

Research Article

Application of X-Ray Computed Tomography in Monitoring Chloride Ion Penetration Paths in Recycled Aggregate Concrete

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The penetration paths of chloride ions in recycled aggregate concrete (RAC) are of significant interest and have not been well studied previously. This study used X-ray computed tomography (X-CT) as a novel approach to investigate chloride ion penetration paths in RAC. The results indicate that X-CT can be used for the constant monitoring of chloride ion penetration paths in RAC, and the influence of mix proportions on the chloride ion penetration can be understood through the X-CT visualization.

1. Introduction

For the past few years, recycling of construction and demolition wastes (C&DW) has improved the sustainability of the construction industry and reduced consumption of natural resources. In China, the amount of C&DW has reached 1.5 billion tons annually and is expected to peak in the year 2020. Consequently, the Chinese government has paid close attention to the recycling use of C&DW. Policies and specifications have been published to encourage the environmentally friendly disposal of C&DW.

The properties of recycled aggregate concrete (RAC) such as workability, mechanical performance, and durability have been widely investigated [1–5]. The incorporation of recycled aggregate (RA) into concrete typically leads to the performance degradation of the concrete. However, there have been some cases where this performance decrease was not observed. This difference is related to the quality of recycled aggregate compared to natural aggregate (NA) and the mix proportions of RAC. Also, the microstructure of RAC is more complicated than that of NA due to two interfacial transition zones (ITZs) [6, 7]. In RAC, the weakest ITZ depends on the properties of the newly mixed concrete and the original concrete from which the recycled aggregate was crushed.

There have been some studies on the chloride permeability of RAC by experiment and numerical simulation [8–10]. These studies have shown that the chloride permeability of RAC is significantly different compared to natural aggregate concrete. However, the chloride ion penetration paths in RAC have not been researched, to our knowledge. X-ray computed tomography (X-CT) is a non-destructive method which can obtain the microstructure information of materials and is a potential method to investigate the chloride ion penetration paths. Previous researchers have used X-CT to evaluate pore structure [11], cracks [12], ITZs [13], and water transport [14, 15] of cement-based materials. In this study, chloride ion penetration paths in RAC are studied using in situ monitoring of microfocus X-ray computed tomography. The influence of water/cement (W/C) ratio, fly ash (FA), and carbon-conditioned recycled aggregate on the chloride ion penetration paths is discussed.

2. Materials and Methods

The recycled coarse aggregates used in this paper were self-made in our lab. The particle size was about 8 mm–10 mm. The normal aggregate used was basalt gravel. The properties of the aggregates are shown in Table 1 [16]. The mortar in recycled coarse aggregates was prepared with a W/C ratio of

TABLE 1: Properties of coarse aggregates [16].

Aggregate	Apparent density (kg/m ³)	Water adsorption (%)	Particle size (mm)
NA	2720	0.4	4–5
RA	2610	3.8	8–10

0.5 and without mineral admixtures. The chemical compositions of the cement and fly ash are presented in Table 2 [16]. The self-made recycled coarse aggregates were cured in a saturated solution of calcium hydroxide at $20 \pm 2^\circ\text{C}$ and 95% relative humidity for 60 days. After curing, samples with dimensions of $10 \text{ mm} \times 10 \text{ mm} \times 20 \text{ mm}$ and with variable mix proportions as listed in Table 3 were molded for the X-CT testing. The tested samples were dried at 60°C to achieve a constant weight before the test. Except for the two opposite vertical surfaces ($10 \text{ mm} \times 10 \text{ mm}$), the other four surfaces of the specimen were sealed by epoxy resins to obtain one-dimensional penetration evolution. The micro-focus X-CT was Yxlon CT Precision S. The sample was scanned by cone-beam tomography, and the sample platform rotated 360 degrees. The number of pixels was 1024×1024 . VG Studio MAX software was used for the image analysis. The samples were fixed on a tray at the bottom where a 1 mol/L cesium chloride solution was added to enhance the contrast of the chloride solution in comparison to the concrete. A schematic of the experiment is shown in Figure 1.

