Research Article

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Influence of recycled clay brick aggregate on the mechanical properties of concrete

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Abstract: This article presents the experimental results of the compressive strength, the splitting tensile strength, the macro destruction mode, and the microstructure of recycled clay brick aggregate concrete (RBC) with different recycled clay brick aggregate (RBA) replacement rates. The results show that the compressive strength and the splitting tensile strength of RBC are lower than those of natural aggregate concrete (NAC), but the effect of RBA on the splitting tensile strength of concrete is not significant. The effect of the water–cement ratio (w/c) on the splitting tensile strength of RBC is smaller than that on the splitting tensile strength of NAC. The compressive strength of concrete shows a trend of first decreasing and then increasing with the increase in RBA replacement rates. The effect of RBA replacement rates on the compressive strength gradually decreases with the increase in the w/c. The AFt in NAC is thicker than that in RBC, and the C–S–H of RBC is in the form of agglomerated networks with large and uniform pores and less filler.

Keywords: recycled brick aggregate concrete, recycled clay brick aggregate replacement rate, compressive strength, splitting tensile strength, microstructure

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1 Introduction

With the rapid development of the construction industry, concrete has been widely used as the main building material [1]. Global demand for concrete is expected to grow to approximately 18 billion tons per year by 2050 [2]. As a result, natural sand and gravel resources are almost exhausted, and their prices continue to rise [3]. In addition, a large amount of construction waste will be generated in the process of building reconstruction and expansion [4]. The waste clay bricks (WB) and waste concrete (WC) are the main components of construction waste [5], and the resource utilization and utilization methods of WB and WC directly affect the process of construction waste recycling and industrialization [6]. Recycled aggregate concrete (RAC) could improve the utilization of construction waste and promote the sustainable development of the construction industry [7].

Scholars have completed the research on the concrete with recycled concrete aggregate (RCA) [8,9]. Xu et al. [10] point out that the compressive strength of RAC was lower than that of natural aggregate concrete (NAC), while the flexural strength showed a trend of first decreasing and then increasing continuously with the increase in the RCA replacement rates. Wang [11] found that the compressive strength and splitting tensile strength of concrete decreased with the increase in RAC replacement rates, and the water–cement ratio (w/c) has a great influence on the compressive strength and splitting tensile strength of RAC. Xiao et al. [12] point out that most studies found that the long-term performance of RAC was inferior to that of NAC, and there were different opinions among researchers that the long-term performance of RAC was worse than that of NAC.

Some scholars have also conducted research on improving the performance of RAC. Corinaldesi [13] proposed a good method for configuring RAC, which can meet the requirements for the strength, durability, and workability of RAC. Gao et al. [14] investigated the effect of CO_2-enhanced RCA on the performance of RAC, and found that the method of CO_2-enhanced aggregate significantly reduced the water absorption rate of RCA and significantly improved the compressive strength and resistance to chloride-ion penetration of RAC. Lei et al. [15] point out that the mechanical properties and frost resistance of RAC were effectively improved with the increase in graphene oxide content.

Actually, most of the demolished buildings in China are brick-concrete structures. However, the research on concrete with recycled clay brick aggregate (RBA) was less [16]. Compared with natural aggregate, RBA has the characteristics of high porosity, low density, and high water absorption [17]. Cachim [18] investigated the compressive strength, the tensile splitting strength, the elastic modulus, and the stress–strain of recycled clay brick aggregate concrete (RBC) and found that the type of brick could affect the mechanical properties of RBC; care must be taken when substituting crushed brick for natural aggregate. Zhang and Zong [19] point out that the compressive strength of RBC was lower than that of NAC, while the compressive strength of RBC with 30% RBA could meet the requirements of strength standards. Khalaf and Devenny [20] found that a portion of the brick aggregate had good physical and mechanical properties, which could be used to produce high-quality concrete. Mohammed et al. [21] point out that RBA could be used to produce concrete with strengths ranging from 20.7 to 31.0 MPa. Liu et al. [22] found that the equal volume substitution method was better than the equal quality substitution method to replace the crushed stone with RBA. Yan and Chen [23] investigated the mechanical properties of RBC and found that the compressive strength and flexural strength of RBC increased with age, while the compressive-compression ratio decreased, but the brittleness was lower than that of NAC. Chen et al. [24] and Poon et al. [25] investigated the effect of RBA replacement rate on concrete strength and found that when the replacement rate was controlled within a certain range, it would not have a great impact on the mechanical properties of concrete. Li et al. [26] investigated the effect of RBA on the mechanics and frost resistance of concrete and discussed its effect on the microstructure of concrete by analyzing the micro-hardness and porosity of concrete. Due to the high water absorption characteristics of RBA, the method of pre-wetting aggregate affected the interface transition zone of RBC [27]. The concrete prepared by soaking RBA in the water had better performance [28], so RBA should reached the surface-dry moisture state before mixing [29,30].

