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Fracture toughness of concretes at high temperature

G. PROKOPSKI
Civil Engineering Department, Technical University of Rzeszów, Powstańców Warszawy 6, 35-959 Rzeszów, Poland

The fracture toughness of ordinary and refractory concretes in the range of 20–1300 °C was investigated, and the stress intensity factor, K_{Ic}, on three-point bent specimens (according to ASTM E-399 recommendation) determined. With an increase in testing temperature, the stress intensity factor decreases for both concretes. The values of K_{Ic} at 20 °C for both concretes are comparable, being equal to 0.64 $\mathrm{MNm}^{-3/2}$ for ordinary concrete, and 0.72 $\mathrm{MNm}^{-3/2}$ for refractory concrete, respectively. At 1100 °C, K_{Ic} has a value of 0.043 $\mathrm{MNm}^{-3/2}$ for ordinary concrete, and for the refractory concrete at 1300° C, $K_{Ic} = 0.34\ \mathrm{MNm}^{-3/2}$. The method presented for predicting the behaviour of concrete at high temperature may be used in engineering practice.

1. Introduction

In industrial building engineering, several types of concrete and reinforced concrete structures are found, which are exposed to the influence of high temperature. A high temperature effect on ordinary and reinforced concretes causes structural changes that depend on the type of concrete, as well as on existing strains and stresses, and cracks. This causes deterioration of the strength properties, which can lead to the failure of a construction.

Previously, the behaviour of concretes and reinforced concretes has been examined in connection with the production development of pre-tensioned, prestressed concretes designed for pressure vessels in nuclear power stations; for the construction of rocket launchers; and also in consideration of their fire resistance [1–3]. These investigations included the physical and strength properties of these materials at high temperature, but did not consider fracture toughness when heated, which plays a decisive role in the failure of a construction.

Understanding the fracture phenomenon in concretes is difficult because of large structure discontinuities occurring in concretes, and connected with these, local differences in mechanical properties, which cause such stress concentrations that failure may take place at low stress values. The failure process does not occur in the whole volume, but consists in the formation, accumulation and propagation of internal cracks and defects, which lead to the loss of internal stability, primarily in the contact zone between the grains and cement paste, and then in the whole volume.

The fracture toughness of concrete, which is a brittle material, may be defined by the critical value of the stress intensity factor, K_{Ic}. This factor characterizes the stress field at the crack tip at the moment of crack initiation.

$$K_{Ic} = \sigma(\pi a)^{1/2}$$

where σ = stresses in the crack region, and a = crack length. The stress growth around the crack may be a result of the action of external forces (construction load), thermal stresses or structural stresses. An increase in these stresses above the critical values causes a dramatic crack propagation which may lead to damage to the construction.

2. Experimental procedure

Two grades of concrete were used, ordinary concrete and refractory concrete, as used in metallurgy. Their compositions are set out in Table I.

The following investigations were carried out: (a) compressive strength; (b) tests of stress intensity factor, K_{Ic} (tension at bending). The compressive strength of concretes was tested using five concrete cubes (side = 0.15 m), whereas the examination of fracture toughness was performed on ten specimens (at particular temperatures), each having one notch (Fig. 1).

The specimens were cured for 7 days in a water bath and then stored under normal laboratory conditions for further 21 days. After a 28-day curing period they were subjected to fracture toughness tests.

The strength of concretes after pressure tests was as follows: ordinary concrete, 28.3 MPa; refractory concrete, 33.2 MPa. The fracture toughness tests were performed on a test stand as shown in Fig. 2.

The specimens were subjected to bending after they had been heated up to a preset temperature and held at that temperature for ~ 2 h, until the temperature was reached in the whole volume of the specimen. Measurements were taken at three points in the specimens using NiCr = Ni thermocouples. The measurements were taken every 100 °C, in the following temperature ranges: ordinary concrete, 20–1100 °C; refractory concrete, 20–1300 °C. At each temperature,

TABLE I Composition of concretes used.

	Grain size (mm)	Composition ($kg\,m^{-3}$)
Ordinary concrete		
Gravel aggregate	2–10	1100
Quartz sand	0–2	620
Portland cement "35"		310
Water		170
Refractory concrete		
Burnt clay	2–5	520
Burnt clay	0.1–2	200
Burnt clay	0–0.1	50
Alumina cement, type "Górkal 70"		250
Water		150

ten specimens were bent. The load was measured with a strain gauge against crack displacement, and registered on an x–y plotter.

In bending tests of each specimen tested, a value of maximum force, $P_{\max}$, was obtained, which was considered to be a failure force as once it had been reached, a dramatic crack propagation ensued resulting in failure of specimens. K_{Ic} was determined according to the following formula given for steel [4] which is also widely used for concrete

$$K_{Ic} = \frac{P_{\max}}{BW^{1/2}} Y\left(\frac{a}{W}\right)$$

where $P_{\max}$ = specimen failure force, B = specimen thickness, W = specimen height, a = primary crack length, and $Y(a/W)$ = function of deformability of bent specimen, determined according to [5].