3. Results and Discussion

Cesium chloride solution was chosen due to the cesium's high atomic number and because the surface tension of cesium chloride solution is close to that of the sodium chloride solution [15]. The brighter regions in X-CT images show the solution ingress into the concrete. As shown in Figures 2–4, the chloride ion transport paths into recycled aggregate concrete can be monitored by the presented method. In these figures, the portion represented by the red dotted line is the recycled aggregate. The red dotted line itself represents the new ITZs, and the yellow dotted line represents the old ITZs.

3.1. Effect of Water-Cement Ratio. Figure 2 shows chloride ion penetration paths in RAC with the W/C ratios of 0.45, 0.50, and 0.55. As seen in Figure 2, the chloride ion penetration path in RAC was quite different for the different W/C ratios. When the W/C ratio of RAC was equal to or smaller than that of the recycled aggregate, the solution penetrated into the interior of recycled aggregates. The chloride ions did transport through the new mortar and its surrounding ITZs but also through the attached old mortar and its surrounding ITZs. This additional transport path occurs because the porosity of mortar and ITZs with a lower W/C ratio is lower than the porosity of mortar and ITZs with a higher W/C ratio. This additional porosity provides more paths for chloride ion penetration. When the W/C ratio of RAC was higher, the chloride ions transport only through the new mortar and its surrounding ITZs and not through the

TABLE 2: Chemical composition of cement and FA [16].

	SiO ₂ (%)	Al ₂ O ₃ (%)	CaO (%)	MgO (%)	SO ₃ (%)	Fe ₂ O ₃ (%)	Loss
Cement	21.20	5.32	64.37	0.55	2.00	4.42	1.50
FA	52.85	29.25	6.11	0.78	1.45	5.63	2.97

TABLE 3: Mix proportions of samples.

No.	W/C ratio	Water	Cement	FA
A	0.5	195	390	0
B	0.45	195	433	0
C	0.55	195	354	0
D	0.5	195	273	117

recycled aggregate. Therefore, the W/C ratio shows a strong influence on the chloride ion penetration path in RAC. Using recycled aggregate with a lower W/C ratio than the newly mixed concrete is an effective method to prevent chloride ion penetration into the recycled aggregate.

The dry concrete sample absorbs solutions by capillary action to fill the available pore space. The more complicated pore structure and multiphases of RAC lead to a complicated transmission mechanism for aggressive ions. Based on the above results, it can be concluded that the chloride ion transport path depends upon the relative relationship between the new mortar and the recycled aggregate. It is expected that the chloride ion transport to the phase contained more available pore space. In order to verify this speculation, the relative relationship between the new mortar and the recycled aggregate was changed by two methods and investigated in Sections 3.2 and 3.3.

3.2. Effect of Fly Ash. Figure 3 shows chloride ion penetration paths in RAC that incorporated FA. The results show that the chloride ions transported through both the new and old mortars including the ITZs. However, the filling effect and the pozzolanic reaction of FA ensure that the RAC compactness, the microstructures, and properties of recycled aggregate are not significantly changed. Therefore, using FA cannot prevent chloride ion penetration into recycled aggregate.

3.3. Effect of Carbonated Curing Condition. The recycled aggregate was cured by CO₂ before being used in RAC. The mix proportion used was condition A that was previously reported in Table 3. Figure 4 shows chloride ion penetration evolution in RAC with carbon-conditioned recycled aggregate. It is found that the chloride ion did not transport through the old ITZ and attached mortar in recycled aggregates as evident by comparison to Figure 2(b). This is probably because the carbonation curing produced lower porosity of the old ITZ and mortar in recycled aggregate less than that in the newly mixed concrete. Thus, recycled aggregate curing under a carbonated condition can enhance the resistance of chloride ion penetration into recycled aggregate.

