A Case Study on Utilization of 50-year-old Concrete in Recycled Aggregate

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ABSTRACT: This paper investigates some mechanical properties of recycled aggregate concrete (RAC) with 50-year-old recycled coarse aggregate (RCA), and theoretically analyzes the corresponding RAC stress-strain curves relative to those of normal aggregate concrete. Concrete prism specimens, including 66 standard prisms and 33 nonstandard ones, were fabricated and tested through 11 groups of RCA replacement ratios from 0% to 100% with an interval of 10%. On this basis, the standard prism compressive strength at ages of 28 days and two years, the flexural strength of the nonstandard prism, the cube strength after flexural test and the strain at the maximum standard prism compressive stress for 28 days, as well as Poisson's ratio of the standard prisms for two years was investigated. Finally, analytical expressions were proposed for predicting the peak strain, the stress-strain curves of RAC and the strength conversion relationships.

1. INTRODUCTION

SUSTAINABLE development involves many interlinked aspects including nature, environment, society, economy, technology and politics, and it is an embodiment of an integrated performance index. In developing countries, due to great efforts in infrastructure constructions, the urbanization process is surely accelerated at a high-speed rate. However, along with the rapid development of construction, construction waste has been produced continuously, which exerts a side effect on environmental quality. The term "construction and demolition waste (CDW)" has been widely used for referring to the solid waste produced during new construction, renovation, and demolition of buildings [1]. To a large extent, CDW has caused a series of terrible environmental problems, and produced a bad effect on economic construction and social development. Around the world, CDW frequently accounts for 10%–30% of the solid waste at many landfill sites [1]. Worse still, it accounts for 30%–40% of the total municipal solid waste in China. It is noticed that waste concrete is the main ingredient of CDW, and its content accounts for more than 40% of the total amount [2].

In order to effectively utilize the waste concrete, it is necessary to employ it as recycled aggregate of new concrete, which can be named as recycled aggregate concrete (RAC). In view of this, mechanical properties of RAC need to be deeply investigated so as to expand the application scope of RAC, especially in building structures. In China, RAC has attracted much attention from construction departments as a structural concrete [2]. So far, some research has been carried out on its material properties. For example, Zhu *et al.* [3] carried out some experimental investigations on the thermal properties of concrete blocks prepared with low grade recycled aggregates; Akash *et al.* [4] studied the behavior of RAC under drop weight impact load; Belen *et al.* [5] analyzed the concrete with 100% recycled coarse aggregate (RCA) content for the structural RAC; Xiao *et al.* [6] conducted a series of tests on shear transfer across a crack in RAC. Besides, some studies on the durability properties of RAC have been launched by some researchers, such as Salomon *et al.* [7], Abbas *et al.* [8], and Patrícia *et al.* [9]. Notably, the above strength indexes of RAC were all tested after a standard curing age (28 days).

2. RESEARCH SIGNIFICANCE

It seems that the research on time-based mechanical properties of RAC under uniaxial compression and

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flexural condition is still limited for using the original RCA, and the experimental data based on the long-age concrete are in a state of blank. Meanwhile, previous studies just selected rough and large interval of RCA replacement ratio, which might lose some special performances of RAC under certain kinds of RCA replacement ratio. Further, the constitutive relationship between stress and strain also needs to be clarified for RAC with micromesh increasing ratio when it is applied to structural members. This paper just attempt to address the above listed issues so as to fill the lack of knowledge in this filed.

3. EXPERIMENTAL INVESTIGATION

The design consisted of two batches of concrete: one was tested after maintained for the standard age (28 days), and the other was tested after a long age (two years) of maintenance. 11 groups of concrete with RCA replacement ratios of δ = 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% were fabricated, and three specimens were prepared under the given replacement ratio in each group. The RAC specimens included 66 standard prisms (5.91 in. × 5.91 in. × 11.81 in. [150 mm × 150 mm × 300 mm]) and 33 nonstandard prisms (5.91 in. × 5.91 in. × 21.64 in. [150 mm × 150 mm × 550 mm]). Standard tests were carried out to determine their basic mechanical properties: the prism compressive strength cured under the standard age and the long age, the flexural strength using the nonstandard prism specimens under the standard age and the long age, and the Poisson's ratio.

