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Prediction of the structural behaviour of oil palm shell lightweight concrete beams

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HIGHLIGHTS

- Moment–rotation approach gave good overall flexural behaviour prediction of OPSC beams.
- Closed-form solution could be used to predict deflection of OPSC beams at serviceability level.
- Good agreement exists between predicted and experimental crack width and spacing.
- Model gave fairly good comparison with the behaviour of other types of LWC beams.

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ABSTRACT

The use of structural lightweight concrete (LWC) has the potential to substantially reduce construction costs as its lower density allows for longer spans, reduced self-weight and a reduction in foundation size. Despite its usefulness, LWC with natural aggregates sees limited use in design due to a lack of design guidelines. This lack of guidance arises primarily due to the highly empirical nature of the design standards in predicting behaviour at all load levels i.e. empirical equations are used at the serviceability limit to predict for flexural rigidities and crack widths as well as at the ultimate limit to predict hinge rotation and moment redistribution. It is thus costly and time-consuming to conduct large scale member testing for a particular type of LWC in order to establish design guidelines. To address this, a generic, mechanics based, segmental moment–rotation (M/θ) approach has been proposed to simulate the flexural behaviour of reinforced concrete at all load levels, in which the only empiricisms required are the definition of fundamental material properties. In this paper, it is shown that the M/θ approach and the subsequent existing closed-form solutions derived based on the approach can predict the full range of flexural behaviours of oil palm shell (OPS) LWC beams such as load–deflection and crack width at all load levels. The successful application of the M/θ approach suggested that the approach can be used as a basis for developing design guidelines for LWC. This was further enforced by the good agreement between the predicted response using the M/θ approach and the published test results for other types of LWC material.

1. Introduction

Lightweight concrete (LWC) permits increased flexibility in structural design, allowing for longer span structures, smaller foundations and fewer piles due to the reduced self-weight of the structural members. Moreover, due to its reduced density, considerable savings in construction costs, such as those during transportation and handling, can be achieved.

The most common technique for the production of LWC is through the replacement of conventional coarse aggregates with lightweight alternatives. Lightweight aggregates are generally divided into two categories – manufactured and natural occurring. Manufactured aggregates are principally obtained through the process of expansion and agglomeration and include expanded clay, shale and slate; while natural-occurring aggregates include unprocessed by-products and organic materials. Oil palm shell (OPS), a waste material from the palm oil industry, falls under the latter category. In recent years, research [1] has been devoted to utilizing OPS to produce structural grade lightweight OPS concrete (OPSC). Besides possessing the advantages of LWC, the use of such agriculture waste has the potential to significantly reduce environmental

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concerns caused by the stockpiling and dumping of OPS as well as the burning of OPS to generate electricity.

In the past, researchers [2–4] investigated the flexural behaviour of reinforced OPSC beams experimentally and found comparable performance to conventional reinforced normal weight concrete (NWC) beams; in fact, it has been shown that OPSC beams have the potential to exhibit enhanced ductility compared to the reinforced NWC beams [3]. Despite the potential benefits of using LWC manufactured from natural aggregates little attempt has been made to analytically simulate the behaviour seen in practice. As such, there is insufficient information regarding the structural performance of such reinforced LWC beams to serve as a guide for practising engineers and designers. Of the existing analytical models for LWC beams the majority are empirically derived [5,6], and, hence, are only applicable to the particular LWC from which the experimental data was obtained. Hence, in order to include OPSC or any other type of new concrete into these models a substantial amount of high cost empirical research is required.

To address the issue of a lack of generic analysis procedure for LWC, in the present investigation, an attempt is made to utilize a generic, mechanics based analysis technique: the moment–rotation (M/θ) approach, which was previously developed by Haskett et al. [7] and Visintin et al. [8] to simulate the flexural behaviour of a reinforced lightweight OPSC beam. This approach is considered to be valid for any type of concrete and reinforcement, as long as the required material properties are available. In previous research, this approach was found to be applicable in the prediction of performance of a wide range of structural members, such as reinforced concrete columns [9], reinforced concrete beams with fibre reinforced polymer reinforcement [10] and the time-dependent behaviour of reinforced concrete beams [11]. No previous works were carried out that used the M/θ approach to simulate the behaviour of LWC structural members.