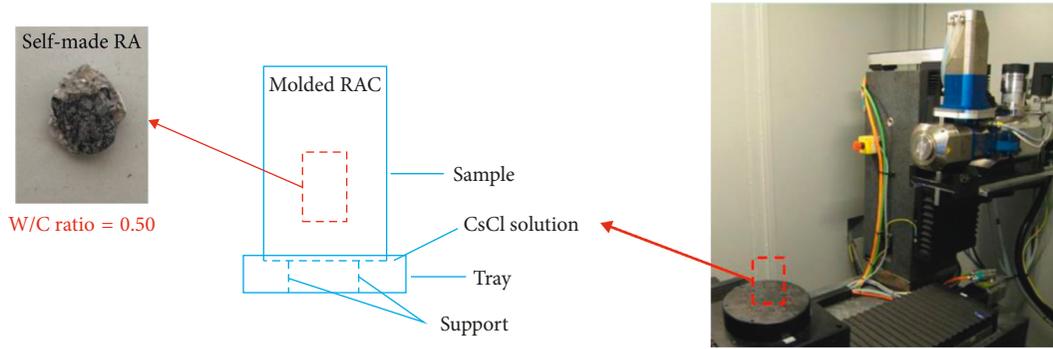


FIGURE 1: Experiment schematic for monitoring chloride ion penetration paths.

