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Bond Performance Between Recycled Coarse Aggregate Concrete Reinforced with Polypropylene Fibers and Steel Bars After High-temperature Treatment

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This paper systematically studies the compressive strength of recycled coarse aggregate concrete with different dosages of polypropylene fibers at high temperatures and the influence of polypropylene fibers on the bond performance between recycled concrete and steel bars at high temperatures. The research results indicated that as the temperature increased, the compressive strength of the concrete decreased. Fibers can improve the compressive strength of concrete, but this effect needs to be controlled within a certain range. As the temperature increased, the bond strength between the concrete and steel bars decreased, while the bond slip increased. The addition of fibers improved the bond performance between the recycled concrete and steel bars, which was mainly reflected by increasing the bond strength and reducing the bond slip. With increasing fiber content, the bond strength between the recycled concrete and steel bars first increased and then decreased. When the fiber content was 0.12 %, the bond strength between the recycled concrete and steel bars was the highest. In addition, a calculation model of the bond strength between steel bars and recycled coarse aggregate concrete with fibers after exposure to high temperatures was established.

Keywords: recycled coarse aggregate concrete, polypropylene fiber, high temperature, compressive strength, bond performance.

1. INTRODUCTION

With the acceleration of urbanization, the contradiction between the scarcity of natural resources and the sharp increase in construction waste has become increasingly prominent [1]. The construction of new buildings requires a large amount of resources such as sand and gravel, while the demolition of old buildings generates a large amount of construction waste [2]. Recycled concrete technology is a new type of concrete that breaks waste concrete into recycled aggregates and replaces natural aggregates [3]. This technology can not only solve the problem of dealing with construction waste but also effectively alleviate the current situation of natural resource scarcity [4].

However, due to the adhesion of old cement mortar on the surface of recycled coarse aggregate, its physical and mechanical properties are inferior to those of ordinary coarse aggregate, resulting in the inferior mechanical and durability performance of recycled concrete compared to that of ordinary concrete [5]. Research has shown that adding a certain amount of polypropylene fibers to recycled concrete can improve its mechanical performance [6]. Fang [7] found that adding polypropylene fibers to recycled concrete can effectively improve its compressive strength, tensile strength, and flexural strength. However, Tian [8] reported that the addition of fibers can decrease the compressive strength, flexural strength, and elastic modulus of recycled concrete while improving the splitting tensile strength of recycled concrete. Moreover, with increasing waste polypropylene fiber content, the reinforcement effect becomes more significant. Abdul [9] reached a similar conclusion: when the content of polypropylene fibers was 2.0 %, the decrease rate of the concrete compressive strength reached 45.9 %.

The reason for the different results mentioned above is that both fiber length and fiber content have varying degrees of influence on the mechanical properties of recycled concrete. Yazdanbakhsh [10] and Zhou [11] found that when the fiber length was 30 mm, the compressive strength of concrete was the best; when the fiber length was 19 mm, the splitting tensile strength was the best. When the fiber length and fiber content exceed a certain range, they will have adverse effects on the mechanical properties of recycled concrete.

In addition, the good bond performance between steel bars and concrete is the foundation for ensuring their resistance to external loads [12]. The greater the compressive strength of the concrete and the tensile strength of the steel bars are, the greater the bond strength between the steel bars and the concrete. Therefore, adding fibers can not only improve the mechanical and durability properties of recycled concrete but also enhance the bond performance between recycled concrete and steel bars [13]. The bond strength increased with increasing steel fiber volume fraction [14]. After adding basalt-polypropylene hybrid fibers to recycled concrete, the bond strength of the recycled concrete specimens decreased [15]. Therefore, excessive fiber content was not conducive to improving the bond strength of recycled concrete specimens.

Fire is a high-frequency disaster [16], and the fire resistance of reinforced concrete under high temperatures mainly depends on the mechanical properties of the steel

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bars and concrete, as well as the bond performance between the steel bars and concrete [17]. At high temperatures, the bond strength between steel bars and concrete severely deteriorates [18 – 20]. The bond strength damage effect between the round steel bars and the concrete was more obvious. When the temperature reached 300-400 ℃, the bond strength was only half of the strength at room temperature, and the higher the temperature was, the more severe the damage [21]. After high temperature, cracks formed between the aggregates inside the concrete and the cement slurry [22, 23], and at higher temperatures, the cement slurry underwent chemical reactions and decomposed [24]. Therefore, it is necessary to improve the bonding performance between recycled concrete and steel bars in high-temperature environments.

