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Abstract

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Compressive Behaviour of FRP-Confined Rubber Concrete

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Abstract: Extensive research has been conducted on the use of tyre-derived products (e.g. rubber crumb and granule) to replace aggregates in producing concrete (i.e. rubber concrete). However, rubber concrete has so far been mainly limited to non-structural applications due to its well-known disadvantages including the relatively low stiffness and strength as well as early cracking as a result of lack of proper bonding between rubber and the paste matrix. The weaknesses of rubber concrete may be minimised in a hybrid column through lateral confinement by a fibre-reinforced polymer (FRP) tube and longitudinal reinforcement by steel or FRP. This paper presents an experimental study on FRP-confined rubber concrete (FCRC), which covers a large range of replacement ratio (0-75% by volume) of fine aggregates and three thicknesses of FRP. The test results confirmed the effectiveness of FRP confinement in improving the axial behaviour of rubber concrete, and clarified the effects of the two important parameters (i.e. replacement ratio of fine aggregates and FRP thickness). The test results also show that the behaviour of FCRC can be significantly different from that of FRP-confined natural aggregate concrete (NAC) with the same unconfined strength and confinement stiffness. By the inclusion of a simple coefficient to consider the effects of rubber aggregates, the existing models for FRP-confined NAC can be modified to provide reasonable prediction of the test results of FCRC.

Keywords: rubber concrete; FRP; end-of-life tyre; crumb rubber; recycled aggregate; confinement

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1 INTRODUCTION

Appropriate disposal of end-of-life (waste) tyres has become a worldwide challenge. Taking the situation in Australia as an example, the number of waste tyres in Australia has been largely increased from the 2007-2008 financial year to the 2013-2014 financial year with an average annual growth rate of around 18.5% [1].

In the last three decades, the use of tyre-derived products (e.g. rubber crumb and granule) to replace or partially replace natural aggregates in producing concrete (i.e., rubber concrete) has attracted an increasing attention [2-8]. The use of rubber concrete in construction can reduce the dependency on natural resources (e.g. mineral aggregates), leading to an environmentally sustainable construction. It has been found in the existing studies that the replacement of natural aggregates with tyre rubber in producing concrete can lead to a reduced compressive strength (e.g. [3]); the percentage of strength reduction compared with natural aggregate concrete (referred to as NAC for simplicity) is dependent on the replacement ratio and grading of the rubber aggregates, and can be up to 85%. Based on their test results, some studies [2, 3, 5, 8] concluded that: (1) the replacement ratio of aggregates in rubber concrete should not exceed 10% of the total aggregates by volume (hereafter in this paper, the replacement ratio is by volume unless otherwise specified), to avoid/mitigate the detrimental effect on the strength of the rubber concrete; and (2) compared with the use of tyre rubber chips (with a size between 10 mm and 76 mm) to replace coarse aggregates, the use of crumb rubber (with a size between 0.425 mm and 4.75 mm) to replace fine aggregates can lead to a smaller reduction in the concrete strength, when the same replacement ratio is adopted. It is interesting to note that some other studies [9, 10] reported a small increase in the strength of rubber concrete when the replacement ratio of aggregates with rubber particles was relatively low (e.g. less than 2.5% of total aggregates), which could be attributed to the optimised grading of aggregates of so-produced rubber concrete. In addition to a reduced strength, rubber concrete has also been reported to have a lower elastic modulus and higher water permeability than its NAC counterpart [3, 11]. Another important issue with rubber concrete is the early cracking within the concrete due to the lack of proper bonding between the rubber and the paste matrix [9]. Due to the above demerits of rubber concrete, it has so far been mainly limited to non-structural applications in practice (e.g. land-fills, road bases).

It has been well known that the use of fibre-reinforced polymer (FRP) composites as an external confinement device to reinforced concrete (RC) members can improve both the axial strength and deformation capacity of the members [12, 13]. Naturally, it may be expected that the use of FRP composites for the confinement of rubber concrete has similar effects. Capitalizing on this confining effect, the weaknesses of rubber concrete, as mentioned above, may be minimized when being used together with an FRP confining tube. Therefore, the resulting FRP-confined rubber concrete (referred to as FCRC hereafter for simplicity) columns, provided with additional longitudinal reinforcement, have great potential to facilitate the wide structural applications of rubber concrete. In such FCRC columns, the FRP tube also serves as a protective skin against corrosion and a stay-in-place form for casting concrete, leading to excellent durability and a reduced construction cost. The FCRC columns are therefore an attractive alternative to traditional RC bridge piers and piles in harsh environments.