3.1. Materials

River sand was used as the fine aggregate (FA) in this study. The RCA was obtained from the artificial broken concrete poles, which started to serve at the year of 1958 and were dismantled and transported to the laboratory because of the ice disaster at the year of 2008 in P.R China. The particle size of RCA was 0.552–1.103 in. (14–28 mm), and the bulk density was 1385 kg/m^3. The natural coarse aggregate (NCA) was continuously graded gravel with particle size of 0.394–1.103 in. (10-28 mm), and its bulk density was 1437 kg/m^3. The RCA and NCA were washed for several times and dried out naturally before concrete mixing.

3.2. Concrete Mixtures

In fact, the most distinctive feature of RCA compared to NCA is its higher water absorption capacity, which is mainly due to the adhered mortar (also called as old cement mortar substrate) [10]. In other words, additional absorbed moisture of RCA can reduce the actual water-cement ratio (W/C) in concrete, which means a curing effect on concrete strength. Based on the above considerations, in this study, the designed W/C was kept constant for each concrete type in order to focus only on the influences of RCA water absorption capacity on the mechanical performances of RAC. The mix proportions of concrete are shown in Table 1.

3.3. Preparation of Specimens

The fabrication and curing of all mixtures were conducted in the Chinese Education Ministry Key Laboratory of Disaster Prevention and Structural Safety at Guangxi University, P.R. China. The cement, sand and coarse aggregate were placed and dry-mixed for about 3 min before water addition. After another three-minute mixing with water, a slump test was carried out to determine the workability. For the standard prism

Table 1. Mix Proportions of Concrete.

No.	δ (%)	W/C	Sand Ratio	C (kg/m^3)	W (kg/m^3)	FA (kg/m^3)	NCA (kg/m^3)	RCA (kg/m^3)
RAC-0	0	0.41	0.32	524	215	532	1129	0
RAC-10	10	0.41	0.32	524	215	532	1016	113
RAC-20	20	0.41	0.32	524	215	532	903	226
RAC-30	30	0.41	0.32	524	215	532	790	339
RAC-40	40	0.41	0.32	524	215	532	677	452
RAC-50	50	0.41	0.32	524	215	532	564	565
RAC-60	60	0.41	0.32	524	215	532	452	667
RAC-70	70	0.41	0.32	524	215	532	339	790
RAC-80	80	0.41	0.32	524	215	532	226	903
RAC-90	90	0.41	0.32	524	215	532	113	1016
RAC-100	100	0.41	0.32	524	215	532	0	1129

specimens, the mixture in each group was cast in 5.91 in. × 5.91 in. × 11.81 in. (150 mm × 150 mm × 300 mm) prisms in six wood moulds. In contrast, for the nonstandard prism specimens, the same type mixture in each group was tossed in 5.91 in. × 5.91 in. × 21.64 in. (150 mm × 150 mm × 550 mm) prisms in three wood moulds. One day after casting, the prisms were demoded and then cured in a fog room (20 ± 2°C, 95% relative humidity) for 28 days (the standard age). After that, the first batch of specimens, including 33 standard prisms and 33 nonstandard prisms, were taken to test the uniaxial compressive strength, the stress-strain curves and the flexural strength, respectively. As for the rest specimens, they were cured under the same laboratory conditions for two years, and then used to test the axial compressive strength and the Poisson's ratio at a long-term age.

3.4. Test Settings and Methods

For the axial compression test, the loading setup was an RMT-201 rock and concrete mechanics test system. In order to get complete stress-strain curves, the displacement-controlled loading method was adopted and the loading rate was kept constant as 1.97 × 10^{-4} in./s (0.005 mm/s). Each specimen was preloaded before actual loading in order to lessen the impacts due to the loose of specimen end. For the flexural strength test, the loading setup was a flexural testing device, and the span of testing segment was 17.73 in. (450 mm).

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Compressive Stress-strain Relationships

Figure 1 shows the typical stress-strain curves of RAC with different RCA contents at the standard age. It can be seen that there is basically no deviation from the stress-strain theory of elasticity-plasticity in the structural design process.

