# Fracture toughness of polypropylene fibre concrete

*B. I. G. Barr*, W. T. Evans** and R. C. Dowers****

**SYNOPSIS**
The paper describes two simple tests which have been developed to determine the fracture toughness of concrete materials. In the first case, the test is carried out using ordinary concrete cubes, modified by the introduction of two slits, and then subjected to an eccentric load. In the second case, CTS specimens are used to evaluate fracture toughness. Tests have been carried out using a 'stiff' Instron testing machine and a 'soft' hydraulic bench-mounted test rig. The fracture toughness is determined from the load at crack initiation. The effect on fracture toughness of introducing various amounts of polypropylene fibre into a concrete mix is discussed. The results show that there is very little variation in fracture toughness values, as determined by this test, for the range of fibres added. However, the complete load-displacement curve during the fracture process shows considerable variation.

**KEYWORDS**
Fracture strength, fibre reinforced concrete, polypropylene fibres, notch tests, cracking (fracturing, crack propagation, testing toughness, energy dissipation, split-cube test, CTS specimens, strength of materials, failure.

**INTRODUCTION**

Kaplan [1] was the first to apply fracture mechanics concepts to investigate the failure of concrete. In his experiments Kaplan used rectangular beams containing sharp, uniform V-notches which were subjected to three or four-point bending. Other workers [2,3,4] in the 1960s used similar notched beams to determine fracture toughness.

In the 1970s a large number of test specimens were introduced and developed to evaluate fracture toughness for concrete materials. A comprehensive review of the application of fracture mechanics to concrete has been given by Swamy [5]. This work is of particular interest as it reviews the available test results to date.

Carpinteri [6] and Saouma, Ingraffea and Catalano [7] have recently applied fracture mechanics to the study of the fracture characteristics of concrete with some interesting results. A review of the literature on the application of fracture mechanics to fibre reinforced and polymer impregnated cements and concretes has been given by Mindess [8]. The paper by Mindess was one of five in a recent issue of this Journal devoted entirely to papers on the application of fracture mechanics to cement and concrete.

The first test geometry described in this paper is a development of two tests used by Bear and Barr [9] to evaluate the fracture toughness of rocks and mortar. In the first test circumferentially notched round bars were

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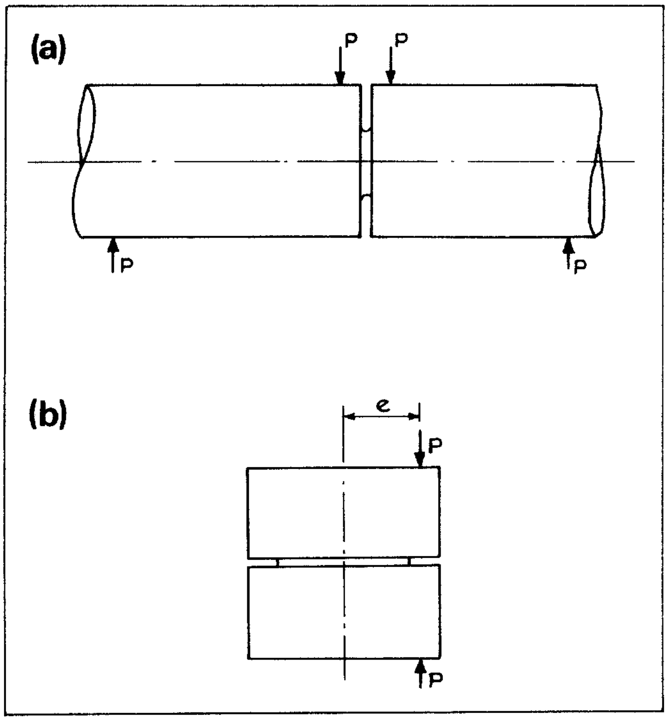


**Figure 1 Circumferentially notched round bar test specimens. (a) Test specimen subjected to four-point bending (b) Test specimen subjected to eccentric loading**

subjected to four-point loading as shown in Figure 1(a) and in the second test similar specimens were subjected to an eccentric longitudinal load as shown in Figure 1(b). It can be seen that the bend specimen and the eccentrically loaded specimen are similar to the standard bend and compact tension specimens used to evaluate the fracture toughness of high-strength metals. The loading system shown in Figure 1(a) has been used by Javan and Dury [10] to determine the fracture toughness of fibre concrete.

