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Effect of high temperature on the bond performance between steel bars and recycled aggregate concrete

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Abstract. The use of recycled aggregate concrete for the purpose of environmental and resource conservation has gained increasing interest in construction engineering. Nevertheless, few studies have reported on the bonding performance of the bars in recycled aggregate concrete after exposed to high temperatures. In this paper, 72 pull-out specimens and 36 cubic specimens with different recycled coarse aggregate content (i.e., 0%, 50%,100%) were cast to evaluate the bond behavior between recycled aggregate concrete and steel bar after various temperatures (20°C, 200°C, 400°C, 600°C). The results show that the recycled aggregate concrete pull-out specimens exhibited similar bond stress-slip curves at both ambient and high temperature. The bond strength declined gradually with the increase of the temperature. On the basis of a regression analysis of the experimental data, a revised bond strength mode and peak slip ratios relationship model were proposed to predict the post-heating bond-slip behavior between recycled aggregate concrete and steel bar.

Keywords: high temperature ; concrete; bond strength ; pull-out ; peak slip

1. Introduction

During the last ten years, many studies have been carried out on recycled aggregate concrete (RAC) materials. The use of RAC is one way to reduce not only energy consumption, but also that of the available natural resources. Shatarat *et al.* (2018) studied the influence of using recycled coarse aggregate (RCA) and recycled asphalt pavement (RAP) on the properties of pervious concrete. They found that using RCA, RAP, and (RAP-RCA) enhanced the properties of pervious concrete in general and improved the mechanical properties. Dan *et al.* (2018) determined the ultimate load carrying capacity of two self-similar flat-slab specimens and validate the results experimentally for the natural aggregate as well as recycled aggregate based concrete. Thomas *et al.* (2018) studied strength and durability of concrete containing recycled concrete aggregates. Amix design methodology using the developed models was proposed to aid practicing engineers to determine the mix proportions of RCA concrete. Zhao *et al.* (2017) studied the properties of Recycled Aggregate Concrete (RAC) with four different water control methods: the control group, pre-wetting with the same total water amount group, pre-wetting with the same mixing water amount group and adding extra mixing water group. Xuan *et al.* (2016) studied mechanical properties of concrete incorporating carbonated recycled concrete aggregates.

And some previous work were conducted on the bond between steel bars and recycled aggregate concrete. Shang *et al.* (2017) investigated the bond strength and the bond stress-slip curves of steel bar embedded in recycled coarse aggregate concrete under the action of lateral compression load. Kim and Yun (2014) investigated the effects of bar location and recycled fine aggregate (RFA) grade on bond strength between reinforcing bar and recycled aggregate concrete. Breccolotti and Materazzi (2013) evaluated the structural reliability of bonding between steel rebars and recycled aggregate concrete.

Recently, more attention has been paid to the mechanical behavior of recycled aggregate concrete at high temperature or to the residual behavior of recycled aggregate concrete after exposure to high temperature (Liang *et al*. 2017, Laneyrie *et al*. 2016, Chen *et al*. 2014). Bui *et al*. (2018) investigated the effects of mineral admixtures on properties of RAC at high temperature. They proposed the equations to predict the residual compressive strength and elastic modulus of heated RAC. Liang *et al*. (2018) present the results of an experimental study to investigate the influences of high temperatures on the mechanical properties of concrete containing recycled fine aggregate. Yang *et al*. (2016) studied the shear behavior of concrete with different levels of recycled coarse aggregate after being subjected to different temperatures.

However, the bond-slip behavior between recycled aggregate concrete and steel bar after high temperature has rarely been reported. The objective of this study is to investigate the bond-slip behavior for steel bar in recycled aggregate concrete. The results can be used as a theoretical and experimental basis for fire prevention design and fire safety assessments of recycled aggregate concrete structures.