4.2. Peak Strain

Peak strain is the strain corresponding to peak stress in the stress-strain curve. In this study, three peak strain values of each group of RAC specimens with different RCA contents are got averaged as the final peak strain. It can be seen that the value of peak strain presents an increasing trend as the RCA content increases. The main reason for the increase of the peak strain can be attributed to the brittleness of RCA containing old

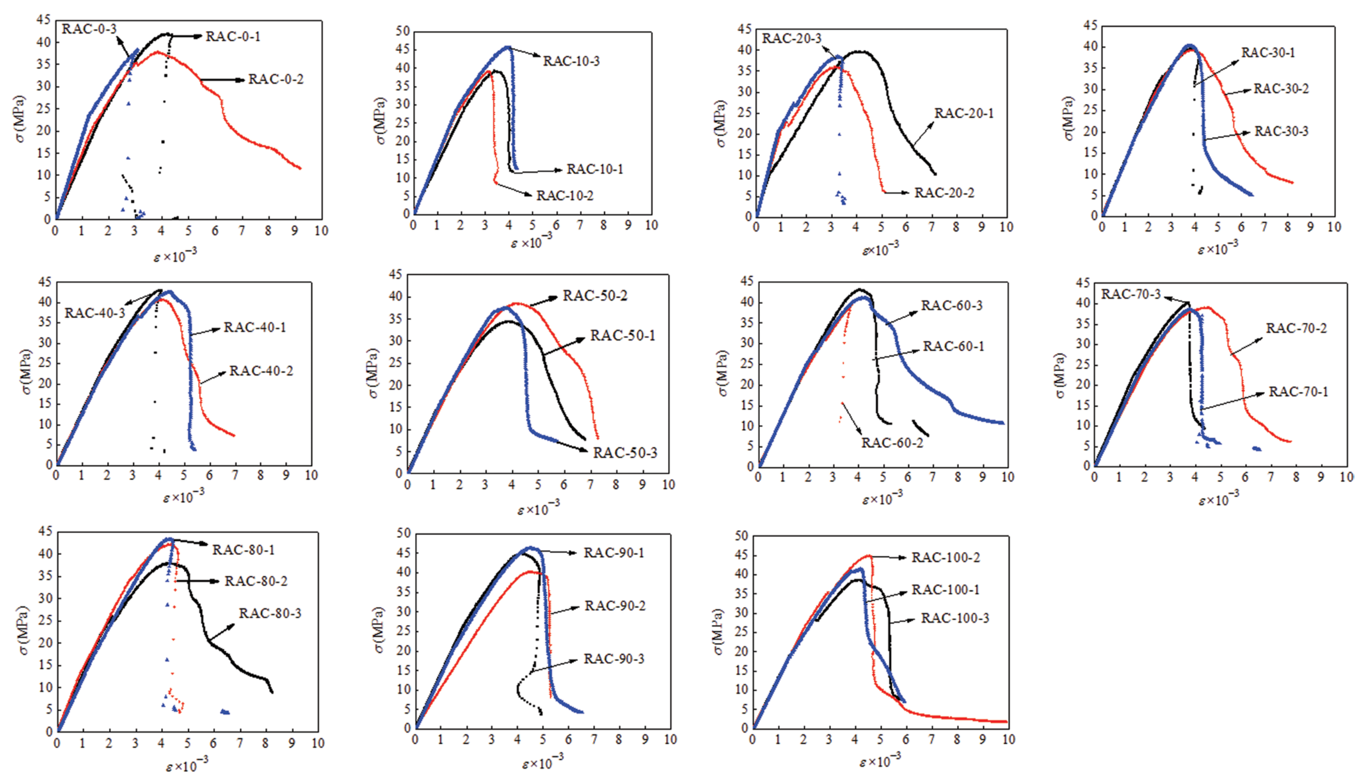

Figure 1. *Stress-strain curves of RAC standard prisms at the age of 28 days.*

cement-mortar substrate, which can lead to a larger deformation. In this study, the following fitting expression is suggested for calculating the peak strain:

$$\varepsilon_0^r = \varepsilon_0^n \times (-7\times10^{-7}\delta^3 + 9\times10^{-5}\delta^2 + 4\times10^{-3}\delta + 1.642) \quad (1)$$

where ε_0^n is the peak strain of NAC, and ε_0^r is the peak strain of RAC.