The test results for stress intensity factor, K_{Ic}, for both concretes are shown in Table II. Based on these results the following relationships between K_{Ic} and temperature were derived:

Ordinary concrete

$$K_{Ic} = 0.584931 - 0.000454T$$

Refractory concrete

$$K_{Ic} = 1.195322T^{-0.170483}$$

where T = temperature. Graphs of the above functions are plotted in Figs 3 and 4.

3. Discussion

It can be noted from Figs 3 and 4 that at 20 °C, the K_{Ic} values for both concretes are comparable: $0.64\,MNm^{-3/2}$ for the ordinary concrete, and $0.71\,MNm^{-3/2}$ for the refractory concrete. With the increase in testing temperature, the stress intensity factor, K_{Ic}, of the ordinary concrete decreases monotonically, reaching the value of $0.043\,MNm^{-3/2}$ at 1100 °C.

The refractory concrete shows different behaviour: while a considerable drop in fracture toughness was

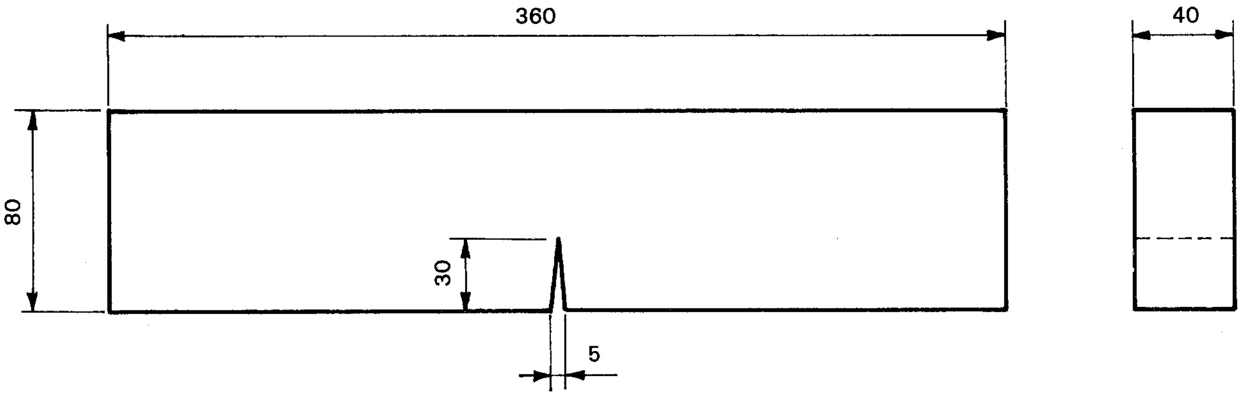

Figure 1 Sample used for fracture toughness tests.

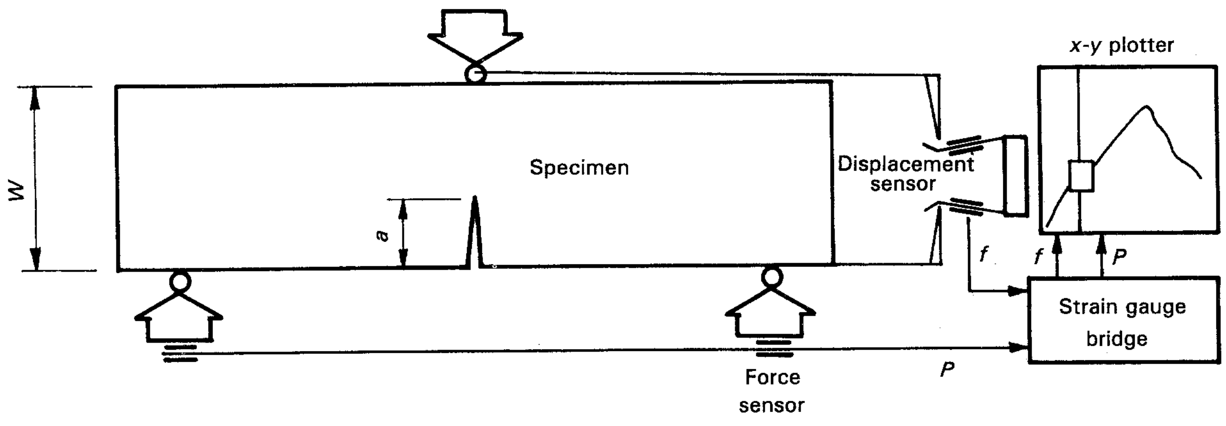

Figure 2 Diagram of test stand.

TABLE II Stress intensity factor, K_{Ic}.

