FRACTURE ENERGY AND BRITTLENESS OF PLAIN CONCRETE SPECIMENS UNDER DIRECT TENSION

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Direct tension tests were conducted on plain concrete specimens in a stiff loading frame which allowed the complete stress–deformation relations to be obtained. The behaviour of notched and unnotched specimens with different water–cement ratios was examined and compared. Relationships between two fracture parameters, i.e. fracture energy and a brittleness index, and other basic mechanical properties were also investigated.

INTRODUCTION

In the behaviour of concrete structures, cracking is one of the most critical considerations and is characterized by a complete tensile stress–strain curve which includes nonlinear portions before and after peak stress. Previous research has shown that plain concrete has strain–softening properties, but not many experimental results in direct tension have supported this. Difficulties in obtaining such a complete stress–strain relationship lie in the geometry of the test specimens, and the need for a stiff testing machine and an accurate measuring system.

Rüsch and Hilsdorf(1), Gopalaratnam and Shah(2), Reinhardt et al.(3) have obtained accurate complete stress–deformation relations of plain concrete in direct tension, especially for notched specimens, but the correlation of results between notched and unnotched specimens is not well established. Furthermore, the effect of the water–cement ratio (w/c) on fracture parameters, in particular fracture energy and the brittleness index, and the relationships between both compressive and tensile strengths and these parameters in direct tension have not been systematically studied. This paper summarises part of a study which addressed these aspects of the fracture of plain concrete under direct tension.

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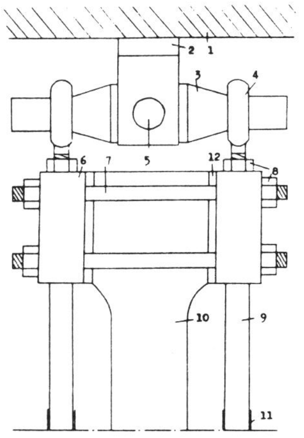
EXPERIMENTAL INVESTIGATION

Loading Frame

The uniaxial tension tests were conducted in a 2000 KN LOS universal testing machine which incorporated a specially designed stiff frame (Fig.1). This consisted of two parallel 32mm diameter mild steel bars connecting end pieces which gripped two opposite sides of the specimen at its ends, thereby transfering tension into the specimen by friction forces. Four bolts were used to clamp the end pieces to the specimen. It was found that a 50 N.m torque on each bolt was sufficient for the strength of concrete used to provide the necessary resistance against sliding without causing excessive stress concentrations which could initiate cracking in the ends of the specimen. This was also confirmed by finite element analysis(4). The total stiffness of this loading system was calculated to be 3.5×10^5 N/mm.



1 — Platens of LOS testing machine
2 — Coupler
3 — Universal joint
4 — Eyebolt
5 — Bar
6 — Frictional loading block
7 — Bolt
8 — Nut
9 — Reinforcing bar
10 – Specimen
11 – Straingauge
12 – Steel and aluminium membranes

Figure 1 General sketch of direct tension testing apparatus

Specimens

Variable section specimens with a total length of 700 mm were used. These incorporated a uniform region of 300 mm length and 100 × 100 mm cross-section in the middle of the specimen, in which it was expected that crack initiation and propagation would occur.

Five water-cement ratios from 0.3 to 0.6 were used. The concrete mixes comprised ordinary Portland cement (C), natural river sand (S) and gravel (G) with a maximum aggregate size of 15 mm. A liquid mortar plasticizer (P) was added into concrete with lower water-cement ratios. Eight specimens were cast for each w/c ratio. Four specimens were symmetrically notched at the middle to gain an effective cross section of 100 × 55 mm, whilst the other four were unnotched. The compressive strength f_{cu} and splitting strength f_t' were obtained using 100 mm cubes and 300 × 150 mm dia. cylinders. Tables 1 and 2 list the mixes and measured material properties.

TABLE 1 – Mix of concrete

Mix ratios				Quantity (kg/m³)				ml/100kg C
W	C	S	G	W	C	S	G	P
0.30	1	0.99	2.3	157	523	516	1204	420
0.35	1	1.08	2.3	178	507	549	1166	280
0.40	1	1.19	2.3	197	491	582	1130	0
0.50	1	1.29	2.3	235	471	610	1084	0
0.60	1	1.41	2.3	271	452	637	1040	0

Test Procedure

The tests were conducted at a displacement rate of 1.2×10^{-3} mm/s using a linear voltage displacement transducer between the main machine platens. For the notched specimens, deformations were monitored by two 100 mm gauge length extensometers placed on opposite sides of the specimen, symmetrically about the notch. For the unnotched specimens, two 150 mm gauge length extensometers were used in series on one side of the specimen whilst one 300 mm gauge length extensometer measured the extension on the other side. The force in the parallel steel bars were measured by means of electrical resistance strain gauges. All data was automatically recorded using X– Y plotter and data logging facilities.

