Hindawi
Geofluids
Volume 2022, Article ID 1341185, 12 pages
https://doi.org/10.1155/2022/1341185

Research Article

Effects of Coarse and Fine Crushed Clay Brick Content on the Compressive Strength of Recycled Aggregate Concrete and the Microscopic Mechanism

Jin Chang,[1] **Shi-lin Luo**,[1,2] **Aierken Ailifeila**,[1] **Lin-lin Chong**,[1] **and Jian-qing Jiang**[1]

[1]*College of Civil Engineering, Changsha University, Changsha 410022, China*
[2]*Guizhou Provincial Key Laboratory of Rock and Soil Mechanics and Engineering Safety, Guizhou University, Guiyang, Guizhou 550025, China*

Correspondence should be addressed to Shi-lin Luo; rosilynn@cqu.edu.cn

Received 20 January 2022; Accepted 13 May 2022; Published 28 May 2022

Academic Editor: Yongfa Zhang

The objective of this study is to investigate the compressive strength and microstructural evolution of recycled aggregate concrete (RAC) containing coarse and fine clay brick aggregates. The compressive strength tests, scanning electron microscopy (SEM) observations, and X-ray diffraction (XRD) tests were performed on RAC and natural aggregate concrete (NAC) containing different coarse and fine crushed clay brick contents. The results showed that the compressive strength of NAC and RAC decreased with the increase of crushed clay brick content, and the growth rate of their compressive strength slowed down with the increase of age. At the same age and replacement rate, fine crushed clay bricks had less effect on the compressive strength of RAC than coarsely crushed clay bricks. The compressive strength of RAC aged 60 days, mixed with 60% fine brick slag and mixed with 60% coarse brick slag, is 10.49% and 14.75% lower than that of RAC aged 60 days and mixed with 0% fine brick slag, respectively. Compared with RAC, the compressive strength of NAC was more significantly affected by grading. The interfacial transition zones inside RAC had loose crystals and high porosity, with a weak adhesion between the crushed clay bricks and mortar interfaces. The crushed clay bricks did not affect the types of concrete hydration products, and Calcium-Silicate-Hydrate (C-S-H) and $Ca(OH)_2$ crystals remained the early hydration products in RAC with crushed clay bricks. Nevertheless, the crushed clay bricks inhibited the hydration reaction of the concrete, resulting in decreasing hydration products in NAC, RAC, and RAC with crushed clay bricks.

1. Introduction

Concrete is one of the most common and widely used building materials in highway engineering. In recent years, the construction of expressways and urban highways has raised issues concerning natural resources, sustainable development, and environmental protection. The increasing demand for concrete greatly increases the extraction and consumption of sand, stone, and other resources. In addition, new construction and reconstruction of highways generate massive waste concrete and waste bricks, occupying land and polluting the surrounding environment [1]. Therefore, recycling solid construction wastes can mitigate the exploitation and destruction of natural resources and promote the sustainable development of highway engineering.

Currently, RAC containing crushed clay bricks is the major solid waste from building demolition, which has become an important research direction [2]. Many scholars have investigated the effects of different crushed clay brick contents and different water-cement ratios on the mechanical properties of RAC [3–7]. Disfani et al. [8] evaluated the performance of RAC with waste bricks. The results showed that concrete with less than 50% of crushed clay brick content could be used in the cement stabilized subgrade. The

German guideline for the application of RAC [9]suggested that the content of crushed clay brick should be between 6% and 10%, and the content above 15% could significantly reduce the performance of RAC. Mills-Beale et al. [10] compared the strength of RAC with different water-cement ratios and found that the strength of RAC increased with the decrease of water-cement ratio. This result indicated that additional water should be considered for RAC, and the application of RAC was feasible. Similar conclusions were reached by Dang et al. [11] with studying the effects of fine waste clay brick aggregates on the mechanical properties and microstructure of concrete. A study by Xiao et al. [12] revealed that the crushed clay brick content should be controlled in engineering applications, and the moisture content of RCA should be kept within the optimal range. Suo et al. [13] found that soaking the recycled aggregates with the acid solution could remove the old mortar from the surface, and the order of material addition when mixing the RAC affected its strength. Lei et al. [14] found that more uniform grading of recycled aggregates resulted in a higher modulus of elasticity. Appropriately, increasing medium and large particles could improve the compressive strength of RAC. Li et al. [15] found that adopting recycled coarse aggregates with gradings of 16.0-31.5 mm and 5.0-31.5 mm at an appropriate replacement rate could significantly improve the compressive strength of RAC at 112 d. Hu et al. [16] suggested that the replacement rate of natural coarse or fine aggregates should not exceed 70% and 90%, respectively. Yang et al. [17] investigated the effects of crushed clay brick content on the physical and mechanical properties of RAC. The results demonstrated that a 50% replacement rate of crushed clay bricks reduced the workability of RAC and increased the difficulty of effective RAC compaction. Mehta [18] and Aitcin et al. [19] found that various properties of RAC can be satisfied with a certain mix ratio of cement paste and recycled aggregates. Zhao et al. [20, 21] explored the development law of mortar microfractures based on fractal theory and nuclear magnetic resonance technology. Chen et al. [22] studied the compressive strength of cement mortar with different replacement ratios of recycled fine aggregates. They found that the compressive strength of cement mortar with recycled fine aggregates was significantly lower than that with natural fine aggregates. Through indoor tests and practical works, Ma et al. [23] found that RAC with coarse crushed clay bricks could meet the performance requirements of medium and low-strength pumped concrete.