Due to the relatively small dimensions of the test specimens described in [9], the tests were limited in their application to rocks and mortars. However, the split-cube test developed by Barr *et al.* [11] may be used for ordinary concrete mixes. The split-cube test is carried out using modified concrete cubes loaded as shown in Figure 2. This paper describes the application of the split-cube test to determine the fracture toughness of polymer fibre reinforced concrete. The second testing geometry used in the experimental work was based on the traditional compact tension specimen developed for testing high strength metals. Two types of notches were used — notches cut by the 'Clipper' and notches which were cast or 'inbuilt' into the test specimen. The same variation of fibre content was used for both the split-cube and CTS specimens.

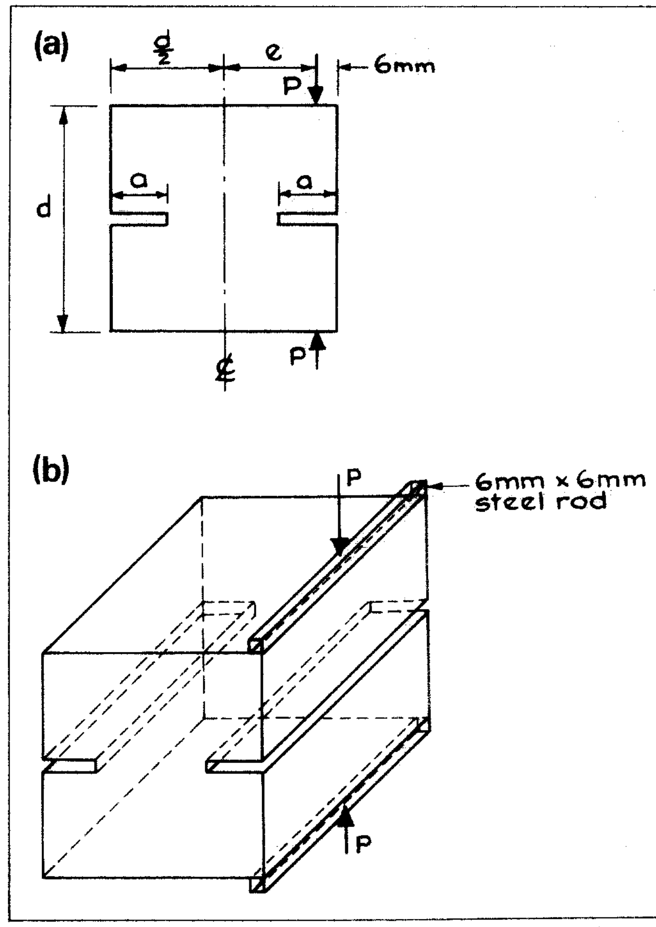


**Figure 2 Geometry and loading details of test specimen. (a) Geometrical details of split-cube (b) Loading arrangement for split-cube**

## EXPERIMENTAL DETAILS

One of the major objectives of the experimental work described here and in previous work [9] and [11] has been to develop simple fracture tests based, if possible, on the normal quality control samples, i.e. cylinders and cubes. It was also considered that if such a test was to become widely accepted, the specimen preparation and testing apparatus would need to be kept as simple as possible.

**Test Geometry** The first series of tests were carried out using modified 100 mm cubes. The cubes were notched by means of a 'Clipper' masonry saw along two opposite faces as shown. For the tests described here, the notch depth was kept constant at 30 mm. (When this testing system was used to determine the fracture toughness of ordinary concrete [11], there were no noticeable notch depth effects.) The 30 mm depth of cut was chosen for two main reasons. Smaller notch depths often result in shear failures of the specimens near the point of loading while deeper notches result in small areas of uncut concrete which may introduce problems related to the aggregate size used in the concrete.

