DAMAGE MECHANISM OF CONCRETE WITH RECYCLED BRICK AGGREGATE

by

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WIt has great environmental potential to replace natural aggregates by recycled brick aggregates. To investigate the deterioration mechanism of recycled brick aggregate concrete, this paper designed eight groups of recycled brick aggregate sub-lightweight concrete with different water-cement ratios, maximum aggregate sizes and coarse aggregate type ratios, and carried out mechanical property test to analyze the aggregate interface characteristics and the damage mechanism of recycled brick aggregate concrete. The results show that the increase of replacement ratio and water-cement ratio leads to a significant decrease of compressive strength and splitting tensile strength of concrete, and the influence of the maximum aggregate size on strength is small. Unlike the recycled concrete aggregate – mortar interface, the microstructure of recycled brick aggregate – mortar interface is dense and the interface performance is enhanced. Recycled brick aggregate concrete is in non-interface damage mode, and the strength of brick aggregate is the main influence to determine the mechanical properties of concrete factor.

Key words: *construction waste, recycled clay brick aggregate, mechanical properties, failure mechanism*

Introduction

The total annual consumption of concrete in the world is about 17.5 billion tons [1]. Natural sand resources are nearly depleted, and natural sands price is rocketing. In addition, the construction waste from natural disasters, and a long-term service is needed due to the degradation of concrete performance and demolition. In China, as much as 400 million tons of clay brick waste is generated annually due to demolition. The traditional method of disposing clay brick waste was physical landfill, which had increased environmental pollution.

Yang *et al.* [2] prepared concrete using brick coarse aggregate instead of natural aggregate, the results showed that there was no significant decreasing trend in the mechanical properties of brick aggregate concrete (BAC) when the replacement was below 20%, while the mechanical properties of BAC decreased significantly when the replacement was higher than 50%. Zong *et al.* [3] found that the permeability of BAC was deeply increased. Wong *et al.* [4]

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showed that the use of brick aggregate as coarse aggregate had no significant enhancement effect on concrete performance due to its porous characteristics. Therefore, the recycled of waste bricks from construction waste was very low and mostly used in laying pavement subgrade, the scope of application was very limited [5]. Relative to light aggregate concrete, the specified density concrete (SDC) has higher strength and elastic modulus, lower shrinkage and deformation, could significantly reduce the cost, and it had good potential for applications [6].

In summary, few reports have been published on brick coarse aggregate feasibility and damage mechanisms for the preparation of SDC. In addition, the existing BAC is mostly replaced by a single brick aggregate, ignoring the actual situation of the mixed state of construction waste [7]. Considering the above facts, this work investigates the feasibility of using brick aggregate and mixed recycled aggregate to prepare SDC, and studies mechanical properties of recycled brick aggregate concrete (RBAC) with different concents and maximum coarse aggregate sizes.

Experimental materials

Coarse aggregates

Basic features

The recycled clay brick aggregate (RCBA) and recycled concrete aggregate (RCA) used in this work were produced by Shanxi Jianxin Environmental Protection Company. The performance indicators such as bulk density, crushing index and water absorption of the recycled aggregates were tested according to the Chinese Standard GB/T 14685-2011 (Crushed Stone and Pebbles for Construction) and compared with natural aggregates as well as commonly used light aggregates (shale vitrified light aggregates), see tab. 1. From the analysis of aggregates, brick aggregate has the potential to replace lightweight aggregate. This paper considers the use of pre-wetting method to treat RCBA.

Table 1. Physical properties of clay brick aggregate, RCA, natural aggregate and shale ceramsite

Code	Bulk density [kgm^{-3}]	Apparent density [kgm^{-3}]	Crushing index [%]	Water absorption [%]	
				24 hours	3 days
Clay brick aggregate	890	1 697	22.4	20.3	21.7
RCA	1 450	2 693	9.8	3.5	3.6
Natural aggregate	1 550	2 780	7.2	1.2	/
Shale ceramsite	745	1 480	24.1	4.8	/

Materials and test methods

Mixing

This work uses brick aggregate and mixed recycled aggregate to prepare RBAC. The mixed recycled aggregate adopts the equal volume substitution method. Both the brick aggregate and the RCA account for 50% of the total coarse aggregate volume. The mass ratio is calculated by the bulk density. The concrete prepared with 100% brick aggregate is called recycled clay brick aggregate concrete (RBC-RCBA) and the concrete prepared with mixed recycled aggregate is called mixed recycled aggregate concrete (RBC-MRA). The cement adopts Jidong brand 42.5R OPC, its density is 3.15 g/cm^3, the specific surface area is 337

m^2/kg; Polycarboxylic acid liquid high-efficiency water reducing agent. The fine aggregate is natural river sands, the fineness modulus is 2.6, medium sand with fineness modulus 2.62. The mixing water is supplied by the laboratory. The mixing is showed in tab. 2.

