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Shape of corrosion-induced cracks in recycled aggregate concrete

Yuxi Zhao*, Jianfeng Dong, Hangjie Ding, Weiliang Jin

Institute of Structural Engineering, Zhejiang University, Hangzhou 310058, China

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ABSTRACT

This study investigated four groups of reinforced concrete specimens with different replacement percentages of recycled aggregate (RA). The corrosion-induced crack development in the concrete cover was investigated with a digital microscope, and the total circumferential crack widths at different radii were measured. A linear model was adopted to describe the variation of the crack width along the radial direction in the recycled aggregate concrete (RAC). The corrosion-induced crack shapes of normal concrete and RAC were schematically described. The employment of RA in the concrete mixture results in a wider-opening crack shape.

1. Introduction

One way to extensively make modes of production in the construction industry relatively more sustainable is to reduce construction waste by reusing or recycling construction materials into new structures, rather than consuming natural resources. The durability of concrete structures can also be improved to prolong their service lives. A common approach to reusing or recycling construction waste crushes waste concrete to produce recycled coarse aggregate (RA) to add to recycled aggregate concrete (RAC); this can be used in place of some or all of the natural coarse aggregates (NA) in concrete mixtures. Because corrosion-induced cracking is the major cause of durability deterioration in reinforced structures [1,2], research on corrosion-induced cracking in RAC is of great importance for sustainable development in the construction industry.

As steel corrosion develops, the resulting corrosion product places pressure on the surrounding concrete because its volume is approximately 2–6 times of that of original steel [3–5] and eventually causes cracking of the concrete cover. A considerable number of experimental studies have been conducted on corrosion-induced concrete cracking in natural aggregate concrete (NAC), primarily focusing on two aspects of the cracking process: (1) predicting steel corrosion at surface cracking [6–9] and (2) linking the crack width on the surface of the concrete cover with steel corrosion [6,10–13]. Along with empirical models based on experimental data [6–16], many analytical [17–20] and numerical [21–24] methods have been proposed based on geometrical dimensions, concrete properties, and corrosion to study the corrosion-induced cracking process. However, little research has been performed on corrosion-induced cracking in RAC.

The corrosion-induced concrete cracking process of RAC is more complex than that of NAC. The greater porosity of RAC can provide more space to accommodate corrosion products and delay the appearance of cracks on the surface of concrete cover to some extent. However, initial imperfections such as internal flaws in the RA and more complex interfaces decrease can the tensile strength of RAC [25–28] and accelerate the steel corrosion process and corrosion-induced crack propagation in concrete cover [29].

This study investigates the cracking process and the shape of the corrosion-induced cracks in both NAC and RAC. Four groups of reinforced concrete specimens with different replacement percentages of RA were cast, and the corrosion-induced crack development in each concrete cover was investigated with a digital microscope; the crack widths at different radials were measured. The results of this study contribute to the understanding of corrosion-induced cracking process in both NAC and RAC.

2. Experimental programme

2.1. Reinforced concrete specimens

Cylindrical reinforced concrete specimens with 0%, 33%, 67% and 100% replacement of NA with RA were used in the study; the dimensions are shown in Fig. 1. Each specimen had a diameter of 75 mm and a height of 150 mm, with a 16-mm-diameter plain hot-rolled steel bar in the centre. To avoid the corrosion of steel at the end of each specimen, both ends of the specimens and the exposed steel bars were coated with epoxy resin. The top end of each steel bar was attached to a wire, and the bottom end was treated with protective

* Corresponding author. Tel.: +86 571 8820 8726; fax: +86 571 8820 8685.
E-mail address: yxzhao@zju.edu.cn (Y. Zhao).

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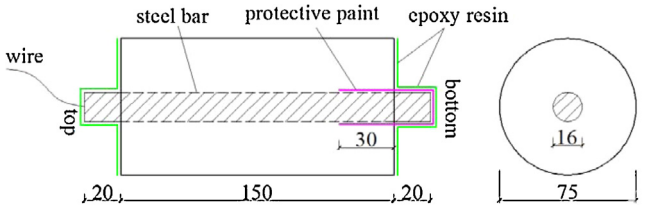

Fig. 1. Layout details of specimens (dimensions are in mm).

paint to prevent corrosion products from dissolving in the NaCl solution with a concentration of 3.5% in which the specimens were to be submerged. Two specimens were cast at each percentage of RA replacement and were labelled RXXX-N, where XXX was the percentage of RA replacement and N was the specimen number for a given RA replacement percentage. For example, R067-1 represents the first specimen with a NA replacement rate of 67%.

