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Cement and Concrete Research 35 (2005) 1187–1194
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Cement and Concrete Research

Mechanical properties of recycled aggregate concrete under uniaxial loading

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Received 17 June 2004; accepted 23 September 2004

Abstract

In this paper, the compressive strength and the stress–strain curve (SSC) of recycled aggregate concrete (RAC) with different replacement percentages of recycled coarse aggregate (RCA) are investigated experimentally. Concrete specimens were fabricated and tested with different RCA replacement percentages of 0%, 30%, 50%, 70% and 100%, respectively. Uniaxial compression loading is applied in the experiments. Special attention of the analysis is devoted to the failure behaviour and the influences of the RCA contents on the compressive strength, the elastic modulus, the peak and the ultimate strains of RAC. Analytical expressions for the peak strain and the stress–strain relationship of RAC are given, which can be directly used in theoretical and numerical analysis as well as practical engineering design of RAC structures.

Keywords: Recycled aggregate; Concrete; Mechanical properties; Uniaxial loading

1. Introduction

Recycling of waste concrete is beneficial and necessary from the viewpoint of environmental preservation and effective utilization of resources. For the effective utilization of waste concrete, it is necessary to use waste concrete as recycled aggregates for new concrete. To make this technology feasible, a significant amount of experimental works has been carried out. Various investigations mainly engaged in the processing of demolished concrete, the mixture design, the physical and the mechanical properties as well as the durability aspects. Most of the findings have been extensively reviewed and discussed by Nixon [1], Hansen [2,3] and ACI 555 Report [4]. It is shown that some properties of recycled aggregate concrete (RAC) may be generally lower than those of normal concrete (NC), but they are still sufficient for some practical applications in Civil Engineering.

The most important mechanical properties of RAC are the compressive strength, the tensile and the flexural strengths, the bond strength and the elastic modulus of such concrete. In particular, the stress–strain relation of RAC is especially important in theoretical and numerical analysis as well as engineering design of RAC structures. The peak value of the stress–strain curve yields the compressive strength, and the area under the descending portion of the curve provides a measure of the toughness resistance of RAC. The descending portion of the stress–strain curve is essential when a RAC structure is subjected to impact, earthquakes, or fatigue loading. Many investigations on the compressive stress–strain behaviour of natural aggregate concrete have been conducted and numerous stress–strain relationships have been developed [5]. In recent years, several investigations have also been performed for the stress–strain relation of recycled aggregate concrete. Henrichshen and Jensen [6] found that the stress–strain relationship for recycled aggregate concrete is

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0008-8846/$ - see front matter
doi:10.1016/j.cemconres.2004.09.020

similar in shape to that of normal concrete. Thus structures made of recycled aggregate concrete can be designed according to the theory of plasticity just like structures made of normal concrete. Bairagi and Kishore [7] also found that the stress–strain curves of concretes with different recycled coarse aggregate (RCA) replacement percentages follow similar trends, but the curvature of each curve progressively improves with the increase of replacement percentage. In his investigation, Topcu [8] obtained the complete stress–strain curve of recycled aggregate concrete with the RCA replacement percentages of 0%, 30%, 50%, 70% and 100%, and he found that with the increase of recycled coarse aggregate amount, the values of compressive strength, toughness, plastic energy capacity and elastic energy, and the elastic modulus decrease. Rühl and Atkinson [9] also investigated the complete stress–strain curve of recycled aggregate concrete with different RCA contents, they found that the peak strain increases as the recycled aggregates increase. However, to the best knowledge of the authors, only few investigators presented an analytical expression for the stress–strain relation of RAC, which prohibits a direct application of their results to the analysis and the practical design of RAC structures.

In this study, experiments are performed to provide a comprehensive experimental and analytical evaluation of the stress–strain relation of RAC with different RCA contents in compression. The influences of RCA on the peak stress and the peak strain, the shape of the SSC (in particular its descending portion), and the elastic modulus are analyzed. An analytical expression is given to describe the complete SSC of RAC in terms of the RCA contents. The results presented in this paper are significant to efficiently use the RAC in practical applications.

