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Uniaxial Compression Performance of Recycled Brick Aggregate Concrete with Basalt Fibers and its Bonding Performance with Steel Bars

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This paper systematically analyzes the basic mechanical properties, uniaxial compression performance, and bonding performance of recycled brick aggregate concrete treated with basalt fibers with steel bars. The results show that the addition of recycled brick aggregate not only reduces the basic mechanical properties and uniaxial compression performance of recycled brick aggregate concrete but also reduces the bonding performance between concrete and steel bars. The addition of basalt fiber can increase the cube compressive strength and splitting tensile strength of recycled brick aggregate concrete by 18.66 % and 22.68 %, respectively, and increase the uniaxial compressive stress and strain by 20.59 % and 11.11 %, respectively. Basalt fiber can effectively improve the bonding performance between recycled brick aggregate concrete and steel bars, increasing the peak bonding strength by 1.17 MPa and reducing the peak slip by 0.136 mm. A calculation model for the uniaxial compressive stress of basalt fiber recycled brick aggregate concrete and a calculation model for the bond strength between basalt fiber recycled brick aggregate concrete and steel bars were constructed.

Keywords: recycled brick aggregate, uniaxial compression performance, basalt fiber, bonding performance, steel bar.

1. INTRODUCTION

During the process of urban modernization, billions of tons of building demolition waste are generated annually, which exacerbates environmental pollution and adds to stacking pressure with a large amount of construction waste. Recycled aggregate concrete achieves the dual benefits of waste disposal and natural resource protection through the resource utilization of construction waste. Although the compressive strength, splitting tensile strength, and elastic modulus of recycled aggregate concrete have decreased compared with those of natural aggregate concrete, its mechanical properties can still meet practical engineering needs, such as those of road substrates [3], prefabricated components [4], and building load-bearing structures [5], through various improvement methods (such as fiber reinforcement).

Recycled brick aggregate concrete faces more complex performance issues because of its differentiated material properties. Owing to the porous structure of recycled brick aggregate, the density of recycled brick aggregate concrete is significantly lower than that of natural aggregate [6, 7], and high porosity leads to an increase in water absorption [8, 9]. Therefore, excessive drying of recycled brick aggregate can cause rapid loss of slump [10]. In addition, when the replacement rate of recycled brick aggregate exceeds 30 %, the compressive strength of concrete decreases by more than 20 % [11]. When the replacement rate of recycled brick aggregate reaches 100 %, its peak compressive stress and elastic modulus are reduced by 40 % and 50 %, respectively, compared with those of natural aggregate concrete [12]. The failure mode of tensile strength is similar to that of natural aggregate concrete [13, 14], but its overall deterioration is due mainly to the high water absorption of the porous structure of recycled brick aggregate [15]. Research has shown that basalt fiber (BF), steel fiber (SF), polyvinyl alcohol fiber (PAF), carbon fiber (CF), and other materials can improve compressive strength and toughness by suppressing microcracks [16 – 18]. Although steel fibers (SFs) improve tensile performance, they are prone to corrosion [19]. Polyvinyl alcohol fiber (PAF) has weak bonding with large aggregates because of its short fiber characteristics [20], and the high cost of carbon fiber (CF) limits its application [21]. Compared with other materials, basalt fiber (BF) has the advantages of a high elastic modulus, high tensile strength, and low cost [22], which can significantly improve the performance of recycled concrete, but its dosage needs to be controlled within a reasonable range [23].

