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ARTICLE

Influence of Different Fibers on the Bonding Performance between Recycled Aggregate Concrete and Steel Bars

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ABSTRACT: This paper analyzes the influence of different fibers (polypropylene fibers and basalt fibers) and fiber contents (0%–0.20%) on the bonding performance between recycled coarse aggregate concrete and steel bars. The results show that the addition of recycled aggregates can reduce the fluidity of concrete, whereas the addition of fibers can further reduce the fluidity of concrete. The addition of fibers can effectively improve the mechanical properties of concrete (polypropylene fiber can increase compressive strength and splitting tensile strength by 7.80% and 6.09%, respectively, while basalt fiber can increase compressive strength and splitting tensile strength by 8.78% and 8.31%, respectively), but excessive fiber content can actually reduce the mechanical properties of concrete. The addition of fibers can enhance the bond strength between recycled concrete and steel bars and limit the relative slip between recycled concrete and steel bars, thereby improving the bond performance. The improvement effect of basalt fibers on the mechanical and bonding properties of recycled concrete is superior to that of polypropylene fibers. The correlation between the bond strength between fiber-reinforced recycled concrete and steel bars and the splitting tensile strength of recycled concrete is better, and a calculation model for the bond strength between fiber-reinforced recycled concrete and steel bars is constructed on the basis of the splitting tensile strength as the mechanical performance index. This study can provide a basis for the application of fiber-reinforced recycled concrete technology in engineering.

KEYWORDS: Recycled aggregate concrete; basalt fiber; polypropylene fiber; mechanical performance; bonding performance

1 Introduction

With the acceleration of urbanization and the continuous promotion of infrastructure construction, the demand for concrete materials in the construction industry continues to grow, generating a large amount of construction waste. For example, in China, the annual generation of construction waste has exceeded 2 billion tons, of which waste concrete accounts for a considerable proportion [1]. The traditional methods of disposing of construction waste involve landfilling and stacking, which not only consume a large amount of land resources but also cause severe pollution to the environment [2,3]. In this context, recycled concrete technology has emerged as an important way to achieve the resource utilization of construction waste [4]. However, defects such as old mortar and internal microcracks attached to the surface of recycled aggregates [5] have led to poor workability, low mechanical properties, and insufficient bonding performance with steel bars in recycled concrete, severely limiting its promotion and application in practical engineering [6,7].

To improve the performance defects of recycled concrete, scholars at home and abroad have tried various technical methods, among which fiber reinforcement technology has received widespread attention because of its significant strengthening effect [8,9]. The addition of fibers can form a three-dimensional network structure inside concrete, effectively suppressing the propagation of cracks and improving the toughness and durability of concrete [10,11]. The commonly used fiber types currently include steel fibers, polypropylene fibers, basalt fibers, etc. Different types of fibers have significant differences in performance characteristics and reinforcement mechanisms [12]. High modulus fibers directly enhance load-bearing capacity through elastic bridging, while low modulus fibers improve deformation ability through plastic deformation. At the same time, the quality of interface bonding determines the efficiency of stress transmission, and geometric features affect the effectiveness of spatial distribution. Therefore, in order to meet the different performance requirements of recycled concrete, it is necessary to choose appropriate fiber types.

In concrete structures, the bonding performance between steel bars and concrete is a key factor in ensuring their collaborative work and joint force bearing [13,14]. Good bonding performance not only ensures the full utilization of steel reinforcement strength but also effectively controls crack width, improving the safety and durability of the structure [15]. However, the bonding performance between recycled concrete and steel reinforcement is generally lower than that of ordinary concrete, which has become an important bottleneck restricting the application of recycled concrete [16,17].

Polypropylene fibers are commonly used to improve the properties of civil engineering materials because of their low cost, alkali resistance, and good dispersibility [18,19]. Ali Boucetta et al. [20] systematically tested the effects of different lengths of polypropylene fibers on the mechanical properties of recycled concrete. The results revealed that 18 mm polypropylene fibers with a volume fraction of 0.2% increased the splitting tensile strength of recycled concrete by approximately 15% and significantly suppressed shrinkage cracks. Wang et al. [21] reported that when the content of recycled polypropylene fibers was 1.5%, the axial tensile strength of recycled concrete reached its peak, which was 21.14% higher than that of recycled concrete without fibers; however, after the content of polypropylene fibers increased to 2%, the strength decreased, showing a “first increase and then decrease” characteristic. Liu et al. [22] compared the mechanical properties of recycled coarse aggregate mixed with fibers with those of ordinary recycled coarse aggregate. The experimental results revealed that when the polypropylene (PP) fiber content was 3 kg/m, the bending strength increased by 12%. When the fiber content increased to 9 kg/m, the occurrence of fiber agglomeration led to a weakening of the interfacial properties, ultimately resulting in a 6% decrease in the bending strength of the sample. When polypropylene fibers are used to strengthen recycled concrete, the fiber content needs to be controlled within a certain range.

Basalt fibers, as a new type of inorganic nonmetallic material, have excellent properties, such as high strength, high elastic modulus, high temperature resistance, acid and alkali corrosion resistance [23,24], and low cost, and are widely used in the field of concrete reinforcement [25]. Wu et al. [26] conducted experimental research on the influence of basalt fibers on the dynamic and mechanical properties of concrete, as well as the relationship between the two. Taha et al. [27] studied the bending performance of basalt fiber-reinforced recycled concrete beams and analyzed the improvement effect of fibers on the interface transition zone. Through beam bending tests, Wei et al. [28] comprehensively evaluated the improvement effect of basalt fibers on the toughness and deformation performance of concrete. Gao et al. [29] established a theoretical model for the compressive strength of basalt fiber-reinforced concrete on the basis of microstructure analysis and revealed its reinforcement mechanism.

