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MECHANICAL PROPERTIES OF RECYCLED CONCRETE WITH BRICK BLOCKS UNDER DIFFERENT COMPRESSION CONDITIONS

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Standard brick blocks were prepared using recycled aggregate (RCA) with different particle size ranges to fully use RCA produced by crushing waste concrete. In this experiment, vertical loads are applied to different loading surfaces of recycled concrete brick blocks, and the compressive strength and stress–strain curves of recycled concrete brick blocks prepared with two different particle sizes of RCA under different compression conditions are obtained. The relationship between the failure mode and the loading surface of the brick blocks produced by the two different particle sizes of RCA is analyzed. At the same time, the stress–strain curve of the compressive test of the recycled concrete brick block is verified by using the finite element software ABAQUS, and the results are fitted by the concrete compression constitutive equation. The results show that the 28d compressive strength performance of each loading surface of the recycled concrete brick block prepared by the RCA with a particle size range of 0–9.5 mm is better than that of the brick block prepared by the RCA with a particle size range of 0–4.75 mm. The failure modes of the two brick blocks under different compression conditions are analyzed. The ordinary concrete compression constitutive equation can fit the stress–strain curve of the compressive test of recycled concrete brick blocks, and the test results are similar to the calculation results of the finite element software ABAQUS, which provides a reference for the practical engineering application of recycled concrete brick blocks.

***Keywords*: recycled concrete, brick blocks, mechanical properties, aggregate particle size, failure.**

Introduction. China is a resource-consuming country, with resource shortage and environmental concerns increasingly constraining its economic growth. It is estimated that mainland China currently produces about 200 million tons of concrete waste per year [1, 2], but the waste utilization rate of construction waste is less than 5% [3]. Currently, most of the existing construction waste is treated by incineration and landfill, which will cause serious environmental pollution [4, 5]. To solve the above problems, many countries encourage the production of construction waste as RCA for the manufacture of recycled concrete or concrete products to save natural materials and make full use of construction waste [6, 7]. Some scholars have studied the mechanical properties of recycled concrete to understand its durability and mechanical properties [8, 9] and found that RCA concrete has lower compressive strength, higher water absorption capacity, and more internal pores than natural aggregate concrete. Still, RCA can meet the basic requirements of low-strength concrete production through the practical design of mix ratio.

With the continuous improvement of the research results of recycled concrete, the research on the preparation of brick blocks using recycled concrete has attracted more and more attention [10–12]. Through research, it is found that the treated RCA can completely replace the natural aggregate to produce concrete blocks [13], and the mechanical properties of the produced recycled concrete brick blocks can still meet the requirements of European standard EN

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771-3 [14]; when the replacement rate of RCA is 30–50%, the mechanical properties of recycled concrete brick blocks decrease slightly [15, 16]; when the replacement rate of RCA reaches 80%, the mechanical properties of recycled concrete brick blocks will decrease significantly [17], and the production of recycled concrete brick blocks can greatly reduce carbon dioxide emissions compared with traditional sintered bricks [18]. Most existing studies focus on the influence of the RCA replacement rate on the mechanical properties of recycled concrete brick blocks, and there are relatively few studies on different RCA particle sizes and different compression conditions.

So far, there is little research on the performance of recycled concrete brick blocks. Therefore, based on the existing RCA production process and the masonry method of brick blocks in practical engineering, this paper studies the relationship between the compressive strength of recycled concrete brick masonry and different RCA particle sizes and verifies the test results by finite element software ABAQUS. Considering that in practical engineering applications, the stress of each section is also different due to the different masonry methods. Therefore, the compressive tests are carried out on different surfaces of brick blocks, which provides a reference value for the practical engineering application of recycled concrete brick blocks.

1. Experimental Investigation.

1.1. Material and Specimen Preparation. Ordinary Portland cement with a strength grade of 42.5 MPa was used. The water-reducing agent was a polycarboxylate high-performance water-reducing agent. The coarse and fine aggregates were RCAs obtained by crushing the waste concrete with a design compressive strength of C30 by a jaw crusher. The RCAs with particle size ranges of 0–4.75 mm and 0–9.5 mm were obtained by screening. Two batches of brick masonry with standard sizes of 240×115×53 mm were poured, respectively. The size error range in each direction was within ±1mm. The specimen was demolded 24 h after preparation and placed in a standard curing room for curing. The design mix ratio of the recycled concrete brick block is shown in Table 1. The preparation process of recycled concrete brick is shown in Fig. 1. The particle gradation of RCA with the particle size range of 0–4.75 mm and 0–9.5 mm is chosen from Table 2.

