Effect of Temperature and Number of Heating–Cooling Cycles on the Mode I, Mode II and the Mixed-Mode I-II Fracture Toughness of concrete

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ABSTRACT

In this research, the effects of temperature and number of heating–cooling cycles on the mode I, mode II and the effective value of the mixed-mode I-II fracture toughness of concrete were investigated through two series of tests. In the first series of tests, the effect of temperature was studied in a heating–cooling cycle at ambient temperature (25°C) and 60, 150, 200, 300, 500, and 700°C. The highest and lowest mode I, mode II and the effective value of the mixed-mode I-II fracture toughness were, respectively, observed at 150 and 700°C. In the second series of tests, the effect of number of heating–cooling cycles was investigated on the mode I, mode II and the effective value of the mixed-mode I-II fracture toughness of concrete specimens at 150°C and a crack inclination angle of 45°. According to the results, the mode I, mode II and the effective value of the mixed-mode I-II fracture toughness increased in the first cycle and decreased with increasing the number of heating–cooling cycles. As the crack inclination increased, the effective value of the mixed-mode I-II fracture toughness of the concrete specimens increased. The mode II fracture toughness increased up to a crack inclination angle of 45° and then decreased. Moreover, with increasing the crack inclination angle, the mode I fracture at the inclination angle of 0° was changed into the mixed-mode (tension–shear) fracture at inclination angles smaller than 28.8°. The mixed-mode tension–shear fracture was changed into the mixed-mode compressive–shear fracture at crack inclination angles larger than 28.8°.

Key Words: **Fracture toughness, heating–cooling cycle, mixed-mode, concrete, crack inclination angle**

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Introduction

Fracture mechanics is one of the branches of mechanics engineering concerned with the study of the propagation of cracks in concrete. From a microscopic point of view, crack growth occurs due to the separation of molecular bonds at the crack tip. When an external force is applied to the concrete, microcracks are formed and propagated, leading to macro-fractures and eventually concrete fracture [1].

According to the fracture mechanics definition, unstable fracture occurs when tension is concentrated near the crack tip. In this case, one of the stress intensity factors, namely the mode I factor (KI), the mode II factor (KII) or the mixed-mode factor, reaches a critical value of KIC or KIIC. This critical value, called fracture toughness.

Various methods are available for determining the fracture toughness of rock specimens. In this research, the conventional test on the cracked straight through Equations (1) and (2) proposed by Atkinson et al. [2] and Eq. (3) suggested by Funatsu et al. [3] were used to calculate the critical stress intensity factors and the mode I, mode II, and mixed-mode I-II fracture toughness.

$$K_{Ic} = \frac{P\sqrt{a}}{\sqrt{\pi}RB} N_I \qquad (1)$$

$$K_{IIc} = \frac{P\sqrt{a}}{\sqrt{\pi}RB} N_{II} \qquad (2)$$

$$K_{eff} = \sqrt{K_{Ic}^2 + K_{IIc}^2} \qquad (3)$$

Where K_{IC}, K_{IIC} and K_{eff} represent the mode I, mode II and the effective mixed-mode I-II fracture toughness respectively, R the Brazilian disc radius, B disc thickness, P pressure load at fracture point, and a half-length of the crack. Moreover, N_I and N_{II} denote the dimensionless intensity factors which are dependent on a/R and β (loading angle relative to the crack direction). Equations (4) and (5) were proposed by Atkinson et al. [2] to determine N_I and N_{II} for a/R<0.3:

$$N_I = 1 - 4(\sin\beta)^2 + 4(\sin\beta)^2 * \left(1 - 4(\cos\beta)^2\right)\left(\frac{a}{R}\right)^2 \qquad (4)$$

$$N_{II} = \left[2 + \left(8\cos^2\beta - 5\right)\left(\frac{a}{R}\right)^2\right]\sin 2\beta \qquad (5)$$

In this paper, the effects of temperature and number of heating–cooling cycles on the mode I, mode II and mixed-mode I-II fracture toughness of concrete were investigated through two series of tests. In the first series of tests for physical modeling fire, the concrete undergo a heating and cooling cycle, which means they are exposed to considerable heat first and then cooled after extinguishing the fire. In the fire, the temperature gradually rises, so these 7 temperatures are selected to consider the fracture toughness of concrete at each temperature after extinguishing the fire. In the first series, the effect of temperature was studied in a heating–cooling cycle at the ambient temperature (25°C) and 60, 150, 200, 300, 500, and 700°C. In the second series of tests, the effect of number of heating–cooling cycles was investigated on the mode I, mode II and the mixed-mode I-II fracture toughness of concrete at 150°C and a crack inclination angle of 45°. A review of the literature indicates that most studies have focused on the effect of temperature and number of heating–cooling cycles on the mode I and mode II fracture toughness. The novelty of this study is to investigate the effect of temperature and number of heating–cooling cycles on the mixed-mode I-II fracture toughness, especially the fracture toughness of concrete.