At present, most of the existing research has focused on the mechanical and durability properties of polypropylene fiber-reinforced recycled concrete [25, 26], while there is relatively little research on the bond performance between polypropylene fiber-reinforced recycled concrete and steel bars, especially in the study of the bond performance between polypropylene fiber-reinforced recycled concrete and steel bars in high-temperature environments [27]. Therefore, this paper systematically studies the compressive strength of recycled concrete with different dosages of polypropylene fibers at high temperatures and the influence of polypropylene fibers on the bond performance between recycled concrete and steel bars at high temperatures, providing a theoretical basis for effectively improving the bonding performance between recycled concrete and steel bars at high temperatures.

2. EXPERIMENTAL

2.1. Materials

PO 42.5 ordinary Portland cement conforming to GB175-2007 [28] was used in this paper, and the basic properties of the cement are shown in Table 1. Sand with a fineness modulus of 2.61 was used as fine aggregate, and natural crushed stone was used as natural coarse aggregate. The recycled coarse aggregate was obtained from crushed waste concrete. The basic properties of natural coarse aggregate (NCA) and recycled coarse aggregate (RCA) are shown in Table 2 [29]. An HRB400 threaded steel bar was used as the pulling steel bar, while an HPB300 plain round steel bar was used as the stirrups; the basic properties of the steel bars are shown in Table 3. Polypropylene fibers with a tensile strength of 420 MPa and a density of 0.91 g/cm^3 were used as reinforced fibers in the concrete. The volume incorporation ratios of the polypropylene fibers were 0.04 %, 0.08 %, 0.12 % and 0.18 %.

Table 2. Mixture design of concrete

Type	Cement, kg/m^3	Water, kg/m^3	Sand, kg/m^3	RCA, kg/m^3	NCA, kg/m^3	Fiber length, mm	Fiber ratio,%
NC-0.00	425	185	435	0	985	14	0.00
NC-0.12	425	185	435	0	985	14	0.12
RC-0.00	425	185	435	985	0	14	0.00
RC-0.04	425	185	435	985	0	14	0.04
RC-0.08	425	185	435	985	0	14	0.08
RC-0.12	425	185	435	985	0	14	0.12
RC-0.18	425	185	435	985	0	14	0.18

Table 1. Basic properties of the cement

Specific surface area, m^2 kg^{-1}	Final setting times, min	Initial setting times, min	28-day compressive strength, MPa	28-day flexural strength, MPa
327	420	185	49.1	9.1

Table 2. Basic properties of the coarse aggregates

Type	Size of particles , mm	Water absorption, %	Crushing index, %
NCA	5-31.5	1.5	11.2
RCA	5-31.5	4.8	16.9

Table 3. Basic properties of the steel bars

Type	Diameter, mm	Yield strength, MPa	Tensile strength, MPa
HRB400	20	520	710
HPB300	6	425	310

2.2. Concrete mix design

According to JGJ55-2019 [30], the concrete mix is shown in Table 4 (RC represents the recycled coarse aggregate concrete; NC represents the natural coarse aggregate concrete).

2.3. Specimen design

The cube specimens were used to measure the compressive strength of the concrete after high-temperature treatment, and the prism pull-out specimens (Fig. 1) were used to measure the bond performance of the concrete and steel bars after high-temperature treatment. The details of the specimen grouping are shown in Table 4.