The split-cubes were loaded as shown in Figure 2, the load being applied via two 6 mm square, 100 mm long, steel bars. These bars were positioned parallel to each other, at the edges of the test specimen, as shown. The point of application of the load was taken at the edge of the steel bars nearest the notch-root since, as deformation took place, the load was concentrated to these edges.

The specimens were tested using two loading systems. A 1251 Model Instron machine was used to provide a 'stiff' testing machine and a hydraulic bench-mounted rig [12] was also used in the testing programme. The results from the 'soft' test rig were compared with the results from the Instron machine. All tests were carried out at nominal room temperature and the strain rate for the Instron was kept constant at $10 \times 10^{-3}$/sec.

For the second series of tests, compact tension specimens (CTS) were used as shown in Figure 3. Unfortunately, it was not possible to exactly simulate the standard ASTM specimen due to problems encountered with the machining of the loading holes in the specimen. As a result, the load was applied by means of polyester straps loading the two cantilever arms with the line of action of the load still being located at the correct distance from the notch-root.

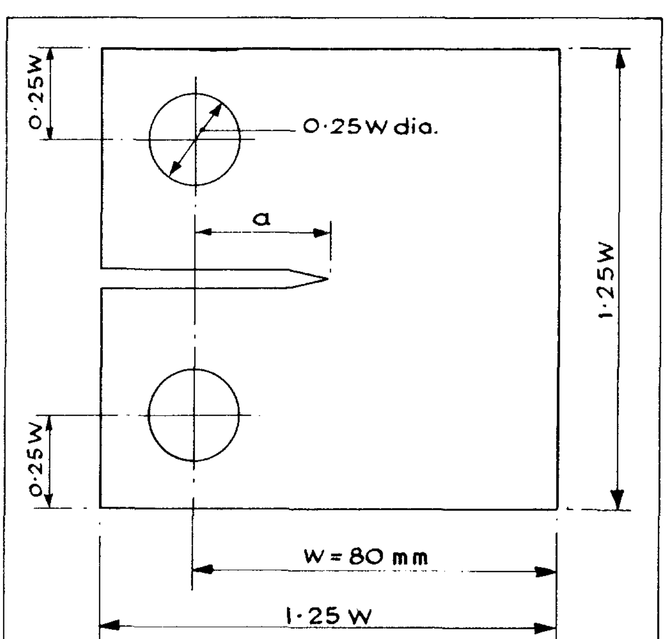


Figure 3 Compact tension specimen details

Notching of the compact tension specimens was carried out by two methods. The first involved the adaption of standard 100 mm cube moulds to incorporate a plate so that a notch was effectively 'cast-in'. The second method made use of the 'Clipper' to insert a notch after fabrication. It is possible to obtain two specimens from one 100 mm cube as the required breadth to satisfy ASTM requirements is 40 mm. All the CTS specimens were loaded in the Instron.

**Mix Details** The concrete used was a mix of 1 : 1.8 : 2.8, cement : fine aggregate : coarse aggregate. The cement used was Aberthaw OPC, the fine aggregate was dredged sand corresponding to zone 3 grading and the coarse aggregate used was 10 mm single size. Full details of the mix are given in [12]. The water-cement ratio was kept constant throughout the work at 0.5 as this ratio gives a satisfactory workability for all mixes used. The constituents were mixed in a 2-cubic-foot pan mixer and the cubes compacted using a vibrating table.

The polypropylene fibre added to the above mix was of 12,000 denier (700 m/kg) in 50 mm single size strand. The fibres were added in percentages by weight (of the total wet solids) in multiples of 0.05 from 0.1% up to a maximum of 0.3%. The concrete was cured under water for 27 days.

The mixing of the fibre concrete was standardised as follows: First the dry constituents were mixed in the pan for one minute, the water being added during the next two minutes. The fibre was then added using a 25 mm sieve to shake the fibres into the mix in a random, but uniform manner. The total load was then mixed for a further minute. Using this method no noticeable 'balling' of the fibres occurred, the fibres were reasonably uniform in distribution and the necessity for admixtures to aid the introduction of the fibre did not arise.

