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Research Article

Mechanical Properties of Recycled Aggregate Concrete at Low and High Water/Binder Ratios

Gai-Fei Peng,[1] Yan-Zhu Huang,[2] Hai-Sheng Wang,[3] Jiu-Feng Zhang,[1] and Qi-Bing Liu[1]

[1] *Faculty of Civil Engineering, Beijing JiaoTong University, Beijing 100044, China*
[2] *BBMG Cement Energy Saving Technology Co., Ltd, Beijing 102403, China*
[3] *Beijing Building Materials Inspecting and Testing Center, Beijing 100041, China*

Correspondence should be addressed to Gai-Fei Peng; gfpeng@bjtu.edu.cn

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This paper presents an experimental research on mechanical properties of recycled aggregate concrete (RAC) at low and high water/binder (W/B) ratios. Concrete at two W/B ratios (0.255 and 0.586) was broken into recycled concrete aggregates (RCA). A type of thermal treatment was employed to remove mortar attached to RCA. The RAC at a certain (low or high) W/B ratio was prepared with RCA made from demolished concrete of the same W/B ratio. Tests were conducted on aggregate to measure water absorption and crushing values and on both RAC and natural aggregate concrete (NAC) to measure compressive strength, tensile splitting strength, and fracture energy. The mechanical properties of RAC were lower than those of NAC at an identical mix proportion. Moreover, the heating process caused a decrease in compressive strength and fracture energy in the case of low W/B ratio but caused an increase in those properties in the case of high W/B ratio. The main type of flaw in RCA from concrete at a low W/B ratio should be microcracks in gravel, and the main type of flaw in RCA from concrete at a high W/B ratio should be attached mortar.

1. Introduction

Recycling of demolished concrete is an important way of utilizing building waste as a resource of the whole society and an important part of the recycling process in the building and construction field. There are a great number of publications on research of recycling of demolished concrete, of which most are in regard to recycled concrete aggregate (RCA) made from demolished concrete [1–6]. Generally RCA is different from natural aggregate so that the properties of recycled aggregate concrete (RAC), which employs RCA as coarse aggregates, are also different from those of ordinary concrete which employs natural aggregates [7–11]. It is commonly believed that RCA has high porosity, low apparent density, and high water absorption. The normally used mechanical process of breaking blocks of demolished concrete into relatively small grains may cause RCA suffering internal damage such as microcracks [12–15] so that RAC has relatively lower strength compared to natural aggregate concrete (NAC) at the same water/binder (W/B) ratio [8, 12, 14, 16]. Some investigations found that a couple of approaches such as particle shaping and heating plus grinding can considerably improve the quality of RCA, in the forms of enhanced density and lowered crushing value of RCA, and hence improve mechanical strength of RAC [16–18]. However, there is a lack of understanding of the characteristics of flaws in RCA composed of original coarse aggregate and attached mortar and the influence of the flaws in RCA on fracture behavior of RAC.

In this paper, an experimental investigation was conducted, using two types of concrete with natural aggregate at a high and a low W/B ratio, respectively, as control concrete. The control concretes were processed via two approaches, that is, crushing and heating plus removal of attached mortar, to obtain RCA, which was used to prepare RAC. Mechanical properties of concrete, such as compressive strength, tensile splitting strength, and fracture energy, were measured. The results of mechanical properties of RAC, with relation to the water absorption and crushing value of RCA, were discussed to identify the characteristics of flaws in RCA and their influence on mechanical properties of RAC.

2. Experimental Details

2.1. Process from Control Concrete to RCA and Tests of RCA. The process from original concrete to RCA is shown in Figure 1. A type of heating was used, in which aggregates were heated under 620°C for 3 hours. Natural aggregate was designated as NA, and that treated by heating was designated as H-NA. A part of 100 mm cubes of NAC at both 0.255 and 0.586 W/B ratios was compressed into broken pieces which were further crushed by hand with a hammer into RCA particles to fully remove attached mortar, of which the sizes ranged from 5 mm to 30 mm. The RCA treated by this heating and crushing process was designated as H-RCA.