Table 4. Details of specimen grouping

Type	Specimen size, mm	Temperature, °C
NC	150×150×150	20, 100, 150, 200, 250, 300
RC	150×150×150	20, 100, 150, 200, 250, 300
NC	150×150×300	20, 100, 150, 200, 250, 300
RC	150×150×300	20, 100, 150, 200, 250, 300

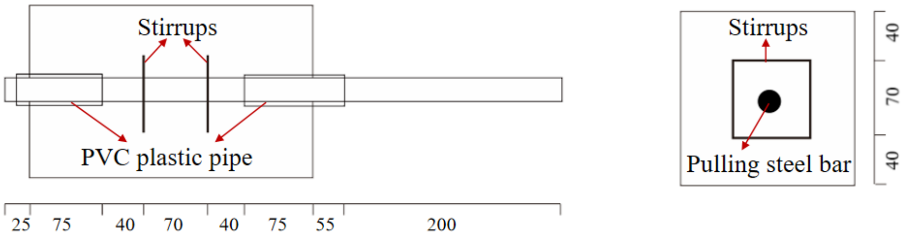


Fig. 1. Size schematic diagram of the pull-out specimen

2.4. Test method

The specimens were heated by an industrial resistance furnace to reach the rated temperature at a heating rate of 10 °C/min and maintained for 4 hours. Then, the specimens were removed from the industrial resistance furnace after natural cooling to 20 °C [31].

The pull-out test was carried out on a hydraulic servo testing machine with a displacement loading rate of 0.3 mm/min, as shown in Fig. 2. Displacement sensors and load sensors were used to collect the corresponding data.

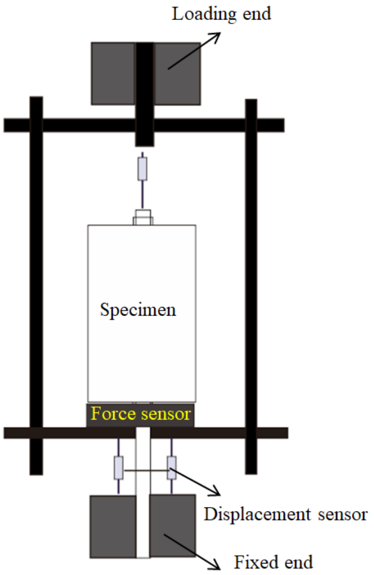


Fig. 2. Loading scheme for bond performance

3. RESULTS

3.1. Compressive strength after high-temperature treatment

Fig. 3 shows the compressive strength of recycled coarse aggregate concrete and natural coarse aggregate concrete after high-temperature treatment. The compressive strength of recycled coarse aggregate concrete was lower than that of natural coarse aggregate concrete after high-temperature treatment. At 300 °C, the compressive strength of the natural coarse aggregate concrete was 1.62 times that of the recycled coarse aggregate concrete. The reasons for this phenomenon are as follows: on the one hand, because the crushing index of recycled coarse aggregate is 1.5 times that of ordinary coarse aggregate, its mechanical properties are lower than those of ordinary coarse aggregate, resulting in recycled concrete having lower mechanical properties than ordinary concrete. On the other hand, the surface of recycled coarse aggregate is attached to old cement slurry, which leads to an increase in the interfacial transition zone in recycled concrete, thus reducing the mechanical properties of recycled concrete [32].

As the temperature increased, the compressive strength of each group of concrete specimens decreased. After reaching 300 °C, the compressive strengths of NC-0.00, NC-0.12, RC-0.00, RC-0.04, RC-0.08, RC-0.12, and RC-0.18 decreased by 24.4 %, 15.0 %, 41.7 %, 34.2 %, 33.1 %, 36.1 % and 44.8 %, respectively. This is because high temperatures can cause changes in the pore structure of concrete, leading to stress concentration inside the concrete and thus reducing its strength. In addition, high temperatures can exacerbate the development of internal damage, thereby accelerating the decrease in concrete strength.

