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Research Article

Effect of the Aggregate Size on Strength Properties of Recycled Aggregate Concrete

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The study on preparation technology of recycled concrete with economical and technical feasibility has gained more serious attention in each country due to its involvement and effect on the environment protection and the sustainable development of human society. In this study, we conducted a control variable test to investigate and assess the influence of the aggregate size on the strength characteristics of concrete with different diameters of recycled aggregates. Concrete with recycled aggregates of 5~15 mm (A), 15~20 mm (B), 20~30 mm (C), and their combinations were subjected to a series of unconfined pressure tests after curing for 28 days. Based on the results obtained from the tests, an effort was made to study the relationship between the mechanical characteristics of recycled aggregate concrete and aggregate particle size. Also, a regression model of recycled concrete was proposed to predict the elasticity modulus and to adjust the design of mixture proportion. It is believed that these experiment results would contribute to adjust the remediation mixture for recycling plants by considering the influence of recycled aggregate size.

1. Introduction

With the rapid development of the civil engineering, it is reported that approximately 200 million tons of waste concrete are generated per year in the mainland of China [1]. Recycling of concrete blocks and reusing recycled aggregate is an important approach to solve the difficulties of disposing of construction and demolition waste (C&DW). The physical properties of recycled aggregates can realize the production of recycling plants by reducing the mortar content [2, 3]. Recycled coarse aggregates are mainly composed of independent natural coarse aggregate and aggregate with the old cement mortar. It is generally agreed that there is much difference in physical properties between recycled concrete aggregate and ordinary aggregate: high porosity, high water absorption, high void ratio, high abrasion loss, and low bulk density [4]. This is due to the fact that recycled concrete aggregate is angular grain, rough surface, and aggregate with mortar adhered. In addition, recycled aggregate had a large number of internal microcracks due to the accumulated damage caused in the process of crushing. Researches from some countries such as Hansen [5] and Xiao [6] showed that the main reason for the randomness and variability of physical parameters of recycled coarse aggregate is the wide and uncertain sources of waste concrete. Many scholars [7–9] research on the mechanical properties of recycled concrete, mainly concentrated in the correlation between the compressive strength/elastic modulus of recycled concrete and content of recycled aggregate. There are some different conclusions on the regulation of the compressive strength and the content of recycled aggregate in literature research. Triplicate experiment research conclusions were summarized. First, Nixon [10], Hansen [5], and other scholars' [9, 11] research found that the compressive strength of recycled aggregate concrete decreases with the content of recycled aggregate increase, reducing the range of 0% to 30%. Second, Wang [12] experimental studies showed that the compressive strength of concrete has no obvious regularity with the content of recycled aggregate.

Third, Yoda et al. [13], Ridzuan et al. [14], Ke et al. [15], and other scholars found that the compressive strength of recycled aggregate concrete decreases with a certain range of contents, while the strength of concrete increases with other certain range of contents. With the replacement level of recycled aggregate increase, the elastic modulus of recycled concrete usually decreases, generally about 20% lower, which has been confirmed by most of the experimental researches [16]. And mostly the studies on the mechanical behavior of recycled aggregate concrete did not consider the particle size of recycled aggregates. This study presents an investigation of the influence of the aggregate particle size on the mechanical behavior and the elastic modulus of recycled concrete on the basis of scholar research. In this research, recycled aggregate concrete with recycled aggregate size (5~15 mm (A), 15~20 mm (B), 20~30 mm (C) and their combinations to replace the weight of natural aggregate) is subjected to a series of unconfined pressure tests after curing for 28 days. Based on the results obtained from the tests, an effort is made to study the relationship between the mechanical characteristics of recycled concrete and particle size of recycled aggregate. Also, a regression model is proposed to predict the elastic modulus and to design the mixture proportion of recycled concrete. It is believed that these experiment results would contribute to adjust the remediation mixture for recycling plants by considering the influence of recycled aggregate size.

2. Experimental Program

2.1. Materials

2.1.1. Composite Portland Cement. Composite Portland cement with slag and fly ash from China United Cement Corporation in Jiangsu province was used in this research. The test result by Somna [17] proved that the ground fly ash could be remarkably useful to facilitate the compressive strength and durability of recycled aggregate concrete with the same water to binder ratio.

