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INFLUENCE OF AGE OF LOADING ON MIXED MODE FRACTURE PARAMETERS OF CONCRETE

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Abstract
In this paper, the influence of age of loading on mixed mode I and II fracture parameters of concrete is studied by means of four-point-shear tests on single edge notched beams. Computer model shows agreement with the experimental results in predicting the peak loads.

1 Introduction

Even though we do not understand many aspects of toughnessing mechanisms of fracture in concrete, successful approaches are being made to use fracture mechanics concept in design. Several models have been demonstrated to correctly predict the structural response of concrete. The shortcomings of those models are that they are confined to mode Ⅰ. Many structural problems, however, ask for more generally applicable models since the behaviour of a structure is most confined to mixed mode Ⅰ and Ⅱ, and seldom confined to mode Ⅰ. Different fracture parameters associated with each model should be experimentally evaluated first in order to use those models to predict the structural response under mixed mode Ⅰ and Ⅱ loading.

Different testing geometries have been used in an attempt to induce mixed mode crack initiation and extension. In this study the single edge notched (SEN) beams subjected to four point shear are used. Thus, pure mode Ⅰ and mixed mode Ⅰ and Ⅱ tests can be performed using similar specimens.

The aim of this contribution is to study the influence of age of loading on mixed mode fracture parameters $\overline{K}_c$(conventional critical mixed mode stress intensity factor) and G_f^* (mixed mode fracture energy).

2 Experimental program

A test series has been carried out with identical specimens where the age of loading was varied between 14 and 180 days.

Table 1 shows the dimensions of the specimens and the ages of loading of those specimens. In order to eliminate the effect of the size of the specimen, the three point bend beams with the same size as that of the four point shear beams are used to determine mode Ⅰ fracture parameters of concrete. Mix proportions and the relevant mechanical properties (measured after 180 days from moulding) are listed in Table 2 and Table 3. The experimental procedure and configuration details were given by Hu Beilei et al. (1994).

Table 1. Test parameters

Specimen	Age of loading (days)	t (mm)	h (mm)	l (mm)	a (mm)	c (mm)
SE1	14	100	200	800	80	80 160 240
SE2	28	100	200	800	80	80 160 240
SE3	60	100	200	800	80	80 160 240
SE4	90	100	200	800	80	80 160 240
SE5	120	100	200	800	80	80 160 240
SE6	180	100	200	800	80	80 160 240

Table 2. Properties of concrete

Cement		370kg/m^3
Water		185kg/m^3
Aggregate	10—20mm	1263kg/m^3
Sand	0—2mm	680kg/m^3

Table 3. Mechanical properties

Cube compressive strength	38. 2MPa
Cube splitting strength	2. 3MPa
Young' s modulus	32200MPa

3 Experimental results

3. 1 Maximum loads and the conventional critical mixed mode stress intensity factors ($\overline{K}_c$)

There are three different failure mechanisms in four point shear beam tests, see Carpinteri et al. (1989), Ballatore et al. (1990), Hu Beilei et al. (1994) and Hu Beilei (1995). In this study, for c/h=1. 2, the failure mechanism was due to flexure at the support for all the specimens.

For plain concrete under mixed mode (mode I and mode II) loading, a mixed mode stress intensity factor (K) was defined by Jenq & Shah (1988).

$$K=[K_I^2(\theta)+K_{II}^2(\theta)]^{1/2} \tag{1}$$

The conventional critical mixed mode stress intensity factors ($\overline{K}_c$), which are calculated from the measured peak load, and the maximum loads are listed in Table 4. The values are the average of four specimens at least. Fig. 2 shows the increasing of $\overline{K}_c$ with the increasing of the age of loading.

The fracture toughness K_{IC}, which are determined from the three point bend beams with the same size as that of the four point shear beams, are listed in Table 4. It is seen that the conventional critical mixed mode stress intensity factors $\overline{K}_c$ is always smaller than the fracture toughness K_{IC}. Fig. 2 shows the increasing of K_{IC} with the increasing of the age of loading.

As can ben seen in Fig. 1 and Fig. 2, $\overline{K}_c$ and K_{IC} are strongly affected by the age of loading when the age of loading is smaller than 60 days. $\overline{K}_c$ and K_{IC} seems to be affecter slightly by the age of loading when the age of loading is greater than 60 days.

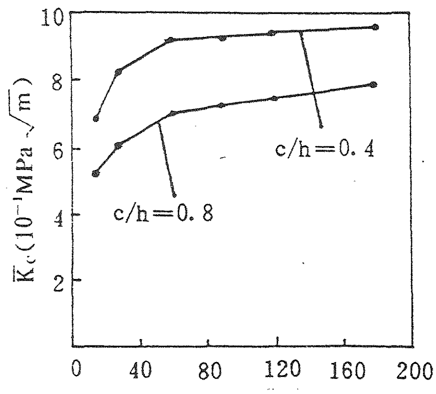

Fig. 1 $\overline{K}_c$ as function of age of concrete

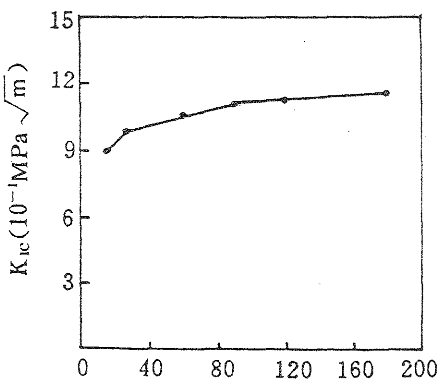

Fig. 2 K_{IC} as function of age of concrete

Table 4 Experimental results of peak load, $\overline{K}_c$ and K_{IC}

Specimen	Age of loading (days)	c/h	P_{max} (kN)	$\overline{K}_c$ (Mpa$\sqrt{m}$)	K_{IC} (MPa$\sqrt{m}$)
SE1	14	0.4 0.8	28.3 23.8	0.686 0.531	0.912
SE2	28	0.4 0.8	38.9 27.9	0.839 0.618	1.150
SE3	60	0.4 0.8	45.7 39.3	0.925 0.711	1.197
SE4	90	0.4 0.8	45.9 41.2	0.937 0.737	1.219
SE5	120	0.4 0.8	46.2 43.9	0.955 0.756	1.227
SE6	180	0.4 0.8	47.8 44.7	0.965 0.759	1.247

