Construction and Building Materials 156 (2017) 1043–1052

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Strength and deformation of recycled aggregate concrete under triaxial compression

Zhiheng Deng, Yumei Wang *, Jun Sheng, Xu Hu

*College of Civil Engineering and Architecture, Guangxi University, 100 University Road, Nanning, Guangxi 530004, China*

## HIGHLIGHTS

- Mechanical properties of recycled concrete under triaxial compression were studied.
- The effect of RCA content and stress ratio on mechanical properties were analyzed.
- Triaxial strength of recycled concrete were depicted in octahedral stress space.

## ARTICLE INFO

*Article history:*
Received 11 April 2017
Received in revised form 13 August 2017
Accepted 31 August 2017

*Keywords:*
Recycled aggregate concrete
Triaxial compression
Replacement ratio of recycled coarse aggregate
Stress ratio
Strength
Deformation

## ABSTRACT

Experiment was carried out to better understand the behaviors of recycled aggregate concrete under triaxial compressive stresses. The test was performed on 100 mm × 100 mm × 100 mm cubic specimens with five replacement ratios of recycled coarse aggregate (RCA) at four kinds of stress ratios, using a servo-controlled static-dynamic triaxial machine (TAWZ-5000/3000). The failure modes, ultimate strength and deformation under triaxial compression were observed, and the effect of RCA replacement ratio and stress ratio on these characteristics was analyzed. The results show that the triaxial compressive strength of the specimens is much higher than the corresponding uniaxial strength, and the strength and deformation depend on both RCA replacement ratio and stress ratio. Moreover, the factors affecting triaxial strength were quantitatively analyzed by variance calculation. Based on the triaxial strength, the relationship between normalized octahedral normal stress $\sigma_{oct}/f_c$ and octahedral shear stress $\tau_{oct}/f_c$ with RCA replacement ratio and stress ratio was discussed.



## 1. Introduction

Recycled coarse aggregate (RCA) obtained from construction and demolition (C&D) wastes has become a valuable resource as an alternative material to natural aggregate [1]. Using cracked concrete as coarse aggregate can not only decrease the usage of natural aggregate, but also reduce pollution. The main difference between recycled aggregate and natural aggregate is the presence of residual mortar in RCA. Some work has been carried out to explore the important properties of recycled concrete [2–5]. Compared with natural aggregate concrete, recycled aggregate concrete has higher porosity, lower density, and weaker interfacial transition zones (ITZs), the property of RCA has a great influence on the mechanical properties of recycled concrete. Tam et al. [6–8] found that the microstructure of recycled concrete is much more complicated than that of the conventional concrete, recycled concrete has two ITZs: one is between the original aggregate and the residual mortar; the other is between the recycled aggregate and the fresh paste, a two-stage mixing approach (TSMA) has been proposed to strengthen the weakened ITZs. Poon et al. [9–11] found that the microstructure of recycled aggregate has an adverse effect on the mechanical properties of concrete, recycled aggregate from high strength concrete is recommended to reduce the adverse effects. Xiao et al. [12–15] analyzed the failure mechanism of recycled aggregate concrete under uniaxial compression and simulated the process. Casuccio et al. [16] and Kwan et al. [17] found that the failure of recycled concrete was characterized by low strength, high peak strain and low fracture energy. Poon et al. [18,19] pointed out the influence of RCA on the long-term mechanical properties of concrete, and studied the performance of low-grade recycled concrete. Hansen [20] found that the compressive strength of recycled aggregate concrete can be reduced by 25%, depending mainly on the quality of recycled concrete aggregate. However, some researchers observed that the compressive strength of concrete was not affected, and some slightly increased

* Corresponding author.
*E-mail address:* anniedd1207@163.com (Y. Wang).

http://dx.doi.org/10.1016/j.conbuildmat.2017.08.189
0950-0618/

when RCA replacement ratio was less than 25% [3,21–23]. Most of the structures are actually in multiaxial stress state, such as beam-column connection, steel tube confined concrete structure, shell structure, etc. Therefore, the structural design based on uniaxial strength theory is neither economic nor reasonable [21,24–26]. It is necessary to study the mechanical behavior of recycled aggregate concrete under multiaxial stress state. The mechanical properties of concrete under multiaxial stress states are different from those of uniaxial mechanics, the strength of concrete greatly improved, and many researchers have revealed these properties [27–31]. Although the mechanical behavior of ordinary concrete under multiaxial stress has been extensively studied, the study of recycled concrete under multiaxial stress is rare.He et al. [32] revealed the strength and failure criterion of recycled aggregate concrete under biaxial and triaxial compression with two kinds RCA replacement ratio, which is the only published article on multiaxial compression of recycled concrete. In this study, the mechanical properties of recycled concrete under triaxial compression were tested, and the effects of RCA replacement ratio and stress ratio on failure modes, strength and deformation were analyzed. The purpose of this research is to provide experimental data for the application of recycled aggregate concrete in structural engineering.

