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Behavior of CFRP-confined recycled aggregate concrete under axial compression

G.M. Chen [a], Y.H. He [a], T. Jiang [b,*], C.J. Lin [a]

[a] School of Civil and Transportation Engineering, Guangdong University of Technology, Guangzhou 510006, China
[b] Space Structures Research Center, Department of Civil Engineering, Zhejiang University, Hangzhou 310058, China

HIGHLIGHTS

- FRP confinement is effective for recycled aggregate concrete (RAC).
- The behavior of FRP-confined RAC is similar to FRP-confined normal concrete.
- The replacement ratio has a limited effect on the FRP confinement effectiveness.

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ABSTRACT

Over the past decade, recycled aggregate concrete (RAC) has attracted world-wide research interests due to its environmental and economic significance. However, RAC has mainly been limited to non-structural uses, largely due to the disadvantages of RAC (e.g. lower strength/stiffness, larger creep and shrinkage, poorer durability) compared to natural aggregate concrete (NAC). A possible approach of using RAC in structural compressive members is to confine RAC in a fiber reinforced polymer (FRP) jacket as the compressive performance of concrete can be significantly improved through confinement. To understand the compressive behavior FRP-confined RAC, this paper presents the results of a large number of compression tests on CFRP-confined RAC cylinders whose major test parameters are the replacement ratio of coarse aggregate and the CFRP jacket stiffness. The test results show that the replacement ratio does not have a significant effect on the FRP confinement effectiveness. The compressive behavior of FRP-confined RAC is similar to that of FRP-confined NAC and can be reasonably approximated by existing stress–strain models for FRP-confined NAC.

1. Introduction

The reusing of waste concrete as recycled concrete aggregate (RCA) to partially or totally replace natural concrete aggregate (NCA) for the production of recycled aggregate concrete (RAC) has significant environmental and economic benefits such as avoiding the depletion of natural resources and saving landfill spaces [1–4]. The research conducted on RAC in recent years covered different topics, such as mix designs for both normal strength [5] and high strength [6] RAC, short-term [7,8] and long-term properties [9] of RAC, performance of structural members with RAC [10] and effect of curing conditions on the properties of RAC [11,12], among many others. It is well known that RAC possesses two interfacial transition zones (ITZs), one is between the RCA and new mortar matrix, and the other is between the original aggregate of RCA and the old mortar attached. The old mortar of RCA, composed of many porosity and cracks [2], formed the weak link in RAC. As a result, some drawbacks of RAC compared to its natural aggregate concrete (NAC) counterpart have been identified by existing research, such as lower strength [13–15], poorer workability (due to the large water absorption of RCA) [16], larger shrinkage and creep [17,18], lower resistance to carbonation and chloride penetration [19,20]. Furthermore, the replacement ratio of coarse aggregate (referred to as the replacement ratio hereafter for brevity), which is defined as the ratio of the mass of RCA to the total mass of coarse aggregate was found to have a significant effect on the properties of RAC (e.g. strength, stiffness, creep and shrinkage) [8,21]. To date, the applications of RAC have mainly been limited to non-structural situations such as road pavement and backfilling largely due to the above mentioned shortcomings [22].

* Corresponding author.
E-mail address: cetjiang@zju.edu.cn (T. Jiang).

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Table 1
Specimen details.

Size	Replacement ratio (r) (%)	Number of CFRP plies	Specimen name
ϕ150 × 300	r = 0	0	R0C0-1,2,3
		1	R0C1-1,2,3
		2	R0C2-1,2,3
		3	R0C3-1,2,3
	r = 25	0	R25C0-1,2,3
		1	R25C1-1,2,3
		2	R25C2-1,2,3
		3	R25C3-1,2,3
	r = 50	0	R50C0-1,2,3
		1	R50C1-1,2,3
		2	R50C2-1,2,3
		3	R50C3-1,2,3
	r = 75	0	R75C0-1,2,3
		1	R75C1-1,2,3
		2	R75C2-1,2,3
		3	R75C3-1,2,3
	r = 100	0	R100C0-1,2,3
		1	R100C1-1,2,3
		2	R100C2-1,2,3
		3	R100C3-1,2,3

To explore the potential applications of RAC in structural members, various methods have been attempted to mitigate its disadvantages. It has been reported that the adverse effect of RCA on the mechanical and durability properties can be mitigated by incorporating a certain amount of mineral admixtures [23,24]. It has also been shown that the addition of fibers can improve the performance of RAC, such as the toughness of RAC [25], and the ductility and the cracking behavior of RAC after exposure to high temperatures [26]. It is well known that lateral confinement is an effective way to improve the mechanical properties of concrete. In particular, the compressive strength and the deformation ability of concrete can be significantly enhanced because the development of internal micro-cracks is restricted [27] by lateral confinement. Yang and Han [28] conducted tests on RAC confined by steel tubes subjected to either concentric or eccentric compression, and showed that the compressive performance of RAC-filled steel tubes were similar to that of normal concrete-filled steel tubes.