Table 2. Mix proportions of RBC

No.	*w/b*	Coarse aggregate size [mm]	Water [kgm^{-3}]	Cement [kgm^{-3}]	Sand [kgm^{-3}]	RCA [kgm^{-3}]	RCBA [kgm^{-3}]	Superplasticizer
R1	0.3	5-31.5	138	460	570	0	700	1.2
R2		5-20	138	460	570	0	700	
R3	0.4	5-31.5	185	460	570	0	700	0.5
R4		5-20	185	460	570	0	700	
M1	0.3	5-31.5	138	460	570	560	350	1.2
M2		5-20	138	460	570	560	350	
M3	0.4	5-31.5	185	460	570	560	350	0.5
M4		5-20	185	460	570	560	350	

Note: R stands for concrete prepared by 100% brick aggregate, M stands for concrete prepared by mixed recycled aggregate. Figures 1-4, respectively, represent the groups under the conditions of corresponding water-cement ratio and aggregate particle size. For example, fig. 1 represents the experimental condition of water cement ratio 0.4 and aggregate maximum particle size 31.5 mm.

Test method

Natural sand and cement were mixed with a mixer for 2 minutes, and then coarse aggregates were added for 2 minutes, after that water and water reducer were added, and finally the concrete was poured onto an iron plate and tested for slump using a slump cylinder. In this paper, pumpable concrete was used as a reference, and the amount of water reducing agent was adjusted during the preparation process to keep the slump at (180 ±10) mm. The concrete was naturally cured indoors for 1 day and then demolded and cured under standard curing conditions. The experiment method is shown in tab. 3. Small pieces of specimens were taken and immersed in acetone to terminate hydration, before observation, the specimens were dried to constant weight, coated with conductive tape and pasted with specimens, sprayed with gold using an E-1045 ion sputtering instrument, and microscopic morphological observations were made using a Quanta 600FEG type environmental SEM. The brick aggregates were crushed and ground to powder state and analyzed for physical phase using a D/MAX 2200 X-ray diffractometer.

Table 3. Experiment method

	Standard	Specimen size [mm]	Curing age, [days]	Group number	Total number
Working performance	GB/T 50080-2002	–			
Dry density	JGJ51-2002	100×100×100	28	8	24
Compressive strength	GB/T 50081-2002	100×100×100	7, 14, 21, 28	32	96
Splitting tensile strength	GB/T 50081-2002	100×100×100	28	8	24

Results and discussion

Compressive strength

As shown in fig. 1, the water-cement ratio, *w/c*, for RBC-RCBA decreased by 18.84% at 7*d* and 9.07% at 28*d* from 0.3 to 0.4, while for RBC-MRA, the *w/c* concent decreased by 16.55% at 7*d* and 11.65% at 28*d* from 0.3 to 0.4. The results showed that the compressive strength of concrete at 7*d* and 28*d* age decreased differently as the *w/c* content increased from 0.3 to 0.4, with the former decreasing more (9.77%) than the latter (4.9%). The reason for this is related to the mortar strength at different hydration stages, with the 7*d* compressive strength being more influenced by the mortar strength at the hydration stage and less influenced by the strength of the aggregates. When the hydration is complete after 28*d* of maintenance, the mortar strength remains stable and the aggregate gradually becomes the most important factor limiting the strength growth [8]. Therefore, limited by the strength of the aggregate, it is difficult to continuously increase the strength of concrete in the later stage, the compressive strength of concrete with different *w/c* contents gradually become progressively closer with the growth of the curing age.