Most scholars have conducted systematic research on the mechanical characteristics of recycled aggregate concrete at the macro level. The stress-strain curve of recycled aggregate concrete shows that its elastic modulus and peak stress are lower than those of natural aggregate concrete, and the descending section of the curve is steeper, with more significant brittleness [24]. To improve its

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performance, the old mortar on the surface of recycled aggregates is generally removed by mechanical grinding, presoaking or acid treatment [25], or the old mortar interface is strengthened by soaking in volcanic ash solution or the carbonization method [26]. In addition, the addition of fibers can significantly improve the mechanical properties of recycled aggregate concrete, effectively alleviating material brittleness deterioration by suppressing crack propagation. Yuan et al. [27] studied the uniaxial compression constitutive relationship of basalt fiber-reinforced recycled brick aggregate concrete. Based on the Weibull distribution and Lemaitre strain theory, a segmented model was used to describe the stress–strain response from the elastic stage to the peak and softening stages. The model parameters are nonlinearly coupled with the replacement rate of recycled brick aggregates and the content of basalt fibers. The propagation of microcracks can be quantified by combining the damage model with the Weibull distribution. The results revealed that when the replacement rate of recycled brick aggregate was 40 % and the basalt fiber content was 2 kg/m^3, the elastic modulus of the recycled brick aggregate significantly improved. Microscopic analysis confirmed that basalt fibers could suppress cracks and strengthen the interface transition zone.

The substitution rate of recycled aggregates has a significant effect on the bonding performance between recycled concrete and steel bars. Research has shown that as the proportion of recycled brick aggregate substitution increases, the bonding strength tends to increase, but a high substitution rate decreases the interfacial performance. Zhao et al. [28] reported that there was no significant difference in the ultimate bond strength between recycled aggregate concrete samples and natural aggregate concrete samples containing stirrups, indicating that stirrups can effectively bridge the discreteness of their bond characteristics. Through experiments on the bond performance between concrete and steel bars with 20 %, 50 %, and 100 % replacement rates of recycled brick aggregates, Sindy et al. [29] reported that the bond strength is nonlinearly correlated with the replacement rate of recycled brick aggregates. The change in bond performance is not significant at a 50% replacement rate of recycled brick aggregates, whereas its anti-slip performance significantly deteriorates at a 100% replacement rate. Hameed et al.'s study also confirmed the above conclusion [30] that a 50 % replacement rate of recycled brick aggregate has no significant effect on the bond performance between concrete and steel reinforcement, but its degradation degree is significant when the replacement rate is 100 %. Adding steel fibers and polypropylene fibers can partially compensate for mechanical losses and improve interfacial toughness. In addition, the bonding performance between basalt fiber-reinforced recycled brick aggregate concrete and steel bars is controlled by the recycled brick aggregate replacement rate and the fiber content. Research has shown that the replacement rate of recycled brick aggregates is too high, leading to weak interface transition zones and a 10 % – 15 % decrease in steel bond strength due to increased porosity [28, 29]. The addition of 0.15 % – 0.2 % basalt fibers can increase the bonding strength by 8 % – 12 % and delay the occurrence of slip by bridging cracks and dispersing stress [22]. Microscopic analysis revealed that basalt fibers form a dense network in the interfacial transition zone, suppressing microcrack propagation and increasing the interfacial toughness [17, 18].

On this basis, this paper systematically analyzes the basic mechanical properties, uniaxial compression performance, and bonding performance of recycled brick aggregate concrete with steel bars and basalt fibers. The influence of basalt fibers on the mechanical properties of recycled concrete and its bonding performance with steel bars is explored, and calculation models for the uniaxial compression strength and bonding strength of recycled brick aggregate concrete samples are established.

2. EXPERIMENTAL DETAILS

2.1. Raw materials

The natural coarse aggregate used in this experiment is natural crushed stone, and the recycled coarse aggregate is crushed and cleaned recycled brick aggregate. Its basic physical properties were measured according to JGJ52-2006 [31] and are shown in Table 1. Natural river sand with a fineness modulus of 2.8 and an apparent density of 2850 kg/m^3 was used as the fine aggregate. The cement used is ordinary Portland cement (P.O42.5), and according to GB175-2007 [32], the 3-day compressive strength/3-day flexural strength are 19.4 MPa and 4.2 MPa, respectively; the 28-day compressive strength and 28-day flexural strength are 45.5 MPa and 7.4 MPa, respectively. The diameter of the basalt fibers is 11 μm, the length is 6 mm, the elastic modulus is 95 GPa, and the tensile strength is 2800 MPa. The load-bearing steel bars are made of HRB400 grade deformed steel bars, and the stirrups are made of HPB300 grade smooth round steel bars. The basic mechanical properties of the samples are shown in Table 2.