2. Experimental descriptions

2.1. Materials

Ordinary Portland cement with a 28d compressive strength of 32.5 MPa was used in this investigation. The fine aggregate used was river sand. The used coarse aggregates were natural coarse aggregates (NCA) and recycled coarse aggregates (5–15 mm accounting for 60%, and 15–31.5 mm accounting for 40% in weight) obtained from the waste concrete brought from the runway of an airport in Shanghai, PR China. The physical properties of the natural coarse aggregates and the recycled coarse aggregates are shown in Table 1.

Table 1
Physical properties of NCA and RCA

Coarse aggregate	Grading (mm)	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Water absorption (%)	Crush index (%)
Natural	5–31.5	1453	2820	0.4	4.04
Recycled	5–31.5	1290	2520	9.25	15.2

Table 2
Mix proportions of concrete (kg/m^3)

No.	RCA Replacement percentage	W/C	C	S	NCA	RCA	Mixing water
NC	0	0.43	430	555	1295	–	185
RC-30	30	0.43	430	534	872	374	185
RC-50	50	0.43	430	522	609	609	185
RC-70	70	0.43	430	510	357	832	185
RC-100	100	0.43	430	492	–	1149	185

2.2. Mix proportions

Due to the high water absorption, the used RCAs were presoaked before mixing. The water amount used to presoak the RCA was calculated according to the effective absorption of RCA. The water/cement ratio was kept constant as 0.43. The mixtures were divided into five groups. The main difference between these five groups is the RCA replacement percentage, which is 0%, 30%, 50%, 70% and 100%, respectively. In the case of a RCA replacement percentage equals 0%, the concrete is the normal concrete, which served as the reference concrete. The mix proportions of concretes are shown in Table 2.

2.3. Preparation of specimens

The preparation and the cure of all the mixes were conducted in the State Key Laboratory for Concrete Material Research at Tongji University in Shanghai, PR China. All mixing was conducted under laboratory conditions. The sand, cement and coarse aggregates were placed and dry-mixed for about 2 min before water was added. After 3 min of mixing followed when water was added, a slump test was run to determine its workability. The mixture in each group was cast in 100×100×300 mm prisms in six steel moulds and 100×100×100 mm cubes in three steel moulds, then compacted on a vibration table. They were demolded a day after casting and were cured in a fog room (20±2 °C, 95% relative humidity) for 28 days. The prism specimens were used to obtain the stress–strain curves, and the cube specimens were used to obtain the cube compressive strength of the RAC.

2.4. Test setup and test method

The loading setup as shown in Fig. 1 was a LAX-W500 microcomputer controlled electro-hydraulic servo tester. In order to get the complete SSC, the strain rate of the test specimens was kept constant to 44×10^{-6}/s. During the experiment, the axial compression and the vertical defor-

Fig. 1. Test setup for the SSC.

mation of the test specimens were automatically collected by the computer installed. The measured vertical deformation is the deformation of the middle 1/3-part (100 mm from the specimen-top) of the concrete prism specimen. Each specimen was preloaded before the actual loading in order to lessen the impacts on the test results due to the loose of the specimens end. As pre-loading, 30–40% of the estimated peak loading (according to the test results for the cube compressive strength) is applied, and the loading is repeated three times.

3. Test results

3.1. Failure behaviour

3.1.1. Normal concrete

In the early stage of the loading, the test specimens did not show any cracks. With the increase of the compression loading, small vertical micro-cracks were gradually formed in the test specimens. After reaching the peak stress, the loading decreased slowly. Several discontinuous short vertical cracks appeared, and they then coalesced into inclined macro-cracks. The inclination angle of the macro-cracks with respect to the vertical loading plumb is about 58–64°.

