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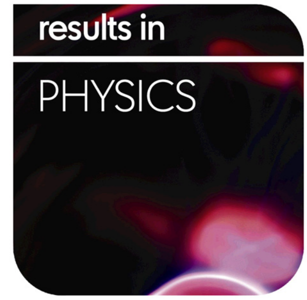

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Mechanical Properties of Recycled Concrete with Demolished Waste Concrete Aggregate and Clay Brick Aggregate

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Abstract – This paper presents an experimental investigation on the effect of the replacement of natural coarse aggregate (NCA) with either recycled concrete aggregate (RCA) or recycled clay brick aggregate (RBA) on the compressive strengths of the hardened concrete. Two grades (C25 and C50) of concrete were investigated, which were achieved by using different water-to-cement ratios. In each grade concrete five different replacement rates, 0%, 25%, 50%, 75% and 100% were considered. In order to improve the performance of the recycled aggregates in the concrete mixes, the RCA and RBA were carefully sieved by using the optimal degradation. In this way the largest reduction in the 28-day compressive strength was found to be only 7.2% and 9.6% for C25 and C50 recycled concrete when the NCA was replaced 100% by RCA, and 11% and 13% for C25 and C50 recycled concrete when the NCA was replaced 100% by RBA. In general, the concrete with RCA has better performance than the concrete with RBA. The comparison of the present experimental results with those reported in literature for hardened concrete with either RCA or RBA demonstrates the effectiveness in improving the compressive strength by using the optimal gradation of recycled aggregates.

Keywords: Recycled aggregate concrete, waste concrete aggregate, clay brick aggregate, mechanical properties, experiments

1. Introduction

Concrete, owing to its availability, easy preparation and fabrication, is the most popular construction material. Today, concrete is the second most used material after water, with nearly three tonnes used annually for each person on earth. Due to the vast amount of concrete being produced and the huge amount of demolition waste from old concrete structures, the reuse of concrete waste by the construction industry is becoming increasingly important. This is motivated not only by the environmental protection, but also by the conservation of natural aggregate resources, the shortage of waste disposal land, and the increasing cost of waste treatment prior to disposal. In Chinait is estimated that there are approximately 15.5 million tonnes of construction waste produced annually [1], the majority of which is the concrete and bricks.

Research work on the use of recycled materials is mainly focussed on the use of recycled concrete aggregate (RCA) and its influence on the properties of the fresh and hardened recycled concrete [2-11]. RCA is different from virgin aggregate only due to the adhered old cement and/or mortar that is attached to the natural aggregate present at the core. The volume fraction of adhered mortar in a RCA decreases with the increase in the nominal size of RCA [12]. It was reported that for RCA with sizes of 4–8 mm, 8–16 mm and 16–32 mm, the volume fraction of mortar is about 60%, 40% and 35%, respectively [13]. Although it has been a long history to use RCA as granular material in pavement design, extensive research on the performance of RCA in structural applications is only very recent [14]. The use of RCA in high performance concrete has not been widely accepted, primarily due to the reduction in both mechanical and durability properties found in recycled aggregate concretes [15]. The statistical analysis showed that RCA derived from crushed concrete consists of 65-80 vol.% of natural coarse and fine aggregates and 20-35 vol.% of old cement paste [16]. It was reported that the mortar in RCA contributes to a lowered relative density and higher water absorption than virgin aggregate [17-19]. The higher portion of attached mortar and weaker interface between aggregate and mortar in RCA lead to lower concrete quality such as low compressive strength and poor durability. It was also reported that the use of RCA leads concrete to have higher shrinkage and creep strains [20]. It was suggested that a good RCA should meet certain criteria in order to be suitable for use in reinforced concrete [21]. These include an aggregate relative density of 2.3 or higher, a maximum mortar content of 50%, and a maximum water absorption of 3%. Some practice codes restrict the use of RCA with water absorption capacity greater than 7-10% to be used in structural concrete.