In summary, most of the existing studies on RAC focused on the mechanical properties and durability of concrete with natural coarse aggregates partially replaced by recycled coarse aggregates or recycled fine aggregates and natural coarse aggregates. As a result, the utilization rate of construction solid waste is too low to affect the increasing amount of construction waste in China. Currently, there is a lack of research on RAC with high recycled aggregate replacement rates or RAC made entirely from recycled coarse and fine aggregates. In addition, most studies on waste bricks focused on partial replacement of natural coarse aggregates with crushed clay bricks or partial replacement of cement with ground clay bricks as mineral admixtures. Although the strength and durability of the obtained RAC could meet the practical requirements, the recycling rate of crushed clay bricks is still limited. Little research has been conducted on the effects of size, content, and age of crushed clay bricks on the physical and mechanical properties and microstructure of RAC. For the above shortcomings, this study focuses on the influence of the content of coarse and fine clay brick on the compressive strength of recycled aggregate concrete and its micromechanism.

In order to study the effects of size, content, grading, and age of crushed clay bricks on the compressive strength of RAC, waste brick aggregates were used to partially replace recycled aggregates in RAC. In addition, scanning electron microscope (SEM) and X-ray diffraction (XRD) were employed for the in-depth analysis of the microscopic mechanism. This study can provide a useful reference for recycling waste concrete and coarse and fine crushed clay bricks.

2. Materials and Methods

2.1. Materials. The red brick mixed in the test is the waste red bricks in the process of building demolition (Figure 1(a)). After crushing and sorting (Figure 1(b)), the particle sizes of clay bricks are 4.75-9.5 mm, 9.5-19 mm, and 0-4.75 mm. The crushed clay bricks are shown in Figure 1(c).

The recycled aggregates were obtained from waste concrete retaining wall blocks (Figure 2(a)), which were provided by the Wutong Plant of Hunan Yunzhong Recycling Technology Co., Ltd. After crushing and sorting (Figure 2(b)), the aggregates were divided into three ranges: 4.75-9.5 mm, 9.5-19 mm, and 0-4.75 mm. The recycled aggregates are shown in Figure 2(c).

The basic test methods specified in *Sand for Construction* (GB/T 14684-2011) and *Pebble and Crushed Stone for Construction* (GB/T 14685-2011) were used to measure the basic properties of the RAC aggregates and crushed clay bricks, as shown in Table 1. The cement for the concrete is PC32.5 Portland composite cement, which was provided by Hunan Ningxiang South Cement Co., Ltd. The cement indicators are shown in Table 2.

2.2. Design of Mix Ratio. Since the water absorptions of recycled aggregates and crushed clay bricks are very different from that of natural aggregates, it is necessary to consider the effects of additional water. A trial mixing was conducted using the preliminary mix ratio in Table 3. In maintaining the water-cement ratio at 0.40, the amounts of sand and water were adjusted until the slump met the design requirements. Finally, the standard mix ratio that meets the design and workability requirements was obtained, as shown in Table 4. Table 4 includes the additional water for coarse and fine recycled aggregates. The additional water for crushed clay bricks can be adjusted according to the water absorption rate in Table 1.

2.3. Fabrication and Curing of Concrete Specimens. The specimens for the compressive strength test were made

(a) The new standard new clay brick

(b) Brick crusher

(c) The crushed clay bricks

FIGURE 1: The crushed clay brick aggregates used in the tests.

(a) Waste concrete

(b) Crushing machines

(c) The recycled aggregates

FIGURE 2: The recycled concrete aggregates used in the tests.

from a standard compressive strength test block mold of 150 mm × 150 mm × 150 mm and cured in a standard curing chamber with a temperature of 20 ± 2°C and relative humidity above 95%.

2.4. Compressive Strength Test. The compressive strength test for RAC with recycled fine and coarse aggregates or fine and coarse crushed clay bricks was conducted following the Standard for Test Method of Mechanical Properties on

Table 1: Properties of RAC aggregates and crushed clay bricks used in the tests.

Test indexes	RAC aggregate			Crushed clay bricks		
	0-4.75 mm	4.75-9.50 mm	9.50-19 mm	0-4.75 mm	4.75-9.50 mm	9.50-19 mm
Apparent density/(g•cm^{-3})	2.60	2.65	2.61	2.30	2.43	2.41
Water absorption/(%)	8.20	4.58	3.43	11.30	11.55	10.72
Flat and elongated particles/(%)	—	7.7	6.8	—	7.6	7.8
Crushing strength/(%)	—	23.6		—	29.3	
Liquid limit/(%)	27.3	—		27.8	—	
Plastic limit/(%)	22.2	—		23.4	—	
<0.075 mm/(%)	2.7	—		3.5	—	

Table 2: Technical indicators of the cement.

Standard consistency/(%)	Setting time/min		Flexural strength/(MPa)		Compressive strength/(MPa)	
	Initial setting	Final setting	3 d	28 d	3 d	28 d
28	128	235	4.4	7.6	17.3	33.2

Table 3: Preliminary mix ratio.

Mix ratio/(kg·m^{-3})				Water-cement ratio	Sand ratio/%	Additional water/(kg·m^{-3})
Cement	Water	Sand	Coarse aggregate			
462.5	185	576.4	1070.8	0.40	35	86

Ordinary Concrete (GB/T 50081-2016). The specific test scheme is shown in Table 5. Similar to recycled aggregates, the fine and coarse crushed clay bricks were graded according to the threshold of 4.75 mm and separately mixed into the concrete according to the designed mix ratio. The size of the test piece is 150 mm ∗ 150 mm ∗ 150 mm, and the test loading rate is 0.4 MPa/s.

2.5. Microscopic Tests. SEM and XRD were employed to examine and analyze the microscopic structure, hydration reactions, hydration products, and crystalline mineral components at the interfacial transition zones between different aggregates and cement mortars.