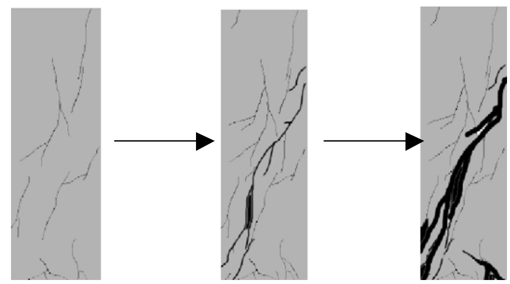
3.1.2. Recycled aggregate concrete

In the early stage of the loading, nearly the same behaviour as the normal concrete was observed. However, after the compression loading exceeding the peak stress, the first vertical micro-cracks appeared which are very short and thin. By continuing the test, it was very fast to form an inclined macro-crack through the specimen, and the load went down immediately. For some test specimens, a sound induced by cracking could be heard. After forming a through macro-crack, the test specimen was supported by itself and the friction between the cracks. Some vertical or slightly inclined branch cracks were observed on some samples, while the loading was stable. As the strain was controlled effectively, most of the specimens did not spall and maintained its completeness at the end of the test. All the test samples showed an inclined failure plane, with an inclination angle of about 63–79° with respect to the vertical load plumb. The inclination angle of the failure plane of RAC is considerably larger than that of the normal concrete. In general, the plastic deformation of recycled aggregate concrete is less than that of the normal concrete. By carefully analyzing the failure plane, it can be concluded that a fracture of the recycled and natural coarse aggregates is rarely seen. The experimental results indicated that the failure mode of RAC is a shear mode, at least under the experimental conditions of this investigation. The typical failure process and failure pattern of RAC are shown in Fig. 2.

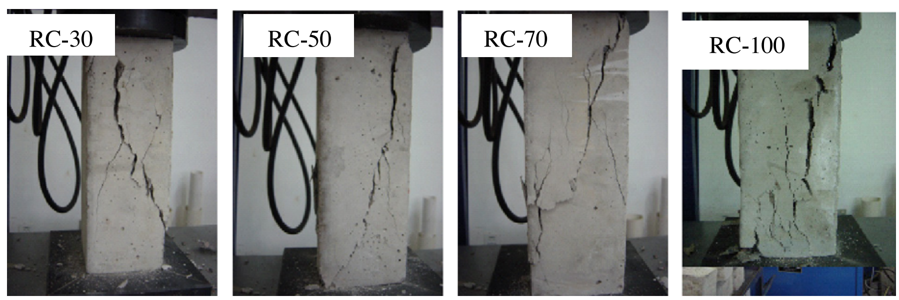
3.2. Stress–strain curves

The typical stress–strain curves (SSC) of RAC with different RCA contents are shown in Fig. 3. Fig. 3 illustrates that the RCA replacement percentage has markable influences on the SSC of RAC. Nevertheless, the shape of the stress–strain curve for all the recycled aggregate concrete was similar to that of the natural aggregate concrete, irrespective of the RCA replacement percentages, which leads to the conclusion that there would be in principle no objection in the structural design process to the application of the theory of plasticity. It is worth mentioning that the strains were higher than those of the natural aggregate concrete under the same loads mainly due to the lower elastic modulus of the recycled aggregate concrete. Roughly speaking, the SSC can be divided into three characteristic parts. The first part represents the linear portion and the second represents the nonlinear portion of the ascending branch, and the third part is the descending branch. The curvature of each ascending branch of the SSC improves with the increase of the RCA content. The presence of interfaces between the new cement mortar–aggregate, old cement mortar–aggregate, and old cement mortar–new cement mortar may give rise to a progressive development of micro-cracks at these interfaces. There are a large number of such interfaces in concrete containing higher proportion of recycled coarse aggregate [10,11,12]. Thus, the strain increases at a faster rate than the applied stress does and so the curvature of the stress–strain curves increases with increasing RCA content. The shape and the surface properties of RAC may also have influences on the stress–strain curves and the elastic modulus.

Another notable fact of the SSC is that the slope of their descending branch decreases as the RCA content increases. In conclusion, the addition of RCA into a normal concrete leads to a substantial change in its stress–strain responses. This change is generally characterized by an increase in the peak strain (strain at peak stress) and a significant decrease in the ductility of the concrete as described by the descending portion of the SSC.



(a) Failure process of recycled aggregate concrete prisms



(b) Failure pattern of recycled aggregate concrete prisms

Fig. 2. Failure process and failure pattern of recycled aggregate concrete prism.