Youssf et al. [10] compared the behaviour between FRP-confined NAC and FCRC, and found that the enhancement of the compressive strength of rubber concrete (with a replacement ratio of total aggregates being 7%) caused by the FRP confinement was approximately 30% higher than that of the corresponding FRP-confined NAC, and the strength reduction of FCRC caused by the replacement of aggregates with crumb rubber was approximately 50% lower than that of unconfined rubber concrete with the same replacement ratio. Li et al. [14] conducted four tests on FCRC cylinders and reported that FCRC has higher confinement effectiveness and ductility than the corresponding FRP-confined NAC. In the preparation of the present paper, two more studies were published [15, 16] on FCRC, indicating the increasing research interests on this topic. In Ref. [15], Youssf et al. presented a series of compression tests in which rubber concrete with a single replacement ratio was confined by carbon FRP; Raffoul et al. [16] also presented compression tests on six FCRC cylinders with a single replacement ratio. Both of the two recent studies [15, 16] have again demonstrated the beneficial effects of FRP confinement on the behaviour of rubber concrete.

This paper presents the first systematic experimental study on FCRC cylinders with a large range of replacement ratios (i.e. 0%, 12.5%, 25%, 50% and 75%). In the experimental study, glass FRP (GFRP) was used due to its lower cost and larger rupture strain which make it a more suitable confining material than carbon FRP. The hoop-to-axial strain behaviour of FCRC cylinders were examined in detail, as it is the key to understand the behaviour of passively-confined concrete such as FCRC [12, 13]. Comparisons between the test results and the

predictions of two analysis-orientated models for FRP-confined NAC are also presented in this paper.

2 EXPERIMENTAL PROGRAM

2.1 Test Specimens

In total, 15 unconfined rubber concrete (referred to as URC hereafter for simplicity) cylinders and 14 FCRC cylinders were prepared and tested under concentric compression, covering four replacement ratios of fine aggregates R_f (i.e., 0%, 12.5%, 25%, 50% and 75%) and three thicknesses of FRP wrap (i.e., 2, 4 and 6 plies). All specimens had a nominal diameter of 150 mm (diameter of concrete core) and a height of 300 mm. The details of both confined and unconfined specimens are summarised in Table 1, where the replacement ratios of fine aggregates by volume, R_f , and the replacement ratios of total aggregates (including both fine and coarse aggregates) by volume, R_t , are also given.

For unconfined specimens, each specimen is given a name, which starts with a letter 'U', followed by an Arabic numeral to represent the R_f (e.g. 50 strands for an R_f of 50%), and then a Roman numeral to differentiate the three nominally identical specimens for each R_f value. For FRP-confined specimens, the name of each specimen starts with a letter 'C', followed by an Arabic numeral to represent the R_f value, and then another Arabic numeral to represent the number of plies of the FRP composite (2, 4 or 6 plies), and finally a Roman numeral to differentiate nominally identical specimens. For example, Specimen C-50-2-I refers to the first specimen of the two FCRC specimens that had an R_f value of 50% and a two-ply FRP wrap.

2.2 Material Properties

2.2.1 Density of crumb rubber and fine aggregates

The crumb rubber used in the present study was recycled from waste passenger car tyres provided by an Australian supplier. A photo of the crumb rubber is shown in Fig. 1. The density of fine aggregates, obtained by adopting the standard method recommended in AS1289.3.5.1 [17], was found to be 2580 kg/m³. The density of the rubber is usually smaller than that of the water (e.g. [18]) and thus AS1289.3.5.1 [17] is not applicable. Therefore, to determine the density of the crumb rubber used in the present study, a special approach was proposed and adopted, which consists of the following steps: (1) fill a clean container with tap water halfway

and submerge a sieve with fine holes into the water; (2) record the volume of the water with the fully submerged sieve, V_1 ; (3) weigh the crumb rubber, M , and then submerge the crumb rubber into the water, using the sieve to avoid floating of the rubber; (4) record the volume of the water with the fully submerged sieve and crumb rubber, V_2 ; (5) the density of the crumb rubber is then calculated by dividing the mass of the rubber by the volume difference, i.e., $M/(V_2 - V_1)$. It should be noted that this method was based on an assumption that the crumb rubber does not absorb water [19]. The above procedure was repeated to measure the density of crumb rubber with a mass of 100 g, 150 g, 200 g and 250 g respectively, and the average density of the crumb rubber obtained is 870 kg/m³. With the densities of the crumb rubber and the fine aggregate, the replacement of fine aggregates with crumb rubber for a certain replacement ratio by volume can be easily implemented using the density ratio between the fine aggregates and rubber, which is approximately 3 (i.e., 2580/870=2.97).