The RAC at a certain (low or high) W/B ratio was prepared with RCA made from demolished concrete (i.e., original concrete) of the same W/B ratio; that is, both 255RAC and H-255RAC employed the original concrete (255NAC) at the W/B ratio of 0.255, while 586RAC and H-586RAC employed the original concrete (586NAC) at the W/B ratio of 0.586.

2.2. Preparation of Original Concrete and Recycled Aggregate Concrete (RAC). Mix proportions and compressive strength of NAC and RAC at 28 days are given in Table 1. The mix proportion design of NAC was according to the China standard JGJ 55-2011 [19]. RAC had almost the same mix proportion as that of NAC, but the only difference in mix proportion of RAC is that NA was replaced by weight with RCA. Since RCA had a lower specific gravity compared to that of NA, the mix proportions of RAC were adjusted with data of density measurement on RAC specimens after casting.

Raw materials were crushed limestone as natural coarse aggregate for control concrete (NAC) with specific gravity (oven dried) of 2.84 g/cm^3, RCA as coarse aggregate for RAC with specific gravity of 2.61 g/cm^3 before exposure to heating and 2.77 g/cm^3 after exposure to heating, river sand with a fineness modulus of 2.5 and specific gravity of 2.60 g/cm^3, ordinary Portland cement of 42.5 MPa strength grade, and silica fume with specific gravity of 2.09 g/cm^3. Polycarboxylate superplasticizer was used to maintain slump of mixtures within the range from 80 mm to 150 mm. Specimens of 100 mm cubes for strength measurement and 400 mm × 100 mm × 100 mm notched beams for fracture energy measurement were prepared. After demolding at one day, all the specimens were cured in water at 20°C until being tested at 28 days.

In Table 1, the quantities of aggregate were for dry aggregate, and the quantities of water were for mixing water. But it is important to mention that, throughout this research, dry coarse and fine aggregates had been weighed as required by calculation according to Table 1, one day ahead of concrete mixing, and then subjected to immersion in water for 24 hours for saturation. Following such weighing and immersion, saturated and surface dried aggregates were used for concrete mixing, so that the negative effect of high absorption capacity of dry RCA on workability of fresh RAC [2, 12, 20] would be prevented.

2.3. Test Methods

2.3.1. Aggregate. Three samples a batch were used to provide a mean value as a test result. Tests were conducted on aggregates including NA and RCA, to measure crushing value and water absorption, according to the China standard GB/T 14685-2011 [21] which is similar to BS 812-110 and BS EN 1097-6.

2.3.2. Concrete. At 28 days, three specimens a batch were used to provide a mean value as a test result.

Determination of compressive strength and tensile splitting strength was conducted on cube specimens of 100 mm size at 28 days, according to the China standard GB/T 50081-2002 [22] which is similar to BS 1881: Part 116.

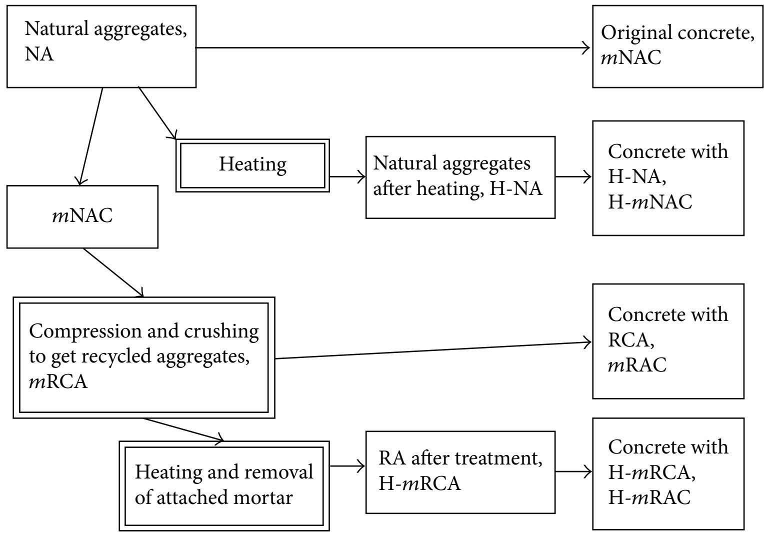
Fracture energy determination was conducted on notched beam specimens of 100 mm × 100 mm × 300 mm according to a RILEM method [23]. A notch was prepared on each beam specimen during casting, to form a crack at the mid-span of each specimen prior to heating. In a three-point bending test on a beam specimen, mid-span deflection δ was recorded during the whole loading process until failure. The loading was in a displacement-controlled manner at a rate of 0.05 mm/min. From a load-deflection curve recorded, the fracture energy of concrete could be calculated by using (1) that is specified in the RILEM method [23]:

