On the Strengthening of Structural Concrete Beams with Polymeric Fibers

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Abstract. A study has been made of the effect of short randomly dispersed polypropylene fibers on the fracture behavior of lightweight structural concrete. The concrete mixture was prepared using expanded clay as coarse lightweight aggregate and a superplasticizer was added in order to enhance fiber dispersion throughout the mixture. Plain and fiber reinforced concrete fracture test specimens were cast and appropriate toughness parameters were determined. Different approaches were adopted for toughness evaluation, using unnotched and precracked beams subjected to bend loading, whereby it was possible to determine the toughness factor TF and to estimate specific J integral parameters, namely J_{Ic} and J_{max} corresponding to the onset of fracture initiation and to the attainment of ultimate load, respectively. The results have indicated a considerable improvement in the fracture behavior associated with the presence of fibers. More specifically this improvement was manifested by a 400% increase in both TF and J_{Ic}. Finally the results are presented and discussed focusing on the comparison between the different test methods adopted in the study.

Introduction

It is well known that the presence of short randomly dispersed fibers in a cementitious matrix can result in an appreciable improvement in the mechanical behavior of the produced composite. This improvement is clearly manifested by the significant superiority of the composite´s toughness in comparison with that of the plain matrix. The increase in toughness, due to the incorporation of fibers, can be attributed, largely, to the fiber bridging mechanism, whereby the fibers take an active part in supporting tensile loading, in controlling matrix microcracking and in reducing the rate of crack propagation. The fiber reinforced concrete will, therefore, exhibit a pseudoductile behavior, maintaining considerable load carrying capacity after cracking of the matrix.

Starting early seventies, a number of studies [1-4] have been made regarding the use of natural fibers, such as sisal and bamboo, as reinforcing elements in cement mortars and in concretes. The focus in these works has been on the evaluation of the mechanical properties of the resulting composites as a function of the characteristics of their constituents, and the results obtained have indicated the viability of using natural fibers as reinforcing agents in cementitious matrices. However, the susceptibility of natural fibers to degradation due to ambient and biological factors implies in a significantly reduced durability of the fiber composite material, and hence the use of synthetic fibers, as has been the case, represents a viable alternative. In addition to being resistant to attacks by bacteria and fungi, polymeric fibers, such as polypropylene and polyethylene fibers, are not reactive to cement hydration products, thus implying in a good durability of composites reinforced with such fibers.

The present work was initiated with the purpose of evaluating the effect of the presence of short randomly dispersed polypropylene fibers on the toughness of hardened lightweight concrete. Different methodologies for toughness testing were adopted and appropriate toughness parameters were determined for the fiber reinforced concrete, which were then compared with those of the concrete in the absence of fibers. The toughness levels are presented and discussed focusing on the comparison between the test methods and on the influence of fiber presence in improving fracture behavior of the concrete.

Materials and Experimental Procedure

The concrete mixture used in the present study was prepared aiming at achieving a 30 MPa compressive strength level for the hardened lightweight concrete. Accordingly, the mixture was composed of Portland cement PC II E 32, washed dry sand and expanded clay in the respective proportions of 608, 570 and 240 kg per cubic meter of the concrete. Water-cement ratio was taken as 0,38 and a superplasticizer was added in the proportion of 1.5% of the weight of cement. The high cement and sand contents of the concrete mixture also had the purpose of producing an adequate volume fraction of cement mortar so as to promote a uniform distribution of the fibers throughout the hardened concrete.

The expanded clay used as lightweight coarse aggregate had an apparent density of 380 kg/m^3 and was composed of rounded particles (9.5 mm maximum diameter), with a vitrified, almost impermeable, surface. The sand used as fine aggregate had a fineness modulus of about 3.33, a maximum particle diameter of 2.38 mm and an apparent density of 1.6 g/cm^3. As to polypropylene fibers, these were 100 μm in diameter and had an aspect ratio of 500 and density of 0.91 g/cm^3. In fact, a mass of one kg was found to contain about 2.8×10^6 fibers.

