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Shear behavior of recycled aggregate concrete after exposure to high temperatures

Haifeng Yang [a,b], Yinghong Qin [a,b,*], Yi Liao [a], Wei Chen [a]

[a] College of Civil Engineering and Architecture, Guangxi University, 100 University Road, Nanning, Guangxi 530004, China
[b] Key Laboratory of Disaster Prevention and Engineering Safety of Guangxi, Nanning 530004, China

HIGHLIGHTS

- Increasing RCA content has minimal effect on the shear behavior.
- The shear behavior of RAC is significantly affected by high temperatures.
- Shear stress–strain relation of RAC exposed to high temperatures is suggested.

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ABSTRACT

This paper studied the shear behavior of concrete with different levels of recycled coarse aggregate (i.e., 0%, 50% and 100%) after being subjected to different temperatures (i.e., 20 °C, 200 °C, 300 °C and 400 °C). Thirty-six beam specimens with uniform depth and varying width were designed to test their mechanical parameters including shear strength, peak shear strain, stress–strain curves and shear modulus. We analyze how these parameters are influenced by recycled coarse aggregate (RCA) content and by high temperature. We establish the shear stress–strain equations for RCA-embedded concrete after exposure to different temperatures. It is found that the aforementioned mechanical parameters are minimally influenced by the RCA content at ambient temperature (about 20 °C). After exposure to high temperatures, the RCA content affects the shear strength insignificantly but increases the peak strain slightly. As the temperature elevates, the residual shear strength and shear modulus decline rapidly whereas the peak strain increases linearly. Furthermore, the normalized shear stress–strain curves become more disperse with the increment of temperature.

1. Introduction

Limited natural resources, huge demand for building material, and increasing demolished waste are calling to reclaim the demolished concrete [1–4]. Concrete with RCA embedment is considered to be inferior than convectional concrete due to the attached mortar at the aggregate surface and to the demolition-induced microcracks. While compressive strength, tensile strength, and static modulus elasticity have been studied widely [5–10], shear behavior of RCA-embedded concrete is a critical parameter in failure criterion of shear design for reinforced concrete element but has been few reported [5,11,12]. Although the properties of plain natural aggregate concrete (NAC) and reinforced NAC in or after fire have been widely investigated [13–20], it remains unknown the mechanical behavior of RCA-embedded concrete when or after being subjected to high temperature due to the different performance on physicochemical reaction, dehydration of cement paste, and crispness of aggregate, comparing with those of NAC [17,18].

Concrete containing RCA subjected to elevated temperature has been the subject of previous literature. Recycled aggregate concrete (RAC) with a water to cement ratio of 0.40 has been found performing better than conventional concrete when heated to 500 °C for 1 h [21,22]. A similar conclusion was obtained by Xiao [23], who found that the residual compressive strength of RAC was higher than NAC when the RCA-replacement percentage reached to 50–100%. In contrast, Vieira et al [24] found minimal differences between RAC and NAC with respective to the post-fire residual mechanical properties of RAC including compressive strength, tensile splitting strength and elastic modulus. The residual strength of concrete containing different waste materials such as bricks, glasses, and RCA were reviewed by Cree [25], which called for more experiments to understand the performance of RCA-containing structure exposed to fire.

* Corresponding author at: College of Civil Engineering and Architecture, Guangxi University, 100 University Road, Nanning, Guangxi 530004, China.
E-mail address: yinghong231@gmail.com (Y. Qin).

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Although the performance of heated RAC has been reported [21–24], shear behavior of RAC after exposure to high temperatures remains unknown. This paper investigates the residual shear strength, peak shear strain, shear stress–strain relation, and shear modulus of RAC after being subjected to temperatures of 20–400 °C. These mechanical properties of concrete samples with three RCA-replacement percentages (i.e., R = 0%, 50% and 100%) are tested and discussed.

2. Experimental programs

2.1. Comparison of existing test methods

Approaches to testing the shear stress of concrete samples have been well documented. The most frequently used is the tensile failure model because it is difficult to get a pure shear failure model [26,27]. The experimental setups [26–31] to test the shear behavior of concrete are shown in Fig. 1. According to [26], the test components shown as (a), (b), and (e) have some defects so the suggested testing setup is a double shear test specimen (Fig. 1(d)). Nonetheless, the result obtained by component (d) may be higher than actual shear strength [29]. While the failure pattern of (c) does not coincide with pure shear stress distribution because the stress concentrates in the V-shape indentation. Different from other testing types, the stress in middle span section of a four-point loaded beam with uniform depth and varying width (Fig. 1(f)) is highly close to a pure shear stress [29]. This testing setup is selected in this study.