$$G_F = \frac{\left[\int_0^{\delta_0} P(\delta)\, d\delta + mg\delta_0\right]}{A_{\text{lig}}}, \quad (1)$$

where G_F is the fracture energy (J/m^2), $m = m_1 + m_2$ (kg), $m_1 = M\, s/L$ (weight of the beam between the support, calculated as the beam weight multiplied by s/L), M is the mass of the specimen, m_2 is the weight of the part of the loading arrangement which is not attached to the machine but follows the beam until failure, s is the span, L is the length of the specimen, $g = 9.81$ m/s^2, δ_0 is the the mid-span deflection of the specimen at failure (m), A_{lig} is the area of the ligament (m^2), δ is the mid-span deflection (m), and P is the load (N).

3. Results and Discussion

3.1. Water Absorption and Crushing Value of Coarse Aggregate. The results of water absorption tests on various types of aggregates are given in Figure 2. Water absorption of RCA was considerably higher than that of NA. Since water absorption of RCA decreased from 4.07% to 2.89% and from 7.89% to 2.77%, respectively, after removal of attached mortar, attached mortar should be responsible for a part of the increment of water absorption of RCA on the base of NA. The contents of mortar attached to RCA listed in Table 2 were measured on RCA before heating and after heating plus crushing. The greater content of mortar in 255RCA in Table 2 and the smaller decrease in water absorption of RCA at 0.255



Note:

m: for W/B ratio, for example, 260 for the W/B ratio of 0.260

H: for aggregates heated under 620°C for 3 hours

Figure 1: Process from NA to RCA and preparation of concrete.

Table 1: Mix proportions and compressive strength of concretes#.

Type of concrete	W/B ratio	Quantity of raw materials (Kg/m^3)							$f_{\text{cu, 28}}$ (MPa)
		C	S	NA	RCA	W	SF	SP	
255NAC	0.255	518	578	1119	0	145	62	29.35	80.8
H-255NAC	0.255	518	578	1119	0	145	62	29.35	76.8
255RAC	0.255	491	548	0	1061	138	59	27.83	70.9
H-255RAC	0.255	507	566	0	1095	142	61	28.72	65.6
586NAC	0.586	393	578	1119	0	258	47	0	31.9
H-586NAC	0.586	393	578	1119	0	258	47	0	31.6
586RAC	0.586	365	536	0	1038	239	44	0	25.3
H-586RAC	0.586	369	542	0	1050	242	44	0	31.1

#Note: the symbols in Table 1 are as follows: C for cement, S for sand, NA for natural coarse aggregates, RA for recycled coarse aggregates, W for water, SF for silica fume, SP for superplasticizer, and $f_{\text{cu,28}}$ for compressive strength of concrete at 28 days.

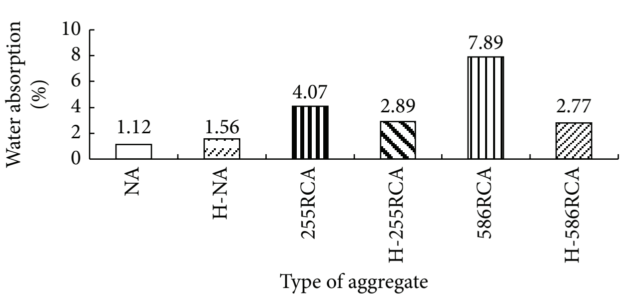


Figure 2: Water absorption of various types of aggregates.