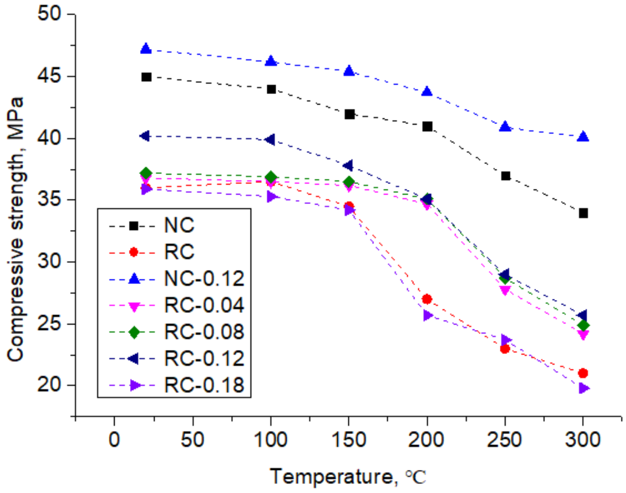


Fig. 3. Compressive strength after high temperature

Fig. 4 shows the effect of polypropylene fibers on the compressive strength of concrete after exposure to high temperatures. When the fiber content was 0.12 %, the fibers had the greatest effect on improving the mechanical properties of the recycled coarse aggregate concrete. At 20 °C, 100 °C, 150 °C, 200 °C, 250 °C, and 300 °C, the compressive strength of the recycled coarse aggregate concrete increased by 11.7 %, 9.3 %, 9.6 %, 30.0 %, 26.1 %, and 22.4 %, respectively. When the fiber content was 0.18 %, the mechanical properties of the fiber-reinforced recycled coarse aggregate concrete were lower than those of the recycled coarse aggregate concrete. At 20 °C, 100 °C, 150 °C, 200 °C, 250 °C, and 300 °C, the compressive strength of the recycled coarse aggregate concrete decreased by 0.3 %, 3.3 %, 0.9 %, 4.8 %, 3.0 %, and 5.7 %, respectively. This is because polypropylene fibers can effectively prevent the development of internal cracks in concrete, thereby limiting the stress deformation of concrete and improving its mechanical properties [25]. However, when the content of polypropylene fibers is too high, the fibers aggregate inside the concrete, causing stress concentration during the stress process, thereby deteriorating the mechanical properties of the concrete.

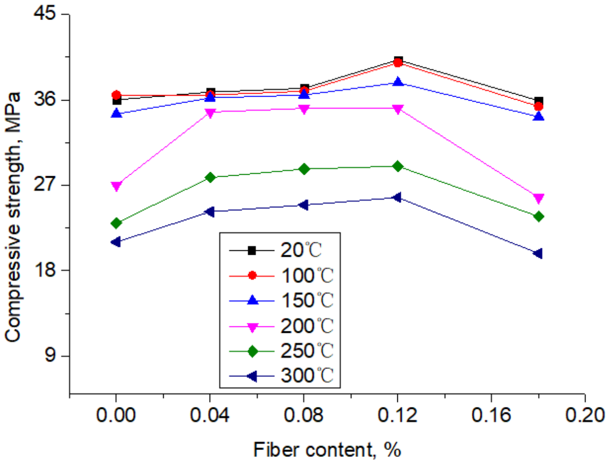
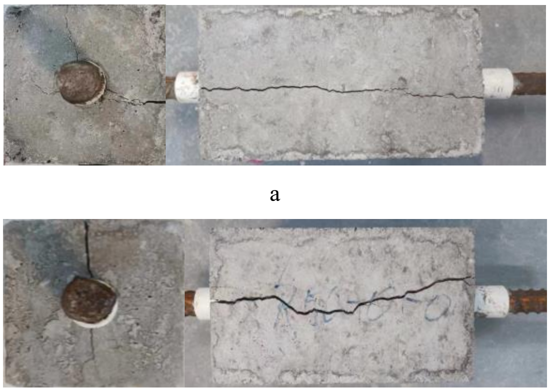


Fig. 4. Compressive strength of fiber reinforced concrete

3.2. Bond failure modes

Fig. 4 shows the bond failure mode of the recycled coarse aggregate concrete after reaching a high temperature. The bond failure modes of the recycled coarse aggregate concrete specimens without polypropylene fibers and the recycled coarse aggregate concrete specimens with polypropylene fibers were both pull-out splitting failure; that is, obvious cracks appeared on the surface of the concrete while the steel bars were pulled out. In addition, the width of the cracks generated by the tensile test of the recycled coarse aggregate concrete specimens with polypropylene fibers was smaller than that of the recycled coarse aggregate concrete specimens without polypropylene fibers. This is because polypropylene fibers can inhibit the development of concrete cracks.


a

b

Fig. 5. Bond failure mode: a – recycled coarse aggregate concrete with polypropylene fibers; b – recycled coarse aggregate concrete without polypropylene fibers

