The influence of carbonized recycled fine aggregate on the bond properties between recycled aggregate concrete and corroded rebars

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Abstract. Recycled aggregate concrete (RAC) technology is one of the important measures for the development of green concrete, which can realize the sustainable development of architecture, resources and environment. Steel corrosion has great influence on the safety and durability of reinforced concrete structure, the research problem of bonding between corroded steel bars and RAC has important significance and engineering value. The effect of carbonized recycled fine aggregate (C-RFA) on bond behaviour between corroded rebars and RAC was studied through 28 sets of pull-out tests, were performed on RAC with recycled coarse aggregate (RCA) replacement percentage of 70%. Four carbonized recycled fine aggregate replacement percentages (0%, 20%, 30% and 40%) and four corrosion rates (0%, 1%, 2% and 4%) were considered in this study. The results show that carbonized RFA improved the peak pull-out strength of the specimens. The peak pull-out strength of the specimens with 20% C-RFA replacement percentage had only 1.02% decrease compared with those of unincorporated of RFA. When rebar corrosion rates was less than 4%, the corrosion of rebar improved peak pull-out strength of the specimen. It was found that 2% corrosion rate had the most significant effect.

1. Introduction

The bonding properties of RAC and rebar are different from those of ordinary silicate concrete. Corroded rebar has a great influence on the durability and safety of recycled aggregate concrete structures [1-3]. Xiao et al.’s [4] research showed that the bond-slip relation between corroded rebar and RAC was similar to that of ordinary concrete. Yang et al.’s research [5-6] indicated that increasing rebar corrosion rate would reduce the bond strength between rebar and RAC, and weaken the anti-slip property of recycled aggregate concrete specimen. Wang et al [7] studied the bond properties between RAC and corroded steel bars using reinforced concrete beams specimens. The results showed that the bond strength increased with the increase of rebar corrosion rate at first and then the opposite, however, the slip value increased with the increase of rebar corrosion rate. These researches on the bond slip between rebar and RAC were mainly focused on recycled coarse aggregate concrete. Therefore, there is a lack of research on recycled concrete using RFA. Recently carbonation treatment of recycled aggregate (RA) has been brought forth and considered promising in enhancing the properties of RCA and even RAC. Studies showed that carbonation treatment can improve the density of RA and reduce the porosity and crush index of RA, and the basic mechanical of RAC effectively [8-10]. In addition, if the emission of CO₂ produced by production of
cement can be captured and used in the treatment of RA, it will be more valuable. Normally, there are three distinct processes for CO₂ capture and storage [11]. First, capturing CO₂ from the gas streams emitted during electricity production, industrial processes or fuel processing; second, transporting the captured CO₂ by pipeline or in tankers; and third storing CO₂ underground in deep saline aquifers, depleted oil and gas reservoirs or unmineable coal seams.

In this paper, C-RFA replacement percentages and rebar corrosion rates were taken as parameters to investigate bond behaviour between RAC and corroded rebar when RCA replacement was kept constant at 70%. Furthermore, the results were then compared with those with normal RFA.

2. Experimental program

2.1. Material

The RA derived from the waste concrete which obtained from road demolition waste with original compressive strength of 20 MPa. The RCA of the particle size 5~25mm and recycled fine aggregate (RFA) of the particle size 5~25mm were obtained by crushing and sieving waste concrete. Main physical properties of RCA and RFA are shown in Table1 and Table 2 respectively.

| Properties | Apparent density / kg/m³ | Water absorption rate /% | Crushing index /% |
|------------|--------------------------|--------------------------|-------------------|
| value      | 2506                     | 4.7                      | 13.2              |

| Properties | fineness modulus | Apparent density / kg/m³ | porosity /% | water demand ratio of recycled mortar | compressive strength ratio of recycled mortar |
|------------|------------------|--------------------------|-------------|--------------------------------------|---------------------------------------------|
| value      | 3.4              | 2518                     | 42          | 1.25                                 | 0.91                                        |

Ordinary cement PO 42.5(C) was used and river sand (S) with fineness modulus of 2.14 was used as fine aggregate. The apparent density of natural coarse aggregate (NA) with a particle size of 5~25 mm was 2652 kg/m³, the water absorption rate was 1.32%, and the crushing index was 4%. Tap water (W) and polycarboxylic acid superplasticizer (SP) were used. The RFA was carbonized by carbonization box inside which the concentration of CO₂ was 17% ~ 23%, the humidity was 65% ~ 75%, and the temperature was 15 ~ 25 °C. The water demand ratio of recycled mortar was 1.19 and the compressive strength ratio of recycled mortar was 0.94 after RFA was carbonized for 7 days.

