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Self-healing behaviour of multiple microcracks of strain hardening cementitious composites (SHCC)

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HIGHLIGHTS

- Influence of crack width on the crack sealing degree was studied.
- Correlation between the crack closure and water absorption reduction was analysed.
- Multiple microcracks has the best healing ability under $Ca(OH)_2$ solution/dry cycles.
- $Ca(OH)_2$ solution promotes the healing process of microcracks in fly ash-rich SHCC.
- Neutron radiography visualization confirms water absorption reduction after healing.

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ABSTRACT

Strain Hardening Cementitious Composites (SHCC) exhibit multiple crack characteristics when subjected to a bending or tensile load. In this paper, SHCC specimens were preloaded under three-point bending to introduce multiple microcracks and exposed to different conditions to assess their self-healing. Observation and analysis of crack characteristics, water absorption tests by a gravimetric method and neutron radiography were conducted to study the self-healing behaviour of microcracks in SHCC under three conditions (water fog, water/dry cycle, $Ca(OH)_2$ solution/dry cycle). The results indicate that self-healing is a slow process, even in the presence of liquid water or calcium hydroxide solution. The crack sealing degree decreases with the increase in crack width, and only fine cracks of 10–20 μm can be healed completely. $Ca(OH)_2$ solution promotes the healing process due to the enhancement of the pozzolanic reaction of fly ash. Water capillary absorption can be significantly reduced by crack sealing. The correlation between the crack sealing degree (crack closure) and water absorption reduction can be described well by a linear function.

1. Introduction

Currently, reinforced concrete is the most widely used building material in the world for both entire buildings and key structural elements that withstand various substantial loads. However, it is generally accepted that the service life of many reinforced concrete structures is frequently insufficient. Repair and maintenance of the existing reinforced concrete structures have become serious economic and ecologic problems [1,2].

As a rather brittle material, concrete can easily crack under imposed strain, thereby allowing water, dissolved chlorides and other aggressive ions to enter the material and to cause a series of deteriorating processes. Therefore, it is necessary to find ways to limit crack formation and improve the ductility of concrete. Many such attempts have been made during the development of modern concrete technology. Among these materials, strain hardening cementitious composites (SHCC) exhibit pseudo-strain hardening characteristics and multiple crack characteristics when subjected to a bending or tensile load [3–5].

Multiple microcracks are formed in SHCC instead of the wide cracks in normal concrete, with the hope that the transport of aggressive substances in the fine cracks can be limited. Previous studies by Wang et al. [6], Sahmaran et al. [7] and Mihashi et al. [8] have shown that very fine cracks can delay the ingress of liquids and chlorides into cement-based materials. Kobayashi et al. [9,10] also found that cracked SHCC with fine cracks exhibited higher corrosion protection performance than normal concrete did.

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However, water still quickly penetrated the microcracks and then migrated further into the porous cement paste. This was also observed by Zhang et al. [11,12] and Schroefl et al. [13]. Paul et al. [14] also stated that significantly more chloride can build up in cracked SHCC specimens than in uncracked SHCC. Microcracks in this case served as the preferential paths for mass transport.

However, concrete has the natural capacity of autogenous crack healing, as first found in 1836 (stated by Hearn [15]). A number of studies [16–27] have investigated the self-healing behaviour of cement-based materials. Suryanto et al. [16] found that narrow cracks of less than 10 μm healed in a short time, while 20–30 μm cracks only partially healed. Lepech et al. [17], Ma et al. [18] and Zhang et al. [19] found that the water permeability of cracked SHCC drops drastically over time due to self-healing. In addition, Yang et al. [20] studied the relationship between self-healing and the crack width and concluded that the crack can be considerably healed when it is below 50 μm. Snoeck et al. [28–30] improved the healing of cracks in SHCC using superabsorbent polymers (SAP). Ferrara et al. [31] combined fibres and crystalline admixtures to enhance the self-healing performance of HPFRCCs. Sisomphon et al. [32] stated that wet/dry conditions had the optimum mechanical recovery but that indoor air-cured conditions contributed no visible healing. Qian et al. [33] studied the effect of slag and limestone powder on the recovery of mechanical properties of pre-cracked SHCC under different conditions.

In this paper, SHCC specimens with multiple microcracks were prepared by three-point bending test. The crack pattern (number of cracks and crack width distribution) was analysed based on microscopic observations. The cracked SHCC specimens were then exposed to three climatic conditions (water fog, water/dry cycle, and saturated $Ca(OH)_2$ solution/dry cycle) for preselected durations of time, with the aim of following the process of self-healing. The sealing degree of these fine cracks was then determined and evaluated with respect to the crack width and healing period. The effect of time-dependent crack healing on the water capillary absorption of cracked SHCC was also studied quantitatively by the gravimetric method and neutron radiography test.

