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Fracture behaviors of a new steel fiber reinforced recycled aggregate concrete with crumb rubber

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HIGHLIGHTS

- The fracture behaviors of steel fiber-reinforced RA concrete which consists of crumb rubber were investigated.
- The effects of rubber content on the fracture behaviors of the RSRAC subjected to different temperatures were analyzed.
- The fracture properties were obtained in different temperatures.
- The fracture toughness and fracture energy first increase and then decrease.
- The thermal damage increases the fracture energy and CMODc.

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ABSTRACT

This paper investigated the fracture behaviors of a new Steel fiber reinforced Recycled Aggregate Concrete which consists of crumb Rubber (RSRAC). The effects of rubber content on the fracture behaviors of the RSRAC subjected to different temperatures were analyzed. In RSRAC, the steel fiber was used to improve the crack resistance of concrete, and the inclusion of crumb rubber is mainly for environment protection, energy dissipation and reducing the risk of explosive spalling during exposure to high temperatures. A series of concrete mixes were prepared with ordinary Portland cement, recycled coarse aggregates (RCA) or natural coarse aggregates (NCA), steel fiber with volume-ratio of 1% and crumb rubber with different replacement ratios of 0%, 4%, 8%, 12% and 16% for fine aggregate (sand). The fracture properties, including fracture toughness (K_{IC}) and fracture energy (G_F), of the different concrete mixes subjected to different temperatures (25 °C, 200 °C, 400 °C and 600 °C), were obtained through three-point bending tests on 72 notched beams with sizes of 100 mm × 100 mm × 515 mm. The results indicated that both the fracture toughness and fracture energy first increase and then decrease with increase of the rubber content; at certain rubber content, the mixes had the highest toughness. The thermal damage due to heating from 25 °C to 600 °C also obviously increased the fracture energy and critical crack mouth opening displacement ($CMOD_{cri}$), but it was not the case for the fracture toughness. It demonstrated that exposure to high temperature made all cementitious materials tested significantly more ductile and less resistant to crack propagation.

1. Introduction

A new type of Steel fiber reinforced Recycled Aggregate Concrete (RSRAC), which consists of crumb rubber, is a concrete material patented by the authors (China invention patent No.: ZL. 201010019345.3). This new material has been coined on the following considerations: (1) the inclusion of recycled concrete aggregate (RCA) and rubber particles is mainly for the environmental and economic significance [1–3], (2) the steel fiber and rubber particles are used to improve the performances of concrete both before [4–6] and after [7] exposure to different temperatures, (3) the advantageous interaction exists between steel-fiber and rubber as mentioned in the literature [8–10].

Strength, stiffness, toughness and brittleness are the fundamental mechanical properties of concrete. The changes of these properties after exposure to high temperatures are of great importance for the design of concrete structures [11]. It is, thus, more important to investigate the mechanical properties of concrete in the structures subjected to long-term high temperatures. More and more attentions [12,13] have been paid to the mechanical properties of concrete at high temperature or the residual properties of concrete after exposure to high temperatures. Moreover, the compressive properties of RSRAC mixes have already been analyzed

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and discussed by the authors, and the relevant achievements have been reported in a separate paper, which is under review. In addition, the poor performance of the RCA is associated with the cracks and fissures formed in processing recycled aggregates, which makes concrete prepared with RCA suffer brittleness problems [14]. Therefore, the experimental research on the fracture properties of RSRAC mixes in this paper is in urgent need.

The fracture properties of concrete significantly influence the structural behavior of concrete components at high temperatures [11]. Studies on the fracture properties of concrete have recently attracted more attentions. The fracture energy is defined as the energy absorbed to create a unit area of fracture surface, representing the energy dissipation capacity of overall loading process. RILEM [15] recommended the three-point bending method for determination of the fracture energy with specimens of notched beams. Menou et al. [16] examined the residual fracture energy of cement paste, mortar and concrete subjected to high temperature and found that the thermal damage due to heating from 120 to 400 °C increases the fracture energy by 50% compared with the reference tests at room temperature. Peng et al. [13] conducted an experimental research to explore the relationship between explosive spalling and the residual fracture properties of concrete exposed to high temperatures; their results showed that the residual fracture energy increased after heating. Nielsen et al. [17] also suggested that the damage introduced by a temperature within 300–400 °C increased the fracture energy by 50% compared with the tests at room temperature. Since the fracture toughness represents the resistance to instable crack propagation, namely the resistance to brittle fracture, Hisham Abdel-Fattah et al. [18] experimentally investigated the variation of the residual fracture toughness of concrete with different temperatures and pointed out that the residual fracture toughness of concrete decreases with the increase in temperature.

This paper studies the fracture behaviors properties (including the fracture energy G_F and fracture toughness K_{IC}) of a new steel fiber reinforced Recycled Aggregate Concrete (RSRAC) subjected to different temperatures. From the test results, a preliminary understanding of the fracture failure mechanism of RSRAC after exposure to different temperatures can be achieved. This study may provide a basis for the further research on RSRAC and its potential applications.