The RFA and C-RFA with varying replacement percentages (0%, 20%, 30% and 40%) were used for concrete preparation. RAC replacement percentage was 70% for all groups. The mix proportions of specimen are shown in Table 3.

The performance of deformed bar is detailed in Table 4.

2.2. Test specimens

The pull-out tests, designed according to the Chinese Standard Methods for testing of Concrete Structures (GB 50152-2012) [12], were performed on 10d cubes with the reinforcing bars centrally embedded in the cubes. The steel bars were 480 mm in length, the embedment length for the bond behaviour test was set to 5 days to prevent the yielding of the steel bar before bond failure under the pull-out load. The length of unbonded part and the free end are 5 days and 20 mm respectively. In the unbonded area, the steel and concrete were separated by 5 days long plastic casing at the loading end. Before pouring the concrete, the epoxy resin was used to apply the nonbond steel bar to prevent corrosion during the test. Four sets of pull out specimens were made for each proportion according to
different desired corrosion rates of steel bar (0%, 1%, 2%, 4%). Twenty eight groups were fabricated and cured to 28 days and the specimens are shown in Figure 1.

Table 3. Mix proportions, workability and strength of concretes

| Code     | Mix proportion/(kg·m⁻³) | Slump (mm) | 28d cube compressive strength (MPa) |
|----------|-------------------------|------------|-------------------------------------|
| C        | NA                      | RCA        | RFA       | S   | W   | SP   |                       |
| RAC-70-0 | 450                     | 327        | 764       | 0   | 669 | 180  | 3.15                   | 170 | 44.3                  |
| RAC-70-20| 450                     | 327        | 764       | 134 | 535 | 180  | 3.60                   | 170 | 42.4                  |
| RAC-70-30| 450                     | 327        | 764       | 201 | 468 | 180  | 3.96                   | 165 | 40.9                  |
| RAC-70-40| 450                     | 327        | 764       | 268 | 401 | 180  | 4.37                   | 165 | 38.7                  |
| RAC-70-20C| 450                  | 327      | 764      | 201  | 468  | 180  | 3.38                   | 170  | 42.8                  |
| RAC-70-30C| 450                  | 327     | 764     | 268  | 401  | 180  | 3.74                   | 170  | 40.5                  |

Note: RAC-X-Y, RAC-X-YC, RAC-reycled aggregate concrete, X-recycled coarse aggregate replacement percentage is X%, Y-recycled fine aggregate replacement percentage is Y%, YC-carbonized recycled fine aggregate replacement percentage is Y%.

Table 4. Summary of reinforcement properties

| Rebar type       | Yield stress $f_y$ MPa | Ultimate stress $f_u$ MPa | Elastic modulus $E_s$ MPa | Elongation % |
|------------------|------------------------|---------------------------|---------------------------|--------------|
| Φ16, HRB400E     | 428                    | 579                       | 1.96x10⁵                  | 21.8         |

2.3. Steel corrosion

Electrochemical method was adopted to accelerate rebar corrosion. The specimens were completely soaked in the NaCl solution with a mass fraction of 5% for 4 days before the test. The steel bars of 3 specimens with the same mix proportions and rebar corrosion rate were connected to the cathode of DH1718E-4 by series system. While the copper pipe was put into solution and be connected to the power supply. The specimen was semi-immersed in the solution and the current intensity was 0.05 A during the process of accelerate rebar corrosion. To ensure uniform corrosion of the steel, the specimen was regularly rotated in the process of corrosion. The corrosion test device was shown in Figure 1.

