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# Variation of the fracture toughness of concrete with temperature

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This paper presents an experimental investigation on the variation of residual fracture toughness of concrete with elevated temperatures. A total of 80 beams 150 × 150 × 750 mm were tested under three-point bending, half of which had a 25-mm initial notch at mid-span and the rest of which had a 60-mm initial notch. The temperatures used in the study were 50, 100, 150, 200, 250 and 300°C. The study also includes cyclic heating effects where the specimens were subjected to cycles of heating and cooling. In each cycle, the specimens were placed in a furnace preheated to the desired temperature for 24 h and then removed and left to cool for another 24 h. The process was repeated for the desired number of cycles. The results show that the residual fracture toughness of concrete decreases with the increase in temperature. The results also show that the fracture toughness is further reduced with the increase of number of heating and cooling cycles. © 1997 Elsevier Science Ltd.

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In some structures such as chimneys and nuclear power plants, the concrete may be exposed to high temperatures during operating hours. Although the concrete in such structures is always provided with adequate insulation, nevertheless, it is difficult to inspect the insulation and there is always a possibility of its deterioration. Also, problems with the cooling system in nuclear power plants may lead to hazardous situations were the concrete overheats. The exposure of concrete to elevated temperatures has a direct effect on its compressive, tensile and flexural strength[1]. In order to be able to assess the concrete performance in general, it is always important to determine its fracture toughness ($K_{IC}$) under operating conditions. So far, little research has been done to study the fracture behavior of concrete under elevated temperatures.

Tests on notched metallic specimens have shown that the temperature variations have a significant impact on the Mode I fracture toughness $K_{IC}$[2-5]. The tests show that for metals such as structural steel, the fracture toughness increases with the increase in temperature. For brittle materials such as ceramics, a different behavior is exhibited[6] where, unlike metals, the fracture toughness decreases at elevated temperatures. Tests on different sizes and shapes of notched specimens[7-10] have shown a similar behavior. Bazant and Prat[7] tested three-point bend and eccentric compression specimens with a notch-to-depth ratio of 1:6. The tests were carried out at temperatures of up to 200°C and the results show a smooth decrease in the fracture toughness of concrete as temperature increases. Maturana *et al.*[8] studied the fracture behavior of concrete in the freezing range and indicated an increase in the fracture toughness at temperatures down to approx. −20°C.

In this study, the main objective is to determine the residual fracture toughness of concrete after being heated to temperatures up to 300°C. An experimental program was carried out in which beams with an initial notch at mid-span were tested under three-point bend loading after being subjected to different temperatures.

Since cyclic temperature changes occur in nuclear reactors and can lead to a further decrease in concrete strength[11], the experimental program was expanded to include the effect of cyclic heating on the residual fracture toughness of concrete.

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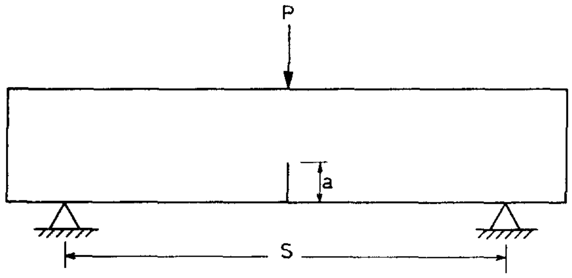

**Figure 1** The tested beam with initial crack

## Experimental investigation

A total of 80 beams were tested in this study. All the beams had the same dimensions $150 \times 150 \times 750$ mm ($6 \times 6 \times 30$ inches). The tests were carried out at three-point bending with a span-to-depth ratio of four as shown in *Figure 1*. All the beams had a notch thickness of 2.5 mm (0.1 inch) at mid-span. The notch was made by placing a piece of plexiglass with the desired crack dimensions into the molds prior to casting of concrete. After hardening of concrete and removal of the molds, the plexiglass plate was removed, thus leaving the desired notch.

Two different notch depths were investigated in this study. For some beams, the notch was 25 mm (1 inch) deep, i.e. the notch length-to-depth ratio was $a{:}b = 1{:}6$. For the other beams, the notch was 60 mm (2.36 inches) deep.

For the batches of concrete used in the experimental program, the mix had a water–cement ratio of 0.45. The mix proportioning of the concrete is presented in *Table 1*. Type I cement was used and the gravel had a 12.7 mm (0.5 inches) maximum size. The aggregates were washed and oven-dried prior to casting. A superplasticizer was added to the concrete mix to increase its workability (approx. 3.0 litres were needed per $m^3$ to produce a slump within 30–50 mm).

In order to determine the compressive strength of the concrete, control cylinders 150 mm (6 inches) in diameter and 300 mm (12 inches) in length were tested (three cylinders for each beam).

All the specimens were cast vertically in steel molds and vibrated on a shaking table to ensure proper compaction. Each specimen was first hand compacted with a rod and then put on the shaking table for 2–3 min. The molds were removed after 24 h and all specimens were moisture cured in a curing room at 70°F (21°C) and 95% relative humidity for 28 days before testing.

