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Article

Multi-Scale Investigation on Concrete Prepared with Recycled Aggregates from Different Parent Concrete

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Abstract: Recycled aggregates (RA) are frequently obtained from various unknown sources, which caused variation in properties among recycled aggregates concrete (RAC). This paper investigated the macro and microscopic properties of RAC prepared with RAs originated from different parent concretes with 90-day strength ranging from 30 MPa to 100 MPa. These parent concretes were prepared in advance and crushed to produce RA of distinct qualities. The attached mortar content can reach up to 69% in the concrete with highest strength grade. The microscopic investigation on different RAC was conducted with the X-ray Micro-Computed Tomography scanning technique and image process. Experimental results showed that the properties of RA derived from various parent concrete varied because of the amount of residual mortar. The development of mechanical properties and chloride-ion penetration of RACs all followed a binomial trend with the strength grades of the parent concrete because of the different quantity and quality of RAs.

Keywords: Recycled aggregate; recycled aggregate concrete; parent concrete; mechanical property; CT scanning; image process

1 Introduction

Construction and demolition waste (CDW) have become one of the most significant problems around the world, so its recycling has become a hot spot accordingly. According to Tchobanoglous et al. [1], wastes from destroyed buildings and other structures are classified as demolition wastes, and wastes from the construction, remodeling, and repairing of individual residences, commercial buildings, and other structures are classified as construction wastes. CDW may contain a variety of complex components, depending on the sources of demolition and production process. CDW typically include concrete, bricks, tiles, ceramics, wood, glass, metals, making up 30–40% of total solid waste [2]. In 2014, the amount of CDW exceeded 1.13 billion tons [3], whereas the estimated amount of CDW in China was 2 billion tons in 2017 [4], so its recycling is imperative. The CDW can be recycled in to secondary building materials, such as fine RA, coarse RA, and recycled powders [5,6]. The mining of natural resources for natural aggregate (NA) requires heavy equipment and consumes a massive amount of energy, causing lots of environmental problems. With the diminishing sources and increasing cost, sourcing NA has become a challenge in the construction industry, using RA may be the most promising way right now to ease the

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pressure on environment. However, the practical application of RA is still limited because of a lack of awareness and guidelines.

The production and application of RA have increasing attention worldwide where it is still arguable that RA can or cannot be an environment friendly alternate material. Studies prove that the concrete made with RA up to 45 MPA can be put into category of environmentally friendly option but when the strength grade is higher than 45 MPa, the additional cement can produce a carbon emission to 3 times that of NAC [7]. Researches on the characteristics of RA and RAC have experienced explosive growth in the past two decades as a guarantee of their safe and efficient application as construction materials [8–10]. The main parameter for controlling the quality of RA apart from the production process is the source, quality or the basic parameters of the parent concrete such as strength, composition, and aggregate gradation. The production process, which includes the number of crushing cycles, can also influence the properties of produced aggregates [11]. These days researchers are trying to use all the fraction i.e., fine fraction (0.16–4.75 mm) and coarse fraction (4.75–35 mm) which is produced during the recycling of waste concrete [12].

Many researchers used the direct replacement method, which requires them to use the different sizes of aggregates in concrete. The replacement rate of RA is limited to 30% in non-structural applications, even with the successful laboratory studies [13]. But, for a rational comparison between the parent concrete and the concrete made with RA, the size of aggregates should be kept the same [14]. By keeping the same particle size, aggregates derived from the weaker parent concrete have larger dry density and less mortar [15], which was attributed to the number of crushing cycles used to produce the aggregates.

The amount of hardened mortar attached to RA can affect the properties of RAC. The porous residual mortar significantly affects the specific gravity and water absorption of RA. Because of the lower density and porous nature of the attached mortar, properties like workability, density, mechanical properties, and durability are affected [14,16]. It is generally agreed that the residual attached mortar is the critical factor for the poor quality of RA. The strength grade of parent concrete also affects the amount of residual mortar. According to research [17], the proportion of residual mortar ranges from 42% and 46% when the parent concrete is of 20 MPa and 30 MPa strength grade, respectively. The workability and density of RAC decrease with an increase in the amount of RA due to its high-water absorption and low specific gravity. It should be noted that the influence of RA on workability could be ignored when it is used in saturated surface dry condition.

The crucial factors influencing the hardened properties of concrete are w/c ratio, type of aggregates, and quality and replacement percentage of NA with RA [19–21]. Gholampour et al. [21] investigated the compressive and splitting tensile strength of RAC. The results showed that the compressive strength of RAC was 10–25% lower than concrete made with NA. Liu et al. [22] investigated the effect of the parent concrete, which was produced in the lab and cured for 90 days before crushing. With an increase in the strength of the parent concrete used, the crushing index and water absorption rate of the RA decreased. The strength loss after freeze-thaw cycles in RAC with low strength aggregates (34.9 MPa) and high strength (57.3 MPa) was 25.3% and 8% when compared with NAC. Besides, when RAC is made with RA from parent concrete of higher strength, it can achieve comparable strength with NAC. The flexural strength of RAC can increase up to 8% for the same w/c ratio but decrease if fine RAs are used [21,23–27].

Some research investigated the effect of RAs by using Scanning Electron Microscopy (SEM) to test the microstructural characteristics of RACs [21,28]. However, the images from SEM were in 2D, which caused a lack of understanding of the pore structure in 3D. X-ray Micro-Computed Tomography (μCT) has been successfully used in the fracture's investigation and pore-structure of concrete during the last two decades. Leite et al. [29] investigated the microstructures of different RACs using synchrotron μCT. The RAC prepared with RA in the oven-dry condition showed a higher porosity surrounding the RA, which was not observed in RAC prepared with RA in the saturated surface dry condition. Duan et al. [27] investigated the influence of the RA along with the recycled powder in self-compacting concrete. A higher porosity was observed in concrete with higher recycled powder content, which was attributed to the agglomeration of finer particles in the cement matrix.