In order to widely apply recycled concrete in building structures, many scholars have studied the calculation model of the bond performance between recycled concrete and steel bars. Hoque et al. [30] established a bond strength calculation model for recycled concrete based on the AS 3600 Australian standard model [31]. Seara-Paz et al. [32] proposed a formula for predicting the bond strength between recycled concrete and steel reinforcement based on the Model Code-2010 [33] specification. Xiao and Falkner [34] proposed the establishment of a bond slip relationship model between recycled concrete and steel reinforcement. Huang et al. [35] established a predictive model for fiber-reinforced concrete.

Thus it can be seen, existing research has mostly focused on the influence of a single fiber type on mechanical properties, lacking systematic comparison between basalt fibers and polypropylene fibers in improving the bonding performance of recycled concrete. Furthermore, the determination of the optimal fiber content and its influence on bond-slip behavior remain unclear, and there is a lack of theoretical models capable of quantitatively predicting the bond strength between fiber-reinforced recycled concrete and steel reinforcement. Therefore, this study systematically investigated the influence of different fiber types and contents on the workability, mechanical properties, and bond performance of recycled concrete with steel bars and established a calculation model for the bond strength between fiber-reinforced recycled concrete and steel bars.

2 Experiment

2.1 Materials and Mix Proportions

The materials for preparing concrete mainly include cement, sand, water, stones, and fibers. The cement used is 42.5 P Portland cement produced by Huaxin Nantong Cement Co., Ltd. Its 3 d compressive strength and 28 d compressive strength are 19 and 52.5 MPa, respectively. The 3 d flexural strength and 28 d flexural strength are 4.5 and 7.5 MPa, respectively. The initial setting time is 240 min, and the final setting time is 320 min. The sand is natural river sand with a fineness modulus of 2.7, an apparent density of 2500 $kg \cdot m^{-3}$, and a mud content of 2.3%. The water used is laboratory tap water. The stones are divided into natural coarse aggregates (NCA) and recycled coarse aggregates (RCA), as shown in Fig. 1), with particle sizes ranging from 5–31.5 mm. The performance indicators are shown in Table 1. The reinforcing fibers selected are polypropylene fibers and basalt fibers (as shown in Figs. 2 and 3), and their performance indicators are shown in Table 2. The tensile reinforcement used for the bond performance test between the concrete and steel was HRB400 deformed steel bars with a yield strength of 505 MPa and a diameter of 20 mm; the stirrups were HPB300 plain steel bars with a yield strength of 350 MPa and a diameter of 8 mm.

Figure 1: Recycled coarse aggregates.

Table 1: Performance indicators of the coarse aggregate.

Performance Indicators	Natural Coarse Aggregate	Recycled Coarse Aggregate
Sediment percentage	0.8%	1.9%
Water absorption rate	1.3%	5.2%
Apparent density	2780 kg·m^{-3}	2430 kg·m^{-3}
Crushing index	7.9%	14.2%

Figure 2: Polypropylene fibers.

Figure 3: Basalt fibers.

Table 2: Performance indicators of the reinforced fibers.

Performance Indicators	Polypropylene Fiber	Basalt Fiber
Density	950 kg·m^{-3}	2700 kg·m^{-3}
Breaking strength	760 MPa	1850 MPa
Breaking elongation	16.5%	3.0%
Elastic modulus	4.1 GPa	95 GPa

2.2 Concrete Mix Design

The target strength grade of the recycled concrete is C30, which is designed according to the mix ratio of concrete specified in JGJ55-2019 [36]. In previous research, the fiber length was uniformly set at 18 mm, with fiber volume fractions of 0%, 0.05%, 0.10%, 0.15%, and 0.20%, to investigate the effects of varying the fiber content. To minimize fiber agglomeration during concrete mixing, fibers are added in batches with 1-min mixing after each addition to ensure uniform dispersion in the concrete. The mix ratios for each group of concrete are shown in Table 3, where N represents ordinary concrete, R represents recycled concrete, P represents polypropylene fibers, B represents basalt fibers, and 0.05, 0.10, 0.15, and 0.20 indicate the fiber content. Owing to the significant difference in water absorption between recycled aggregates and ordinary aggregates (the water absorption of recycled coarse aggregates is 4 times greater than that of ordinary coarse aggregates), all coarse aggregates are saturated to a surface-dry state before being poured to mitigate their impact.

Table 3: Concrete mix.

Type	NA	RA	Sand	Water	Cement
N	1085	0	674	187	415
R-P-0.00	0	1085	674	187	415
R-P-0.05	0	1085	674	187	415

(Continued)

Table 3 (continued)

Type	NA	RA	Sand	Water	Cement
R-P-0.10	0	1085	674	187	415
R-P-0.15	0	1085	674	187	415
R-P-0.20	0	1085	674	187	415
R-B-0.00	0	1085	674	187	415
R-B-0.05	0	1085	674	187	415
R-B-0.10	0	1085	674	187	415
R-B-0.15	0	1085	674	187	415
R-B-0.20	0	1085	674	187	415

2.3 Concrete Sample Design and Experimental Plan

2.3.1 Concrete Samples

The samples used for compressive strength testing and splitting tensile strength testing were cubic samples with dimensions of 150 mm × 150 mm × 150 mm, whereas the concrete samples used for tensile testing were prismatic samples with dimensions of 150 mm × 150 mm × 200 mm. A schematic diagram of the concrete sample used for pull-out testing is shown in Fig. 4.