TABLE 1. The Mixed Proportion Design of Recycled Concrete Brick

Cement (kg)	Water (kg)	Coal ash (kg)	RCAs (kg)	Water-reducing agent (kg)
1.00	0.74	0.25	4.51	0.01

TABLE 2. Grading of Fine Aggregates with Different Particle Sizes

Grain size range (mm)	0–1.18	1.18–2.36	2.36–4.75	4.75–9.50
Weight (kg)	3.68	1.99	3.10	3.88

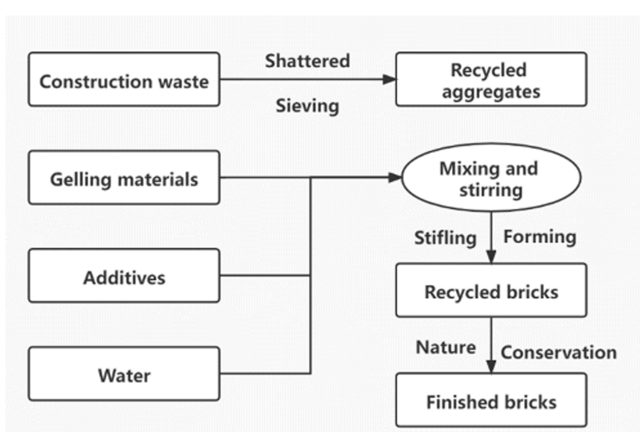


Fig. 1. Preparation of recycled concrete brick.

1.2. Experimental Grouping and Test Methods. This test was divided into two groups according to different particle size ranges of RCAs, with six specimens in each group. The loading tests under different compression conditions were carried out respectively. The test groups are shown in Table 3.

TABLE 3. The Group of Specimens in the Test

Specimen group	Aggregate size (mm)	Loading surface size (mm)
RB1-A	0–4.75	115×53
RB1-B	0–4.75	240×53
RB1-C	0–4.75	240×115
RB2-A	0–9.50	115×53
RB2-B	0–9.50	240×53
RB2-C	0–9.50	240×115

In this experiment, HUT-106, A universal testing machine, was used to test the compressive strength of recycled concrete brick blocks for 7, 14, and 28 d. The test loading device is shown in Fig 2. The estimated strength determines the loading speed of each group of recycled concrete brick blocks, and the loading is classified according to the different sizes of the loading surface. The loading situation is shown in Table 4, and the loading is stopped after the specimen is destroyed.

TABLE 4. The Test Method Used in the Experiment

Loading surface size (mm)	240×115	240×53	115×53
Loading speed (kN/s)	8	4	2

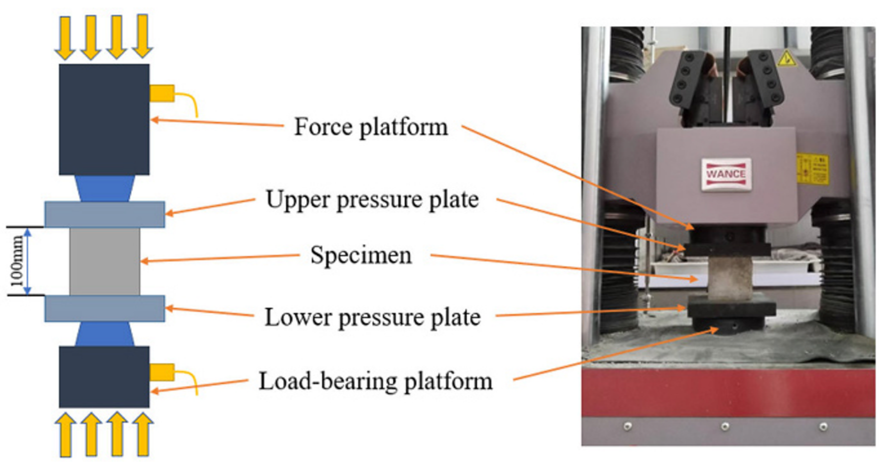


Fig. 2. Loading device used.

2. Results and Discussion.

2.1. Compressive Strength. The compressive test results of recycled concrete brick blocks prepared by RCA with different particle size ranges are shown in Fig. 3. From Fig. 3, the compressive strength of the 240×115 mm loading surface of recycled concrete brick block prepared by RCA with the particle size range of 0–9.5 mm is 1.39 MPa higher than that of recycled concrete brick block prepared by RCA with the particle size range of 0–4.75 mm. The compressive strength of the 240×53 mm loading surface of recycled concrete brick block prepared by RCA with the particle size range of 0–9.5 mm is 4.55 MPa higher than that of recycled concrete brick block prepared by RCA with the particle size range of 0–4.75 mm. The compressive strength of the 115×53 mm loading surface of recycled concrete brick block prepared by RCA with the particle size range of 0–9.5 mm is 7.32 MPa higher than that of recycled concrete brick block prepared by RCA with the particle size range of 0–4.75 mm. The 7 d compressive strength of the 240×115 mm loading surface of the two groups of recycled concrete brick blocks is greater than 30 MPa, which meets the strength requirements of the strength grade of MU30 ordinary brick, indicating that the reasonable adjustment of the mix ratio can make the recycled concrete achieve higher strength. After 28 d standard curing, the ultimate compressive strength of each loading surface of the 28 d brick block is significantly improved compared with 7 d, and the 240×115 mm loading surface is the most significant, about 30.86%.