2.2.2 Concrete mix design

Sieving tests were first conducted for both natural aggregates and rubber aggregates used in the concrete mixes, according to AS 3638 [20]. In the present study, crushed dolomite stones with nominal sizes of 10 mm and 20 mm were used as coarse aggregates, and river sands with a nominal size of 5 mm were used as fine aggregate. The obtained cumulative percent retained versus nominal aperture size of the test sieve curves for all aggregates used in the present study are plotted in Fig. 2a, in which the cumulative percent retained was the value averaged from three repeated standard tests for each aggregate. The cumulative percent retained versus nominal aperture size of the test sieve curves for the combined aggregates used in casting concrete with different replacement ratios are plotted in Fig. 2b. It is evident from Fig. 2b that the grading of aggregates can be significantly affected by the R_f value, particularly for the range of nominal aperture size between 0.15 mm and 2.36 mm. For comparison purpose, the four cumulative percent retained versus nominal aperture size of the test sieve curves of aggregates, which have been proven to represent the ideal grading of aggregates for concrete mixture [21], are also plotted in Fig. 2b. As can be seen from Fig. 2b, the grading of aggregates used in the present study with R_f values of 0, 12.5%, 25% and 50%, respectively, are well enveloped by the four ideal curves, while for aggregates with an R_f of 75%, a small portion of the curve (with the nominal aperture size between 0.15 mm and 2.36 mm) is outside the region enveloped by the four ideal curves.

The concrete mixture design is shown in Table 2. In order to reduce the slump loss caused by the replacement of fine aggregates with crumb rubber, superplasticizer was used in casting the concrete.

2.2.3 FRP composites

The fibre sheets used in this study consist of glass fibres oriented in two directions: 90% of the fibres are oriented in the major direction, which was aligned with the hoop direction when making the fabricated FRP tubes, while the remaining 10% oriented in the minor direction, which was aligned with the longitudinal direction when making the fabricated FRP tubes. In the present study, tensile tests on five flat GFRP coupons were conducted according to ASTM D3039/D3039M [22]. The test region of the FRP coupons had a width of 25 mm and a length of 250 mm respectively. Three strain gauges with a gauge length of 20 mm were installed at the mid-length of the test region to measure the axial strains of the FRP; two of the strain gauges were on one side and the other one on the other side. The obtained average tensile strength and elastic modulus of the GFRP coupons in the longitudinal direction were 1490 MPa and 74.0 GPa respectively, based on a nominal FRP thickness of 0.174 mm.

2.3 Preparation of Specimens

To the authors' best knowledge, there is no standard method/procedure for casting rubber concrete. As a result, in the present study, the rubber concrete was casted using the procedure recommended by AS1012.2 [23] for normal concrete. The test specimens were prepared using the following steps: (1) put cement and all aggregates into a concrete mixer and stir them for around 2 minutes; (2) add water and superplasticiser into the fully mixed cement and aggregates and stir the mixture for another 2 minutes; (3) after 2 minutes' resting, stir the mixture for another 2 minutes and then pour the mixture into the steel formwork (circular steel tubes), with a tamping rod and a rubber mallet used to squeeze out the air bubbles in the wet concrete; (4) after 14 days' curing, the glass fibre sheets were wrapped onto the hardened concrete cylinders through a wet lay-up process using the adhesive recommended by the manufacturer; the length of overlapping zone was 150 mm, which is approximately 1/3 of the circumference of the concrete cylinder (see Fig. 3a).

2.4 Test Set-Up and Instrumentation

The axial deformation of FCRC specimens was measured using two pairs of linear variable differential transformers (LVDTs): (1) one pair (LVDT-A1 and LVDT-A2 shown in Fig. 3b), placed 180° apart from each other, were used to measure the overall shortening of the

specimens; and (2) another pair (LVDT-B1 and LVDT-B2 shown in Fig. 3b), placed 180° apart from each other, were installed to measure the deformation of the 105 mm (i.e. approximately 1/3 height of the specimens) mid-height region of the specimens. The layout of the LVDTs is shown in Fig. 3b. In addition, two axial strain gauges (i.e., A1 and A2 shown in Fig. 3a) with a gauge length of 20 mm were attached on the outer surface of FRP wrap at the mid-height of the specimen, and three hoop strain gauges (i.e., H1, H2 and H3 shown in Fig. 3a) were installed along the circumference at the mid-height of the specimen outside the overlapping zone.

All specimens were tested under concentric axial compression at the University of Wollongong, Australia using a 500-tonne Avery Compression Testing Machine. The test setup is shown in Fig. 3b, and the load was applied through displacement control with a rate of 0.3 mm per minute. To ensure uniform loading across the specimen section, the top and bottom ends of the specimens were capped with gypsum plaster, and two thick steel plates (as shown in Fig. 3b) were used to transfer the load onto the specimen.