It can be found that RBA can be used as coarse aggregate for the preparation of concrete [31]. However, there is no consensus on the basic mechanical properties of RBC with different RBA replacement rates. Therefore, this article investigated the compressive strength, the splitting tensile strength, and macro destruction mode of RBC with different RBA replacement rates and analyzed the reason for the difference in mechanical properties between RBC and NAC by microstructural analysis.

2 Experiment

2.1 Materials

2.1.1 Natural coarse aggregate (NCA)

The NCA was natural crushed stone, and the particle range of NCA was 5–26.5 mm; the sieving result of NCA is shown in Figure 1. The water absorption rate of NCA was 1.9%, and the crushing index was 9.8%.

2.1.2 Fine aggregate

The fine aggregate was natural river sand with a 2.64 fineness module conforming to the Chinese standard JGJ52-2006 [32]. The mud content of fine aggregate was 2.1%. The bulk density and apparent density were 1,439 and 2,639 $kg \cdot m^{-3}$, respectively.

2.1.3 Cement

The cement used in this article was P.O 42.5 conforming to the Chinese standard GB 175-2007 [33]. The specific surface area of cement was 354 $kg \cdot m^{-3}$, and the ignition

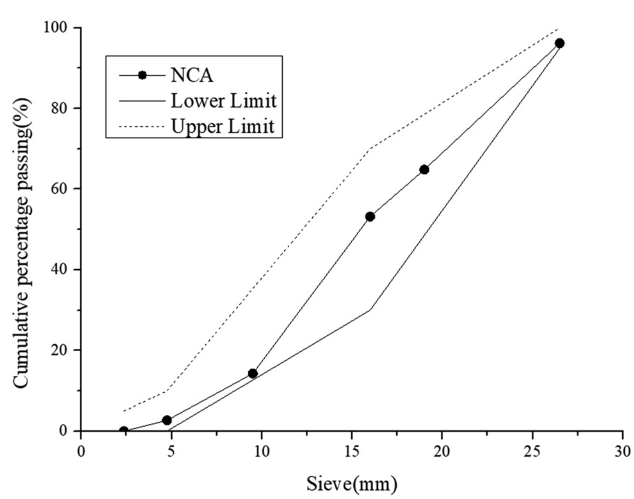

Figure 1: Sieving result of NCA.

Figure 2: Aggregate crushing.

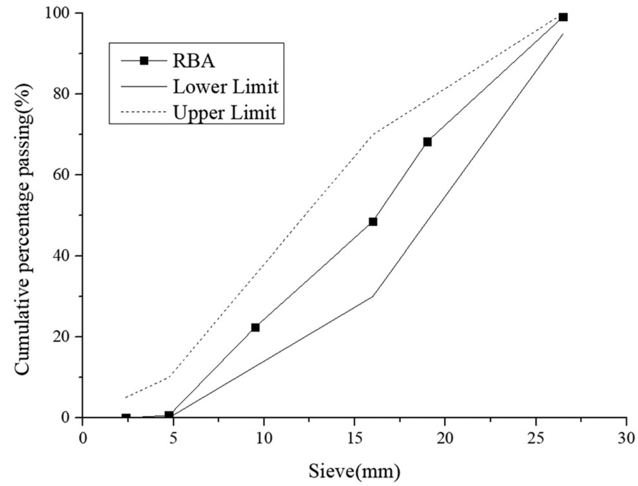

Figure 3: Sieving result of RBA.

loss was 1.8%. The 28-day compressive strength and flexural strength were 51.2 and 9.3 MPa, respectively. The initial setting time and final setting time were 208 and 273 min, respectively. The SO_3 content is 2.31%, while MgO content is 1.68%.

