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Influence of lightweight aggregate on the bond properties of concrete with various strength grades

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HIGHLIGHTS

- Higher bond strength of OPSC compared to NWC with similar compressive strength.
- OPSC and NWC exhibit similar shape of bond stress–slip curves.
- Proposed bond models for OPSC and NWC gave good match to experimental values.
- Determination of prediction equation for mechanical properties and shrinkage of OPSC.

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ABSTRACT

This paper presents the comparison of the bond and mechanical properties of lightweight oil palm shell concrete (OPSC) and normal weight concrete (NWC) with three different strength grades of 25, 35 and 45 MPa. Although the mechanical properties such as splitting tensile strength and modulus of elasticity as well as the performance of drying shrinkage of OPSC were found to be inferior compared to NWC, the bond strength of OPSC was found to be up to 80% higher compared to the corresponding NWC of equivalent cube compressive strength grade. Results also showed that the shape of the bond stress–slip curve for OPSC was similar to conventional NWC. In addition, in this paper, modified bond models based on the CEB–FIP bond model was proposed for both OPSC and NWC which were found to give good prediction of the experimental bond stress–slip curve of the concretes.

1. Introduction

A recent development in the manufacture of lightweight concrete (LWC) is the utilization of oil palm shell (OPS) as lightweight aggregate. OPS is an agriculture waste material resulting from the extraction of palm oil and are widely available in countries with vast oil palm plantation, particularly in the South East Asia region. In the past, studies on the production of lightweight OPS concrete (OPSC) [1–3] as well as the cement-less geopolymer OPSC [4] have been carried out with the aim of producing a more environmental friendly concrete. These works have mainly focused on obtaining basic mechanical properties [5] as well as preliminary studies to define bond capacities [6,7].

The bond between concrete and reinforcing bar is an important property in reinforced concrete member since it is responsible for transfer of axial force between these two materials. Insufficient bond strength could lead to loss of strain compatibility and excessive slip which could result in permanent deformation of reinforced concrete structures. The adequate knowledge of the bond properties is also required to determine the development length to prevent premature bond failure of reinforced concrete members. The lack of available information relating to development lengths in LWC is evidenced by the incorporation of an additional safety factor for LWC in ACI-318 [8]. The magnitude of this additional safety factor is however debatable as there are inconclusive reports on the bond strength of LWC. For instance, Lyse [9] and Shideler [10] reported that the bond strength of LWC made with slag and expanded shale aggregate were comparable to NWC, while Lachemi et al. [11] found lower bond strength of lightweight self-compacting concrete (SCC) containing both of these lightweight aggregates compared to normal weight SCC. Several other investigations have also reported inferior bond strength of LWC made with lightweight aggregates such as pumice [12] and tuff [13] compared to NWC. On the contrary, Clarke and Birjandi [14]

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found higher bond strength for LWC containing expanded clay, sintered pulverized fuel ash and pelletized expanded blast furnace slag aggregates. Maree and Riad [15] also reported higher bond strength of foamed LWC compared to NWC.

In addition, the local bond properties can be utilized in numerical model to simulate the tension stiffening behaviour such as in the well-established mechanics of partial interaction analysis [16] to predict short term deflections of structural members [17]. Furthermore, the knowledge of the local bond properties allows for the determination of the crack spacing and crack width of structural members through the use of a mechanics-based moment-rotation approach for member analysis [17].

The lack of information on the bond behaviour of lightweight OPSC has enthused research interest to carry out this investigation of the bond characteristics of OPSC. OPSC and NWC with similar targeted cube compressive strengths of 25, 35 and 45 MPa were tested to facilitate the comparison of their bond behaviours. In addition, this paper also deals with the effect of the aggregates, namely OPS and conventional crushed granite used in LWC and NWC, respectively on the mechanical properties and drying shrinkage behaviour of concrete. The knowledge of the mechanical properties of OPSC such as tensile strength and modulus of elasticity (MoE) is essential since as they are interrelated with the bond properties and are generally required in structural analysis while the shrinkage strain could also be applied in the partial interaction analysis [16] to predict changes in the tension stiffening behaviour over time and hence long term deflections of structural members [18]. It should be noted, however, that the analysis of member behaviour is not the purpose of this paper but rather the study of the material properties for future use in numerical model.

