FRACTURE IN METAKAOLIN CONCRETE UNDER DIFFERENT LOADING CONDITIONS

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ABSTRACT

The study presents the results of fracture tests conducted on concrete in which metakaolin is used to partially replace the cement. The energy required to cause catastrophic failure in concrete cubes containing two symmetrical notches is determined using two approaches. The first is based on the stress intensity factor determined by finite element analysis and the second utilises the energy absorbed by the test specimen up to failure. The test methodology enables estimates to be made of the extent of tortuosity of the fracture surface. The tests are conducted in a stiff testing machine under axial and eccentric loading conditions. The notched samples were allowed to cure in water at room temperature until testing at 28 and 91 days. It is found that increasing cement replacement levels by metakaolin (up to 15%) results in systematic increases in compressive strength and fracture energy. Metakaolin is also found to reduce the tortuosity of the fracture surface. This phenomenon is attributed to the additional strength imparted to the paste component of the matrix and the reduction in the thickness of the interfacial layer, resulting in more composite action between the paste and the coarse aggregates. Visual inspection of the fracture surfaces confirms the role played by the incorporation of metakaolin in causing the fracture to propagate across the coarse aggregates, thus resulting in smother surfaces.

KEYWORDS

Metakaolin, Compact specimen, Fracture, Tortuosity.

INTRODUCTION

There are two main approaches in fracture mechanics for determining the fracture toughness. These are characterised by E_f, which is the fracture energy required to create a crack extension of unit area and K_c, which is the critical value of the stress intensity factor. Several investigations, e.g. [1-3], have been carried out to assess the fracture parameters in concrete using approaches recommended in [4,5]. Despite the testing complexities involved the results of such investigations have not been consistent and controversy exists regarding the applicability of these tests. Furthermore, the tests employ specimens of relatively large sizes, which render them to be impractical and expensive in practice.

A compact compression eccentrically loaded (CCEL) specimen for evaluating the fracture toughness of concrete has previously been reported by the author [6]. The test employs 100 mm concrete cubes modified by introducing two symmetrical notches on opposite faces and loaded eccentrically. The test provides the critical load at fracture, which is employed in a finite element analysis [7] to give the fracture toughness. The testing system was shown to be effective in identifying the differences in the toughness characteristics of concretes of different formulations [6].

The present study utilises this test to determine the fracture energy of concrete using two approaches, i.e. directly from the area under the load-displacement graph and indirectly from the stress intensity factor K. An alternative testing arrangement in which the specimen is loaded along the plane containing the two notches is also used to evaluate the fracture energy of the concretes employed. This test is referred to as the compact compression axially loaded (CCAL) specimen test.

STRESS ANALYSIS

Analyses of the two test geometries have been carried out using isoparametric finite elements [7,8]. Figure 1 gives the variations of the σ_y stress (normal to the crack plane) and the shear stress σ_{xy} along the plane containing the cracks for a unit applied load P on specimens with 30 mm symmetrical notches. The results demonstrate the rapid increase in the tensile σ_y stress along the ligament as the crack tips are approached. The absence of shear stresses along the ligament confirms that the fracture process is predominantly in the opening mode, which is evidenced in the actual tests.