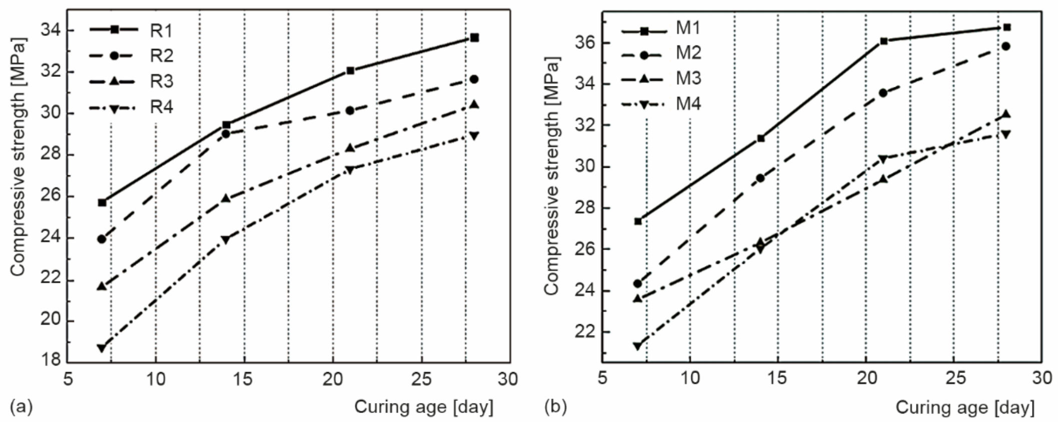

Figure 1. Cubic compressive strength of RBC; (a) RBC-RCBA and (b) RBC-MRA

The effect of the maximum aggregate size on the compressive strength can be obtained from fig. 2. It shows that the concrete prepared with 31.5 mm maximum aggregate size has a relatively higher compressive strength than 20 mm, but the effect was weaker. Comparing figs. 1(a) and 1(b), the compressive strength of RBC-MRA increased more significantly than RBC-RCBA. This is due to that aggregate strength is an important influencing factor of the concrete strength, and it is known from the aforementioned aggregate properties that the crushing index of RCBA is 2.29 times higher than that of RCA, so the compressive strength of concrete prepared with mixed recycled aggregates is more excellent.

Splitting tensile strength

The splitting tensile strength values of RCBA with different *w/c* contents and maximum aggregate sizes are given in fig. 2. It can be seen that the splitting tensile strength of RBC-MRA is significantly increased compared to that of RBC-RCBA, with a percentage increase of about 11.81%. When the w/c content increased from 0.3 to 0.4, the concrete splitting tensile strength decreased by 12.1%. In contrast, the splitting tensile strength of the concrete prepared with the maximum aggregate size of 20 mm was reduced by only 6.25% compared to the maximum aggregate size of 31.5 mm. The results showed that the growth trend of the splitting tensile strength is consistent with the compressive strength. The *w*/*c* content, aggregate type and maximum and size are the factors influencing the splitting tensile strength of concrete. Aggregate type and w/c had a greater influence on splitting tensile strength, and the maximum aggregate size had the least influence on splitting tensile strength.

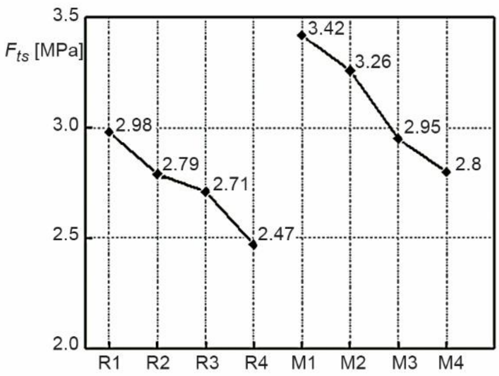

Figure 2. Splitting tensile strength of RBC

Macroscopic damage modes

Concrete specimens show two damage modes during loading. Interface damage – the aggregate is not damaged and cracks develop along the aggregate interface. Non-interface damage – the aggregate suffered damage and the aggregate interface did not crack [9].

The compressive damage trend of RBAC is shown in fig. 3(a). The specimen underwent transverse volume expansion due to Poisson effect during compression, and its internal micro-cracks expanded and merged, followed by new cracks through the surface and interior [10]. The compressive and splitting tensile damage morphology are shown in fig. 3. Observation of the post-damage sections revealed that almost all brick aggregates showed fracture morphology, the cement interface of the bonded brick aggregate did not crack, and RBC-RCBA showed a non-interface damage pattern. For RBC-MRA, the cement interface of the bonded RCA and brick aggregate cracked at the same time, but most of the RCA did not crack, two damage modes of concrete non-interface damage and interface damage coexisted.

