Experimental investigation on the properties of lightweight concrete containing waste oil palm shell aggregate

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Abstract

This paper presents a study on the properties of a sustainable lightweight concrete incorporating high volume of waste materials. The concrete was produced utilizing lightweight oil palm shell (OPS), which is a waste material from the palm oil industry as well as manufactured sand, which is obtained from the processing of quarry waste, to replace conventional materials as coarse and fine aggregate in the concrete, respectively. In addition, ground granulated blast furnace slag (GGBS) was utilized at 20% cement replacement level to reduce the cement content in the OPS concrete (OPSC) as to further encourage the environmental-sustainability of the concrete. In the experimental study, selected properties such as the mechanical, permeation and structural properties of the OPSC were compared with those of conventional normal weight concrete (NWC) of equal targeted strength grade. While the performance of the mechanical properties such as splitting tensile strength and modulus of elasticity of the OPSC were inferior compared to NWC, the OPSC exhibited improved permeation properties such as the water absorption and sorptivity. The investigation of the structural properties such as the steel-concrete bond behavior as well as the flexural performance of reinforced concrete beam also demonstrated that the OPSC could behave similarly as NWC. The experimental results obtained in this study thus indicate the possibility of utilizing such concrete as a viable alternative for conventional NWC for practical applications.

Keywords: Oil palm shell; lightweight concrete; mechanical properties; permeation properties; structural properties.

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1. Introduction

South East Asia countries such as Indonesia, Malaysia and Thailand are currently among the major producers of crude palm oil in the world. Oil palm shell (OPS) is one of the solid wastes stemming from the process of palm oil extraction. The lack of proper disposal of the OPS could result in environmental pollution and wastage of land area. Utilization of OPS as lightweight coarse aggregate to produce lightweight concrete has been trialed, even for structural member such as reinforced concrete beams [1-2].

Recently, in order to counter the negative effects of carbon dioxide emission caused by the usage of high cement content in lightweight OPSC, ground granulated blast furnace slag (GGBS) was utilized by partial cement replacement. Results revealed that incorporating GGBS by 20% as cement replacement could still yield OPSC with similar strength properties as the concrete without any GGBS [3]. Besides that, research works were carried out to enhance the sustainability of the OPSC through the incorporation of manufactured sand as fine aggregate as opposed to the use of conventional mining sand [3,4]. Manufactured sand is a processed by-product from quarry, whereby quarry wastes were impacted with centrifugal force to produce manufactured sand which is less flaky and more cubical in shape.

While the mechanical properties of the OPSC incorporating GGBS and manufactured sand was investigated previously [3], little information is available regarding the performance of such concrete in comparison with conventional normal weight concrete (NWC). Therefore, in this paper, an experimental investigation was carried out to compare the hardened concrete properties (mechanical properties and permeation properties) and structural properties (steel-concrete bond behavior and flexural performance of reinforced concrete beam) between OPSC and conventional NWC of similar compressive strength.

2. Experimental program

2.1. Materials and mix proportion

In the production of the OPSC, total binder content of 520 kg/m³ was adopted in the mix design which consisted of 80% ordinary Portland cement and 20% GGBS. The physical properties of the binder materials were similar to that reported previously [5]. OPS (sizes between 2.36 – 9 mm) was used as coarse aggregate while manufactured sand (sizes between 0.3 – 5 mm) was used as fine aggregate in the OPSC mix. The waste OPS was collected from a local palm oil mill and washed with detergent to remove excess oil and dirt on the surface. After that, the washed OPS was dried and crushed using an aggregate crushing machine to obtain the require sizes of OPS. The manufactured sand was obtained at a local quarry, whereby quarry wastes were impacted using vertical shaft impact machine. In the vertical shaft machine, the quarry wastes were subjected to centrifugal force in the crusher and forced to hit with one another, thereby removing the flaky particles and obtain a more rounded-shape aggregate [4]. After the collection of the manufactured sand, the manufactured sand was also washed, dried and sieved to obtained the require sizes. The coarse and fine aggregate contents used in this investigation were 400 and 940 kg/m³, respectively. The specific gravities for the OPS and manufactured sand were 1.35 and 2.56, respectively. The OPS used had water absorption of 25% and the aggregate was soaked 24 hours and then air-dried to saturated surface dry condition before being used in the concrete casting. Potable water was used as mixing water with a water-to-binder ratio of 0.33 while polycarboxylate ether based superplasticizer was added at 1.0% of the mass of binder to ensure sufficient workability. The OPSC mix design was based on the trial mix method to produce concrete strength of 30 MPa.

