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Mechanical Properties of Recycled Concrete with Polypropylene Fiber and Its Bonding Performance with Rebars

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This paper explores the influence of polypropylene fiber on the mechanical properties of recycled concrete and the bonding performance between recycled concrete and steel bars. The results indicate that the compressive strength and splitting tensile strength of concrete decrease with the increase in the replacement rate of recycled aggregate. When the replacement rate of recycled aggregate was 100 %, the compressive strength of concrete decreased by 25.0%, while the splitting tensile strength of concrete decreased by 21.7 %. The compressive strength and splitting tensile strength of recycled aggregate concrete show a trend of first increasing and then decreasing with increasing fiber content. When the fiber content is 0.09 %, the compressive strength and tensile strength of recycled aggregate concrete are optimal. The bond strength of recycled concrete pullout specimens with fiber is higher than that of recycled concrete pullout specimens without fiber, while the slip of recycled concrete pullout specimens with fiber is lower than that of recycled concrete pullout specimens without fiber. The maximum improvement in bonding performance between recycled concrete and rebars with a 50 % recycled aggregate replacement rate is 13.7 %, and the maximum improvement in bonding performance between recycled concrete and rebars with a 100 % recycled aggregate replacement rate is 11.8 %. The bond strength shows a trend of first increasing and then decreasing with increasing fiber content, but the degree of decrease was not significant, while the slip shows a trend of first decreasing and then increasing with increasing fiber content. Compared to the compressive strength of concrete, the splitting tensile strength can better reflect the bond strength between concrete and rebar. The nonlinear relationship between the bond strength, compressive strength, and splitting tensile strength of recycled concrete is established. This study can effectively improve the mechanical properties of recycled concrete, expand the application scope of recycled concrete technology, and promote the sustainable development of the construction industry.
Keywords: recycled aggregate, polypropylene fiber, compressive strength, splitting tensile strength, bond strength.

1. INTRODUCTION

The rapid development of the construction industry has also led to the continuous growth of solid waste from construction, which has brought about increasing attention to environmental pollution issues [1]. To effectively treat construction solid waste, scholars have conducted extensive research [2, 3]. Research has found that waste concrete can be crushed to produce recycled aggregates, thereby preparing recycled concrete. This can not only handle waste concrete but also solve natural stone resources [4, 5].

At present, research on the mechanical properties of recycled concrete is relatively extensive [6]. The development law of the compressive strength of recycled concrete with age is similar to that of benchmark concrete, but the addition of recycled aggregate will lead to a lower compressive strength of recycled concrete than that of ordinary concrete, and there is a downward trend with the increase in recycled aggregate addition [7, 8]. Ramamurthy [9] found that the compressive strength of recycled concrete is lower than that of ordinary concrete by 15 % – 42 %. This is because recycled aggregate causes three interface transition zones in recycled concrete (including the interface transition zone between new mortar and old mortar, the interface transition zone between new mortar and old aggregate, and the interface transition zone between old mortar and old aggregate), resulting in inferior compressive strength of recycled concrete compared to ordinary concrete [10]. The flexural strength of concrete also shows a decreasing trend with the addition of recycled aggregate [11], but the change in flexural strength compared to compressive strength is not significant and is even comparable to the flexural strength of ordinary concrete. Moreover, the ratio of flexural strength to compressive strength of recycled concrete is similar to that of ordinary concrete [12, 13]. However, the low compressive strength of recycled concrete limits its application in engineering, and effectively mentioning the mechanical properties of concrete is one of the important directions for future research [14].