In many developing countries, such as in China and India, most buildings are built using bricks or the combination of bricks and concrete. The demolishing of this kind of buildings generates huge waste. Currently, most of the demolished bricks are used by landfills, which not only are very costing but also can cause environmental problems. Research on the use of recycled brick aggregate (RBA) starts in the late of 1990s [22-31].It has been suggested that, although the mechanical properties of recycled aggregate concrete are generally inferior to those of conventional concrete, there is a great potential to incorporate RCA and/or RBA in structural concrete applications [30-33]. Compared to the RCA, the research on RBA has more challenges due to the variety of types of bricks used in different regions, which inevitably leads to the variation in theproperties of the mixed concrete. In literature, large reduction in compressive strength was reported when the concrete used the RCA or RBA as the replacement of NCA. For instance, Debieb and Kenai [28] reported that the reduction in compressive strength was about 30% when 100% of the NCA was replaced. Yang et al. [22] found that the compressive strengths of the concrete containing 20% and 50% recycled aggregate made from fired clay waste decreased by 11% and 20%, respectively. Marinez-Lage et al. [34] reported the decreases in compressive strength up to 13% and 23% in recycled concrete with 50% and 100% replacements of mixed recycled aggregates. Mas et al. [35] reported the 13%-39% reduction of compressive strength in 40% substitution. Medina et al. [36] found that the compressive strength in the recycled concrete with 25% and 50% replacement ratios was 8.7%-15.9% and 15.1%-18.4% lower than that of the controlled concrete with no recycled aggregate at 7 and 28 days of curing, respectively. In this paper, an experimental investigation is presented on the

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effect of the replacement of coarse aggregate with either RCA or RBA on the compressive strengths of the hardened concrete. Two grades (C25 and C50) of concrete were investigated, which were achieved by using different water-to-cement ratios. In each grade concrete five different replacement rates, 0%, 25%, 50%, 75% and 100% were considered. In order to improve the performance of the RCA and RBA used in the concrete mixes, both the RCA and RBA were carefully sieved by using the optimal degradation before they were used. The comparison of the present experimental results with those reported in literature for hardened concrete with either RCA or RBA demonstrates the effectiveness in improving the compressive strength by using the optimal gradation of recycled aggregates.

2. Experimental details

2.1 Materials

The materials used in the present experimental studies are as follows. The ordinary Portland cement with a targeted28-day compressive strength of 42.5 MPa for water-to-cement ratio of 0.4, specified surface area of 340 m^2/kg and a fineness of 0.65 was used as the binder. The chemical composition of the cement used is shown in Table 1. The locally available river sand of sizes not greater than 5 mm with the fineness modulus of about 2.9 was used as the fine aggregate. The crushed stones with the size range of 3-35 mm and a fineness modulus of 7.10 were used as the coarse aggregate in the mix design of the concrete or part of the coarse aggregate in the mixed design of recycled aggregate concrete. The water used was the tap water.

Two types of recycled aggregates were used. One is the RCA and the other is the RBA. The former was obtained from the concrete cubes previously prepared in laboratory, which were mixed using water-to-cement ratio of 0.50 and have the 28-day compressive strength of about 32 MPa. The cubes were cured for 56 days under standard curing conditions before they were smashed using jaw crusher. The latter was obtained directly from the sintered clay bricks removed from a demolition site of an old building. The strength test of the bricks showed their compressive strength meets the MU10 stipulations in GB 5101-2003 Field Common Bricks[34]. After the concrete cubes and the clay bricks were smashed using jaw crusher, they were cleaned, oven dried, sorted and screened using sieves to achieve the coarse aggregates of the size range from 4 mm to 32.5 mm, with the fineness of 7.36 for RCA and 7.05 for RBA. Fig.1 shows the appearance of the RCA and RBA used in the present experimental study.

It is known that the gradation of aggregates has a remarkable influence on the performance of the mixed concrete. To achieve the best performance of the concrete with recycled aggregates, the particle size distributions of both the RCA and RBA were carefully adjusted by using sieves of different sizes. This was donebased on the sampling mode, sampling quantity, and experimental methods as indicated in JGJ 52-2006 standard code for quality of sand and stone used for normal concrete and the inspection procedure [38]. In addition to remove large and small particles from the crushed RCA and RBA, the particle size distributions of the remained RCA and RBA are adjusted to match the particle size distribution of the natural coarse aggregate (NCA). Fig.2 shows a comparison of the particle size distributions of the RCA, RBA and NCA after the grading optimization, whereas their physical properties are given in Table 2, respectively.