On the other hand, for the production of conventional NWC, only ordinary Portland cement was used as the binder material, and the total binder content was fixed at 320 kg/m³. Crushed granite (sizes between 5 – 14 mm) and conventional mining sand (sizes between 2.36 – 9 mm) was used as coarse and fine aggregate, respectively. The coarse and fine aggregate content for the NWC mix was 810 and 1030 kg/m³, respectively. A water-to-binder ratio of 0.625 was selected for the NWC mix. This NWC mix design was used for the first part of the study involving hardened concrete properties. The mix design for OPSC and NWC is shown in Table 1. For the second part of the study which dealt with the casting of bond and reinforced concrete beam specimens, the NWC used was obtained from a local ready-mix plant with concrete of grade 30.
Table 1. Mix design for OPSC and NWC

<table>
<thead>
<tr>
<th>Mix designation</th>
<th>Content (kg/m³)</th>
<th>Cement</th>
<th>GGBS</th>
<th>OPS</th>
<th>Granite</th>
<th>Sand</th>
<th>Water</th>
<th>Superplasticizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPSC</td>
<td></td>
<td>416</td>
<td>104</td>
<td>400</td>
<td>-</td>
<td>940</td>
<td>170</td>
<td>5.2</td>
</tr>
<tr>
<td>NWC</td>
<td></td>
<td>320</td>
<td>-</td>
<td>-</td>
<td>810</td>
<td>1030</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

2.2. Test specimen and method

Compressive and splitting tensile strength tests were carried out on 100 mm cube and 100 mm $\phi \times 200$ mm height cylinder, respectively according to BS EN 12390-3: 2002 and BS EN 12390-6: 2000. The modulus of elasticity test was done on 150 mm $\phi \times 300$ mm height cylinder in accordance with ASTM C469-02. Water absorption and sorptivity tests were both carried out on 100 mm $\phi \times 50$ mm thick disc specimens according to the procedure set out by Liu et al. [6]. The tests were carried out on concrete specimens which were water-cured for 28 days.

For the evaluation of steel-concrete bond behavior, concrete specimen measuring $200 \times 200 \times 350$ mm$^3$ reinforced with 12 mm $\phi$ high yield steel reinforcing bar was used. The bonded length of the steel bar was fixed at 48 mm for all specimens, which was 4 times the diameter of the steel bar. For the flexural test, reinforced concrete beam with dimension of 150 width $\times$ 300 mm height reinforced with 2 layers of tension reinforcement of 3 nos. of 12 mm $\phi$ steel bars (reinforcement ratio = 1.5%) was used. The details of the reinforced concrete beam specimen are shown in Fig. 1. Both the bond and flexural tests carried out were similar to those done previously by Mo et al. [5]. The bond and reinforced concrete beam specimens were tested after water-curing for 28 days and further air-curing up until the age of 180 days.

3. Results and discussion

In the first part of the study, the concrete specimens cast were tested for the mechanical properties (compressive strength, splitting tensile strength and modulus of elasticity) and the permeation properties (water absorption and sorptivity) while the concrete specimens were tested for steel-concrete bond behavior and the flexural performance of reinforced concrete beams in the second part of the study. The discussion of the results are presented in the following sub-sections.

3.1. Mechanical properties

The 28-day mechanical properties results of the concrete specimens are presented in Table 2. For similar compressive strength of concrete, it was noticed that the splitting tensile strength for OPSC was slightly lower compared to that for NWC while the modulus of elasticity was only about 25% of that for the corresponding NWC. The lower mechanical properties of OPSC compared to NWC could be reasoned by the weaker aggregate-matrix bond in the OPSC [7] and this was caused by the presence of micro-pores on the outer surface of the OPS aggregate [8]. Nevertheless, all of the mechanical properties of OPSC obtained in this study falls within the range of values observed in past investigations.

Table 2. 28-day hardened concrete properties

<table>
<thead>
<tr>
<th>Mix</th>
<th>Compressive strength (MPa)</th>
<th>Splitting tensile strength (MPa)</th>
<th>Modulus of elasticity (GPa)</th>
<th>Initial water absorption (%)</th>
<th>Sorptivity (mm/min$^{0.5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPSC</td>
<td>34.2</td>
<td>2.36</td>
<td>7.4</td>
<td>3.14</td>
<td>0.124</td>
</tr>
<tr>
<td>NWC</td>
<td>32.3</td>
<td>2.77</td>
<td>30.2</td>
<td>4.21</td>
<td>0.282</td>
</tr>
</tbody>
</table>
3.2. Permeation properties

