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Triaxial compressive strength experiment study of recycled aggregate concrete after high temperatures

Ercong Meng [a,*], Yalin Yu [a], Jun Yuan [a], Ke Qiao [a], Yisheng Su [b]

[a] School of Engineering and Technology, Southwest University, Chongqing 400715, China
[b] School of Civil and Architectural Engineering, Guangxi University, Nanning 530004, China

HIGHLIGHTS

- Recycled aggregate concrete (RAC) tested under triaxial stress after high temperatures.
- Influence of replacement rate, lateral confining stress and high temperatures to triaxial strength of RAC was discussed.
- Triaxial strength is almost equal to each other when temperatures do not exceed 400 °C.
- Triaxial strength calculation formula of RAC is suggested.

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ABSTRACT

To study the triaxial compressive properties of recycled aggregate concrete (RAC) after high temperature, 100 Φ100 mm × 200 mm cylindrical RAC specimens with different replacement rate (0%, 30%, 70%, 100%) were fabricated to the conventional triaxial experiment (with the lateral confining stress of 0 MPa, 5 MPa, 10 MPa, 15 MPa and 20 MPa) after exposure to different high temperatures (20 °C, 200 °C, 300 °C, 400 °C, 500 °C). The results show that the specimens present longitudinal splitting failure form when under uniaxial stress condition and inclined plane shear or flake splitting failure form when under triaxial stress condition. The triaxial compressive strength presents the trend of decreasing → increasing → decreasing with the increase of replacement rate. Improving lateral confining stress can effectively improve the compressive strength of RAC. The triaxial strength of specimens is almost equal to each other when the temperatures do not exceed 400 °C. After 500 °C high temperature, the triaxial strength will gradually decrease, but the decrease amplitude is far less than that of uniaxial strength. Based on test data and some related theories, the triaxial strength calculation formula of RAC with different replacement rate after high temperatures was given. And it can provide some references for the related research and practical engineering application of RAC.

1. Introduction

In recent years, a lot of construction waste was caused by earthquake, urbanization, old city renovation and some other reasons in different countries, e.g., in China, Xiao et al. [1,2] investigated that every year about 200 million tons of waste concrete were produced, and it has amounted to about 30–40% total city solid wastes. So large amounts of construction waste have caused a lot of social, environmental and economic problems, etc. [3], and RAC technology is one of the effective ways to solve the problem [4].

RAC refers to the reuse of recycled coarse aggregate (RCA) that comes from the waste concrete after crushing, screening and cleaning, then use it to instead part or all natural coarse aggregate (NCA) to produce new concrete [5]. The mechanical behavior between RAC and natural aggregate concrete (NAC) is different due to the micro-cracks produced in RCA during the crushing process and old cement mortar attached to RAC. Many scholars all over the world had done a lot of researches on the mechanical properties of RAC, but most of them [6–13] were focused on the uniaxial stress under normal temperature condition. In practical engineering, concrete may be under high temperature working condition such as the structure of metallurgical workshop (200 °C–300 °C), chimney lining (500 °C–600 °C), etc. Numerous studies on NAC after high temperatures have been investigated [14–18]. However, the studies on RAC after high temperatures are relatively less [19–22]. Zega et al. [19,20] found that RAC performed better than NAC when heating to 500 °C for 1 h with

* Corresponding author.
E-mail address: ec-dream@qq.com (E. Meng).

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the water to cement ratio of 0.4. Xiao et al. [21] found a similar conclusion about that the residual compressive strength of RAC was higher than NAC when the RCA replacement rate reached to 50–100%. In contrast, with respect to the residual compressive strength, elastic modules and tensile splitting strength, Vieira et al. [22] found minimal difference between RAC and NAC. In general, the aforementioned researches about RAC after high temperatures were all under uniaxial stress condition. The limited researches showed that RAC has sufficient spalling resistance.

Furthermore, in practical engineering, concrete are often under triaxial stress condition such as the concrete in the steel tube and spiral hoop, etc. Hence, to extend the usage of RAC in practical engineering, one of the main concerns is the triaxial compressive performance of RAC [23]. Some researchers have studied the triaxial mechanical behavior of NAC [24–29]. But until now, only a few researches about the triaxial mechanical behavior of RAC have been carried out. He et al. [23] studied the failure mode characteristics and triaxial strength of RAC through the test performed on the cubic specimens with the dimensions of 150 mm × 150 mm × 150 mm, and a new failure criterion was proposed for the plain RAC in his research. Folino et al. [30] investigated the triaxial compressive mechanical behavior of RAC through the Φ100 mm × 200 mm cylindrical specimens, and concluded that the replacement rate has no substantial influence to the failure modes of RAC when under triaxial compression. And up to now, the existing literature about the triaxial compressive behavior of RAC after exposure to high temperatures is much more limited.

Based on the background, this paper designed 100 Φ100 mm × 200 mm cylindrical RAC specimens with the parameters of different replacement rate, high temperatures and confining stress, and it can provide some reference for the further theoretical research and practical engineering application of RAC structure.