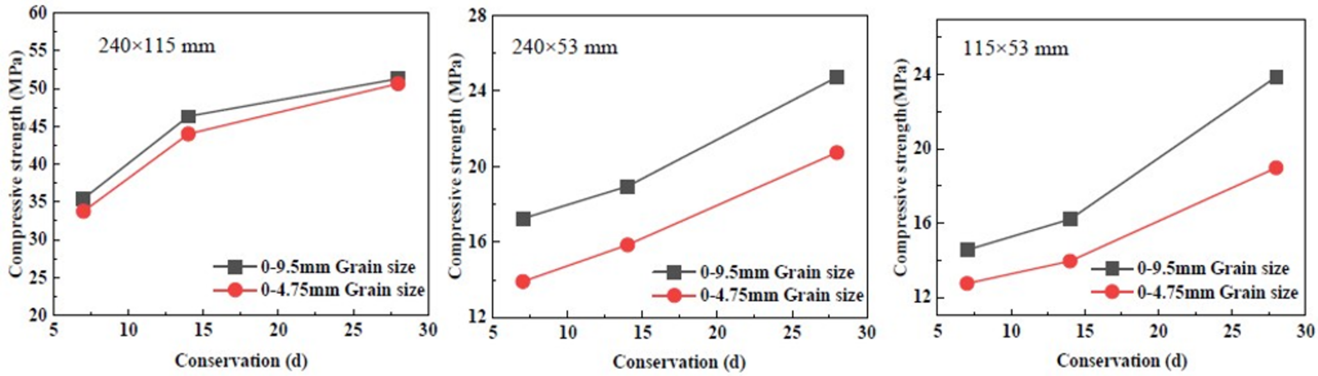


Fig. 3. Compressive strength of different compression conditions.

The test results show that the compressive strength of the recycled concrete brick block prepared by the RCA with a particle size range of 0–9.5 mm at 7 d, 14 d, and 28 d is higher than that of the RCA with a particle size range of 0–4.75 mm. Among them, the 28 d compressive strength of the 115mm×53mm loading surface is the most significant, and the RCA with a particle size range of 0–9.5 mm is more conducive to improving compressive strength.

2.2. Stress–Strain Curve of Recycled Concrete Brick Block. According to the different compression conditions, the 28 d stress–strain curves of each recycled concrete brick block loading surface under three compression conditions are drawn, as shown in Fig. 4. The axial peak stress and axial peak strain measured by the test are shown in Table 5.

TABLE 5. Compressive Test Results of Recycled Concrete Brick Block

Specimen group	Aggregate size (mm)	Loading surface size (mm)	Peak stress (MPa)	Peak strain (10^{-2})
RB1-A	0~4.75	115×53	16.65	0.39
RB1-B	0~4.75	240×53	18.08	0.91
RB1-C	0~4.75	240×115	48.90	6.05
RB2-A	0~9.5	115×53	23.97	0.47
RB2-B	0~9.5	240×53	22.63	1.41
RB2-C	0~9.5	240×115	50.29	9.87

It can be seen from Table 5, that the peak strain of the compressive test of the 240×115 mm loading surface of the recycled concrete brick block prepared particle size range of 0–9.5 mm is 3.82×10^{-2} higher than that of recycled concrete brick block prepared by RCA with a particle size range of 0–4.75 mm. That the peak strain of the compressive test of the 240×53 mm loading surface of the recycled concrete brick block prepared particle size range of 0–9.5 mm is 0.5×10^{-2} higher than that of recycled concrete brick block prepared by RCA with the particle size range of 0–4.75 mm. That the peak strain of the compressive test of the 115×53 mm loading surface of the recycled concrete brick block prepared particle size range of 0–9.5 mm is 0.08×10^{-2} higher than that of the recycled concrete brick block prepared by RCA with a particle size range of 0–4.75 mm.

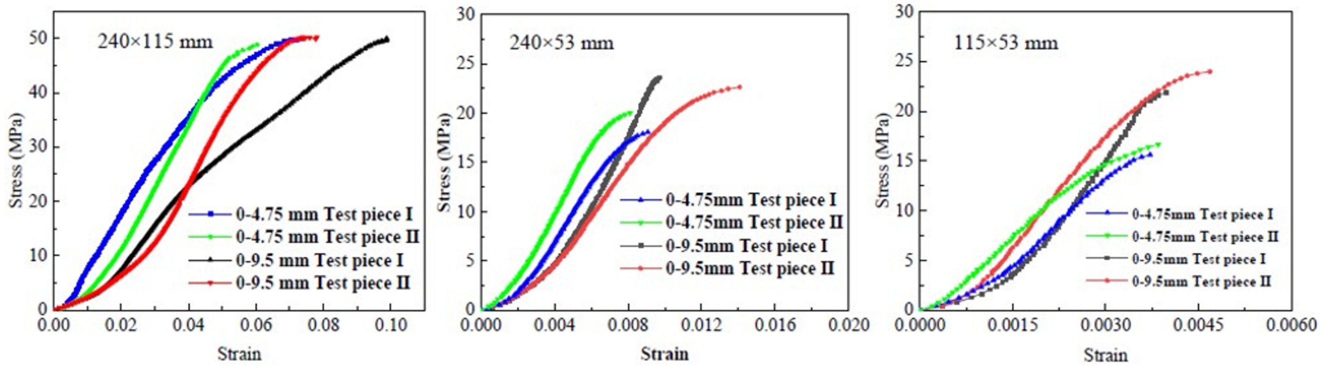


Fig. 4. Compressive stress–strain curves of different compression conditions.

Figure 4 shows recycled concrete brick blocks' peak stress and strain with different particle sizes. It shows that the peak stress and strain of concrete prepared by RCA with a particle size range of 0–9.5 mm are higher than those of recycled concrete brick blocks prepared by RCA with a particle size range of 0–4.75 mm. The compressive stress–strain curve of recycled concrete brick blocks prepared by RCA with a particle size range of 0–9.5 mm is relatively flat. The experimental results show that recycled concrete brick blocks prepared by RCA with a particle size range of 0–9.5 mm contribute to the increase of peak stress and peak strain. The recycled concrete brick block has better deformation ability, and the 240×115 mm loading surface is the most significant.