3 EXPERIMENTAL OBSERVATIONS AND RESULTS

3.1 Failure Mode

The failure modes of unconfined specimens and FRP-confined specimens are shown in Fig. 4 and Fig. 5 respectively. It can be seen from Fig. 4 that there are no significant differences in the failure mode between NAC and URC. As can be seen from Fig. 5, the FCRC specimens failed by explosive rupture of FRP in the hoop direction, which was associated with loud noises. The rupture of FRP generally happened near the mid-height for FRP-confined specimens with an R_f of less than 75% (Figs. 5a-d), while the rupture of FRP happened near one of the two ends for the specimens with an R_f of 75% (Fig. 5e).

3.2 Stress-Strain Behaviour

In the present study, unless otherwise specified, the axial strains used in plotting the axial stress-strain curves were obtained from the average reading of the two LVDTs (LVDT-B1 and LVDT-B2, as shown in Fig. 3b) covering the 105 mm mid-height region of the specimen. The so-obtained axial strains are generally similar to the readings from the axial strain gauges (A1 and A2), especially in the initial stage of loading, and do not suffer from more localised

deformation in the later stage of loading which may not be captured by the strain gauges with a gauge length of 20 mm.

A comparison of typical axial stress-axial strain curves between FCRC specimens and the corresponding URC specimens is shown in Fig. 6, while the axial stress-strain curves of all confined specimens with a 4-ply FRP wrap are shown in Fig. 7a. Similar to FRP-confined NAC, due to the confinement effect from the FRP wrap, both the axial strength and the ultimate axial strain of the rubber concrete were significantly improved, as shown in Fig. 6. It can also be seen from Fig. 6 that before the peak stress of URC specimen (i.e., U-12.5-I), the axial stress-axial strain curve of the FCRC specimen (i.e., C-12.5-4-I) generally coincides with that of the URC specimen. Afterwards, the axial stress of the URC specimen drops significantly, while the axial stress of the FCRC specimen increases linearly with the axial strain until rupture of the FRP wrap. This indicates that the confinement effect from the FRP wrap in FCRC specimens was not activated when the axial stress is lower than the axial strength of the corresponding URC specimens. From Fig. 7a, it can be seen that the axial stress-strain curves of all FRP-confined specimens have two ascending branches which are connected by a smooth transition region, and the slope of the second ascending branch is much smaller than that of the first one. It can also be seen from Fig. 7a that the second branch of the axial stress-strain curves has a gradually decreasing slope. The thickness of FRP wrap has a significant effect on the axial stress-strain curve, as shown in Fig. 7b. A thicker FRP wrap leads to a larger slope of the second ascending branch of the axial stress-strain curve, a higher compressive strength and a larger ultimate axial strain. All the above observations are similar to what have been widely reported for FRP-confined NAC (e.g. [12, 24]). The hoop rupture strain of GFRP was found to be generally in the range of 1.5-2% for all the specimens, which is also consistent with the values widely reported for GFRP-confined NAC (e.g. [25-28]).

The axial stress and axial strain of the FCRC specimens with a 4-ply FRP wrap are normalised with respect to the unconfined compressive strength and axial strain at peak stress of unconfined concrete strength, respectively, as plotted in Fig. 8. It is evident from Fig. 8 that the first ascending branches of the normalised axial stress versus strain curves of all specimens nearly coincide with each other, while the slope of the second branch of the curves is dependent on the R_f . When the R_f is relatively low (i.e., 0%, 12.5% or 25%), the normalised axial stress versus strain curves of FCRC specimens have only a slightly higher second ascending branch than their FRP-confined NAC counterparts. The difference between the curves of FCRCs and FRP-confined NAC becomes much more evident when the R_f is relatively high (e.g. 75%). The above observations suggest that the FRP confinement is more efficient for rubber concrete with a high R_f value, which is at least partially due to the fact that such rubber concrete has a relatively low unconfined concrete strength (the unconfined concrete strength of specimens with a R_f value of 75% is only around 25% the strength of the concrete without rubber aggregates).

3.3 Compressive Strength and Ultimate Axial Strain

3.3.1 URC specimens

The key test results of URC specimens are summarised in Table 3. It can be seen from Table 3 that when the R_f increases from 0% to 12.5%, 25%, 50% and 75%, the average compressive strength f'_{co} of the URC specimens decreases from 53.0 MPa to 48.8 MPa, 42.1 MPa, 33.2 MPa and 13.9 MPa, respectively, corresponding to a reduction percentage of 7.91%, 20.6%, 37.4% and 74.3%, respectively. The average axial strain ϵ_{co} at the peak stress of the URC specimens gradually decreases from 0.270% to 0.221% when the R_f increases from 0% to 50%, but increased to 0.265% again when the R_f reaches 75%.

