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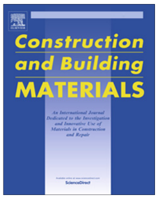

# Evaluation of bond performance between deformed bars and recycled aggregate concrete after high temperatures exposure

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## HIGHLIGHTS

- RCA embedment results in a minor decrease of post-fire compressive strength.
- Exposed to high temperature, RAC performs better bond than those of NCA.
- The descending branch of bond-slip curve becomes flatter at higher temperature.
- Bond-slip relation between RAC and rebar after high temperature is suggested.

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## ABSTRACT

In this paper, 84 pull-out specimens and 60 cubic specimens with different levels of recycled coarse aggregate (i.e. 0%, 30%, 50%, 70% and 100%) were fabricated to evaluate the post-fire bond at the interface between recycled aggregate concrete (RAC) and deformed rebar. Those specimens designed for thermal temperature were first heated to high temperatures of 300, 400, and 500 °C for 6 h, and then were submitted to the test. The testing results were compared with the results obtained from the testing for the specimens at ambient temperature (about 20 °C). A semi-empirical formula was finally suggested to model the bond-slip relation between the heated RAC and the deformed rebar. The results demonstrate that an increment of the heating temperature decreases both the bond strength and the compressive strength continuously but increase the peak slip. Before and after high temperature, increasing the RAC replacement percentage gradually increases the relative bond strength. The ascending branches of bond-slip curves are uniform for all the tests. However, as an increment of the temperature and of the lateral confinement provided by stirrups, the descending branch curve of RAC becomes flatter.

## 1. Introduction

A reinforced concrete structure probably can be subjected to high temperature in its service life, for example, in the case of a fire disaster. The exposure of a reinforced concrete structure to high temperature damages both concrete and steel rebar, deteriorating the bond at the interface between the concrete and the rebar and undermining the integrity of the entire structure [1–4]. Accordingly, the post-heating properties of a reinforced concrete structure is critical to assess whether the structure subjected to fire remains sound or should be demolished.

Recently, there has been an increasing interest in recycling construction waste to reproduce new concrete for the purpose of environmental and resource conservation. Numerous experimental works [5–11] have been conducted to study the properties of RAC. The effect of recycled coarse aggregate (RCA) on bond strength of rebar embedded have been widely reported [12–20], because the bond at the interface between steel rebar and RAC dominates the mechanical performance of the reinforced concrete. Nonetheless, the information on the fire performance of the RAC and reinforced RAC is still limited.

Only a few studies [21–26] concerned with the effect of high temperature on the mechanical properties of RAC were reported. The object of those investigations was to determine the strength and deformation of RAC after exposed to high temperatures. In general, the limited testing results demonstrated that RAC has sufficient spalling resistance [21], and the replacement of natural coarse aggregate (NCA) with RCA influences the residual compressive strength [21–23,25]. However, compared with the post-heating property on RAC material, far less is known about the

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response of the bond behavior between steel rebar and RAC after high temperature exposure.

In this context, the present paper aimed to evaluate the residual bond between RAC and deformed rebar after exposed to high temperatures of 300, 400, and 500 °C for 6 h. The effects of high temperatures, RAC replacement percentages, and stirrup confinement on bond performance are investigated by comparing the results against specimens that were tested at ambient temperature and made with NCA.

## 2. Experiments

### 2.1. Materials and mixtures

Common Portland cement type 42.5 and natural medium-size river sand were used in the production of concrete. Demolished concrete from an urban pavement of Nanning, China was crushed and sieved for RCA, and the crushed limestone was employed as NCA. Before the preparation of mixtures, the physical properties of both NCA and RCA were tested (see Table 1). Deformed rebar type HRB400 with a yield strength of 358.3 MPa and an elastic modulus of $2.17 \times 10^5$ MPa was used and a diameter size of 20 mm was adopted, while the plain steel bars type HPB300 with diameters of 6 mm and 8 mm were employed as stirrups.

The designed mixtures for RAC and for the control natural aggregate concrete (NAC) are given in Table 2. To compare the compressive strength, the concrete mixtures were designed with varying RAC replacement percentages (i.e., R = 0%, 30%, 50%, 70%, and 100%).

### 2.2. Specimens preparation and curing

Pull-out specimens designed according to Chinese Standard Methods for Testing of Concrete Structures (GB 5015292) are shown as Fig. 1. Table 3 presents the details of the pull-out specimens. With each group in Table 3, twelve pull-out specimens were casted to test the bond behavior between RAC and deformed rebar after temperatures of 20, 300, 400, and 500 °C. Three samples were prepared for each testing at a specific temperature. For each mixture, twelve cubic specimens with an edge length of 150 mm were also prepared to determine the compressive strength after the aforementioned temperatures exposure. In total, 84 pull-out specimens and 60 cubic specimens were prepared. All the specimens were de-molded on the third day after casting and then were cured at an ambient temperature for 28 days.