3. Results and Discussion

3.1. Effects of Coarse Crushed Clay Brick Content on the Compressive Strength of RAC and NAC. Figures 3(a) and 3(b) show the relationship between compressive strength and age of NAC and RAC at different coarse brick contents. As shown in Figure 3(a), the compressive strength of NAC gradually decreases at each age with the increase of coarse crushed clay brick content. In addition, the compressive strength increase rate of NAC slows down with age, which is consistent with the findings of Hu et al. [16]. The main reason is that the strength of waste brick aggregates is lower than that of natural aggregates. At the age of 3 d, the compressive strength of NAC with 60% coarse crushed clay bricks is 17.3 MPa, which is 22.07% lower than that with 0% coarse crushed clay bricks. At the age of 60 d, the decrease reaches 30.66%.

As shown in Figures 3(a) and 3(b), the compressive strength of RAC is significantly lower than that of NAC with the same content of crushed clay bricks. For example, at the age of 3 d, the compressive strength of RAC with 60% coarse crushed clay bricks is 11.3 MPa, which is 27.98% lower than that of NAC with 60% coarse crushed clay bricks. Therefore, the compressive strength of RAC with different coarse crushed clay brick content has a relatively large dispersion. Nevertheless, with the higher content of the crushed clay bricks, the compressive strength at each age is lower, and the increase of compressive strength slows down. Thus, crushed clay brick content is a key factor affecting the compressive strength [24].

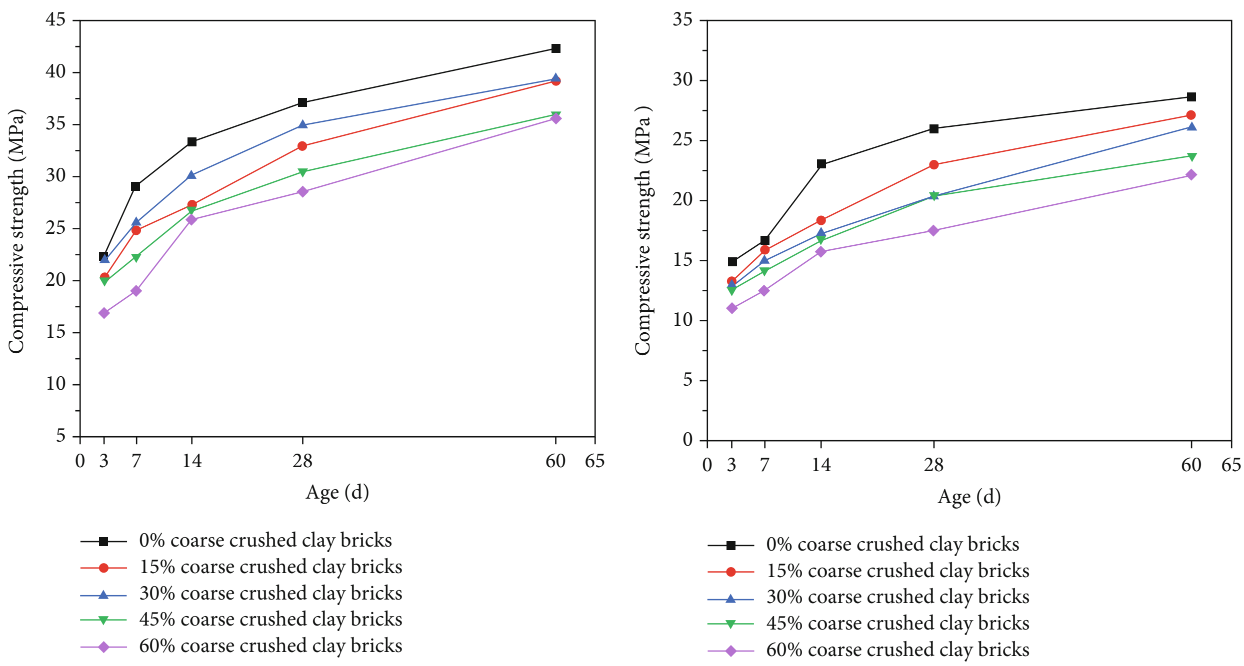
3.2. Effects of Fine Crushed Clay Brick Content on the Compressive Strength of RAC and NAC. Figures 4(a) and 4(b) show the relationship between the compressive strength and age for NAC and RAC with different fine crushed clay brick contents. According to Figures 3 and 4, the change of compressive strength over time for NAC and RAC with different fine crushed clay brick contents is similar to that with coarse crushed clay bricks. However, the line distribution of the compressive strength data for different fine brick contents is closer in Figure 4 than in Figure 3, indicating less dispersion of the data. For example, at the age of 60 d, the compressive strength of RAC with 60% fine crushed clay bricks is 25.6 MPa, which is 10.49% lower than that with 0% fine crushed clay bricks. Under the same conditions,

Table 4: Standard mix ratio.

Mix ratio/(kg·m^{-3})				Water-cement ratio	Sand ratio/(%)	Additional water/(kg·m^{-3})
Cement	Water	Sand	Coarse aggregate			
493.8	195	576.4	1070.8	0.40	35	86

Table 5: Compressive strength test scheme.

Experiments	Concrete type	Water-cement ratio	Coarse crushed clay brick content/(%)	Fine crushed clay brick content/(%)	Age/(d)
Compressive strength	RAC	0.4	0, 15, 30, 45, 60	0, 15, 30, 45, 60	3, 7, 14, 28, 60
	NAC		0, 15, 30, 45, 60	0, 15, 30, 45, 60	



