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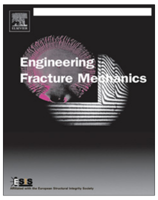

Determination of the softening curve and fracture toughness of high-strength concrete exposed to high temperature

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A B S T R A C T

Determination of the softening curve and the fracture toughness of high-strength concrete exposed to high temperature from 200 °C to 800 °C employing the three point bending test were presented. The softening curves of post-fire high-strength concrete specimens were calculated by using the inverse analysis. The fracture parameters were obtained by analytical and weight function method. The validation of double-K fracture model to the post-fire high-strength concrete specimens was proved based on the calculated softening curves. The toughness values obtained by the weight function method coincided well with the ones obtained by the analytical method.

1. Introduction

With the development of concrete technology, high-strength concrete (HSC) is increasingly popular in modern complicated structures which are more vulnerable to damages caused by earthquake and other disaster due to its brittleness caused by the increase of strength [1]. Hence the fracture properties of HSC are more important than those of normal-strength concrete (NSC) with regard to safety assessment and design of modern structures.

As fire still constitutes a tremendous risk to the human society, the fracture properties of HSC in or after fire remained to be studied. Various researches have concentrated on the reduced strength or stiffness (modulus) of HSC subjected to elevated temperatures [2–6]. Relatively fewer researches works on the residual fracture properties of high strength concrete, such as the fracture energy [7–10] and the fracture toughness [11–12]. Hence, the influence of temperature on the fracture properties needs to be further studied.

The fracture energy, the fracture toughness and the softening curve of high strength concrete are the important input parameters for numerical simulation of reinforced structure elements such as concrete beams and columns subjected to static, dynamic and environmental load. The design code of CEB-FIP model code 1990 in Europe provides the fracture energy and softening curve of concrete at room temperature but lacking of the data during or after the high temperature. Hence, the softening curves and the fracture properties of post-fire concrete would be useful for the analysis of post-fire concrete structural elements.

The softening curve, expressing the cohesive stress distribution along the fictitious fracture zone, is a prior to determine K_c. The softening curve could be obtained by direct tensile test, but with tremendous difficulty. Hence, it is popular for researchers to calculate the softening curve using the inverse analysis. However, to date, few researches focused on the softening curve of HSC and post-fire HSC.

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Nomenclature

a	equivalent-elastic crack length
a_c	critical notch depth of the specimen
$CMOD$	crack mouth opening displacement
$CTOD$	crack tip opening displacement
E	residual Young's modulus
G_F	fracture energy (N/m)
h_0	thickness of the clip gauge holder
K_{un}^{E}	unstable fracture toughness by experiment
K_{un}^{w}	unstable fracture toughness by weight function method
K_{c}^{W}	cohesive fracture toughness by weight function method
$m(x, a)$	weight function
$\sigma(w)$	cohesive stress at the tip of initial notch
$\sigma(x)$	cohesive stress at equivalent-elastic crack length x
P_u	maximum load
w_0	crack width at stress-free point
w	crack opening displacement at the tip of initial notch
a_0	initial notch depth of the specimen
a_s	effective crack length corresponding to w_s
$CMOD_c$	critical crack mouth opening displacement
$CTOD_c$	critical crack tip opening displacement
f_t	tensile strength
h	height of wedge-splitting specimens
K_{ini}	initial fracture toughness
K_{un}^{A}	unstable fracture toughness by analytical method
K_{c}^{A}	cohesive fracture toughness by analytical method
K_c	cohesive fracture toughness
M_1, M_2, M_3, M_4	parameters of weight function
σ_s	cohesive stress at the break point of softening curve
P_{ini}	the initial cracking load
T_m	heating temperatures
w_s	crack width at break point of softening curve

Experimental results show that the fracture process of concrete structures undergoes three main stages: (i) crack initiation, (ii) stable crack propagation, and (iii) unstable fracture. Accordingly, the double-K fracture criterion initially introduced by Xu and Reinhardt [13] shows that the initial cracking toughness K_{ini} and unstable fracture toughness K_{un} can be used to study the crack propagation of concrete. An analytical method [14] describing the above-mentioned three phases of concrete fracture process was developed using three-point bending test.

In order to determine the double-K fracture parameters analytically [14,15] the value of cohesive toughness, K_c due to cohesive stress distribution in the fictitious fracture zone is computed using method proposed by Jenq and Shah [16]. The determination of K_c should be done using a special numerical technique because of existence of singularity problem at the integral boundary. However the use of universal form of weight function will provide a closed form expression to avoid the singularity problem. It has proven its accuracy in determining the double-K fracture parameter compared to analytical method [17,18].

The present paper is aimed to determine the softening curve of post-fire HSC by inverse analysis using the three point bending (TPB) test. Afterward, the residual fracture toughness of post-fire HSC would be calculated and the validation of double-K fracture model would be proved. The validation of the double-K fracture model in turn would prove the correctness of softening curves of post-fire concrete. Hence, the paper is structured as follows: (i) experimental program and results, (ii) determination of softening curves by the inverse analysis, (iii) determination of fracture parameters of post-fire concrete, and (iv) validation of double-K fracture model to post-fire HSC.

2. Experimental program and results

2.1. Experimental program

Two concrete strengths, C80 and C100 were prepared in present research. A total of 50 TPB beams with the uniform dimension (100 mm × 100 mm × 515 mm) according to RILEM [19] were cast. The concrete mix proportions (by weight)