Homogenization of the concrete mixture was carried out using a slow rotating vertical propeller and no significant segregation of expanded clay was observed. As to the production of the reinforced concrete, the polypropylene fibers were added gradually, along the homogenization process, in the proportion of 1.5% of the cement weight. This proportion, which amounts to a total fiber volume fraction of approximately 0.02, was defined considering the necessity of maintaining the level of the concrete compressive strength within acceptable limits.

Compression tests were carried out to determine the compressive strength f_c, modulus of elasticity E and Poisson´s ratio υ, using cylindrical specimens that were cast from the plain and fiber reinforced concrete mixtures. Fracture testing, on the other hand, was aimed at evaluating the toughness of both cast materials by adopting three different methodologies. The first method, which is based on linear elastic fracture mechanics, makes use of a precracked cylindrical specimen (Fig. 1) to be loaded in diametrical compression.

The critical stress intensity factor K_{Ic} can be estimated from the expression [5].

$$K_{Ic} = \frac{2P_{max}}{LD}\sqrt{\frac{a}{\pi}}\, f(2a/D) \quad (1)$$

where P_{max} is the maximum load. L, D and a, which are shown in Fig. 1, are equal to 200, 100 and 17.5 mm, respectively and the function f for 2a/D = 0.35 [6] is equal to 1.20.

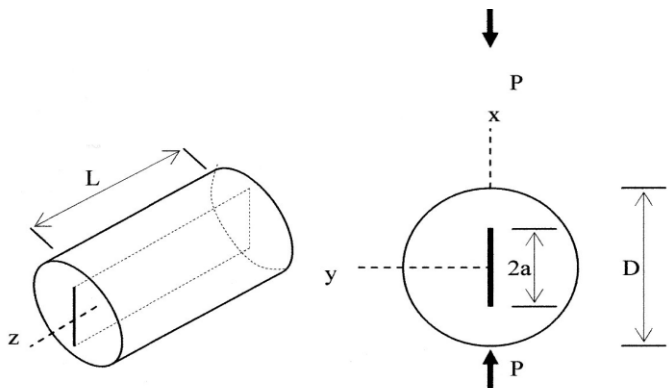


Fig. 1. Geometry of the centrally cracked cylindrical specimens.

The second method [7] is based on determining the work done T_b on achieving a beam deflection equivalent to L/150 in four point bending of unnotched prismatic beams (Fig. 2). This work, which is represented by the area under the load-deflection curve, can be used to calculate the toughness factor TF as [7]

$$TF = \frac{T_b}{\delta_{tb}}\frac{L}{bh^2} \quad (2)$$

where L is the beam span, b and h are the dimensions of the beam cross section (10x10 cm) and δ_{tb} is the beam deflection.

The third adopted approach, for toughness evaluation, is based on determining the J integral value corresponding to specific physically significant events observed during loading of precracked specimens. The specimens, which had the geometry and dimensions depicted in Fig. 2, were precracked in its midsection to a crack-width ratio a/W of 0.5. The precracked beams were then subjected to four point bend loading and J values were calculated using Rice´s estimation formula [8].

$$J = \frac{2U}{B(W-a)} \quad (3)$$

where B and W are the beam cross sectional dimensions, equivalent to b and h. The term U in the above formula refers to the amount of energy stored in the beam for a given applied load, as for example fracture initiation load.

The precrack root radius amounts to 1 mm, which, in virtue of the heterogeneous nature of the concrete, is considered to be sufficiently sharp and therefore the J integral value corresponding to the onset of fracture initiation would seem to be a fairly good estimate of J_{Ic}.

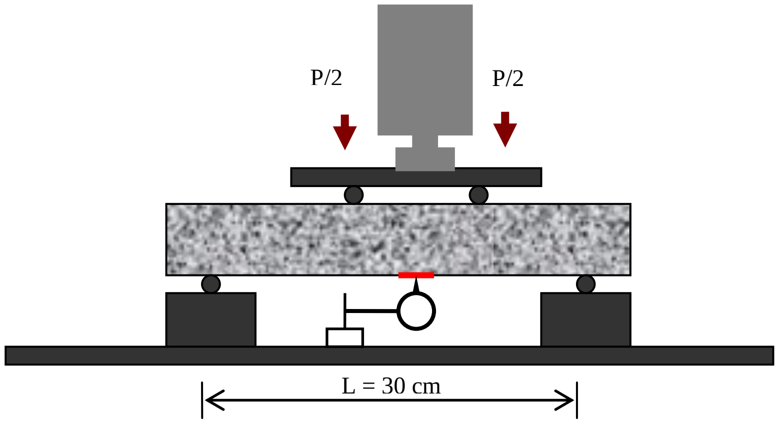


Fig. 2. Schematic of the setup used for four point loading of the concrete beams.