Although some studies have already been carried out, the effects of parent concrete on the properties of RAC deserve an in-depth study by systematic experiments. But lacks in providing the information regarding the key characteristics of RA derived from different parent concrete. This study provides the state-of-the-art techniques like CT and image processing to understand the mechanism behind the types of aggregates used in the study. The key characteristics of RAs from different parent concrete of various strength grades are tested and used to prepare RACs in this study. The mechanical properties of RACs are also tested, and based on that the relationship between characteristics of RAs and mechanical properties of RACs is established. For further investigation on the mechanism of this relationship, μCT scanning and image process of RACs are conducted.

2 Material and Methods

Fig. 1 shows the experimental program undertaken in this study, and which was divided into three sections:

Preparation of the parent concrete and the corresponding RA.

Preparation of the new concrete with RAs of different quality.

The microscopic, mechanical and durability properties tests of RAC.

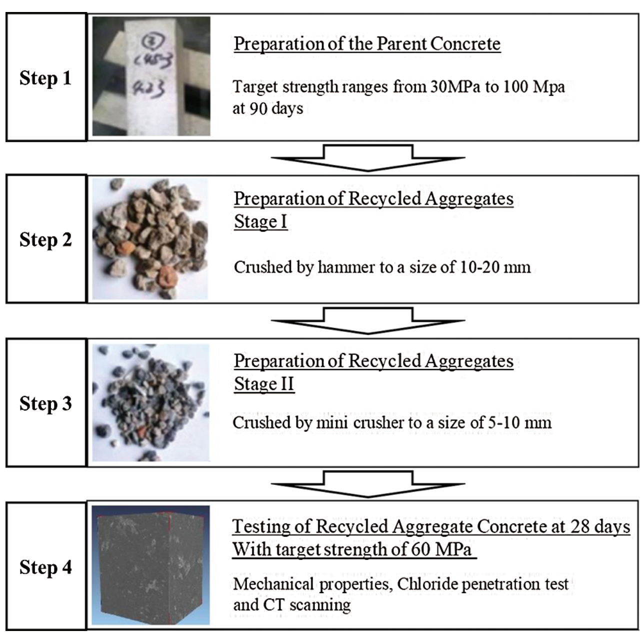

Figure 1: Flow chart of the experimental program

2.1 Materials

The cement used in this study was an ASTM Type I Portland cement with a density of 3.15 g/cm^3. To keep consistency, crushed stone fines (CSF) with a fineness modulus of 3.28 as fine aggregate was used in both the parent concrete and new concrete mixes. Crushed granite was used as the natural coarse aggregate to prepare the parent concrete and also for the control group of the new concrete mixes. RA used in this study was crushed by hammer and then by mini crusher from each group of parent concrete with 90 days compressive strength ranged from 30 MPa to 100 MPa. The detailed mix proportions of the parent concrete are listed in Tab. 1, and the crushed RAs were named as RA30, RA45, RA60, RA80, and RA100, respectively, according to the strength grades of their parent concrete. Super-plasticizer (SP) (Grace, ADVA-109) obtained from Hong Kong Grace Construction Products Limited was also used in the new RAC to achieve a slump value of 150 ± 10 mm.

Table 1: Mix proportions and properties of parent concrete with different strength grades

Target Strength (MPa)	w/b[1]	Mix Proportions (kg/m^3)						Compressive Strength (MPa)	
		Water	Cement	SF[2]	CSF	NCA		28 d	90 d
						10 mm	20 mm		
30	0.68	205	300	0	697	379	758	35.6	**39.2**
45	0.51	180	350	0	706	384	768	49.4	**53.6**
60	0.44	185	425	0	695	362	725	57.4	**66.4**
80	0.34	165	485	0	696	726	363	72.9	**80.6**
100	0.30	168	510	50	685	685	342	88.5	**100.3**

[1]w/b = water to binder ratio; [2]SF = silica fume

Six concrete mixes with a 28-day target strength of 60 MPa were designed using the absolute volume method, as shown in Tab. 2. The aggregates were used in saturated surface-dried (SSD) condition, and the actual proportions at mixing were adjusted according to the moisture conditions of the stockpiled aggregates. As regards the reference concrete (NAC), 100% RA30, RA45, RA60, RA80, and RA100 were used to replace natural coarse aggregates by volume to produce the corresponding RAC30, RAC45, RAC60, RAC80, and RAC100, respectively. For all the RAC mixtures produced, the water-to-cement ratio (w/c), cement, and CSF contents were maintained at 0.35, 440 kg/m^3, and 666 kg/m^3, respectively.

Table 2: Mix proportions of the new concrete mixtures

Notation	w/c	Mix Proportion (kg/m^3)				
		Water	Cement	CSF	NCA	RA
NAC	0.35	155	440	666	1166	0
RAC30	0.35	155	440	666	0	1070
RAC45	0.35	155	440	666	0	1077
RAC60	0.35	155	440	666	0	1083
RAC80	0.35	155	440	666	0	1090
RAC100	0.35	155	440	666	0	1094

Considering the high-strength of concrete, and due to development of the new technologies in concrete technology, to improve the properties and the microstructure of concrete silica fume pozzolanas can be used as weight replacement. Moreover, Maximum cement content is restricted to reduce cracking due to thermal contraction and drying shrinkage. As per, BS 8007 [30] the limits for reinforced concrete are 400–550 kg/m^3

are allowed for concrete but also can be adjusted based on discretion of researcher or the mix design. Considering all the limitation and requirement the cement is replace with SF for the mix with 100 MPa as target strength.