2.3. Failure Mode. The failure mode of the recycled concrete brick block is related to the size of its loading surface. The compressive failure mode of each loading surface of recycled concrete brick block prepared by RCA with a particle size range of 0–4.75 mm and 0–9.5 mm is shown in Fig. 5. It shows that the failure modes of recycled concrete brick blocks can be roughly divided into two types. When the loading surface is 240×115 mm, both recycled concrete brick blocks occur compression failure. When the loading surface is 240×53 mm and 115×53 mm, both recycled concrete brick blocks occur shear failure along the diagonal direction of the test block. The results show that the failure mode of the recycled concrete brick test block is not related to the size of the RCA, and the failure mode is mainly related to the compression condition.

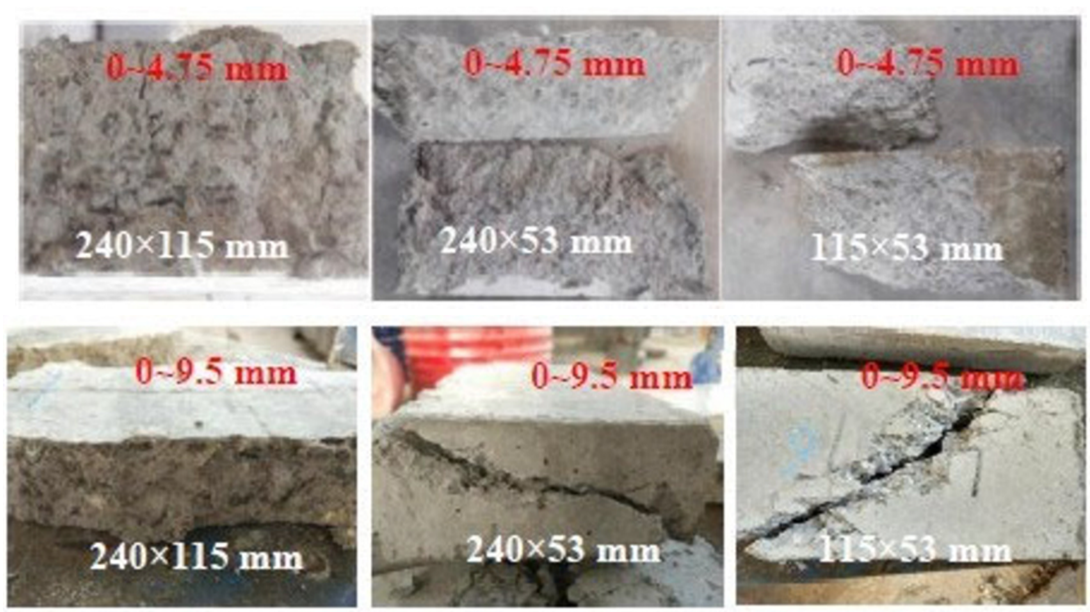


Fig. 5. Failure mode of the recycled concrete brick block with different particle sizes.

It can be seen from Fig. 6 that at the loading surface of the recycled concrete brick block of 240×115 mm, the compressive specimen has a potential shear surface according to the Mohr–Coulomb criterion. When the specimen is subjected to pressure in both upper and lower directions simultaneously, it can be considered that there are four symmetrical potential shear bands at this time. An ideal compression model can be obtained by superimposing these four shear bands. In this model, there is a disintegration zone on both sides of the left and right sides (the concrete in this area collapses to both sides after crushing), and there is a piercing zone on both ends, i.e., the stress concentration zone formed after horizontal displacement is limited. When the loading surface of the recycled concrete brick block is 240×115 mm, the angle between the diagonal of the specimen and the horizontal plane is only 24.7°. According to the research of Kang et al. [19], when the angle between the diagonal of the specimen and the horizontal plane is less than 26.6°, the shear strength of all inclined sections in the compression area of the specimen is greater than the shear stress, which does not meet the necessary conditions for shear failure. The final failure is compression. The results of this study are consistent with the actual compression test results.