3.3. Compressive strength

The compressive strength is the peak stress of the test specimens under uniaxial compression. The prism compressive strength f_c and the cube compressive strength f_{cu} of RAC with different RCA replacement percentages are given in Table 3. It can be seen from Table 3 that the RCA contents have significant influences on the compressive strength of RAC. Generally, the compressive strength of RAC decreases with the increase of RCA. It is worth mentioning that the f_c/f_{cu} ratio of RAC is higher than that of normal concrete, except in the case of RC-30. The average f_c/f_{cu} ratio of RAC is 0.81, which is 8% higher than that of normal concrete. However, both f_c and f_{cu} are lower than that of the normal concrete, because of the existence of RCA.

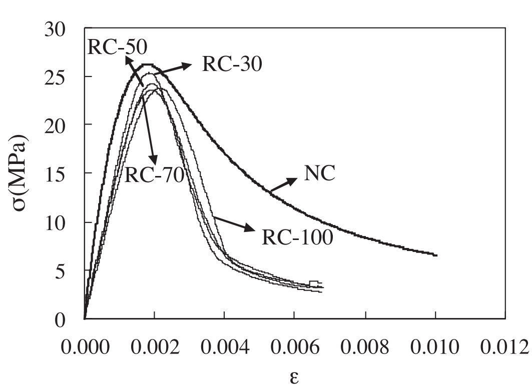


Fig. 3. Typical stress–strain curves of RAC.

3.4. Elastic modulus

The elastic modulus E_c of the RAC was determined from the SSC according to

$$E_c = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - 0.005\%}, \tag{1}$$

where σ_2 is the stress corresponding to the 40% of the peak load, σ_1 is the stress corresponding to a strain of 0.005%, and ε_2 is the strain at the stress level σ_2, respectively. The elastic modulus of RAC is shown in Fig. 4, versus the RCA replacement percentage r. Fig. 4 shows that the elastic modulus of the RAC is lower than that of the normal concrete (i.e., r=0%), and it decreases with increasing RCA replacement percentage. When the RCA replacement percentage is 100%, the elastic modulus is reduced by 45%. This is the consequence of the application of the RAC with a lower elastic modulus than that of the natural coarse aggregates. In previous

Table 3
Compressive strengths of RAC

No.	Slump (mm)	Density (kg/m^3)	f_{cu} (MPa)	f_c (MPa)	f_c/f_{cu}
NC	42	2402	35.9	26.9	0.75
RC-30	33	2368	34.1	25.4	0.74
RC-50	41	2345	29.6	23.6	0.80
RC-70	40	2316	30.3	24.2	0.80
RC-100	44	2280	26.7	23.8	0.89

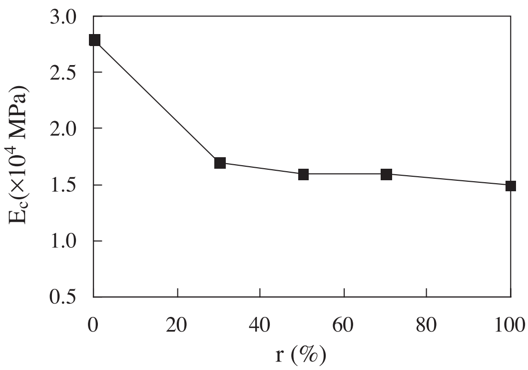


Fig. 4. Elastic modulus of RAC.

studies, Topcu [8] found that the reduction of the elastic modulus of RAC was 80%, while Fdrondistou [13] and Hansen [14] reported that the reductions of the elastic modulus of RAC were 33% and 14–28%. The main reason for the differences in the reduction of the elastic modulus is due to the different elastic modulus of RCA used by the investigators. Dhir and Limbachiya [15], and Ravindrarajah and Tam [16] also investigated the elastic modulus of RAC and suggested approximate calculation formulae. It was found that the commonly used relationship between compressive strength and modulus of elasticity for normal concrete was not applicable to recycled aggregate concrete.

3.5. Peak strain

The peak strain is the strain corresponding to the peak stress. The peak strains of the RAC with different RCA contents are shown in Fig. 5. From Fig. 5, it can be seen that the value of the peak strain increases as the RCA content increases. For a RCA replacement percentage r=100%, the peak strain is increased by about 20%. This is consistent with the results of Rühl and Atkinson [9]. The main reason for the increase of the peak strain of RAC is due to the reduced elastic modulus of RAC, which leads to a larger deformation.