(a) Compressive strength of NAC at the water-cement ratio of 0.40

(b) Compressive strength of RAC at the water-cement ratio of 0.40

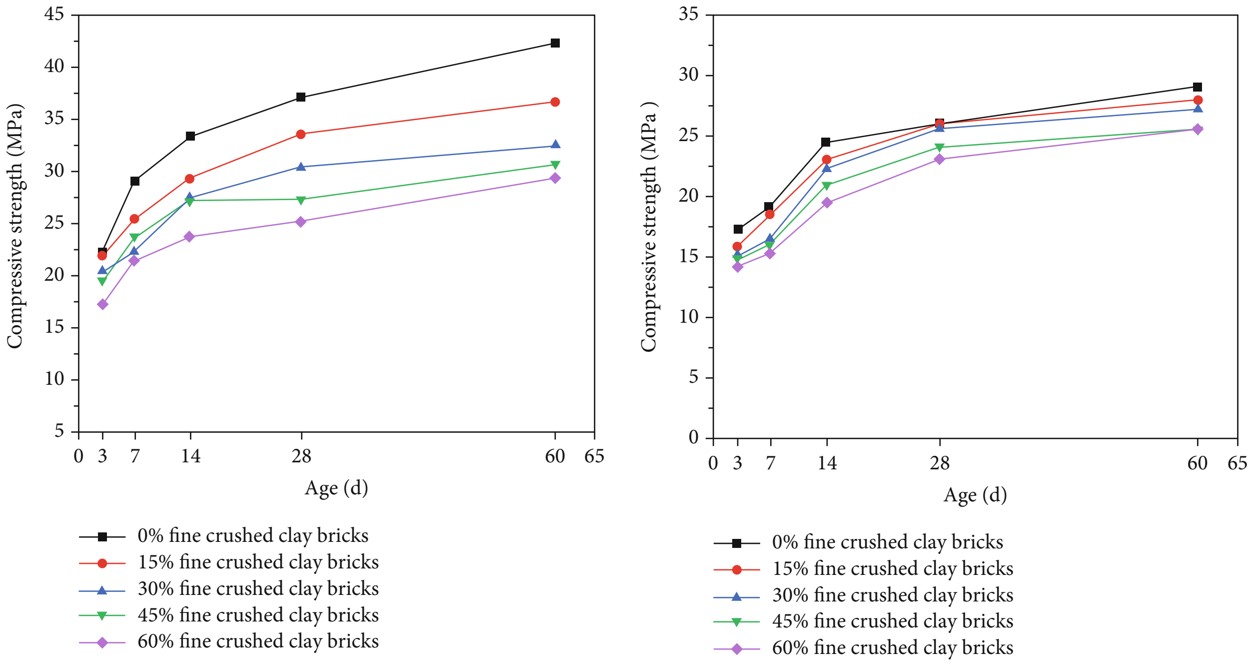
Figure 3: The compressive strength of NAC and RAC with different coarse crushed clay brick contents.

the compressive strength of RAC with coarse crushed clay bricks decreases by 14.75%. Therefore, the effects of fine crushed clay bricks on the compressive strength are relatively small.

At the same age and replacement rate, the compressive strengths of NAC and RAC with fine crushed clay bricks are slightly higher than those with coarse crushed clay bricks at the same age. For example, at the age of 28 d, the compressive strength of NAC with 15% fine crushed clay bricks (35 MPa) is 4.17% higher than NAC with 15% coarse crushed clay bricks (33.6 MPa). At the age of 60 d, the compressive strength of RAC with 30% fine crushed clay bricks is 27.5 MPa, which is 5.36% higher than that with 30% coarse crushed clay bricks.

The reason for the above results may be that the coarse crushed clay bricks (coarse aggregate) are the structural skeleton of the concrete and the main source of compressive strength, while fine crushed clay bricks (fine aggregate) fill the pores in the concrete and have little effect on concrete strength. Furthermore, the coarse crushed clay bricks have a larger particle size, resulting in a smaller total surface area. This structure reduces the interface area of crushed clay bricks and cement mortar, leading to a decrease in the compressive strength of the concrete.

3.3. Effects of Different Gradings on the Compressive Strength of RAC and NAC. Figure 5 shows the effects of different gradings on the compressive strength of RAC and NAC. In



(a) The compressive strength of NAC at the water-cement ratio of 0.40 (b) The compressive strength of RAC at the water-cement ratio of 0.40

Figure 4: The compressive strength of NAC and RAC with different fine crushed clay brick contents.

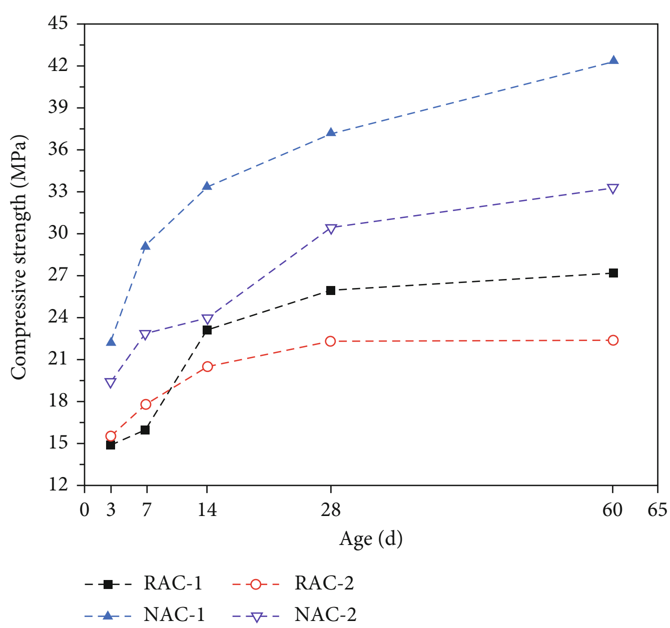


Figure 5: The compressive strength of NAC and RAC with different gradings.

this figure, RAC-1 represents RAC with continuous grading; RAC-2 is RAC with single particle size gap grading (9.5-19 mm); NAC-1 represents NAC with continuous grading; and NAC-2 denotes NAC with single particle size gap grading (9.5-19 mm).

According to Figure 5, the compressive strength of RAC at each age is significantly lower than that of NAC. In addition, the compressive strength of concrete with continuous grading at each age is higher than concrete with single particle size grading, and the difference becomes more obvious with the increase of age. Due to the large pores in the large-sized recycled aggregates and the lack of small-sized aggregates to fill the pores, the compressive strength decreases due to the increased porosity. Compared with

(a) Initial compression state (b) Maximum compression state

Figure 6: Compression failure of RAC with 60% coarse crushed clay bricks.