2.1.2. Fine Aggregate and Coarse Aggregate. Locally produced river sand was used as fine aggregate in this experimental program. Natural coarse aggregate (N) and two types of recycled coarse aggregate (R, S) were selected as the target coarse aggregate. Recycled aggregate (R) was prepared in the laboratory using a small crusher. Recycled aggregate (S) was prepared by the Shou Jia Company using a large crusher. The recycled aggregate was washed to reduce the negative effects on the recycled concrete [18] because the good gradation of coarse aggregate is one of the guarantee factors of concrete stability properties. After that, according to the Chinese specification [19], the crushed coarse aggregate was screened by sieves (passed through a 31.5 mm sieve and retained in a 4.75 mm sieve) to select continuous particle size distribution (5~31.5 mm) and to obtain the coarse aggregate of N, R, and S for mechanics test of concrete. Compared with the requirements of Chinese specification [19], the continuous distribution of particle size for three types of coarse aggregate is shown in Figure 1. According

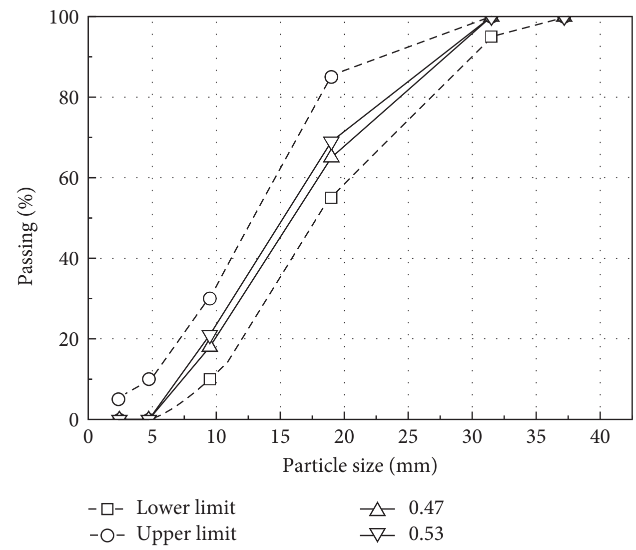

Figure 1: Grading of coarse aggregates.

to the sieve diameter and distribution of particle size, the whole particle size range of coarse aggregate was divided into 3 groups to research the influence of the aggregate size on the properties of recycled aggregate concrete, respectively: 5~15 mm (A), 15~20 mm (B), and 20~30 mm (C).

The physical parameters of the corresponding particle size group (A, B, and C) of coarse aggregate (N, R, and S) were measured by Chinese specification [19], as shown in Figure 2 and Table 1. From Figure 2, the coarse aggregates of N have more sharp edges and corners, uniform color, and less impurity, while aggregates of R and S have relatively light round edges and corners, uneven color, and more impurity, especially aggregates of group A. From Table 1, the aggregate density of R and S is lower than that of N at the same particle size, reducing the range from 8% to 14%. The recycled aggregates of R and S with high porosity and low density of the attached cement or paste mortar on the surface of the old aggregate have low specific gravity compared to the natural aggregate [20]. Many literatures [21] indicated that the water absorption of recycled aggregate was about 6 to 10 times that of the natural aggregate. In this test, the water absorption of recycled aggregate is significantly higher compared to that of the natural aggregate with the same particle size. This is resulted from that the old attached mortar in recycled aggregate had a higher water absorption capacity than that of crushed limestone [22, 23]. As shown in Table 1, with an increase diameter of the aggregate, the water absorption of the coarse aggregates of R and S is obviously increased. The bigger particle size is having greater density and less water absorption compared to the smaller particle size for the recycled aggregates of R and S, as shown in Table 1. For example, aggregates of S in group C had a stacking density of 1245 kg/m^3 and water absorption of 3.39%, while those of groups A and B were 1229 kg/m^3 and 4.79%, 1253 kg/m^3 and 3.87%, respectively. This is due to the fact that the smaller particle size of aggregate had more old attached mortar and internal microcracks.