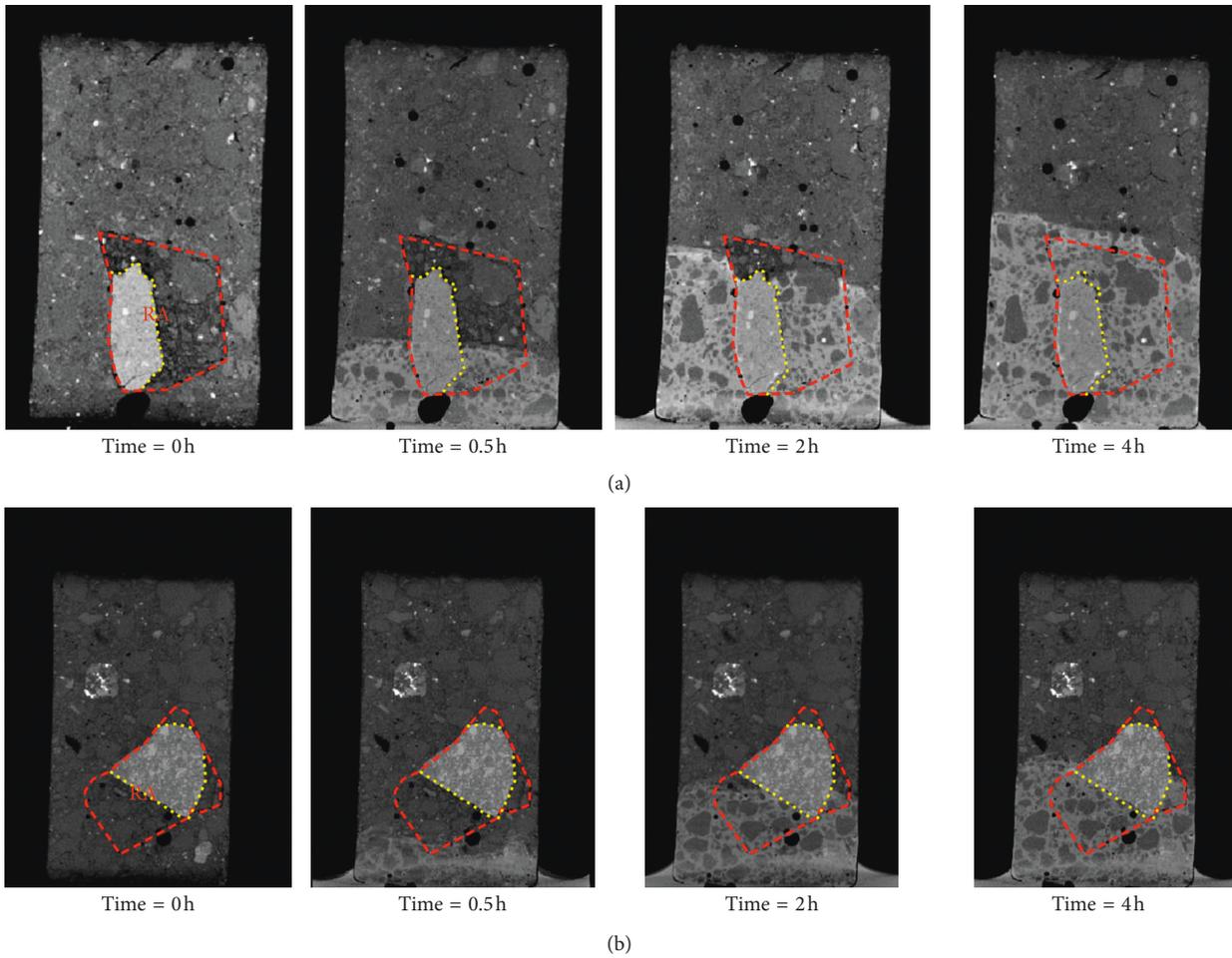


FIGURE 2: Continued.

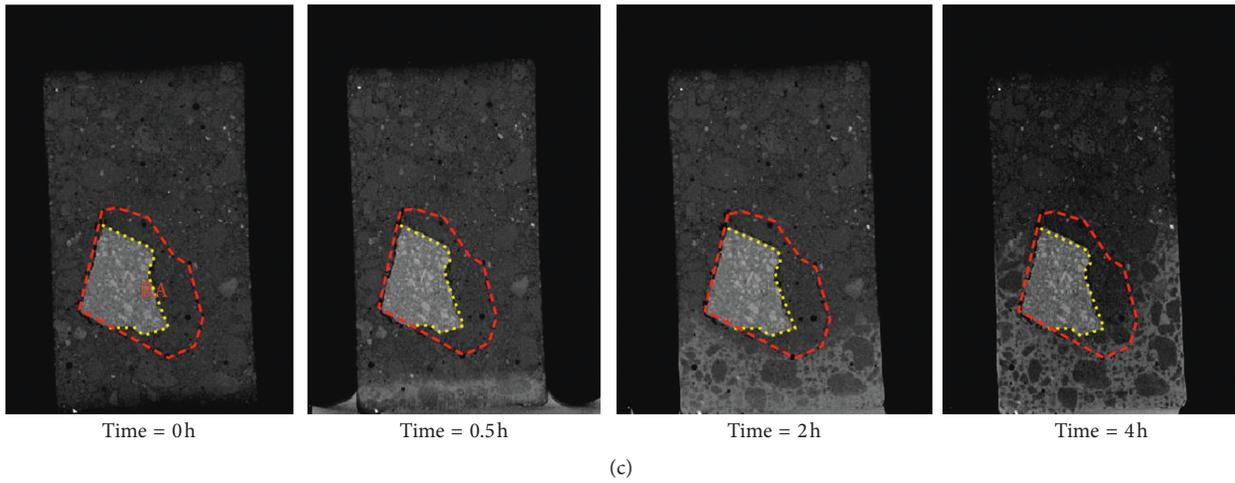


FIGURE 2: Chloride ion penetration paths in RAC with different W/C ratios: (a) W/C ratio = 0.45, (b) W/C ratio = 0.50, and (c) W/C ratio = 0.55.