3.3. Bond strength after high temperature

Fig. 6 shows the bond strength of the concrete specimens after high-temperature treatment. The bond strength of the recycled coarse aggregate concrete specimens was lower than that of the natural coarse aggregate concrete specimens after high-temperature treatment. In addition, as the temperature increased, the difference between the two gradually increased. At 20 °C, the bond strength of the natural coarse aggregate concrete specimens was 1.26 times that of the recycled coarse aggregate concrete specimens; at 300 °C, the bond strength of the natural coarse aggregate concrete specimens was 1.52 times that of the recycled coarse aggregate concrete specimens. This is because the strength of recycled coarse aggregate concrete is lower than that of natural coarse aggregate concrete at the same temperature [26], and the restraining force of recycled coarse aggregate concrete on steel bars is relatively small, resulting in lower bond strength. With increasing temperature, due to the initial defects of recycled coarse aggregate concrete, the damage cracks inside the recycled coarse aggregate concrete specimen develop more rapidly, so the bond strength decreases more significantly.

As the temperature increased, the bond strength of each group of concrete specimens decreased. After reaching 300 °C, the bond strengths of NC-0.00, NC-0.12, RC-0.00, RC-0.04, RC-0.08, RC-0.12, and RC-0.18 decreased by 23.9 %, 22.5 %, 36.9 %, 32.5 %, 33.2 %, 32.6 % and 36.2 %, respectively. This is because the strength of the concrete decreases after reaching a high temperature, thereby reducing its restraining effect on the steel bars.

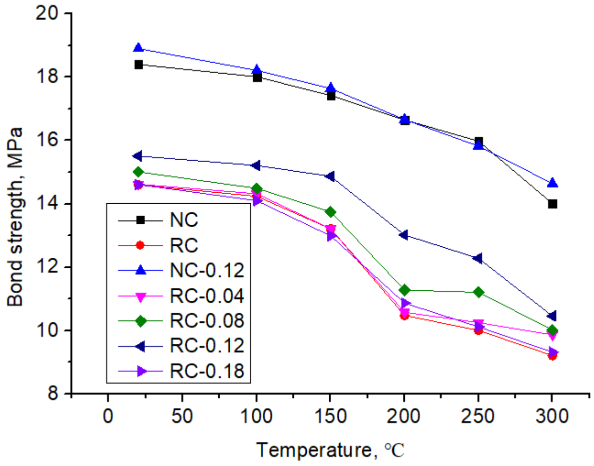


Fig. 6. Bond strength after high temperature

Fig. 7 shows the effect of the addition of polypropylene fibers on the bond strength of the concrete specimens after high-temperature treatment. When the fiber content was 0.12 %, the fibers had the greatest effect on improving the mechanical properties of the recycled coarse aggregate concrete specimens. At 20 °C, 100 °C, 150 °C, 200 °C, 250 °C, and 300 °C, the bond strengths of the recycled coarse aggregate concrete specimens increased by 6.2 %, 6.8 %, 12.6 %, 24.2 %, 22.7 %, and 13.6 %, respectively. When the fiber content was 0.18 %, the effect of the fibers on the bond performance of the recycled coarse aggregate concrete specimens was not significant. At 20 °C, 100 °C, 150 °C, 200 °C, 250 °C, and 300 °C, the compressive strength of the recycled coarse aggregate concrete increased by 0.1 %, -1.0 %, -1.7 %, 3.7 %, 1.1 %, and 1.2 %, respectively. This is because when the fiber content is within a reasonable range, the mechanical properties of recycled coarse aggregate concrete can be effectively improved, thereby improving the bond performance between recycled coarse aggregate concrete and steel bars. However, when the fiber content exceeds a reasonable range, the fiber agglomeration phenomenon reduces the mechanical properties of recycled coarse aggregate concrete, resulting in a poor improvement in the bond performance of recycled coarse aggregate concrete and steel bars.