2.1.4 Clay brick aggregate

RBA adopted a combination of manual and mechanical crushing methods: first, it was initially crushed manually to remove impurities; then, it was further crushed with a small jaw crusher, as shown in Figure 2, and the particle range was 5–26.5 mm. The sieving result of RBA is shown in Figure 3. The water absorption rate of RBA was 12.5%, and the crushing index was 27.5%. The apparent density was 2,445 kg·m^{-3}.

2.2 Mix proportions

The mix proportions for RBC and NAC are shown in Table 1. Note that RBA reached the surface-dry moisture state by pre-soaking it in water for 24 h before use [34].

2.3 Specimen pouring and curing

The 150 mm × 150 mm × 150 mm cubic specimens were cast to investigate the compressive strength and the splitting tensile strength of concrete, three specimens per group.

Table 1: Mix proportions (kg·m^{-3})

Concrete type	w/c	RBA replacement rates (%)	Water	Cement	Sand	NCA	RBA
NAC	0.48	0	185	385.4	695	1,200	0
	0.58	0	185	319	720	1,176	0
	0.68	0	185	272	738	1,158	0
RBC	0.48	10	185	385.4	695	1,080	105
		20	185	385.4	695	960	210
		30	185	385.4	695	840	315
		40	185	385.4	695	720	420
		50	185	385.4	695	600	525
	0.58	30	185	319	720	823.2	308.7
		50	185	319	720	588	514.5
	0.68	30	185	272	738	810.6	304
		50	185	272	738	579	506.6

After the specimens were cast, they were placed in an air-conditioned room for 24 h; then, the mold was removed, watered for 7 days, and then cured at room temperature until the test began.

3 Tests and results

3.1 Compressive strength test

Cube compressive strength test was performed according to Chinese standard GB50081-2016 [35]. The formula for calculating the cube compressive strength of the concrete was as follows:

$$f_{\mathrm{cu}} = F/A, \tag{1}$$

where f_{cu} is the cube compressive strength, MPa; F is the cube specimen failure load, N; A is the pressure-bearing area, mm^2.

Figure 4 shows the relationship between the compressive strength of concrete and RBA replacement rates.

As shown in Figure 4, the compressive strength of RBC was lower than that of NAC (RBA replacement rate is 0%), which agree with the findings of Zhang and Zong [19]. The main reasons are as follows: first, the damage cracks appear in the RBA during the crushing process, and there is attached waste brick powder on the surface of RBA (as shown in Figure 5), resulting in poor adhesion with the cement paste, so the strength of RBC was lower than that of NAC; second, the crushing index of RBA is 2.8