A standard dry to wet mixing approach was adopted for the production of the concrete mixes. All the raw material was mixed in the dry state for 30 seconds, and then 3/4th of the mixing water (premixed with SP) was added and mixed for another 60 seconds. Finally, the rest of the water was added, and then mixed till a homogeneous mix was obtained. The total duration of the mixing time was not exceeding 150 seconds. For each concrete mix, $100 \times 100 \times 100$ mm^3 cubes and 100×200 mm^2 cylinders were cast. The cubes were used to determine the compressive strength of concrete, and the cylinders were used to test the corresponding splitting tensile strength, static modulus of elasticity, and chloride-ion penetration of concrete. The specimens were demolded after curing for 24 hours at a controlled laboratory environment and then cured in water at 27 ± 1°C until the age of testing.

2.2 Experimental Methods

2.2.1 Mortar Content Test of RAs

As there is no standard method in measuring the old cement mortar contents of RAs, the measurement of attached mortar content in this study was based on a modified hydrochloric acid dissolution method proposed by Duan et al. [14], as shown in Fig. 2. For each type of RA, six samples with each one of about 100 g were tested to obtain the average value. In this procedure, the produced RA is washed with distilled water and oven-dried at a temperature of 105°C for 24 h (m_1). Then the oven-dried RA was immersed in a 10% HCl solution for 8 h and then washed away to remove the loose and the finer particles followed by oven drying of samples for another 24 h. After oven drying, the samples were gently ramming to remove the attached mortar. The samples were then sieved through the 4.75 mm sieve to obtain the mass of the aggregate (m_2). The mortar content (M_c) was calculated by using the following equation.

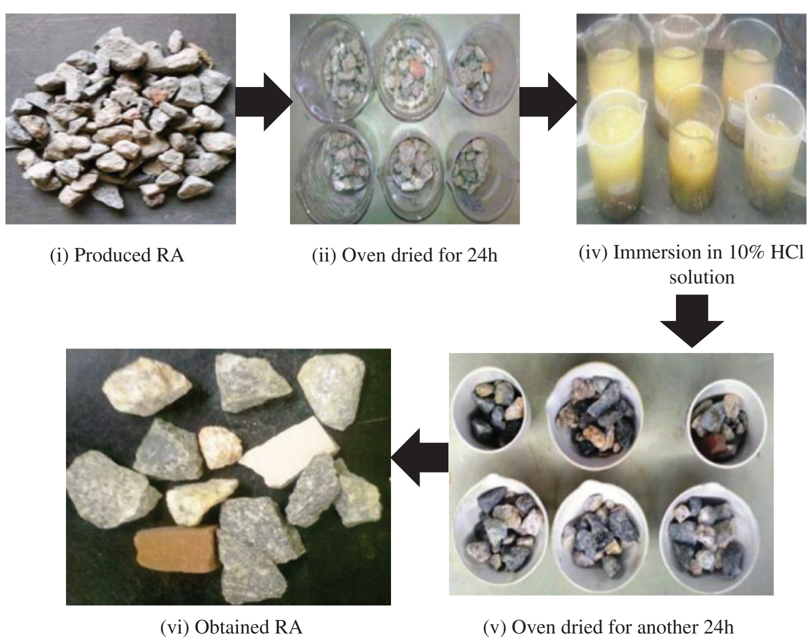

Figure 2: Test procedures of old mortar content of RAs [14]

$$M_c(\%) = \frac{(m_1 - m_2)}{m_1} \times 100 \quad (1)$$

2.2.2 *Macro Property Test of RAC*

The hardened density, compressive strength, splitting tensile strength, and elastic modulus of concrete were measured according to BS 1881 Part 114, 116, and 117 [31–33], respectively, while the chloride penetrability of concrete was tested following ASTM C1202-19 [34]. Immediately after the tensile splitting test, the fracture surface of each cylinder mix was selected, with the original aggregate, the residual mortar, new mortar, and aggregate-mortar interface marked by using different colors. Each component was then calculated by using an image processing software (Image pro plus) to further analyze the crack growth path of NAC and RACs.

2.2.3 *Micro Property Test of RAC*

Each specimen of group NAC, RAC30, RAC60, and RAC80 was selected respectively to conduct μCT scanning test. The NIKON XTH320 was used in this study for μCT scanning with 80 kV tube voltage and 120 μA current. The scanning time of each process was 15 min, and 1600 2D slices of each specimen were obtained. The CT raw data was acquired from 2D slices collected from different angles, and the linear attenuation coefficients of the components of specimens were recorded. The linear attenuation coefficients of materials are generally positively related to the intensity of materials.

After data collection, 3D digital models were established, and also a set of 2D cross-section images were obtained. The linear attenuation coefficients were transferred to the gray value of each voxel. So, the inner-structures of specimens can be identified by gray threshold segmentation, and some morphological parameters (e.g., volume and position) can be analyzed. As shown in Fig. 3, the density of recycled aggregate is uneven in the CT scan image. The gray value of the old mortar is significantly lower than that of the new mortar and has a lower density. The 3D-reconstruction and analysis of scanning results were conducted using a commercial image processing software VGStudio, as shown in Fig. 4.