4.3. Compressive Strength

Compressive strength is the peak stress of the test specimen under uniaxial compression. Table 2 gives the prism compressive strength at the standard age (f_c^s) and at two years (f_c^1) with different RCA replacement ratios. As can be seen, the prism compressive strength of RAC is generally higher than that of NAC except that of RAC-10, RAC-50, RAC-60 and RAC-80 at the standard age and that of RAC-20, RAC-50 and RAC-70 at two years. Overall, the prism compressive strength of RAC at the long age on average is 16.8% higher than that of NAC at the standard age. As for a certain replacement ratio, the former is also higher than that of the latter. That is to say, as the curing time goes on, the hydration extent of internal cement colloid develops deeply so that the strength of RAC is improved.

According to the test results of strength waving phenomenon, it can be concluded that there is a close relationship between the concrete compressive strength and RCA properties. The water absorbing capacity of RCA, the micro-crack in RAC and the content of old adhered mortar attaching to the original coarse aggregate can significantly affect the strength of concrete. Because of the stronger water absorbing capacity of RCA, the actual water-cement ratio in concrete mixture will be lower compared to the designed water-cement ratio, so that the concrete strength will be improved to some extent. In this study, the designed water-cement ratio is controlled at the same level ($W/C = 0.41$). Thus, with increasing the replacement ratio of RAC, its prism compressive strength will be enhanced naturally, which means that the better water absorbing capacity of RCA plays a positive role in improving the concrete strength. On the other hand, the concrete strength may be undermined due to the micro-crack in RAC and the content of old adhered mortar attaching to the original coarse aggregate. The micro-crack is formed in the process of crushing the RCA, and its existence will increase the brittleness of the coarse aggregate. As a result, the RAC strength will become worse with the increase of the replacement ratio of RAC. At the same time, the old adhered mortar attaching to the original coarse aggregate will change the interfacial bonding conditions between the original natural coarse aggregate in RCA and the new formed adhered mortar. Because of the lower compressive strength of old adhered mortar and its brittleness compared to NCA, it is obvious that the RAC prism compressive strength will be reduced. Comprehensively speaking, if the positive effect is stronger than the negative one, the RAC strength will be improved; otherwise, the strength will be worsened.

4.4. Flexural Strength

The flexural strength f_t($f_t = F_t\ l/bh^2$) of RAC is determined by the Chinese Code [JTG E30–2005] 'Test method of cement and concrete for highway engineering'. Here, F_t is the failure flexural load, l is the length of prism specimen, b is the breadth of the cross-section, and h is the height of cross-section. In this test, l is set to 17.73 in. (450 mm), b is 5.91 in. (150 mm), and h is 5.91 in. (150 mm). The flexural strength of RAC is also shown in Table 2. It can be seen that RCA content has significant influences on the flexural strength of RAC.

Table 2. Test Results of RAC Strength.

No.	RAC –0	RAC –10	RAC –20	RAC –30	RAC –40	RAC –50	RAC –60	RAC –70	RAC –80	RAC –90	RAC –100
f_t (MPa)	5.50	5.70	5.90	6.00	6.10	5.10	5.70	5.50	5.30	5.40	5.90
f_c^s (MPa)	39.33	41.35	38.03	39.75	42.06	36.77	41.3	39.32	41.06	43.83	41.63
f_c^1 (MPa)	46.67	44.27	50.57	46.67	46.71	46.15	43.60	49.76	46.03	46.86	50.67
f_{cu} (MPa)	45.30	46.50	44.70	47.20	46.80	43.40	49.20	44.60	48.40	47.40	48.40
f_t/f_{cu}	0.12	0.12	0.13	0.13	0.13	0.12	0.12	0.12	0.11	0.11	0.12
f_c^s/f_{cu}	0.87	0.89	0.85	0.84	0.90	0.85	0.84	0.88	0.85	0.92	0.86
f_t/f_c	0.14	0.14	0.16	0.15	0.15	0.14	0.14	0.14	0.13	0.12	0.14
f_c^1/f_c^s	1.19	1.07	1.33	1.17	1.11	1.26	1.06	1.27	1.12	1.07	1.22