3.3.2 FCRC specimens

The key test results of FCRC specimens are summarised in Table 4. It is evident from Tables 3 and 4 that, when an FRP wrap is used to confine rubber concrete, both the axial strength and the axial deformation capacity of the rubber concrete can be significantly improved. The reduction percentages of the axial strength of the FCRC specimens due to the replacement of fine aggregates with rubber crumb are significantly smaller than those of the corresponding URC specimens.

It can be seen from Table 4 that, for FCRC specimens with a 4-ply FRP wrap, when the R_f increased from 0 % to 75 %, the ratio between the average compressive strength f_{cc} of FCRC

specimens and f'_{co} of the corresponding URC specimens increased from 1.37 to 2.46. Table 4 also shows that the average rupture strain $\varepsilon_{rup,frp}$ of FRP wrap of FCRC specimens in the hoop direction slightly decreases with R_f , but the ratio between the average ultimate axial strain ε_{cc} of FCRC specimens and the average strain ε_{co} at the peak stress of corresponding URC specimens increases with R_f . This observation suggests that the expansion of rubber concrete, especially that with a larger replacement ratio, is smaller than that of NAC for the same axial strain, which is at least partially due to the smaller unconfined strength of rubber concrete.

The average compressive strengths of the URC specimens and FCRC specimens with a 4-ply FRP wrap are plotted in Fig. 9 with respect to the replacement ratio of fine aggregates. It can be seen from the Fig. 9 that the compressive strengths of both URC specimens and FCRC specimens decrease nearly linearly with the replacement ratio of fine aggregates. Furthermore, the difference in the compressive strength of the FCRC specimens and the corresponding URC specimens with various R_f values are nearly constant, which means the value of R_f has a marginal effect on the absolute strength increase caused by the confinement from the FRP wrap. For comparison purpose, the compressive strengths, predicted by the stress-strain model proposed by Jiang and Teng [24] for FRP-confined NAC, are also plotted in Fig. 9. It can be seen from Fig. 9 that Jiang and Teng's model [24] overestimates the compressive strength of FCRC specimens, and the difference between the prediction and the test result increases with R_f . It is worth noting that Jiang and Teng's model [24] also slightly overestimates the FRP-confined NAC specimens (i.e. specimen with $R_f = 0$) tested in the present study, as shown in Fig. 9.

3.4 Hoop-Axial Strain Behaviour of FCRC

The hoop-axial strain curves of the FCRC specimens with a 4-ply FRP wrap are plotted in Fig. 10a. It is evident that the hoop-axial strain curves of FCRC specimens with an R_f equal or less than 50% are generally close to each other, while the hoop-axial strain curves of the two FCRC specimens with an R_f of 75% diverge from other curves. At the same axial strain, the absolute value of the hoop strain of the FCRC specimens with an R_f of 75% is significantly smaller than that of other specimens. This is believed to be at least partially due to the relatively low strength of the specimens with an R_f of 75%, which leads to a relatively large confinement ratio [29].

The effect of FRP thickness on the hoop-axial strain relationship of FCRCs is similar to that for FRP-confined NAC, as shown in Fig. 10b. It can be seen from this figure that a thicker FRP

wrap leads to a higher hoop-axial strain curve, i.e., the absolute value of hoop strain is lower at a given axial strain if the FRP wrap is thicker.

To further examine the lateral expansion of FCRC at different stage of loading, the dilation rate, which is defined to be the ratio of the increase of lateral strain to that of the axial strain [30], was calculated for the elastic stage and the second stage (i.e. corresponding to the second linear portion of stress-strain curve) of all the specimens. For the elastic stage, the dilation rate is the same as the Poisson's ratio, and it was calculated in accordance with ASTM C469 [31]. For the second stage, the dilation rate was calculated using the two lateral strains at 75% and 90% of the ultimate axial strain. The so-calculated dilation rates are plotted in Fig. 9 and are referred to as the initial and final dilation rates, respectively. It is evident from Fig. 9 that the initial dilation rate increases with the replacement ratio because of the relatively high Poisson's ratio of rubber aggregates [10]. The final dilation rates are significantly higher than the corresponding initial dilation rates, and decrease with the replacement ratio. This is probably due to the relatively low strength and thus high confinement ratio of concrete with a high replacement ratio.