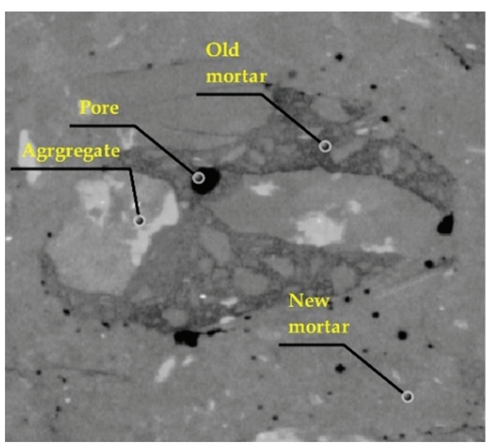

Figure 3: CT scanning image of RAC

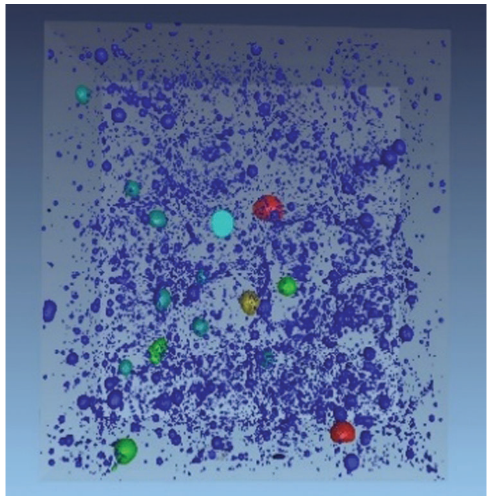

Figure 4: 3D reconstruction of pore-structure

3 Results and Discussions

3.1 Properties of RAs from Different Strength Grades Concrete

The presence of the residual mortar in RAs is the main reason for the poor performance of RAC. The test results of old mortar contents for RAs from different parent concrete is shown in Fig. 5. It can be seen that the amount of the attached mortar in each type of RAs produced from respective parent concrete all exceed 45% and increased with higher strength of parent concrete. This trend is the opposite in the case of other researchers, where the higher strength of parent concrete leads to lower mortar content [17,35,36]. This opposite trend can be attributed to the crushing process. Generally, when RA obtained from the crushing plant, contains a less amount of attached mortar [16] because of the intensive automated crushing techniques. At high strength concrete, the cement paste plays an important role in attaining the strength [37], so higher energy is required to break the mortar apart from aggregate, which is not sufficient during the manual crushing. The high mortar content of all RAs can be attributed to the simple hammer crushing method used in this study. The mortar content of RA30 and RA45 was 47.8% and 47.9%, respectively. When the strength grade of parent concrete went over 45 MPa, the residual mortar content increased rapidly since they had a higher bond between mortar and aggregate and is difficult to remove without special or additional treatment.

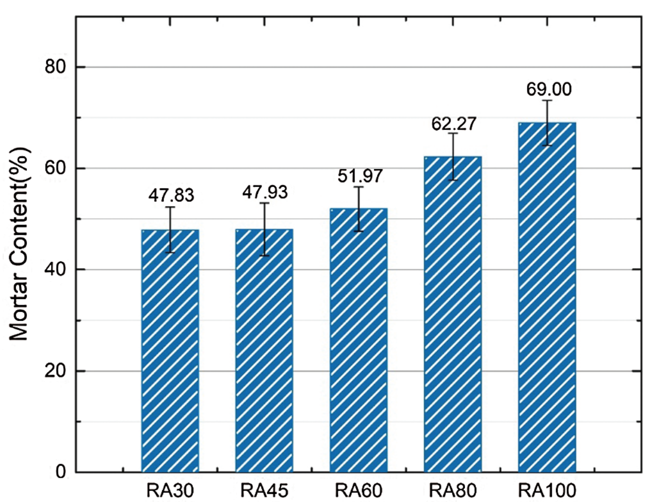

Figure 5: Mortar contents of RAs from different strength grades concrete

Fig. 6 shows the relationship between the residual mortar content and the other fundamental characteristics of RAs. When the strength grade of parent concrete increased from C30 to C45, the mortar content remains the same. The water absorption value decreased by 1.2%, and the TFV increased by 23 kN. With the increase of the parent concrete strength from C45 to C100, the properties of the attached mortar improved, proving that the quality of parent concrete does play a role in the quantity of attached mortar. The quality of residual mortar was improved with an increase in the strength grades of parent concrete, which resulted in improved performance of RA. However, when the strength grade of parent concrete increased from C60 to C100, these characteristics of RA were insensitive to the grade of parent concrete since the quality of parent concrete was no longer the only influential parameter. The quality and quantity of residual mortar can interact with each other and influenced the performance of RA together. The specific density, ACV, and TFV increased slightly, while the water absorption stabilized at 5.36%, which was much higher than that of natural aggregate.