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2.2 Mix proportion

Two types of concrete mixes were made. One used RCA and the other used RBA. In each type of the mixes two different water-to-cement ratios were used. One is the w/c = 0.55 which was for the C25 grade concrete; the other is the w/c = 0.35 which was for the C50 grade concrete. Five different mixes were made for each water-to-cement ratio by using different replacements (0, 25%, 50%, 75% and 100%) for NCA with RCA or RBA. Thus, there are a total of 2x2x5=20 (two different w/c ratios, two different testing ages, and five different replacements) mixes that were made. Tables 3 and 4 give the details of the mix proportion for the two types of concrete mixes. Note that due to the high water absorption of RBA, extra water was used in the mixes with RBA. Also, for the mixes with low water-to-cement ratio (w/c=0.35) P-C300superplasticizer was used for the improvement of the workability during the mixing process.

Six specimens were cast for each mix, three of which were tested at the same time either on 28 days or on 56 days. So there are a total of 120 specimens that were cast. All specimens were cast into 10 cm x 10 cm x10 cm cubic steel moulds by vibration. They were demoulded after 24 hours and then cured in a laboratory controlled curing condition for 28 days or 56 days before they were tested.

2.3 Mechanical properties test

The compressive strength tests were carried out following the procedure specified in Chinese Standard for cubic concrete specimens. After the curing, the specimens were tested by using TONIPACT 300 compression testing machine (see Fig.3), from which the compressive strengths of the specimens at 28 days and at 56 days were obtained for each concrete mixture.

2.4 Scanning electron microscopy analysis

In order to understand the performance of RCA and RBA in concrete, scanning electron microscopy (SEM) was also used to provide images from which the microstructure and the interfacial transition zones (ITZs) between the new mortar and RCA and RBA in the concrete with RCA or RBA were examined. The core section of the concrete cubes was cut out by removing the outer sections of the cubes. A small sample of size less than 10 mm in dimensions was taken. The collected samples were carbon coated before the test was conducted using the scanning electron microscope.

3.Results and discussion

Fig.4 shows the compressive strength of the cubic specimens with RCA for w/c = 0.55, tested on 28 and 56 days, respectively, in which the strength plotted is the mean value of the three tests of the same mix, while the error bar plotted in the figure represents the variation of the test results. Overall, the variation of the test results obtained from the same mixes is much smaller than the corresponding mean value, indicating that the test results are reliable. It can be seen from the figure that for both the specimens tested on 28 days and 56 days the compressive strength drops with the increased RCA replacement. For example, the strength is reduced by 2%, 4.4%, 5.6% and 7.2% on 28 days and 3.7%, 6.8%, 9.6% and 11% on 56 days when the NCA was replaced with RCA by 25%, 50%, 75% and 100%, respectively. The reduction rate is slightly higher in the 56-day strength than in the 28 day-strength. Also, it can be seen that the compressive strength of the specimen tested

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on 28 days is remarkably lower than that tested on 56 days; the latter one is about 1.23~1.29 time the former one.

Fig.5shows the compressive strength of the cubic specimens with RCA for w/c = 0.35, tested also on 28 and 56 days, respectively. The main feature shown in this figure is similar to that shown in Fig.4. For example, the compressive strength is reduced by 2.6%, 5.9%, 8.0% and 9.6% on 28 days and 3.0%, 9.4%, 10%and 12% on 56 days when the NCA was replaced with RCA by 25%, 50%, 75% and 100%, respectively. However, it is noticed that the strength difference between the specimens tested on 28 days and 56 days is only from 3% to 6.7%, which is much smaller than the specimens of w/c = 0.55. The reason for this is probably due to the use of superplasticizer in the C50 grade concrete, which accelerates the strength development of the concrete at earlier ages [39].

Fig.6shows the compressive strength of the cubic specimens with RBA for C25 grade concrete, tested on 28 and 56 days, respectively. It can be seen from the figure that the compressive strengths of both the specimens tested on 28 days and 56 days decrease with the increase of the replacement of NCA with RBA. For example, the strength is reduced by 1.6%, 5.6%, 7.6% and 11% on 28 days and 4.7%, 9.3%, 12% and 14% on 56 days when the NCA was replaced with RBA by 25%, 50%, 75% and 100%, respectively. The reduction rate is slightly higher in the 56-day strength than in the 28 day-strength. Similarly to the C25 grade concrete (w/c = 0.55) with RCA, the compressive strength of the specimen with RBA tested on 28 days is remarkably lower than that tested on 56 days; the latter one is about 1.22~1.29 time the former one.