The water absorption and sorptivity of concrete indicate the presence of pores and connectivity of the pores in the concrete, respectively. These permeation properties are essential towards the durability of concrete; reinforced concrete structure made with concrete with high water penetrability could have reduced service life as the concrete are more susceptible towards the ingress of external deleterious agents. As shown in Table 2, it is interesting to note that the OPSC had lower initial water absorption and sorptivity values compared to the corresponding NWC. The higher water-to-binder ratio of the NWC could be the main cause for this phenomenon, according to Liu et al. [9]. Moreover, in this investigation, the water-to-binder ratio of the NWC was almost doubled of that for the OPSC mix, and this could explain the significantly higher sorptivity value of the NWC. Another possible reason of the higher permeability characteristics of the NWC is the existence of micro-cracks in the interfacial transition zone around the stiffer coarse aggregate [9]. Besides that, the use of GGBS in the OPSC mix could have reduced the sorption of the concrete due to the pore refinement effect of the finer GGBS particles.

3.3. Steel-concrete bond properties

The second part of the study involves bond specimens and reinforced concrete beams which were cast separately with the specimens tested for the hardened concrete properties in the first part of the study. For the second part of the study, the cube compressive strength of the OPSC was 30.9 MPa at the testing age while the cube compressive strength for the ready-mixed NWC was 27.0 MPa at the age of testing.

The bond stress-slip curves of both OPSC and NWC are shown in Fig. 2 and generally both exhibited similar curve shape. Both OPSC and NWC failed by pull-out with no visible splitting cracks observed around the specimens. The bond strength of OPSC and NWC was 15.5 MPa and 8.6 MPa, respectively. This shows that the bonding between steel bar and OPSC was almost twice as much as that compared to the bonding between steel bar and NWC. One of the reason could be the significantly lower water-to-binder ratio adopted in the mix design of OPSC compared to
NWC. It was reported previously that the type of aggregate had minimal effect on the bond strength [10], hence, the lower water-to-binder ratio used in the OPSC could have contributed to its higher bond strength due to the enhanced paste quality [11]. It should also be noted that similar range of bond strength was obtained in the past for lightweight aggregate concrete prepared with expanded shale [12] and ceramsite aggregates [13] with similar compressive strength.

Fig. 2. Steel-concrete bond behavior of OPSC and NWC

3.4. Flexural behavior of reinforced concrete beam

The reinforced concrete beams were cast Fig. 3 shows the moment-deflection relationship of reinforced concrete beams prepared with OPSC and NWC which were subjected to flexural loading. Both OPSC and NWC beams generally behaved in similar manner and failed in flexural failure mode (Fig. 4) and as shown in Fig. 3, the ultimate moment for both beams was found to be similar. However, it could be observed that the ascending portion of the moment-deflection curve for NWC beam was steeper compared to that for the OPSC beam and this is attributed to the lower modulus of elasticity of the OPSC as described earlier. Besides that, it is noticed from Fig. 4 that the crack spacing of the OPSC beam was smaller compared to that of the NWC beam. The average primary crack spacing for the OPSC was measured to be 95 mm while the average primary crack spacing for the NWC beam was 151 mm. This justifies the better bond between the steel bar and OPSC compared to NWC, which justifies the reasoning given by Alengaram et al. [14].

Fig. 3. Moment-deflection relationships of reinforced concrete beams prepared with OPSC and NWC
4. Conclusions

From the experimental investigation carried out to compare the properties of GGBS-blended OPSC incorporating manufactured sand and conventional NWC, the following conclusions could be drawn:

a. For concrete with similar compressive strength, the OPSC had slightly lower splitting tensile strength compared to NWC while the modulus of elasticity was about 25% of that for the corresponding NWC.

b. The initial water absorption and sorptivity of the OPSC were lower compared to the corresponding NWC.

c. Similar shape of the bond stress-slip curve was observed for both OPSC and NWC bonded with steel bar. However, the bond strength was about 2 times higher in the case of OPSC.

d. Both OPSC and NWC beams exhibited similar flexural failure mode and also had similar ultimate moment, but the NWC beam exhibited steeper ascending branch of the moment-deflection curve. The primary crack spacing was smaller for the OPSC due to better bonding between OPSC and steel bar.

These findings indicate that in terms of the mechanical, permeation as well as the structural properties, the OPSC incorporating GGBS and manufactured sand could potentially be utilized as actual construction material. Nevertheless, considering that the OPSC produced in the study consisted largely on waste materials, in-depth durability investigation should be carried out to ascertain the suitability of such concrete in the long run and this shall form the future work on the GGBS-blended OPSC.

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