Results and Discussion

The values of the compressive strength f_c, modulus of elasticity E and Poisson´s ratio υ of the plain concrete are presented in Table 1, together with those corresponding to the fiber reinforced concrete. The K_{Ic} values obtained using Eq. 1 are also listed in the same table.

Table 1. Mechanical properties for the concretes in question

Concrete	f_c (MPa)	E (GPa)	ν	K_{Ic} (MPa$\sqrt{m}$)
Plain	30 ± 2.0	27 ± 1.5	0.21	0.37 ± 0.01
Reinforced	24 ± 1.0	23 ± 0.5	0.25	0.36 ± 0.02

These results indicate that the presence of fibers is associated with a reduction in concrete compressive strength and modulus of elasticity. This is attributed to the fact that fibers do not take an active part in supporting the compression load applied during the test.

Examples of the loading curves obtained in diametrical compression are presented in Fig. 3, where one can verify the marked influence of fiber presence on the concrete behavior. Whereas rupture of the plain concrete occurred in an unstable manner, the reinforced concrete continued to deform with a gradual drop in the applied load.

At this point, it is important to mention that Eq. 1 can be considered applicable to the plain concrete, as its loading curves are essentially linear elastic. However, this cannot be stated with regard to the fiber reinforced concrete, given its nonlinear behavior as exhibited in Fig. 3 and therefore the corresponding K_{Ic} value listed in Table 1 does not reflect the reality of the fracture behavior. A more realistic estimate of the fracture toughness in this case may be obtained by substituting P_{max} in Eq. 1 by P_{max} given by the expression

$$P'_{máx} = \left(\frac{2}{C} \int_0^{\delta_m} P d\delta \right)^{1/2} \tag{4}$$

where C is the specimen compliance represented by the inverse of the gradient of the linear part of the P-δ curve and δ_m is the load displacement corresponding to P_{max}.

A more adequate approach to establish a relevant comparison between the toughness values of fiber reinforced and plain concretes can be based on determining T_b and then calculating TF using Eq. 2. Alternatively, one can adopt the J integral approach to estimate J_{Ic} and/or J_{max} to be calculated for both materials using Eq. 3.