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Table 1 Physical properties of RCA

Grading (mm)	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Water absorption (%)	Silt content (%)	Crushing value (%)
5-20	1385	2490	8.47	5.5	13.2

Table 2 Mix proportion of the recycled coarse aggregate concrete

No.	Replacement (%)	RCA (kg·m^{-3})	C (kg·m^{-3})	S (kg·m^{-3})	NA (kg·m^{-3})	W (kg·m^{-3})
RAC0	0	0	513	474	1218	195
RAC50	50	609	513	474	609	195
RAC100	100	1218	513	474	0	195

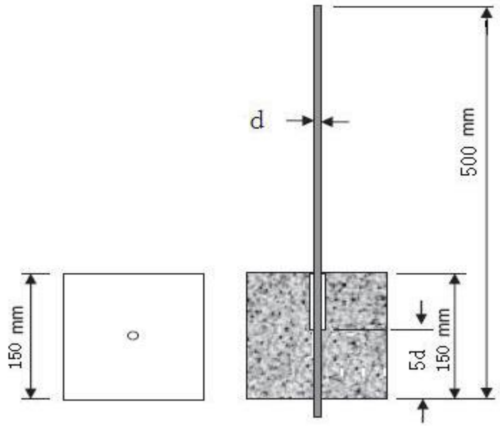

Fig. 1 Dimensions of test specimens

Fig. 2 Test setup

2. Experimental programme

2.1 Materials and mix proportions

The recycled aggregate concrete (RAC) mixes were made up of cement, a natural fine aggregate, a natural coarse aggregate, a recycled coarse aggregate and water (W). Common Portland cement (C) of type 32.5R, in according with the Chinese standard GB 175-1999, was used in this study. The used fine aggregates were river sand (S) with fineness modulus of 2.7 and 0.6% moisture content. The coarse aggregates used in this study were both natural aggregate (NA) and recycled concrete aggregate (RCA). The physical properties of RCA is shown in Table 1.The NA size fraction used was 5-20 mm. The RCA obtained from waste concrete brought from the reclamation depot, which in the range 5-20mm.The deformed steel bars (HRB335) of 10mm diameter with yield strength 375 MPa were used in this pullout tests. Table 2 provides the design of the concrete mix, which were designed with varying the replacement ratio of recycled coarse aggregate in the concrete (i.e., RCA replaced 0, 50 and 100% of coarse aggregate in the concrete, respectively.)

2.2 Specimens preparation

The pull-out specimens were designed and manufactured according to Chinese Standard Methods for Testing of Concrete Structures (GB 5015292) (1992). A total of 72 pull-out specimens were prepared using 10-mm-diameter steel bars embedded vertically in concrete cubes (150×150×150 mm) with a bonded length of five times the bar diameter as shown in Fig. 1. In order to control the bonded length, the steel bars were prepared with a bond breaker using soft PVC tubes inserted around the bar to prevent contact of steel rebars with concrete. And the PVC tubes were placed at the loaded end side to minimize the effect of the stress from loading plate. And 36 cubic specimens were also prepared to determine the compressive strength. After being cured for 2 days, the specimens were demoulded, stored at ambient temperature of 20℃ for 28 days and then placed in high temperature furnace for heat treatment. The specimens were heated in an electric furnace to temperatures of 200, 400, 600℃. The target temperature was maintained constant for 1 hour to achieve uniform distribution of the heat across the specimens.

2.3 Testing

The loading setup for the pullout test was a UTM-300 microcomputer controlled electro-hydraulic servo tester, as shown in Fig. 2. The pullout was applied through a displacement control rate of 1 mm/min to comply with GB 5015292 maximum rate of 12 kN/min. The load was measured with the electro-hydraulic servo tester. The free-end slip of the steel rebar relative to concrete was measured using a LVDT (Linear Variable Differential Transformer). The following equation was used to calculate the value of the bond strength.

$$\tau_u = \frac{P_u}{\pi d l_a} \tag{1}$$

where τ_u is the peak bond stress (MPa) between concrete and steel rebar, which is also termed the bond strength; P_u is the peak load (N); d is the diameter of the steel rebar (mm); and l_a is the embedded length of the steel rebar (mm).