Table 1. Properties of coarse aggregate

Type	Particle size range, mm	Apparent density, kg/m^3	Crushing index, %	Water absorption, %
Natural coarse aggregate	5 – 40	2650	9.1	1.6
Recycled brick aggregate	5 – 40	2310	31.5	14.9

Table 2. Properties of the steel bars

Type	Ultimate strength, MPa	Yield strength, MPa	Elastic modulus, GPa	Elongation, %
HRB400	543	490	210	16.2
HPB300	435	385	210	21.5

2.2. Concrete mixture design

Referring to JGJ55-2011[33], the mix proportion of concrete is designed, and the recycled brick aggregate is replaced by volume. The design variables for concrete are the volume substitution rate of recycled brick aggregates and the amount of basalt fiber added. The mix proportions of each group of concrete are shown in Table 3.

Table 3. Mix proportion

Type	Cement, kg/m^3	Water, kg/m^3	Fine aggregate, kg/m^3	Natural coarse aggregate, kg/m^3	Recycled brick aggregate, kg/m^3	Basalt fiber content, %
NAC-0	360	180	618	1142	0	0
RBC-0	360	180	618	0	995.5	0
RBC-0.1	360	180	618	0	995.5	0.1
RBC-0.2	360	180	618	0	995.5	0.2
RBC-0.3	360	180	618	0	995.5	0.3
RBC-0.4	360	180	618	0	995.5	0.4

2.3. Test samples

Cubic concrete samples with dimensions of 150 mm × 150 mm × 150 mm were poured to test the compressive strength and splitting tensile strength of the concrete. prismatic samples with dimensions of 100 mm × 100 mm × 300 mm were poured to test the uniaxial compression performance of the concrete. Pull-out samples with dimensions of 150 mm × 150 mm × 150 mm were used to test the bonding performance between the concrete and steel bars, as shown in Fig. 1. Three identical specimens were designed in each group, and the accuracy of the experimental data was ensured by calculating the average value. In addition, it should be noted that in order to ensure the uniform dispersion of fibers in the concrete, fibers are added evenly in three stages during the concrete mixing process.

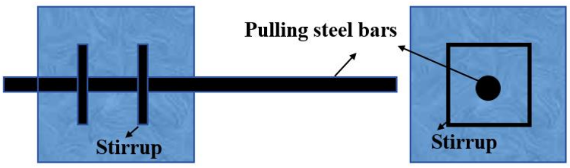

Fig. 1. Uniaxial compression test device

2.4. Experimental loading

A hydraulic servo testing machine was used to test the compressive strength, splitting tensile strength, uniaxial compression performance, and bonding performance of the samples separately (GB/T 50081-2019 [34]). The specific loading method is as follows:

1. Compressive strength. The surface of the compression test piece was wiped clean, the sample was placed in the center of the pressure plate under the testing machine, and the testing machine was adjusted to ensure even contact with the test piece. Load at a speed of 0.3 – 0.5 MPa/s continuously and uniformly until the sample is damaged.
2. Splitting tensile strength. The shims and brackets are placed on the centerline of both sides of the split tensile test specimen, and the shims and brackets are placed together on the lower pressure plate of the pressure testing machine so that the axis of the sample coincides with the centerline of the press. The mixture was continuously and uniformly loaded at a speed of 0.02 MPa/s until the sample was destroyed.
3. Uniaxial compression performance. The uniaxial compression sample was placed at the center of the lower pressure plate of the testing machine, and steel pads were placed between the sample and the upper and lower pressure plates to ensure a uniform stress distribution on the sample, as shown in Figure 2. Preloading should be carried out before the experiment to ensure that the specimen is in close contact with the base. The mixture was continuously and uniformly loaded at a speed of 0.02 mm/min until the sample was destroyed.
4. Bond performance. Using displacement control loading, a downward load was applied to the steel bar loading end at a loading speed of 0.3 mm/min until the sample failed, as shown in Fig. 3. Preloading should be carried out before the experiment to ensure that the specimen is in close contact with the loading frame.