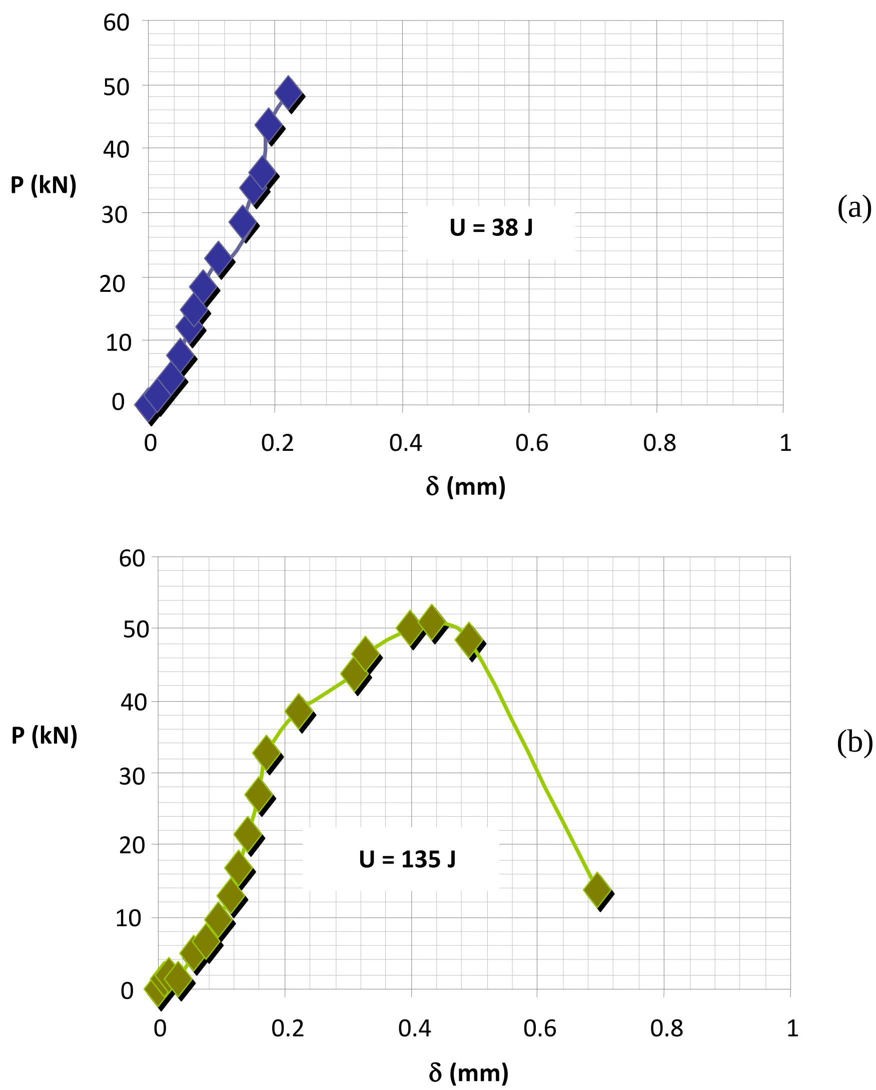
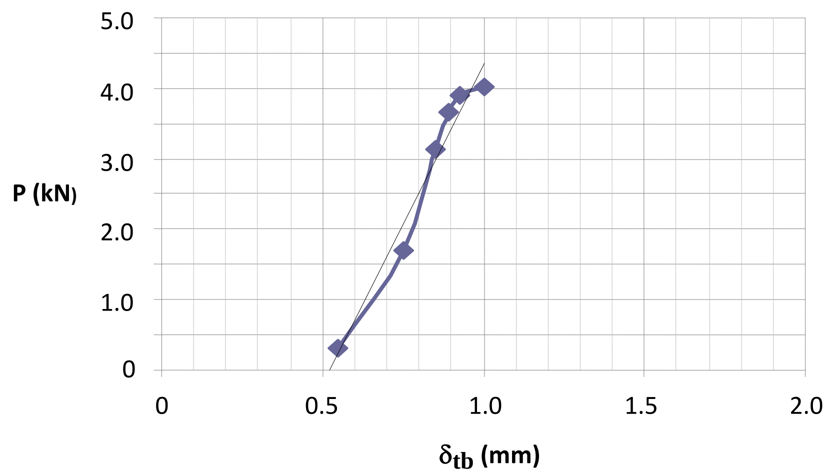


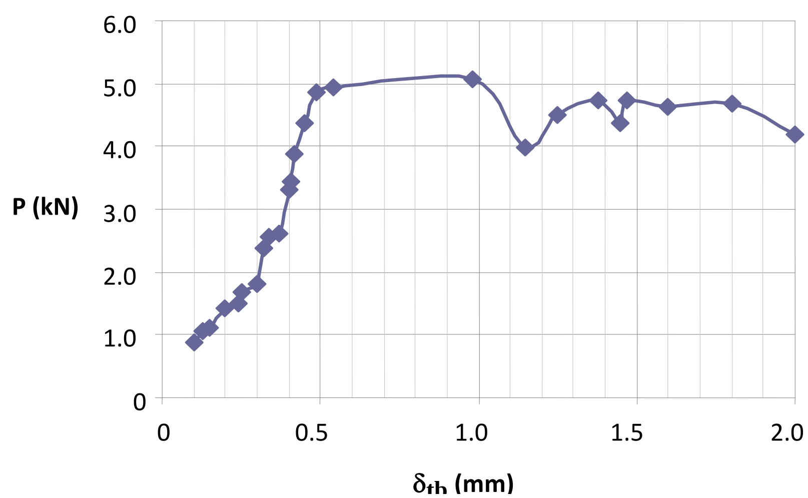
Fig. 3. Load-deflection curves in diametrical compression for plain concrete (a) and fiber reinforced concrete (b).