4 COMPARISON WITH THEORETICAL MODELS

A large number of stress-strain models have been proposed for FRP-confined NAC, including analysis-oriented models (e.g. [24]) which generate the stress-strain curves through an iterative process, and design-oriented models (e.g. [29, 32]) which describe the stress-strain curves using simple and explicit equations. In the present study, the analysis-oriented model, that was proposed by Jiang and Teng [24] and has been widely accepted as an accurate model for NAC, is first adopted to do comparison with test results. The comparisons between the predicted axial stress-strain curves and hoop-axial strain curves and the test results of the specimens with a 4-ply FRP wrap are plotted in Fig. 11 and Fig. 12, respectively, while the comparisons of the key results are given in Table 5.

4.1 Comparison for FRP-confined NAC

As can be seen from Fig.11a, for FRP-confined specimens without rubber aggregates (i.e., Specimens C-0-4-I, II), Jiang and Teng's model [24] provides very close predictions of the test results when the axial strain is smaller than 0.011, after which the performance of the model becomes not as good: the predicted axial stress becomes larger than the test result and the difference between the two increases with the axial strain. This relatively inadequate

performance of Jiang and Teng's model [24] for large axial strains is believed to be at least partially due to the limitation of their test database. In Jiang and Teng's database [24], the FRP wraps that are as stiff as or stiffer than the 4-ply GFRP wrap used in the present study were all made of carbon fibres which had a much smaller rupture strain than glass fibres; as a result, the ultimate axial strains of the CFRP-confined concrete are expected to be much smaller than concrete confined by GFRP with the same stiffness. The stiffest GFRP wrap covered in Jiang and Teng's study [24] had a nominal thickness of 0.51 mm according to the weight of the fibres (i.e. Specimens 24, 25, 32 and 33 in [24]), which is smaller than the 4-ply GFRP wrap used in the present study (i.e. nominal thickness = 0.696 mm). It is also worth noting that even for Specimens 24 and 25 in Jiang and Teng's paper [24], the model appears to overestimate the axial stress at relatively large axial strains [24].

More recently, Dai et al. [33] proposed a revised version of Jiang and Teng's model [24] based on their test results of large rupture strain FRP-confined concrete. The only difference between the two models lies in the equation for the axial-hoop strain relationship. The predictions of Dai et al.'s model [33] are also compared with the test results in Table 5 and Figs. 11 and 12, respectively. It is evident from Figs. 12a and 12a that, compared with Jiang and Teng's model [24], Dai et al.'s model [33] provides slightly better predictions for the axial-hoop strain curves of Specimens C-0-4-I, II, but overestimates the axial stress-strain curves slightly more significantly. The above observation suggests that for more accurate predictions of axial stresses at large axial strains, the active confinement model adopted by Jiang and Teng [24] and Dai et al. [33] may also need to be refined.

4.2 Comparison for FCRC

Figs. 12b-e show that at a given axial strain, both Jiang and Teng's model [24] and Dai et al.'s model [33] generally underestimate the hoop strain of FCRC, and such underestimation is more pronounced for rubber concrete with a relatively large replacement ratio of fine aggregates (e.g. 50% and 75%, see Figs. 12d and 12e). As a result, the two models generally overestimate the ultimate axial strains of FCRC (Table 5 and Fig. 11).

Considering that both Jiang and Teng's model [24] and Dai et al.'s model [33] can reasonably predict the hoop-axial strain curves (and the ultimate axial strains) of FRP-confined NAC (Fig. 12a), the different performance of the models for FCRC (Fig. 12b-e) evidently shows the effect of rubber aggregates: when all the other parameters (i.e. unconfined concrete strength f'_{co} , axial

strain at peak stress of unconfined concrete ε_{co} , confinement stiffness of FRP) are the same, the lateral expansion of rubber concrete at a given axial strain appears to be larger than that of NAC. This important feature, which is a result of the existence of rubber aggregates, needs to be captured in the development of a new stress-strain model for FCRC. A simple way of such development is to introduce an additional coefficient k_R , which should be a function of the replacement ratio R_f , in the hoop-axial strain relationship of existing models for FRP-confined NAC. For example, k_R may be assumed to be linearly related to R_f as expressed in the following equation:

$$k_R = 1 - \alpha R_f \quad (1)$$

in which α is a constant and can be determined to be 0.73 by a regression analysis of the test data in the present study.

By doing so, the hoop-axial strain relationship used in Dai et al.'s model [33] becomes:

$$\frac{\varepsilon_c}{\varepsilon_{co}} = \left(1.0 + 8.0 \frac{f_l}{f'_{co}}\right) k_R \left[1.024 \left(\frac{\varepsilon_l}{\varepsilon_{co}}\right)^{0.350} + 0.089 \left(\frac{\varepsilon_l}{\varepsilon_{co}}\right)\right] \quad (2)$$

where ε_c , ε_l and f_l are the axial and lateral strains of confined concrete, and the confining pressure provided by the FRP tube, respectively.