RAC, the compressive strength of NAC is more significantly affected by grading. Before the age of 14 d, the compressive strength of RAC with continuous grading is similar to that of RAC with single particle size grading. With the increase of age, the difference in the compressive strength of RAC with the two gradings gradually becomes larger. At the age of 3 d, the compressive strength of RAC with continuous grading is 14.9 MPa, which is 3.87% higher than that of RAC with single particle size grading. At the age of 60 d, the compressive strength of the former reaches 27.2 MPa, which is 21.43% higher than that of the latter.

3.4. Analysis of RAC Compression Failure Characteristics. Figure 6 shows the compression failure of concrete with crushed clay bricks at different pressure levels. As shown in Figure 6(a), near-vertical cracks appear near the vertical edges of RAC with 60% coarse crushed clay bricks under a certain load, most of which are in the lower and lateral parts of the concrete specimens. As the load increases, more cracks appear, and the existing cracks expand. In addition, numerous new cracks appear on both sides (Figure 6(b)), extending diagonally to form a V shape and increasing the damage in the upper part of the concrete specimen. Because many cracks appear in the same place, new and old cracks gather and cause the cement and fine sand to fall off separately. Since the aggregate and cement are tightly combined in the upper part of the concrete specimen, a bulge is formed and separated from the original bonding surface, with the corners of the specimen gradually falling off.

Figures 7(a) and 7(b) show the damage morphology at the interfacial transition zones in NAC and RAC with 60% coarse crushed clay bricks after the compression failure test under pressure. According to Figures 7(a) and 7(b), the failures in RAC with 60% coarse crushed clay bricks are at the interfacial transition zones between the aggregate and cement and inside the crushed clay bricks. The difference in elasticity modulus between aggregate and cement mortar is large, and the strength of crushed clay bricks is low. Therefore, reducing the difference in elastic modulus between the aggregate phase and the mortar phase can delay the formation of cracks, thereby increasing the strength of concrete [6]. The old cement mortar on the surface of the recycled aggregates in RAC with 60% coarse crushed clay bricks is easier to be crushed due to its loose and porous structure. The failures in NAC are at the interfacial transition zones because the aggregate is strong and not easily crushed.

4. Microscopic Analysis

4.1. SEM Results and Analysis

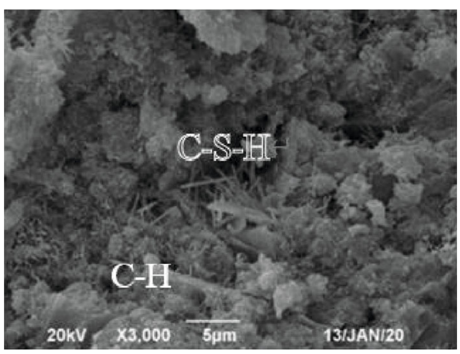
4.1.1. Hydration Reactions with Different Crushed Clay Brick Contents. Figures 8 and 9 show the SEM images of NAC and RAC with 0% and 60% coarse crushed clay bricks at the ages of 7 d and 28 d, respectively. As shown in Figures 8(a) and 9(a), the hydration products of NAC at the age of 7 d are flaky $Ca(OH)_2$ crystals, vertical strips of hydrated calcium silicate crystals (C-S-H), and irregular cement materials, which exist in the interstices of concrete aggregates. According to Figures 8(a)–8(c), the hydration products in NAC and RAC with 0% coarse crushed clay bricks and RAC with 60% coarse crushed clay bricks decrease sequentially at the age of 7 d. This result may be attributed to the small particle size of the recycled coarse aggregate and the large specific surface area. This structure leads to high water absorption, depriving the cement paste of abundant free water and making the cementitious material completely hydrated [15]. As shown in Figures 8(c) and 9(c), the crushed clay bricks do not affect the types of concrete hydration products, and C-S-H and $Ca(OH)_2$ crystals remain as the early hydration products in RAC with 60% coarse crushed clay bricks. Moreover, the microstructure of RAC with 60% coarse crushed clay bricks at the age of 28 d is denser than that at the age of 7 d, and the hydration products significantly increase. As a result, the later hydration reaction is very violent, producing large hydration products that form a dense structure around the cement particles, thus substantially increasing the compressive strength.

4.1.2. Analysis of SEM Images of the Interfacial Transition Zone. Figure 10 shows SEM images of the interfacial transition zone between natural aggregate, recycled aggregate, crushed clay bricks, and cement mortar at the age of 28 d. As shown in Figure 10(a), the interfacial transition zone between the natural aggregate and cement paste is not obvious, indicating that the cement paste bonds well with natural aggregates at the interfacial transition zones. Figure 10(b)

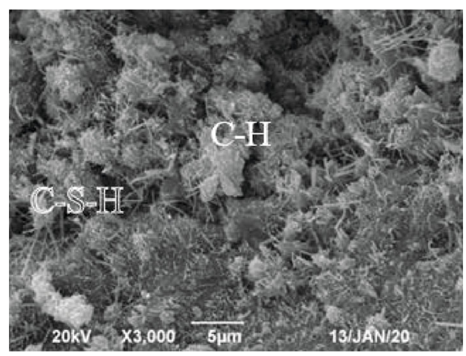
(a) NAC

(b) RAC

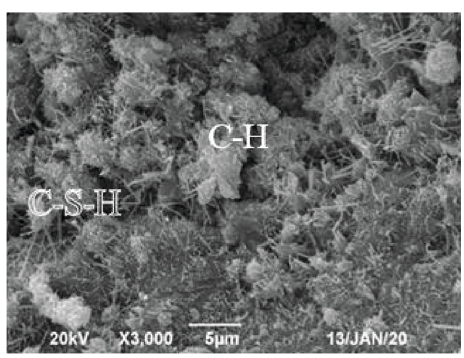
Figure 7: Compression failure morphology at the interfacial transition zones.



