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Effect of fine crack width and water cement ratio of SHCC on chloride ingress and rebar corrosion

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ABSTRACT

SHCC (Strain Hardening Cement-based Composite) is a material known for its strain-hardening behavior under tensile and bending stress and its characteristic numerous small cracks. SHCC is expected to show superior durability because of the fineness of the cracks. In this study, chloride ingress through cracks into SHCC and progress of rebar corrosion in three mixtures of SHCC with various water-cement ratios were investigated. Through a chloride solution immersion test, it was confirmed that chloride could penetrate through even very fine cracks. The resistivity of cracked SHCC against chloride ingress is mainly governed by the accumulated crack width and the water cement ratio. Chloride pre-mixed SHCC specimens were left in a high-temperature, high-humidity chamber for 11 months to promote rebar corrosion. While the accumulated crack width and the water cement ratio were both influential to an increase in corrosion area, only the water cement ratio had bearing on corrosion loss.

1. Introduction

Reinforced concrete has superior mechanical characteristics and high durability due to the complementary combination of steel and concrete. The high alkalinity of concrete creates a passive film on the steel and prevents rebar corrosion. However, once the passive film is damaged by carbonation of cover concrete caused by the carbon dioxide in the atmosphere, or by chloride migration through the cover concrete, the rebar starts to corrode by chemical reaction with water and oxygen.

In order to build a durable concrete structure, it is essential to prevent aggressive agents from penetrating through the cover concrete and reaching the rebar. For this purpose, the model codes for concrete structural design specify the upper limit of water binder ratio, the minimum cover depth, etc., and include formulas for calculating these values. The drawback of concrete is its low tensile ductility, because of which cracks can easily form under a tensile load or during shrinkage. Cracks can be fatal in terms of durability as they provide bypass routes for aggressive agents to ingress into the structures [1,2]. Therefore, while bending cracks are tolerated in RC structures, an upper limit is usually specified for the crack width from the viewpoint of securing durability.

Strain hardening cement-based composite (SHCC) is a material that exhibits strain-hardening characteristics and forms numerous cracks under tensile and bending stresses. The high tensile ductility of SHCC depends on the dispersion and orientation of fiber, which, however, can be largely affected by the shape and dimension of structure, construction quality, fresh properties of SHCC, and so on. It is therefore difficult to effectively utilize the SHCC's superior tensile ductility in structural design, and constructing SHCC structures without using tensile rebar entails many issues. Meanwhile, when we look at the durability, SHCC is believed to have low water and gas permeability, and low chloride diffusion rates thanks to the small crack width. Previous investigations with a variety of test methods such as chloride spraying, chloride ponding, and electrolytic acceleration have shown that SHCC has better abilities to protect rebar from corrosion than conventional types of concrete [3–11].

A water sorption test conducted by Wittmann et al. shows that water can penetrate into even very fine cracks in SHCC immediately [12,13]. Generally, chloride is dissolved in water and diffuses into concrete with the water, and if the water could penetrate concrete through micro cracks, chloride will penetrate easily, too. However, the chloride penetration through cracks in SHCC has not been sufficiently investigated yet in a quantitative manner. Furthermore,

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if chloride can diffuse in SHCC easily, then the reason why the previous reports showed that SHCC still exhibited high rebar corrosion prevention performance should be clarified.

In view of the above, the effects of crack properties on the amount of chloride penetration through cracks were investigated by immersing SHCC specimens with fine cracks in a chloride solution. Simultaneously, SHCC specimens with pre-mixed chloride were left in a high-temperature humid chamber for 11 months, after which the amount of rebar corrosion was measured to investigate the effects of fine cracks on the rebar corrosion rate after the chloride-induced destruction of the passive film.

2. Chloride penetration through cracks in SHCC

In this section, for quantitative understanding of chloride penetration through fine cracks in SHCC, cracked SHCC specimens were immersed in a chloride solution, after which the amount of chloride inside the cracks was determined.