Figure 1. Corrosion test
The corrosion of rebar was measured according to the Chinese Code JTJ 270-98 [13]. Four theoretical corrosion rates (i.e., 0%, 1%, 2% and 4%) were considered in this study. Corrosion results of steel bars are shown in Table 5.

| Code     | Theoretical corrosion rate (%) | Actual corrosion rate (%) | Code     | Theoretical corrosion rate (%) | Actual corrosion rate (%) |
|----------|--------------------------------|---------------------------|----------|--------------------------------|---------------------------|
| RC-70-0-0| 0                              | 0.00                      | RC-70-40-2| 2                              | 1.87                      |
| RC-70-0-1| 1                              | 0.89                      | RC-70-40-4| 4                              | 3.76                      |
| RC-70-0-2| 2                              | 1.84                      | RC-70-20C-0| 0                              | 0.00                      |
| RC-70-0-4| 4                              | 3.77                      | RC-70-20C-1| 1                              | 0.89                      |
| RC-70-20-0| 0                             | 0.00                      | RC-70-20C-2| 2                              | 1.81                      |
| RC-70-20-1| 1                             | 0.88                      | RC-70-20C-4| 4                              | 3.78                      |
| RC-70-20-2| 2                             | 1.85                      | RC-70-30C-0| 0                              | 0.00                      |
| RC-70-20-4| 4                             | 3.79                      | RC-70-30C-1| 1                              | 0.87                      |
| RC-70-30-0| 0                             | 0.00                      | RC-70-30C-2| 2                              | 1.80                      |
| RC-70-30-1| 1                             | 0.91                      | RC-70-30C-4| 4                              | 3.75                      |
| RC-70-30-2| 2                             | 1.87                      | RC-70-40C-0| 0                              | 0.00                      |
| RC-70-30-4| 4                             | 3.82                      | RC-70-40C-1| 1                              | 0.84                      |
| RC-70-40-0| 0                             | 0.00                      | RC-70-40C-2| 2                              | 1.80                      |
| RC-70-40-1| 1                             | 0.89                      | RC-70-40C-4| 4                              | 3.68                      |

2.4. Pull-out tests

Chlorophytum device as shown in Figure 3 was used for the pull-out test and specimens were loaded in an electrohydraulic servo tester. Spherical hinge was put in the load-end in order to ensure the direction of rebar and load were uniform. The bottom fixture was fixed, the top fixture and pedestal were risen with suspension cage and specimens. High precision displacement sensors were installed on the free end of the rebar, the surface of concrete and both sides of plates in the loading ends, as shown in Figure 2. Base on the reference [14], the average bond stress $\tau$ and the average slip $S$ of steel and concrete were calculated.

3. Results and discussion

3.1. Failure process and bond stress-slip curve of specimens

3.1.1. Failure process of specimens: The main failure mode of the specimens was the pulling out of rebar and the cracking of RAC. When the rebar was pulled out, the steel which had 20 mm extension to the concrete surface was drawn into the specimen because of drawing in the loading end. It was
obvious that the RAC before the ribs were shredded almost from the rebar. It can also be clearly observed that the traces left on the concrete surface by the mechanical bite force when the steel was pulled out. When the RAC experienced splitting failure, the splitting direction of specimen was perpendicular to the longitudinal rib of rebar. The RAC in front of the ribs had been partially crushed, but it was not complete shear break.

3.1.2. Bond stress-slip curve of specimens: Figure 3 shows the influence of carbonized and replacement rate of RFA on bond stress-slip curves of specimens when replacement rate of RFA was constant in each group. Figure 4 shows the influence of rebar corrosion rate on bond stress-slip curves of specimens when replacement rate of RFA was constant in each group.

Figure 3. Influence of replacement rate of recycled fine aggregate on bond stress-slip curves of specimens
Figure 4. Influence of corrosion rate of steel bar on bond stress-slip curves of specimens

The bond stress-slip curve of the specimens with different replacement rates of C-RFA had a similar development compared to ordinary concrete which is shown in Figure 3. It can be divided into 5 stages based on the feature points. And with the replacement rate of C-RFA changed the feature point varied. Carbonized RFA improved the peak bond stress of the specimens and slowed the residual section compared with the uncarbonized ones.