Fig.7shows the compressive strength of the cubic specimens with RBA for C50 grade concrete, tested on 28 and 56 days, respectively. It can be seen from the figure that the compressive strengths of both the specimens tested on 28 days and 56 days drop with the increase of the replacement of NCA with RBA. However, the drop of the compressive strength of the specimens tested on 56 days is quicker than that of the specimens tested on 28 days. For example, the compressive strength is reduced by 3.3%, 8.0%, 11% and 13% at 28 days and 5.1%, 13%, 16% and 17% at 56 days when the NCA was replaced with RBA by 25%, 50%, 75% and 100%, respectively. It is interesting to note that for the specimens with 50% replacement of NCA or over the compressive strengths tested on 28 days and 56 days are almost the same, indicating that the strength development in the specimens with higher RBA replacement rate is rather quick.

In literature, large reduction in compressive strength was reported when the concrete used the RCA or RBA as the replacement of NCA [22, 28, 34-36], ranging from 8% to 40%. Some of studies showed that the removal of the floating particles could reduce the strength differences between the recycled and controlled concrete. In contrast, in the present study the largest reduction in the 28-day compressive strength is only 7.2% and 9.6% for C25 and C50 recycled concrete when the NCA was replaced 100% by RCA, and 11% and 13% for C25 and C50 recycled concrete when the NCA was replaced 100% by RBA, which are much smaller than the reported values in literature. This demonstrates the importance of the gradation of recycled aggregates and the effectiveness by matching the particle size distribution of recycled aggregates with that of natural aggregates in order to improve the performance of recycled aggregates.

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Fig.8 shows a comparison of the 28-day compressive strengths of the specimens with RCA and RBA for C25 and C50 grade concrete. It can be seen from the figure that, overall the use of RCA is better than the use of RBA. However, the difference between them seems negligible for the C25 grade concrete and marginal for C50 grade concrete. This suggests the brick can also be used as the recycled aggregates if their particle size distribution is well controlled. It should be noted that the underperformance of the RBA in the present study could be partially related to the extra water used in the mixture, which, at a certain degree, will decrease the compressive strength of the hardened concrete.Fig.9 shows the comparison of the 56-day compressive strengths of the specimens with RCA and RBA for C25 and C50 grade concrete. Again, the difference between the use of RCA and RBA is small for C25 grade concrete, but more remarkable for C50 grade concrete. The latter is because the effect of curing age. For concrete with RCA the development of strength continues after 28 days; whereas for concrete with RBA the development of strength seems very slow after 28 days, as is demonstrated in Fig.7.

It is known that the ITZs have a great influence on both the mechanical properties and durability of the concrete. The micro-cracks are usually initiated in ITZs when the concrete is under the action of loading. The interface between the mortar and aggregates can be clearly seen in the SEM images shown in Fig.10a for the concrete with RCA and Fig.10b for the concrete with RBA. It can be observed from Fig.10 that the concrete with RCA had a few discontinuous voids near the transition zones, whereas the concrete with RBA had visible micro-cracks in the ITZs. Also, it can be seen from Fig.10b that there were a few internal voids in the RBAs. This may explain why the concrete with RBA has lower compressive strength than the concrete with RCA, particularly for the high grade concrete (C50).

In summary, the experimental results obtained from the present study showed that the compressive strength of the hardened concrete decreases with the increased replacement of coarse aggregate by RCA or RBA. In general, the concrete with RCA has better performance than the concrete with RBA. Also it is shown that, due to the use of optimal gradation of recycled aggregates, the compressive strength of the present recycled aggregate concrete is much higher than that reported in literature when the same replacement rate is used.

4.Conclusions

This paper has presented an experimental investigation on the effect of the replacement of natural coarse aggregates with recycled aggregates on the compressive strength of the hardened concrete. The experiments involved the use of two types of recycled aggregates, namely RCA and RBA, and two types of concrete mixes (C25 and C50 grade concrete) which were achieved by using different water-to-cement ratios. From the obtained experimental results the following conclusions can be drawn.

- The compressive strength of the hardened concrete decreases with the increased replacement of NCA by RCA or RBA and in general, the concrete with RCA has better performance than the concrete with RBA.

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- For C25 grade concrete the compressive strength of the concrete with RBA is close to that of the concrete with RCA. The 28-day compressive strength of the concrete drops only by 7.2% or 11% when the NCA is completely replaced with RCA or RBA.

- For C50 grade concrete there is a remarkable difference between the compressive strengths of the concrete with RCA and RBA. The 28-day compressive strength of the concrete drops by 9.6% or 13% when the NCA is completely replaced with RCA or RBA.