Generally, there are two tendencies for different levels of replacement ratio of RAC: when the replacement ratio is lower than 50%, the flexural strength of RAC increases with the increase of RCA content, whereas when the replacement ratio is over 50%, the flexural strength decreases with the increase of RCA content. Besides, it is well worth mentioning that the average ft of RAC is 5.66 MPa, which is 2.91% higher than that of NAC.

4.5. Poisson's Ratio

Poisson's ratio υ_c is an important index of the lateral deformation of concrete. Although this ratio at the standard age has been researched already, it is not the real value when the RAC is applied to structural concrete for long-time use. In this test, the longitudinal strain ε' and lateral strain ε of all prism specimens were acquired in the stable stress stage. Thus, the value of Poisson's ratio can be easily calculated by the equation of $\upsilon_c = \varepsilon'/\varepsilon$.

Figure 2 shows the influence of the RAC replacement ratio on Poisson's ratio. Based on the test results, an empirical formula can be given as follows:

$$\upsilon_c = 0.21 - 0.0003\delta \tag{2}$$

4.6. Approximation of the Stress-strain Relation

Nondimensionalization is an unexceptionable way to probe the variation rules at different stress stages in the constitutive relationship curves. For structural analysis and design in practical engineering applications, an analytical expression for the stress-strain curves of RAC is desirable. In this study, the analytical expression of normalized stress-strain relation of RAC is approximated by the following equation:

$$\bar{\sigma} = \begin{cases} a\bar{\varepsilon} + (3-2a)\bar{\varepsilon}^3 + (a-2)\bar{\varepsilon}^3, & 0 < \bar{\varepsilon} < 1 \\ \bar{\varepsilon} \big/ [b(\bar{\varepsilon}-1)^2 + \bar{\varepsilon}], & \bar{\varepsilon} \geq 1 \end{cases} \tag{3}$$

where a is the slope of the initial tangent of the dimensionless stress-strain curves, which reflects the initial elastic modulus of RAC; b is related to the area under the descending portion of the dimensionless stress-strain curves. Based on 11 groups of the acquired curves of RAC, the parameters a and b can be obtained by data fitting analysis, as shown in Table 3. Here, the curves of specimens with δ = 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% are selected for data fitting, and their rendezvous graph is shown in Figure 3. It can be seen that the curves at the ascent stage are basically coincident, and their discreteness is relatively large once the curves exceed the peak stress. Compared to NAC, with the increase of the RAC replacement ratio, the declining curve is much steeper, which means that the variation tendency of RAC replacement ratio at the stress nonlinear stage of each curve plays a vital role in the concrete ductility.

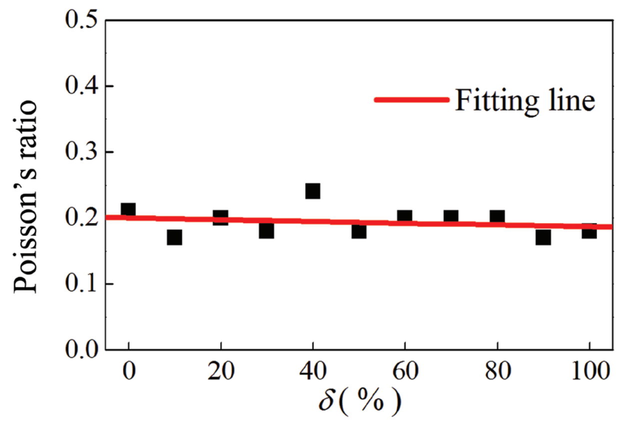

Figure 2. *Poisson's ratio of RAC.*

5. CONCLUSIONS

Based on the results of this experimental investigation, the following conclusions are drawn:

1. The peak strain value of RAC generally increases with the increase of the RCA content. For the RCA replacement ratios of 80%, 90% and 100%, the peak strain values increase by about 15% compared to that of the NAC.
2. The compressive strength of RAC including the prism compressive strength at the standard age and at two years, the flexural strength and the cube compressive strength generally increase with the increase of RCA content.