2. Materials and mix proportions

The uncrushed OPS (Fig. 1) with sizes between 2.36 and 14 mm and bulk density of 587 kg/m^3 were used in the manufacture of OPSC. The specific gravity and 24 h water absorption of the OPS were respectively 1.34 and 26%. The OPS was pre-soaked for 24 h and used in saturated surface dry (SSD) condition. In the manufacture of NWC, crushed granite coarse aggregate of sizes between 5 and 14 mm and with a specific gravity of 2.65 was used. The gradation curves of OPS and granite are shown in Fig. 2.

Fig. 1. OPS as lightweight coarse aggregate.

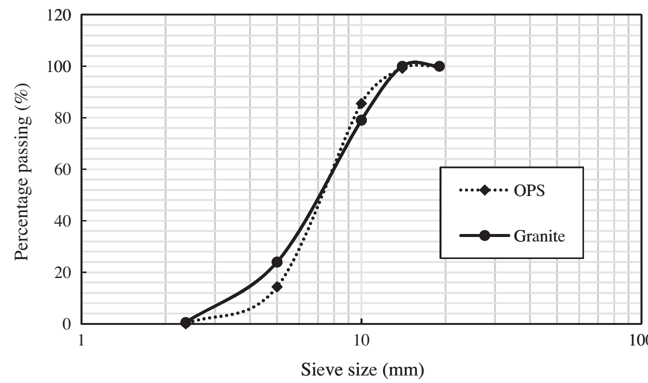

Fig. 2. Gradation curve of OPS and granite.

Table 1
Mix proportions for OPSC and NWC.

Mix	Mix proportions (kg/m^3)					
	Cement	OPS	Granite	Sand	Water	SP
L1	470	425	0	850	200	–
L2	515	410	0	950	160	5.2
L3	560	365	0	960	175	5.6
N1	295	0	855	975	205	–
N2	320	0	810	1030	200	–
N3	350	0	1345	535	175	–

Mining sand with specific gravity of 2.73 passing through 5 mm sieve was used as fine aggregates for all the mixes.

Ordinary Portland cement (OPC) with specific gravity and surface area of 3.10 and 352 m^2/kg, respectively, was used. Potable water that was free from contaminant and impurities was used as the mixing water in all the mixes.

Concrete strength grades of 25, 35 and 45 for both OPSC and NWC were targeted and trial mixes were carried out beforehand to ensure the targeted strength could be achieved. Mix proportions for all OPSC and NWC grades are presented in Table 1, where the mixes with designations 'L' and 'N' denote OPSC and NWC, respectively; furthermore the numberings '1', '2' and '3' denote targeted concrete strength grade of 25, 35 and 45, respectively. Polycarboxylate-ether based superplasticizer (SP) was used at 1.0% by the mass of cement for mixes L2 and L3 to ensure sufficient workability.

In the mixing process, coarse aggregates and sand were initially dry mixed for 3 min and this was followed by the addition of cement and a further mixing was done for another 3 min. And with the addition of water, wet mixing was carried out for a further 6 min. After the mixing was completed, the concrete was poured into oiled moulds and compacted. All the specimens were de-moulded after 24 h and water-cured until the age of testing.

3. Test methods

3.1. Mechanical properties

The compressive strength (BS EN 12390-3: 2002), splitting tensile strength (BS EN 12390-6: 2000) and modulus of elasticity (ASTM C469-10) tests were carried out at the age of 28 days on specimens of 100 mm cube, 100 mm $\phi \times$ 200 mm height cylinder and 150 mm $\phi \times$ 300 mm height cylinder, respectively. A total of three specimens were tested for each mix and the average of the three values was reported.

3.2. Drying shrinkage

After de-moulding of specimens, demountable mechanical (DEMEC) gauge studs were attached to prism specimens of dimension 75 × 75 × 300 mm. The specimens were then kept in a room in which the temperature and humidity were maintained at 20 ± 2 °C and 60 ± 5%, respectively. Observations on the initial position of DEMEC studs were taken using a length comparator (Fig. 3).