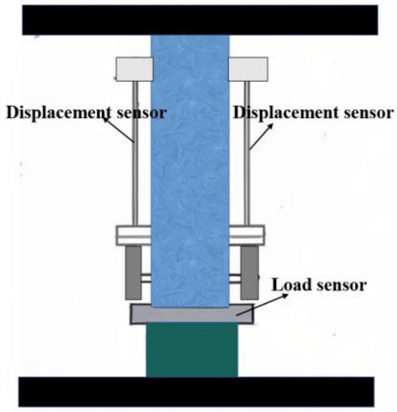

Fig. 2. Uniaxial compression test device

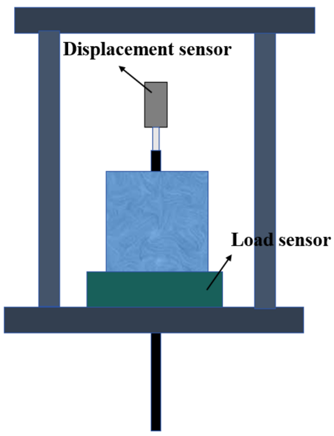

Fig. 3. Bond performance test device

3. RESULTS ANALYSIS

3.1. Basic mechanical properties

The cube compressive strength and splitting tensile strength of recycled brick aggregate concrete with basalt fibers are shown in Fig. 4. As shown in Fig. 4, the cube compressive strength and splitting tensile strength of recycled brick aggregate concrete are 26.8 MPa and 2.38 MPa, respectively, whereas the cube compressive strength and splitting tensile strength of ordinary concrete are 33.5 MPa and 3.15 MPa, respectively. The addition of recycled brick aggregate reduces the cube compressive strength and splitting tensile strength of concrete by 20.0 % and 24.4 %, respectively, which is consistent with the results obtained by Wang [35]. The reasons for this situation are as follows:

1. Recycled brick aggregates are obtained by crushing and screening waste bricks, and there are many pores and microcracks inside, which reduce the strength of the aggregates and lead to poor mechanical properties of the concrete;
2. The porosity of recycled brick aggregates is relatively high. During the concrete mixing process, recycled brick aggregates absorb a large amount of moisture, which affects the workability of the concrete mixture. Moreover, during the hardening process of concrete, owing to the uneven migration and distribution of moisture, more pores and defects form around the aggregates, thereby reducing the compactness of the concrete;
3. The shape of recycled brick aggregates is usually irregular, with many edges and corners. When concrete is under stress, the irregular shape of the aggregates can easily cause stress concentration and reduce the mechanical properties of the concrete. Although some studies have found that the combination of recycled brick aggregate and mortar is denser and can improve the mechanical properties of concrete to some extent, the negative effects mentioned earlier are more significant. Therefore, the addition of recycled brick aggregate ultimately leads to a decrease in concrete strength.

In addition, the addition of basalt fibers effectively improved the cube compressive strength and splitting compressive strength of recycled brick aggregate concrete. When the fiber content is 0.3 %, the improvement effect is optimal, the cube compressive strength can be increased by 18.66 %, and the splitting tensile strength can be increased by 22.68 %. At this point, the differences in compressive strength and splitting tensile strength between recycled brick aggregate concrete and ordinary concrete cubes are reduced to 5.07 % and 7.30 %, respectively. The reasons for this situation are as follows [36]:

1. Recycled brick aggregate concrete is prone to stress concentration inside because of the characteristics of recycled aggregates, which can cause microcracks. The presence of fibers can withstand partial tensile stress, reduce the stress concentration at the aggregate interface, and decrease the probability of crack formation;
2. Active groups such as silicon hydroxyl groups on the surface of basalt fibers can react chemically with calcium ions in cement hydration products, forming chemical bonds, enhancing interfacial adhesion, effectively transmitting stress, and improving the overall mechanical properties of concrete;
3. Fibers themselves have high toughness and energy absorption capacity. When concrete is subjected to external forces, fibers can absorb a large amount of energy through their own stretching, deformation, and fracture;
4. Fibers are evenly dispersed in concrete and can act as "dispersants", increasing the uniformity of the distribution of recycled brick aggregates in concrete and reducing the local accumulation and pore formation of aggregates.

