
	180	0.604	0.800	0.912	---	0.051	0.068	0.078	---
	320	1.396	1.771	---	---	0.069	0.085	---	---
HSC-0.5	90	0.221	0.447	0.903	1.90	0.038	0.076	0.154	0.324
	180	0.839	1.793	3.882	8.39	0.071	0.153	0.331	0.714
	320	2.321	5.188	11.151	22.35	0.111	0.248	0.534	1.071
HSC-1.0	90	0.234	0.546	1.243	3.94	0.040	0.093	0.217	0.671
	180	0.925	2.165	5.187	12.18	0.079	0.184	0.442	1.037
	320	2.629	6.368	14.825	29.62	0.126	0.305	0.710	1.418

Note that values are omitted when the experimental CMOD range is smaller than the limit.

The absolute load-deflection area is used as the toughness measure by JCI (1984) and RILEM (1984) recommendations. A similar toughness measure T_n^A can be defined as the load-CMOD area until a CMOD of d/n. The average values of T_n^A are given in Table 1 for values of n = 250, 500, 1000 and 2000. It can be seen that T_n^A increases with V_f, for all n and d. For better comparison between the different sizes, the T_n^A can be divided by the unnotched ligament area and denoted as T_n^E. These values are also given in Table 1 and show that the T_n^E increases with specimen size, reflecting the greater effectiveness of the fibers in the larger specimens.

To quantify the relative performance of the fibers, German standards (DBV, 1992) define toughness as the difference between the energies absorbed by the FRC and plain concrete specimens until a certain limit. An analogous relative toughness measure is defined here as $T_n^{Er} = T_n^E$ (for FRC) - T_n^E (for unreinforced concrete). These values are tabulated in Table 2 for the two FRCs. They indicate clearly the increase in fiber effectiveness with V_f and specimen size. Instead of requiring the casting and testing of a companion specimen of plain concrete, an analytically obtained curve can be used, as in the German standard (DBV, 1992).

In general, it can be stated that the load-CMOD area is a good basis for defining the toughness of FRC, and that the toughness is dependent on the specimen size and the CMOD limit (i.e., d/n).

Table 2. Fiber Contribution to Toughness

Material	d (mm)	T_n^{Er} (N/mm)		
		$n = 2000$	$n = 1000$	$n = 500$
HSC-0.5	90	0.005	0.025	0.089
	180	0.020	0.085	0.253
	320	0.042	0.163	---
HSC-1.0	90	0.007	0.042	0.149
	180	0.028	0.116	0.364
	320	0.057	0.220	---

5 Conclusions

1. The area under the load-CMOD curve obtained experimentally from notched beam tests provides a satisfactory basis for the toughness characterization of FRC. This procedure avoids the problems associated with deflection measurements and with the identification of the first-crack load.

2. The toughness measures defined in this work reflect the effectiveness of the fibers adequately.

3. There is a significant influence of the specimen size on the toughening achieved by the fibers.

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