(a) 7 d NAC



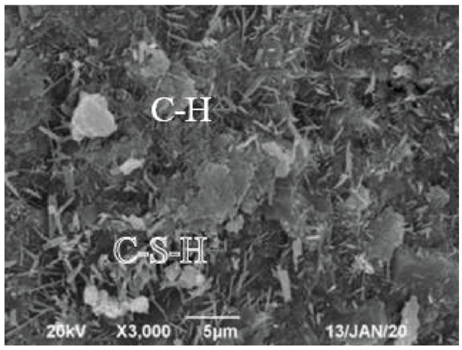
(b) 7 d RAC with 0% crushed clay bricks



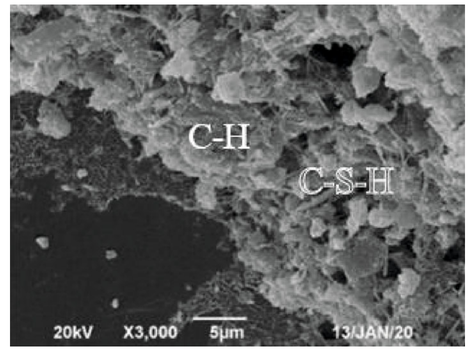
(c) 7 d RAC with 60% coarse crushed clay bricks

Figure 8: Microscopic morphology of NAC and RAC with 0% or 60% coarse crushed clay bricks at the age of 7 d (magnified 3000 times).

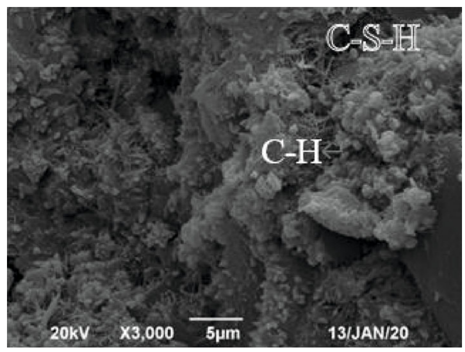
shows the old interfacial transition zone between recycled aggregate and old cement mortar, the new interfacial transition zone between recycled aggregate and new cement mortar, and the interfacial transition zone between the new and old cement mortar blocks. During crushing and concrete sample preparation, the adhesion between the recycled aggregate and the old cement mortar decreases due to collision and friction between the recycled aggregate and the old cement mortar. The microstructure of crushed clay bricks in Figure 10(c) is loose and porous, which is looser than that of the cement at the age of 28 d. However, the early strength of the concrete with crushed clay bricks is relatively low due to the rough brick surface and good adhesion to new cement paste. The slow hydration reaction of the cement paste at an early age leads to incomplete hydration and a small amount of cement that can be bonded with crushed clay bricks. At the later stage, the cement paste in the concrete with crushed clay bricks is fully hydrated, producing large



(a) 28 d NAC

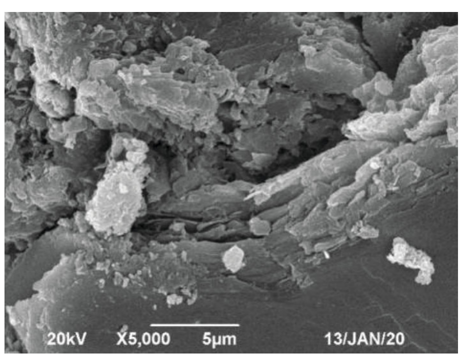


(b) 28 d RAC with 0% crushed clay bricks

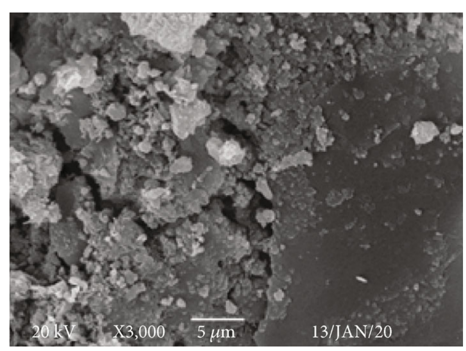


(c) 28 d RAC with 60% coarse crushed clay bricks

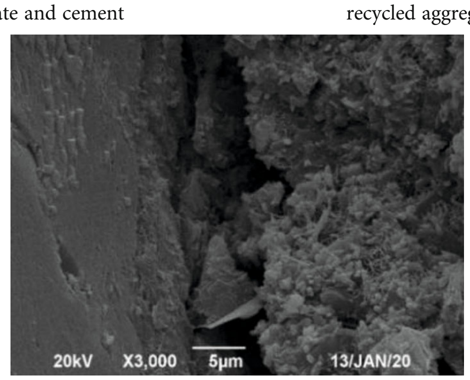
Figure 9: Microscopic morphology of NAC and RAC with 0% or 60% coarse crushed clay bricks at the age of 28 d (magnified 3000 times).