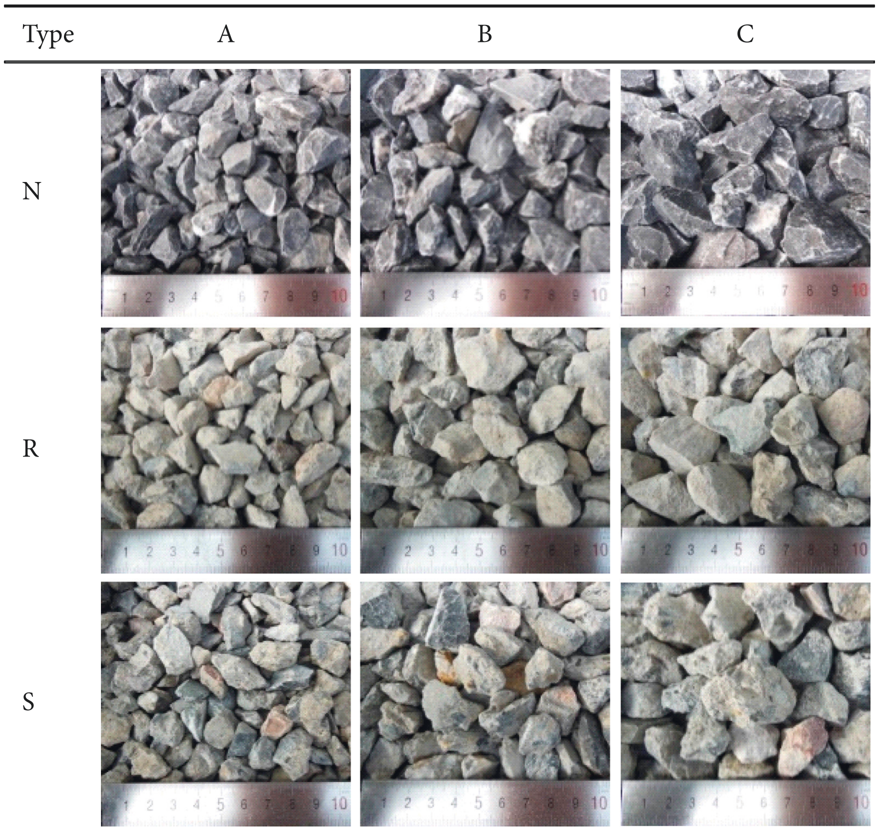

Figure 2: Appearance of coarse aggregates.

Table 1: The aggregate parameters.

Particle size	Stacking density (kg/m^3)			Water absorption (%)		
	N	R	S	N	R	S
5~16 (A)	1436	1282	1229	0.52	2.97	4.79
16~20 (B)	1436	1288	1253	0.30	2.79	3.87
20~31.5 (C)	1405	1297	1245	0.24	2.38	3.39

Table 2: Mixture proportions of NAC ($1\,m^3$).

Mix	Cement (kg)	N (kg)			Sand (kg)	Water (kg)	W/C
		A	B	C			
47N	4125	4600	4600	4600	6820	1925	0.47
53N	4070	4470	4470	4470	6875	2145	0.53

2.2. Mixture Proportion and Experiment Specimen. As shown in Table 2, the water to cement ratios of 0.47 and 0.53 are determined depending on the mixture proportions of control concrete. Mixture proportion of recycled aggregate concrete is obtained by using recycled coarse aggregate as the same weight to replace the natural aggregate of the control concrete at 16.7%, 33.3%, 50%, 66.7%, and 100%. The concrete that included recycled aggregate of R with a water/cement ratio of 0.47 was taken as an example, as shown in Table 3. To ensure the workability of recycled concrete, the additional water consumption in the mix proportion was calculated by the water absorption of recycled aggregates. The formula for additional water consumption was suggested by Zhang [24]:

$$\begin{aligned}\Delta W &= m_{RA} \times [(s_{RA} - w_{RA}) - (s_{OA} - w_{OA})] \\ &= (\alpha m_A) \times [(s_{RA} - w_{RA}) - (s_{OA} - w_{OA})],\end{aligned} \quad (1)$$

where ΔW is the additional water consumption in concrete mixture; m_{RA} is the mass of recycled aggregate in concrete; w_{RA} and w_{OA} are the water contents of recycled aggregate and ordinary aggregate, respectively; s_{RA} and s_{OA} are the water absorption of recycled aggregate and ordinary aggregate, respectively; m_A is the mass of recycled concrete; and α is the percentage of recycled aggregate in the total aggregate of concrete.

In this study, two-stage mixing approach was adopted since the literature from Tam et al. [19] reported that it had a considerable influence on the pressure strength and other mechanical behaviors of the recycled aggregate concrete. The concrete mixtures of one hundred sixty-two concrete specimens were poured into a polyvinyl chloride mold with a dimension of $150\,mm \times 150\,mm \times 150\,mm$ to measure compressive strength and the elasticity modulus of recycled aggregate concrete. The concrete specimens were carefully taken out of the molds and cured at a relative humidity of 96% and a temperature of $20^{\circ}C \pm 2^{\circ}C$ nearly 24 hours after casting. The compressive strength and the elasticity modulus of all control concretes and recycled concretes were observed after curing for 28 days following Chinese specification [20], as shown in Figure 3. The final result data were determined

Table 3: Coarse aggregate of recycled aggregate concrete.