**Stress intensity factor** Finite element solutions for the split-cube shown in Figure 2 have been obtained for both 100 mm and 150 mm cubes [13]. Plane strain conditions were assumed and several notch depths were considered giving a range of crack length/specimen width ratios. Stress intensity factors are often expressed in terms of polynomial functions of the crack size/specimen width $(\frac{a}{d})$. The five $(\frac{a}{d})$ ratios considered in the finite element analyses enabled the results to be expressed in terms of five powers of $(\frac{a}{d})$, similar to those used for the compact tension specimen [14]. For 100 mm cubes, the following expression is obtained:

$$K_1 = \frac{P}{B d^{\frac{1}{2}}}\left[18.3\left(\frac{a}{d}\right)^{\frac{1}{2}} - 430\left(\frac{a}{d}\right)^{\frac{3}{2}} + 3445\left(\frac{a}{d}\right)^{\frac{5}{2}} - 11\,076\left(\frac{a}{d}\right)^{\frac{7}{2}} + 12\,967\left(\frac{a}{d}\right)^{\frac{9}{2}}\right]$$

where $K_1$ = stress intensity factor in opening mode
$P$ = load

B = width of specimen (100 mm)
d = depth and width of specimen (100 mm)
a = depth of slot

This expression for $K_1$ reduces to the simple form of:

$$K_1 = P\,Y$$

where Y is a function of notch depth ratio. In practice there were small variations in the notch depths introduced into the cubes and these variations were taken into account in the calculations.

The stress intensity factor for the CTS is given by:

$$K_1 = \frac{P}{BW^{\frac{1}{2}}}\left[29.6\left(\frac{a}{w}\right)^{\frac{1}{2}} - 185.5\left(\frac{a}{w}\right)^{\frac{3}{2}} + 655.7\left(\frac{a}{w}\right)^{\frac{5}{2}} - 1017\left(\frac{a}{w}\right)^{\frac{7}{2}} + 638.9\left(\frac{a}{w}\right)^{\frac{9}{2}}\right]$$

## TEST RESULTS

Only a summary of the test results obtained for varying geometry, loading arrangements and fibre content is given here. Detailed results for the tests carried out may be found elsewhere [12].

**Fracture toughness** The fracture toughness values obtained from the Instron tests and the hydraulic rig tests are given in Table 1 and Table 2 respectively and presented graphically in Figure 4. The addition of polypropylene fibre, in the percentages used, has little effect on the fracture toughness. The inability of the addition of fibres up to a maximum of 0.3% (by weight) to increase the fracture toughness may be attributed to several factors. The mix used was very 'rich' and the toughness of the plain concrete, itself, was high. Furthermore, some difficulty was experienced in obtaining satisfactory compaction of the fibre concrete which can result in an increased porosity of the concrete with increasing fibre content.

The results for the CTS specimens are given in Table 3 and illustrated in Figure 5. The results suggest that the overall effect of the different notch types is very small. This is surprising since for the inbuilt notch there is an area of cement paste surrounding the crack tip, whereas for the Clipper notch the crack front is a mixture of aggregate and paste. The close agreement of results for the two types of notch is probably due to the aggregate and cement paste having a similar toughness value.

**Load/deflection curves** Typical load/deflection graphs

**Table 1 Fracture toughness results using Instron machine**

| Fibre content (%) | Notch depth (mm) | No. in sample | $K_{1C}$ ($N/m^{\frac{3}{2}} \times 10^6$) | Coeff. of variation (%) |
|---|---|---|---|---|
| 0 | 30.3 | 9 | 0.614 | 6.4 |
| 0 | 30.6 | 10 | 0.563 | 8.1 |
| 0.10 | 31.0 | 7 | 0.529 | 5.2 |
| 0.15 | 30.7 | 7 | 0.514 | 5.8 |
| 0.20 | 30.4 | 27 | 0.514 | 7.8 |
| 0.20 | 30.1 | 37 | 0.487 | 11.8 |
| 0.25 | 30.8 | 14 | 0.522 | 3.8 |
| 0.30 | 31.0 | 7 | 0.565 | 4.7 |