However, when the fiber content reaches 0.4 %, the improvement effect slightly decreases compared with that when the fiber content is 0.3 %. This is mainly because the surface of the basalt fibers is relatively smooth. When the dosage is too high, it is difficult to evenly disperse in the concrete mixture, and fiber aggregation is prone to occur, thereby forming stress concentration points and reducing the mechanical properties of the concrete. With increasing basalt fiber content, the flowability of the concrete mixture gradually decreases, thereby affecting the compactness and integrity of the concrete. Excessive fibers may cause the spatial network structure formed inside the concrete to be too dense, and the fibers are prone to mutual compression and sliding under stress, making it difficult for them to effectively cooperate and fully exert their reinforcing effect.

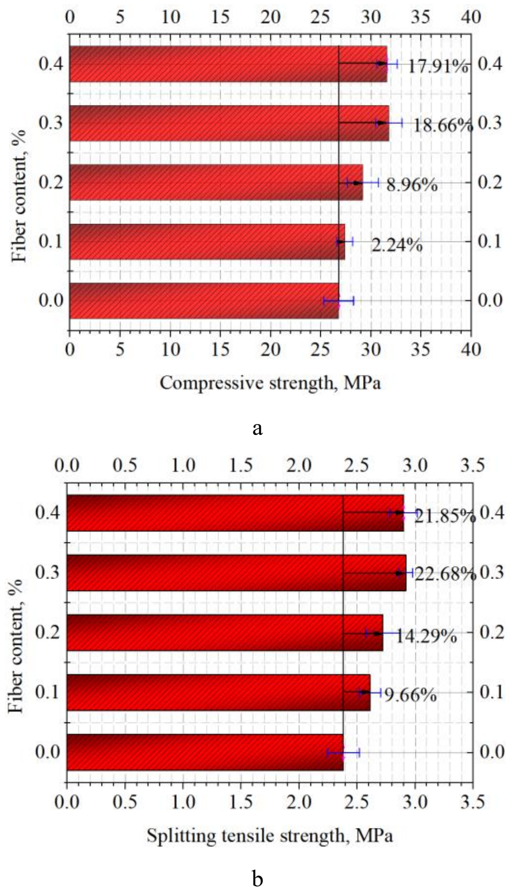

Fig. 4. Basic mechanical properties of recycled concrete with basalt fibers: a – cube compressive strength; b – splitting tensile strength

3.2. Uniaxial compression performance

3.2.1. Peak stress

The peak stress of recycled brick aggregate concrete with basalt fibers is shown in Fig. 5. The peak stress of recycled brick aggregate concrete without basalt fibers is 20.4 MPa, which is significantly lower than the peak stress of ordinary concrete (26.4 MPa), indicating that the addition of recycled brick aggregate reduces the peak stress of concrete by 22.7 %. This is mainly due to the low strength of recycled brick aggregates, high internal porosity, unsatisfactory shape and grading of the aggregates, and poor interfacial bonding performance of recycled brick aggregate concrete.

The addition of basalt fibers can effectively increase the peak stress of recycled brick aggregate concrete. The optimal improvement effect on peak stress is achieved when the dosage is 0.3 %, which is consistent with the results obtained from the basic mechanical properties. On the one hand, when subjected to uniaxial compressive stress, fibers can disperse the stress and distribute it more evenly inside the concrete, thereby improving the compressive strength of the concrete. On the other hand, fibers can effectively transmit stress to the cement matrix, allowing the two to work together and enhance the overall strength of the concrete.