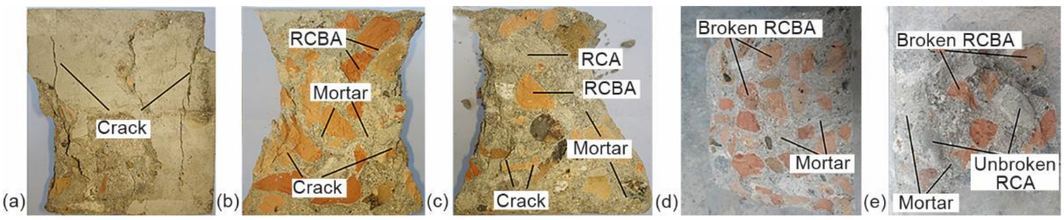

Figure 3. Failure modes of RBC compressive and splitting tensile test

Damage mechanism

The interfacial transition zone (ITZ) is a weak region within ordinary concrete, and its properties have a significant impact on the mechanical properties of concrete [11, 12]. The incorporation of brick aggregates and RCA has complicated the internal interface of concrete and the type of ITZ is different from that of ordinary concrete. It is necessary to analyze the concrete ITZ type to study the damage mechanism of RBAC in order to provide a basis for studying the macroscopic property changes of concrete. In fig. 4(a), two aggregate – mortar ITZ models are established. Due to the old mortar attached to the surface of RCA, the RCA-mortar ITZ is divided into three types: RCA-old mortar, RCA-new mortar, and old mortar-new mortar. In fig. 4(b), there is almost no old mortar attached to the surface of RCBA, and there is only one ITZ between aggregate and mortar, the ITZ between RCBA and new mortar. In addition, the surface of the brick aggregate is inevitably wrapped with a layer of waste brick powder adhered due to multi-segment crushing.

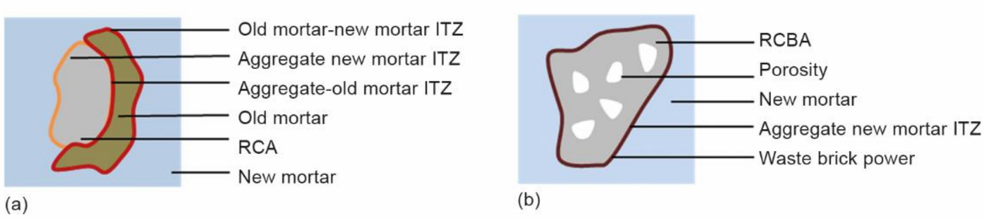

Figure 4. Aggregate interface model; (a) RCA interface model and (b) RCBA interface model

Microstructure of the transition zone of RCBA-mortar interface

The microscopic morphology of the transition zone of the recycled brick aggregate-mortar interface was characterized by SEM. As shown in fig. 5(a), the microstructure at the brick-aggregate-mortar ITZ is dense, with no obvious boundary between brick aggregate and mortar, and the aggregate-mortar interface is very tight. For concrete, the bond between mortar and aggregate interface are important factors affecting the mechanical properties of the ITZ. The rough surface and higher porosity of brick aggregate are conducive to the enhancement of interfacial bond. In fig. 5(b), significant hydration products were observed in the pores of the brick aggregate surface, indicating that the hydration products were precipitated into the pores of the brick aggregate and nested with the aggregate to form a nested zone, improving integrity of the brick aggregate and the concrete matrix consisting of calcium silicate hydrate (C-S-H), which enhanced the interfacial bond of the aggregate [13].