- For concrete with RCA the strength development continues after the 28 days curing; whereas for concrete with RBA the strength development becomes very slow after the 28 days curing. This is particularly so for the C50 grade concrete with high RBA replacement rate.

- The comparison of the present experimental results with those reported in literature for hardened concrete with RCA or RBA demonstrates the effectiveness in improving the compressive strength by using the optimal gradation of recycled aggregates.

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Table 1. Chemical composition of cement

SiO_2: %	Al_2O_3: %	Fe_2O_3: %	CaO: %	MgO: %	SO_3: %	Loss on ignition: %	Others
22.5	4.4	2.1	61.7	3.6	2.2	2.9	0.6

Table 2. Physical properties of NCA, RCA, and RBA

Type of aggregate	Specific gravity	Bulk density (kg/m^3)	Loose porosity (%)	Water absorption (%)
NCA	2.687	1470	45.3	1.2
RCA	2.214	1103	50.2	2.7
RBA	1.702	874	48.6	14.9

Table 3. Mix proportion of recycled concrete with RCA (kg/m^3)

No.	Cement	Water	Sand	NCA	RCA	Super-plasticizer
C25						
RCA1-00	436	244	616	1143	0	0
RCA1-25	436	244	616	857.25	285.75	0
RCA1-50	436	244	616	571.5	571.5	0
RCA1-75	436	244	616	285.75	857.25	0
RCA1-100	436	244	616	0	1143	0
C50						
RCA2-00	528	185	478	1259	0	0.13
RCA2-25	528	185	478	944.25	314.75	0.13
RCA2-50	528	185	478	629.5	629.5	0.13
RCA2-75	528	185	478	314.75	944.25	0.13
RCA2-100	528	185	478	0	1259	0.13

Table 4. Mix proportion of recycled concrete with RBA (kg/m^3)

No.	Cement	Water	Sand	NCA	RBA	Extra water	Super-plasticizer
C25							
RBA1-00	436	244	616	1143	0	0	0
RBA1-25	436	244	616	857.25	285.75	6	0
RBA1-50	436	244	616	571.5	571.5	12	0
RBA1-75	436	244	616	285.75	857.25	18	0
RBA1-100	436	244	616	0	1143	24	0
C50							
RBA2-00	528	185	478	1259	0	0	0.13
RBA2-25	528	185	478	944.25	314.75	6	0.13
RBA2-50	528	185	478	629.5	629.5	12	0.13
RBA2-75	528	185	478	314.75	944.25	18	0.13
RBA2-100	528	185	478	0	1259	24	0.13

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(a) (b)

Figure 1. Appearance of RCA and RBA particles. (a) RCA and (b) RBA.

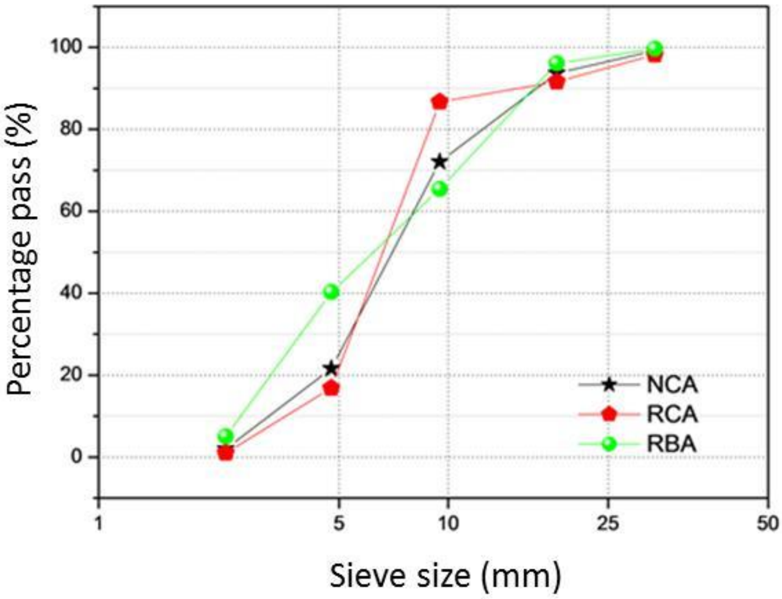

Figure 2. Comparison of the particle size distributions of NCA, RCA and RBA.

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Figure 3. Compressive strength test of concrete cubic specimen.