However, the dosage of basalt fiber also needs to be controlled within a certain range to achieve optimal results. When the fiber content exceeds 0.4 %, the improvement effect slightly decreases, from 20.59 % to 19.12 %. This is mainly because excessive fibers can easily lead to uneven distribution and fiber aggregation, resulting in more defects inside the concrete, weakening the interfacial bonding force between the fibers and the matrix, and thereby reducing the overall strength of the concrete [37].

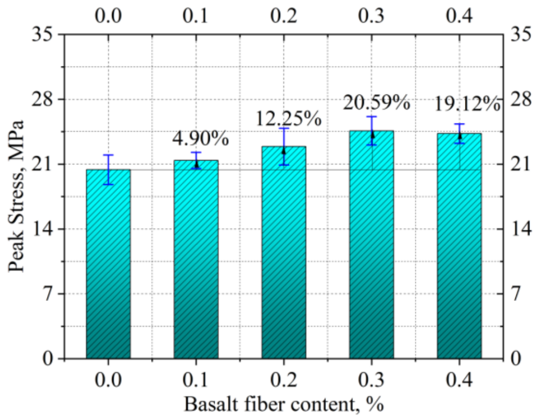

Fig. 5. Peak stress

3.2.2. Peak strain

The peak strain of the concrete with basalt fiber recycled brick aggregate is shown in Fig. 6. The peak strain of recycled brick aggregate concrete (1354.1 $\mu\varepsilon$) is greater than that of ordinary concrete (1125.4 $\mu\varepsilon$), with an increase of 20.3 %. Owing to the low elastic modulus and high porosity of recycled brick aggregates, their internal structure is relatively loose, making them more prone to deformation and microcrack propagation during compression, resulting in an increase in peak strain. After adding basalt fibers, the peak strain increased slightly, and the magnitude of the increase continued to increase with increasing dosage. When the fiber content reaches 0.4 %, the peak strain increases by 19.12 %. This is because during the compression process, fibers can disperse stress, delay the brittle failure of concrete, and thus increase the peak strain.

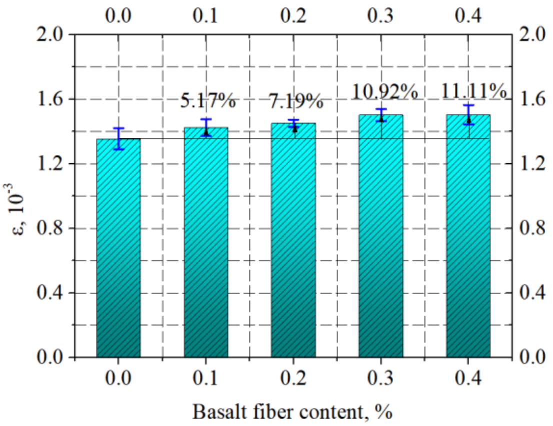

Fig. 6. Peak strain

The addition of basalt fibers can compensate for the low elastic modulus of recycled brick aggregate concrete to some extent, thereby improving the deformation capacity of concrete. In addition, basalt fibers themselves have a certain degree of ductility, which can absorb and dissipate energy during compression, making the failure process of concrete more ductile.

3.2.3. Peak stress calculation model

The peak stress of recycled brick aggregate concrete under uniaxial compression is linearly related to the basalt fiber content. Therefore, a linear fit of the data can be obtained:

$$F_s=11c+20.52, \quad (1)$$

where F_s is the uniaxial compression peak stress of recycled brick aggregate concrete; c is the content of basalt fibers.

As shown in Fig. 7, the correlation coefficient is 0.9175, indicating that the calculation model can effectively predict the peak uniaxial compressive stress of recycled brick aggregate concrete with basalt fibers.

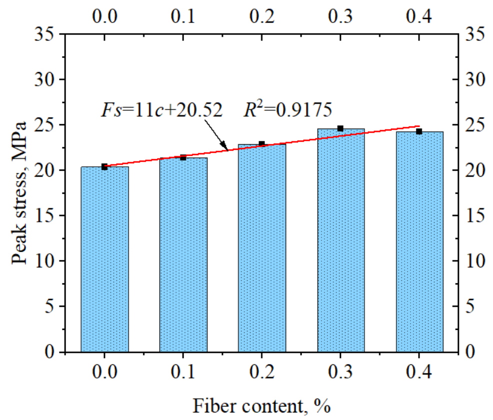

Fig. 7. Relationship between peak stress and fiber content

3.3. Bond performance

3.3.1. Bond strength

The ultimate bond strength between basalt fiber recycled brick aggregate concrete and steel bars is shown in Fig. 8.