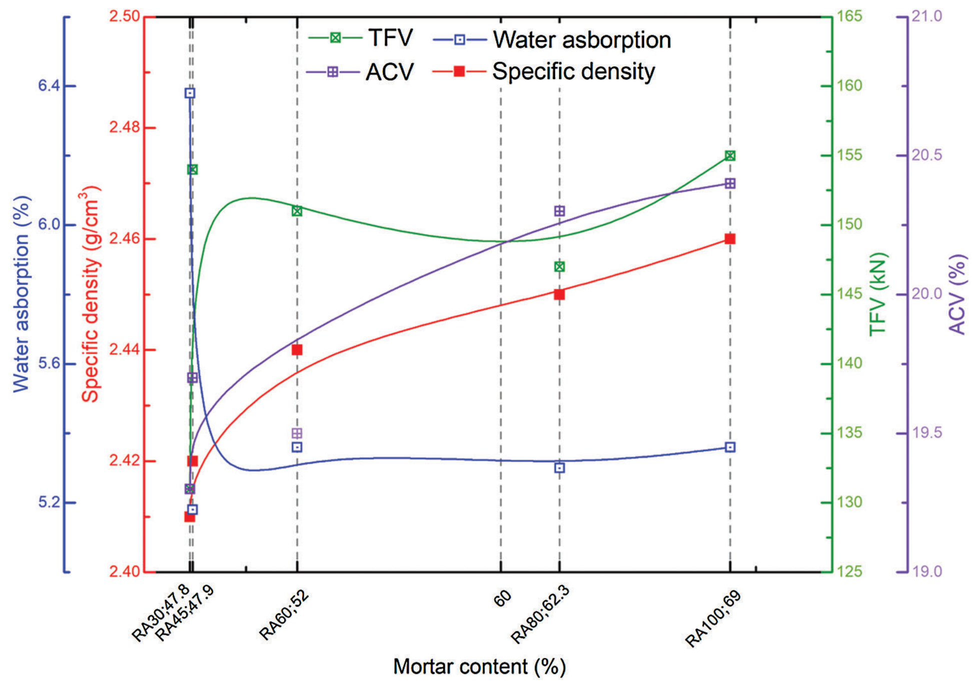

Figure 6: Main properties of RA from different strength grades concrete. (TFV: ten-percent fine value; ACV: average crush value)

Higher-strength of parent concrete usually led to a better quality of residual mortar. However, as shown in Fig. 6, higher strength grade of parent concrete was also accompanied by more residual mortar, which is detrimental to the performance of RA. So, even the residual mortar is of higher quality, this high content of residual mortar still limits the improvement of RA performance.

3.2 Properties of RAC with RAs from Different Strength Grades Concrete

3.2.1 Hardened Properties of RACs

Fig. 7 shows the compressive strength, splitting tensile strength, hardened density, and the elastic modulus of RAC with RAs of different qualities at 28 days. All the mechanical behaviors follow a binomial relation with the grades of parent concrete. Most of RAC specimens reach the target compressive strength of 60 MPa except for RAC30, which had the lowest compressive strength of about 59.3 MPa. However, the value still far exceeds that of the parent concrete, which confirms the view of

Ajdukiewicz et al. [18]. The increase in the compressive strength can be attributed to the quality and quantity of the attached mortar in RAs.

The characteristics of RACs increased at the early period when the grade of parent concrete varies from C30 to C60, which was consistent with the mechanical properties of RA. In this period, the principal factor that may affect the properties of RAC was the grade of parent concrete. The compressive strength of RAC45 and RAC60 reached up to 69.8 MPa and 67.8 MPa, while the corresponding elastic modulus was about 27.3 GPa and 27.0 GPa, respectively.