(a) The interfacial transition zone between natural aggregate and cement

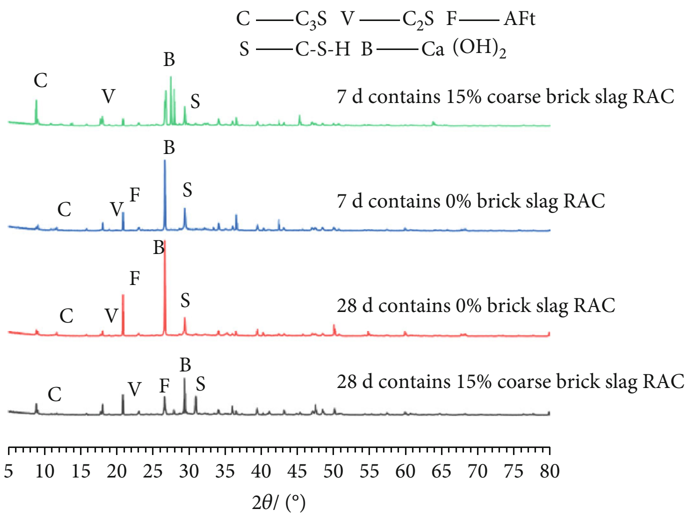


(b) The interfacial transition zone between recycled aggregate and cement

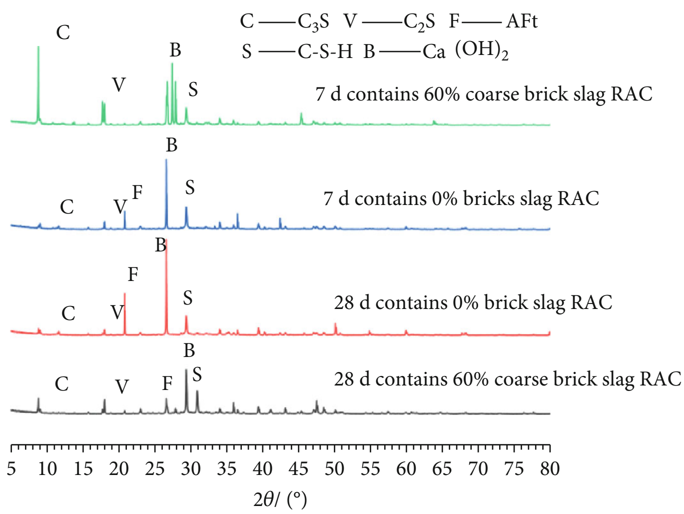


(c) The interfacial transition zone between coarse crushed clay bricks and cement

Figure 10: Microscopic morphology of the interfaces between the three aggregates and the cement paste (magnified 3000 times).



(a) RAC with 0% and 15% crushed clay bricks



(b) RAC with 0% and 60% crushed clay bricks

Figure 11: XRD diffraction spectra.

hydration products that fill the pores on the crushed clay brick surface. Then, the cement is bonded with the crushed clay bricks so that the later stage strength of the RAC is significantly increased. Nevertheless, the strength of crushed clay bricks is very low and even lower when water is absorbed, resulting in the concrete with crushed clay bricks having lower strength than RAC.

4.2. XRD Results and Analysis. Figure 11 shows the XRD spectra of the slurry mineral phases of the three RACs (0%, 15%, and 60% crushed clay bricks) at different ages.

As shown in Figure 11, a small amount of C_3S and C_2S peaks, a large number of C-S-H and $Ca(OH)_2$ peaks, and a small amount of AFt peaks can be observed in the hydration products of RAC at the age of 7 d, indicating a high level of hydration reaction. In contrast, at the age of 7 d, the intensity of C-S-H and $Ca(OH)_2$ crystals peaks in the RAC with 15% or 60% coarse crushed clay bricks gradually decreases, the intensity of C_3S and C_2S peaks increases in that order, and no AFt peaks are observed. Therefore, the hydration reaction of RAC with coarse crushed clay bricks is insufficient at the age of 7 d, and few hydration products are produced. With the increase of crushed clay brick content, this trend becomes more significant, resulting in the lower early-stage strength of RAC with coarse crushed clay bricks than RAC at the age of 7 d. At the age of 28 d, the C_3S and C_2S peaks in RAC almost disappear, and the intensities of C-S-H, $Ca(OH)_2$ crystals, and AFt peaks continue to increase, indicating that the hydration reaction of RAC is basically completed. Similarly, the intensities of C-S-H, $Ca(OH)_2$ crystals, and AFt peaks of RAC with 15% or 60% coarse crushed clay bricks are enhanced at the age of 28 d. However, the intensity of hydration product peaks is still lower than that of the RAC with 0% crushed clay bricks, resulting in the compressive strength trend of RAC with different coarse crushed clay brick contents shown in Figure 3(b). Without sufficient hydration products, the porosity of the RAC microstructure increases, causing the macroscopic manifestation of decreased compressive strength.

5. Conclusions

(1) Crushed clay bricks reduce the compressive strength of NAC and RAC, this is because coarse crushed clay bricks (coarse aggregates) are the main source of structural skeleton and compressive strength of concrete, while fine crushed clay bricks (fine aggregates) fill the pores in the concrete. Therefore, the compressive strength of RAC with coarse crushed clay bricks is lower than that of RAC with fine crushed clay bricks under at same age and content

(2) The compressive strength of concrete with continuous grading at each age is higher than that with single particle size grading. Compared with RAC, the compressive strength of NAC is more significantly affected by grading

(3) The interfacial transition zones inside RAC have loose crystals and high porosity, and the bonding between the crushed clay bricks and mortar interfaces is weak. However, the crushed clay bricks do not influence the types of concrete hydration products, and C-S-H and $Ca(OH)_2$ crystals remain as the early hydration products in RAC with crushed clay bricks

(4) The crushed clay bricks have an inhibiting effect on the hydration reaction of concrete, and a higher amount of crushed clay bricks has a more significant inhibiting effect. Since the hydration products mainly play the role of filling and bonding in the RAC microstructure, their reduced output can decrease the compactness of the RAC microstructure, which ultimately reduces the compressive strength of the RAC

Data Availability

The data used to support the results of this study are available from the corresponding authors upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Jin Chang contributed to the experiment, methodology, and revision. Shi-lin Luo and Ailifeila Aierken contributed to the algorithms, analysis, and writing-original draft. Lin-lin Chong contributed to the data curation and language editing. Jian-Qing Jiang contributed to the revision.

Acknowledgments

This research was financially supported by the National Natural Science Foundation of China (42107166), the Hunan Provincial Natural Science Foundation (2021JJ30758 and 22021JJ40632), the Scientific Research Project from the Education Department of Hunan Province (21C0753), and Changsha Municipal Natural Science Foundation (kq2007089 and kq2202065).