The same k_R may also be simply introduced in the peak axial stress equation of active confinement model used in existing models for FRP-confined NAC, so that the peak axial stress (f'_{cc}) can be expressed by:

$$f'_{cc} = f'_{co} + k_s k_R f_l \quad (3)$$

where k_s is taken as 3.5 in both Jiang and Teng's model [24] and Dai et al.'s model [33].

With the simple change to Dai et al.'s model [33] by the inclusion of k_R in Eqs. 2 and 3, it can now make reasonably accurate predictions of the test results in the present study; the predictions of the simply modified model are labelled as "Prediction (modified model)" in Figs. 11 and 12. It should, however, be noted that the equation of k_R (Eq. 1) is based on limited test data and its wide applicability needs to further examined when more test data becomes

available. In particular, the peak axial stress equation of active confinement model may only be well established with a large test database of actively-confined rubber concrete, which is not available in the open literature and is beyond the scope of the present study.

5 CONCLUSIONS

This paper has presented results from an experimental study on the axial compressive behaviour of both unconfined rubber concrete (URC) and FRP-confined rubber concrete (FCRC). The experimental program included a total of 29 specimens (15 URC specimens and 14 FCRC specimens), covering a large range of the replacement ratio of fine aggregates. Comparisons between the test results and two existing stress-strain models for FRP-confined NAC have also been presented. Based on the test results and comparisons presented above, the following conclusions can be made:

- (1) The unconfined compressive strength of rubber concrete decreases approximately linearly with the replacement ratio of fine aggregates, and the reduction of the compressive strength reached 74.3% in the present study when the replacement ratio of fine aggregates was 75% by volume;
- (2) The use of FRP wrap to confine rubber concrete can largely increase its compressive strength and ultimate axial strain. The replacement ratio of fine aggregates has a marginal effect on the increase in the compressive strength caused by FRP confinement. However, the ratio of compressive strength between confined and unconfined concrete increases with the replacement ratio of fine aggregates.
- (3) Similar to FRP-confined NAC, the stress-strain curves of FCRC also has an approximately bilinear shape; the slope of the second linear branch, as well as the ultimate strength and ultimate axial strain, all increase with the thickness of FRP.
- (4) The lateral expansion of FCRC can be significantly larger than that of FRP-confined NAC with the same unconfined strength and confinement stiffness. Therefore, existing stress-strain models for FRP-confined NAC generally cannot provide reasonable predictions for FCRC.
- (5) By the inclusion of a simple coefficient to consider the effects of rubber aggregates, the existing models for FRP-confined NAC can be modified to provide reasonable prediction of FCRC. However, further research, including that on actively-confined

rubber concrete, is needed to confirm the reliability of this method or to develop a more reliable model.

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TABLE

Table 1. Details of specimens

Series	Specimen	R_f (%)	R_t (%)	FRP wrap
1	U-0-I, II, III	0	0	N/A
	C-0-4-I, II			4-ply
2	U-12.5-I, II, III	12.5	5.5	N/A
	C-12.5-4-I, II			4-ply
3	U-25-I, II, III	25	11	N/A
	C-25-4-I, II			4-ply
4	U-50-I, II, III	50	22	N/A
	C-50-2-I, II			2-ply
	C-50-4-I, II			4-ply
	C-50-6-I, II			6-ply
5	U-75-I, II, III	75	33	N/A
	C-75-4-I, II			4-ply

Table 2. Mix proportions of concrete

Series	W/C	Cement (kg/m ³)	Water (kg/m ³)	Superplasticizer (kg/m ³)	Coarse aggregate (kg/m ³)		Fine aggregate (kg/m ³)	Crumb rubber (kg/m ³)
					10 mm	20 mm		
1	0.4	425	170	2.13	614	369	772	0
2							676	32
3							579	64
4							386	129
5							193	193

Table 3. Key test results of URC specimens

Specimen	f'_{co} (MPa)	Average f'_{co} (MPa)	Reduction percentage of f'_{co}	ε_{co} (%)	Average ε_{co} (%)
U-0-I	52.7	53.0	0	0.268	0.270
U-0-II	53.4			0.255	
U-0-III	53.0			0.286	
U-12.5-I	48.3	48.8	7.91%	0.269	0.257
U-12.5-II	49.0			0.259	
U-12.5-III	49.2			0.242	
U-25-I	42.8	42.1	20.6%	0.268	0.240
U-25-II	41.2			0.193	
U-25-III	42.3			0.259	
U-50-I	33.1	33.2	37.4%	0.242	0.221
U-50-II	33.5			0.269	
U-50-III	33.0			0.152	
U-75-I	14.9	13.9	74.3%	0.291	0.265
U-75-II	12.9			0.228	
U-75-III	14.0			0.277	