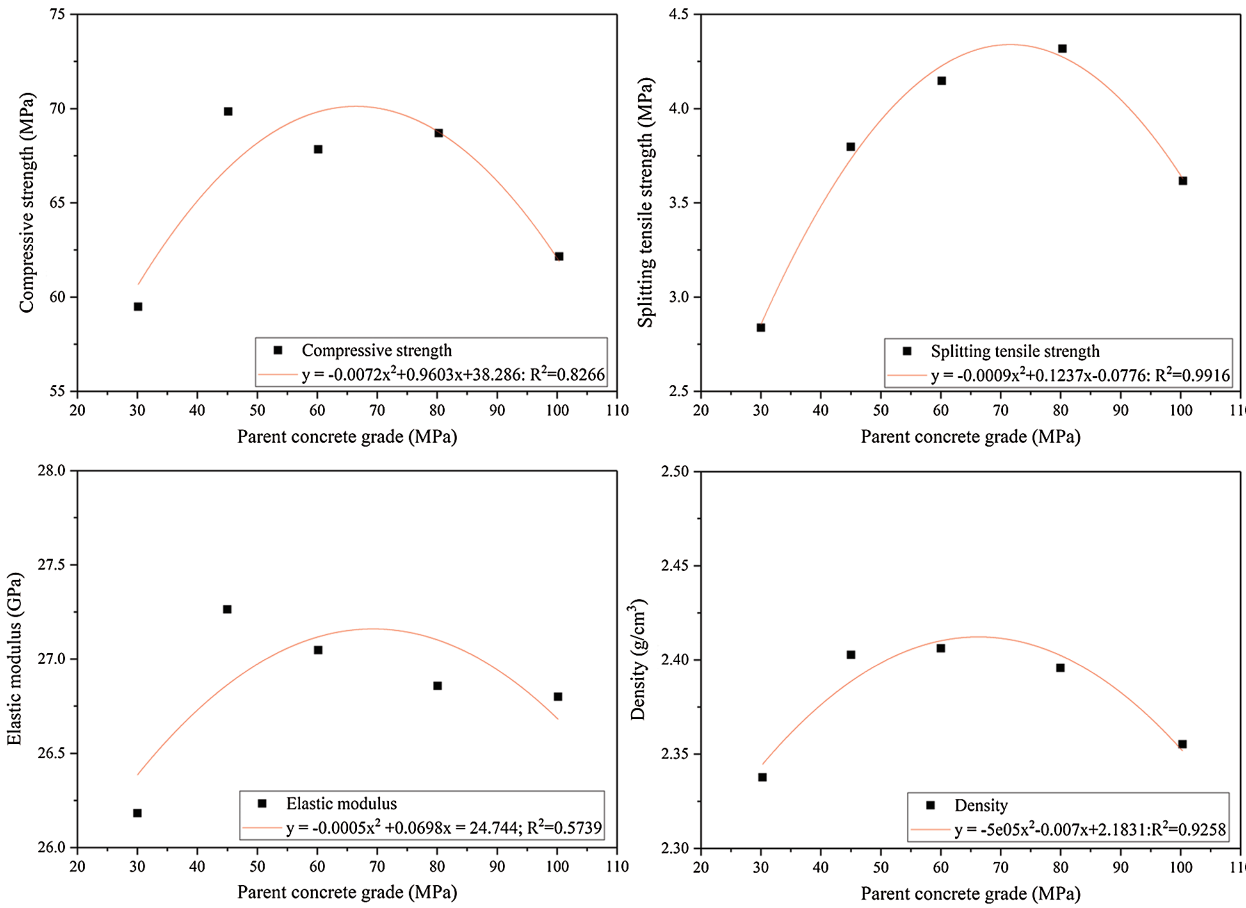

Figure 7: Mechanical properties of RACs with RAs of different qualities

When the grade of parent concrete increased to C80 and C100, as mentioned earlier, the improvement of RA performance was weakening because of the negative influence of excess mortar content. Literature suggest that with higher strength grade of parent concrete the amount of attached mortar is higher [38]. This can be attributed to the stronger bond between the mortar and the aggregate. Moreover, the total porosity of attached mortar somehow influences the total water absorption of aggregates in high strength grade concrete leading to a lower performance of RAC concrete made from the higher strength grade of parent concrete [12]. For the parent concrete of RA30-RA60, coarse aggregates of 5–10 and 10–20 mm fractions were mixed in a ratio of 1:2. In contrast, coarse aggregates of 5–10 and 10–20 mm fractions were mixed at a rate of 2:1 for parent concrete of RAC80 and RAC100. The mortar content in coarse aggregates of 5–10 mm was more than that in coarse aggregates of 10–20 mm, so the influence of mortar content in RAC was magnified and became the crucial factor that may affect the RAC properties. As shown in Fig. 7, the properties of RAC went through a degradation with the increase of parent concrete grades. Still, the compressive strength of RAC100 exceeded the target strength.

3.2.2 Chloride-Ion Penetrability

Fig. 8 shows a comparison of the experimental results between the chloride-ion penetration of NAC and RAC made with different RAs. The total charge passed of NAC at the age of 28 days was used as a benchmark.

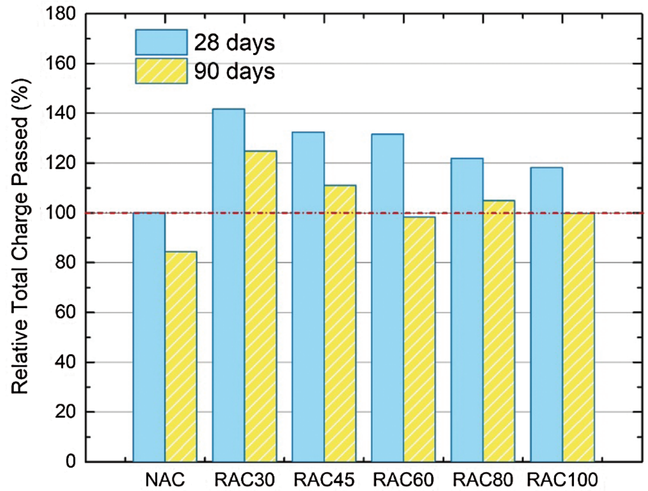

Figure 8: Chloride-ion penetration of RACs with different grade parent concretes

The chloride penetration resistance of RACs was much worse than that of the corresponding reference group at 28 days and 90 days, which is generally accepted for old attached mortar in RACs. The ability of NAC and RACs to resist the chloride-ion penetration was both enhanced from 28 days to 90 days because of the further hydration of new mortar. Besides, the relative total charge passed of RACs at 28 days and 90 days presented a reducing trend. The relative total charge passed of RAC30 was highest up to 141.7% and 124.9% at 28 days and 90 days, respectively. Because of the lower quality of RA30. The chloride penetration resistance enhanced gradually with the improvement of the strength grade of parent concrete at both 28 days and 90 days. A reduction of 23.6% and 25.1% can be noticed in the relative total charge from RAC30 to RAC100 at 28 days and 90 days, respectively. The reduction in concrete mixes can be attributed to the number of different sizes of pores. As seen from Tab. 3, the amount of total porosity is reduced with increase strength of concrete and the quality of the attached mortar, which increases with an increase in the strength of parent concrete.

Table 3: Porosity of mixes (%)

Notation	Porosity (size of pores)				
	1500–1000 μm	1000–500 μm	500–100 μm	100–50 μm	Total porosity
NAC	0.07	0.12	0.28	0.02	0.49
RAC30	0.12	0.22	0.37	0.05	0.76
RAC60	0.23	0.19	0.21	0.01	0.64
RAC80	0.09	0.14	0.26	0.01	0.50

3.3 CT Test Result Analyses of RACs with RAs from Different Strength Grade Concrete

3.3.1 Pore Characteristic Analysis Results

Fig. 9 shows a comparison of the pore structure between NAC and different RACs produced by CT scanning. As compared with NAC, the micropores of RAC were large and denser, and numerous pores distributed around the RA particles because of the weak residual mortar. Such a porous structure was clearer in RAC30 while hardly observed in RAC60 and RAC80. The attached mortar in RAC60 and RAC80 was much denser than that in RA30 because of the use of high-quality RAs.