References

[1] J. Xiao, H. F. Ma, C. F. Wu, M. Yang, and J. S. Zhang, "Study on the performance of recycled granular base mixture of construction solid waste," *Journal of Building Materials*, vol. 21, no. 3, p. 6, 2018.

[2] C. L. Wong, K. H. Mo, P. Yaps, U. Alengaram, and L. Tung-Chai, "Potential use of brick waste as alternate concrete-making materials: a review," *Journal of Cleaner Production*, vol. 195, pp. 226–239, 2018.

[3] L. H. Zhu and Z. M. Zhu, "Reuse of clay brick waste in mortar and concrete," *Advances in Materials Science and Engineering*, vol. 2020, 11 pages, 2020.

[4] C. C. Zheng, C. Lou, G. Du, X. Z. Li, Z. W. Liu, and L. Q. Li, "Mechanical properties of recycled concrete with demolished waste concrete aggregate and clay brick aggregate," *Results in Physics*, vol. 9, pp. 1317–1322, 2018.

[5] Z. P. Chen, D. H. Zhan, and J. Q. Xu, "Analysis of recycled coarse aggregate content on mechanical properties of recycled concrete," *Industrial construction*, vol. 45, no. 1, pp. 130–135, 2015.

[6] Q. Liu, J. Z. Xiao, Z. S. Pan, and L. Li, "Investigation on modeled recycled concrete prepared with recycled concrete aggregate and recycled brick aggregate," *Journal of Architectural Structure*, vol. 41, no. 12, pp. 136–143, 2020.

[7] J. Xiao, C. F. Wu, Z. H. Zhan, X. G. Tang, and W. J. Dong, "Research on performances of cement stabilized brick and concrete recycled aggregate base," *China Journal of Highway and Transport*, vol. 30, no. 2, pp. 25–32, 2017.

[8] M. M. Disfani, A. Arulrajah, H. Haghighi, A. Mohammadinia, and S. Horpibulsuk, "Flexural beam fatigue strength evaluation of crushed brick as a supplementary material in cement stabilized recycled concrete aggregates," *Construction & Building Materials*, vol. 68, pp. 667–676, 2014.

[9] D. A. fur Stahlbeton, *Beton mit rezykliertem Zuschlag*, Dafstb-Richtline, 1998.

[10] J. Mills-Beale, Z. You, R. C. Williams, and Q. L. Dai, "Determining the specific gravities of coarse aggregates utilizing vacuum saturation approach," *Construction & Building Materials*, vol. 23, no. 3, pp. 1316–1322, 2009.

[11] J. T. Dang and J. Zhao, "Influence of waste clay bricks as fine aggregate on the mechanical and microstructural properties of concrete," *Construction and Building Materials*, vol. 228, article 116757, 2019.

[12] J. Xiao, H. F. Ma, C. F. Wu, M. Yang, and J. S. Zhang, "Study on performance of construction and demolition waste recycled aggregate base mixture," *Journal of Architectural Structure*, vol. 21, no. 3, pp. 511–515+522, 2018.

[13] L. Suo, P. Peng, and Y. R. Zhao, "Research on intensified recycled coarse aggregate," *Materials Reports*, vol. 2015, no. 5, pp. 362–365, 2015.

[14] B. Lei, Z. X. Li, J. G. Xiong, and G. Q. Song, “Review on the properties of recycled concrete based on meso scale,” *Bulletin of the Chinese Ceramic Society*, vol. 36, no. 6, pp. 1921–1928, 2017.

[15] Q. Li, Q. Feng, and H. Cao, “Effects of recycled aggregates gradation on mechanical performance of concrete and microscopic performance analysis,” *Journal of Jiangsu University (Natural Science Edition)*, vol. 40, no. 5, pp. 614–620, 2019.

[16] L. Q. Hu and A. M. Sha, “Performance test of cement stabilized crushed clay brick for road base material,” *China Journal of Highway and Transport*, vol. 25, no. 3, 2012.

[17] J. Yang, Q. Du, and Y. W. Bao, “Concrete with recycled concrete aggregate and crushed clay bricks,” *Construction and Building Materials*, vol. 25, no. 4, pp. 1935–1945, 2011.

[18] P. K. Mehta, “Advancements in concrete technology,” *Concrete International*, vol. 1999, no. 6, pp. 69–76, 1999.

[19] P. C. Aitcin and A. M. Neville, “High performance concrete demystified,” *Concrete International*, vol. 15, no. 1, pp. 21–26, 1993.

[20] Y. Zhao, C. L. Wang, L. Ning, H. F. Zhao, and J. Bi, “Pore and fracture development in coal under stress conditions based on nuclear magnetic resonance and fractal theory,” *Fuel*, vol. 2022, no. 309, article 122112, 2022.

[21] Y. Zhao, C. Wang, M. Teng, and J. Bi, “Observation on microstructure and shear behavior of mortar due to thermal shock,” *Cement and Concrete Composites*, vol. 121, p. 104106, 2021.

[22] J. Chen, Y. Geng, Y. Y. Wang, and W. J. Sun, “Basic mechanical properties and stress-strain relationship for recycled concrete including crushed clay bricks,” *Journal of Architectural Structure*, vol. 41, no. 12, pp. 187–195, 2020.

[23] K. L. Ma, X. Y. Huang, M. W. Hu et al., “Mechanical properties and engineering application of brick-concrete recycled coarse aggregate concrete,” *Bulletin of the Chinese Ceramic Society*, vol. 39, no. 8, pp. 2600–2607, 2020.

[24] D. X. Xuan, A. A. A. Molenaar, and L. J. M. Houben, “Evaluation of cement treatment of reclaimed construction and demolition waste as road bases,” *Journal of Cleaner Production*, vol. 100, pp. 77–83, 2015.