Examples of the load-deflection curves obtained on the basis of these two approaches are presented in Fig. 4 and 5. The values of T_b, TF, J_{Ic}, K_{Ic} and J_{max} are given in Table 2 for the concretes in question. One should point out that the J_{Ic} values listed in this table were estimated based on the assumption that the onset of fracture initiation in the reinforced concrete takes place essentially at the proportionality limit load. It is also to be added that K_{Ic} values were calculated from the relation.

$$J_{Ic} = \frac{K_{Ic}^2(1-\nu^2)}{E} \tag{5}$$



(a)



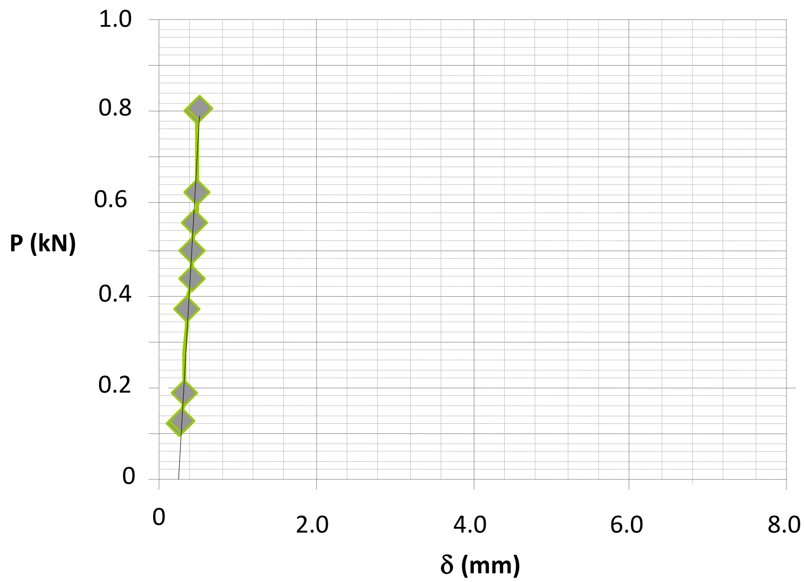
(b)

Fig. 4. Typical load deflection curves obtained in four point bending of unnotched beams for plain concrete (a) and fiber reinforced concrete (b).

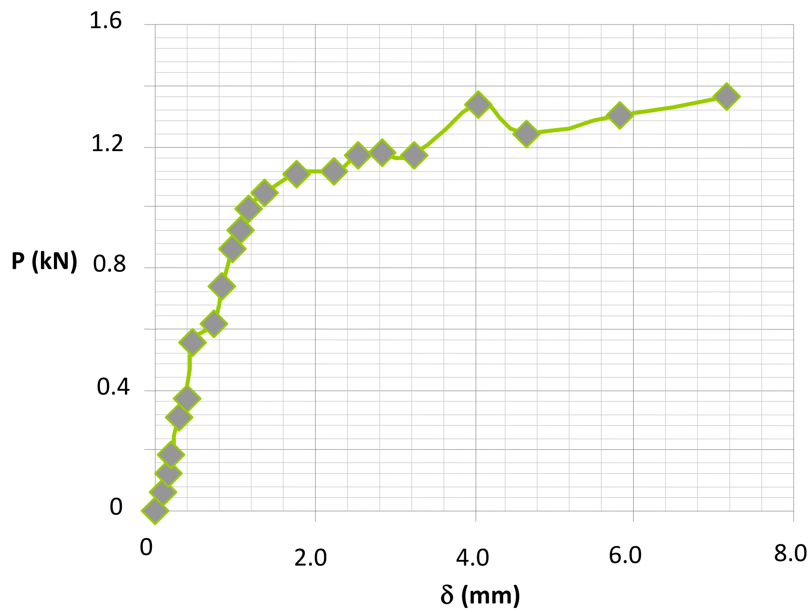
Table 2. Toughness parameters as determined for the concretes in question