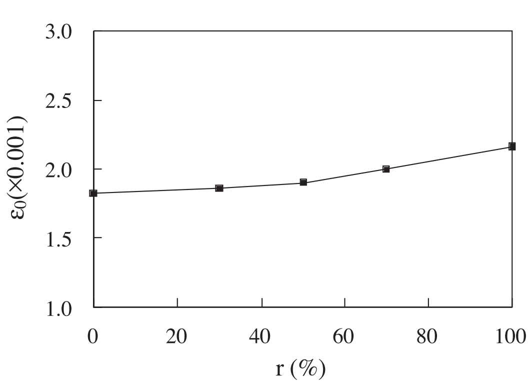


Fig. 5. Peak strain of RAC.

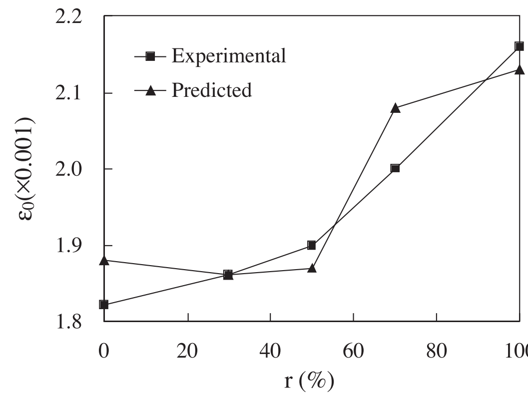


Fig. 6. Comparison of the peak strain of RAC.

Based on the analysis of many related test results and a data regression, Nicolo [17] proposed an approximate formula for the peak strain of the normal concrete

$$\varepsilon_0^{\mathrm{n}} = 0.00076 + \left[\left(0.626 f_{\mathrm{c}}^{\mathrm{n}} - 4.33\right) \times 10^{-7}\right]^{0.5}. \qquad (2)$$

For the RAC, we suggest the following empirical formula for calculating the peak strain

$$\varepsilon_0^{\mathrm{r}} = \varepsilon_0^{\mathrm{n}} \times \left(1 + \frac{r}{\beta}\right), \qquad (3)$$

where ϵ_0^{r} is the peak strain of RAC, r is the RCA replacement percentage, and β=65.715r^2−109.43r+48.989. Comparisons of the experimental and the predicted values of peak strain by Eq. (3) presented in Fig. 6 show that Eq. (3) fits the experimental results satisfactorily.

3.6. Ultimate strain

The ultimate strain is taken as the longitudinal strain at a stress level equals to 85% of the peak stress. The dependence of the ultimate strain on the RCA replacement percentage is shown in Fig. 7. Fig. 7 reveals that the ultimate strain may decrease or increase with increasing RCA replacement percentage, depending on the value of r. For a small value of r the ultimate strain decreases with increasing r, while the opposite may be the case for a large value of r.

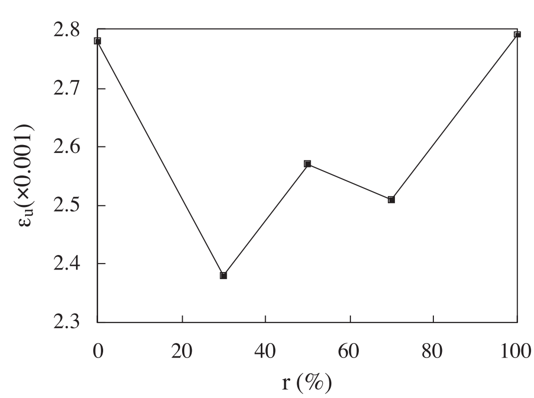


Fig. 7. Ultimate strain of RAC.

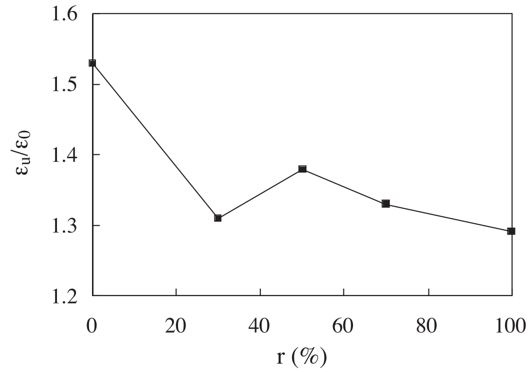


Fig. 8. Dependence of ϵ_u/ϵ_0-value on r.