2. Materials and methods

2.1. Materials and preparation of test specimens

The composition of the cement-based matrix of the SHCC used in this project was as follows: 550 kg/m^3 ordinary Portland cement (Type 42.5), 650 kg/m^3 fly ash, 550 kg/m^3 fine sand with a maximum grain size of 0.3 mm, and 395 kg/m^3 water. After mixing the different components for 2 min, 2% by volume of PVA (Polyvinyl Alcohol) fibres with a diameter of 40 μm and length of 12 mm were added into the fresh mix, followed by another 2 min of mixing. Then, specimens with dimensions of 40 (height) × 25 (width) × 160 mm^3 (length) were cast in steel forms. The specimens were reinforced with two round steel bars, as shown in Fig. 1. After hardening for 24 h, the forms were removed. The specimens were then placed in a humid room (T = 20 °C and RH 100%).

2.2. Crack formation and measurements

At 28 days, the specimens were removed from the curing room for crack formation. At this relatively early stage, the fly ash added to the SHCC normally has not hydrated completely due to the slow process of the pozzolanic reaction. Hence, the simulated healing effect of fly ash can be enhanced under certain conditions. The specimens were loaded by three-point bending to induce microcracks, as shown in Fig. 2(a). The beams were small, with a span of 150 mm between the supports. The typical crack pattern on the bottom and side surfaces of one SHCC sample is shown in Fig. 2(b). The imposed strain was measured near the centre of the beams with strain gauges. The load was removed when the steel rebar began to carry the load. Typical results are shown in Fig. 3. As shown, the imposed tensile strain varied between 1.9 and 2.5%. In this way, a characteristic crack pattern was produced in the SHCC specimens.

Using high-resolution digital photos taken by a microscopic device, the opening of the cracks on the bottom surface of the specimens were measured, as shown in Fig. 4. The average value of four measurements of each crack represented the crack width.

2.3. Self-healing under different conditions

After crack formation, the four side surfaces of the beams were covered with self-adhesive aluminium foil, leaving the bottom and top surfaces (25 mm × 160 mm) open. The cracked SHCC specimens prepared in this way were then exposed to three different environmental conditions for self-healing: a) Storage in a climate room with water fog; b) Immersion (the bottom surface) in water for 6 days and drying at RH 50% for 1 day; and c) Immersion (the bottom surface) in saturated $Ca(OH)_2$ solution and drying at RH 50% for 1 day. In the following section, these conditions are referred to by the following abbreviations: “water fog”,

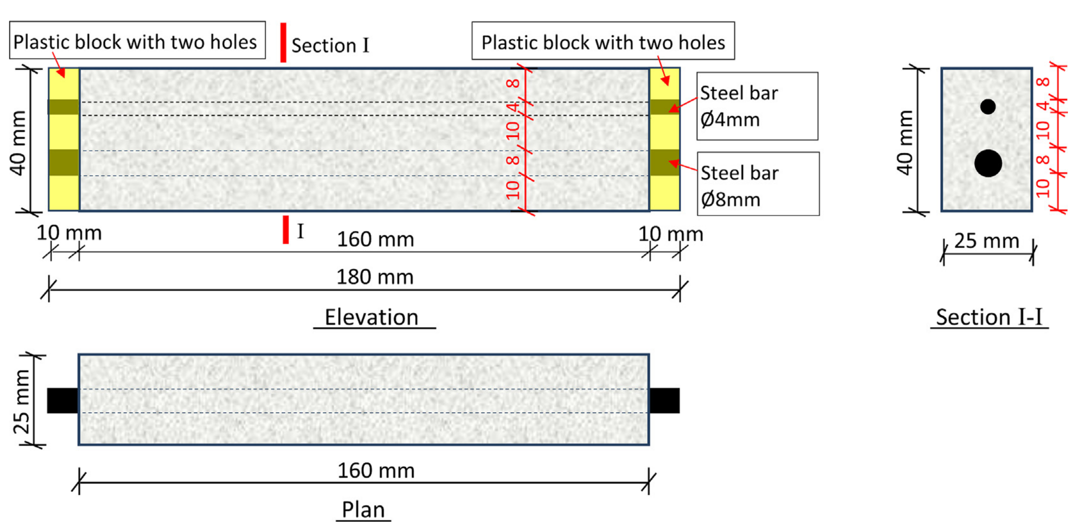

Fig. 1. The shape and size of the prismatic specimens used in this project and the positions of the steel reinforcements embedded in the specimens.