Mix	r (%)	N (kg)			R (kg)		
		A	B	C	A	B	C
0.5A47R	16.7	2300	4600	4600	2300	—	—
0.5B47R	16.7	4600	2300	4600	—	2300	—
0.5C47R	16.7	4600	4600	2300	—	—	2300
A47R	33.3	—	4600	4600	4600	—	—
B47R	33.3	4600	—	4600	—	4600	—
C47R	33.3	4600	4600	—	—	—	4600
A0.5B47R	50	—	2300	4600	4600	2300	—
0.5AB47R	50	2300	—	4600	2300	4600	—
B0.5C47R	50	4600	—	2300	—	4600	2300
0.5BC47R	50	4600	2300	—	—	2300	4600
AB47R	66.7	—	—	4600	4600	4600	—
BC47R	66.7	4600	—	—	—	4600	4600
ABC47R	100	—	—	—	4600	4600	4600

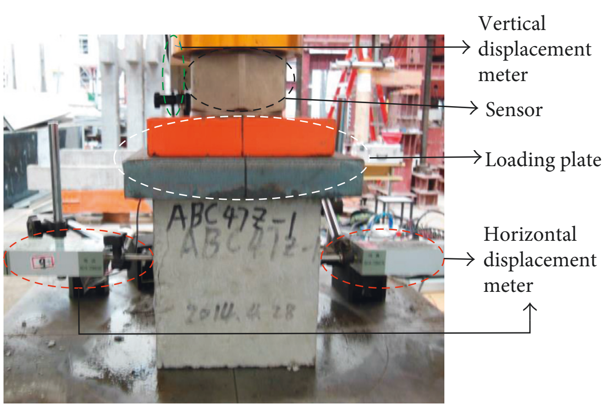

Figure 3: Test setup.

from the average of triplicate measurements of each concrete samples to ensure accuracy of compressive strength and the elasticity modulus.

3. Results and Discussion

3.1. Compressive Strength

3.1.1. Content Factor. Figure 4 shows the correlation between the compressive strength and the content of recycled aggregate (R and S) for recycled concrete with two water to cement ratios of 0.47 and 0.53. The strength of recycled concrete that included R and S was lower than that of control concrete; the value of concrete with content of 66.7% was lowest. The reason was that physical properties (density and water absorption) of recycled aggregate were weaker than that of natural aggregate. When the content of recycled aggregate was from 0% to 66.7%, the strength of recycled concrete was decreased with increase of content. While the content of recycled aggregate was more than 66.7%, the strength of recycled concrete was increased with the content increase. That was to say, concrete that included only one type of coarse aggregate (0% and 100%) had a higher strength compared to

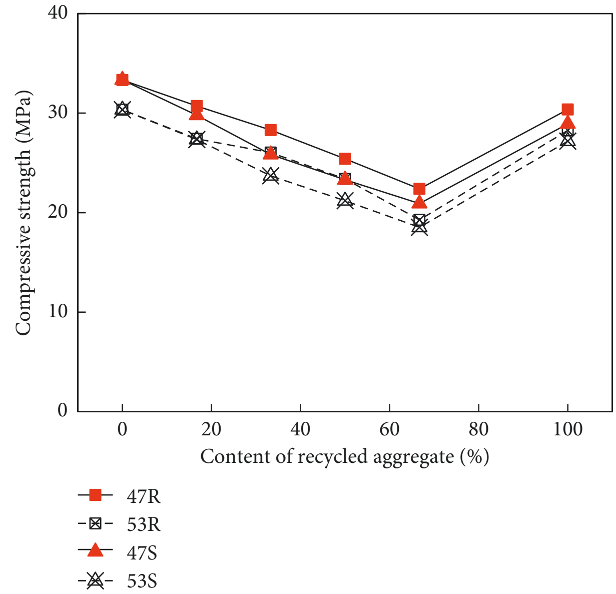

Figure 4: Relationship between compressive strength and content of recycled aggregates.

concrete that included both natural aggregate and recycled aggregate. This was because the difference between the physical parameters of aggregate groups for concrete (0% and 100%) was less compared with other replacement levels of concrete.

Figure 5 shows the relationship between the compressive strength of recycled concrete with aggregate groups A, B, and C and the replacement ratio of recycled aggregate at the same water to cement ratio. The compressive performances of the recycled concrete with the different aggregate sizes were having similar tendencies under the same condition of the aggregate type and water to cement ratio. The compressive behavior of recycled concrete with 2 types of aggregate and 2 water to cement ratios was decreased quasilinearly with an increase of aggregate content. The difference in the compressive value of the content 16.7% was less than that of the content 33.3% among recycled concretes with aggregate groups of A, B, and C. The lower content of recycled aggregate was advantageous to reduce the difference in the compressive value.