Experimental Results

Selected experimental results are present in Table 2. These include the direct tensile strength (f_t), fracture energy (G_F) and brittleness index (B). Complete axial tensile stress– deformation curves for all w/c ratios are shown in Fig.2. For the notched specimens the deformation is given over an effective length of 100 mm whilst for unnotched specimens the effective length is 150 mm.

ANALYSIS AND DISCUSSION OF THE RESULTS

Failure Phenomena

For notched specimens, cracks occured through the pre– cut notches. The majority of unnotched specimens fractured within the uniform region. Thus, much data on the initiation and propagation of cracks was captured by the pre– arranged extensometers. The specially designed stiff frame proved highly effective for obtaining very stable complete stress– deformation curves, including the strain softening region, for both the notched and unnotched specimens.

Fig.2 shows that similar characteristics were exhibited in the stress– deformation curves for both notched and unnnotched specimens, both in shape and in the failure deformations (from 0.10 to 0.15 mm). The results for the unnotched specimens were slightly more scattered. Fig.3 shows a typical curve, defining significant points. Nonlinear behaviour is apparant both before and after peak stress and there is a definite change in strain softening behaviour at about 0.35 f_t. From Table 2, the direct tensile strengths for notched specimens were on average about 6% lower than for unnotched specimens (the difference tending to be higher for higher w/c ratios), indicating that concrete is to some degree a notch– sensitive material.

TABLE 2 – Fundamental properties and fracture parameters of concrete

w/c		0.30	0.35	0.40	0.50	0.60
f_{cu} (MPa)		88.25	78.33	60.35	51.10	38.45
f_t' (MPa)		4.35	4.10	3.68	3.40	2.96
f_t	(unnotched specimen)	3.98	3.89	3.52	3.31	2.93
	(notched specimen)	3.83	3.67	3.28	2.98	2.86
G_F	(unnotched specimen)	146.34	129.63	108.99	103.05	85.50
	(notched specimen)	139.68	134.81	109.39	95.88	91.06
E (10^4 MPa)		3.34	3.29	3.26	3.22	3.11
δ_{CR} (mm)		0.02126	0.02050	0.01958	0.01938	0.01875
δ_F (mm)		0.1004	0.1129	0.1214	0.1349	0.1441
δ_0 (mm)		0.00491	0.00318	0.00265	0.00336	0.00297
$B = \delta_e/\delta_F$		0.1690	0.1534	0.1395	0.1188	0.1095

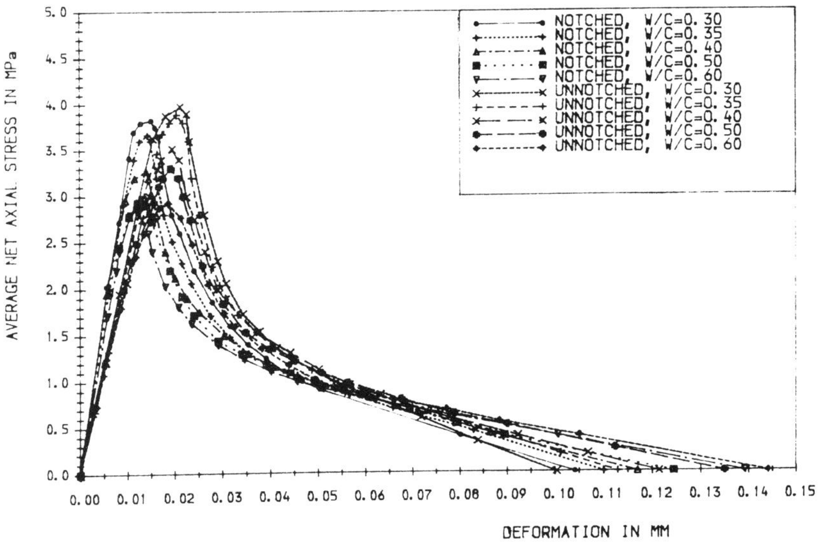


Figure 2 Average net axial stress – deformation curves of both notched and unnotched specimens at different water–cement ratios

Fracture Energy G_F

G_F is an important parameter governing the fracture of concrete, defined as the total energy dissipated on unit crack surface. Theoretically it is equal to the area under the stress–deformation curve under direct tension, i.e.

$$G_F = \int_0^{w_c} \sigma(w)\, dw \tag{1}$$

where w_c is the final crack width at which the stress reduces to zero, given by $w_c = \delta_F - \delta_0$, where δ_F is the failure deformation and δ_0 is the residual deformation on unloading (see Fig.3). From Table 2, the values of G_F show little difference for notched and unnotched specimens. The data indicates that G_F increases with both compressive strength f_{cu} and tensile strength f_t' (Fig.4). A linear relationship between G_F and f_{cu} was obtained as follows:

$$G_F = 43.15 + 1.13 f_{cu} \qquad (r=0.9976) \tag{2}$$

where r is the linear correlation coefficient. Also, a quadratic relationship between G_F and f_t' was obtained as follows