In addition, the bonding performance between concrete and steel bars is crucial for ensuring the normal use of reinforced concrete structures [15]. Once the bonding performance between concrete and steel bars is damaged, it will inevitably affect the safety and durability of concrete structures [16]. Therefore, the good bonding performance between recycled concrete and steel bars is also one of the key factors in promoting recycled concrete technology [17, 18]. The water cement ratio, recycled aggregate water absorption rate, steel bar diameter, and recycled aggregate

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replacement rate all have varying degrees of influence on the bonding performance between recycled concrete and steel bars [19]. In general, the bond slip behavior and bond failure mode between steel bars and recycled aggregate concrete are very similar to those of ordinary aggregate concrete [20], but the bond strength between recycled concrete and steel bars is lower than that of ordinary concrete and steel bars, mainly due to the initial defects of recycled concrete [21]. Some scholars have also found that when the amount of recycled aggregate is within a certain range, the bonding performance between recycled concrete and steel bars is better than that of ordinary concrete and steel bars [22]. Zhao [23] found through experimental research that the bonding strength between recycled concrete and steel bars is closely related to the compressive strength of recycled concrete, mainly because the mechanical biting force between concrete and steel bars increases with increasing concrete strength. The water cement ratio, as a key influencing factor, affects the bond failure mode between recycled concrete and steel bars. As the water cement ratio decreases, the bond failure mode changes from pull-out failure to pull-out splitting failure [24]. In addition, a high water cement ratio will weaken the influence of recycled coarse aggregate on the bonding performance between concrete and steel bars [25]. Prince [26] found that the diameter of steel bars also affects the bonding performance between recycled concrete and steel bars. As the diameter of the steel bars increases, the bonding strength shows a decreasing trend.

Polypropylene fiber has advantages such as high strength, good elasticity, wear resistance, and corrosion resistance. By evenly dispersing the short fibers in concrete, it can improve the mechanical properties of concrete and is not easy to aggregate [27]. The addition of polypropylene fibers can improve the mechanical properties of concrete. During the process of generating strength, concrete continuously undergoes hydration reactions and releases a portion of heat, which can lead to microcracks. The addition of waste fibers can combine with concrete, weaken the generation of microcracks, and improve the mechanical properties of concrete [28]. Zhou [29] found that the addition of fibers has a significant impact on the flexural strength, dynamic modulus, and frost resistance of concrete but has a smaller impact on the compressive strength. The research of relevant scholars has reached similar conclusions [30, 31] that adding polypropylene fibers can improve its tensile strength to a certain extent, but when the fiber content reaches a certain value, it will reduce its compressive strength.

Therefore, the addition of fibers needs to be controlled within a reasonable range to improve the mechanical properties of recycled concrete [32], thereby enhancing the bonding performance between recycled concrete and steel bars [33, 34]. At present, there has been some research on the application of polypropylene fiber in recycled concrete, but there is no clear conclusion on how to control its dosage. In addition, there is relatively little research on the bonding performance between recycled concrete with polypropylene fibers and steel bars, and the influence of polypropylene fibers on the bonding performance has not been explored. Therefore, this paper conducts a study on the mechanical properties of recycled concrete with different amounts of polypropylene fiber and its bonding performance with steel bars through mechanical performance tests, providing a basis for improving the mechanical properties of recycled concrete and its bonding performance with steel bars.

2. EXPERIMENTAL DETAILS

2.1. Raw materials and mix design

The coarse aggregate was crushed gravel with a size distribution of 5 – 26.5 mm, and the water absorption and crush index were 6.3 % and 2.5 %, respectively. The recycled coarse aggregate was obtained by crushing and sieving waste concrete blocks, and the water absorption and the crush index were 15.3 % and 5.1 %, respectively [35]. Natural river sand with a fineness modulus of 2.6 was used as the fine aggregate, and the cement used was ordinary Portland cement P. O 42.5. The main chemical composition of ordinary Portland cement P. O 42.5 is shown in Table 1.

Table 1. Main chemical composition of ordinary Portland cement

	SiO_3	MgO	Al_2O_3	Fe_2O_3	CaO
Content,%	2.45	1.82	5.45	4.76	64.41

HRB400 deformed rebar with a diameter of 18 mm was used for the central pulling rebar, and the yield strength of the central pulling rebar was 535 MPa; the tensile strength was 365 MPa; and the elastic modulus was 200 GPa. Polypropylene fibers with a length of 19 mm, density of 0.89 g cm^{-3}, tensile strength of 360 MPa, and elastic modulus of 4.5 GPa were used as reinforcing fibers.