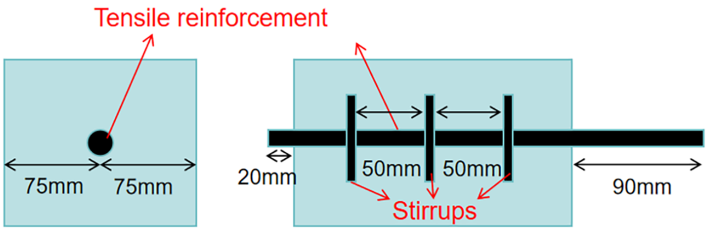


Figure 4: Bond performance test samples.

2.3.2 Experimental Plan

(1) Concrete compressive strength test: After standard curing for 28 days, the sample is placed at the center of the press and loaded at a constant speed of 0.5 MPa/s until failure. The compressive strength of the concrete is obtained by dividing the average maximum load of three samples by the compressive area.

(2) Concrete splitting tensile strength test: After 28 days of standard curing, axial tension is applied to the sample on a universal testing machine, the maximum load at the middle of the sample when it fractures is recorded, and the load is divided by the fracture cross-sectional area to obtain the axial tensile strength. If the fracture position deviates from the middle by 1/3, the data are invalid.

(3) Bond performance test (Fig. 5): After standard curing for 28 days, the sample is pulled and loaded at a rate of 1 MPa/min. The slip and load of the steel bars are recorded synchronously throughout the process, and the bond strength is calculated according to Formula (1), where l_a is the embedded length and d is the diameter of the steel bars.

$$\tau = \frac{F}{\pi d l_a} \tag{1}$$

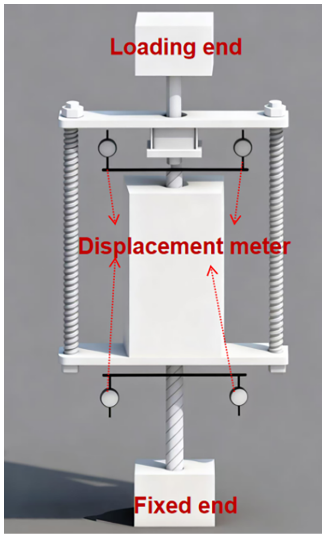


Figure 5: Bond performance test.

3 Results and Analysis

3.1 Slump Analysis

The slump of each group of concrete is shown in Fig. 6. The slump of recycled concrete is significantly lower than that of ordinary concrete, with a slump that is 17.2% lower. The main reasons for this are as follows: (1) the surface of recycled aggregate has attached mortar, which has a higher porosity than natural aggregate does, resulting in a water absorption rate four times greater than that of ordinary concrete, which can absorb more free water and reduce the slump; (2) the crushing process causes microcracks and sharp edges on the surface of the recycled aggregate, increases the internal friction angle, enhances the interlocking effect between particles, and increases the flow resistance; and (3) after water absorption and wetting, a highly viscous transition layer is formed on the surface of the recycled aggregate, which increases the overall consistency of the slurry and reduces its flowability.

Fig. 6 also shows that the slump of recycled concrete decreases with the addition of fibers and gradually decreases with increasing fiber content. When the content of polypropylene fibers reaches 0.2%, the slump of recycled concrete decreases by approximately 28.9%; when the content of polypropylene fibers reaches 0.2%, the slump of recycled concrete decreases by approximately 21.1%. The reasons for this situation are as follows: (1) Fibers are randomly distributed in three dimensions in concrete, forming a network structure that hinders the flow of aggregates and slurry, thereby reducing fluidity; (2) the addition of fibers increases the total surface area of the solid phase, requiring more water to wet the surface, resulting in a decrease in effective free water and a decrease in slump; and (3) fibers improve the cohesion of concrete, making it more difficult to flow, especially at higher dosages.

In addition, when the amount of fiber added is the same, the slump of recycled concrete with basalt fibers added is greater than that of recycled concrete with polypropylene fibers added. When the fiber content is 0.05%, 0.10%, 0.15%, and 0.2%, the slump of recycled concrete with basalt fibers added is 5, 7, 9, and 14 mm greater than that of recycled concrete with polypropylene fibers added, respectively. This is because the surface hydrophilicity of basalt fibers is weaker than that of polypropylene fibers, and they have higher stiffness and are less prone to bending and entanglement, resulting in weaker "scaffolding" and slurry absorption effects and less impact on fluidity.

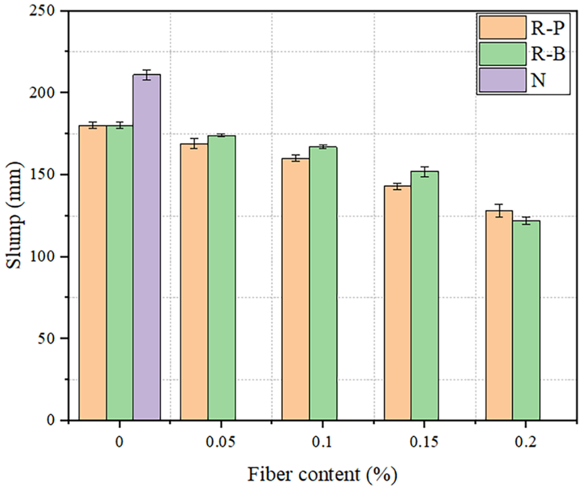


Figure 6: Slump analysis.