3. 2 Mixed mode fracture energy

Mixed mode fracture energy value G_f^* was calculated as the total dissipated energy W divided by the cracked area. W is obtained by summation of W_1、W_2 and W_3. W_1 and W_2 represent the work done by force F_1 and F_2 respectively and are calculated from following equation:

$$W_i = \int_0^{\delta_{0i}} F_i d\delta_i, \quad i=1,2 \tag{2}$$

W_3 is the work done by the specimen weight. In Table 5 fracture energy values for both three point bend tests and four point shear tests are given. The values are the average of four specimens at least. A careful examination of the Table 5 indicates that the mixed mode fracture energy of concrete increases with the increasing of age of loading.

The difference between the fracture energy derived from the three point bend tests and the four point shear tests is small. This agrees with that observed by Ballatore et al. (1990) and Schlangen (1993). Fig. 3 shows the increasing of G_f^* with the increasing of the age of loading. From Fig. 3 it is can be seen that G_f^* and G_f are strognly affected by the age of loading when the age of loading is smaller than 60 days. Slihgt influence of the age of loading on G_f^* and G_f is observed when the age of loading is greater than 60 days.

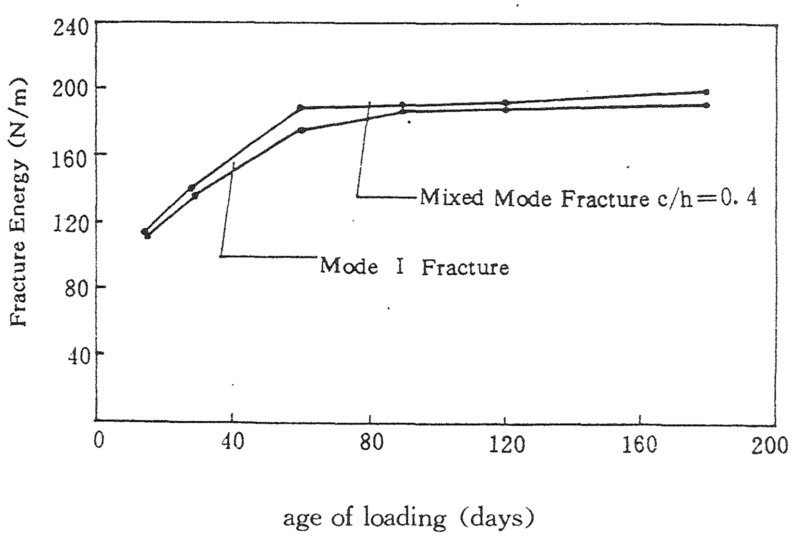

Fig. 3 Fracture energy-age of loading curves

Table 5. Fracture energy determined from mode Ⅰ and mixed mode Ⅰ and Ⅱ tests

Specimen	c/h	Mixed mode Ⅰ+Ⅱ G_f^* (N/m)	Model Ⅰ G_f (N/m)	$\frac{G^*-G_f}{G_f}\times 100$
SE1	0.4 0.8	117.52 121.24	111.67	5.24 8.57
SE2	0.4 0.8	141.53 142.12	139.58	1.39 1.82
SE3	0.4 0.8	189.77 193.20	176.49	7.52 9.47
SE4	0.4 0.8	191.61 202.54	184.05	4.10 10.05
SE5	0.4 0.8	192.86 207.81	189.17	1.95 9.85
SE6	0.4 0.8	199.54 213.74	193.82	2.95 10.28

4 Numerical analysis

The endochronic damage constitutive model was developed by Song Yupu and Zhao Guofan (1991). In this study an incremental nonlinear iterative finite element analysis program based above model is developed. The eight-noded isoparametric element is used. The numerical simulation of the $F_1-\delta_1$ and $F_2-\delta_2$ curves of all the specimens is given by Hu Beilei (1995). The comparisons of the peak load, obtained from experiments and computations are shown in Table 6. Good agreement on peak load predictions with experimental data is seen.

Table 6 Comparisons of the peak load, obtained from experiments and computation

Specimen	Age of loading (days)	c/h	Experiments p_{max} (KN)	Calculation p_{max} (KN)
SE1	14	0.4 0.8	28.3 23.8	25.3 21.7
SE2	28	0.4 0.8	28.9 27.9	25.8 24.5
SE3	60	0.4 0.8	45.7 39.3	40.9 35.1
SE4	90	0.4 0.8	45.9 41.2	48.8 44.7
SE5	120	0.4 0.8	46.2 43.9	49.8 46.9
SE6	180	0.4 0.8	47.8 44.7	51.1 48.2

5 Conclusions

1. The results of the investigation show that the conventional critical mixed mode stress intensity factors $\overline{K}_c$ is always smaller than the fracture toughness K_{IC}. $\overline{K}_c$ increases with the increasing of age of loading.
2. The mixed mode fracture energy of concrete increases with the increasing of age of loading.
3. The results from computations agree with the experiments for peak load.

6 References

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CHAPTER SIX

Scaling Theories and Size Effect