The target strength of ordinary concrete was designed to be 40 MPa [36], and recycled concrete was produced by replacing ordinary coarse aggregate with recycled coarse aggregate. The mix design of ordinary concrete and recycled concrete is shown in Table 2. It was worth noting that because the density of fibers was much lower than the density of materials in concrete, the fiber mass mixing method could not be used, while the fiber volume mixing method could be used. In addition, Wang [30] found that excessive fiber content had adverse effects on the performance of concrete. Therefore, the fiber volume fraction of 0 %, 0.03 %, 0.06 %, 0.09 %, 0.12 %, 0.15 %, and 0.18 % were selected in this paper.

2.2. Specimen design and loading

Ninety cubic specimens (100 mm × 100 mm × 100 mm) were cast to investigate the compressive strength and splitting tensile strength of concrete. Forty-five center pull out specimens (150 mm × 150 mm × 150 mm) were cast to investigate the bonding performance of concrete with rebar, as shown in Fig. 1 (It is worth noting that in order to prevent stress concentration at the loading end during the loading process, and to ensure that the load distribution in the bonding area is relatively uniform, PVC pipes are installed at both the loading end and the free end of the rebars).

The loading scheme for mechanical properties is shown in Fig. 2. The compressive strength of concrete was tested by an electrohydraulic servo universal testing machine with a loading rate of 0.3 MPa/s; the splitting tensile strength of concrete was tested by an electrohydraulic servo universal testing machine with a loading rate of 0.05 MPa/s. The pull-out test was tested by a hydraulic servo testing machine, and the displacement rate was 0.5 mm/min, as shown in Fig. 3.

Table 2. Mixture design of concrete

Type	Water, kg/m³, %	Cement, kg/m³, %	Fine aggregate, kg/m³, %	Normal aggregate, kg/m³, %	Recycled aggregate, kg/m³, %	Fiber, %
NAC-0	185; 7.84	412; 17.45	680; 28.80	1084; 45.91	0; 0	0
RAC-50-0	185; 7.84	412; 17.45	680; 28.80	542; 22.96	542; 22.96	0
RAC-50-3	185; 7.84	412; 17.45	680; 28.80	542; 22.96	542; 22.96	0.03
RAC-50-6	185; 7.84	412; 17.45	680; 28.80	542; 22.96	542; 22.96	0.06
RAC-50-9	185; 7.84	412; 17.45	680; 28.80	542; 22.96	542; 22.96	0.09
RAC-50-12	185; 7.84	412; 17.45	680; 28.80	542; 22.96	542; 22.96	0.12
RAC-50-15	185; 7.84	412; 17.45	680; 28.80	542; 22.96	542; 22.96	0.15
RAC-50-18	185; 7.84	412; 17.45	680; 28.80	542; 22.96	542; 22.96	0.18
RAC-100-0	185; 7.84	412; 17.45	680; 28.80	0; 0	1084; 45.91	0
RAC-100-3	185; 7.84	412; 17.45	680; 28.80	0; 0	1084; 45.91	0.03
RAC-100-6	185; 7.84	412; 17.45	680; 28.80	0; 0	1084; 45.91	0.06
RAC-100-9	185; 7.84	412; 17.45	680; 28.80	0; 0	1084; 45.91	0.09
RAC-100-12	185; 7.84	412; 17.45	680; 28.80	0; 0	1084; 45.91	0.12
RAC-100-15	185; 7.84	412; 17.45	680; 28.80	0; 0	1084; 45.91	0.15
RAC-100-18	185; 7.84	412; 17.45	680; 28.80	0; 0	1084; 45.91	0.18