The bond stress-slip curve of the specimen with different rebar corrosion rate has a similar change law compared to ordinary concrete which is shown in Figure 4. The feature points changed with rebar corrosion rates. When rebar corrosion rate was 2%, the peak bond stress of the specimens reached the maximum and the corresponding residual stress was larger.

3.2. Effects of C-RFA replacement percentages and rebar corrosion rates on peak pull-out strength

3.2.1. Effects of C-RFA replacement percentages on peak pull-out strength: The influence of C-RFA replacement percentages on peak pull-out strength when the rebar corrosion rate was constant in each group is shown in Figure 5. The peak pull-out strength decreased with the increase of RFA replacement percentages, as showed in Figure 6. When rebar corrosion rates was 0%, the peak pull-out strength of the specimens with the replacement rate of 20%, 30% and 40% was reduced by 5.2%, 7.5% and 12.4% respectively, compared to those without RFA. Carbonized RFA increased the peak pull-out strength of the specimens. When rebar corrosion rate was 0%, the peak pull-out strength of the specimens which incorporated C-RFA with the replacement rate of 20%, 30% and 40% was 4.4%, 4.9% and 4.8% higher than the specimens which mixed with RFA. The peak pull-out strength of the specimens which C-RFA replacement percentages was 20% had only 1.02% decrease compare with those without RFA. When rebar corrosion rates were less than 2%, carbonized RFA improved the peak pull-out strength of the specimens obviously. When rebar corrosion rate was 2% and C-RFA replacement rate was 20%, the peak pull-out strength of the specimens was increased by 1.0% compared to those without RFA.
3.2.2. Effects of rebar corrosion rates on peak pull-out strength: The influence of rebar corrosion rates on peak pull-out strength when RFA replacement percentage was constant in each group is shown in Figure 6. It can be observed from Figure 6 that when rebar corrosion rates were less than 4%, the corrosion of rebar could improve peak pull-out strength of the specimen. And the degree of improvement increased first and then decreased with the increase of rebar corrosion rates. Especially, the 2% corrosion rate has the most significant effect. When C-RFA replacement rate was 30%, the peak pull-out strength of the specimens with the rebar corrosion rates of 1%, 2% and 4% was increased by 2.6%, 7.7%, 2.2% respectively compared to those without corrosion.

In the early stage of corrosion, the volume of corrosion products expanded and the RCA of surrounded rebar was compressed which increased the bond behavior between corroded rebars and RAC, and further improves peak pull-out strength of specimens. Corrosion products accumulated and swelled with the increase of the corrosion level. It led to the corrosion cracks in the concrete cover, in addition, the restraining effect of concrete to the reinforcement was reduced. The friction between corrupted reinforcement and RAC was reduced because the corrosion products were loose; The corruption in transversal ribs on the reinforcement could damage the mechanical interaction between corrupted reinforcement and RAC, resulting in the decline of bonding between reinforcement and RAC.
4. Conclusion

1. Carbonized RFA improved the peak pull-out strength of the specimens. When rebar corrosion rate was 0%, the peak pull-out strength of the specimens which incorporated C-RFA with the replacement rate of 20%, 30% and 40% was 4.4%, 4.9% and 4.8% higher than specimens which used RFA. The peak pull-out strength of the specimens with 20% C-RFA replacement percentage had only 1.02% decrease compared with those of unincorporated of RFA. When rebar corrosion rates was less than 2%, carbonized RFA improved the peak pull-out strength of the specimens obviously. For example, when rebar corrosion rate was 2% and C-RFA replacement rate was 20%, the peak pull-out strength of the specimens increased by 1.0% compared with those without RFA.

2. When rebar corrosion rates was less than 4%, the corrosion of rebar improved peak pull-out strength of the specimen. And the degree of improvement increased at the beginning and then decreased with the increase of rebar corrosion rates. It was found that 2% corrosion rate had the most significant effect.

5. Reference

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