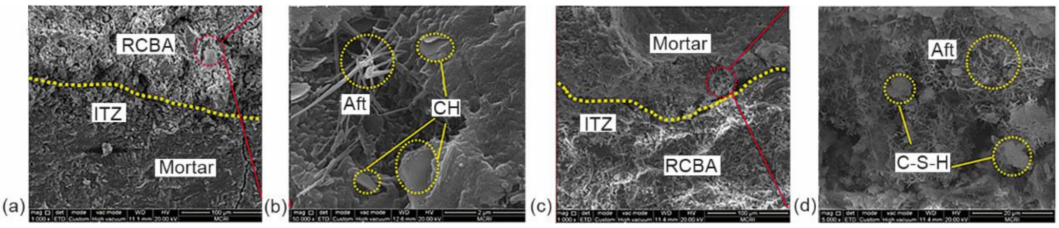

Figure 5. The SEM images of RCBA-mortar ITZ

During the concrete curing phase, the water-saturated brick aggregate releases its own moisture into the space formed by the chemical shrinkage of the mortar [14], which promotes the hydration of the cement paste in the interfacial zone and plays an internal curing role. It can be observed from fig. 5(c) and 5(d) that there are indeed hydration products such as generated calcium alumina, Aft, and C-S-H within the micro-cracks in the ITZ, and these gel products are mostly filled in the micro-cracks and pores in the ITZ, reducing the porosity of the mortar around the ITZ. In addition, observation of fig. 5(c) and 5(d) show that the yield of CH in the ITZ is small. Due to the presence of active oxides such as SiO_2 indicates that the waste brick powder adhered to the surface of brick aggregate has volcanic ash activity and can react with hydration products to generate gel material, which improves the performance of the ITZ from two aspects. Firstly, the lamellar crystalline CH is poorly compacted and contributes little to the concrete strength, and is easily destroyed when subjected to loading. Secondly, the generated Aft and C-S-H can fill the pore cracks. Equations (1) and (2) are the volcanic ash reaction mechanism, where the water released from the aggregate promotes the reaction of the waste brick powder adhering to the surface of the brick aggregate with CH to produce products such as hydrated calcium silicate and hydrated calcium aluminate. These hydration products precipitate on the brick aggregate surface and form a dense microstructure at the interface, which improves the mechanical properties of the mortar in and around the interface transition zone [15-17]:

$$x\mathrm{Ca(OH)_2} + \mathrm{SiO_2} + m\mathrm{H_2O} \rightarrow x\mathrm{CaO}\cdot\mathrm{SiO_2}\cdot(m+1)\mathrm{H_2O} \tag{1}$$

$$y\mathrm{Ca(OH)_2} + \mathrm{Al_2O_3} + n\mathrm{H_2O} \rightarrow y\mathrm{CaO}\cdot\mathrm{Al_2O_3}\cdot(n+1)\mathrm{H_2O} \tag{2}$$

Microstructure of the transition zone of RCA-new mortar interface

Figure 6(a) shows the microscopic morphology of the RCA – new mortar ITZ. Different the morphology of cracks at the transition zone of the brick aggregate – mortar interface, the micro-cracks at the transition zone of the recycled concrete aggregate – new mortar interface are still not observed to be filled with obvious cementation products. And because the surface of RCA is flatter than that of brick aggregate, the interfacial bond is also lower than that of brick aggregate-mortar interface. Therefore, the incorporation of RCA has no significant enhancement effect on the mechanical properties of the concrete ITZ, and the RCA – new mortar ITZ is one of the weak areas of concrete.

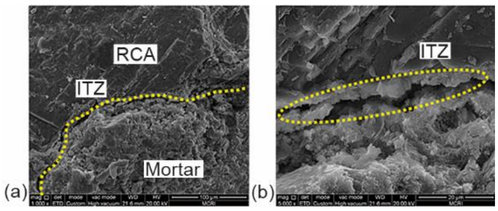

Figure 6. The SEM image of RCA – new mortar ITZ

In summary, the incorporation of brick aggregate makes the brick-aggregate-mortar interface performance enhanced, the ITZ is no longer a weak region of concrete. The lower strength brick aggregate becomes the most important factor affecting the mechanical properties of RBAC. When concrete was prepared using mixed recycled aggregates, the incorporation of RCA had no significant enhancement effect on the concrete interfacial properties, and the RCA-new mortar ITZ and brick aggregate together formed the weak zone of concrete. In addition, the damage mechanism of RBAC was significantly associated with its damage mode. The brick aggregate-mortar interface properties were enhanced and the concrete cracked at the brick aggregate, and the RBC-RCBA showed a non-interface damage mode. In contrast, the performance of the RCA-new mortar interface was not enhanced, and the cementitious interface and brick aggregate bonded with the RCA and the BAC simultaneously, but most of the RCA did not crack, so the non-interface and interface damage modes of RBC-MRA coexisted.

Conclusions

- Concrete mechanical properties tests show that it is feasible to use RCBA for the preparation of low and medium strength concrete, the use of brick aggregate and mixed recycled aggregate as coarse aggregate can prepare the physical and mechanical properties to meet the requirements of the use of the SDC, with good economic and engineering applications.
- The *w*/*c* content and the maximum coarse aggregate size affect the mechanical properties of RBAC. The 28*d* compressive and splitting tensile strengths of the concrete prepared with 0.4 *w*/*c* were reduced by 10.36% and 12.10%, respectively, compared with that with 0.3 *w*/*c*. While the effect of maximum aggregate size was relatively small, the maximum aggregate size was reduced from 31.5 mm to 20 mm, the compressive and splitting tensile strengths of the concrete decreased only by 4.05% and 6.25%, respectively.
- The concrete prepared with 100% brick aggregate replacement showed a non-interfacial damage mode during destruction, the lower strength brick aggregate became the most important factor affecting the mechanical properties of RBAC. The damage mechanism of mixed RCA is more complex, and the RCA – new mortar ITZ and brick aggregate together form an internal weak zone, and the non-interface and interface damage modes coexist when the concrete is damaged.

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