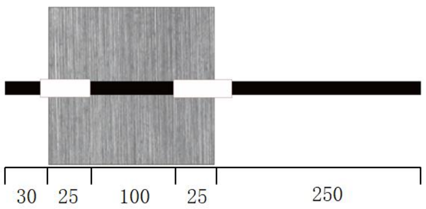
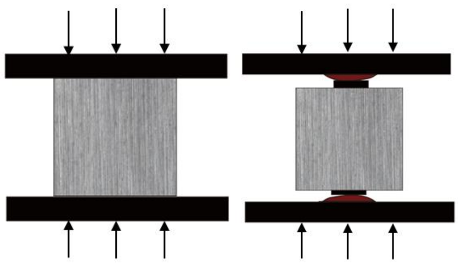


Fig. 1. Schematic diagram of the central pull-out specimen

Displacement meters were arranged at the loading and free ends of the steel bars, and the displacement of the steel bars was the average value of the free and loading ends.



a b

Fig. 2. Loading scheme for mechanical properties: a – compressive strength; b – splitting tensile strength

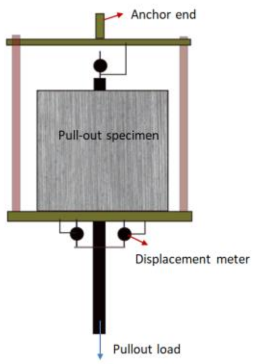


Fig. 3. Loading scheme for bonding performance

3. RESULTS AND DISCUSSION

3.1. Mechanical properties

3.1.1. Effect of recycled aggregate replacement rate on mechanical properties

The compressive strength and splitting tensile strength of concrete with different replacement rates of recycled coarse aggregate are shown in Fig. 4 and Fig. 5, respectively.

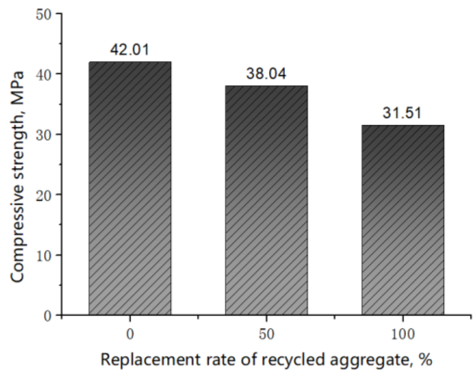


Fig. 4. Splitting tensile strength with different replacement rates of recycled coarse aggregate

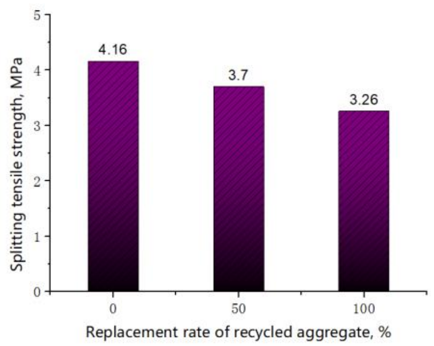


Fig. 5. Splitting tensile strength with different replacement rates of recycled coarse aggregate

The compressive strength and splitting tensile strength decreased with increasing recycled aggregate replacement rate. This is consistent with the conclusion of Li [37]. When the replacement rate of recycled aggregate was 50 %, the compressive strength of concrete decreased by 9.5 %, while the splitting tensile strength of concrete decreased by 11.2 %. When the replacement rate of recycled aggregate was 100 %, the compressive strength of concrete decreased by 25.0 %, while the splitting tensile strength of concrete decreased by 21.7 %. There are two reasons for this situation: on the one hand, the damage and cracks that may occur during the crushing process of recycled coarse aggregate, leading to a decrease in aggregate performance, thereby reducing the mechanical properties of concrete [38]. On the other hand, there are three interface transition zones (the interface transition zone between old cement mortar and aggregate, the interface transition zone between new cement mortar and aggregate, and the interface transition zone between new cement mortar and old cement mortar) in recycled concrete: the interface between recycled aggregate and new mortar, the interface between recycled aggregate and old mortar, and the interface between new and old mortar. There are many weak areas inside the concrete, which are more prone to damage when subjected to external loads [39].