The influence of the RCA replacement percentage r on the ϵ_u/ϵ_0-value of RAC is shown in Fig. 8. From Fig. 8, it can be concluded that the ϵ_u/ϵ_0-value of RAC is smaller than that of the normal concrete. This means that under the same loading and deformation conditions, the energy absorption capacity of RAC is reduced. Compared to the normal concrete, the RAC is more brittle with a poor ductility.

4. Approximation of the stress–strain relations

An analytical expression for the stress–stain curves of RAC is desirable for the structural analysis and design in many practical engineering applications. In this paper, the analytical expression proposed by Guo and Zhang [18], adopted by Chinese Code GB50010 [19], for uniaxial compression of normal concrete is used. This expression was developed for normal concrete and is extended in this study to RAC. The normalized stress–strain relation of RAC is approximated by the following equation

$$\bar{\sigma} = \begin{cases} a\bar{\epsilon} + (3-2a)\bar{\epsilon}^2 + (a-2)\bar{\epsilon}^3, & \text{for } \bar{\epsilon}<1, \\ \dfrac{\bar{\epsilon}}{b(\bar{\epsilon}-1)^2 + \bar{\epsilon}}, & \text{for } \bar{\epsilon}\geq 1. \end{cases} \tag{4}$$

In Eq. (4), $\bar{\epsilon}=\epsilon/\epsilon_0$, $\bar{\sigma}=\sigma/f_c$, a and b are constants to be determined. The parameter a is the slope of the initial tangent of the dimensionless SSC, which reflects the initial elastic modulus of RAC. The smaller the a-value is, the smaller is the proportion of the plastic deformation at the peak stress with respect to the total deformation. The parameter b is related to the area under the descending portion of the dimensionless SSC. The larger the b-value is, the steeper is the descending portion, and the smaller is the ductility of the RAC.

Based on the experimentally obtained stress–strain curves of RAC, the parameters a and b were obtained by a data regression analysis. The results are given as follows

$$a = 2.2\left(0.748r^2 - 1.231r + 0.975\right), \tag{5}$$

$$b = 0.8(7.6483r + 1.142), \tag{6}$$

where r is the RCA replacement percentage.