Concrete can also be effectively confined through fiber reinforced polymer (FRP) jacketing [29,30]. In addition to the improvement of concrete strength and ductility, extra durability can be achieved due to the excellent corrosion resistance of the FRP jacket. Nevertheless, a thorough review of existing studies reveals that only a very limited number of studies have been carried out on RAC with FRP confinement. The study by Xiao et al. [31] indicates that the compressive behavior of RAC-filled glass fiber reinforced polymer (GFRP) tubes is similar to that of NAC-filled GFRP tubes in general, with the peak load decreasing with the replacement ratio. Xiao and Huang [32] performed low frequency cyclic loading test on six RAC-filled GFRP tubes and showed that the effect of replacement ratio on the load-bearing capacity is not significant. More recently, Zhao et al. [33] conducted the first study on the compressive behavior of RAC confined with FRP wraps, in which 18 GFRP-confined concrete specimens (including 12 GFRP-confined RAC specimens) were tested. Their test results showed that the compressive behavior of FRP-confined RAC is generally similar to that of FRP-confined NAC. It should be noted that Zhao et al.'s tests only employed three replacement ratios (0%, 20% and 100%).

Against the above background, this paper presents a systematic experimental study on the compressive behavior of RAC cylinders confined by CFRP wraps, aiming to further investigate the compressive behavior of FRP-confined RAC. It should be noted that FRP wraps instead of FRP tubes were used as the confining material in the presented study for a more convenient and accurate evaluation of the effect of FRP confinement as the former purely provides confinement and does not carry axial load, although in practice the latter is probably more suitable for new construction. In total, 45 CFRP-confined concrete specimens (including 36 CFRP-confined RAC specimens) were tested. The major test parameters included the replacement ratio and the CFRP jacket stiffness. In particular, five replacement ratios were employed (0%, 25%, 50%, 75% and 100%) in the present tests for a more comprehensive assessment of the effect of the replacement ratio. The compressive behavior of CFRP-confined RAC, including the stress–strain behavior, the dilation properties and the ultimate condition is carefully investigated. The test results are also compared with the predictions of two existing stress–strain models for FRP-confined NAC to examine the applicability of such models to FRP-confined RAC. This study enriches the test database of FRP-confined RAC and contributes to the potential use of RAC as structural concrete.

2. Experimental program

2.1. Test specimens

A total of 60 concrete cylinders with a dimension of 150 mm × 300 mm (diameter by height) were prepared and tested. These cylinders were divided into five series in terms of the replacement ratio r. Each series consisted of three unconfined cylinders as control specimens and nine CFRP-confined cylinders. Three nominally identical specimens were prepared and tested for each test configuration to ensure the reliability of the test results. The naming of specimens followed the rules below: (1) the first letter R followed by a numeral represents the replacement percentage of RCA (i.e. the replacement ratio); (2) the second letter C followed by a numeral (1/2/3) defines the number of plies of CFRP; and (3) the last numeral (1/2/3) differentiates the three nominally identical specimens. For instance, R50C3-1 refers to the first of the three nominally identical specimens confined by three plies of CFRP with a replacement ratio of 50%. The details of the test specimens are summarized in Table 1.

2.2. Constituent materials

The constituent materials of concrete include: (1) cement with a strength grade of 42.5 MPa according to the data sheet provided by the material supplier; (2) naturally sourced medium-coarse river sand with an apparent density of 2580 kg/m^3 and a fineness modulus of 2.52; (3) limestone natural coarse aggregate (NCA) with a maximum size of 20 mm; (4) recycled concrete coarse aggregate with size ranging from 4 mm to 20 mm. The weight ratio of fine recycled coarse aggregate (FRCA, with aggregate size in the range between 4 mm and 8.5 mm) to coarse recycled coarse aggregate (CRCA, with aggregate sizes in the range of 10 mm and 20 mm) was 3:2. The recycled concrete aggregates (both FRCA and CRCA) were provided by a professional local company with the original concrete obtained from a single source (demolished concrete pavement in Shenzhen); and (5) naphthalene-based high efficiency water-reducing admixture with a water reducing rate of 40%. The water absorption capacity of the recycled coarse aggregates (RCAs) was tested as 4.4%.

2.3. Mix proportion

A total of five concrete mixes were designed corresponding to the five replacement ratios employed in the tests. The five concrete mixes had the same free water-to-cement ratio of 0.5 and the same