3.3.2. Effect of fiber content on mechanical properties

The compressive strength and splitting tensile strength of recycled aggregate concrete with different fiber contents are shown in Fig. 6 and Fig. 7, respectively.

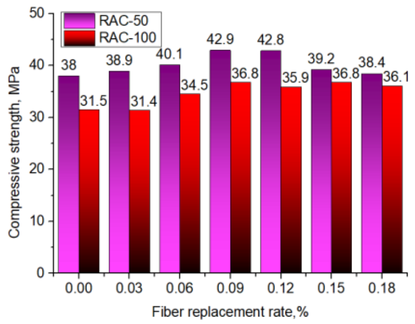


Fig. 6. Compressive strength with different fiber contents

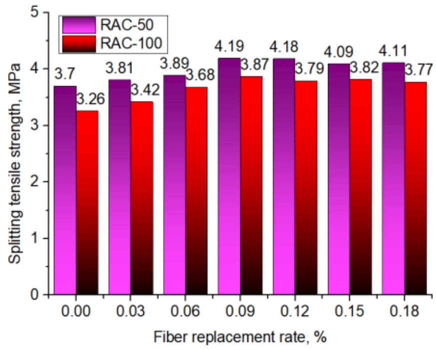


Fig. 7. Splitting tensile strength with different fiber contents

The compressive strength and splitting tensile strength of recycled aggregate concrete showed a trend of first increasing and then decreasing with increasing fiber content. When the fiber content was 0.09 %, the compressive strength and tensile strength of recycled aggregate concrete were optimal. However, after the fiber content exceeded 0.09 %, the decrease in the splitting tensile strength of recycled aggregate concrete was not significant. When the replacement rate of recycled aggregate was 50 %, the compressive strength of concrete decreased by 12.9 %, while the splitting tensile strength of concrete decreased by 13.2 %. When the replacement rate of recycled aggregate was 100 %, the compressive strength of concrete decreased by 16.8 %, while the splitting tensile strength of concrete decreased by 18.7 %. This is consistent with the conclusion drawn by Ghosni [40], that when the fiber content in concrete exceeds 1.0 %, its compressive strength is lower than that of concrete without fibers.

The reason for this result is as follows: the addition of fibers inhibits the development of cracks in recycled aggregate concrete, thereby improving the compressive strength of concrete. However, when the fiber content is too large, it reduces the uniformity and compactness of the concrete and instead reduces the compressive strength of the concrete [41].

Fibers play a role in strengthening steel bars on the splitting surface of concrete. When the specimen cracks, fibers can effectively suppress the development of cracks, thereby improving the ductility of concrete and thereby enhancing the splitting tensile strength of concrete. Even the disordered distribution of fibers can still inhibit the development of cracks. Therefore, when the fiber content exceeds 0.09 %, the decrease in the splitting tensile strength of concrete is not significant [42].

3.2. Bonding performance

3.2.1. Bond strength

The ultimate bond strength between recycled concrete and rebar is shown in Fig. 8.

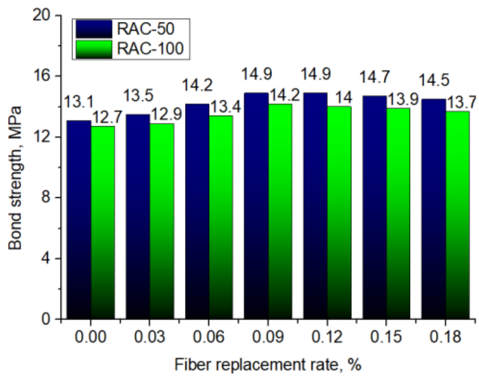


Fig. 8. Ultimate bond strength between recycled concrete and rebar

The bond strength of recycled concrete pullout specimens with fiber was higher than that of recycled concrete pullout specimens without fiber. The maximum improvement in bonding performance between recycled concrete and rebars with a 50 % recycled aggregate replacement rate is 13.7 % (when the fiber content is 0.09 % and 0.12 %), and the maximum improvement in bonding performance between recycled concrete and rebars with a 100 % recycled aggregate replacement rate is 11.8 % (when the fiber content is 0.09 %). This is because the addition of fibers can improve the mechanical properties of concrete and thereby enhance its bonding performance with rebar, generating a gripping force on the steel bars. With the larger elastic modulus and tensile strength of fibers, energy is consumed to improve the ultimate bonding strength of the recycled concrete pullout specimen [43].