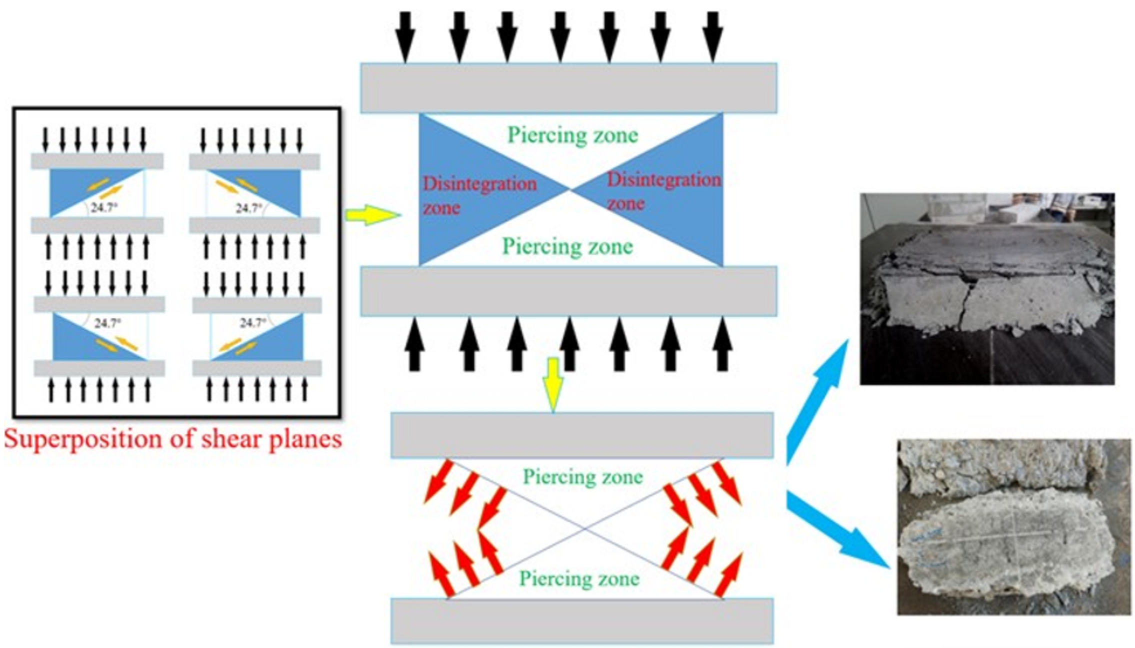


Fig. 6. Failure analysis of the loading surface of 240×115 mm.

It can be seen from Fig. 7, according to the Code for Design of Concrete Structures (GB50010-2010), the azimuth angle of the fracture surface is between 63.3° and 78.3° in theory when the shear failure of concrete occurs. Through calculation, it can be found that when the loading surface is 240× 53 mm and 115×53 mm, the angle between the diagonal of the specimen and the horizontal plane is 64.3° and 65.2°, respectively, both of which are within the allowable range of the azimuth angle of the fracture surface. Therefore, when the recycled concrete brick block is subjected to axial compression, the concrete specimen shear failure occurs, and the surface of the compressed specimen appears along the diagonal direction.

2.4. Theoretical and Finite Element Analysis. The above test results show that the performance of recycled concrete brick block prepared by RCA with a particle size range of 0–9.5 mm is better than that of recycled concrete brick block prepared by RCA with a particle size range of 0–4.75 mm. Therefore, the formula fitting analysis and numerical simulation analysis of this group of test blocks are carried out to explore the possibility of using it as masonry material.

2.4.1. Stress–Strain Curve Fitting Analysis. The stress–strain fitting curves of each group of specimens are shown in Fig. 8, and the curves are dimensionless.

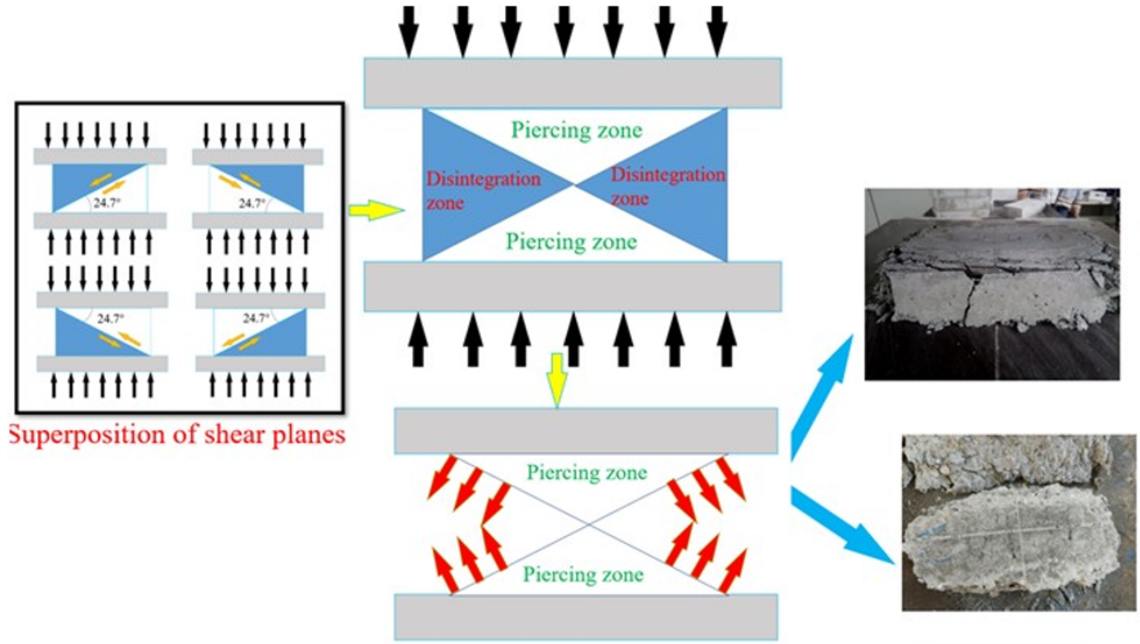


Fig. 7. Failure analysis loading surfaces of 240×53 mm and 115×53 mm.