Table 4. Key test results of FCRC specimens

Specimen	f_{cc} (MPa)	Average f_{cc} (MPa)	Reduction percentage of f_{cc}	f_{cc}/f'_{co}	ε_{cc} (%)	Average ε_{cc} (%)	$\varepsilon_{cc}/\varepsilon_{co}$	$\varepsilon_{rup,frp}$ (%)	Average $\varepsilon_{rup,frp}$ (%)
C-0-4-I	71.5	72.5	0.0	1.37	2.02	2.11	7.81	1.93	1.96
C-0-4-II	73.5				2.20			1.99	
C-12.5-4-I	66.9	67.3	7.21%	1.38	2.08	2.01	7.82	1.91	1.87
C-12.5-4-II	67.6				1.93			1.82	
C-25-4-I	62.4	60.8	16.1%	1.44	2.11	2.09	8.71	1.90	1.87
C-25-4-II	59.2				2.07			1.84	
C-50-4-I	54.5	53.9	25.7%	1.64	1.73	1.90	8.60	1.83	1.84
C-50-4-II	53.3				2.07			1.84	
C-75-4-I	34.2	33.4	54.0%	2.46	2.58	2.50	9.42	1.80	1.77
C-75-4-II	32.5				2.42			1.74	
C-50-2-I	43.6	43.2	NA	1.30	1.47	1.36	6.13	2.14	2.01
C-50-2-II	42.8				1.24			1.87	
C-50-6-I	65.8	64.6	NA	1.95	2.25	2.24	10.1	1.85	1.71
C-50-6-II	63.3				2.23			1.56	

Table 5. Comparison between test results and predictions

Specimen	Test Result		Prediction of Jiang and Teng's model [22]				Prediction of Dai et al's model [25]			
	f_{cc} (MPa)	ε_{cc} (%)	$f_{cc,pre}^*$ (MPa)	$f_{cc,pre}/f_{cc}$	$\varepsilon_{cc,pre}^\#$ (%)	$\varepsilon_{cc,pre}/\varepsilon_{cc}$	$f_{cc,pre}^*$ (MPa)	$f_{cc,pre}/f_{cc}$	$\varepsilon_{cc,pre}^\#$ (%)	$\varepsilon_{cc,pre}/\varepsilon_{cc}$
C-0-4	72.5	2.11	84.2	1.16	2.19	1.03	87.9	1.21	1.86	0.88
C-12.5-4	67.3	2.01	79.3	1.17	2.23	1.11	85.5	1.27	1.96	0.97
C-25-4	60.8	2.09	76.6	1.26	2.47	1.18	81.1	1.33	2.18	1.04
C-50-4	53.9	1.90	71.7	1.43	2.94	1.54	74.5	1.49	2.59	1.36
C-75-4	33.4	2.50	56.8	1.70	6.12	2.44	57.4	1.72	5.40	2.16

Note: * Prediction of compressive strength; # Prediction of ultimate axial strain.

FIGURE

Figure 1. Crumb rubber used in the present study

Figure 2. Sieving test results: (a) grading of aggregates used in present study and (b) overall grading of aggregates in concrete mixes

Figure 3. Test set-up: (a) layout of strain gauges; and (b) schematic of test set-up

Figure 4. Typical failure mode of URC specimens

Figure 5. FCRC specimens after test: specimens with replacement ratio of : (a) 0; (b) 12.5%; (c) 25%; (d) 50%; and (e) 75%

Figure 6 Comparison between URC and FCRC

Figure 7. Axial stress-strain behaviour of FCRCs: (a) effect of replacement ratio of fine aggregates; (b) effect of FRP thickness

Figure 8. Normalised axial stress-normalised axial stress curves of FCRC specimens

Figure 9. Relationship between compressive strength and replacement ratio of fine aggregates

Figure 10. Hoop-axial strain relationships of FCRCs: (a) effect of replacement ratio; (b) effect of FRP thickness

Figure 11. Comparison of axial stress-strain curves : specimens with R_t of (a) 0%; (b) 12.5%; (c) 25%; (d) 50%; and (e) 75%

Figure 12. Comparison of hoop-axial strain curves: specimens with R_t of (a) 0%; (b) 12.5%; (c) 25%; (d) 50%; and (e) 75%