The bond strength between recycled concrete and rebar showed a trend of first increasing and then decreasing with increasing fiber content, but the degree of decrease was not significant. This is consistent with the viewpoint proposed by Gao [44] This is similar to the change law of concrete splitting tensile strength. This is because too much fiber will increase the internal defects of concrete to a certain extent, so it will lead to a reduction in bond performance. However, the disordered distribution of fibers can still inhibit the development of cracks, so the decline is not significant. When the fiber content was 0.09 %, 0.12 %, 0.15 and 0.18, the bond strength of the concrete with 50 % recycled aggregate content was 14.9 MPa, 14.9 MPa, 14.7 MPa and 14.5 MPa, respectively; the bond strength of concrete with 100 % recycled aggregate content was 14.2 MPa, 14.0 MPa, 13.9 MPa and 13.7 MPa, respectively.

3.2.2. Slip

The slip between the recycled concrete and rebar is shown in Fig. 9. The slip of recycled concrete pullout specimens with fiber was lower than that of recycled concrete pullout specimens without fiber. When the recycled aggregate replacement rate was 50 %, the slip of the pullout specimens with 0.09 % fibers increased by 8.6 % compared to that without fibers. When the recycled aggregate replacement rate was 100 %, the slip of the pullout specimens with 0.09 % fibers increased by 11.6 % compared to that without fibers. The reason is that the addition of fibers increased the mechanical properties of the concrete, increased its constraint on the steel bars, and thus limited the slip of the steel bars [44].

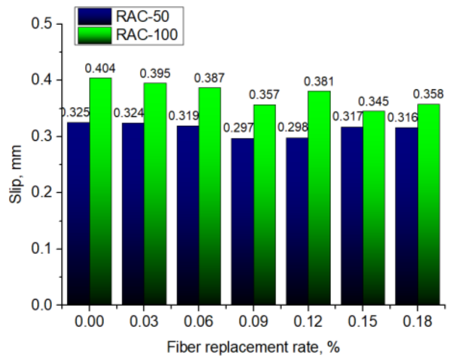


Fig. 9. Slip between recycled concrete and rebar

In addition, as the fiber content increased, the slip between recycled concrete and rebar first decreased and then increased. This is because when the fiber content is greater than a certain degree, the strength of concrete shows a downward trend, which affects its constraint on steel bars, leading to an increase in bond slip [45].

3.3. Relationship between bond strength and mechanical properties.

The relationships between the bond strength of the pullout specimens and the mechanical properties are shown in Fig. 10 and Fig. 11, respectively. When the replacement rate of recycled aggregate was 100 %, the linear correlation between bond strength and concrete mechanical properties (compressive strength and splitting tensile strength) was good, with fitting coefficients R^2 of 0.9474 and 0.9513, respectively. When the replacement rate of recycled aggregate was 50 %, the linear correlation between bond strength and concrete splitting tensile strength was good, with a fitting coefficient of R^2 of 0.9380. However, the linear correlation with the concrete compressive strength was poor, with a fitting coefficient of R^2 of 0.4705. Overall, the splitting tensile strength of concrete could better reflect the bond strength between concrete and rebar because concrete mainly bears tensile force when subjected to a pullout load. Therefore, improving the splitting compressive strength of concrete was one of the key factors in improving the bonding performance between concrete and rebar.