3.1.2. Aggregate Size Favor. Figure 6 shows the relationship between the compressive performance and the aggregate content of recycled concrete with 2 types of aggregates and 2 water to cement ratios. The compressive strengths of recycled concrete with aggregate groups A, B, and C were lower than that of control concrete by 2.3~8.7 MPa. The compressive performance of recycled concrete was increased with an increase of aggregate size. This was mainly due to the adhered mortar content of aggregate group C that was less than that of aggregate groups A and B. The compressive properties were extremely close for recycled concrete that included the same type and size of recycled aggregate. With the recycled aggregate content of 100%, the concrete compressive performance was very close to that of the control concrete due to the only one aggregate style used.

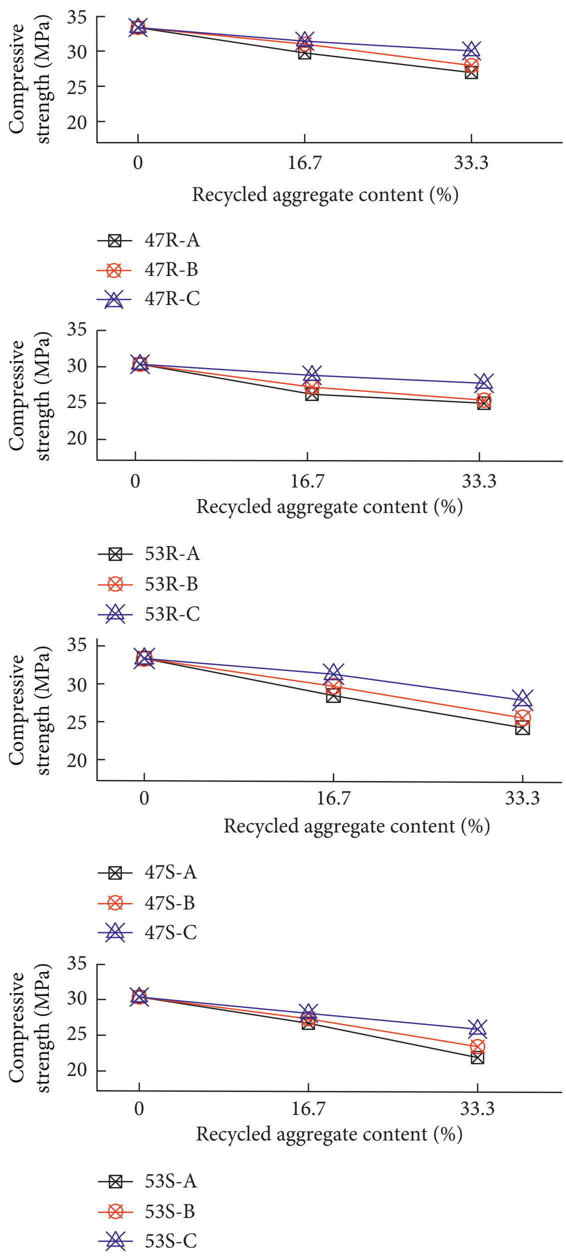

Figure 5: Relationship between the compressive strength and recycled aggregate content at the same aggregate type and water/cement ratio.