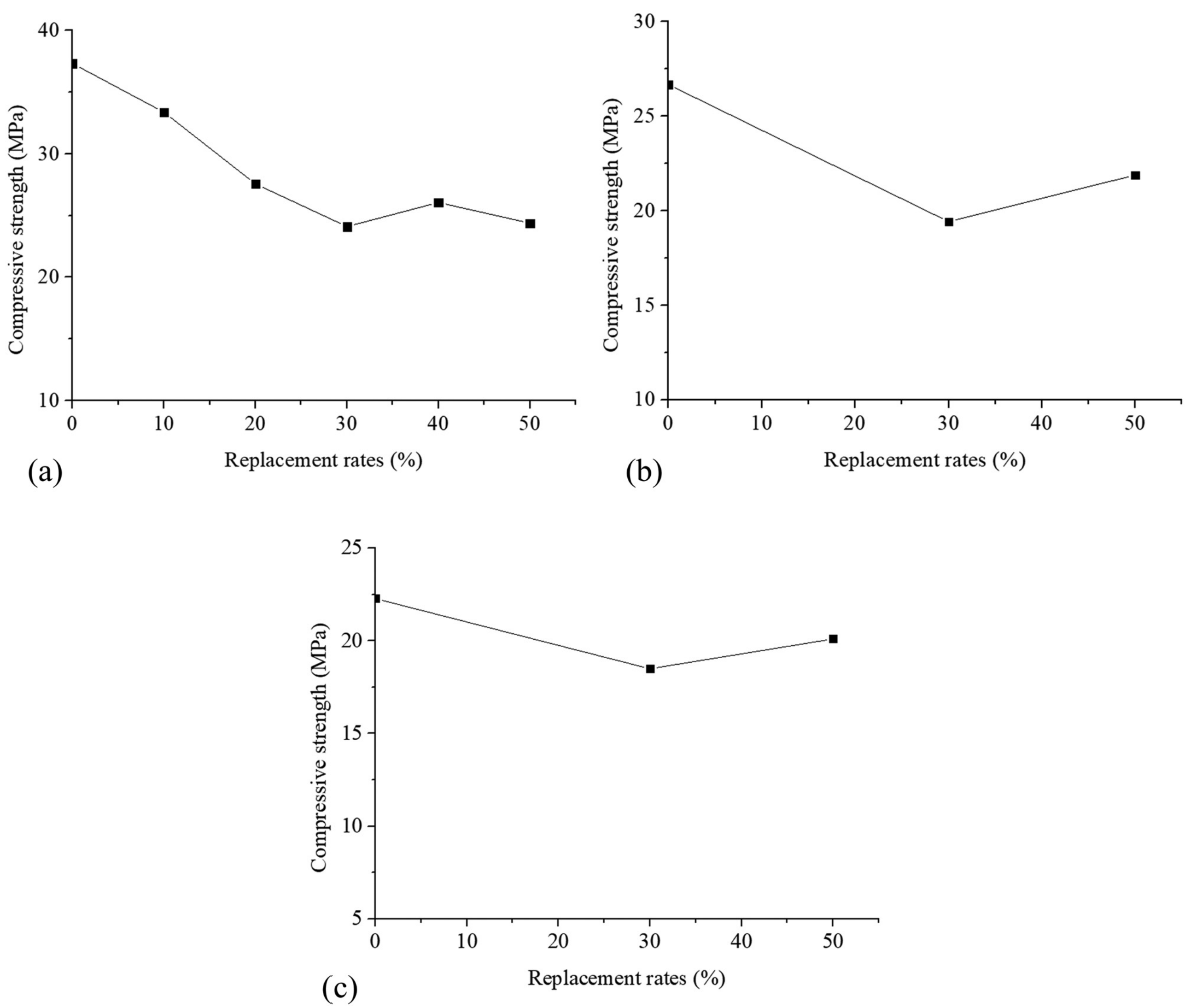

Figure 4: Compressive strength versus RBA replacement rates. (a) w/c = 0.48, (b) w/c = 0.58, and (c) w/c = 0.68.

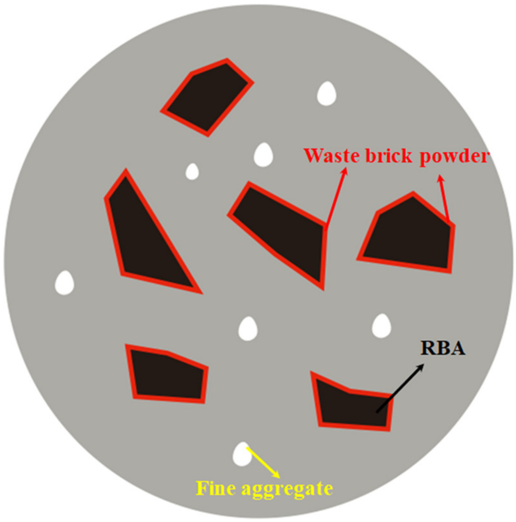

Figure 5: Interface model of RBC.

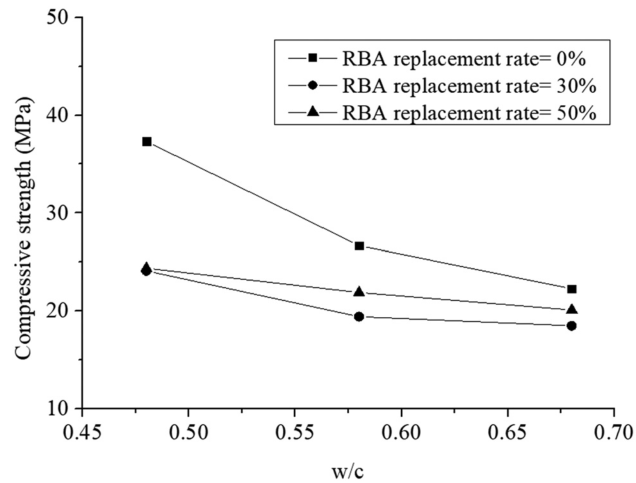

Figure 6: Compressive strength versus w/c.

times that of NCA, so the compressive capacity of RBA is significantly lower than that of NCA; third, the water absorption rate of RBA is 6.6 times that of NCA. The pre-wetting treatment of RBA before concrete pouring leads to the increase in the actual w/c of concrete and the reduction of cement mortar attached to aggregate, resulting in the reduction of compressive strength of RBC.