The M/θ approach is deformation-based and capable of dealing with often-overlooked issues concerning traditional strain-based analysis on both the tension and compression region of flexural members. In the tension region, conventional strain-based analyses assume full interaction between the reinforcement and the surrounding concrete and therefore no relative slip. As a consequence conventional strain based approaches cannot predict concrete crack formation, crack opening or tension stiffening, and, therefore, must resort to empirical models to fill this gap in mechanics. In contrast, the M/θ approach uses the mechanics of the partial interaction theory [12] to directly simulate the slip between the reinforcement and the concrete, and, hence, through mechanics can simulate crack formation, crack widening and tension stiffening. Furthermore, conventional strain-based analysis cannot be used directly to simulate concrete softening caused by the formation of wedges in the compression zone. Rather an assumed hinge length is used to quantify ultimate rotations. However, this approach is not possible in the case of OPSC or even any LWC beam, as test data to quantify hinge lengths is not readily available, and existing empirical models should not be applied to cases where the conditions are beyond the bounds from which the hinge length are derived. In contrast, the M/θ approach uses established shear friction theory, to quantify the size dependent component of the wedge strain using the shear-friction material properties [13]. Using the shear friction approach, Chen et al. [14] proposed a size-dependent compressive stress–strain (σ/ε) relationship, which may be applied based on tests from a single size specimen, which could significantly reduce the extensive experimental works required for derivation of the shear-friction material properties for a relatively new type of concrete.

In order to examine the usefulness and accuracy of the M/θ approach in simulating the flexural behaviour of reinforced OPSC beams, this paper presents the results of a series of reinforced OPSC flexural beam tests in which the cement binder properties and tensile reinforcement ratios are varied. The modelled moment–deflection response is compared to the experimentally obtained response of the tested beams, as well as a series of already published results for various types of LWC. In all cases, it is shown that the M/θ approach can be applied to accurately predict the full range of flexural behaviour. Furthermore, it is shown that the approach is able to reasonably predict the crack spacings and crack widths of the LWC beams tested as part of this study.

2. Experimental programme

In order to validate the application of the segmental M/θ approach, an experimental programme to obtain the moment–deflection behaviour of OPSC beams and the material properties required for analysis is proposed as follows.

2.1. Materials

In order to show the applicability of the M/θ approach to a range of LWC types, here, two different mix designs were considered, as shown in Table 1. Each mix was composed of a blended Ordinary Portland cement (OPC) and ground granulated blast furnace slag (GGBS) binder for which the ratio of OPC:GGBS varied between 4:1 (S1) and 2:3 (S2). These concrete mixes were selected to investigate the effect of concrete compressive strength since the use of GGBS as cement replacement is known to reduce the compressive strength of OPSC [15–17]. In both mixes, crushed OPS and manufactured sand were used as the coarse and fine aggregates, respectively. Potable water, free from impurities, was used as mixing water while a PCE-based superplasticiser (SP) was added at 1.0% by the mass of binder to facilitate workability. High yield deformed steel reinforcing bars of 12 mm diameter with a yield strength of 560 MPa were used as tension reinforcement while steel reinforcing bars of 10 mm diameter with a yield strength of 520 MPa were used as compression reinforcement. Grade 300 plain round mild steel reinforcing bars of 6 mm diameter were used as links. The modulus of elasticity (MOE) of steel was taken as 200 GPa.

2.2. Test method

2.2.1. Material properties test

For analysis, in addition to the basic material properties, that is, the compressive and splitting tensile strength, as outlined below, the material properties used for the simulation of the tension stiffening and concrete softening mechanism are required.

2.2.1.1. Compressive and splitting tensile strength test. Cylindrical specimens with dimensions of 100 mm Ø × 200 mm height were tested for both compressive and splitting tensile strength according to BS EN 12390-3:2002 and BS EN 12390-6: 2000, respectively.

2.2.1.2. Pull-out test. In order to apply the partial interaction theory to simulate tension stiffening [10,12] the local bond stress slip (τ/δ) relationship between the reinforcement and the concrete is required. According to Haskett et al. [12], these material properties can be directly extracted from pull-out tests. The pull-out test set-up is shown in Fig. 1 and consists of concrete specimens measuring 200 × 200 × 350 mm^3. Into this prism, a 12 mm diameter steel reinforcing bar is embedded with a bonded length of 4 × diameter of bar; this dimension was chosen to ensure the constant slip of reinforcement along the bonded length. During testing, the protruding steel reinforcing bar was gripped and a concentric pull-out force was applied via a displacement-controlled Universal Testing Machine. The slip of the steel reinforcing bar relative to the concrete was measured through the use of a linear voltage displacement transducer (LVDT). The slip values measured were then corrected by subtracting the elongation caused by the steel reinforcing bar strain.

2.2.1.3. Compressive stress–strain test. In order to simulate concrete softening using the M/θ approach, a size dependent stress–strain (σ/ε) relationship is required. According to Chen et al. [14], this can be derived using the mechanics of shear friction theory given that the stress–global axial strain relationship is known. To obtain

Table 1
Mix proportions.

Mix	Content (kg/m^3)				
	Cement	GGBS	Sand	OPS	Water
S1	416	104	940	400	170
S2	208	312	940	400	170