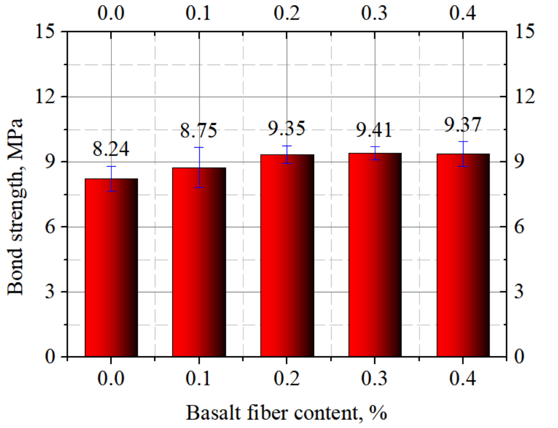

Fig. 8. Ultimate bond strength

The bond strength between ordinary concrete and steel bars (9.78 MPa) is significantly greater than that between recycled brick aggregate concrete and steel bars (8.24 MPa).

The main reason is that there are many microcracks and pores inside the recycled brick aggregate, and the surface is relatively rough and irregular, resulting in weak interfacial bonding between it and the cement matrix, which is prone to bond failure under stress. In addition, the water absorption of recycled brick aggregates is strong, which may affect the hydration reaction and compactness of the concrete, further reducing its bonding performance with steel bars. Moreover, the strength of recycled brick aggregate concrete is usually lower than that of ordinary concrete, and the bond strength is closely related to the compressive strength of the concrete. A lower concrete strength can also lead to a decrease in the bond strength between the steel bars and the concrete. These factors work together to decrease the bond strength between recycled brick aggregate concrete and steel bars compared with that of ordinary concrete.

After adding basalt fibers, the bonding strength between recycled brick aggregate concrete and steel bars significantly improved. When the fiber content is 0.3 %, the bond strength between recycled brick aggregate concrete and steel reinforcement is increased to 9.41 MPa, and the difference in bond strength between recycled brick aggregate concrete and steel reinforcement is reduced from 15.7 % to 3.8 % compared with that of ordinary concrete. The reasons for this situation are as follows: First, basalt fibers have high strength, high toughness, and good interfacial bonding properties, which can effectively bridge microcracks inside concrete, prevent crack propagation, and enhance the overall performance of concrete. Second, fibers form a three-dimensional network structure in concrete, which improves the toughness and crack resistance of the concrete, thereby enhancing its bonding performance with steel bars. In addition, an appropriate amount of basalt fiber can optimize the microstructure of concrete, improve its density and strength, and further increase its bond strength with steel bars.

However, as shown in Fig. 7, when the fiber content reaches 0.4 %, although it still has a good improvement effect on the bonding strength, the bonding strength of the sample decreases compared with that of the sample with a fiber content of 0.3 %. To ensure the optimal improvement effect, the fiber content needs to be controlled within a reasonable range.

3.3.2. Bond slip

The peak slip (the slip value corresponding to the ultimate bond strength) between the basalt fiber recycled brick aggregate concrete and steel bars is shown in Fig. 9. The peak slip between ordinary concrete and steel bars (0.705 mm) is lower than that between recycled brick aggregate concrete and steel bars (1.415 mm). On the one hand, there are many microcracks and defects on the surface of recycled brick aggregate, which leads to greater damage to the interface between recycled brick aggregate concrete and steel bars, resulting in relatively weak bonding performance between steel bars and recycled brick aggregate concrete, making it more prone to slip. On the other hand, a lower bond strength leads to a weakened ability of concrete to constrain steel bars, making them more prone to slip during the stress process, resulting in an increase in peak slip.