3.2 Compressive Strength Analysis

The influence of fibers on the compressive strength of recycled concrete is shown in Fig. 7. Fig. 7 shows that the compressive strength of recycled concrete is significantly lower than that of ordinary concrete, with a strength 18% lower than that of ordinary concrete. This is because (1) the surface of the recycled aggregate is wrapped with old mortar, forming a "secondary interface" between the old mortar and the new mortar. This interface often has high porosity and poor compactness, which can easily lead to stress concentration [37]. (2) During the crushing process of waste concrete, many microcracks are generated, and the crushing index, porosity, and water absorption of the aggregate itself are high. These defects reduce the strength of the aggregate particles [38]. (3) The strength of old mortar attached to recycled aggregates is usually lower than that of fresh mortar, and the elastic modulus is low. Under pressure, the old mortar undergoes significant deformation and cracking, which drives the surrounding new mortar to fail prematurely, resulting in a decrease in overall strength.

Overall, the addition of fibers can enhance the compressive strength of recycled concrete, with a maximum increase of 7.80% (Polypropylene fibers)/8.78 (Basalt fibers), as listed in Table 4. This is because (1) the fibers provide bridging stress across the cracks, inhibiting the cracks from continuing to open and penetrate, thereby delaying the failure process and increasing the maximum load that can be borne; (2) during the process of fiber extraction, it is necessary to overcome interface adhesion and friction, consume a large amount of fracture energy, and transform the failure mode of the matrix from "brittle failure" to "ductile failure"; and (3) the fibers redistribute local high stress to adjacent uncracked areas, reducing the stress concentration caused by the uneven strength of recycled aggregates [39].

However, with increasing fiber content, the improvement effect first tends to increase but then tends to decrease. At this point, when the dosage exceeds a certain threshold, the fibers are difficult to disperse evenly in the mixture and are prone to entangle into bundles, forming "fiber clusters". These aggregates become new weak points and sources of stress concentration within the matrix, initiating microcracks under compression and ultimately weakening its strength.

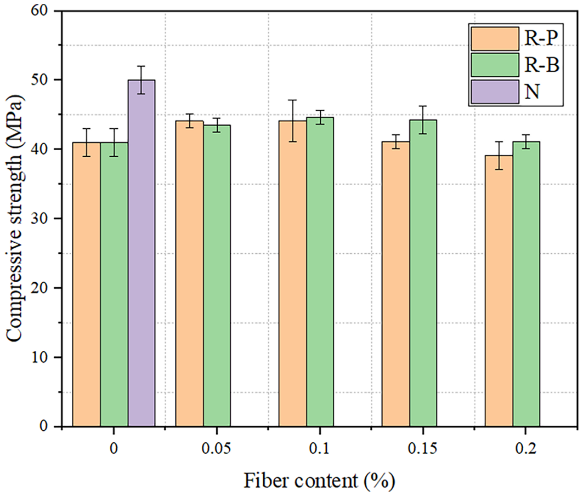


Figure 7: Compressive strength analysis.

Table 4: Comparison between the experimental results and computational results.

Fiber Content	Polypropylene Fibers (MPa)	Improvement Rate (%)	Basalt Fibers (MPa)	Improvement Rate (%)
0	41	–	41	–
0.05	44.1	7.56	43.5	6.10
0.10	44.2	7.80	44.6	8.78
0.15	41.2	0.49	44.3	8.05
0.20	39.1	−4.63	41.2	0.49

When both polypropylene fibers and basalt fibers reach 0.1%, they have the greatest effect on improving the compressive strength of recycled concrete, and the improvement effect weakens after that. However, the weakening effect of basalt fibers is lower than that of polypropylene fibers. In addition, when the contents of polypropylene fibers and basalt fibers are the same, basalt fibers have a better effect on improving the compressive strength of recycled concrete. This is because (1) the elastic modulus of basalt fibers is greater than that of polypropylene fibers, which is more compatible with the cement matrix and can form a high-stiffness bridge at the crack tip, significantly suppressing crack propagation; (2) the splitting tensile strength of basalt fiber monofilaments is greater than that of polypropylene fibers, and basalt fibers have a greater ability to restrict the development of cracks, thereby improving compressive strength; and (3) basalt fibers have a density similar to that of mortar and are not easily floated or agglomerated. However, polypropylene fibers have a low density and are prone to floating into bundles during stirring, resulting in uneven fiber distribution, reduced effective bridging, and decreased reinforcement efficiency.

3.3 Splitting Tensile Strength Analysis

The influence of fibers on the splitting tensile strength of recycled concrete is shown in Fig. 8. Fig. 8 shows that the splitting tensile strength of recycled concrete is significantly lower than that of ordinary concrete, with a splitting tensile strength 5% lower than that of ordinary concrete. This is because recycled aggregates already have many microcracks, resulting in weak tensile strength and making them more prone to becoming crack sources in the tensile zone. Recycled concrete has an interface transition zone with high porosity and poor compactness. When subjected to splitting tension, it first cracks and quickly penetrates along the periphery, reducing the effective bearing area.