2.2. Row materials and mix proportions

Crushed limestone was used as natural coarse aggregate (NCA). Waste concrete demolished from a highway pavement in Nanning, China was crushed and then sieved as RCA. The used natural and recycled aggregates were continuous grade. The physical properties of coarse aggregates were tested according to Chinese standard "pebble and crushed stone for construction" (GB/T14685-2011) and are presented in Table 1. Medium-sized sand with a fineness modulus of 2.7 was adopted in the mixture. Normal composite Portland cement type 32.5R compliant with the Chinese standard GB 175-2007 was used for the beam specimens. Three water-to-cement ratios and different RCA-replacement percentages are used for a comparable compressive strength among the RCA samples (Table 2).

2.3. Specimen preparation

Corresponding to each mix proportion in Table 2, four different kinds of temperatures (i.e., 20 °C, 200 °C, 300 °C, and 400 °C) were considered. In total, 12 groups with 36 beams were manufactured to test the shear behavior of RAC. The detailed dimension and loading arrangement of the loading beam were drawn in Fig. 2. In addition, six 150 mm cubic specimens were casted to determine the compressive strength and splitting tensile strength of RAC at 20 °C for each mixture. The testing results are shown in Table 2.

Table 2
Mix proportions of concrete.

No.	R (%)	W/C	Ingredients (kg/m^3)					f_c (MPa)	f_t (MPa)
			W	C	S	NCA	RCA		
NC	0	0.47	185	394	637	1184	0	30.34	2.14
RC50	50	0.55	217	394	637	592	592	29.45	2.09
RC100	100	0.53	209	394	637	0	1184	30.89	2.15

R = the replacement percentage of RCA, W = water, C = cement, S = sand, f_c = the compressive strength, f_t = the splitting tensile strength.

2.4. High temperature and loading test

All the beams were cured at ambient temperature for 28 days and then submitted to the test. Some beams were tested at ambient temperature and others were heated in the electric high temperature furnace type RX3-45-9 until the temperature of the entire sample rose uniformly to the target temperature. Ultimately, specimens were left cooled in the furnace until the core temperature deceased below 80 °C. After that the beams were moved to the laboratory with normal temperature. The temperature curves for different temperature conditions are shown in Fig. 3 and the beams after exposure to high temperatures are shown Fig. 4.

The strain gauges are attached to both sides of the specimen at the middle span of beam specimen along the directions of horizontal, vertical, and 45° (Fig. 2). The shear strain were acquired are required automatically in an interval of 0.5 s. The beam specimens were tested with two concentrated loads that were applied monotonically and gradually to reach a pure shear state in the middle span. The loading force and the strains at different directions were recorded by force sensors and by static strain acquisition instrument, respectively.

3. Test results

3.1. Failure pattern

Though several visible cracks appeared at the surface of the heated beams, all beams heated at high temperatures of 200 °C, 300 °C and 400 °C exhibited brittle failure pattern, the same

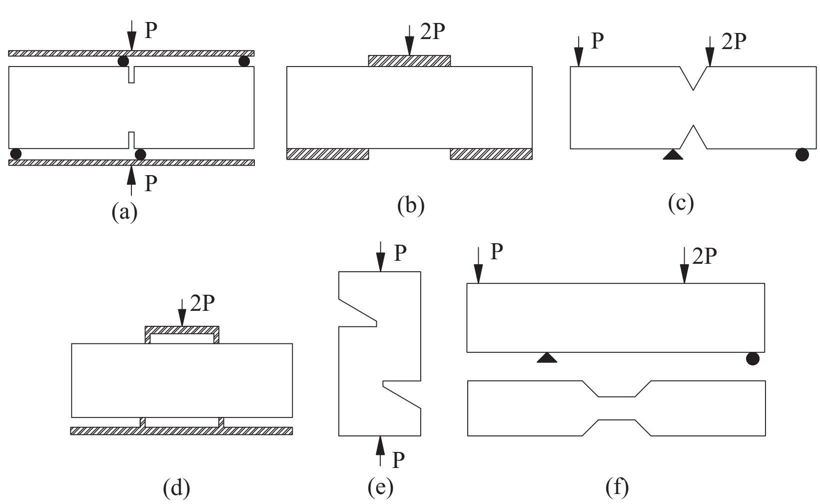

Fig. 1. Part of components used to test shear strength.

Table 1
Physical properties of coarse aggregates.

Aggregate type	Gradation (mm)	Observed Density (kg/m^3)	Bulk density (kg/m^3)	Crushed index (%)	Porosity (%)	Water absorption for 1 h (%)
NCA	5–37.5	2708	1618	4.6	40	0.3
RCA	5–37.5	2625	1523	11.6	42	2.9