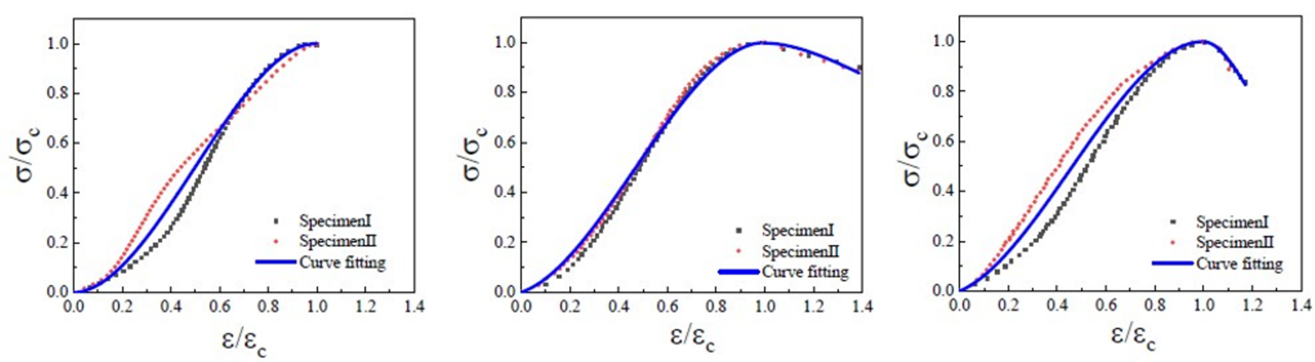


Fig. 8. Stress–strain fitting curves under different compression conditions.

The abscissa is represented by $\varepsilon/\varepsilon_c$ (ε_c is the peak strain), and the ordinate is represented by σ/σ_c (σ_c is the peak stress). It can be observed that the stress–strain curve of recycled concrete brick blocks is similar to that of ordinary concrete. In this paper, the constitutive equation of concrete under uniaxial compression proposed by Guo and Zhang [20], as shown in formula (1), and fitted and analyzed by the parameter iterative calculation method:

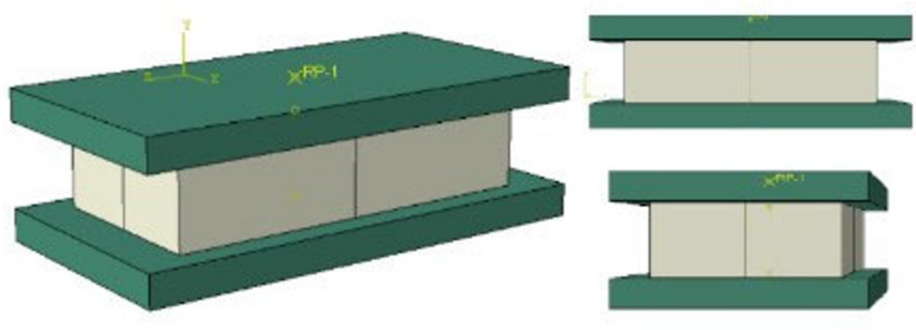
$$y = \begin{cases} ax + (3-2a)x^2 + (a-2)x^3 & (0 \le x < 1), \\ \dfrac{x}{b(x-1)^2 + x} & (x \ge 1). \end{cases} \tag{1}$$

Using the calculation software to construct the model of the defined basic equation, the characteristic parameters a and b are synchronously fitted and calculated, and the calculation results of the parameters a and b in the stress-strain constitutive equation of each test group are shown in Table 6. It can be seen from Fig. 8 that the fitting curves under three different compression conditions obtained by fitting with Eq. (1) have the same development trend as the stress–strain curves of the actual compression block. The peak stress and strain obtained by fitting are close to the test results, and the fitting degree is high. It can be seen from Table 6 that the approximate index R^2 of the fitting curve is generally high, and the fitting degree is good. Combining the parameters a and b in the above list with the constitutive equation can effectively help to analyze the properties of recycled concrete brick blocks. The results show the feasibility of fitting the compressive constitutive equation of ordinary concrete to the recycled concrete brick block, indicating that the recycled concrete has similar compressive mechanical properties to ordinary concrete.

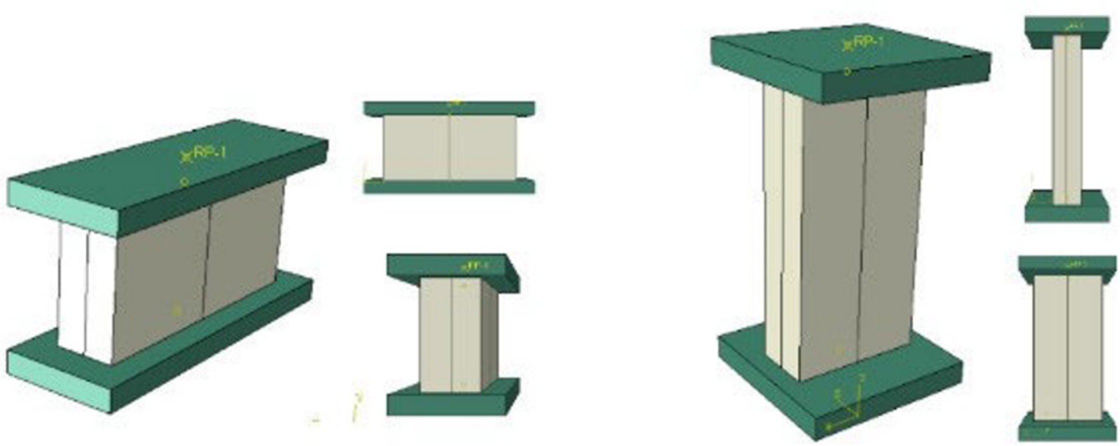
TABLE 6. Fitting Results of Characteristic Parameters a and b