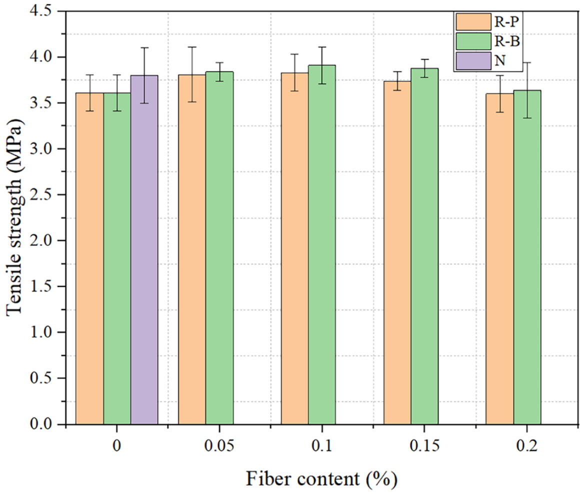


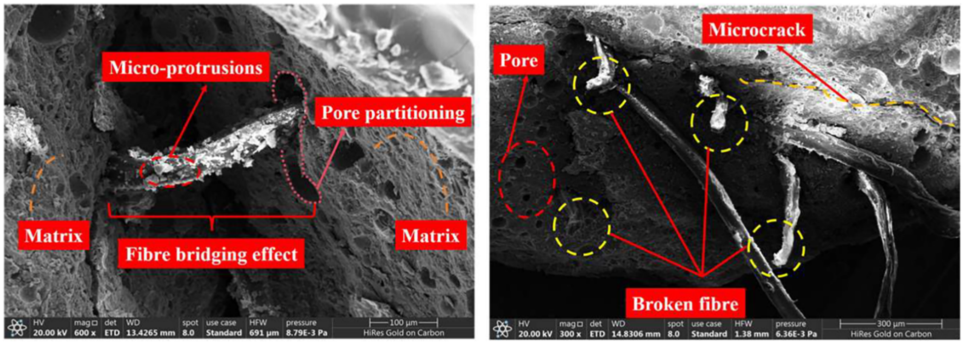
Figure 8: Tensile strength analysis.

The addition of fibers can enhance the splitting tensile strength of recycled concrete (Table 5), with a maximum increase of 6.09% (Polypropylene fibers)/8.31% (Basalt fibers). The reason is that (1) as show in Fig. 9a, when the weak interface around the recycled aggregate cracks, the randomly distributed fibers have a "bridging effect", which pulls both sides of the fibers, causing the cracks to require greater tension to continue expanding, which manifests macroscopically as an increase in tensile stress [40]; (2) as show in Fig. 9b, the energy dissipation during fiber fracture significantly increases the fracture energy, delays crack penetration time, and thus increases the maximum tensile stress that the sample can withstand [40]; and (3) fibers redistribute local high stress to surrounding uncracked areas, reducing the stress concentration caused by defects in recycled aggregates.

In addition, with increasing fiber content, the improvement in the splitting tensile strength first tends to increase but then decreases. When both polypropylene fibers and basalt fibers reach 0.1%, they have the greatest effect on improving the compressive strength of recycled concrete, with 6.09% and 8.31% increases in the splitting tensile strength, respectively.

Table 5: Comparison between the experimental results and computational results.

Fiber Content	Polypropylene Fibers (MPa)	Improvement Rate (%)	Basalt Fibers (MPa)	Improvement Rate (%)
0	3.61	–	3.61	–
0.05	3.81	5.54	3.84	6.37
0.10	3.83	6.09	3.91	8.31
0.15	3.74	3.60	3.88	7.48
0.20	3.6	−0.28	3.64	0.83



(a) (b)

Figure 9: Microstructure of fiber-reinforced recycled concrete.

A comparison of the improvement effects of fibers on the compressive strength and splitting tensile strength of recycled concrete is shown in Fig. 10. The figure shows that both polypropylene fibers and basalt fibers improve the compressive strength better than they improve the splitting tensile strength. When the content of polypropylene fibers (basalt fibers) is 0.05%, 0.1%, and 0.15%, the compressive strength can increase by 7.6%, 7.8%, and 0.5%, respectively (6.1%, 8.8%, and 8.0%), and the splitting tensile strength can increase by 5.5%, 6.1%, and 3.6%, respectively (6.4%, 8.3%, and 7.4%). The reason for this situation is that the fibers act as a hoop to the most lethal vertical interface cracks in recycled concrete under compression, directly increasing the peak compressive stress [28,39]. When under tension, fibers can only play a "connecting" role in transverse cracks and are limited by weak interfaces, resulting in low bridging efficiency and relatively poor improvement effects [39,40].