Figure 4 shows that the compressive strength of concrete showed a trend of first decreasing and then increasing with the increase in RBA replacement rates. These observations agree with the findings of Ji et al. [36]. The compressive strength of concrete was the lowest when the RBA replacement rate was 30%, and then, the compressive strength of concrete showed an increasing trend with the increase in RBA replacement rates. The main reasons are as follows: on the one hand, the lower elastic modulus of RBA is closer to the elastic modulus of hardened cement mortar, and the strength of RBA is lower, so cracks can expand from the cement mortar to the interior of RBA, and RBA can bear part of the pressure. On the other hand, the rough and porous RBA surface leads to a more dense interfacial transition zone, and more cement particles can enter the RBA pores, so that the cement product can be better combined with RBA, resulting in an increase in the compressive strength of RBC [36].

Figure 6 shows the relationship between the compressive strength of concrete and the w/c.

As shown in Figure 6, the lower the w/c, the greater the compressive strength of RBC. The reason is that the higher the w/c, the looser and porous the cement mortar, and the hydration product cannot fill the internal pores of the concrete, and its bonding performance with the aggregate becomes poor, resulting in a decrease in the compressive strength.

In addition, with the increase in the w/c, the effect of the RBA replacement rate on the compressive strength gradually decreased. When the w/c was 0.48, the compressive strength of RBC with 50% RBA replacement rate was 34.67% lower than that of NAC; when the w/c was 0.58, the compressive strength of RBC with 50% RBA replacement rate was 17.92% lower than that of NAC; when the w/c was 0.68, the compressive strength of RBC with 50% RBA replacement rate was 9.78% lower than that of NAC. The reasons for this phenomenon are as follows: when the w/c is low, the strength of the cement mortar is high, and the weak parts of the concrete under compression are more inclined to RBA with lower strength, RBA plays a major role in the compression resistance of concrete; when the w/c is high, the strength of cement mortar is low, the weak parts of concrete under compression are more inclined to the cement mortar in the interface transition zone, and the effect of RBA on the compressive strength of concrete is reduced. Therefore, the effect of RBA on concrete compressive strength decreased when the w/c increased.

3.2 Splitting tensile strength test

Splitting tensile strength test was performed according to Chinese standard GB50081-2016 [35]. The formula for calculating the splitting tensile strength of the concrete was as follows:

