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Performance of recycled concrete beams under sustained loads coupled with chloride ion (Cl^-) ingress

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HIGHLIGHTS

- Long-term coupled damages of sustained loads and Cl^- ingress were applied.
- Load-induced cracking of recycled aggregate concrete (RAC) beams was acceptable.
- Corrosion-induced cracking of RAC beams was much more serious.
- Flexural capacity of RAC beams was comparable with that of natural concrete ones.
- Poorer durability of RAC beams serving in severe conditions should be considered.

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ABSTRACT

This paper presents the experimental results of the cracking propagation and flexural performance degradation of reinforced concrete beams with recycled aggregates (RA), under long-term coupled effects of sustained loads and chloride ion (Cl^-) ingress. Test results show that the load-induced cracking damages of recycled aggregate concrete (RAC) beams were slightly lower while the corrosion-induced cracking damages were larger than the natural aggregate concrete (NAC) beams, through the 20-month coupled damage history. The flexural capacity was found comparable among damaged beams with different RA replacements. Therefore, this paper suggests the mechanical properties of RAC beams should be acceptable, given that they served under sustained loads and the corrosion of the longitudinal reinforcements was relatively low (less than 3%). However, RAC beams' inferior durability against cracking by steel bar corrosion should be considered with great cautious.

1. Introduction

The excessive discharge of construction and demolition (C&D) wastes has become a world-wide problem, leading to not only the scarcity of landfills, but also the potential threats of soil and water pollution. Recycled aggregate concrete (RAC) which utilizes recycled aggregate (RA) to replace part or all of the natural aggregate (NA) used in natural aggregate concrete (NAC), can help control the discharge of C&D wastes and reduce the consumption of natural aggregate resources, thereby leading the construction industry to a sustainable and environmentally friendly way.

As a result of the inferior mechanical properties [1–4] and durability [5,6] of RAC to NAC, which has been widely reported by previous researches, the overall recycling proportions of C&D wastes around the word is quite limited [7]. Till now RAC is mainly applied in road base or in nonstructural elements. In order to help promote the consumption rate of C&D wastes, it is necessary to maximize the amount of RAC materials applied over a broad range of structural members.

Many studies have been carried out on the mechanical performance of reinforced components employing RAC. Take RAC beams for example, it has been widely accepted that their flexural behavior is similar to that of NAC beams [8–12]. The cracking moment of beams with RAC is lower, and decreases with the growth of the RA replacement ratios [8,9,12]. Meanwhile the bending stiffness before reinforcement yield is smaller, leading to a faster gain of deflection under vertical loads [8–10,13]. Besides, it is found that given the same loading level, compared with NAC beams, more transverse cracks will appear in the tensile area on surfaces of RAC beams [12], and the crack spacing is smaller [9]. Though the differences in flexural behavior between reinforced beams with RAC and with NAC, still most studies tend to treat the flexural performance of RAC beams as acceptable, considering their

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comparable flexural capacity to that of NAC beams [8–10], regardless of the RA replacement ratios.

Although the mechanical properties of RAC have been verified as acceptable, it does not mean that it is always feasible to apply RAC in reinforced members. The durability of reinforced members should also be taken into account, because some environmental factors, e.g., Cl^- ingress, CO_2 ingress, etc., can induce corrosion of the embedded reinforcements. It is known that volume of corrosion products of steel was 2–6 times that of the non-corroded steel [14]. The expansion of the corrosion products may induce tension in the surrounding concrete and lead to irreversible damages of beams, e.g., corrosion-induced concrete cracks, and result in performance degradation of these members. Some researchers reported that given the same Cl^- ingress, the steel bars depassivated earlier in RAC than in NAC blocks, meanwhile the corrosion developed faster, thereby leading to earlier surface cracking of reinforced RAC blocks [15,16]. Ref. [17] reported that the width of the corrosion-induced cracks increased faster in RAC blocks than in NAC ones. Hence, the durability of reinforced RAC components against steel bar corrosion induced by Cl^- ingress is poorer.

Almost all the studies referred above were carried out when single impacts were applied onto reinforced RAC components or blocks, e.g., single loads, or single Cl^- ingress. However, for concrete structures serving in severe conditions, like the marine environment, or salty rivers and lakes, those structures must be subjected to the coupled damages induced by both loads and penetration of hazardous materials. Some studies have been carried out on reinforced components with NAC under coupled effects of sustained loads and Cl^- ingress. It is found that, different from the situation when only a single effect of either loads or Cl^- ingress was applied, NAC components subjected to coupled damages presented larger bending stiffness loss [18,19], faster corrosion development [20,21], and wider corrosion cracks [20,22]. Therefore, it can be inferred that if RAC components were to serve in such conditions under coupled damages, the damage rate and degradation patterns may also be quite different from those under single external impacts. However, rarely the studies on RAC components' performance degradation under long-term coupled damages of loads and environmental effects can be found.