3. Results and discussion

3.1 Residual mechanical properties of RAC

Table 3 Experiment results of the pullout specimens

Specimen	Temperature	f_{cu} (MPa)	P_u (kN)	τ_u (MPa)	Unloaded end slip (mm)
RAC0-20	AT (20°C)	37.92	23.09	14.71	0.37
RAC0-200	200°C	35.34	19.34	12.32	0.88
RAC0-400	400°C	32.12	15.40	9.81	1.44
RAC0-600	600°C	25.21	9.18	5.85	1.98
RAC50-20	AT (20°C)	30.53	20.58	13.11	0.43
RAC50-200	200°C	27.62	17.46	11.12	0.92
RAC50-400	400°C	24.15	12.45	7.93	1.51
RAC50-600	600°C	20.26	7.16	4.56	2.05
RAC100-20	AT (20°C)	28.73	19.69	12.54	0.54
RAC100-200	200°C	25.72	16.52	10.52	0.97
RAC100-400	400°C	23.11	12.12	7.72	1.64
RAC100-600	600°C	19.16	6.69	4.26	2.13

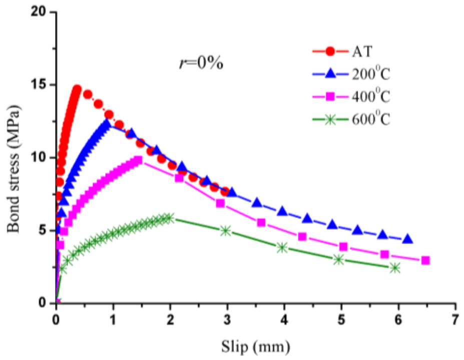

Fig. 3 Bond stress-slip after different temperature for r=0%

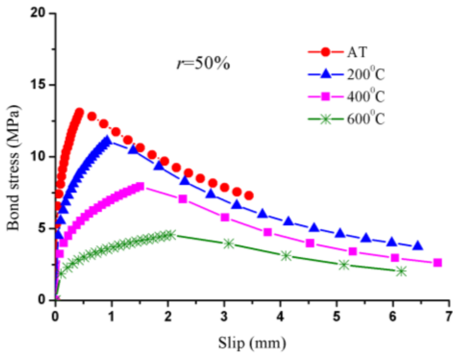

Fig. 4 Bond stress-slip after different temperature for r=50%

The experiment results of the pullout specimens, including compressive strength f_{cu} of recycled aggregate concrete (RAC), peak load P_u, peak bond stress τ_u and unloaded end slip are summarized in Table 3. As shown in Table 3, the recycled coarse aggregate replacement level had certain effect on compressive strength of recycled aggregate concrete. The compressive strength of recycled aggregate concrete declined with increasing temperature.

3.2 Bond stress-slip curves

The bond stress-slip curves of recycled coarse aggregate (RCA) concrete pullout specimens after different temperature exposures are shown in Figs. 3-5, respectively,

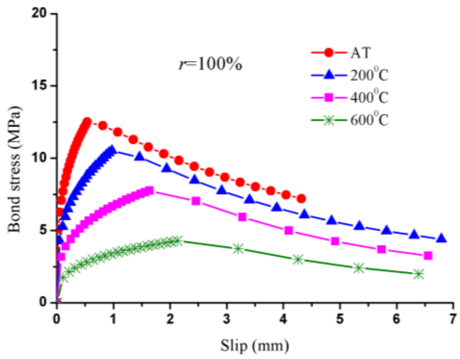

Fig. 5 Bond stress-slip after different temperature for r=100%

in which AT stands for ambient temperature, r stands for RCA replacement level. It is note that the curves of Figs. 3-5 are similar to the bond stress-slip relationships for the natural aggregate concrete (Edwards and Yannopoulos 1997). Each curve reflected the behavior at different stages which were micro-slip, internal cracking, pullout, descending and residual. Figs. 3-5 indicated that the bond stress-slip curves of the unheated RCA specimens showed almost linear trend at low slip ranges before becoming non-linear prior to failure. However, the bond stress-slip curves of the heated RCA specimens showed non-linear behavior over the major slip range with a varying rate of stress change. And the peak bond stress decreased as the temperature increased. Meanwhile, when the temperature increased, the slip increased and the slopes of the ascending portion of the bond-slip curves decreased. It also can be found that RCA replacement level had little effect on the shape of a bond stress-slip curve for recycled coarse aggregate concrete after different temperature exposures.