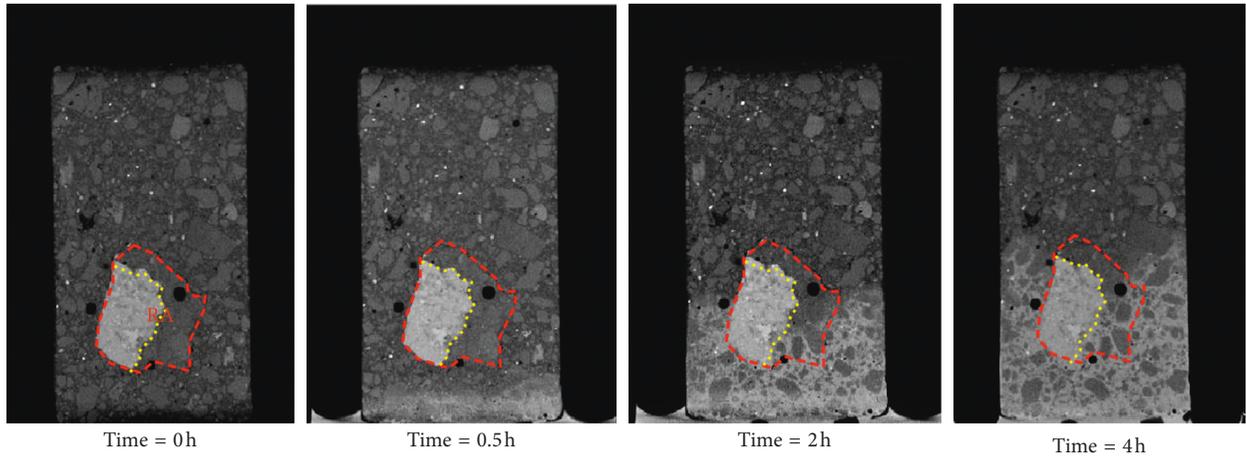


FIGURE 3: Chloride ion penetration paths in RAC with FA.

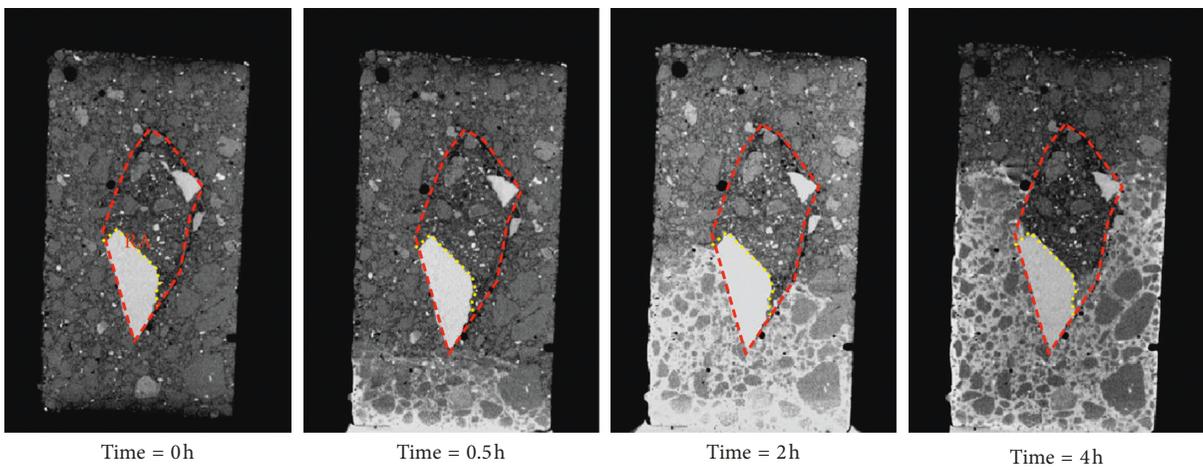


FIGURE 4: Chloride ion penetration paths in RAC with carbon-conditioned recycled aggregate.

4. Conclusions

The microfocus X-ray CT was firstly used for chloride ion penetration observation in RAC. The chloride ion penetration paths were observed directly and nondestructively. The chloride ions were from the cesium chloride solution prepared in this study. Lowering the W/C ratio and curing recycled aggregates by CO₂ both prevented chloride ion penetration into recycled aggregates. The incorporation of FA into RAC cannot prevent chloride ion penetration when the W/C ratio is equal to that of recycled aggregate. These results align with previous research conclusions in the literature. The results of this study can be potentially used to optimize the design of RAC and promote its utilization in practice.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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