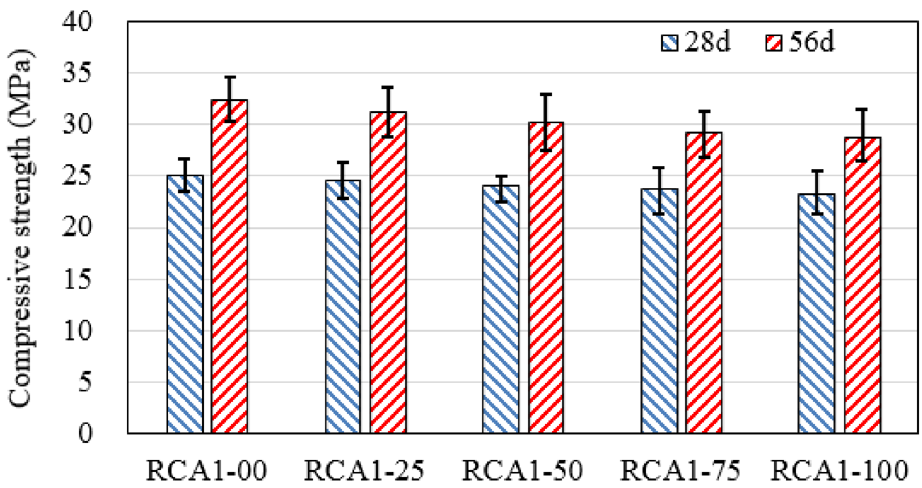

Figure 4. Compressive strengths of specimens with RCA at 28 days and 56 days (w/c=0.55).

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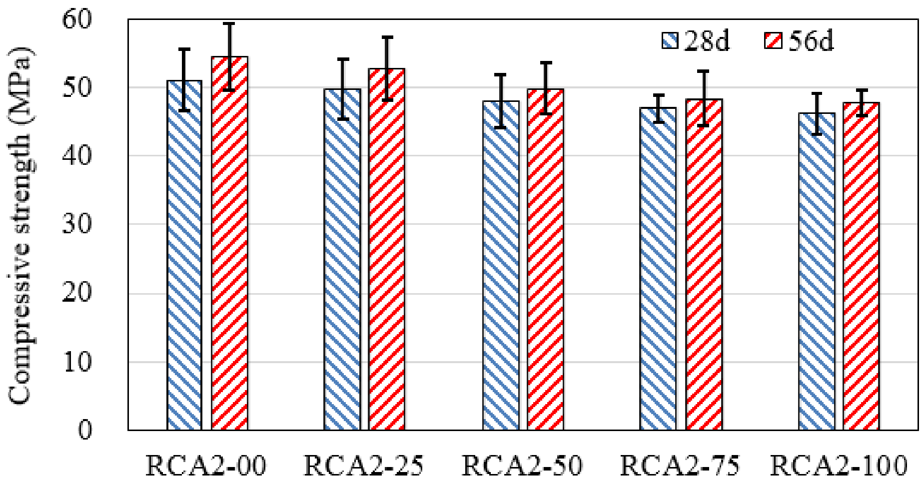

Figure 5. Compressive strengths of specimens with RCA at 28 days and 56 days (w/c=0.35).

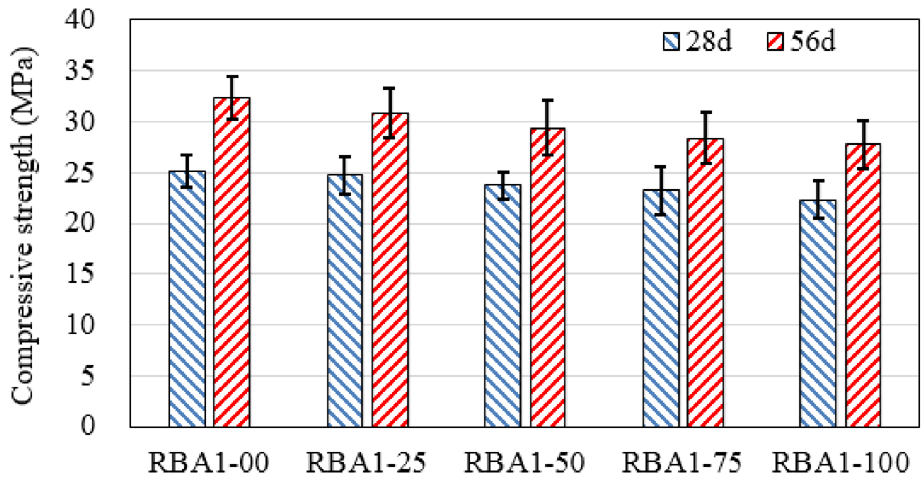

Figure 6. Compressive strengths of specimens with RBA at 28 days and 56 days (w/c=0.55).