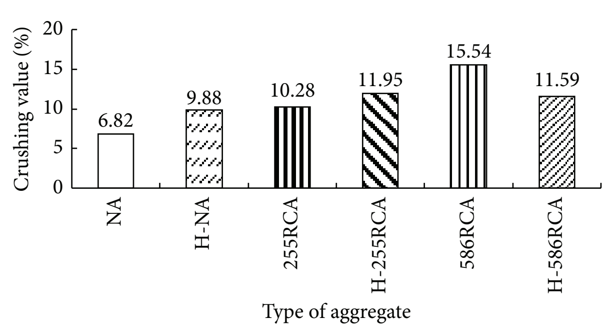
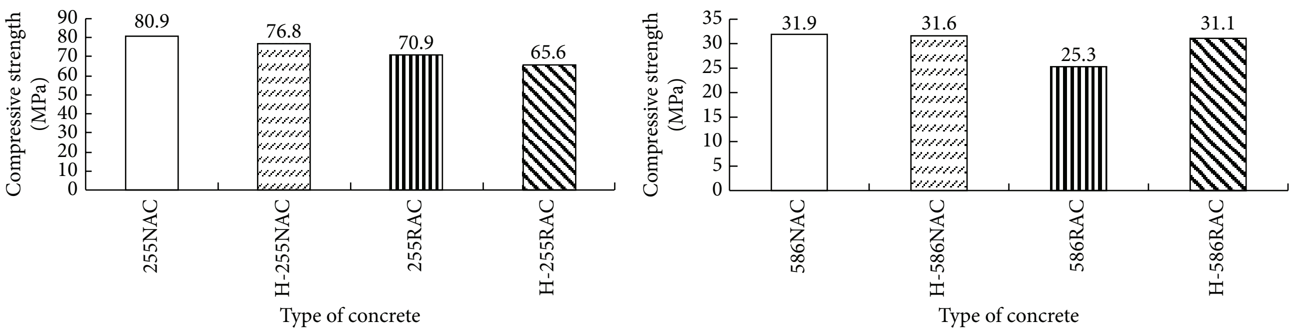


Figure 3: Crushing values of various types of aggregate.

W/B ratio after removal of attached mortar in Figure 2, compared to those of RCA at 0.586 W/B ratio, suggest that, although 255RCA had a higher mortar content that that of 586RCA, porosity rather than content of mortar in RCA had a significant effect on water absorption of RCA, as the mortar in 586 RCA was obviously more porous than that in 255 RCA.



(a) For concrete at a W/B ratio of 0.255

(b) For concrete at a W/B ratio of 0.586

Figure 4: Compressive strength of concrete at W/B ratios of 0.255 and 0.586.

Table 2: Contents of gravel and attached mortar in RCA by mass.

Type of RCA	Content of gravel (%)	Content of attached mortar (%)
255RCA	54.6	45.4
586RCA	61.5	38.5

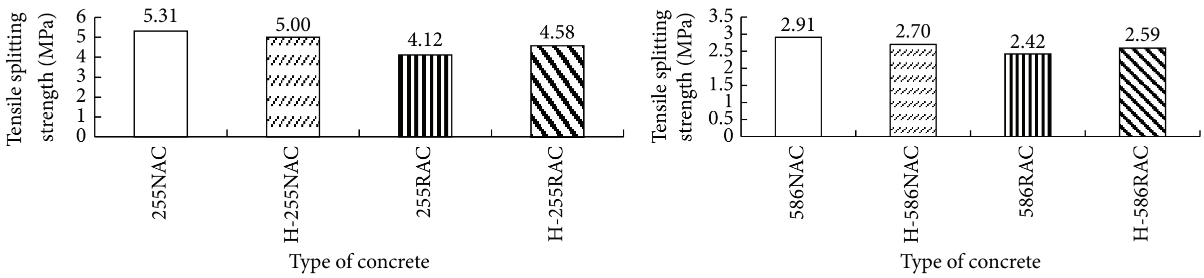
Another part of the increment of water absorption of RCA may be caused by microcracking of original gravel in RCA, which could be induced by the compression and crushing process. It can be found in Figure 2 that heating of NA caused an increment in water absorption to 1.56%. As water absorption of RCA after removal of attached mortar was approximately 2.83% based on the data of H-255RCA and H-586RCA, the part of the increment of water absorption of RCA caused by the compression and crushing process can be calculated as $2.83\% - 1.56\% = 1.27\%$, which is slightly higher than that of NA (1.12%). Such an increase in water absorption should be a result of microcracking of original NA induced by breaking and crushing, which is in consistency with a previous research [24].