**Table 2 Fracture toughness results using bench rig**

| Fibre content (%) | Notch depth (mm) | No. in sample | $K_{1C}$ ($N/m^{\frac{3}{2}} \times 10^6$) | Coeff. of variation (%) |
|---|---|---|---|---|
| 0 | 30.6 | 10 | 0.639 | 7.9 |
| 0 | 30.6 | 11 | 0.601 | 5.6 |
| 0.10 | 31.0 | 7 | 0.645 | 6.0 |
| 0.15 | 30.4 | 7 | 0.562 | 2.7 |
| 0.20 | 30.25 | 39 | 0.563 | 9.0 |
| 0.20 | 30.6 | 26 | 0.606 | 9.0 |
| 0.25 | 31.0 | 14 | 0.645 | 6.4 |
| 0.30 | 30.9 | 7 | 0.624 | 7.1 |

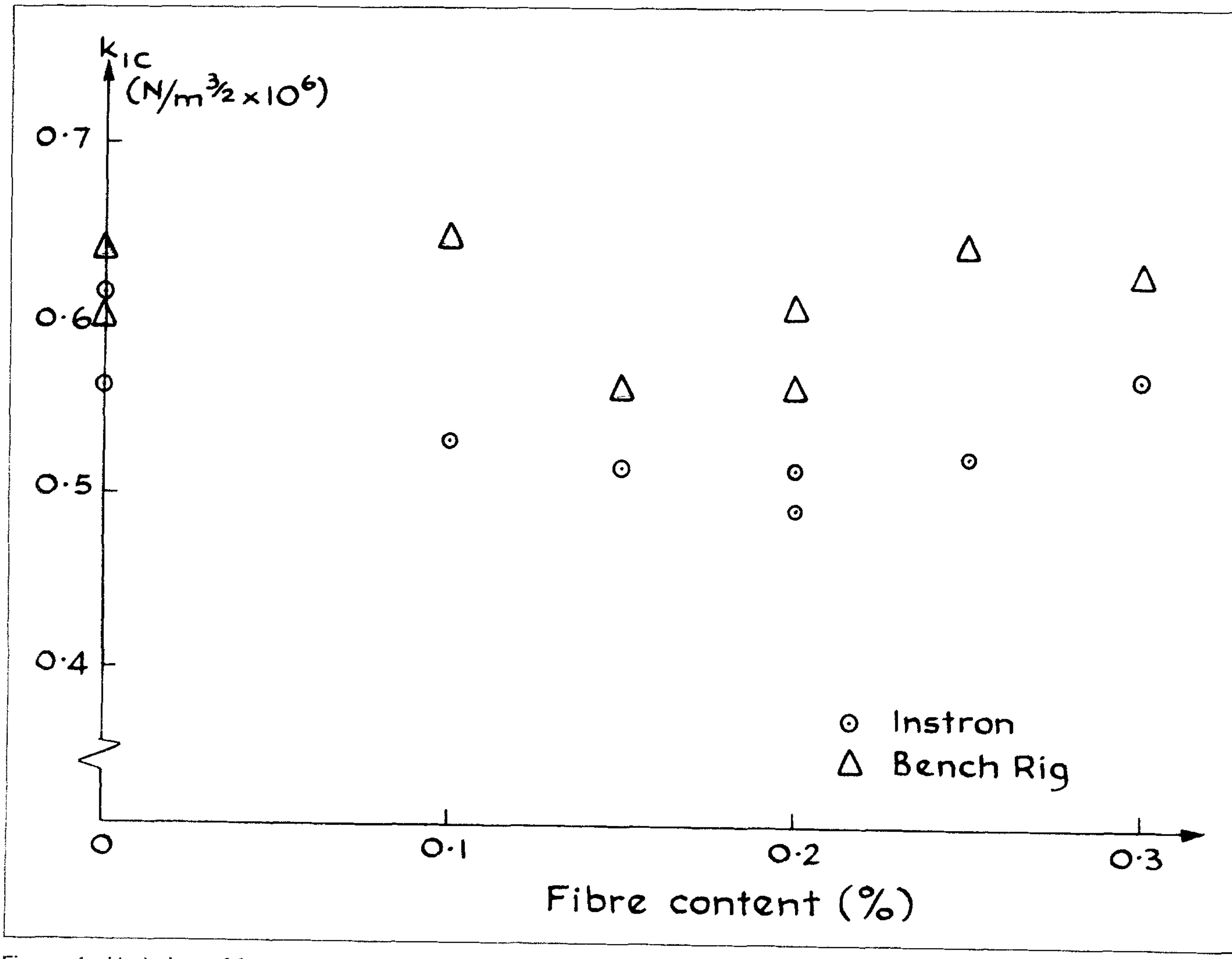


Figure 4 Variation of fracture toughness with fibre content

Table 3 Fracture toughness results for CTS specimens

| Fibre content (%) | Notch type | No. in sample | $K_{IC}$ ($N/m^{\frac{3}{2}} \times 10^6$) | Coeff. of variation (%) |
|---|---|---|---|---|
| 0.10 | Inbuilt | 8 | 0.670 | 9.6 |
| 0.10 | Clipper | 8 | 0.611 | 15.5 |
| 0.15 | Inbuilt | 16 | 0.663 | 12.2 |
| 0.15 | Clipper | 20 | 0.631 | 8.8 |
| 0.20 | Inbuilt | 8 | 0.688 | 7.8 |
| 0.20 | Clipper | 6 | 0.623 | 10.2 |
| 0.25 | Inbuilt | 16 | 0.649 | 8.8 |
| 0.25 | Clipper | 16 | 0.656 | 8.2 |
| 0.30 | Inbuilt | 8 | 0.645 | 9.9 |
| 0.30 | Clipper | 8 | 0.620 | 8.6 |

