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GFRP-tube confined RAC under axial and eccentric loading with and without expansive agent

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HIGHLIGHTS

- GFRP-tube confined RAC was tested under axial and eccentric compressive load.
- Focused on RCA replacement percentage and expansive agent content.
- Strength and deformation of RAC are improved by expansive agent.
- Peak stress decreases but peak strain increases with the increase of RCA content.

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ABSTRACT

This paper presents the results of axial compression tests on recycled aggregate concrete (RAC) confined by glass fiber reinforced plastic (GFRP) tubes. The objective of this study is to evaluate the mechanical properties of GFRP-tube confined RAC under axial and eccentric compressive loading. The main parameters in the experiment are recycled coarse aggregate (RCA) replacement percentages (0%, 30%, 50%, 70% and 100%) and expansive agent contents (0%, 8% and 15%). Sixteen specimens were prepared, six specimens were tested under axial concentric compression load and ten specimens were tested under eccentric compression loading. Research findings indicate that both the RAC strength and deformation are obviously improved with the additions of expansive agent. It is also found that the peak stress of RAC confined by GFRP tubes decreases while the corresponding strain increases when the RCA replacement percentage is increased.

1. Introduction

Waste management has become vitally important since the demand for natural resources and the amount of construction and demolition waste have greatly been increased, putting a huge pressure on the environment. From the total amount of natural resources used around the world, building industry is a major consumer and a major creator of waste. It was found that construction waste constitutes around 30–40% of municipal waste, with a share of about 25–40% of global energy consumption annually (FHWA [1], Marsh [2]). Due to the reducing natural resources such as sand and gravel, preserve the environment by recycling accumulated waste materials has become not only an option, but also a necessity (Ke et al. [3]). However, the use of recycled aggregate (RA) has an important influence on concrete properties.

In comparison to natural coarse aggregate (NCA), recycled coarse aggregate (RCA) have a higher water absorption, which means more water is required for obtaining a similar concrete workability. In the past few years, a wide range of experimental studies has been carried out in searching for a solution in this problem. Tam et al. [4] proposed a two-stage mixing approach to improve the compressive strength of recycled aggregate concrete (RAC) and lower the strength variability, and Etxebarria et al. [5] studied that RCA which are used in wet condition but not saturated, can control the fresh concrete properties and the effective water to cement (w/c) ratio.

Up until now, there have been a number of researches conducting researches on RAC mechanical properties (Ke et al. [3]; Poon et al. [6]; Xiao et al. [7]). It has been investigated that, in general, the compressive strength of concrete decreases as the replacement

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of RCA increases (Kou et al. [8]). The tests carried out by Martinez-Lage et al. [9], Wesche and Schulz [10] and Hansen [11] found that the compressive strength of RAC with 100% replacement rate ranges between 70% and 100% of the parent concrete or the ordinary concrete with the same mix proportion. However, studies have also found that if the RCA content is less than 30%, the influence of the RCA replacement percentages on the compressive strength is not obvious [8,9]. When considering tensile strength of the RAC, experiments carried out by Liu et al. [12] showed that the tensile strength is reduced when the RCA content is increased, with a tensile strength of about 69–88% of the control concrete when having a complete replacement of RCA. However, unlike tensile strength, researchers have determined that there is no significant difference between the flexural strength of conventional concrete and that of RAC (Xiao et al. [13], Ryu [14] and Ravindrarajah et al. [15]). Furthermore, there has been a considerable amount of researches conducted on the RAC deformation characteristics. These have been concluded that the elastic modulus of RAC, when natural aggregate (NA) are entirely replaced by RCA, is about 60–80% of the original concrete's strength (Xiao et al. [7], Kou et al. [11], Paine Kevin et al. [16] and Hao et al. [17]). Due to the reduced elastic modulus from RAC, a larger deformation is given, and in consequence, it has been determined that the peak strain increases as the RCA content increases.

Confinement has found to be an effective method to improve the RAC mechanical properties. Fam et al. [18] determined that the axial compressive strength and deformation performance are improved because the extension of internal micro-cracks is restricted in confinement. Moreover, the outer tube also limits the shrinkage of core concrete. Due to confinement, the core concrete has no moisture exchange with the surroundings. Since the shrinkage and moisture exchange are limited, the creep of confined concrete is also smaller than that of the ordinary concrete [19–22]. In addition to confinement, another method to improve the mechanical properties is with the additions of additives, such as expansive agents. When using expansive agents, the concrete volume increases during the curing stage [23,24]; and if it properly elastically restrained, induces compressive stresses that counteract the tendency of drying shrinkage for inducing tensile stresses [25,26]. Nevertheless, under confinement, the core concrete has no moisture exchange with the surroundings and the outer tube limits the core concrete shrinkage, which diminishes the effect of expansive agent when used under confinement.

Unlike many other researchers which focus on steel confining tubes, this paper investigates the mechanical properties of RAC confined by GFRP tubes. Researches on confined RAC and the use of GFRP tubes as confining material are relatively new research areas. One of the few researches, Xiao et al. [27] performed the comparison on the confinement using steel tubes and GFRP tubes. It was determined that the peak load of RAC confined by GFRP tubes is lower than that of RAC confined by steel tubes, due to the fact that the hoop tensile strength of GFRP tubes is lower than the yield strength of steel tubes. Nevertheless, such as steel tubes, when using GFRP tubes, the peak load decreases as the RCA replacement percentage increases.

