Fracture Toughness of Cement Paste and Mortars

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Fracture toughness methods are being used in a study of the resistance of concrete to cracking. Two techniques are being used, the fracture of a notched beam in flexure and the propagation of a crack along a preformed joint between two cantilevered beams (a DCB test). The two techniques have been described by Brown(1). In the bent beam method the variation in effective fracture toughness could be measured during a crack growth of about 10 mm, whilst in the DCB test it was possible to continue the growth to 100 mm. The geometry of the test specimens limited the aggregate sizes that could be used to $\frac{3}{8}$ in (9.5 mm) for the bent beam and 14 mesh (1.2 mm) for the DCB. To avoid segregation of the cement particles before setting the specimens were cast in sealed moulds that were rotated at about 6 rev/min for 18 hours. The specimens were demoulded at one day and stored in water at 20 ± 1°C until test. During test they were wrapped in aluminium foil to minimise moisture loss.

Bent Beam Tests

To calculate K_{1c} from load/deflection measurements on notched beams in flexure it is necessary to know the crack depth. This was estimated from the compliance of the beam from a second loading after it had been previously loaded until slow crack growth had been observed(1). A succession of loading and unloading cycles caused progressive crack growth, during which the change in K_{1c} was determined. Results for a cement paste and a range of mortars are shown in Figure 1.

It can be seen that in the cement paste there is no change in K_{1c} with crack growth, whilst when aggregate is present the toughness increases with crack growth. There is some evidence that crack initiation occurs at a K_{1c} value corresponding to that for the paste, which suggests that cracking starts within the paste. However a 10 mm crack growth is short, particularly with respect to the maximum aggregate size in the specimens that contained ⅜ in (9.5 mm) gravel.

Double Cantilever Beam Tests

The specimens used for this test comprised two rectangular beams linked by an approximately triangular fillet that was shaped so that as a crack was developed from the apex of the triangle, by mechanically separating the ends of the cantilever, the increase in length of the crack front exactly balanced the increase in bending moment, provided that there was no change in effective fracture toughness with crack growth. The dimensions of the fillet limited the aggregate size that could be used to 1.2 mm, but cracks could be grown 100 mm along a well defined plane.

Figure 2 shows that K_{1c} varied with crack growth for a cement paste that contained different proportions and gradings of Thames Valley sand. Once again K_{1c} is virtually independent of crack growth in cement paste, but on the addition of aggregate there is a marked increase in toughness with crack growth, the proportion of aggregate apparently being of greater significance than the grading. The results obtained from tests on bent beams are included in Figure 2 for the common mortar mix 50M. Although there is a slight difference in the dependence of K_{1c} on crack growth for the two methods, possibly attributable to the different lengths of the crack front, the magnitudes of K_{1c} agree closely.

There is a marked difference between the behaviour of cement paste and of the mortars under load. The paste is brittle and it is difficult to restrict and control the crack growth, particularly in the flexural tests on the bent beams. The mortars are more ductile since the cracks are inhibited by the relatively hard aggregate and they meander and branch thereby increasing the energy required for growth and so increasing the effective fracture toughness.

Aggregate Content

The influence of aggregate content on fracture toughness is shown more conveniently in Figure 3. Measurements using both techniques were used for 10 mm crack growth, whilst only DCB measurements apply to the 100 mm growth. It can be seen that there is an approximately linear relationship between K_{1c} and aggregate volume concentration for each set of data. There is no consistent pattern of the influence of the size of the aggregate particles on toughness, although the results shown in Figure 1 suggest that coarse aggregate imparts less toughness than the same proportion of finer material and this is supported by the DCB measurements on mortars containing 50 per cent aggregate.

Specimen Age

Cement paste and concrete become stronger with age as hydration slowly continues, but the fracture toughness of cement pastes hardly varied in tests made on notched beams in flexure at ages from 14 to 84 days. However, there is a rapid increase in the toughness of a 0.47 water/cement ratio paste between 1 and 7 days (Figure 4).

The strength of cement paste is closely related to porosity. An old high water cement ratio paste has the same strength as a young one of low water cement ratio with the same porosity$^{(2)}$. The toughness values show no such congruity, the toughness increasing consistently with decrease in w/c ratio but not with the decrease in porosity of the individual pastes as hydration continues with age.

Rate of Crack Growth

In the paste tests using the DCB technique cracks were grown at approximately 0.5 and 35 mm/min; the toughness increased with rate, as shown in Figure 4.

Discussion

The toughness values determined using the bent beam and the DCB methods are compatible. Addition of aggregate not only increases the toughness, but results in a progressive increase in toughness with crack growth. The higher the proportion of aggregate the larger the increase in toughness: fine aggregate is possibly more effective than coarse in this respect. With cement pastes, the lower the w/c ratio the greater the toughness, almost irrespective of age. The effect of the unhydrated clinker fraction in the pastes is superficially similar to that of the aggregate fraction in mortar: in both cases the greater toughness can be attributed to crack inhibition by the hard particles.

References

1. J H Brown. Mag. Concrete Research (to be published)
2. C D Lawrence. Cement and Concrete Association, Research Report No 19, 1969.

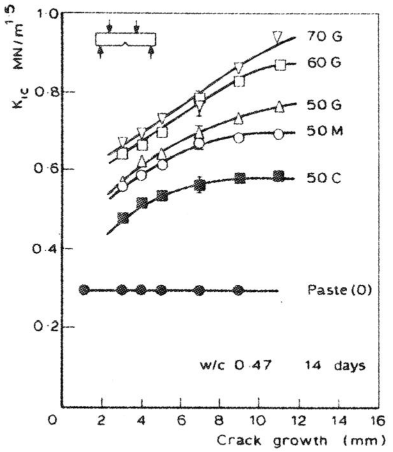

FIGURE 1

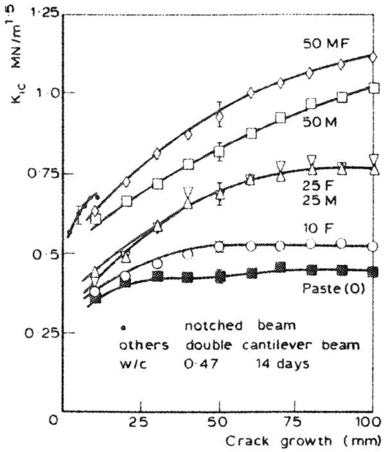

FIGURE 2

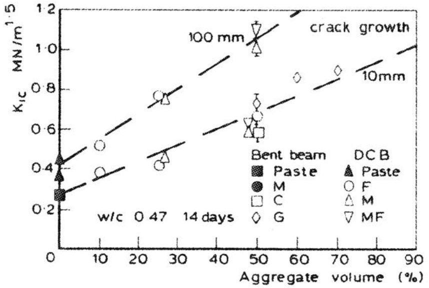

FIGURE 3

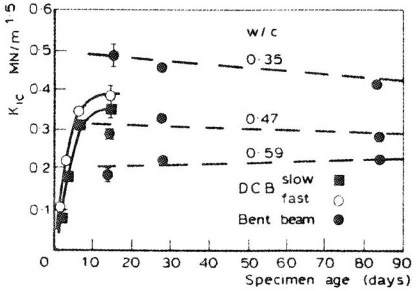

FIGURE 4

Aggregate sizes :

F = fine (52 - 100)

M = medium (14 - 25 mesh)

MF = mixture of equal proportions of M and F

C = coarse ($3/8$ - $3/16$ in.)

G = graded ($3/8$ in. - 100 mesh)

Typical standard errors are shown