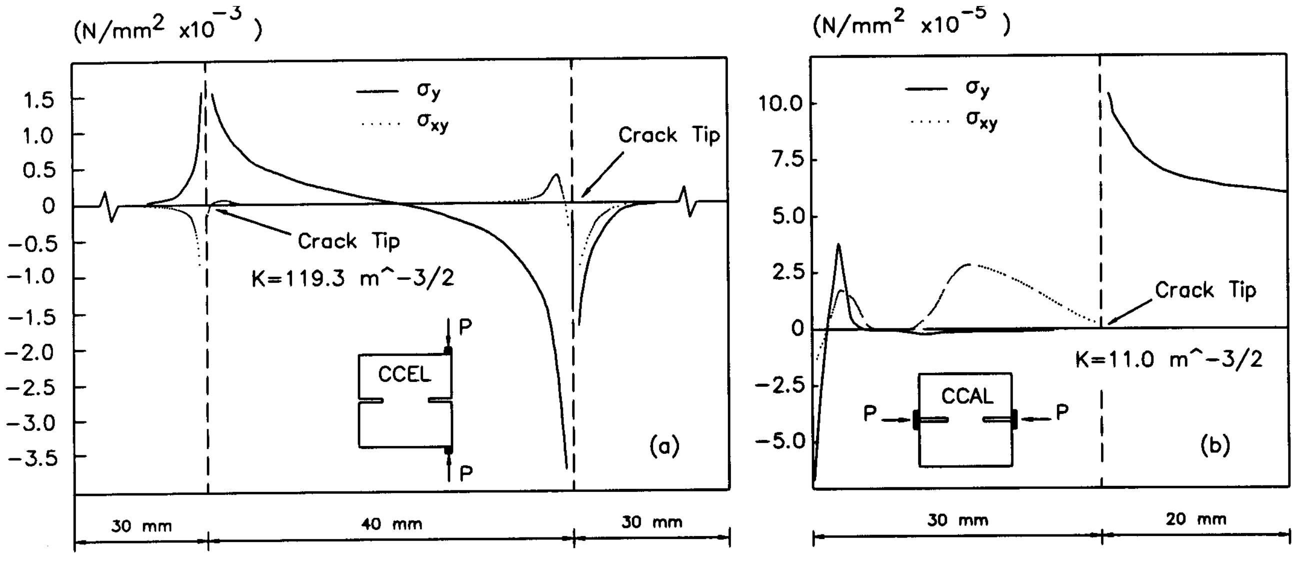

Figure 1. Distribution of σ_y and σ_{xy} along the crack plane
(a) Full CCEL specimen [8] (b) Half CCAL specimen

The fracture toughness K_c is directly related to the stress intensity factor K, which is obtained from the finite element analysis. The fracture toughness K_c is related to the critical value of the strain energy release rate G_c, or fracture energy, as follows:

$$G_c = \frac{K_c^{\ 2}}{E}\ (1-\mu^2) \tag{1}$$

Where E is the elasticity modulus and μ is Poisson's ratio.

The fracture energy E_f can be determined from the load-displacement relationship recorded during the test, viz:

$$E_f = \frac{W_s}{d(d-2a)} \tag{2}$$

Where d is the specimen size, a is the notch size and W_s is the energy consumed in producing the new fracture surface. Full details of the calculation procedure are given in [9].

MATERIALS AND TESTING

Four concrete mixtures were prepared to manufacture the test specimens. Metakaolin (MK) was employed as a partial cement replacement material at 0, 5, 10 and 15%. The mixture without MK is referred to as the control concrete. In all the mixtures, the water to total binder (PC+MK) ratio was kept constant at 0.45. Natural sea-dredged sand of grading M-F complying with BS 882: 1983 and 10mm crushed limestone were used throughout the investigation. The mix proportions of biner:sand:limestone were 1:1.7:3 and the PC content in the control concrete was 395 kg/m^3. A polymeric sulphonate based superplasticiser was added at a dosage of 1 % of the weight of the binder. The concretes produced slumps varying between 15 and 50 mm.

CCEL and CCAL specimens were prepared by means of standard 100 mm steel moulds. Symmetrical notches (30 mm deep) were introduced after curing for 21 days in water at 20^oC. After notching, the specimens were returned to the curing tanks until testing at 28 or 91 days. The fracture tests were conducted at ambient room temperature using a 250 kN Instron testing machine.

Further specimens were prepared to evaluate the compressive strength f_c, the modulus of elasticity E and the modulus of rupture MOR. The results of testing at 28 and 91 days are shown in Table 1. It can be seen that in all cases there are systematic increases in the mechanical properties as the MK content increases. This is attributed to the pozzolanic reaction and the filler effect derived

TABLE 1
MECHANICAL PROPERTIES

MK	Results at 28 days			Results at 91 days		
(%)	f_c (MPa)	E (GPa)	MOR (MPa)	f_c (MPa)	E (GPa)	MOR (MPa)
0	63.1	35.1	8.4	64.2	36.2	9.1
5	64.3	37.3	9.2	68.1	37.0	10.1
10	67.2	38.5	10.5	71.5	39.1	10.8
15	73.1	40.1	11.1	74.3	40.5	11.3

from the incorporation of MK. The results also show small increases due to increased curing time. Tables 2 and 3 give the results of the CCEL and CCAL fracture tests respectively for 28 and 91 days of curing .