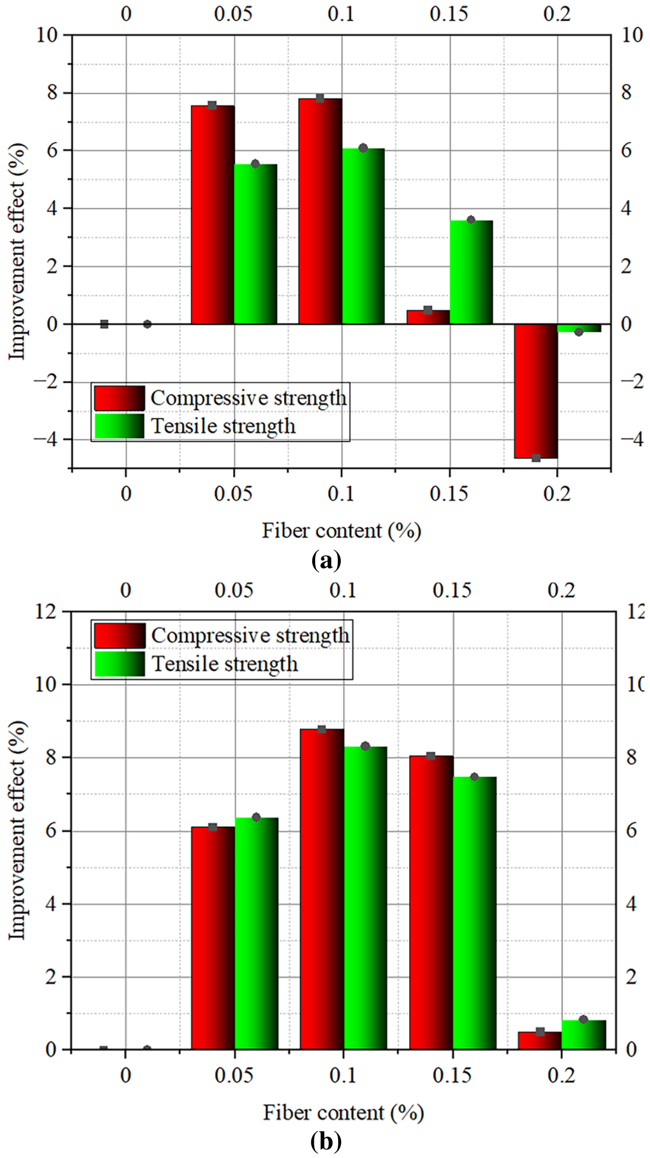
3.4 Bond Performance Analysis

3.4.1 Bond Strength

The influence of fibers on the bond strength between recycled concrete and steel reinforcement is shown in Fig. 11. The addition of fibers improved the bond strength between the recycled concrete and steel bars, with maximum increases of 6.8% (polypropylene fibers) and 8.0% (basalt fibers). Fibers span microcracks, dividing a single main crack into multiple fine cracks, increasing the stress for crack initiation and propagation. After the splitting surface is constrained by fibers, the concrete in front of the steel rib no longer instantly collapses, and the peak bond stress increases accordingly. The fibers form a three-dimensional network in the splitting zone in front of the steel ribs. When the concrete expands outward, the fibers are pulled and provide lateral restraint in the opposite direction, allowing the residual bite and friction after cracking to continue to bear external loads. In addition, fibers can enhance the mechanical properties of recycled concrete, thereby improving its ability to constrain steel bars and enhance bond strength. This is consistent with the trend of changes in compressive strength and splitting tensile strength of recycled concrete. Overall, the improvement effect of fibers on bond strength is slightly lower than the improvement effect of fibers on regenerative mechanical properties. It is because in terms of mechanical properties, fibers directly act inside the concrete matrix, bridging cracks and suppressing expansion to enhance the overall bearing capacity. In terms of bond performance, fibers are difficult to directly strengthen chemical adhesion and mechanical biting force, which are important indicators of bond performance.

However, when the fiber content reaches a certain level, its effect on improving the bond strength between recycled concrete and steel reinforcement weakens and even has adverse effects. When the fiber content reaches 0.2%, the bonding strength decreases by 0.3% (polypropylene fiber) and 0.1% (basalt fiber).

This is because excessive fibers entangle each other during mixing, forming aggregates locally. When the aggregates are located in the high-stress zone in front of the steel ribs, they become the preferred breakthrough for the development of splitting cracks, offsetting the bridging effect that fibers should provide, and the bonding strength begins to decrease [40]. In addition, the total surface area of fibers increases linearly with dosage, requiring more cement slurry to wrap around. When the slurry volume is insufficient, there is a "slurry famine" in the interface area between the steel and the concrete, the filling rate of the rib gaps decreases, and the mechanical biting force decreases.



(a)

(b)

Figure 10: Comparison of improvement effects. (**a**) Polypropylene fiber; (**b**) basalt fiber.

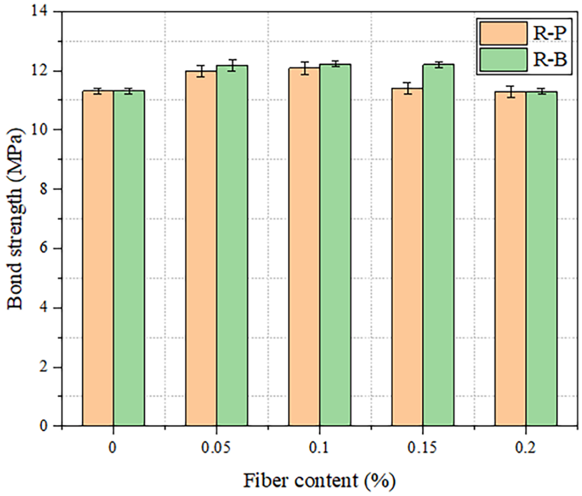


Figure 11: Bond strength analysis.

In addition, the improvement effect of basalt fibers on the bond strength between recycled concrete and steel reinforcement is greater than that of polypropylene fibers. When the content of polypropylene fibers (basalt fibers) is 0.05%, 0.1%, and 0.15%, the compressive strength can increase by 5.9%, 6.8%, and 0.8% (7.7%, 8.0%, and 7.9%), respectively. The obtained pattern is consistent with the improvement effect of fibers on the mechanical properties of recycled concrete. Basalt fibers have higher elastic modulus and tensile strength, and their brittle fracture characteristics enable them to provide stronger bridging constraints when microcracks initiate at the interface between steel reinforcement and recycled concrete; At the same time, basalt fibers have a rough surface and better chemical compatibility with the cement matrix, with high interfacial bonding strength, thereby enhancing the bonding strength. In contrast, polypropylene fibers have a low elastic modulus and mainly play a role in crack resistance and toughening at the interface rather than load-bearing reinforcement. Moreover, their hydrophobic surface has weak bonding with the cement matrix, making it difficult to form an effective stress transmission mechanism. Therefore, the improvement of bonding strength is limited.

3.4.2 Slip

The influence of fibers on the bond slip between recycled concrete and steel bars is shown in Fig. 12. The addition of fibers can reduce the relative slip between recycled concrete and steel bars, with a maximum reduction of 13.6%. The reason is as follows: when the steel bars are under tension, splitting cracks appear in the concrete in front of the ribs. Once the cracks penetrate, the steel bars slip instantly. The fibers divide the main splitting into multiple fine cracks, delaying crack penetration and delaying slip initiation. In addition, the fibers span the cracks and provide closure stress through pull-out resistance, allowing friction and interlocking between crack surfaces to persist. The concrete in front of the steel ribs is not easily crushed or extruded, limiting the development of slip.