2. Experimental program

2.1. Materials

In this test, sand was common natural yellow sand, and according to the Chinese standard "common Portland cement" (GB 175-2007) [31], the domestic Conch brand composite Portland cement type 32.5 was used. RCA came from a teaching building concrete after crushing, sifting and cleaning. The used NCA and RCA were continuous grade. According to the Chinese standard "pebble and crushed stone for construction" (GB/T14685-2011) [32], the basic properties of NCA and RCA were tested and are shown in Table 1.

2.2. Specimens preparation

100 Φ100 mm × 200 mm cylindrical specimens were designed in the test. The specimens were numbered as RCi-j-k, *i* represents replacement rate (0%, 30%, 70%, 100%), *j* represents temperatures (20 °C, 200 °C, 300 °C, 400 °C, 500 °C), *k* represents confining stress (0 MPa, 5 MPa, 10 MPa, 15 MPa, 20 MPa).

The concrete mixtures for RAC with different replacement rates are given in Table 2. After pouring concrete for 24 h, the specimens were put into the standard curing room for maintenance for 28 d [33]. Then the specimens were taken out and ready for the heating and triaxial tests.

2.3. Heating process

The heating processes of the specimens were in the industrial resistance furnace type RX-3-45-9. The processes were wholly controlled by the temperature control system in the furnace. To make the inside and outside temperature of the specimen both reach to its target temperature [34], the temperature was maintained for 1 h when different specimens getting to their target temperatures (200 °C, 300 °C, 400 °C, 500 °C, respectively). The heating curves of different temperatures are shown in Fig. 1. In Fig. 1, it is noted that the 500 °C heating curve appears a suddenly declining phenomenon due to the furnace system reason. This phenomenon may affect the strength of specimens, but it still achieves the temperature goal (500 °C) and maintains for 1 h, so in this paper, we don't consider the influence of the suddenly declining phenomenon. After exposure to high temperatures, the specimens were naturally cooled in the room temperature condition (20 °C). After cooling, the triaxial experiment was then ready to begin.

Table 1
Basic properties of coarse aggregate.

Coarse aggregate type	Particle sizes	Bulk density/(kg/m^3)	Apparent density/(kg/m^3)	Water absorption
NCA	5–20 mm	1523	2652	0.88%
RCA	5–20 mm	1347	2359	6.50%

2.4. Triaxial loading test

The specimens were loaded in RMT-201 tester with sophisticated sensing and triaxial pressure device which can realize the conventional triaxial test. The loading device and mechanical model of specimens are shown in Fig. 2(a) and (b), respectively.

The loading system adopted the method of load and displacement hybrid control. Firstly, the predetermined confining stress value was applied, and the vertical load at 1:1 proportion was synchronously applied during the process. When getting to the target confining stress, keep it constant. Subsequently, the displacement control loading system with the loading rate of 0.01 mm/s was used to apply the vertical load until the specimens damaged. The loading system is shown in Fig. 2(c).

3. Test results

3.1. Test phenomenon after high temperatures

After exposure to different high temperatures, the surface and color of the specimens changed differently. After exposure to 200 °C or 300 °C high temperature, basically no apparent cracks were appeared and the color gradually turned dim. After exposure to 400 °C or 500 °C high temperature, many cracks were appeared in the surface of the specimens and the color turned to gray. The typical characteristics of the specimens after exposure to different high temperatures are shown in Fig. 3.

3.2. Failure pattern

3.2.1. Under uniaxial stress condition

The specimens presented the longitudinal splitting failure form when under uniaxial stress condition. In normal temperature environment, the cracks developed slowly at the beginning of the loading process. One or several parallel longitudinal cracks appeared in the middle position of the specimens when the load was close to the peak point, and developed quickly, then the specimens gradually lost their bearing capacity while the load reached to the peak point. As the loading process continued, the bearing capacity of specimens gradually decreased, and the specimens were split into several small pieces by the longitudinal cracks and the specimens were failure. After exposure to different high temperatures, the failure form of specimens was similar to the ones in normal temperature environment, and the slight difference was that the crack fracture zone of the specimens after high temperatures was more widely than the ones in normal temperature environment. The typical failure form of the specimens under uniaxial stress condition is shown in Fig. 4(a).

When under triaxial stress condition, the failure process cannot be observed because the specimen was in the closed pressure vessel. After the experiment finished, taking out the specimen, we found that the specimens mainly presented the inclined plane shear failure when the confining stress $\sigma_k \leq 10$ MPa. The angle between the inclined crack and cross section was between 40° and 70°. The reason is that when under triaxial stress condition, the inclined plane shear failure phenomenon will happen while the shear stress in the oblique section is more than the critical shear strength. The specimens mainly presented the flake splitting failure when the confining stress $\sigma_k \geq 15$ MPa. The specimens were split into 2–4 pieces, and the main splitting surface appeared irreg-