$$f_{ts} = 2F/\pi A, \tag{2}$$

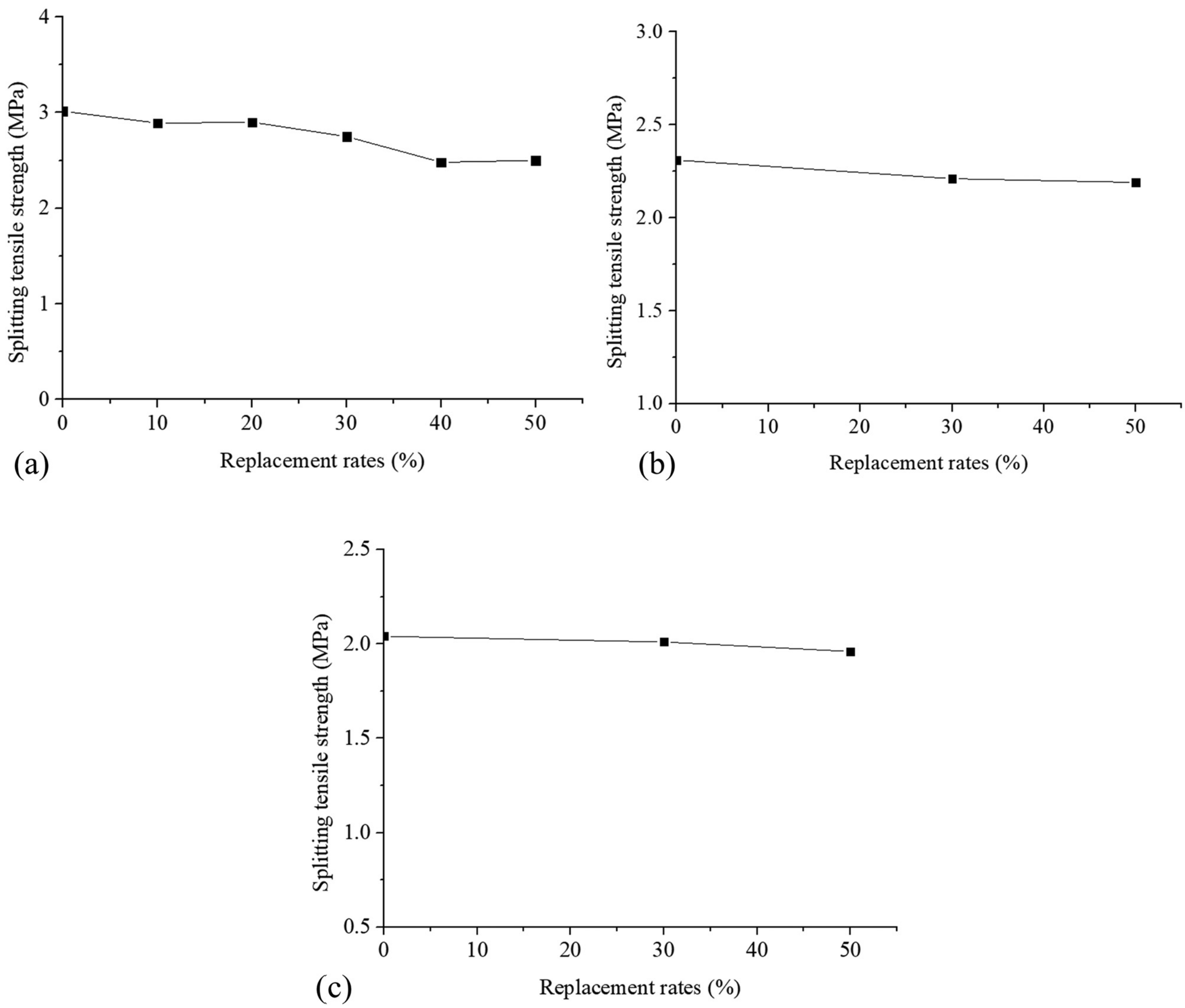

Figure 7: Splitting tensile strength versus replacement rates. (a) w/c = 0.48, (b) w/c = 0.58, and (c) w/c = 0.68.

where f_{ts} is the splitting tensile strength, MPa; F is the cube specimen failure load, N; and A is the pressure-bearing area, mm^2.

Figure 7 shows the relationship between the splitting tensile strength of concrete and RBA replacement rates.

As shown in Figure 7, the splitting tensile strength of RBC was lower than that of NAC (RBA replacement rate is 0%), but the effect of RBA on the splitting tensile strength of concrete was not significant, which was similar to the conclusion obtained by Chen et al. [24] and Poon et al. [25]. When the w/c was 0.48, the compressive strength of RBC with 50% RBA replacement rate was 34.67% lower than that of NAC, while the splitting tensile strength of RBC with a 50% RBA replacement rate was 17.08% lower than that of NAC. The main reason is that the splitting tensile strength is determined by the mortar strength and

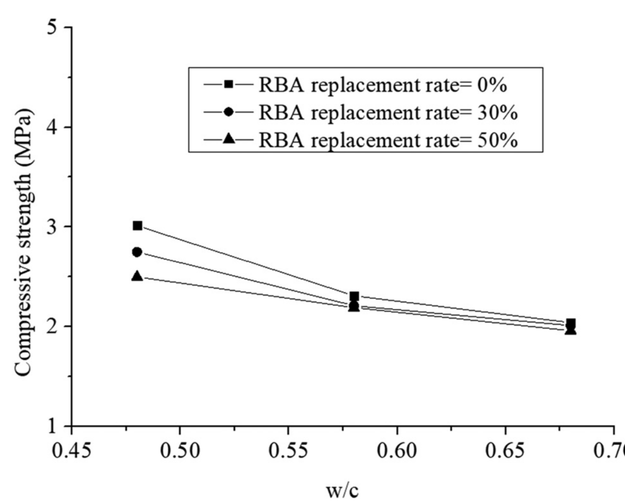

Figure 8: Splitting tensile strength versus w/c.

