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Behavior of flax FRP tube encased recycled aggregate concrete with clay brick aggregate

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HIGHLIGHTS

- Recycled aggregates from old concrete and from clay bricks were used for concrete.
- Flax FRP confinement is effective for recycled aggregate concrete (RAC).
- The behavior of flax FRP confined RAC is different from the confined natural aggregate concrete.

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ABSTRACT

The combined use of environmentally-friendly plant-based natural fibre reinforced polymer (FRP) composites and recycled aggregate concrete (RAC) will be beneficial for the development of sustainable concrete. In literature, a large amount of research has been conducted on unconfined RAC where the recycled aggregates (RAs) mainly came from concrete rubble, but the use of RAs from masonry rubble for RAC is very rare. This study reported the compressive behavior of flax FRP tube encased RAC containing partially clay brick aggregate (CBA), which was termed as FFRP-rAC-CBA. For the RAC, up to 70% of natural coarse aggregates was replaced by recycled aggregates (RAs). The RAs consisted mainly of 60% of recycled clay brick aggregates and 40% of recycled concrete and mortar aggregates. A total of 36 cylindrical specimens including 24 FFRP-rAC-CBA and 12 unconfined rAC-CBA were tested under uni-axial compression. The testing variables included: (i) strength of rAC-CBA (i.e. 27.5 MPa and 32.8 MPa); (ii) thickness of FFRP tube (i.e. 3, 6, 9 and 12 FRP layers); and (iii) size of cylinder (i.e. 75 × 150, 150 × 300 and 300 × 600, unit of mm). Tests results indicated that the natural FFRP tube enhanced the ultimate strength and ductility of the confined rAC-CBA remarkably and the enhancement was more pronounced in specimens with higher concrete strength. Increasing FFRP thickness led to higher compressive stress and strain of the FFRP-rAC-CBA. In addition, stress and strain models were proposed to predict and compare with experimental results of FFRP-rAC-CBA. A size-dependent model was also used to predict the transitional strength and ultimate strength of FFRP-rAC-CBA.

1. Introduction

In recent years, recycled aggregate concrete (RAC) has been widely investigated due to its social, environmental, and economic significance [1–7]. Recycled aggregates (RAs) were mostly crushed and sorted from demolished building wastes. The International Union of Laboratories and Experts in Construction Materials Systems and Structures (RILEM) classified RAs into three major types: (a) aggregates that are implicitly understood to originate primarily from masonry rubble; (b) aggregates that are implicitly understood to originate primarily from concrete rubble; and (c) aggregates that are implicitly understood to consist of a blend of recycled aggregates and natural aggregates [8]. For the first type of RAs originating primarily from masonry rubble, the RAs containing clay brick aggregate (CBA) has potential of being the most widely used RAs because of the considerable amount of clay brick waste generated in many countries. For example, brick masonry buildings have been extensively constructed in China and the amount of brick

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wastes generated in the urbanization is increasing in a geometric progression. How to dispose these wastes effectively becomes a thorny problem in the worldwide.

Recycled aggregate concrete (RAC) is an environmentally-friendly concrete in which a part or all of the natural aggregates (NAs) is replaced by RAs. At present, RAC is mainly used in unbound applications for road base, back fillings rather than for in new structural concrete due to its relatively poor mechanical properties compared with that of natural aggregate concrete (NAC) [9]. Since old mortar attached to the recycled aggregates, it caused the poor mechanical properties such as reduction in compressive strength and stiffness [10], increase of peak strain and enlarged creep and shrinkage [11,12] of RAC. Poon et al. [13] reported that replacing NAs with 25% and 50% of bricks and blocks had insignificant effect on the compressive strength of concrete but higher levels of replacements of bricks and blocks reduced the compressive strength significantly. Debieb and Kenai [14] investigated CBA as both fine and coarse aggregates of RAC and found that the decrease in compressive strength was about 35%, 30% and 40%, respectively, when the coarse, fine, and both fine and coarse aggregates were fully replaced by CBA. The corresponding reduction in modulus of elasticity was 30%, 40% and 50% and that in flexural strength was 33%, 36% and 46%, respectively. Given on these poor mechanical properties, the application of RAC containing CBA (rAC-CBA), especially in structural concrete, is rare. Thus, the mechanical properties of rAC-CBA should be improved if being used in structural concrete considering the environmental benefit by preserving NAs resources and by waste reduction, i.e. preserving the landfill space.