The results of crushing value tests on various types of aggregate are given in Figure 3. Both types of RCA had higher crushing values than that of NA, and heating also caused an increment in crushing value of NA. An interesting inconsistence can be found between the two types of RCA after removal of attached mortar. The RCA at 0.255 W/B ratio had a crushing value that increased from 10.28% to 11.95%, which means the process of heating and crushing for removal of attached mortar causes an increment in crushing value, and the attached mortar at 0.255 W/B ratio itself may cause almost no increase in crushing value of this type of RCA. But the case of the RCA for the W/B ratio of 0.586 was quite different, where crushing value decreased from 15.54% to 11.59%, which means that the attached mortar at the W/B ratio of 0.586 may be either highly porous or with lots of microcracks, as proved by a previous research [25]. Similarly, it has been found by another research [26] that, when the water/cement ratio of RAC is lower than that of the original concrete, the strength of RAC may be controlled by strength of the original concrete, and the weakest point in RAC is RCA and in particular the attached mortar. Therefore the attached mortar itself, at the W/B ratio of 0.586 in the present research, may be regarded as a particular type of flaw of RCA.

3.2. Compressive Strength. The results of compressive strength are given in Figure 4. Compressive strength of RAC was lower than that of NAC at an identical W/B ratio, which is in consistency with previous researches [8, 14, 25, 26]. This can be attributed to flaws in RCA. For RAC at a W/B ratio of 0.255, the fact that compressive strength decreased from 70.9 MPa to 65.6 MPa after heating and removal of attached mortar confirms that the process of heating and removal of attached mortar induces microcracks in gravel and hence causes a decrease in compressive strength. However, for RAC at a W/B ratio of 0.586, compressive strength increased from 25.3 MPa to 31.1 MPa after heating and removal of attached mortar, which confirms the conclusion in the preceding subsection that the attached mortar at the W/B ratio of 0.586 may be regarded as a particular type of flaw of RCA.

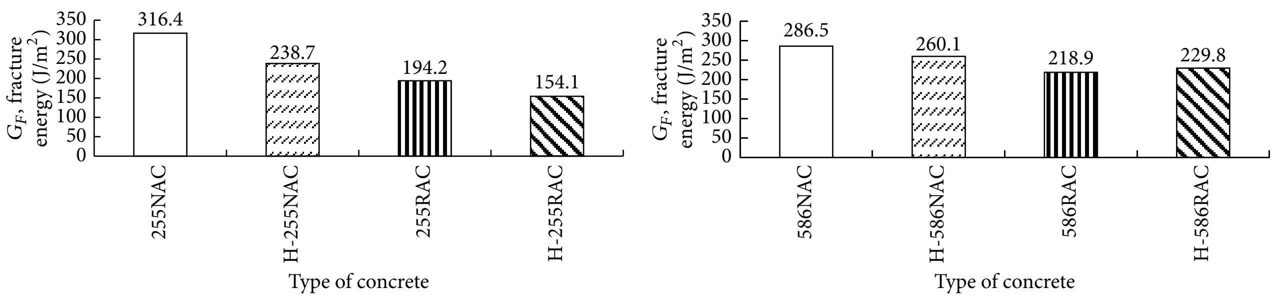
In general, a couple of factors in geometry of coarse aggregate may affect compressive strength of concrete, including size, angularity, and texture of coarse aggregate. In case of using heated RA in this research, as all the residual mortar had been removed, the original NA size was smaller than that of RCA. Another factor that can be responsible for the difference in compressive strength of RAC and NAC is the angularity difference between RCA and NA. In case of crushed limestone, RCA is less angular than NA. Also aggregate texture is another factor affecting compressive strength. Generally, RCA has a more textured surface than NA. Nevertheless, these geometry factors of coarse aggregate in this research did not affect compressive strength of RAC as much as the mortar attached to RCA, which has been revealed by the results in Figure 4.