The specimens were heated by placing them in an oven preheated to the desired temperature. They were kept in the oven for 24 h and then left to cool in room temperature for another 24 h. This represented one cycle of heating and cooling. The temperatures investigated were 50, 100, 150, 200, 250 and 300°C. To study the effect of cyclic heating and cooling, the heating and cooling cycle was repeated several times till the desired number of cycles was achieved. For each beam, at least three control cylinders were subjected to the same cyclic conditions and tested for strength.

The compressive strength tests were carried out on an MTS machine equipped with a moving head platen. The load was applied in increments of 25 kN (5.6 kips). The same machine was used for testing the beams and in this case the load was applied in increments of 1 kN (0.224 kips). The beam deflections were measured by two LVDTs placed on the two sides of the notch and each located 25 mm (1 inch) away from it.

**Table 1** Concrete mix design

| Material | Quantity (kg $m^{-3}$) |
|---|---|
| Type I cement | 421 |
| Fine aggregate (fineness modulus = 2.7) | 709 |
| Water | 190 |
| Coarse aggregate | 933 |

## Experimental results

Each result shown in this section represents an average value obtained from three different specimens. The average compressive strength ($f_c$) for the concrete used in this study was 36 MPa. The effect of temperature on the residual concrete compressive strength is shown in *Figure 2* which shows the effect of one cycle of heating and cooling on the compressive strength measured by the control cylinders. The relationship between temperature and residual compressive strength after heating and cooling shows that a reduction in strength up to 40% occurs as the temperature reaches 300°C. *Figure 2* also shows a comparison with similar tests[14]. For the concrete tested, the effects of temperatures up to 50°C on compressive strength were almost insignificant.

The temperature effects on the behavior of the notched beam specimens are shown in *Figures 3–5*. *Figure 3* shows the test results for the two crack lengths investigated after subjecting each beam to one heating cycle. The results show a steady decline in the fracture

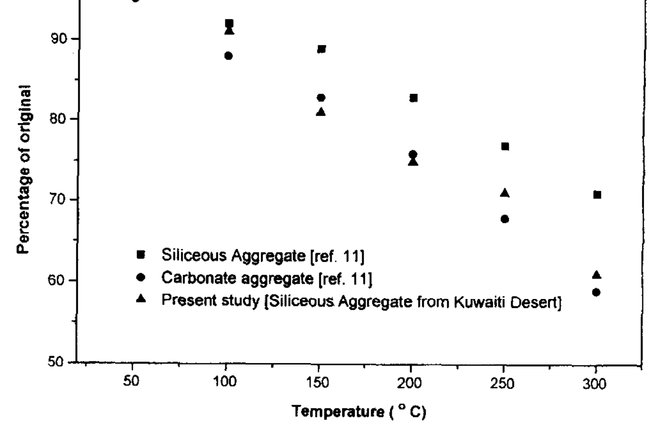

**Figure 2** Effect of temperature on the residual compressive strength of concrete

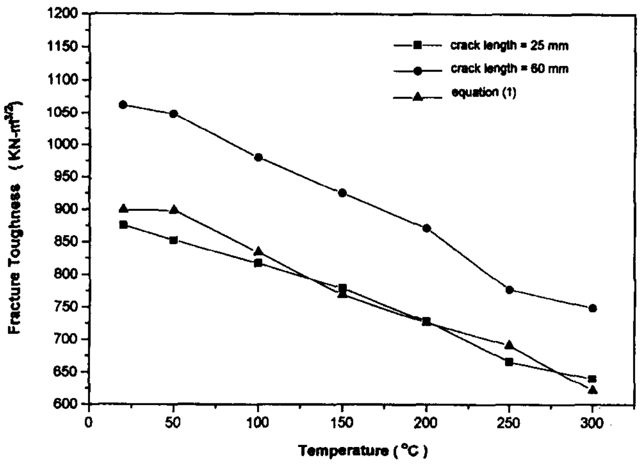

Figure 3 Variation of residual fracture toughness with temperature (one heating cycle)

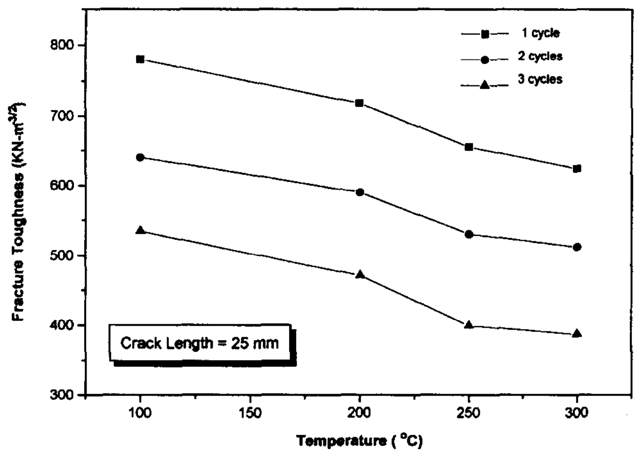

Figure 4 Variation of residual fracture toughness with number of heating cycles for the crack length of 25 mm