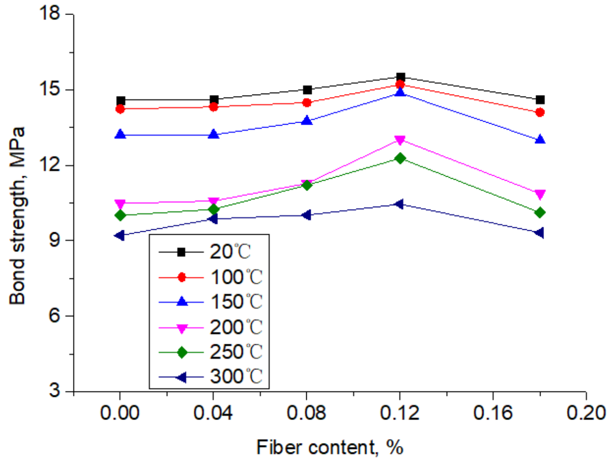


Fig. 7. Bond strength of the fiber reinforced concrete

3.4. Slip after high temperature

Fig. 8 shows the bond slip of the concrete specimens after high-temperature treatment. As the temperature increased, the bond slip between the concrete and steel bars tended to increase.

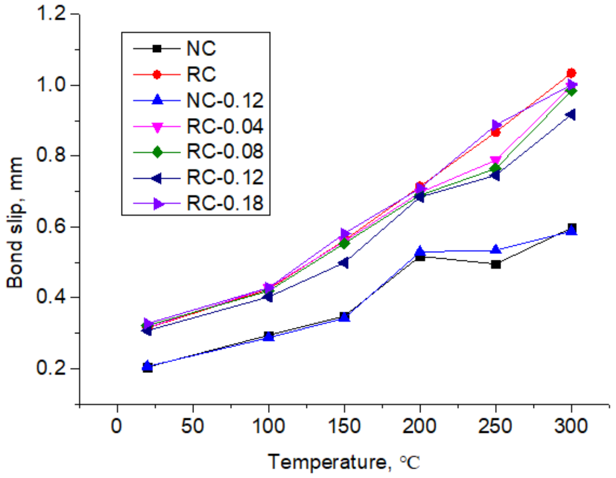


Fig. 8. Bond slip after high temperature

This is because as the temperature increases, the strength of the concrete gradually decreases, and the constraint of the concrete on the steel bars decreases, leading to an increase in the steel bar slip [26, 33]. The bond slip of the recycled coarse aggregate concrete specimens was greater than that of the natural coarse aggregate concrete specimens at the same temperature. At 300 °C, the bond slip of the recycled coarse aggregate concrete specimens was 0.597, while that of the natural coarse aggregate concrete specimens was 1.034.

Fig. 9 shows the effect of the addition of polypropylene fibers on the bond slip of the concrete specimens at high temperatures. At the same temperature, the bond slip between the steel bars and recycled coarse aggregate concrete with fiber was smaller than that between the steel bars and recycled coarse aggregate concrete without fiber. Therefore, the fibers inhibited delamination between the steel bars and recycled coarse aggregate concrete. The effect of different fiber contents on the bond slip between steel bars and recycled coarse aggregate concrete was not significant, but overall, the optimal suppression effect on steel bar slip was achieved when the fiber content was 0.12 %.

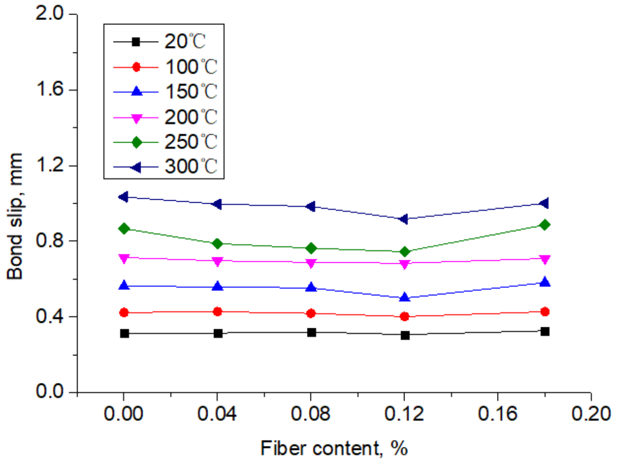


Fig. 9. Bond slip of the fiber reinforced concrete

According to GB50010-2010 [34], the peak bond slip parameter value between concrete and steel bars was 0.04*d* (*d* is the diameter of the steel bars), indicating that before the temperature reached 250 °C, the bond slip between each group of recycled coarse aggregate concrete with fiber and steel bars met the requirements of GB50010-2010 [34].