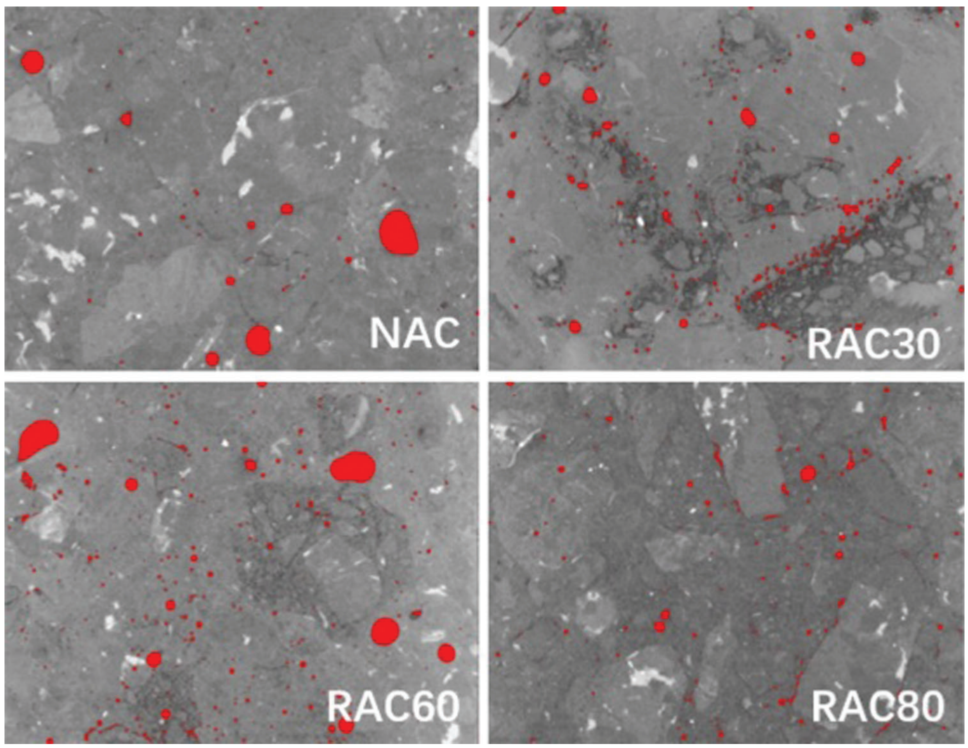

Figure 9: CT scanning images of NAC and different RACs

The further analysis of scanning results was conducted using a commercial image processing software VGStudio. A comparison of the porosity results between NAC and different RACs using the CT test can be seen in Tab. 3, from which it can be noticed that the porosity of NAC was lower than that of all RACs. Besides, the porosity of RACs decreased with an increase in the strength grade of their parent concrete. The total porosity of RAC30 is about 0.76%, which was highest among the mixes with RA. The high porosity in RAC will bring about more passageways for the penetration of water and aggressive ions, which is detrimental to the durability of concrete. The adverse effects may be eliminated with the alternative use of high-quality RA.

3.3.2 Internal Crack Propagation of RACs

There are many forms of fracture section after the failure of concrete under load, the hardened mortar and interfacial transition zone (ITZ) between aggregate and mortar are generally considered as the leading causes, since they are weaker than ITZ between aggregates and matrix. However, the characteristic of the fracture surface in RACs may also be affected by the quality of RA, which depends mostly on the quantity and quality of the residual mortar.

As seen from Fig. 10, two forms of internal crack propagation path were found in the fracture section of RAC: 1) across the RAs, as shown in the red mark; 2) along with the RA-new mortar interface, as shown in the blue mark. To further analyze the crack growth path, a comparison between the sections of NAC and different RACs after splitting tensile test was conducted by using different colors. As shown in Fig. 11, three main phases of NAC and RACs, including the original aggregate, the residual mortar, and the aggregate-mortar interface, were marked as blue, red, and purple, respectively. At the same time, the rest part was considered as the new mortar. In general, the ITZ is usually thin fine lines that cannot be seen by naked eye with in a cross section of the aggregate mortar matrix. After splitting the beam, with visual inspection and image processing, the ITZ that is parallel to the splitting plane is made visible is the pictures and is highlighted in purple color.

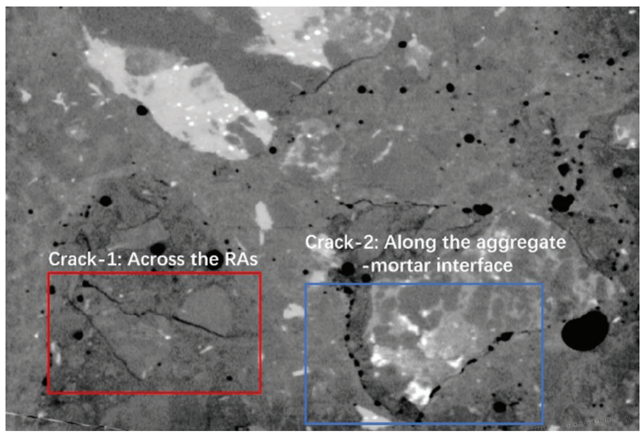

Figure 10: Internal Crack propagation paths of RAC

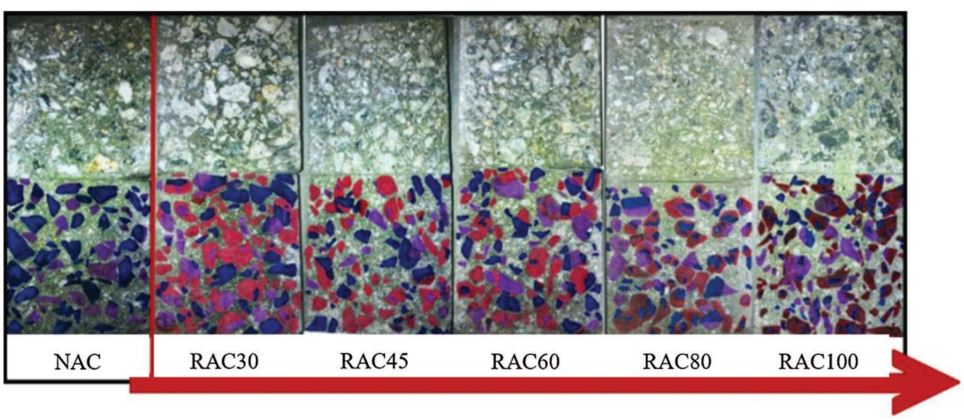

Figure 11: Rupture photograph of the section of hardened concrete after splitting. Note: blue–original aggregate; red–residual mortar; purple-ITZ; else–new mortar