The mixture proportions of the four groups of concrete are shown in Table 1. The binder was ordinary Portland cement of grade 42.5R. The fine aggregate was medium natural river sand with a fineness modulus of 2.5. The NA was normal gravel, and the RA was a commercial product purchased from Shanghai, China. Both the NA and RA consisted of coarse particles in a size range of 5–25 mm. Due to the greater water absorption of RA, extra water, calculated by multiplying the water needed for the NA mixtures by 1.34%, was added to the mixtures to reach the target slump for the fresh concrete, as shown in Table 1. After casting, all of the specimens were covered with damp burlap and wetted once a day for 28 days. Table 1 also shows the 28-day compressive strength (fc) values of the concrete mixtures.

2.2. Accelerated corrosion history

After 28 days of curing, the specimens were wrapped in 36 mesh stainless steel wire mesh with sponge material made of synthetic material filling the spaces between the specimens and the mesh. The wetting and drying cycles were coupled with DC power to accelerate the steel corrosion. The specimens were subjected to a 1-day wetting period followed by a 2-day drying period for each cycle. During the wetting period, the specimens were partially immersed in a 3.5% NaCl solution so that the sponge would remain wet (as shown in Fig. 2), and a 300 μA/cm^2 current was applied between the reinforcing steel bars (acting as anodes) in the specimens and the stainless steel mesh (acting as cathodes). During the drying periods, the DC power was turned off and the specimens were removed from the sponge and exposed to air in the laboratory for two days.

After five cycles, corrosion-induced cracks were observed on the specimens, running approximately parallel to the centre bar inside the specimens. The DC power source was then turned off and the specimens were removed for further investigation. It should be noted that the concrete cover of specimen R100-2 was totally damaged by steel corrosion and could not be used for further investigation.

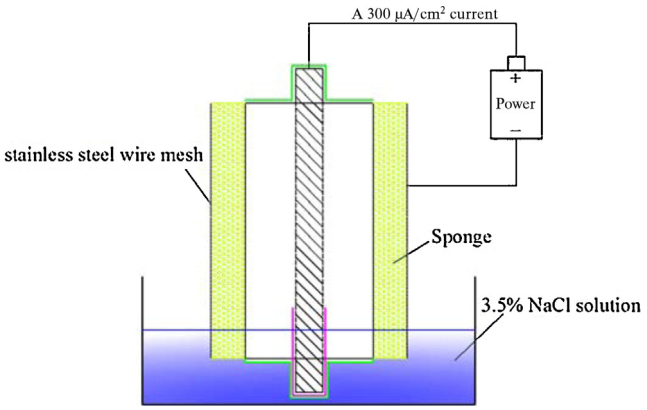

Fig. 2. Wetting and drying cycles combined with a 300 μA/cm^2 current for five cycles.

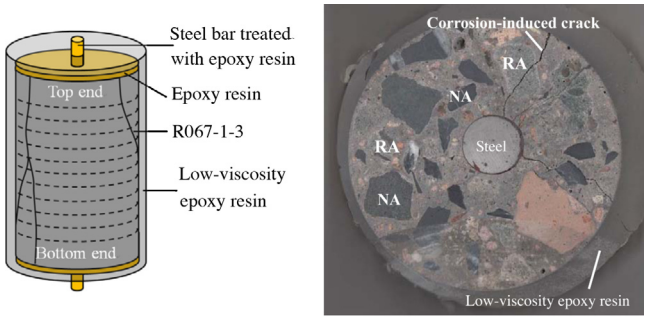

Fig. 3. Schematic diagram of preparation of samples for digital microscopy observation. (a) Cracked parts of specimens were cast in epoxy resin. (b) A sample prepared for digital microscopy observation.

2.3. Sample preparation

The cracked portions of the specimens were cast in a low-viscosity epoxy resin to minimize any artificial damage that might occur. Each specimen was then carefully cut into 10-mm-thick slices, as shown in Fig. 3(a), from top to bottom (except for the two end parts) with a precision saw (SYJ-200). An obtained slice is shown in Fig. 3(b). The slices were labelled as RXXX-N-M. For example, R067-1-3 represents the third slice from the specimen R067-1, as shown in Fig. 3(a). Approximately ten slices were obtained from each specimen; however, some were damaged during the cutting process and only 4–6 slices remained from each specimen. The slices were polished with a precision grinding and polishing machine (UNIPOL-1502). To prevent further corrosion, all samples were kept in a dry environment (relative humidity less than 30%) for several days before observation.

Table 1
Compositions of the concrete specimen mixtures (NA stands for the natural coarse aggregate, and RA stands for the recycled coarse aggregate.).

Specimens	Component (kg/m^3)					f_c (MPa)
	Cement	Water	Sand	NA	RA	
R000	430	185	559	1118	0	30.4
R033	430	190	559	745	373	28.9
R067	430	195	559	373	745	27.4
R100	430	200	559	0	1118	26.2

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