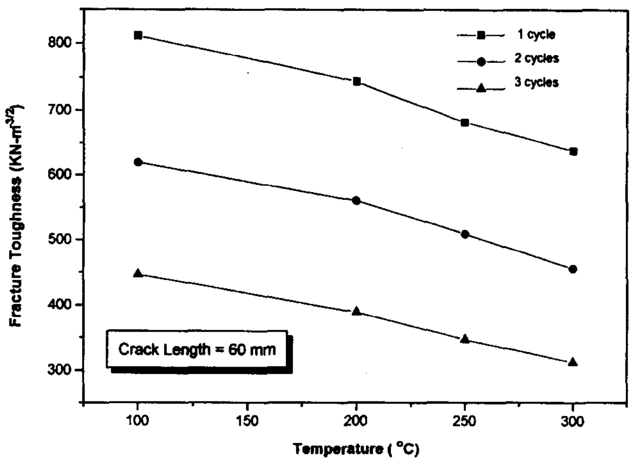

Figure 5 Variation of residual fracture toughness with number of heating cycles for the crack length of 60 mm

toughness with increasing temperature. The fracture toughness was computed using the series of equations given in Appendix A. By substituting the value of the load at failure for ($P$) in Equation (A3), the critical stress intensity factor or the fracture toughness ($K_{\mathrm{IC}}$) can be computed using Equation (A1). The results are compared to the following empirical equation proposed by John and Shah[13]:

$$K_{\mathrm{IC}} = 1.3(f_{c'})^{0.75} \qquad (1)$$

where $f_{c'}$ is the concrete compressive strength in psi and $K_{\mathrm{IC}}$ is the fracture toughness in lb–inch$^{-3/2}$. According to Bertero and Polivka[11], Equation (1) can be used for values of $f_c$ up to 110 MPa (16,000 psi). A plot of this equation shows that it compares favorably to the results obtained for a crack length of 25 mm ($a/b = 1{:}6$).

The effect of the number of cycles on the critical load for different temperatures is shown in *Figure 4* (for $a = 25$ mm) and *Figure 5* ($a = 60$ mm). From the two figures one can estimate that for the number of cycles investigated, each cycle contributes to a loss of approx. 20% in the critical load. It should be noted that tests carried out at 50°C did not show a significant effect on the fracture toughness of concrete as the number of cycles increased.

## Conclusions

1. The fracture toughness of concrete is greatly influenced by temperature even after cooling. For one cycle of heating and cooling the decrease in the residual fracture toughness becomes more significant for temperatures greater than 50°C.
2. The closed-form solution used for computing the fracture toughness for concrete gives different values for different ratios of ($a{:}b$). This is mainly due to the fact that the closing pressure due to the aggregate interlock at the crack tip zone is not taken into consideration in the used closed-form solution. This important point is currently under investigation by the authors.
3. When concrete in some structures, such as chimneys or nuclear reactors, is subjected to cyclic heating, the cyclic effect becomes more significant for temperatures greater than 100°C. For the number of heating cycles investigated in this study, the fracture toughness decreased by almost 20% after each cycle. Thus, keeping the concrete temperature below 100°C should minimize the cyclic heating effects. If more cycles were investigated, it is expected that the fracture toughness will continue to decrease but at a lower rate.
4. The empirical equation given by John and Shah to predict the fracture toughness for concrete of a known $f_c$ can also be used for estimating the residual fracture toughness if the residual concrete compressive strength is known. The equation compares well for notched beams with $a{:}b = 1{:}6$.

## Acknowledgements

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## Appendix

The Mode I stress factor ($K_I$) for a beam with a central crack is given in Tada *et al.*[12] as follows

$$K_I = \sigma\sqrt{\pi a}\,F\left(\frac{a}{b}\right) \tag{A1}$$

The stress $\sigma$ is calculated by:

$$\sigma = \frac{6M}{b^3} \tag{A2}$$

where

$$M = \frac{(P)(S)}{4} \text{ (see \textit{Figure} 1)} \tag{A3}$$

The function $F(a/b)$ is given in Tada *et al.*[12] as follows

$$F\left(\frac{a}{b}\right) = 1.09 - 1.735\left(\frac{a}{b}\right) + 8.2\left(\frac{a}{b}\right)^2 - 14.18\left(\frac{a}{b}\right)^3 + 14.56\left(\frac{a}{b}\right)^4 \tag{A4}$$

where $a$ is the crack length, $b$ is the beam depth, $S$ is the clear span and $P$ is the applied load. The fracture toughness is computed by substituting the value of the critical load at failure in Equation (A3).

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