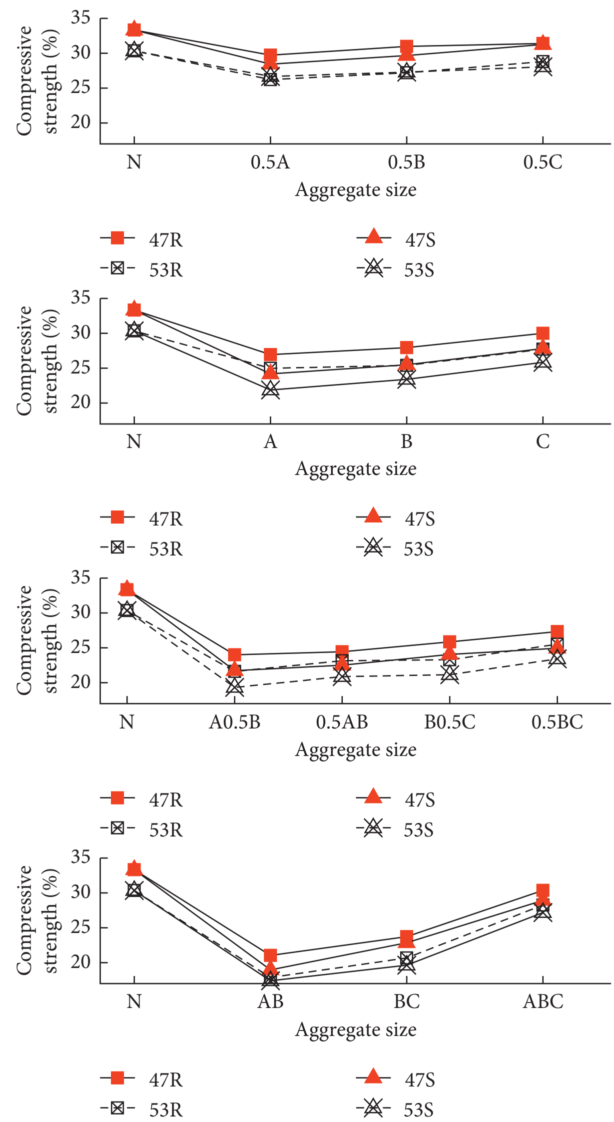

Figure 6: Relationship between the compressive strength and size of recycled aggregate at the same recycled aggregate content of 0%, 16.7%, 33.3%, 50%, 66.7%, and 100%.

3.1.3. Water to Cement Ratio Factor. Figure 7 shows the relationship between the compressive properties and the water to cement ratio for the recycled concrete at the content of 16.7%, 33.3%, 50%, 66.7%, and 100%. The strength properties of the recycled concrete were lower than that of the control concrete and decrease as the water to cement ratio increases, as shown in Figure 7. The dispersion of compressive performance of the recycled concrete with the water to cement ratio of 0.53 was more than that with the water to cement ratio of 0.47. This conclusion was in agreement with the experimental results in many literatures [25].

3.2. Stress-Strain Curve. Take concrete with the water to cement ratio of 0.47, for example, the stress-strain curves of uniaxial compression of the recycled concrete with different replacement rates of recycled aggregate as shown in Figure 8. It can be observed that curve tendencies of the uniaxial compression stress and strain between the recycled concrete and control concrete were similar and uniform, regardless of the percentage of recycled aggregate. The replacement rate of the recycled aggregate affected greatly the stress and strain curve of uniaxial compression for recycled concrete. The curvature of the uniaxial compression stress and strain curve was decreased with an increase of recycled aggregate replacement, which could explain the gradual reduction in the elastic modulus of recycled concrete.