Concrete	T_b [J]	T_F [MPa]	J_{Ic} [J/m^2]	K_{Ic} [MPa]	J_m [J/m^2]
Plain	1.12$\pm$0.23	0.18$\pm$0.03	68$\pm$12	1.39	68$\pm$12
Reinforced	5.00$\pm$1.12	0.75$\pm$0.19	306$\pm$106	2.74	2916$\pm$700

One can observe from the data listed in the above table that both T_b and TF corresponding to the fiber reinforced concrete are almost five times greater than their respective plain concrete counterparts. This is simply due to the fact that, whereas a δ_{th} level of 2 mm (= L/150) is easily achieved in the four point loaded reinforced concrete beams, a maximum deflection of about 0.5 mm is reached on failure of the plain concrete (Fig. 4a).



(a)



(b)

Fig. 5. Typical load deflection curves obtained in four point bending of precracked beams for plain concrete (a) and fiber reinforced concrete (b).

The J_{Ic} data can be rationalized taking into account the fact that fracture initiation in the fiber reinforced precracked beams occurs at higher loads in comparison with the plain concrete beams. Given the additional fact that the beam deflection at the initiation load is also higher in the presence of fibers, the energy term U, in Eq. 2, and consequently J_{Ic} will be higher for the fiber reinforced concrete. Higher J_{max} level, on the other hand, is evidently related to higher beam deflection corresponding to the maximum load. As the fibers play an important role in maintaining the integrity of loaded beams following matrix cracking, high δ_m levels are expected to be achieved in fiber reinforced concrete. This is borne out by the loading curves depicted in Fig. 5 and by the J integral data reported in Table 2.

Although a large degree of scatter characterizes the J integral results, they are seen to agree well with the results obtained from the unnotched four point loaded beams. Both results point out unambiguously to the fact that the addition of polypropylene fibers to lightweight structural concrete results in a considerable increase in J_{Ic}, T_b and TF parameters by a factor of about five and also in achieving high J_{max} levels, consistent with the increase in load carrying capacity as the beam continues to deform.

Conclusions

The addition of short polypropylene fibers, in the proportion of 0.02 volume fraction, to lightweight concrete mixture results in a reduction of about 25% and 15% in the concrete axial compressive strength and modulus of elasticity respectively. However, the presence of the fibers improves considerably the fracture behavior of the hardened concrete as manifested by the increase in its toughness level.

Toughness parameters obtained from bend tests of both unnotched and precracked beams are seen to be convergent. More specifically the results indicate a more than four fold increase in the TF and the J_{Ic} parameter in virtue of the presence of polypropylene fibers.

As the fibers retard and thereafter control cracking of the concrete, the beam integrity is maintained and the J integral value at the maximum load is significantly increased due to fiber presence.

References

[1] R.T. Fujiyama: M.Sc. Thesis, Catholic University of Rio de Janeiro, PUC-Rio (1997).

[2] J. Brescansin: M.Sc. Thesis, Catholic University of Rio de Janeiro, PUC-Rio (2003).

[3] A. T. Sales: D. Sc. Thesis, Catholic University of Rio de Janeiro, PUC-Rio (2006).

[4] E. F. Campello: M.Sc, Thesis Catholic University of Rio de Janeiro, PUC-Rio (2006).

[5] M.D. Moseley, R.P. Ojdrovic and H.J. Petroski: Theoretical and Applied Fracture Mechanics Vol. 76 (1987), p. 207.

[6] H. Tada, P.C. Paris and G.R. Irwin, in: *The Stress Analysis of Cracks Handbook*. Paris Productions Incorporated (1985).

[7] Japan Society of Civil Engineers. *Method of tests for flexural strength and flexural toughness of steel fiber reinforced concrete*. SF4, Part III-2, 3 (1984).

[8] J.R. Rice: J. Appl. Mech. Vol. 35 (1968), p. 379.