3.3 Bond strength

The effect of temperature on the bond strength of RCA concrete pullout specimens are shown in Fig. 6. It can be seen that the bond strength of RCA concrete specimens declined gradually as the temperature increased. In the case of RAC-100 specimens (i.e., the recycled coarse aggregate content is 100%), the bond strength of RAC-100-200 specimen at 200°C was 16.33% lower than that of the RAC-100-20 specimen at At (ambient temperature). After 400°C, the bond strength of the RCA -100-400 specimen decreased by 33.3%. And after 600°C, the bond strength of the RCA -100-600 specimen declined dramatically, which was only 39.9% of the bond strength at ambient temperature. The reason maybe was that the characteristics upon exposure to high temperature might be attributed mainly to physical and chemical changes of cement paste and aggregate used. The coarse limestone aggregate suffered a clear reduction in its strength upon heating as indicated by the abrasion test results reporter earlier. This affected negatively its interlocking with steel rebar.

The effect of recycled coarse aggregate content on the bond strength of RCA concrete pullout specimens is shown in Fig. 7. It can be concluded that the bond strength between the recycled coarse aggregate concrete and steel

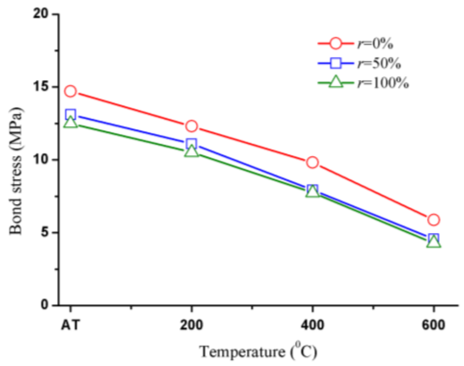

Fig. 6 Effect of the temperature on bond strength

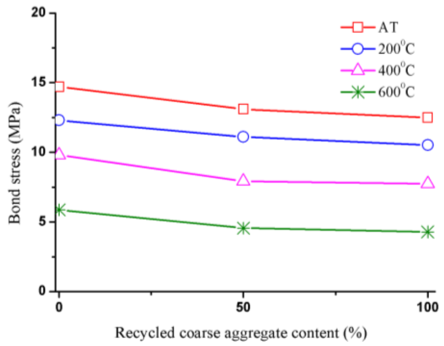

Fig. 7 Effect of RCA content on bond strength

bar at the same temperature decreased as the recycled coarse aggregate content increased. When the temperature exposure to 200℃, the bond strength was 12.3 MPa, 11.1 MPa and 10.5 MPa with recycled coarse aggregate content of 0%, 50% and 100%, respectively. After 400℃ and compared to normal concrete (i.e., the recycled coarse aggregate content is 0), the bond strength of the specimens decreased by 19.2% and 20.9% with an RCA content of 50% and 100%, respectively. After 600℃ and compared to normal concrete, the bond strength of the specimens decreased by 22.3% and 27.1% with an RCA content of 50% and 100%, respectively.

3.4 Peak slip

Fig. 8 shows the peak slip ratios (s_{0T}/s_0) after heating for different temperatures. It can be seem that the peak slip ratios increased rapidly with an increase in temperature, especially in the range of 400-600℃. For example, s_{0T}/s_0 at 200, 400, 600℃ increased by79.6-137.8%, 203.7-289.2%, 294.4-435.1% for different recycled coarse aggregate content, respectively. Nonetheless, the recycled coarse aggregate content was not significant effect on the peak slip ratios. For example, the peak slip ratios at 200, 400 and 600℃ were respectively about 2.4,3.9 and 5.4 for *r*=0% (*r* stands for recycled coarse aggregate content), 2.1,3.5 and 4.8 for *r*=50% and 1.8, 3.0 and 3.9 for *r*=100%.