2. Experimental investigation

2.1. Materials

The cement used in this study was ordinary Portland cement 42.5R. A fourth generation ZY high performance concrete expansive agent was used and mixing water was tap water. All concrete mixes were provided with a constant water–cement ratio of 0.43. Due to the high water absorption rates, the used RCA was presoaked before mixing. The water amount used to presoak the RCA was calculated according to the water absorption of RCA. Each RAC specimen has the same mixture proportion, i.e. Cement: Sand: Coarse aggregate: Water = 430:559:1118:185. When using expansive agent, the same amount of cement was replaced. The RCA was provided by a Shanghai local plant, and was composed of 5–16.5 mm and 16.5–31.5 mm diameter coarse aggregate sizes with a mix ratio of these two sizes of 3:2. The natural coarse aggregate (NCA) was crushed stone with continues grading. Table 1 provides the basic properties of the two types of RCA used.

GFRP is a fiber-reinforced polymer made from plastic matrix reinforced by fine fibers of glass. The tubes used had a thickness of 5 mm, outer diameter of 210 mm and height of 1000 mm. All the GFRP tubes used had the same fiber orientation with an angle of around 30°. The average hoop and axial strength of the GFRP tubes was 350 N/mm^2 and 68 N/mm^2 respectively. These had a hoop elastic modulus of 22 GPa and a longitudinal modulus of 2.1 GPa. These strengths were given by the manufacturer of GFRP tubes and not tested on the laboratory.

According to the Chinese Standard GB/T50081-2002, compressive strength was measured from RAC cubes of $150 \times 150 \times 150$ mm^3. The 28-day cube compressive strengths of the 12 types of concrete were tested on the same day and are presented in Table 2. Taking for example the specimen of RC-30-8, RC represents recycled concrete, with a 30% replacement percentage of RCA in mass, with an 8% of expansive agent content.

2.2. Mixing and specimens design

When preparing the concrete mixtures, cement, expansive agent and 1/3 of water were first added into the mixer and stirred for about 1 min to ensure the ingredients are evenly mixed and the expansive agent can be thoroughly taking effects to the aggregate when added. The aggregate and another 1/3 of the water were then added into the mixer and the whole mix was stirred for about 2 min. Finally the remaining 1/3 of water was added into the mixer and the whole mix was stirred for about 2–3 min.

Before pouring the concrete into the tubes, the consistency was measured by the Abrams cone method. When pouring the concrete into the GFRP tubes, concrete was firstly poured until about 500 mm depth and vibrated with a plug-in vibrator for about 2 min. Then concrete was poured to the top of the tubes and vibrated for another 2 min. The specimens were kept indoors, laying a blanket on top, and sprinkled regularly. It was noticed some small amount of longitudinal shrinkage occurred on the top of specimens before testing, mortar was used to fill in this gap before testing. Furthermore, for those specimens without expansive agent, some radial shrinkage was found, which mitigates the effect of confinement and produces a negative effect on the specimens' strength.

In total, 16 specimens were created, from which 6 were tested under axial concentric compression load, and 10 were tested under eccentric compression load with an eccentric distance from the center of $e = 40$ mm. The specimens created are shown in Table 3, where, for example, the specimen RCFF-30-8-e, represents recycled concrete filled in GFRP tubes (RCFF), with a 30% RCA replacement percentages, with an 8% of expansive agent content and tested under an eccentricity of 40 mm.

2.3. Test setup and testing method

The load was applied to the top of specimens by a 500-ton hydraulic jack. Six strain gauges (four longitudinal and two transverse) and nine strain gauges (six longitudinal and three transverse) were used for axial compression load and for eccentric compression load respectively (see Figs. 1 and 2 respectively). The transverse strain gauges were used for measuring the hoop strain. All of them were located at L/2.

For axial load testing, the vertical displacement in opposite sides of the specimen was calculated with two deflectometers. When testing under eccentricity, three deflectometers were located at L/4, L/2 and 3L/4 for measuring the lateral deflection of specimens.

2.4. Loading program

The hydraulic jack was connected to specimens through a metal plate when loading, through which the vertical load was applied, in order to avoid direct loading of GFRP tubes. A multi-stage loading method was used when testing. Initially, the load intervals were of about 1/10–1/15 with the estimated peak load N_{max}. Once the applied load was $0.5 \cdot N_{max,}$ the loading intervals were of about 1/20–1/25 N_{max}. Load intervals were maintained for approximately 2 min. After the applied load had finally exceeded $0.8 \cdot N_{max}$, a slow continuous loading was carried out.

Before the loading, a preloading stage was carried out. Each specimen was preloaded with a load of 10% of the estimated peak load for avoiding stress concentration and reducing the effect of looseness and unevenness on both sides of specimens.

2.5. Test phenomenon

For the six specimens tested under axial concentric load, at early loading stages, the deformation was insignificant. However, when the applied load was about 65–75% $N_{max,}$ the GFRP tubes began to get a white color. At the same moment, cracking was heard, but not yet seen in the surface of the tubes. When the load applied was about 80–90% of N_{max}, some white cracks started to be seen on the surface of tubes,