It has been widely accepted that confined concrete is an effective way to improve mechanical properties of concrete [15–18]. In the literature, the studies of synthetic fibre reinforced polymer (FRP) confined natural aggregate concrete were documented well [19–22]. In recent, there is an increasing trend to study synthetic FRP confined RAC, i.e. Islam et al. [23] and Xiao et al. [24] explored RAC confined with carbon FRP and glass FRP tubes, respectively. The studies [23,24] demonstrated that the glass/carbon FRP tube confinement caused great enhancement in compressive behavior of RAC. However, the considered recycled aggregates used for RAC in these studies came from demolished concrete components; the use of RAC with CBA was not reported in the literature. Most recently, using natural fibres to replace synthetic fibres has been studied increasingly due to an increasing the environmental impact of using natural fibres [25–28]. Because of the best potential combination of low cost, light weight, and high strength and stiffness for structural applications, amongst natural fibres, flax fibre is one of the most-widely studied [29,30] and flax FRP (FFRP) composites have been used as confinement and external strengthening materials of concrete components. Previous studies [31–33] showed good performance of FFRP tube confined coir fibre reinforced concrete as flexural and axial structural members. In hammer-induced vibrations, the FFRP tube increased the damping characteristics of the confined concrete remarkably, thus reduced the effect of dynamic loadings on the structural response, showing the potential of FFRP tube confined concrete as earthquake-resistant structure [34]. This FFRP tube confined concrete also showed better structural performance (i.e. energy dissipation and load carrying capabilities) than the conventional RC counterparts [35]. Comparisons with glass and carbon FRP tube confined concrete indicated that the confinement performance of natural FFRP tube on concrete is comparable to that provided by the G/CFRP tube [36]. As external strengthening materials, flax FRP plates enhanced the lateral carrying capacity and ductility of the tube confined concrete cylinders and steel reinforced concrete beams remarkably [37,38]. In conventional RC structure, ductility is defined as the ratio of the maximum yield deformation to the deformation at the elastic limit and the ductility comes from steel rebar. For FFRP tube confined concrete, this ductility definition is not appropriate because FFRP composite materials are approximately elastic up to failure without yielding characteristic. Therefore, the *ductility of FFRP tube confined concrete* is defined as the ratio of the axial strain at ultimate strength of confined concrete to that at peak stress of the unconfined concrete [34], which will also be used in current study. Durability studies also indicated that flax FRP composites have potential to be durable construction and building materials with a proper surface treatment [39,40]. Therefore, natural flax FRP can be also used to improve the mechanical properties of RAC with CBA.

In this study, natural flax FRP tube encased recycled aggregate concrete containing clay brick aggregate (termed as FFRP-rAC-CBA) was investigated for the first time as axial structural component. The combined use of natural flax fibre from agricultural waste and the recycled aggregate concrete with recycled clay brick aggregate from demolition waste will be beneficial for the development of new structural concrete with sustainability and low carbon footprint. In literature, most experimental studies on FRP confined natural aggregate concrete used small-scale specimens with a diameter of 150 mm and a height of 300 mm of the concrete. It was reported that the analytical studies of FRP confined natural aggregate concrete generally did not take the size effect into account that have been demonstrated distinct influence on concrete and confined concrete [41]. Hence, the size effect of FFRP-rAC-CBA was also considered. The compressive behavior of FFRP-rAC-CBA was investigated considering following parameters: (1) the strength of the RAC; (2) the number of FFRP layers; and (3) the size of the cylinders. In addition, confinement models were proposed to predict and compare with the experimental results. The size-dependent model proposed by Wang and Wu [42] was used to predict the transitional strength (i.e. defined as the strength at transitional point in the axial compressive stress-strain curve) and ultimate strength (i.e. defined as the strength at ultimate point in the axial compressive stress-strain curve) of FFRP-rAC-CBA.

2. Experimental program

2.1. Test specimens

A total of 36 cylindrical specimens (i.e., 24 confined cylinders and 12 unconfined cylinders) were prepared for the axial compression test. The considered parameters were: (1) the strength of the RAC (i.e. 27.5 MPa and 32.8 MPa), (2) the number of FFRP layers (i.e. 3, 6, 9 and 12 layers), and (3) the size of the cylinders (i.e. 75 × 150, 150 × 300 and 300 × 600, unit of mm). Specimens were classified and labelled by three sets of characters as follows: the first set indicated the type and the strength of the concrete (i.e., RC indicated RAC with CBA; and 2 and 3 indicated 27.5 MPa and 32.8 MPa of the concrete, respectively); and the second set of characters indicated the number of FFRP layers (i.e., F0, F3, F6, F9 and F12 indicated zero, three, six, nine and twelve layers, respectively); and the third set of characters indicated the size of cylinders (i.e., S, M and L indicated small, medium and large size, respectively). The dimensions of the S, M and L concrete specimens were 75 mm, 150 mm and 300 mm in diameter respectively, the slenderness ratio was equal to 2. For FRP confined concrete, the theoretical confining pressure attributed to FRP is defined as $f_l = 2f_{frp}t_f/D$, where f_{frp} is the FRP tensile strength. D and h are diameter and height of specimens, respectively; n_f and t_f are the number of FFRP layers and thickness of FFRP tubes, respectively. To have the same level of confinement (f_l, *MPa*), the number of FFRP layers (n_f) calculated for the small, medium and large-sized FFRP tube confined concrete