3.3. Elasticity Modulus. Static elasticity modulus was calculated from the results of unconfined pressure experiments

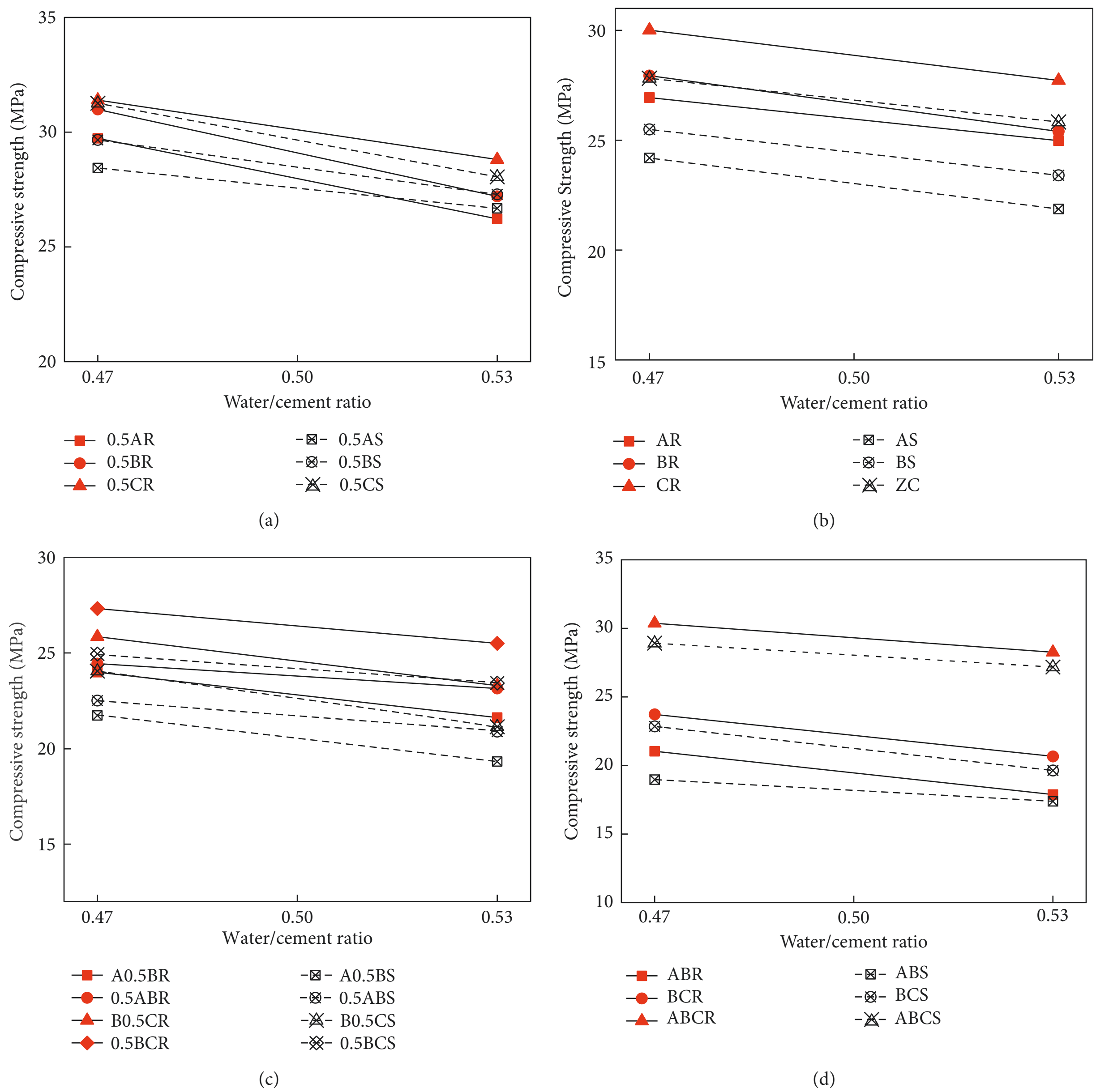

FIGURE 7: Relationship between the compressive strength and water/cement ratio at the same recycled aggregate content (a) 16.7%, (b) 33.3%, (c) 50%, and (d) 66.7% and 100%.

on concrete samples according to China's specification. Figure 9 shows the correlation between elasticity modulus and compressive properties of control concrete and recycled concrete. The elasticity modulus of the concrete that used natural aggregate of N was higher than that of concrete that used recycled aggregates of N and S at the same strength conditions. In given priority to natural aggregate, the modulus of elasticity of the recycled concrete at the water to cement ratio of 0.53 was greater than that of concrete at the water to cement ratio of 0.47; since it was believed that compared to ordinary concrete, the elasticity modulus of recycled concrete is approximately 15–30% lower [26, 27]. The research [28, 29] has shown that void ratios and internal microcracks of mortar adhered lead to a low elasticity modulus of recycled concrete. Moreover, the investigation of Neville [30] reported that the elasticity modulus of concrete was determined depending on the compressive strength and the quality and quantity of coarse aggregates, for example, elasticity modulus and abrasion loss, and adhesive property between cement mortar (old and new) and aggregate (recycled and gravel). It was found that a regression model of recycled concrete with the different aggregate sizes was proposed to fit the experimental result, to predict the elasticity modulus, and to adjust the design of mix proportion in terms of control concrete:

$$E_c = a \times f_{cu} + b, \quad (2)$$

where E_c is the elasticity modulus of recycled concrete (GPa); f_{cu} is the compressive property of recycled concrete (MPa); a and b are the regression parameters (for concrete with aggregate group A, $a = 2.26$ and $b = -34.61$; for concrete with

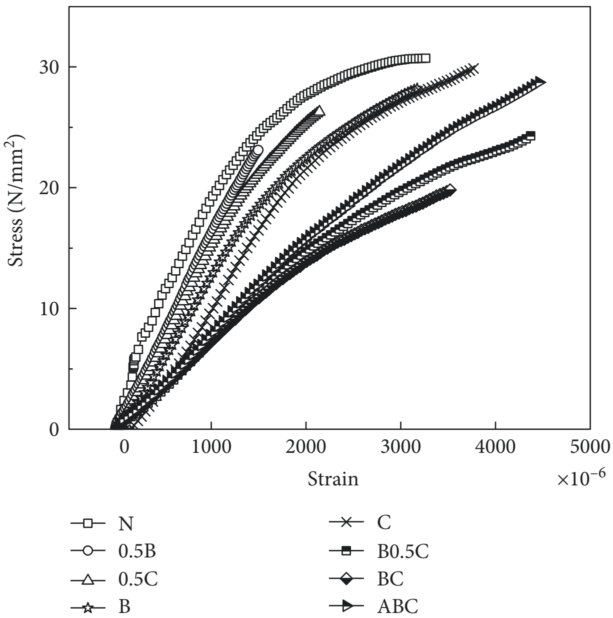

Figure 8: Stress-strain curve of concrete with the water to cement ratio of 0.47.

aggregate group B, $a = 3.50$ and $b = -54.73$; and for concrete with aggregate group C, $a = 0.47$ and $b = 0.43$).