Fig. 12 gives a comparison of the proportion of different phases in the fracture sections of NAC and RACs. The proportion of each component in the rupture photographs was calculated by using an image processing software (Image pro plus). From the Fig. 12, it can be noticed that the failure of NAC mainly occurred in the new mortar, nearly 60% of the total cross-section area. The proportion of failure in new mortar became lower for RACs, although the failure in the new mortar was still the most likely form. The new mortar was no longer the weakest phase with the alternative use of RAs. The proportions of new mortar failure in RAC30 and RAC45 were 42%, which were much lower than those in NAC and other RACs. In contrast, the proportions of the residual mortar failure in these two RACs were much higher than that in the other RACs, even though the quantities of the residual mortar in RA30 and RA45 were much less than that in the other RAs. It was mainly due to the residual mortar attached to RA30 and RA45 had lower qualities that they were more prone to failure than other phases under the failure load. As regards the new mortar failure in the fracture sections among all the RACs, the proportion was up to 58.3% in RAC60, which is similar to that in NAC. The proportion of natural aggregate failure in RAC100 was only about 11.3% of the total cross-section area, and the value was much lower than that in NAC and the other RACs, which can explain the poor performance of RAC100 in mechanical tests.

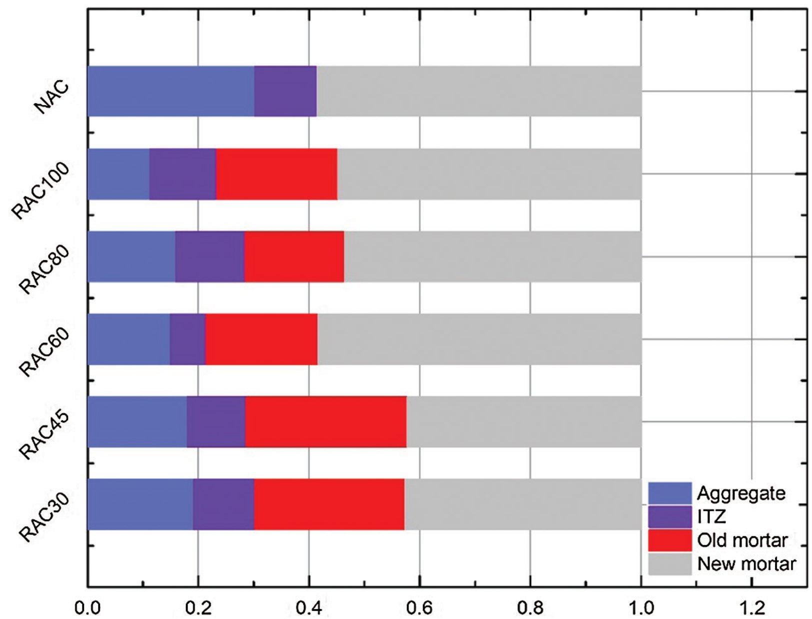

Figure 12: The proportion of different phases in the fracture surface of NAC and RACs

4 Conclusions

RAs from various grades of parent concretes were tested and used to prepare the new RAC. Then a series of mechanical tests and the CT scanning test were conducted to investigate the effect of different RAs on the properties of RACs. The results of this experimental investigation lead to the following conclusions:

For the RAs examined in this study, both the quantity and quality of the residual old mortar were proportional to the strength grade of the corresponding parent concrete, and the behaviors of RA depended on their combined action. The quality of the residual mortar played a leading role when the parent concrete was lower than 60 MPa, and a significant improvement was noticed in the quality of RA with an increase in the strength grade of parent concrete. Whereas, the quality and the amount of residual mortar on aggregates plays an important role in decreasing the strength of concrete made with aggregate from higher strength grade parent concrete which was can be attributed to the amount of attached mortar.

With an increase in the strength grade of parent concrete, the mechanical characteristics and chloride-ion penetrability of RAC prepared with different RAs showed a decrease after showing an increasing trend, and the properties of RACs performed better when the strength of parent concrete was between 60 MPa–80 MPa. The compressive strength of concrete with 45 MPa shows a highest strength of 69 MPa among all the mix with RA. Whereas highest split tensile strength was observed in the mix with 80 MPa strength grade which can be attributed to the better interparticle bonding in concrete matrix.

The microscopic analysis of pore structure by using the CT scanning test showed that, compared with the porosity of NAC, that of RAC30 was significantly higher. At the same time, the porosity of RAC60 and RAC80 was slightly lower. Besides, the residual mortar of RAC30 was much loose and porous, whereas that of RAC80 was denser, similar to new mortar in visual sensation.

Based on the current research, the various optimum combination of the RA from various known sources should be incorporated in the future study. Also, the addition of supplementary cementitious materials (SCMs) such as fly-ash, metakaolin and other industrial by-products should be incorporated to check the effect on the strength and durability of concrete made with RA from known sources.

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