coarse aggregate strength of the failure surface. Although the strength of RBA is lower than that of NCA, the loose and porous surface of RBA can be more closely combined with cement mortar, which improves the mechanical properties of RBC to a certain extent. Therefore, the effect of RBA on the splitting tensile strength of concrete was not significant.

Figure 8 shows the relationship between the splitting tensile strength of concrete and w/c.

As shown in Figure 8, the lower the w/c, the greater the splitting tensile strength of RBC. The reason is that the higher the w/c, the greater the difference between the elastic modulus of the cement mortar and the aggregate. Therefore, the weak part of the specimen under stress is the interface transition zone, and aggregate has less effect on strength of concrete.

In addition, the effect of w/c on the splitting tensile strength of RBC was smaller than that on the splitting tensile strength of NAC. When the RBA replacement rate was 0%, the splitting tensile strength of concrete with 0.68 w/c was 32.34% lower than that with a 0.48 w/c; when the RBA replacement rate was 30%, the splitting tensile strength of concrete with 0.68 w/c was 26.91% lower than that with 0.48 w/c. When the RBA replacement rate was 50%, the splitting tensile strength of concrete with 0.68 w/c was 21.60% lower than that with 0.48 w/c.

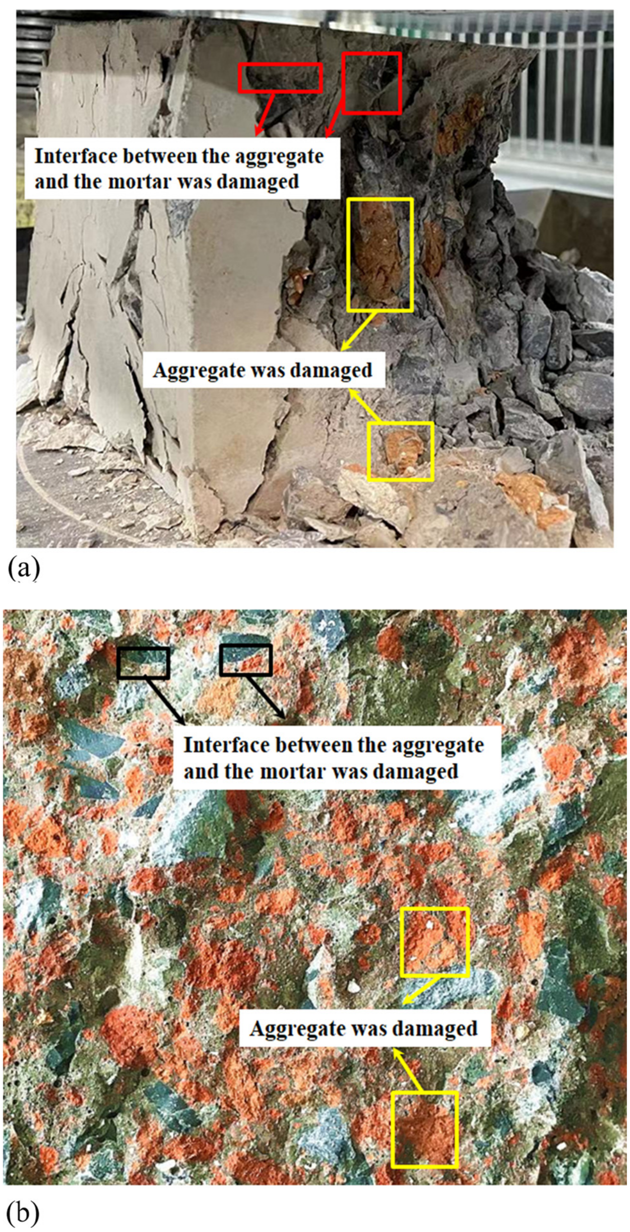

Figure 9: Destruction mode. (a) Compression test failure mode and (b) splitting tensile test failure mode.