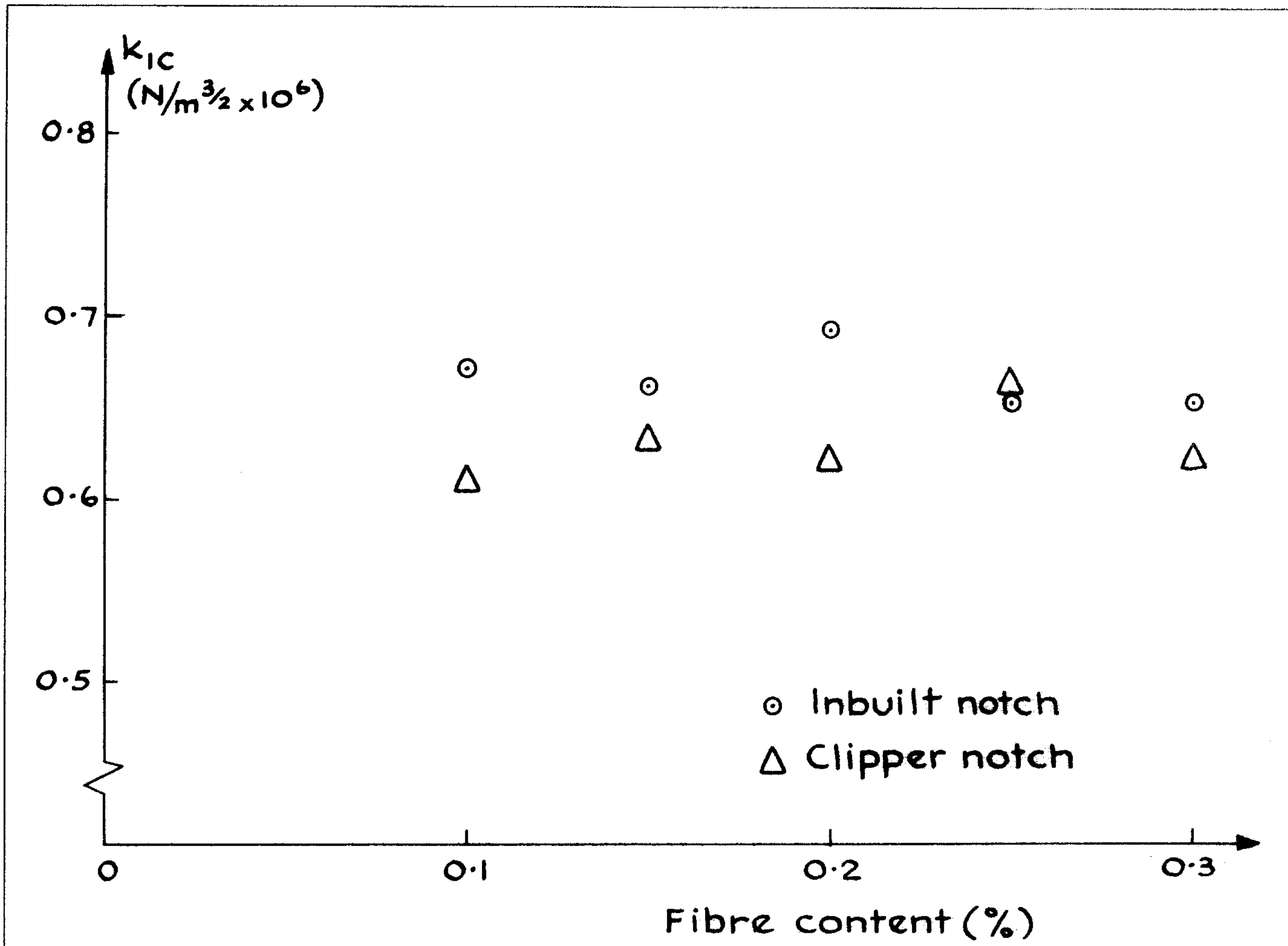


**Figure 5 Variation of fracture toughness for CTS specimens**

are shown in Figure 6. The curves show a linear relationship up to the point where the concrete fails and then the load reduces to a level of residual strength which is provided by the fibres. The residual load is more or less constant (a slight increase may be observed) for increasing deflection, with the value of the residual load increasing with increasing fibre content.

It is important to note that the fracture toughness results are based on the maximum load at failure of the concrete. Clearly this concept does not take account of the beneficial post-cracking behaviours of the material. The post-cracking behaviour is best described by a residual strength index which has been considered by a number of previous research workers, e.g. Nishioka *et al.* [15] and Henager [16].

## CONCLUSIONS

**1.** The results of the tests carried out on polypropylene fibre concrete for both specimen geometries indicate little or no change in the fracture toughness value over plain concrete. For the range of fibres tested and the grade of concrete used, the fracture toughness value obtained does not adequately reflect the useful properties of fibre reinforced concrete.

**2.** The load/deflection curves obtained in the tests using the two specimen geometries confirm that the material behaves linear elastically up to the 'first crack' load at which point the matrix fails. Thus the authors have some confidence in applying LEFM concepts in arriving at appropriate stress intensity factors.

**3.** The split-cube geometry has given reproducible results with low coefficients of variation. The specimens can be manufactured easily using standard moulds and notches inserted with sufficient accuracy even with a Clipper type bench saw. Provided that standard notch