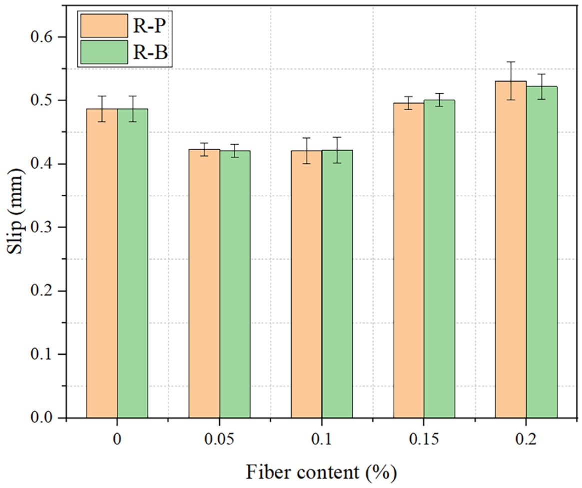


Figure 12: Slip analysis.

However, when the fiber addition reaches a certain level, continuing to add fibers may not further reduce slip and may even lead to a rebound in slip. When the fiber content reaches 0.15% or more, the relative slip between the recycled concrete and steel bars actually increases. At this point, the polypropylene fibers increase the relative slip between the recycled concrete and steel bars by 1.8%, whereas the basalt fibers increase the relative slip between the recycled concrete and steel bars by 2.9%. This is due to the aggregation generated by excessive fibers, which reduces the constraint ability of the concrete on the steel bars, thereby increasing the slip between the steel bars and the concrete.

3.5 Bond Strength Calculation Model

The linear fitting formula for the bond strength between the steel bars and the concrete and the compressive strength of the concrete is as follows (as shown in Fig. 13a):

Polypropylene fiber:

$$F_c = 5.3862\tau - 20.613 \quad R^2 = 0.9046 \tag{2}$$

Basalt fiber:

$$F_c = 3.408\tau + 2.5621 \quad R^2 = 0.9544 \tag{3}$$

where, F_c is the compressive strength; τ is the bond strength.

The fitting formula for the bond strength between the steel bars and the concrete and the splitting tensile strength of the concrete is as follows (as shown in Fig. 13b):

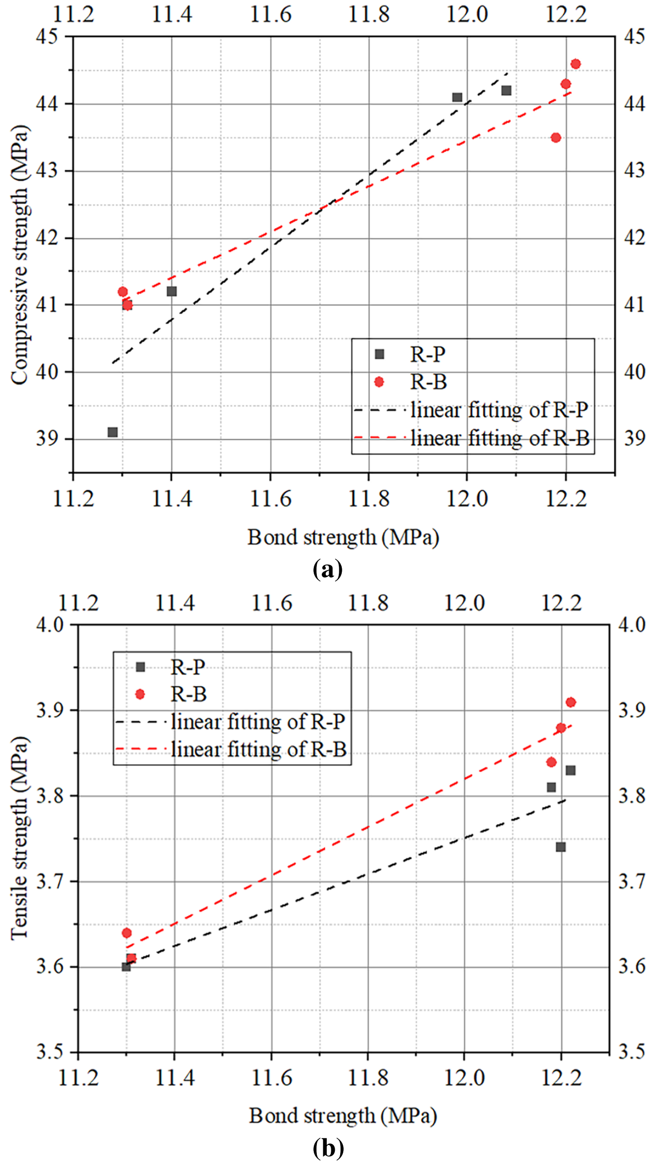
Polypropylene fiber:

$$F_t = 0.2107\tau + 1.222 \quad R^2 = 0.9073 \tag{4}$$

Basalt fiber:

$$F_t = 0.2822\tau + 0.4337 \quad R^2 = 0.9711 \tag{5}$$

where, F_t is the splitting tensile strength.



(a)

(b)

Figure 13: Linear fitting between compressive strength (splitting tensile strength) and bond strength. (**a**) Compressive strength–bond strength; (**b**) splitting tensile strength–bond strength.

By comparison, the linear correlation between the bond strength and splitting tensile strength is greater than the linear correlation between the bond strength and compressive strength. Therefore, the splitting tensile strength can be used as a mechanical performance indicator to calculate the bond strength between recycled concrete and steel bars.