2. Experimental details

2.1. General

A total of six groups of mixes, named NC-R0, RC-R0, RC-R4, RC-R8, RC-R12 and RC-R16, were prepared using 100% recycled concrete aggregate (RCA) or natural concrete aggregate (NCA), 1% steel fiber and rubber crumb with varied content (0%, 4%, 8%, 12% and 16%). Each type of concrete mixes includes 12 cylinders with dimensions of 150 mm × 300 mm (diameter and height) and 12 notched beams with dimensions of 100 mm × 100 mm × 515 mm, every three of which were exposed to a temperature (25 °C, 200 °C, 400 °C and 600 °C). The proportions and compressive strengths are presented in Table 1.

Crumb rubber, obtained from waste tires, has an average particle diameter of 14 ~ 20 sieve size (i.e. 0.85 ~ 1.40 mm according to ASTM-E11-09e1), a specific gravity of 1.05, and a melting temperature of 170 °C. The steel fibers were cut and shaped from steel plate, with a length of 32 mm, an aspect ratio of 45 and a tensile strength of 600 MPa. This type of steel fibers, which were made from ordinary steel, with a melting temperature of 1538 °C and a density of 7.82 g/cm^3, are loose in form at delivery (Fig. 1). In addition, a commercially available naphthalene-based super-plasticizer with a solid content of 30% and a water reducing rate of 20% was used as admixture to achieve slump of the concrete mixes around 150 mm. The amount of plasticizer was 1.0% by weight of cement based on slump tests according to BS 1881: Part 102 (1983). Recycled concrete aggregates, crumb rubber and steel fibers are shown in Fig. 1.

2.2. High temperature program

Among 12 cylindrical specimens in each mix, three were tested immediately after conditioning without being unheated (at the room temperature of 25 °C), the remaining 9 specimens were divided into 3 groups and exposed to 3 temperatures (200 °C, 400 °C and 600 °C) in an electrical furnace, respectively. In the furnace, the specimens were heated at a constant rate of 8 °C/min, from the room temperature to the prescribed temperatures. The temperature–time curves used in heating of the test specimens are showed in Fig. 2, which were adopted from the paper [13]. The target temperature was maintained for 120 min before the electrical furnace was turned off and the specimens were then naturally cooled down to the room temperature. During the heating period, water was allowed to evaporate freely.

2.3. Methods of three-point bending tests

A three-point bending method was used in the study to determine the fracture performance of the new concrete material RSRAC in accordance with the recommendation of RILEM Fracture Mechanics Committee (TC50-FMC) [15]. As showed in Fig. 3(a), the notched beams used for the three-point bending test had dimensions of 100 mm × 100 mm × 515 mm and a span of 400 mm; a notch with a depth of 30 mm (a_0/h = 0.3) was located in the mid-span place. The test was conducted on a closed-loop Electro Hydraulic universal testing machine with a 500-kN capacity and three control modes: load control, displacement control and strain control. In the study of the fracture properties, a 50-kN load cell with the precision of 1 N and a 50-mm displacement transducer (LVDT) with the accuracy of 0.01 mm were applied to obtain the load and deflection at the mid-span respectively, while the crack mouth opening displacement (CMOD) was measured with a 10-mm clip-on gages with the accuracy of 0.001 mm. All the data were recorded via the synchronous collection system of TDS-530. During the loading process, a constant displacement rate of 0.05 mm/min with the central deflection as the control parameter was applied until the final failure of the specimen. In addition, a testing strategy used in the three-point bending method [Fig. 3(b)] was designed to eliminate the negative effect of compressive plastic deformation on the compressed parts of specimens (e.g. the pedestal and actuator head) on the measurement. An advantage of the designed testing strategy is that the reference points located on the neutral axis of the notched beams were applied to measure the mid-span deflection in order to remove the compressive plastic deformation on the other parts of specimens from the measured deflection. As a result, the measured values are authentic deflection of the tested beams. Both the specially designed testing system and the precision of measurement ensure the accuracy of the load–deflection (P–δ) curves and load-CMOD (P-CMOD) curves. The specimen and set-up of three-point-bending test are shown in Fig. 3.

Table 1
Mix proportions and compressive strengths.

Mix	Compressive strength (MPa)	Mix proportions (unit weight:kg/m^3)									
		W/C	W	OPC	S	NCA	RCA	AW	SF	R	WRA
NC-R0	56.52	0.35	170	485	645	1052		–	78	–	4.5
RC-R0	51.41	0.35	170	485	645	–	954	37	78	–	4.5
RC-R4	49.06	0.35	170	485	625	–	954	37	78	7.9	4.5
RC-R8	39.41	0.35	170	485	605	–	954	37	78	15.7	4.5
RC-R12	37.61	0.35	170	485	585	–	954	37	78	23.6	4.5
RC-R16	35.88	0.35	170	485	565	–	954	37	78	31.5	4.5

Note: NC = natural concrete, RC = recycled concrete, R0, R4, R8, R12 and R16 for volume substitution ratio of rubber is 0%, 4%, 8%, 12% and16%, W/C = water/cement ratio(mass), W = water, OPC = ordinary Portland cement, S = sand, NCA = natural coarse aggregate, RCA = recycled concrete aggregate, AW = additional water, SF = steel fiber, R = crumb rubber, WRA = naphthalene-based high-range water-reducing admixture.