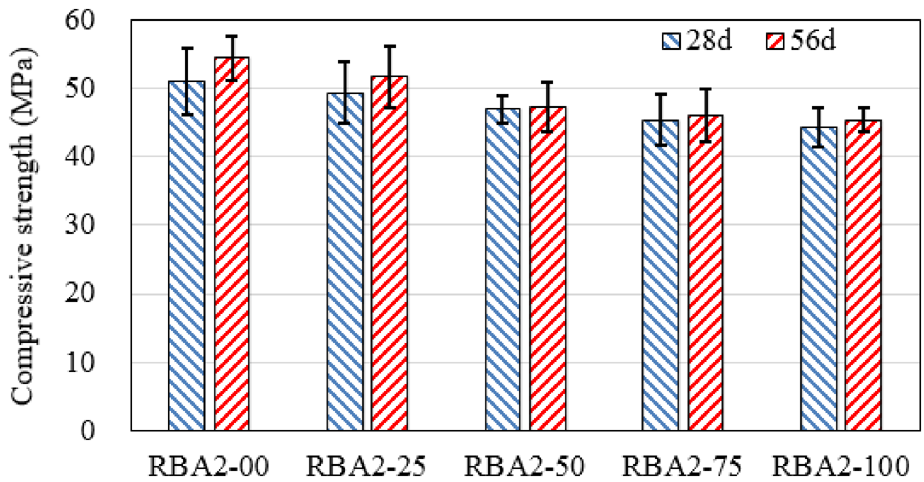

Figure 7. Compressive strengths of specimens with RBA at 28 days and 56 days (w/c=0.35).

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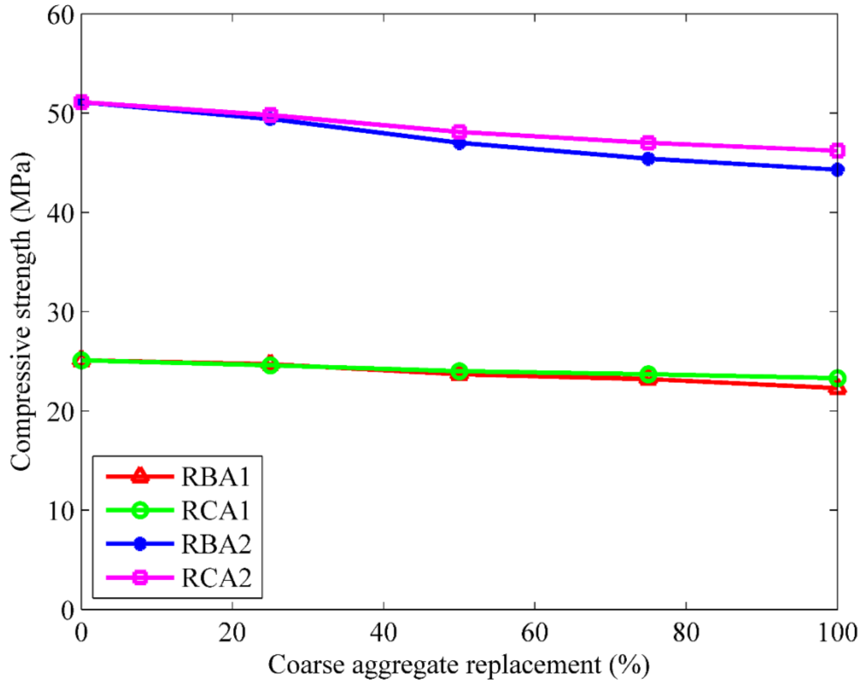

Figure 8. Comparison of 28-day compressive strengths of specimens with RCA and RBA.