The linear fitting formula between the fiber content and splitting tensile strength is as follows (as shown in Fig. 14):

Polypropylene fiber:

$$F_t = -22.571x^2 + 4.3343x + 3.6231 \quad R^2 = 0.9641 \tag{6}$$

Basalt fiber:

$$F_t = -29.714x^2 + 6.1429x + 3.607 \quad R^2 = 0.9916 \tag{7}$$

where, x is fiber content.

By substituting Formulas (6) and (7) into Formulas (4) and (5), respectively, the calculation model for the bond strength between fiber-reinforced recycled concrete and steel bars can be obtained:

Polypropylene fiber:

$$\tau = \left[\left(-22.571x^2 + 4.3343x + 3.6231\right) - 1.222\right]/0.2107 \tag{8}$$

Basalt fiber:

$$\tau = \left[\left(-29.714x^2 + 6.1429x + 3.607\right) - 0.4337\right]/0.2822 \tag{9}$$

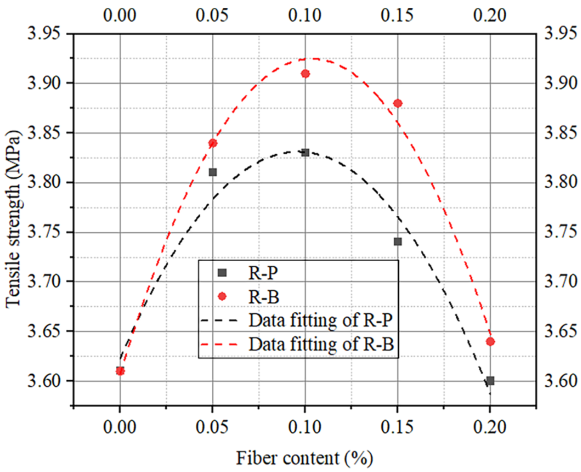


Figure 14: Fitting results of splitting tensile strength and bond strength.

A comparison between the experimental results and the calculated results is shown in Table 6. As shown in Table 6, the calculated results are highly consistent with the experimental results.

Table 6: Comparison between the experimental results and computational results.

Type	Experimental Results (τ_e)	Computational Results (τ_c)	$\tau_c/\ \tau_e$
R-P-0.00	11.31	11.4	1.008
R-P-0.05	11.98	12.16	1.015
R-P-0.10	12.08	12.08	1.000
R-P-0.15	11.4	12.07	1.059
R-P-0.20	11.28	11.23	0.996
R-B-0.00	11.31	11.24	0.994
R-B-0.05	12.18	12.07	0.991
R-B-0.10	12.22	12.37	1.012

(Continued)

Table 6 (continued)

Type	Experimental Results (τ_e)	Computational Results (τ_c)	τ_c/ τ_e
R-B-0.15	12.20	12.14	0.995
R-B-0.20	11.30	11.39	1.008

To verify the accuracy of the model, the experimental data from Yang et al. [41] were input into Formula (8), and the calculated results were compared with the experimental results from Yang et al. [41], as shown in Table 4. As shown in Table 7, the bond strength calculation model proposed in this paper can accurately predict the bond strength.

Table 7: Model validation comparison.

Fiber Content	Experimental Results (τ_e) [35]	Computational Results(τ_c)	τ_c/ τ_e
0	11.40	11.30	1.008
0.06	12.24	11.58	1.057
0.08	12.36	13.17	0.938
0.1	12.38	13.02	0.951
0.12	12.32	12.59	0.979
0.15	12.07	11.21	1.077

4 Conclusions

(1) The addition of recycled aggregates reduces the fluidity of concrete, whereas the addition of fibers further reduces the fluidity of concrete. Therefore, to ensure good workability of the concrete, it is necessary to control the fibers within a certain range.

(2) The addition of recycled aggregates can reduce the mechanical properties of concrete, whereas the addition of fibers can effectively improve the mechanical properties of concrete. However, excessive fiber content can actually reduce the mechanical properties of concrete;

(3) The addition of fibers can improve the bond performance between recycled concrete and steel bars, which is reflected mainly in the increase in bond strength and the limitation of bond slip, but the amount of fibers added needs to be controlled within a certain range.

(4) At the same dosage, the improvement effect of basalt fibers on the mechanical and bonding properties of recycled concrete is greater than that of polypropylene fibers.

(5) A calculation model for the bond strength between polypropylene fibers and basalt fiber-modified recycled concrete and steel reinforcement was constructed, and its reliability was verified.

The research results of this paper can provide a basis for the application of fiber-reinforced recycled concrete in engineering, but the following issues need to be noted: (1) In order to reduce the impact of high water absorption rate of recycled aggregates, the “saturated surface dry” method is used to treat recycled aggregates. In practical engineering, the construction process can be simplified by adding additional water, but this may have a certain degree of impact on the strength of concrete (due to the slightly higher water absorption rate of recycled aggregates, the strength of concrete slightly decreases); (2) To ensure the best performance improvement effect on recycled concrete, it is recommended to prioritize the use of basalt fiber with a dosage of 0.1%, followed by the use of polypropylene fiber with a dosage of 0.1%; (3) According to relevant research, whether using basalt fiber or polypropylene fiber, it is recommended to control the fiber length between 16–19 mm to ensure better improvement effect; (4) The calculation model for the bond strength between recycled concrete and steel bars established in this article is obtained under fixed fiber types (polypropylene fiber and basic fiber) and fiber content (0.05%, 0.10%, 0.15%, and 0.20%). If the fiber type and fiber content change, it will lead to changes in the bond strength. Therefore, it is recommended to verify the calculation results of bond strength through pre experiments when there are significant changes in fiber type and fiber content, in order to ensure the safety of the structure.

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