After adding basalt fibers, the peak slip between recycled brick aggregate concrete and steel bars is reduced. When the fiber content is 0.3 %, the peak slip decreases the most significantly, by 0.136 mm. The reasons for this situation are as follows [38]:

1. The addition of basalt fibers can improve the microstructure of recycled brick aggregate concrete, enhance the interfacial bonding performance between the concrete and steel bars, and thereby reduce the relative slip between the steel bars and the concrete;
2. Basalt fibers improve the crack resistance and toughness of recycled brick aggregate concrete, making it less prone to cracking during the stress process, thereby reducing the slip between the steel bars and the concrete;
3. The addition of fibers enhances the mechanical properties of the concrete, increasing the stability of the interaction between the steel bars and the concrete, thereby reducing slippage.

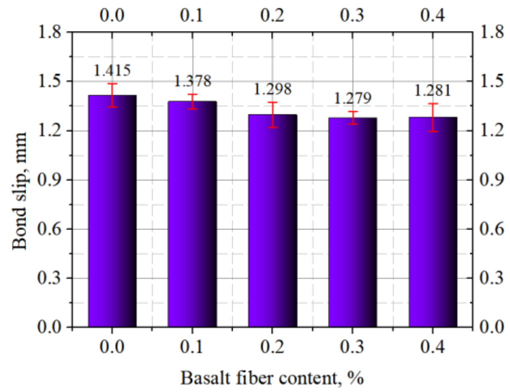

Fig. 9. Peak slip

3.3.3. Bond strength calculation model

The ultimate bond strength between recycled brick aggregate concrete and steel bars shows a linear relationship with the content of basalt fibers. Therefore, a linear fit of the data can be obtained:

$$F_b=2.92c+8.44, \qquad (2)$$

where F_b is the ultimate bond strength between recycled brick aggregate concrete and steel bars; c is the content of basalt fibers.

As shown in Fig. 10, the correlation coefficient is 0.8008, indicating that the calculation model can effectively predict the ultimate bond strength between recycled brick aggregate concrete with basalt fibers and steel bars.

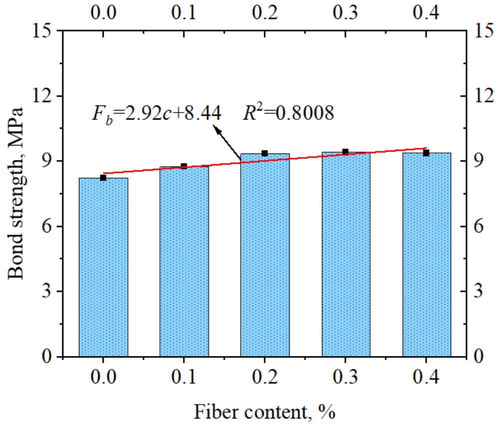

Fig. 10. Relationship between the ultimate bond strength and fiber content

4. CONCLUSIONS

1. The addition of recycled brick aggregate can reduce the cube compressive strength, splitting tensile strength, and uniaxial compressive stress of concrete. In addition, the recycled brick aggregate deteriorates the bonding performance between the concrete and steel bars;
2. The addition of basalt fibers can improve the cube compressive strength and splitting tensile strength of recycled concrete;
3. The addition of basalt fibers can lead to an increase in the uniaxial compressive stress and strain of recycled brick aggregate concrete, and a calculation model for the uniaxial compressive stress of basalt fiber recycled brick aggregate concrete was established;
4. The addition of basalt fibers effectively improved the bonding performance between recycled brick aggregate concrete and steel bars. A calculation model for the bonding strength between basalt fiber recycled brick aggregate concrete and steel bars was established.

According to the results of this paper, it can be concluded that the optimal dosage of basalt fibers can be controlled at 0.3 % in engineering applications to avoid a decrease in the performance of recycled brick aggregate concrete due to fiber aggregation. In addition, in the future, research should be conducted on the frost resistance of recycled brick aggregate concrete with basalt fibers to ensure its widespread application in frozen areas.

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