## 2. Materials and Testing procedure

### 2.1. Materials and mix proportions

Waste concrete was obtained from urban road under demolition in the Guangxi area in China, no detailed information was available on the age of the road, but most constructions in this area took place for no more than thirty years. Large parts of the waste concrete were crushed on site, then the crushed concrete were transported to the laboratory and broken by workers into pieces with size smaller than 20 mm and sieved with a proper gradation of 5–20 mm. The natural aggregate used were common crushed stone. Table 1 shows some of the measured physical properties of the natural and recycled aggregate. As expected, due to the presence of the attached mortar, recycled aggregate has higher water absorption and smaller density than natural aggregate. Using heat-resistant separation method can obtain the attached mortar content, the measured content of 30.55% is much higher than that of natural aggregate, and this feature directly affects the physical and mechanical properties of recycled concrete.

Based on Regulation of Common Concrete Mix Design, the water-cement ratio and the unit water consumption were determined according to the design requirement, and then the amount of cement was determined. Finally, the aggregate content was calculated according to the reasonable sand ratio. For objective comparison on triaxial strength of concrete with different RCA replacement ratio, the unit water consumption was fixed and the water-cement ratio was adjusted to get the same uniaxial strength among different groups. The fine aggregate was natural river sand with a fineness modulus of 2.8. The cementitius material was 42.5R Portland cement, water was tap-water. Table 2 shows the dry-weight proportions of mix designs.

### 2.2. Samples and testing method

Samples were casted in plastic cube molds and cured for 24 h before demolded, and then placed in a moist room with a relative humidity of 95% at $20 \pm 3^{\circ}$C. RCA replacement ratio and stress ratio were the main factors that affect the mechanical properties of recycled concrete. Five levels of RCA replacement ratio (0%, 30%, 50%, 70%, 100%) and four kinds of stress ratios ($\alpha = -0.1 : -0.25 : -1$, $-0.1 : -0.5 : -1$, $-0.1 : -0.75 : -1$, $-0.1 : -1 : -1$) were considered in this study. The principal stresses were expressed as $\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$, compression denoted as negative and tension denoted as positive. $100\ \text{mm} \times 100\ \text{mm} \times 100\ \text{mm}$ cubes were used to measure the strength of specimens under triaxial compression using a servo-controlled test setup (TAWZ-5000/3000) at State Key Laboratory of Structural Engineering in Guangxi University. The test setup consisted of four independent hydraulic actuators, the vertical actuator with loading capacity of 5000 KN, and the others with capacity of 3000 KN. Two linear variable differential transformers(LVDT) were attached along each side of the specimen in loading direction. The tests were carried out at a loading rate of 0.5 MPa/s. A data acquisition system was used to record the applied load and LVDT readings. The deformation of the specimens was obtained by averaging the reading of the two LVDTs. The specimen and test setup are shown in Fig. 1.

## 3. Test results and discussion

### 3.1. Failure modes

The crack patterns and failure modes were observed,in general, there was no fundamental difference between the failure modes due to different RCA replacement ratios. The typical crack patterns are shown in Fig. 2. The failure mode was mainly affected by stress ratio. At stress ratio $\alpha = -0.1 : -1 : -1$, due to the constraints of $\sigma_2$ and $\sigma_3$, tensile strain occurred parallel to $\sigma_1$ direction. As the load

**Table 1**
Physical properties of coarse aggregate.

| Classification | Gradation (mm) | Apparent density (kg/m$^3$) | Crush Index (%) | Water absorption (%) | Attached mortar content |
|---|---|---|---|---|---|
| NCA | 5–20 | 2708 | 4.6 | 0.3 | – |
| RCA | 5–20 | 2485 | 13.4 | 3.0 | 30.55% |

**Table 2**
Mix proportions.

| Unit weight (kg/m$^3$) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Specimens | RCA% | Water/cement | Cement | Sand | Water | NCA | RCA |
| RAC0 | 0% | 0.47 | 415 | 631 | 195 | 1121 | 0 |
| RAC30 | 30% | 0.46 | 424 | 643 | 195 | 767 | 329 |
| RAC50 | 50% | 0.45 | 433 | 656 | 195 | 536 | 536 |
| RAC70 | 70% | 0.44 | 443 | 669 | 195 | 314 | 733 |
| RAC100 | 100% | 0.43 | 453 | 681 | 195 | 0 | 1021 |