By the regression analysis, the relationship between the peak strain slip ratios s_{0T}/s_0 and temperature *T* for different recycled coarse aggregate content *r* can be expressed as Eq. (2). As shown in Fig. 8, the curves proposed by Eq. (2) fitted the test data reasonably.

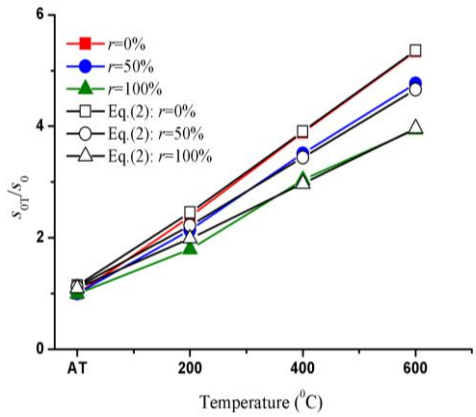

Fig. 8 Peak slip ratios after heating for different temperatures

$$\frac{s_{0T}}{s_0} = 1 + (7.27\times10^{-3}\text{-}2.33\times10^{-3}r)T \qquad T \le 500^0 C \tag{2}$$

3.5 Modeling of the bond strength

At present, a number of researchers have proposed equations that represent the bond strength between concrete and steel bars in which the compressive strength of concrete is a factor involved.

Orangun *et al.* (1977) proposed an empirical formulation as the following formula

$$\tau_u = 0.083045\sqrt{f_c^{'}}[1.2+3\frac{c}{d_b}+50\frac{d_b}{l_d}] \tag{3}$$

where $f_c^{'}$ is the compressive strength of concrete (MPa), and *c* is minimum concrete cover (mm); d_b is the diameter of the steel rebar (mm); and l_d is the embedded length of the steel rebar (mm).

Al-Jahdali *et al.* (1994) proposed an expression (in SI) for bond strength as follows

$$\tau_u = [-0.879+0.324\times(\frac{c}{d_b})+5.79\times(\frac{d_b}{l_d})]\times\sqrt{f_c^{'}} \tag{4}$$

Chapman and Shah (1987) proposed an expression for bond strength as follows

$$\tau_u = [3.5+3.4\times(\frac{c}{d})+57\times(\frac{d_b}{l_d})]\times\sqrt{f_c^{'}} \tag{5}$$

Kemp (1986) proposed a prediction equation for bond strength as follows

$$\tau_u = 232+2.716\times(\frac{c}{d})\times\sqrt{f_c^{'}} \tag{6}$$

Also some Code previsions are currently available for bond strength estimation. The American Concrete Institute (ACI) 318 (2008) and the Canadian Standards Association (CSA) CAN3-A23.3 (2004) codes provide equations to calculate the minimum required bond strength as