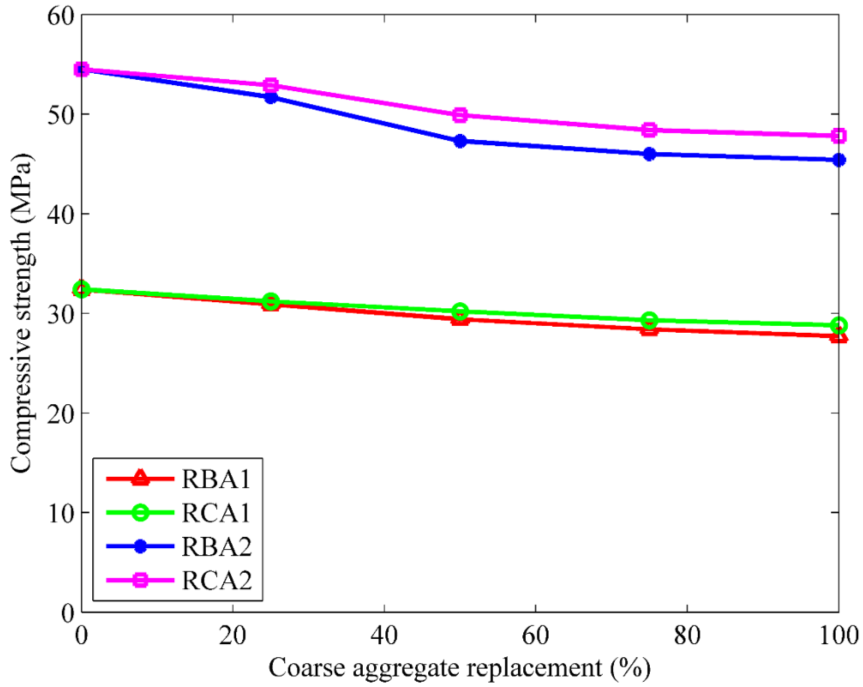

Figure 9. Comparison of 56-day compressive strengths of specimens with RCA and RBA.

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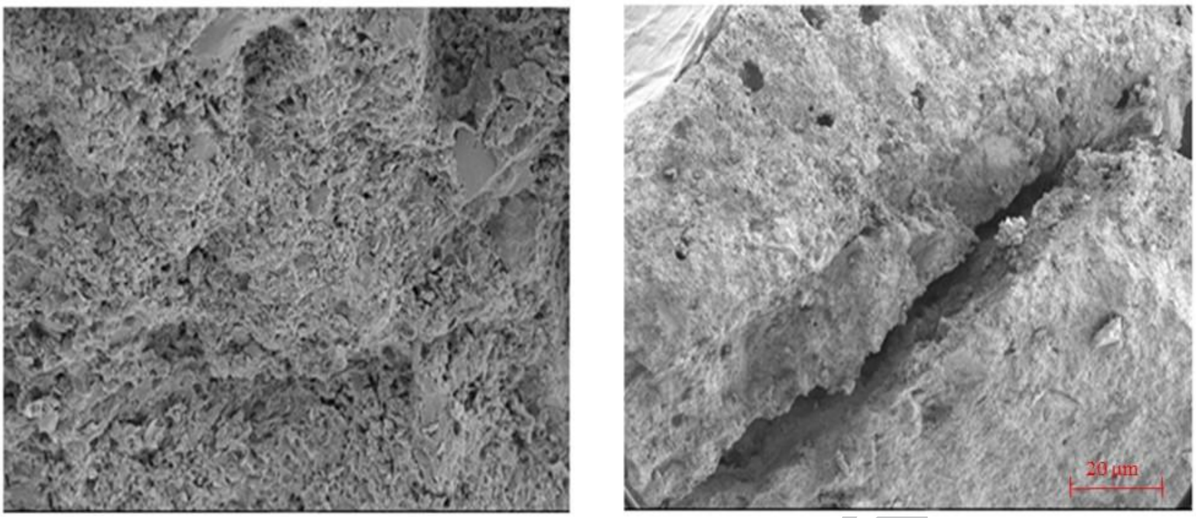

(a) (b)

Figure 10. SEM images of specimens. (a) RCA1-100 and (b) RBA1-100 (w/c=0.55).

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Highlights:

- Compressive strength of concrete containing recycled concrete aggregate or recycled brick aggregate is investigated experimentally.
- Effect of replacement rate of coarse aggregate with recycled concrete aggregate or recycled brick aggregate on the strength of hardened concrete is examined.
- Recycled concrete aggregate and recycled brick aggregate are compared in terms of the compressive strength.
- Effect of particle optimal gradation of recycled aggregates on the compressive strength is also investigated.

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