Specimen group	Ascent parameters a	R^2 (%)	Descending segment parameters b	R^2 (%)
RB2-A	0.42	95.22	8.40	98.60
RB2-B	0.33	99.51	1.24	83.99
RB2-C	0.04	96.33	–	–

2.4.2. Simulation Analysis of Different Compression Conditions. Considering the three possible compression states of brick blocks in the actual compression process, the integral compression model of recycled concrete brick blocks under three different compression conditions was established by finite element software ABAQUS, and the vertical pressure was applied to the brick blocks. The compression model of the recycled concrete brick block is shown in Fig. 9.



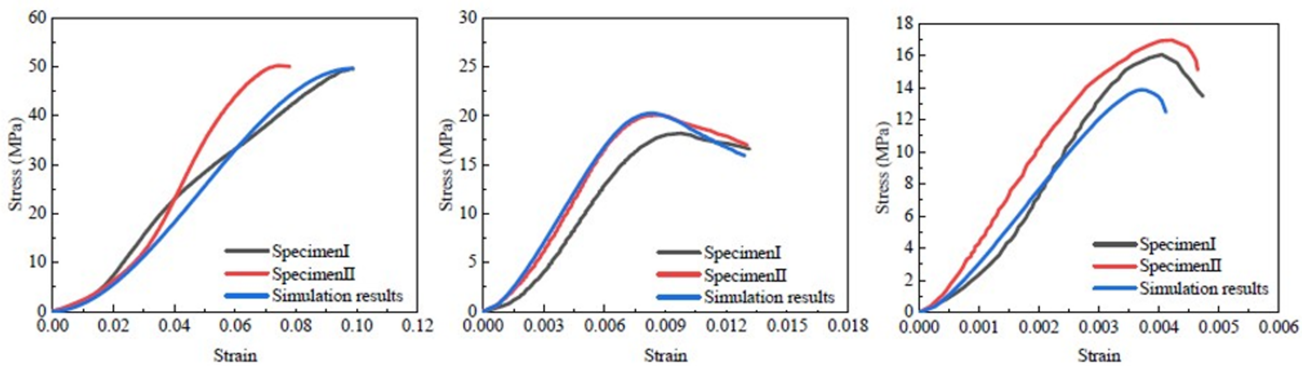
(a) 240×115 mm



(b) 240×53 mm (c) 115×53 mm

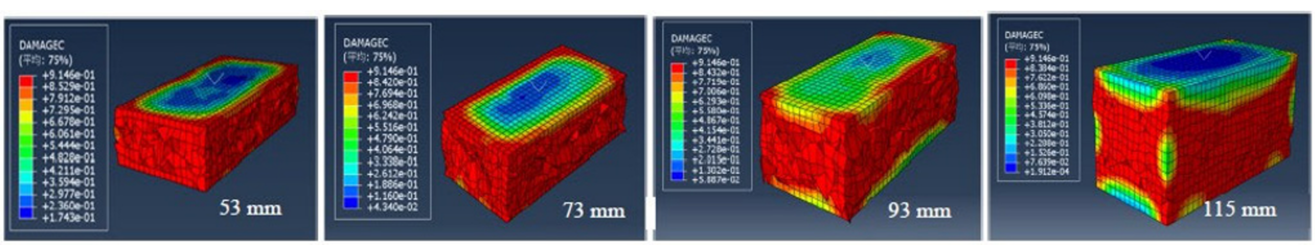
Fig. 9. Comparison of stress-strain under different compression conditions.

This paper takes three sets of corresponding stress–strain curve data into the finite element model for compressive simulation, and the simulated stress–strain curves under different compression conditions are obtained, respectively. Figure 10 shows the above three stress–strain curves compared with those obtained from the test. It can be seen from Fig.10 that the stress–strain curves of the compression specimens under three different compression conditions obtained by finite element simulation can be found that the simulation results of 240×115 and 240×53 mm loading surfaces are more accurate than those of 115×53 mm loading surface. The development trend of stress–strain curves under three compression conditions is roughly the same as that of the test results, and the peak stress and strain obtained by numerical simulation are close to the test results. The results show that the change process of the stress–strain curve of recycled concrete brick block in the actual compression process can be effectively simulated by establishing the compression model of the recycled concrete brick block.