$$\tau = \frac{f_y A_b}{\pi d_b l_d} \tag{7}$$

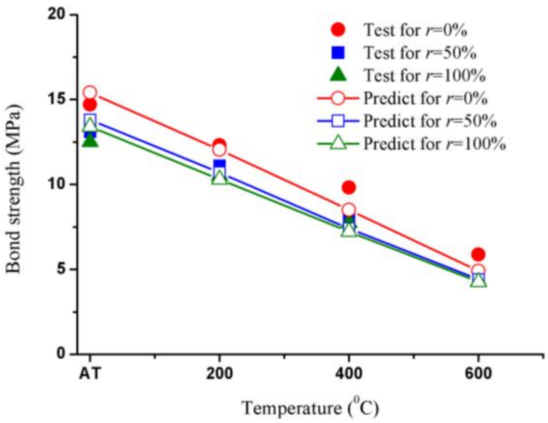

Fig. 9 Comparison of the tested and predicted on bond strength

Table 4 Tested and predicted bond strength

Specimen	τ_{exp} (MPa)	τ_{cal} (MPa)	Error (%)
RAC0-20	14.71	13.10	10.94
RAC0-200	12.32	11.10	9.90
RAC0-400	9.81	7.93	19.16
RAC0-600	5.85	4.56	22.05
RAC50-20	13.11	15.40	.17.46
RAC50-200	11.12	12.05	8.36
RAC50-400	7.93	8.51	7.31
RAC50-600	4.56	4.91	7.67
RAC100-20	12.54	13.40	6.85
RAC100-200	10.52	10.30	2.09
RAC100-400	7.72	7.22	6.47
RAC100-600	4.26	4.27	0. 23

where f_y is the specified yield strength of the tested rebar, and A_b is the area of the tested rebars; d_b is the diameter of the steel rebar; and l_d is the embedded length of the steel rebar.

Eurocode 2 (2004) recommended the following equation

$$\tau_u = 2.25\eta_1\eta_2 f_{ctd} \tag{8}$$

where f_{ctd} is the design value of concrete tensile strength, and η_1 is the coefficient relatedto the quality of the bond condition and the position of the bar during concreting; η_2 is the coefficient related to the diameter of conventional.

NZS-3101 (2006) recommended the following equation

$$\tau_u = \frac{\sqrt{f_c^{'}}}{2\alpha_a\pi} \tag{9}$$

where $f_c^{'}$ is the compressive strength of concrete, and α_a is the location factor for conven- tional reinforcement.

Australian Standard 3600 (1994) recommended the following equation

$$\tau = 0.265\sqrt{f_c^{'}}(\frac{c}{d_b}+0.5) \tag{10}$$

where $f_c^{'}$ is the compressive strength of the cylindrical concrete prism, and c is the radiusof a cylindrical; d_b is the diameter of the steel rebar.

The CEB-FIP code (2012) recommended another equation that depended only on the square root of compressive strength of concrete (in case of good bond), as the following

$$\tau_u = 2.5\sqrt{f_c^{'}} \tag{11}$$

However, the modeling of the bond strength for recycled coarse aggregate concrete and steel rebar after high temperature haven't been proposed yet. So in this study, based on the test data of the bond strength, the calculation model of the bond strength between recycled coarse aggregate concrete and steel rebar after high temperature adopted by CEB-FIP code (2012), was modified. The calculation bond strength of the steel rebar in recycled coarse aggregate concrete after high temperature was approximated by the following equation

$$\tau_u = [1\text{-}1.05\times10^{-3}\times(T\text{-}20)]\times2.5\sqrt{f_c^{'}} \tag{12}$$

where $f_c^{'}$ is the compressive strength of cylindrical concrete prism, and T is temperature.

Fig. 9 shows the comparison of tested and predicted bond stress values. The calculated bond strength τ_{cal} using equation (12) compared to the experimental bond strength τ_{exp} is summarized in Table 4. It can be seen that the developed mode can predict the bond strength for recycled coarse aggregate concrete and steel rebar after high temperature reasonably well.

5. Conclusions

Based on the experimental results presented in the paper, the following conclusions can be drawn:

- With the increase of the temperatures, the bond strength for recycled coarse aggregate concrete and steel rebar declined. The bond strength between the recycled coarse aggregate concrete and steel bar at the same temperature decreased as the recycled coarse aggregate content increased.
- The general shape of the bond-slip curve between recycled coarse aggregate concrete and steel bar was similar, which included micro-slip, internal cracking, pullout, descending and residual.
- The peak slip ratios increased rapidly with an increase in temperature. And the relationship between the peak slip ratios and temperature for different recycled coarse aggregate content was proposed in this paper and in good agreement with test data.
- Taking into account the effects of different temperature, a bond strength revised from CEB-FIP code (2012) was proposed. Equation for the residual bond strength between recycled coarse aggregate concrete and steel rebar with high temperature was given, which could be used for predictive assessment of the post-fire strength of recycled aggregate concrete structures.

Acknowledgments

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