It turned out to be that the elastic modulus value of concrete that included various sizes of recycled aggregate was inclined to be more dependent on the variation of compressive performance. It is believed that these experiment results would contribute to adjust the remediation mixture for recycling plants by considering the influence of recycled aggregate size.

4. Conclusions

This paper investigated the influence of the aggregate size on strength performance of recycled aggregate concrete by unconfined pressure tests. The main conclusions can be drawn as follows:

(1) Concrete that included only one type of coarse aggregate (0% and 100%) had a higher strength compared to concrete that included both natural aggregate and recycled aggregate; the strength value of concrete with the content of 66.7 was lowest. This was because the difference between the physical parameters of aggregate groups for the concrete (0% and 100%) was less as compared with other replacement levels of concrete.

(2) The compressive performance of recycled concrete was increased with an increase of aggregate size. This was mainly due to the adhered mortar content of the bigger aggregate size was less than that of the smaller aggregate size.

(3) According to the content and size of recycled aggregate, a regression model been modified appropriately by test results was proposed to predict the elastic modulus of concrete that included various recycled aggregate sizes.

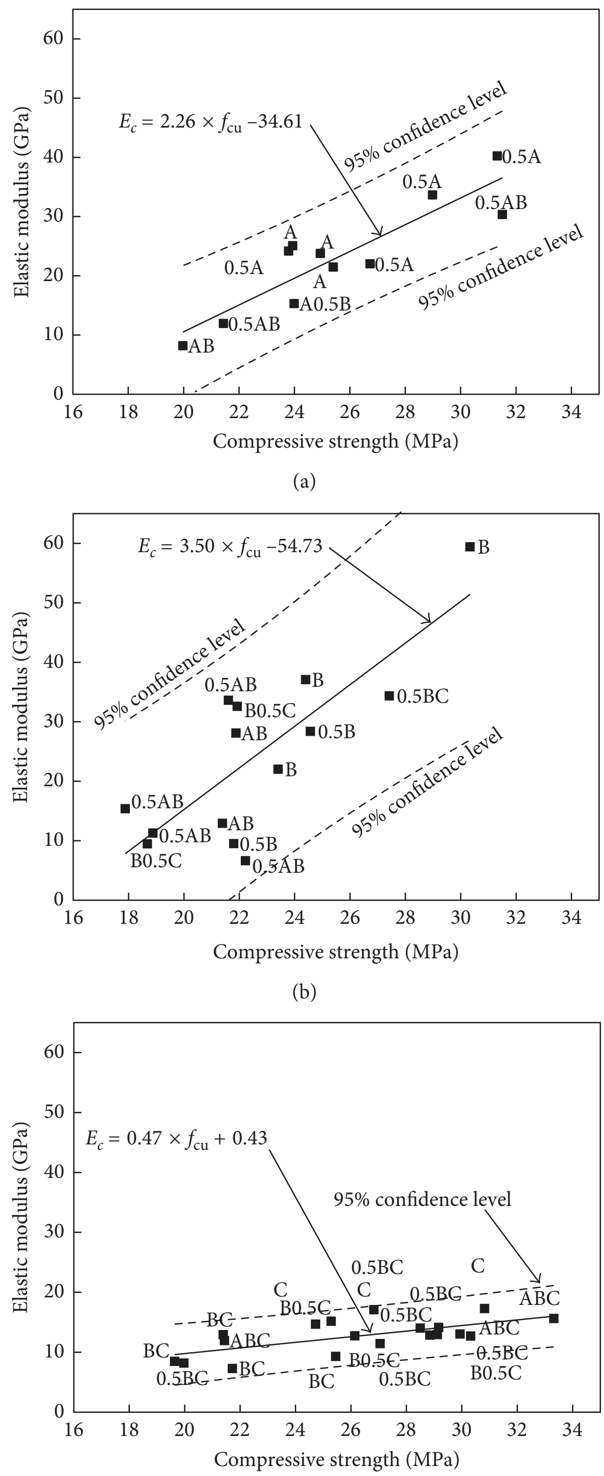

Figure 9: Relationship between the modulus of elasticity and the compressive strength of recycled aggregate concrete. (a) Concrete with aggregate group A, (b) concrete with aggregate group B, and (c) concrete with aggregate group C.

It is believed that these experiment results would contribute to adjust the remediation mixture for recycling plants by considering the influence of recycled aggregate size.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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