Tests conducted on the specimens and the analysis of the results

A number of the discs were prepared to investigate the effect of temperature on the specimens previously subject to heating–cooling cycle. To this end, the discs were first placed in an oven and heated for 12 h. Three or four sandstone discs were placed in the oven (for modeling the heating process) to conduct the tests at each temperature and loading angle. The heating rate in the electrical furnace was 15 °C/min to simulate. In the heating stage, the discs were heated at 25, 60, 150, 200, 300, 500, and 700°C, and then removed and cooled down to the ambient temperature. The second series of discs were prepared to investigate the effect of the number of heating–cooling cycles (1, 5, 10, 15, and 20 cycles) on the specimens heated at 150°C and cooled down to the ambient temperature for modeling hydraulic fracturing. The rate of temperature rise was 1-2°C/min. In the first series, the tests were performed at each temperature at inclination angles of 0, 15, 28.8, 45, 60, 75 and 90°. In the second series, all tests were performed at a crack inclination angle of 45°.

In the first series of tests, the results show that the mode I, mode II and effective value of the mixed-mode I-II fracture toughness increase at all angles from the ambient temperature up to 150°C. Up to 150°C, the effective porosity decreased due to the closure of pre-existing cracks. As a result of the closure of the pre-existing cracks, the fracture toughness increased. The fracture toughness of the concrete decreased from 200 to 500°C due to formation of microcracks. The effective porosity was determined to prove the formation of new microcracks in the concrete specimens. The increase of the effective porosity and decrease of the longitudinal waves velocity from 200 to 500°C is due to the formation of new microcracks. As a result of the formation of new micro-crack, the fracture toughness decreased. At 700°C, evaporation of interstitial water, conversion of $CaCO_3$ (calcite) to CaO, and CO_2 emissions lead to a change in the color, the formation of microcracks, and rapid reduction of the fracture toughness.

In the second series of tests, the results show that **the** mode I, mode II, and the effective mixed-mode I-II fracture toughness of specimens in the first cycle increase relative to the 0th cycle due to the closure of microcracks and evaporation of pore water. However, the density of microcracks increases from the 5th cycle onwards due to thermal shocks. As a result, the mode I, mode II, and the effective mixed-mode I-II fracture toughness fracture toughness of the specimens after 5, 10, 15, and 20 heating–cooling cycles decreased relative to the 0th cycle.

The fracture toughness varies by changing the loading angle relative to the crack direction. The mode I fracture toughness decreases at 25, 60, 150, 200, 500, and 700°C with a negative slope. The fracture toughness approaches 0 at all temperatures at a crack inclination angle of 28.8°. The fracture toughness increases from 45 to 90° with a negative angle, and the maximum fracture toughness is observed at a crack inclination angle of 90° relative to the crack direction. The mode of fracture changes from opening mode (mode I) at the crack inclination angle of zero degree to mixed mode (tension-shear) at the crack inclination angle of less than 28.8°. The mode of fracture changes from tension-shear to compression-shear (The minus sign behind the fracture toughness values indicates the mode of fracture is compression-shear) at the crack inclination angle of greater than 28.8°.

Conclusion

The results of the present paper are as follow:

• The highest and lowest mode I, mode II, and mixed-mode I-II fracture toughness were observed at 150 and 700°C, respectively.

• The effective mixed-mode I-II fracture toughness increased at all temperatures with increasing the crack inclination angle. The lowest and highest mixed-mode I-II fracture toughness were, respectively, observed at inclination angles of 0 and 90°.

• The effective mixed-mode I-II fracture toughness of the concrete specimens in the first cycle increased by relative to the 0th cycle. As the number of heating–cooling cycles increased from 5, 10, 15, and 20, the effective mixed-mode I-II fracture toughness of the concrete specimens decreased, respectively, by relative to the 0th cycle.

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