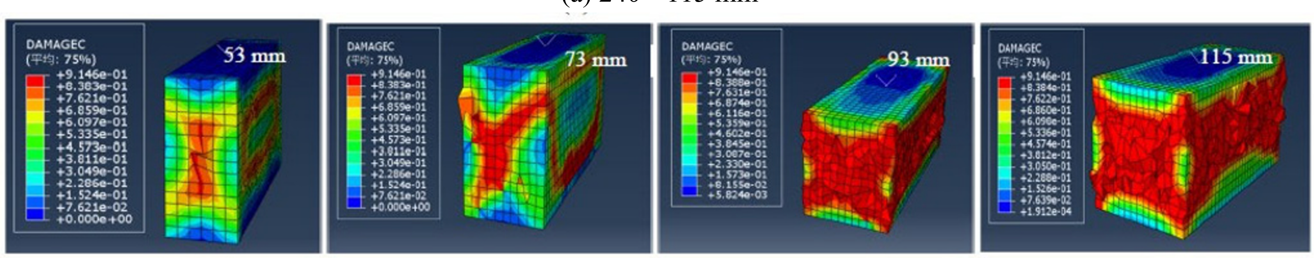


(a) 240×115 mm (b) 240×53 mm (c) 115×53 mm

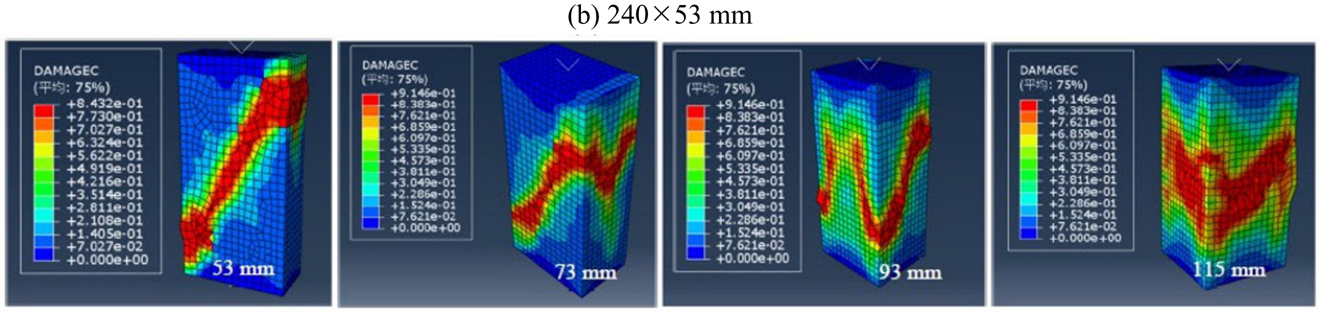
Fig. 10. Comparison of stress-strain under different compression conditions.



(a) 240×115 mm



(b) 240×53 mm



(c) 115×53 mm

Fig. 11. Simulated damage cloud of the recycled concrete brick block under compression.

2.4.3. Optimum Size of Recycled Concrete Block. The relationship between the failure mode and the compression aspect ratio is obtained by summarizing the compression failure mode of recycled concrete brick blocks. For the loading surface of 240×115 mm, the aspect ratios of recycled concrete brick blocks are 0.22 and 0.46 with a compression failure; for the loading surface of 240×53 mm, the aspect ratios of recycled concrete brick blocks are 0.47 and 2.17; for the loading surface of 115×53 mm, the aspect ratios of recycled concrete brick blocks are 2.09 and 4.53.

To explore the relationship between the failure mode and the aspect ratio of the recycled concrete brick block, the height of the recycled concrete brick block is set to 53, 73, 93, and 115 mm, respectively, by modifying the compression model of the recycled concrete brick block. The compression aspect ratio of recycled concrete brick blocks under different compression conditions was adjusted, and the relationship between the size of recycled concrete brick blocks and the failure mode are shown in Fig. 11.

Figure 11 shows that when the loading surface of the recycled concrete brick blocks is 240×115 mm, all recycled concrete brick blocks appear to have compression failure. However, when the height increases, the failure mode changes from shear failure to compression failure, and when the aspect ratio of the recycled concrete brick block is large, the fracture azimuth of the shear failure of the recycled concrete brick block under compression gradually decreases. The results show that the compressive failure mode of recycled concrete brick blocks can be changed by adjusting the height of the recycled concrete brick block, and the occurrence of shear failure can be reduced.

Conclusions. The compressive test of recycled concrete brick blocks prepared by different particle sizes of RCA under different compressive conditions is carried out in this paper, and the following conclusions are drawn through the analysis of the test results:

1. The 7 d compressive strength of 240×115 mm loading surface of recycled concrete brick block prepared by RCA with the particle size range of 0–4.75 mm and 0–9.5 mm exceeds 34 MPa, being higher than the strength requirement of MU30, indicating that reasonable adjustment of mix ratio can make recycled concrete achieve higher strength.

2. The early and final strength and peak strain of recycled concrete brick block prepared by RCA with a particle size range of 0–9.5 mm is larger, which is beneficial to enhance the toughness of the brick block. At the same time, the particle size range of RCA with a particle size range of 0–9.5 mm is wider, the preparation of raw materials is more convenient, and it has good engineering practice.

3. The recycled concrete brick block compressive specimen's failure mode shows that when the loading surface is 240×115 mm, the recycled concrete brick test block has a compressive failure. When the loading surface is 240×53 mm and 115×53 mm, the recycled concrete brick test block undergoes a shear failure.

4. The compressive stress–strain curve of the recycled concrete brick block is similar to that of ordinary concrete. The compressive constitutive equation of ordinary concrete can be used for fitting, and the fitting degree is good. Core concrete creep has little impact on steel tube stress and strain but greatly influences core concrete stress-strain state. The core concrete stress and strain are smaller at low core concrete curing age.

5. The established compression model of recycled concrete brick block can effectively simulate the change process of the stress–strain curve of recycled concrete brick block in the actual compression process.

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