### 2.3. Heating treatment and loading setup

Those specimens subjected to high temperatures of 300, 400, and 500 °C were heated in an electrical furnace type RX3-45-9, with the time-elevated temperature curves are drawn in Fig. 2. For consideration of the temperature in specimens core and the furnace chamber should be uniform, the target temperature was kept constant for 6 h after it reached to the designed level. Subsequently, the heated specimens were left cool inside the furnace until its temperature fell below 80 °C; they then were moved to the laboratory remaining for 7 days. After that, different categories of specimens were submitted to pull-out test and compressive test respectively using RMT-201 shown in Fig. 3.

## 3. Results and discussion

### 3.1. Bond-slip curves and characteristic values

The bond stress ($\tau$) is considered to be uniform along the anchorage length and is given by Eq. (1). The representative bond-slip curves after different temperatures for RAC are plotted in Fig. 4, with the characteristic values are summarized in Table 4.

$$\tau = \frac{P}{\pi D l} \tag{1}$$

**Table 1**
Physical properties of coarse aggregates.

| Aggregate type | Gradation (mm) | Observed density (kg/m$^3$) | Bulk density (kg/m$^3$) | Water absorption (%) | Crushed index (%) |
|---|---|---|---|---|---|
| RCA | 5–26.5 | 3105 | 1325 | 4.54 | 12.6 |
| NCA | 5–26.5 | 2340 | 1521 | 0.35 | 11.4 |

**Table 2**
Mixtures.

| No. | MW/C | R (%) | Ingredients (kg/ m$^3$) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | RCA | NCA | C | S | MW | AW |
| N0 | 0.46 | 0 | 0 | 1269 | 402 | 544 | 185 | 0 |
| R30 | 0.39 | 30 | 365 | 853 | 475 | 522 | 185 | 18 |
| R50 | 0.38 | 50 | 605 | 605 | 487 | 518 | 185 | 30 |
| R70 | 0.37 | 70 | 840 | 360 | 500 | 515 | 185 | 42 |
| R100 | 0.35 | 100 | 1180 | 0 | 529 | 506 | 185 | 59 |

Where C is the cement, S is the sand, MW is the mixing water, and AW is the additional water.

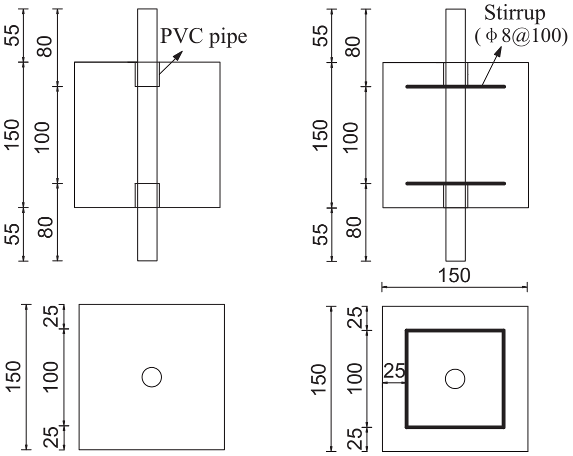

**Fig. 1.** Sketch of pull-out specimens.

**Table 3**
Description of pull-out specimens.

| No. | R (%) | $f_{cu}$ (MPa) | Stirrups |
|---|---|---|---|
| N0-0 | 0 | 43.8 | No |
| R30-0 | 30 | 43.8 | No |
| R50-0 | 50 | 45.6 | No |
| R70-0 | 70 | 44.5 | No |
| R100-0 | 100 | 44.7 | No |
| R100-6 | 100 | 44.7 | ϕ6@100 |
| R100-8 | 100 | 44.7 | ϕ8@100 |

Where $f_{cu}$ is the compressive strength at ambient temperature.

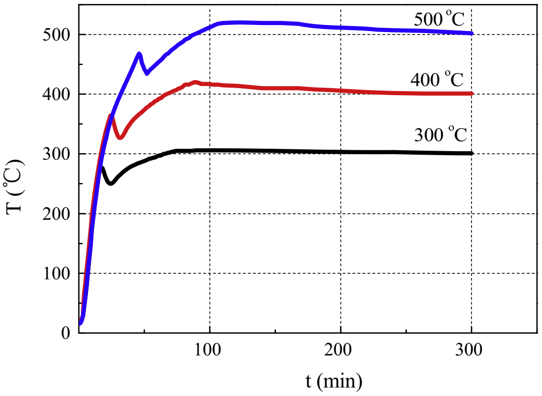

**Fig. 2.** Time-elevated temperature curves.