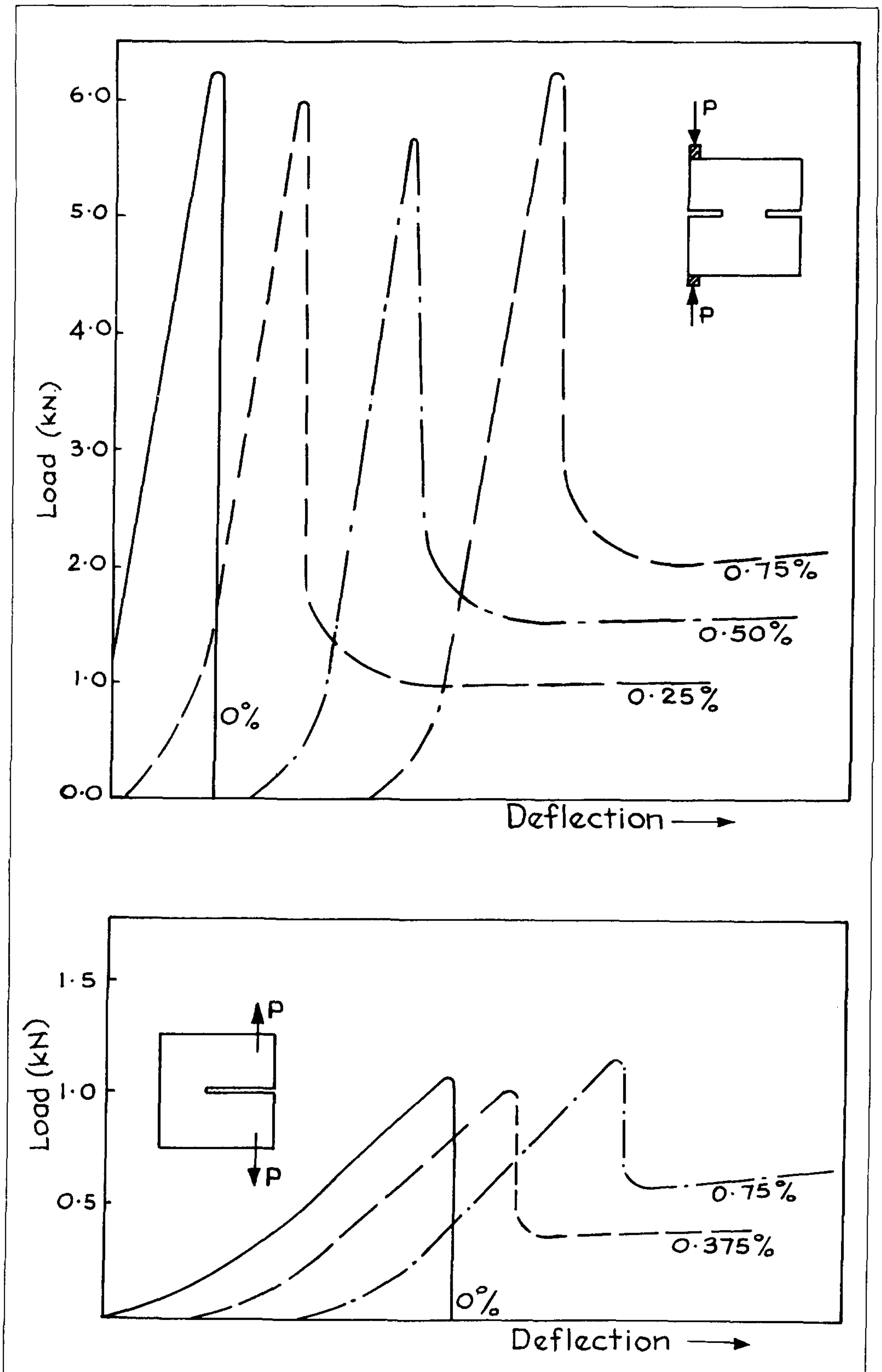


Figure 6
Typical load-deflection curves

depths are introduced into the cubes, the fracture toughness is directly proportional to the load at failure.

**4.** The results show that the tests can be carried out by means of 'soft' hydraulic bench mounted testing rigs which could quite easily be located in site testing laboratories.

**5.** Only a limited number of variables have been investigated in this study. The testing programme should be extended to include a study of the following:

(a) water-cement ratio (0.35 to 0.7)
(b) aggregate type, size, etc.
(c) range of mixes
(d) dimensions of cubes used (up to 300 mm)
(e) other composites (soil – cement)

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