FRACTURE TOUGHNESS AND FRACTURE ENERGY

It has been reported [9] that the fracture toughness K_c, obtained from the stress intensity factor [7] and the load at failure, did not show significant variation with notch size. This behaviour although not always born out in fracture tests, is in agreement with the notion that K_c is a material property, which should be independent of specimen geometry and notch size. The results presented in this paper were obtained from testing specimens containing symmetrical notches 30 mm deep. It is easily seen (Tables 2 and 3) that K_c increases with increasing MK content for both CCEL and CCAL specimens. This increase is similar to that observed for the compressive strength and is attributed to the pozzolanic activity derived from the MK and the calcium hydroxide liberated during the hydration of the cement and the MK filler effects. The resulting concrete is more densified with the interfacial zones being smaller in thickness thus resulting in more composite action between the paste and the aggregates. The increase in K_c for the specimens tested at 91 days are significantly smaller than those obtained at 28 days. This is not surprising as the pozzolanic activity in concrete due to MK is at its peak at 7-14 days [10].

TABLE 2
FRACTURE RESULTS FROM CCEL SPECIMENS

	MK (%)	K_c (MN/m$^{3/2}$)	G_c N/m	E_f N/m	T_f
28 day tests	0	0.60	9.87	19.2	1.95
	5	0.78	15.8	24.8	1.57
	10	0.87	19.1	28.8	1.51
	15	0.99	23.5	35.0	1.49
91 day tests	0	0.94	23.6	23.0	0.98
	5	0.97	24.4	25.8	1.06
	10	1.07	28.2	30.8	1.09
	15	1.10	29.0	33.8	1.16

The reported values for G_c were determined using Eqn. 1 with μ=2. Similar variations in G_c to those of K_c occur with increasing MK content. The fracture energy E_f was evaluated from the area under the load-displacement curves recorded during the tests. The values for E_f obtained from the CCAL specimens are considerably higher than those recorded from the CCEL specimens. This is attributed to the fact that CCAL specimens are much more rigid than CCEL specimens, which was evidenced by the greater load sustainability before failure in the case of CCAL testing. It has been reported [9,11] that both G_c and E_f converge to the same value as the notch size increases. For short cracks, however, E_f is generally greater than G_c. The differences in the values of the fracture energy determined by G_c and E_f are attributed to the assumption of a planar fracture surface in the determination of E_f. In practice the fracture surface is tortuous and can be several times greater than that assumed [12,13].

TABLE 3
FRACTURE RESULTS FROM CCAL SPECIMENS

	MK (%)	K_c ($MN/m^{3/2}$)	G_c N/m	E_f N/m	T_f
28 day tests	0	0.85	19.8	46.8	2.34
	5	1.01	26.5	67.2	2.54
	10	1.18	35.2	70.7	2.01
	15	1.37	45.1	97.4	2.16
91 day tests	0	1.01	27.2	65.0	2.39
	5	1.11	32.0	71.9	2.25
	10	1.13	31.4	78.8	2.51
	15	1.21	35.1	77.5	2.21

FRACTURE SURFACE TORTUOSITY

The fracture energy E_f is evaluated on the basis of the area of the ligament between the two notches. This overestimates E_f by a factor related to the tortuosity of the newly created surface. A tortuosity, or roughness, factor can be estimated as the ratio of the true surface area to the projected area. This definition was used by Wollrab et al [14] during tensile testing of edge notched specimens. In this paper the tortuosity is estimated by a factor T_f (Tables 2 and 3) given by the ratio of E_f to G_c, as evaluated from Eqns. 1 and 2.

It is seen that in general significant decrease in T_f results with increasing MK content. This is a clear indication that the addition of MK results in smoother fracture surfaces. This is largely attributed to the filler effects of MK, which alter the matrix structure of the concrete. The porosity of the matrix in the region of the interfacial zone reduces resulting in a denser and more homogeneous transition zone [15]. Because the interfacial zone is the ‘weak link’ within the concrete, the inclusion of MK results in a more effective composite action with a greater role being played by the coarse aggregate in controlling the fracture path. Whereas in normal concrete crack growth usually takes a path around the aggregates, in the case of MK concrete and because of the reduction in the thickness of the interfacial zone the growth proceeds through the aggregates resulting in smoother fracture surface. This phenomenon was very clear on inspection of the actual fracture surfaces of the specimens at fracture.

CONCLUSIONS

The work presented in this paper demonstrated the effectiveness of two testing systems in assessing the changes in the fracture properties of concrete due to the incorporation of metakaolin. The tests employ compact specimens that are easy to manufacture and simple to handle. Significant increases in the fracture toughness and fracture energy results by the incorporation of up to 15% metakaolin. These increases, which surpass those usually obtained for the compressive strength, are attributed to the filler effects and pozzolanic activity of the metakaolin. Improved composite action between the cement paste and the aggregates is obtained resulting in smoother fracture surfaces, which are confirmed by the significant reductions in the tortuosity factors.

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