Table 3. Fitting Results of Parameters a and b Under Different RCA Replacement Ratios.

Parameter	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	Average
a	0.80	0.80	1.20	1.20	0.98	1.20	1.20	1.40	1.30	1.10	0.95	1.10
b	5.0	10.0	3.0	4.5	8.0	2.3	5.0	13.0	6.0	18.0	38.0	10.3

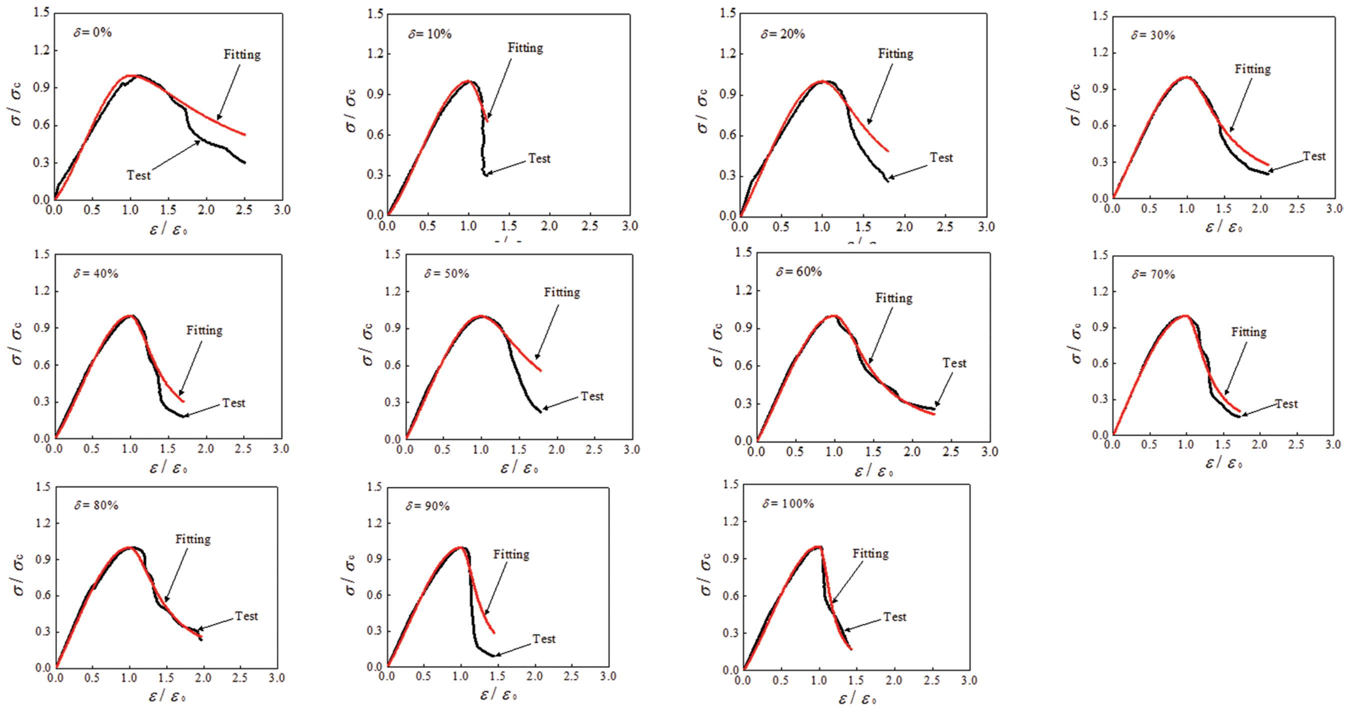

Figure 3. *Normalized stress-strain curves.*

3. The prism compressive strength of RAC at two years is higher than that of the specimens at the standard age.
4. Poisson's ratio of RAC ranges from 0.17 to 0.24.
5. The strength in RAC structures can be predicted by our proposed analytical expression of normalized stress-strain relation of RAC.

6. ACKNOWLEDGMENTS

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