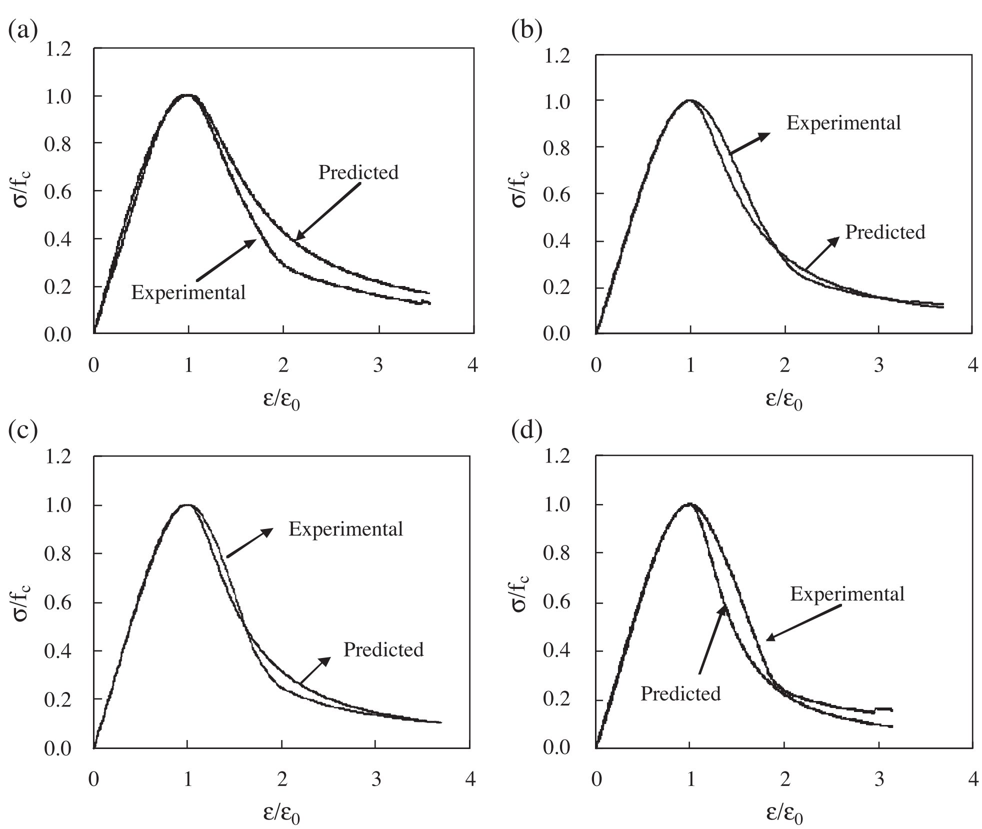


Fig. 9. Comparison of the normalized stress–strain curves. (a) r=30%, (b) r=50%, (c) r=70%, (d) r=100%.

In Fig. 9(a)–(d), a comparison between the experimentally obtained and the approximated stress–strain curves provided by Eq. (4) is shown for different values of the replacement percentage *r*. The approximate stress–strain curves agree quite well with those obtained experimentally. Hence, the approximate stress–strain relations for the RAC can be used in practical engineering applications.

5. Conclusions

In this paper, experimental results for the mechanical properties of recycled aggregate concrete under uniaxial compression loading are presented and discussed. From this investigation, the following conclusions can be drawn:

(1) The failure mode of RAC is a shear mode under the experimental conditions of this study. The failure process of RAC is relatively short. The inclination angle between the failure plane and the vertical load plumb is about 63–79°.
(2) The RCA replacement percentage has a considerable influence on the stress–strain curves of RAC. For all considered cases from r=0% to 100%, the stress–strain curves show a similar behaviour. The stress–strain curves of RAC indicate an increase in the peak strain and a significant decrease in the ductility as characterized by their descending portion.
(3) The compressive strengths including the prism and the cube compressive strengths of RAC generally decrease with increasing RCA contents. But the ratio of the prism compressive strength and the cube compressive strength is higher than that of the normal concrete.
(4) The elastic modulus of RAC is lower than that of the normal concrete. It decreases as the RCA content increases. For a RCA replacement percentage equals 100%, the elastic modulus is reduced by 45%.
(5) The peak strain of RAC is higher than that of normal concrete. It increases with the increase of RCA contents. For a RCA replacement percentage equals 100%, the peak strain was increased by 20%.
(6) The analytical expression initially proposed by Guo and Zhang for normal concrete was extended to RAC in order to obtain approximate stress–strain curves of RAC, which can be used directly in many practical engineering applications of RAC.

6. Notation

The following symbols are used in this paper:

σ_1 the stress corresponding to a strain of 0.005%;
σ_2 the stress corresponding to 40% of the ultimate load;
ϵ_2 the strain corresponding to a stress of σ_2;
ρ the mass density of RAC;
r the RCA replacement percentage;
ϵ_0^r, ϵ_0^n the peak strain of recycled and natural aggregate concrete, respectively;
$\bar{\epsilon}, \bar{\sigma}$ the dimensionless strain and stress, respectively;
ϵ_0, ϵ_u the peak and ultimate strain of concrete, respectively;
f_c, f_{cu} the prism and cube compressive strength, respectively;
E_c the elastic modulus of concrete;
a, b regression parameters in the strain–stress relationship;
β regression parameters in Eq. (2).

Acknowledgments

This work was supported by the Shanghai Science and Technology Committee (No. 02DZ12104), which is gratefully acknowledged. The authors would like to thank Mr. Fei Li for his contribution to the realization of the experimental works, which were carried out at the State Key Laboratory for Concrete Materials Research at Tongji University. The Alexander von Humboldt Foundation in Germany is also gratefully acknowledged, which sponsored the first author to do research in TU Braunschweig, so that he could revise this paper in time.

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