2.1. Outline of the test

Table 1 shows the properties of high strength polypropylene (PE) fiber used in this study. Table 2 shows the mixtures of SHCC and mortar. Mixture A is a standard mixture of SHCC used in previous research by the authors [5–7]. The water cement ratio is 0.3 and the volumetric fiber ratio is 1.5%. In Mixtures B and C, 25% of cement is replaced with limestone powder to increase the workability. The water cement ratio is therefore 0.4, higher than that of Mixture A, and the fiber ratios are reduced to 1.0% and 0.75%, respectively. Mixture O has the same mix proportion as Mixture A except it does not contain any fiber. For all the mixtures, early strength Portland cement, fine silica sand with a diameter ranging from 0.1 to 0.2 mm, a high range water reducing agent (polycarboxylate-based type), and a viscosity-enhancing agent (methylcellulose) were used. For mechanical properties of Mixtures A, B, and C, see Ref. [7].

Eight dumbbell-shaped specimens shown in Fig. 1 were prepared for each mixture in accordance with the JSCE standards [14]. To control the crack width, a glass fiber reinforced plastic (GFRP) bar of 6 mm diameter and 300 mm length was embedded in the specimens of Mixture O. The GFRP rod has a smooth surface so that the bond strength with the mortar is very small. The specimens were cured in water at 20 °C for 28 days after the casting. Notches were cut to a depth of 3 mm at the center of the specimens with a concrete cutter, in an attempt to control the locations of tensile cracks as much as possible. After that, the specimens were subjected to tensile load to form cracks. Fig. 2 shows an example of a cracked specimen. One crack was formed in fiberless Mixture O near the notch, while several cracks appeared in specimens of Mixtures B and C that contain a reduced amount of fiber. A maximum of eight cracks were found in the specimen of Mixture A that has the highest ductility. The number of cracks along the longitudinal center line of the gauge span was counted, and the widths of cracks larger than 0.01 mm were measured with the use of a microscope with a magnification of 50. Table 3 shows the properties of the measured cracks. One of eight specimens with Mixture B had large localized cracks, one of which had a width as large as 0.6 mm, so that the properties of these cracks were excluded from the table.

Table 2
Mix proportions of SHCC and mortar.

Mixture	W/C (%)	Unit mass (kg/m³)						PE fiber (vol. %)
		W	C	Lp*	S**	SP***	Vis.****	
A	30	371	1264	–	395	28.2	0.9	1.5
B	40	340	900	300	462	20.0	0.6	1.0
C		321	851	284	595	18.8	0.6	0.75
O	30	371	1264	–	395	28.2	0.6	–

Lp*: Limestone powder.
S**: Quartz sand with a diameter range of from 100 to 200 mm.
SP***: High range water reducing agent.
Vis.****: Viscosity-enhancing agent.

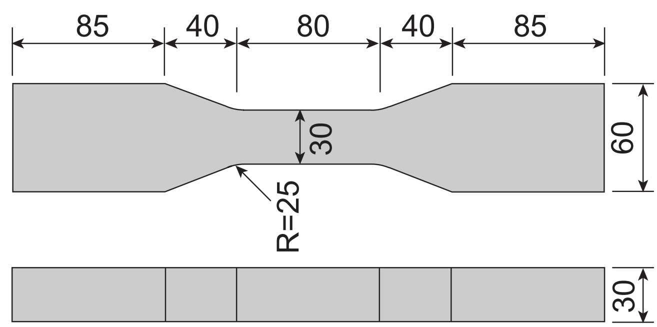

Fig. 1. Uniaxial tensile test specimen [14] (unit: mm).

Fig. 2. An example of crack formed in dumbbell-shaped specimen.

Immediately after the crack introduction, the specimens were immersed entirely in a 10% sodium chloride solution at a temperature of 20 °C for 1, 4, and 11 months, with their casting surfaces facing upward. After that, the specimens were taken out and dried in a room at a temperature of 20 °C for one week or more. The specimens were then subjected again to uni-axial tensile load until they broke up into two pieces. The SHCC specimens that had cracks originating from the notches (see Table 3) ruptured at one of these cracks during the second tensile loading.

The amount of total chloride contained on the crack fracture surface and on the specimen surface was measured with an energy dispersive X-ray fluorescence analyzer [15] shown in Fig. 3. The

Table 1
Mechanical and geometrical properties of PE fiber.

Diameter (mm)	Length (mm)	Density (g/cm³)	Tensile strength (GPa)	Young's modulus (GPa)
0.012	12	0.97	2.6	88