This paper aims at exploring the performance degradation of reinforced beams utilizing RA under long-term coupled damages of sustained loads and Cl^- ingress. Three groups of reinforced concrete beams with different RA replacement ratios, i.e., 0%, 50%, and 100%, were prepared and were subjected to sustained loads by paired anchorage and Cl^- ingress by drying-wetting cycles with NaCl solution. The surface cracking of these beams were recorded and compared, through the 20-month damage history. Afterwards, the flexural capacity of these damaged beams were tested and compared with those beams without any damages. The feasibility of RAC in reinforced beams serving in conditions with coupled damages was then discussed, based on their overall surface damages and flexural capacity degradation.

2. Experimental program

2.1. Specimens

A total of 3 groups of beams with three different RA replacement ratios, i.e., 0%, 50%, and 100%, were prepared in this study, with each beam group containing 3 fabricated beam specimens. All the beams had a reinforcement ratio of 0.94% using two deformed bars with a diameter of 12 mm. Stirrups made with plain bars with a diameter of 8 mm were placed with spacing of 100 or 200 mm along the whole beam span. Dimensions and the reinforcement information of these beams are shown in Fig. 1. All of the reinforced concrete beam specimens were designed in accordance with National Code for Designs of Concrete Structures (*GB50010-2010, in Chinese*) and ensured for flexural failure for testing.

2.2. Materials

The mechanical property parameters of the steel bars are listed in Table 1.

RA used in this study was purchased from a manufacturer in Shanghai, China, by mixing two groups of RAs with different size ranges (5–15 mm and 15–25 mm) together. NA was crushed limestone with the size ranging from 5 to 25 mm. The gradation of NA and RA was tested to be comparable, which can be found elsewhere [23]. The crushing values and the mud contents of RA and NA were tested according to The National Specification Pebble and Crushed Stone for Construction (*GB/T 14685-2011, in Chinese*). Crushing values of RA and NA were 11.3% and 8.0%, and the mud contents were 3.5% and 0.6%, respectively. A natural water absorption of coarse aggregates was defined and measured in this study, based on which the water amount of RC was adjusted. The details of this defined water absorption parameter were introduced elsewhere [23]. In this study, the natural water absorptions of RA and NA were 1.2% and 0.2%, respectively, therefore, the extra water added to RAC was 1.0% of the weight of RA. The cement employed was ordinary Portland cement with a grade of 42.5 MPa. The fine aggregate (FA) was natural sand with a fineness modulus of 2.6 and moisture content of 7.0%.

The three groups of concrete with RA replacement ratios of 0%, 50%, and 100%, were labeled as NAC, RAC50 and RAC100, respectively. Mixture proportions and the material properties of concrete, i.e., slump, cube compressive strength, f_c, and Cl^- diffusion coefficient, D, are shown in Table 2. The target compressive strength of concrete was 30 MPa. After casting, all the beams were moist cured for 28 days in the laboratory.

2.3. Test methods

2.3.1. Design of coupled damages

For each of the three beam groups, one beam worked as the control, without any external damages applied, while the other two were subjected to coupled damages induced by sustained loads and Cl^- ingress after the 28-day curing. The sustained load was applied by paired anchorage of two beams of the same RA replacement ratio, as shown in Fig. 2. It should be noted that, as illustrated by Fig. 2, the upper beam and the lower beam were placed in reverse positions, in order to make sure that the two longitudinal deformed bars in each beam bore tension under the bending moment.

The sustained load was designed as approximated 60% of the nominal flexural capacity, which was 14.5 kN applied by each of the two anchor bolts. After 2 months' loading by anchorage in pairs, when the transverse cracks on the beam surfaces had propagated to a certain extent, the drying-wetting cycles with NaCl solution were applied for 10 months, in order to accelerate Cl^- ingress. The concentration of the employed NaCl solution was 3.5% by mass. Each drying-wetting cycle lasted for 14 days, with the drying period lasting for 10 days and the wetting period for 4 days. Through the 4-day wetting period in each cycle, each pair of beams were covered by cotton quilts which were saturated with NaCl solution, as shown in Fig. 2. Afterwards, the cotton quilts were removed, and the beams were thoroughly dried in the atmosphere for 10 days. For the reinforced members serving in salty lakes or rivers, they may first get damaged under the coupled effects of loads and Cl^- ingress during the rain season. However,