$$G_F = 36.77 + 5.579 f_t'^2 \qquad (r=0.9943) \tag{3}$$

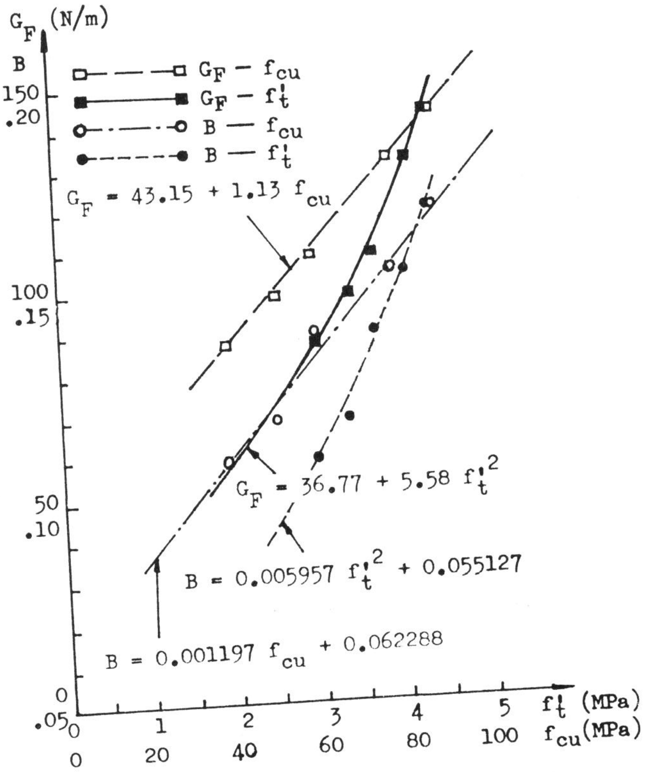


Figure 3 Typical axial stress– deformation curve

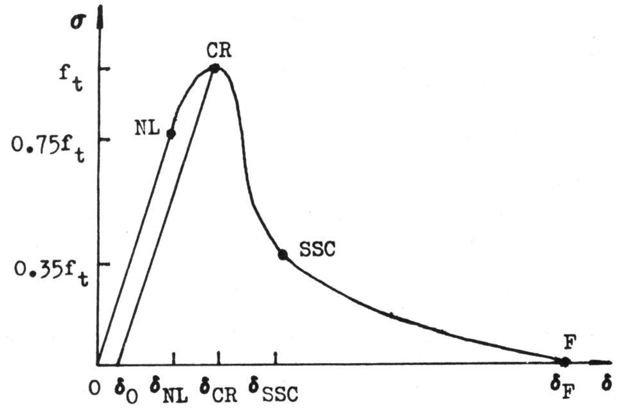


Figure 4 Relationships among G_F, B, f_{cu} and f_t'

Brittleness

Brittleness is a synthetic characteristic defining the deformation and fracture of materials. It is generally understood to be the abrupt fracture at very small deformation. The brittleness of concrete tends to increase with its strength. There does not appear to be a standard criterion for evaluating the brittleness of concrete. In this paper, a ratio of the maximum elastic deformation, δ_e, to the deformation at failure, δ_F, is used to express the brittleness of concrete, i.e. a brittleness index, B, is defined and given by

$$B = \delta_e / \delta_F = (\delta_{CR} - \delta_0) / \delta_F \tag{4}$$

where δ_{CR} is the deformation at which load reaches its peak value (Fig.3). Fig.4 shows a close linear relationship between B and f_{cu} and a quadratic relationship between B and f_t' as follows

$$B = 0.001197\ f_{cu} + 0.062288 \quad (r = 0.9882) \tag{5}$$

and

$$B = 0.005957\ f_t'^2 + 0.055127 \quad (r = 0.9894) \tag{6}$$

Effect of Water– Cement Ratio (w/c)

From Fig.2, the effect of w/c on the fracture of plain concrete is obvious. It is well– known that w/c ratio influences both the strength and elastic properties of concrete, i.e. the lower the w/c, the greater the strength and the slightly higher the elastic modulus. Given the relationships between the strengths, fracture energy and brittleness just presented, it is apparant that the w/c ratio will influence the fracture parameters in a similar fashion, i.e. the lower the w/c, the higher the fracture energy and the higher the brittleness index.

CONCLUSIONS

1. In direct tension tests on both unnotched and notched plain concrete specimens, the specially designed stiff frame proved highly effective for obtaining stable and accurate complete stress–deformation curves.
2. The experimental results on both unnotched and notched specimens did not show a great difference, especially in the shape of the complete stress–deformation curves, fracture energy and failure deformation.
3. The effect of water–cement ratio on the fracture parameters such as fracture energy and brittleness index, is reflected by the relationships between the strengths and those parameters.
4. Fracture energy increased linearly with compressive strength but quadratically with the tensile strength.
5. The ratio of the elastic deformation to the failure deformation can be used as a measure of the brittleness of concrete. This brittleness index increased linearly with the compressive strength and quadratically with the tensile strength.

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