3.5. Bond strength calculation model after high-temperature treatment

The bond strength between the steel bars and recycled coarse aggregate concrete with fibers after reaching a high temperature was fitted by a linear function, as shown in Fig. 10 (y represents the bond strength, and x represents the temperature):

RC-0.04:

$$Y=-0.02x+15.539 \qquad R^2=0.8948; \tag{1}$$

RC-0.08:

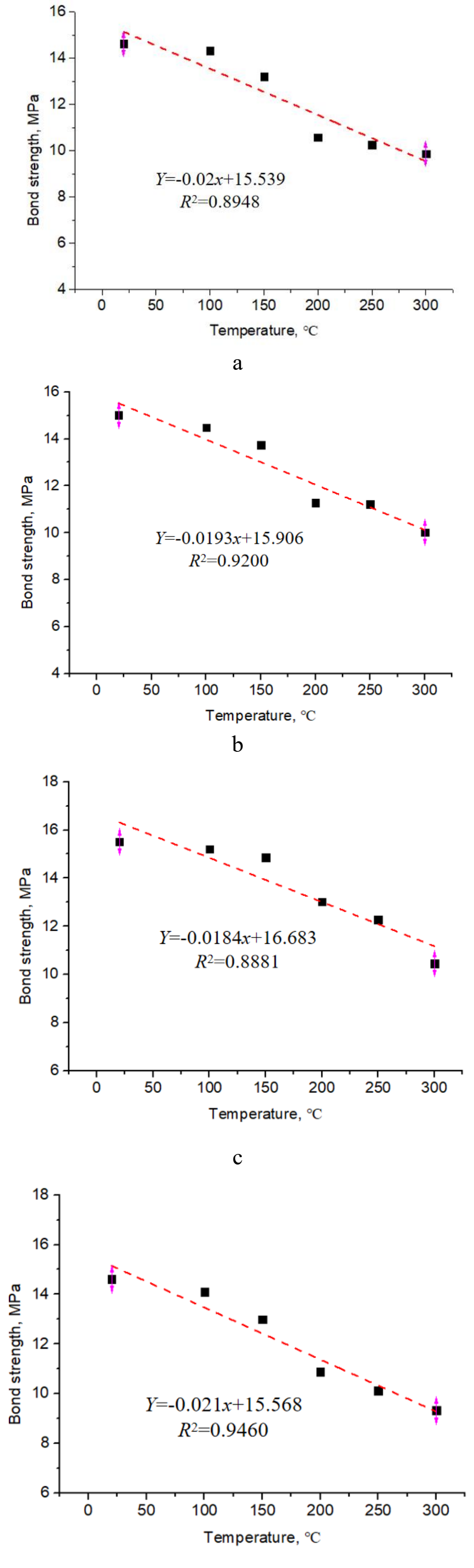
$$Y=-0.0193x+15.906 \qquad R^2=0.9200; \tag{2}$$

RC-0.12:

$$Y=-0.0184x+16.683 \qquad R^2=0.8881; \tag{3}$$

RC-0.18:

$$Y=-0.021x+15.568 \qquad R^2=0.9460; \tag{4}$$



a

b

c

d

Fig. 10. Linear fitting results of the bond strength: a – RC-0.04; b – RC-0.08; c – RC-0.12; c – RC-0.18

4. CONCLUSIONS

1. As the temperature increased, the compressive strength of the concrete decreased. Fibers can improve the compressive strength of concrete, but this effect needs to be controlled within a certain range.
2. As the temperature increased, the bond strength between the concrete and steel bars decreased, while the bond slip increased.
3. The addition of fibers improved the bond performance between the recycled concrete and steel bars, which was mainly reflected by increasing the bond strength and reducing the bond slip.
4. With increasing fiber content, the bond strength between the recycled concrete and steel bars first increased and then decreased. When the fiber content was 0.12 %, the bond strength between the recycled concrete and steel bars was the highest.
5. Before the temperature reached 250 °C, the bond slip between each group of recycled coarse aggregate concrete with fiber and steel bars met the requirements of GB50010-2010.
6. A calculation model of the bond strength between steel bars and recycled coarse aggregate concrete with fibers after exposure to high temperatures was established.

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