3.3. Tensile Splitting Strength. The results of tensile splitting strength are given in Figure 5. The basic tendency in change of tensile splitting strength was the same as that in compressive strength, with the only exception that concrete at a W/B ratio of 0.255 with RCA after removal of attached mortar had tensile splitting strength slightly higher than that before removal of attached mortar. The reason for this abnormal result is unclear in this research and needs further research.



(a) For concrete at a W/B ratio of 0.255 (b) For concrete at a W/B ratio of 0.586

Figure 5: Tensile splitting strength of concrete at W/B ratios of 0.255 and 0.586.



(a) For concrete at a W/B ratio of 0.255 (b) For concrete at a W/B ratio of 0.586

Figure 6: Fracture energy of concrete at W/B ratios of 0.255 and 0.586.

3.4. Fracture Energy. The results of fracture energy are given in Figure 6. Compared with fracture energy of NAC, RAC had lower fracture energy, which is consistent with previous researches [27, 28]. This result, together with the lower fracture energy of concrete with heated NA compared to that of NAC, confirms that the existence of flaws in RCA and heated NA. For RAC at a W/B ratio of 0.255, the fact that fracture energy decreased from 194.2 J/m^2 to 154.1 J/m^2 after heating and removal of attached mortar confirms that the process of heating induces flaws in gravel of RCA and hence causes a decrease in fracture energy. For RAC at a W/B ratio of 0.586, fracture energy increased from 218.9 J/m^2 to 229.8 J/m^2 after heating and removal of attached mortar, which is attributed to the attached mortar at 0.586 W/B ratio as a particular type of flaw in RCA.

However, different from a previous research finding [27] that, as aggregate strength decreases, the fracture energy decreases, the results in Figure 6 that fracture energy of RAC at 0.255 W/B ratio was lower than that of RAC at 0.586 W/B ratio should be of interest. The lower fracture energy of RAC at 0.255 W/B might be due to the more fragile nature of the stronger mortar.

4. Conclusions

Based on the experimental work in this research, the following conclusions can be drawn.

(1) The process of heating and crushing can be used to remove attached mortar in recycled concrete aggregate and to identify the effects of flaws of recycled concrete aggregates either in attached mortar or in gravel on mechanical properties of recycled aggregate concrete.

(2) For recycled aggregate concrete at a low water/binder ratio of 0.255 prepared in this research, flaws in gravel are the main factor responsible for the decrease in mechanical properties, while flaws in attached mortar are the main factor responsible for the decrease in mechanical properties of recycled aggregate concrete at a high water/binder ratio of 0.586.

(3) The main type of flaw in recycled aggregate from concrete at a low water/binder ratio should be microcracks in gravel, and the main type of flaw in recycled aggregates from concrete at a high water/binder ratio should be attached mortar. Therefore, the heating treatment and the removal of attached mortar of recycled concrete aggregate caused a decrease in mechanical properties in the case of low water/binder ratio but caused an increase in mechanical properties in the case of high water/binder ratio.

(4) It is suggested that, prior to mix proportion design and preparation of concrete using recycled concrete aggregates, it is necessary to obtain the details of demolished concrete such as its strength grade or water/binder ratio and of the characteristics of flaws in recycled aggregate induced by processing the demolished concrete.

Acknowledgments

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