3.3 Macro destruction mode

The compression test failure mode of RBC was basically the same as that of NAC. In the compression test, it was

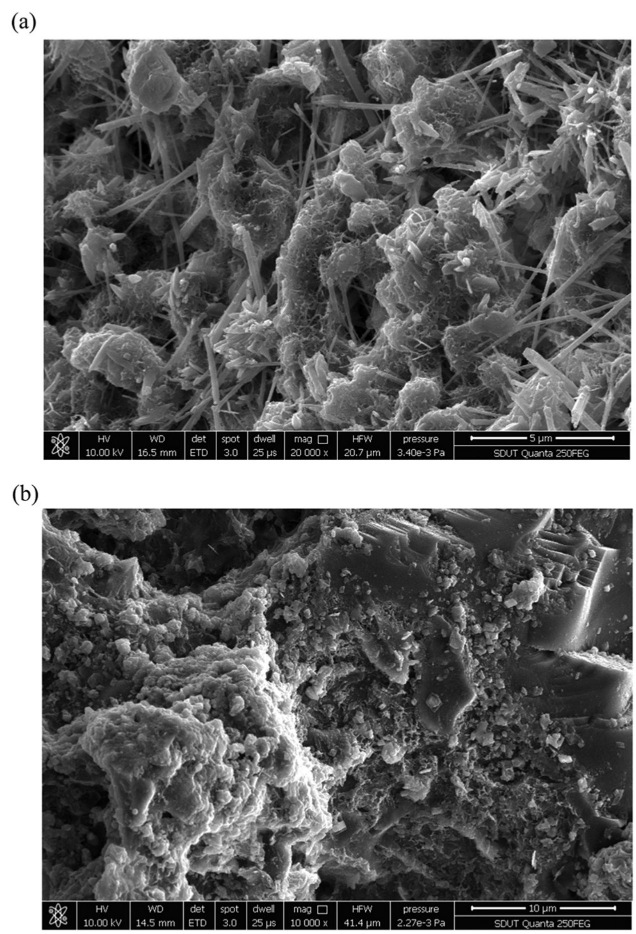

Figure 10: Morphology of RBC. (a) Morphology of AFt and (b) Morphology of C–S–H.

found that the concrete specimen was more brittle when it finally failed when the RBA content was low, which was manifested as a sudden burst and loss of bearing capacity when it reached the ultimate load of the specimen. With the increase in RBA content, the brittle failure phenomenon tended to ductile failure.

When the RBC reached the tensile strength limit, the RBA on the failure surface was split, while the NCA was basically not split. The reason is that the elastic modulus of the cement mortar is quite different from that of NCA, the damage mostly occurs in the interface transition zone, and the force cannot be transmitted to the NCA, so the NCA is not easy to be damaged.

The compressive failure mode and split tensile failure mode of the RBC are shown in Figure 9, respectively. The figure illustrates that there were two failure modes of RBC [5]: (1) the aggregate was damaged during the stress process; (2) the interface between the aggregate and the mortar was damaged. The first kind of failure mode was generally the failure of RBA, and the failure of NCA does not occur; the second kind of failure was generally the failure of the interface between NCA and mortar.

3.4 Microstructure test

The morphology of ettringite (AFt) and the morphology of calcium silicate hydrate (C–S–H) of RBC are shown in Figure 10. Compared with the AFt and C–S–H of NAC in ref. [37], it can be seen that the AFt in NAC was thicker than that in RAC, which were more favorable for improving the strength of concrete, which was the main reason that compressive strength of RBC was lower than that of NAC. In addition, the C–S–H of RBC was in the form of agglomerated networks with large and uniform pores, and less filler. Therefore, the strength of NAC was greater than that of RBC.

4 Conclusion

(1) The compressive strength and splitting tensile strength of RBC were lower than those of NAC, but the effect of RBA on the splitting tensile strength of concrete was not significant.
(2) The compressive strength of concrete showed a trend of first decreasing and then increasing with the increase in RBA replacement rate.
(3) The effect of the RBA replacement rate on the compressive strength gradually decreased with the increase in the w/c.
(4) The AFt of RBC was thicker than that in NAC, and the C–S–H of RBC was in the form of agglomerated networks with large and uniform pores, and less filler.

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Data availability statement: The data used to support the findings of this study are included with in the article.

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