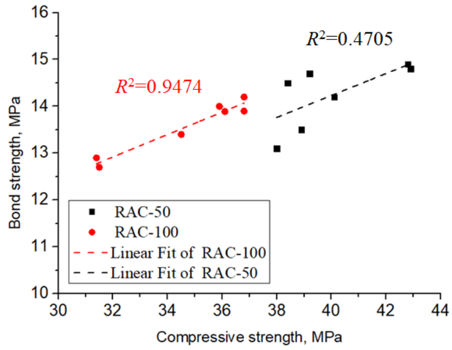


Fig. 10. Relationship between the bond strength and compressive strength

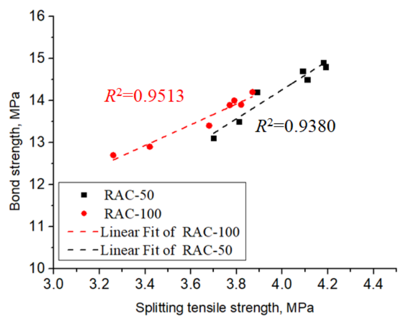


Fig. 11. Relationship between the bond strength and splitting tensile strength

3.4. Nonlinear analysis of mechanical properties and bonding performance.

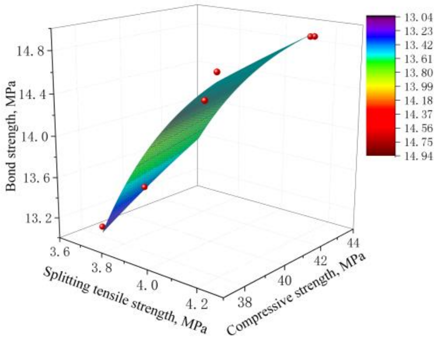
The fitting surface between the bond strength, compressive strength, and splitting tensile strength of recycled concrete is shown in Fig. 12. The nonlinear relationship between the bond strength, compressive strength, and splitting tensile strength of recycled concrete is shown in Eq. 1 and Eq. 2 (x represents the splitting tensile strength (MPa); y represents compressive strength (MPa); z represents the bonding strength (MPa):

RAC-50:

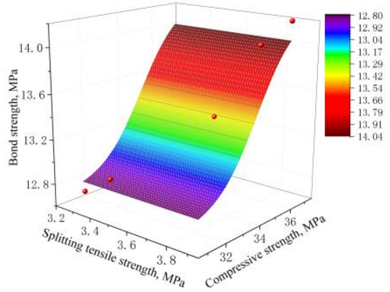
$$z = 15.62579 - 57592.52117 e^{\left(-\frac{x}{0.47075} - \frac{y}{17.66398}\right)}; \tag{1}$$

RAC-100:

$$z = 12.73594 + \frac{1.51868}{\left[1+\left(\frac{x}{9.875e42}\right)^{1.96847e46}\right]\left[1+\left(\frac{y}{34.77358}\right)^{-30.97212}\right]} \tag{2}$$



a



b

Fig. 12. Fitting surface between bond strength, compressive strength, and splitting tensile strength: a – RAC-50; b – RAC-100

4. CONCLUSIONS

1. The compressive strength and splitting tensile strength decreased with increasing recycled aggregate replacement rate. The compressive strength and splitting tensile strength of recycled aggregate concrete showed a trend of first increasing and then decreasing with increasing fiber content.
2. The bond strength of recycled concrete pullout specimens with fiber was higher than that of recycled concrete pullout specimens without fiber, while the slip of recycled concrete pullout specimens with fiber was lower than that of recycled concrete pullout specimens without fiber.
3. The bond strength showed a trend of first increasing and then decreasing with increasing fiber content, but the degree of decrease was not significant. The slip showed a trend of first decreasing and then increasing with increasing fiber content.
4. Compared to the compressive strength of concrete, the splitting tensile strength could better reflect the bonding strength between concrete and rebar.
5. The nonlinear relationship between the bond strength, compressive strength, and splitting tensile strength of recycled concrete was established.

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