	Temperature (°C) 20	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300
Ordinary concrete														
K_{Ic} (MNm$^{-3/2}$)	0.643	0.621	0.359	0.403	0.419	0.353	0.227	0.275	0.237	0.330	0.097	0.044	–	–
$\pm\delta$ (MNm$^{-3/2}$)	0.063	0.134	0.079	0.061	0.079	0.085	0.136	0.124	0.138	0.141	0.037	0.029	–	–
Refractory concrete														
K_{Ic} (MNm$^{-3/2}$)	0.718	–	0.490	0.418	0.488	0.469	0.357	0.328	0.422	0.429	0.497	0.417	0.280	0.343
$\pm\delta$ (MNm$^{-3/2}$)	0.079	–	0.078	0.119	0.155	0.153	0.112	0.070	0.135	0.173	0.109	0.119	0.060	0.061

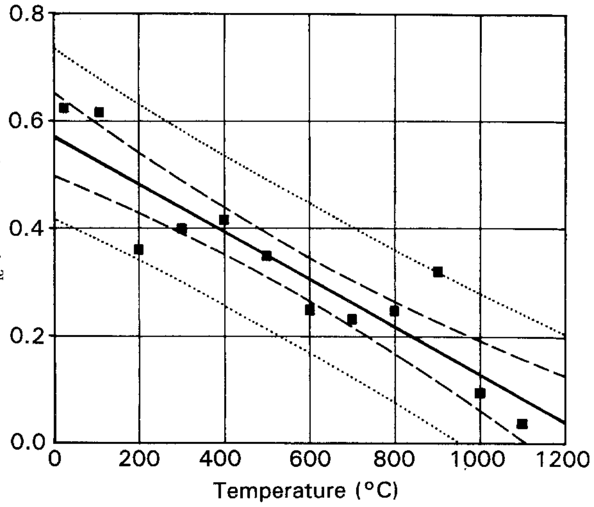

Figure 3 Relation between fracture toughness and temperature (ordinary concrete). (——) Empirical regression line (least squares line); (– – –, . . .) 90% confidence limits. $K_{Ic} = 0.584931 - 0.000454T$.

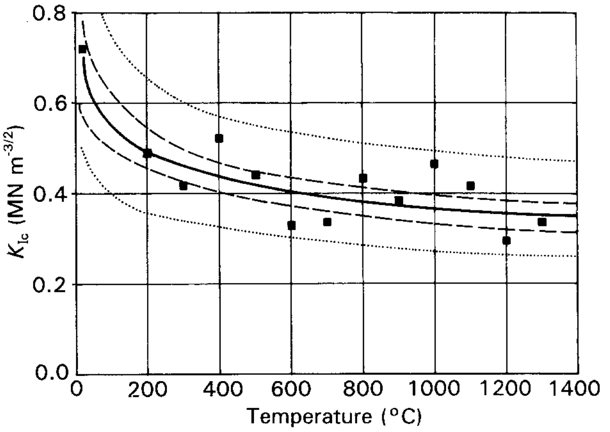

Figure 4 Relation between fracture toughness and temperature (refractory concrete). (——) Empirical regression line (least squares line); (– – –, . . .) 90% confidence limits. $K_{Ic} = 1.195322T^{-0.170483}$.

observed with the increase in temperature up to 300 °C, with a further rise in temperature K_{Ic} remained roughly at a constant level, and at 1300 °C it exceeded that of the ordinary concrete by an order of magnitude, reaching the value of 0.34 MNm$^{-3/2}$.

The fracture surfaces of the ordinary concrete specimens, which were obtained at ambient temperature and at 100 and 200 °C, were granular in character. A crack propagated along the contact surface between gravel aggregate grains and cement paste. The cohesion of the grains with the cement paste was high at those temperatures, which caused grain cracks in numerous sites. At temperatures above 200 °C, no cracks across the grains were observed; pulling of the grains out of the cement paste occurred, and a fracture proceeded along the boundary between the grains and the cement paste. Above 400 °C complete destruction took place in the cement paste, which resulted in the propagation of a fracture through the cement paste.

The fracture surfaces of the refractory concrete specimens were smooth within the full temperature range of the tests, which implies that the cohesion forces between the aggregate grains and the cement paste were comparable with those of the mortar alone.

4. Conclusions

The proposed method for the examination of concretes based on the principles of linear–elastic fracture mechanics has proved to be useful. The stress intensity factor, K_{Ic}, determined in the tests can be used in designing and determining operating conditions for concrete elements in plants working at high temperature. The knowledge of K_{Ic}, on the assumption of a suitable level of structure imperfection, allows the proper values of admissible stresses to be selected. The results presented can be used in the following applications.

1. Evaluation of the behaviour of concretes in plants working at high temperatures.
2. Estimation of a fracture zone after concrete cutting has been done by one of the thermic methods in use.
3. Appraisal of the correctness of the composition of concretes designed for high-temperature duty.
4. Defining a hierarchy of the suitability of cement-based materials for high temperatures.

Further investigations should also take into consideration the destructive influence of high temperature on the microstructure of concretes, as a function of time.

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