Lightweight concrete made from crushed oil palm shell: Tensile strength and effect of initial curing on compressive strength

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1. Introduction

Lightweight concrete (LWC) has been widely used in buildings as masonry blocks, wall panels, roof decks and precast concrete units [1]. Lightweight concretes can be produced with an oven dry density range of approximately 300–2000 kg/m³, with corresponding cube compressive strengths from approximately 1 to over 60 MPa and thermal conductivities of 0.2–1.0 W/mK [2]. It was reported that the reduction in the dead weight of a building by the use of LWC could result in a decrease in the cross section of steel reinforced columns, beams, plates and foundations [3]. The heat insulation of structural LWC is approximately twice that of ordinary concrete. Therefore, for equal thicknesses of a wall, less heating is required with LWC [4]. In most cases, the LWC has been made using a lightweight coarse aggregate and normal weight sand for the fine aggregate [5].

In Malaysia, oil palm shell (OPS) is an agricultural solid waste originating from the palm oil industry. The Palm Oil Industry is a significant industry in the Malaysian economy. This country currently accounts for 51% of world palm oil production and 62% of world exports [6]. Almost 80% of the volume from the processing of the fresh fruit bunch is removed as waste [7]. OPS is one of the wastes produced during the palm oil processing. Recently, plenty of OPS waste, as a lignocellulosic material, was obtained due to the increasing number of plantations of palm oil trees [8].

It was estimated that over 4.56 million tonnes of waste OPS is produced annually [9]. Pressed fibre and shell are traditionally used as solid fuels for steam boilers to run turbines for the electricity production of a palm oil mill. However, the problems associated with the burning of these two solid fuels are the emission of dark smoke and the carryover of partially carbonized fibrous particulates due to incomplete combustion of the fuels [10]. OPS is a porous aggregate with a porosity of about 37% [11]. Porosity is one of the factors affecting the thermal conductivity of concrete and enclosed pores reduce the conductivity due to low thermal conductivity of air [12]. Consequently, the cellular structure of the OPS gives thermal insulation properties to OPS concrete. The density of the shell is within the range of most typical lightweight aggregates [13] and the specific gravity of the shells range from between 1.14 and 1.37. Research over the last two decades shows that OPS can be used as a lightweight aggregate (LWA) for producing structural lightweight aggregate concrete (LWAC) with a density 20–25% lower than normal weight concrete [14]. A cost analysis in Nigeria [15] indicated cost reduction of 42% for concrete produced from OPS is possible. The use of OPS as a LWA in producing LWAC was researched as early as 1984 by Abdullah [16] in Malaysia. Previous researches have shown that, generally, the engineering properties of OPS concrete are satisfactory [17–20]; however, there is still some hesitation with regard to the use of OPS LWC. This may be because the mechanical properties of OPS concretes are slightly lower than other types of LWAC. It was reported [14] that the flexural strength of OPS concrete is lower than the LWAC made using artificial LWA namely expanded clay and shell aggregates.

Abstract

Oil palm shell (OPS) is a waste lightweight aggregate originating from the palm oil industry, which is approximately 50% lighter than conventional aggregate. In this study, crushed old OPS was used as coarse aggregate. Compressive strength under different curing conditions and the splitting tensile and flexural strengths were compared with those of the normal weight granite concrete. The test results showed that OPS concrete with a compressive strength in the range of 34–53 MPa has a splitting tensile strength range of 2.8–3.5 MPa and flexural strength range of 4.4–7.0 MPa. The sensitivity of compressive strength of OPS concrete in this study is significantly lower than uncruched OPS concrete reported in the literature. The sensitivity of OPS concrete, under poor curing regime, can be reduced by decreasing the water/cement ratio, increasing the OPS content or reducing the cement content. It was found that there was no substantial difference in 28-day compressive strength for OPS concretes cured initially for 3, 5 and 7 days. The 28-day compressive, splitting tensile and flexural strengths of OPS concrete was found to be 38%, 28% and 17%, lower than that of granite concrete, respectively.

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Lower flexural strength of OPS concrete resulted in early cracks in OPS concrete beams as reported by Alengaram et al. [17]. Okafor [13] concluded that using OPS cannot produce concrete with compressive strength above 30 MPa. He also revealed [21] the importance of using water reducing admixture and its dosage on the compressive strength of OPS concrete. Mannan et al. [22] reported that by quality improvement of OPS as coarse aggregate (similar to preservative treatment of wood), water absorption of OPS was reduced from 23.3% to 7.2% and there was better adhesion between the pre-treated OPS and the cement paste, which resulted in higher compressive strength. Highest 28-day compressive strength of 32.8 MPa was reported in their study. The OPS concrete under air-drying and full-water curing has water absorption of 11.23% and 10.64%, respectively [23]. It is noticeable that most good concretes have absorption below 10% by mass [24]. Test results of Mannan and Ganapathy [25] showed that OPS concrete is more sensitive than normal weight concrete (NWC) when curing was lacking. In this study, OPS concrete subjected to 7-day moist curing showed 17% lower 28-day compressive strength than under full water curing regime. This rate was 6.5% for NWC. According to Teo et al. [26], 28-day compressive strength, splitting tensile strength, flexural strength and modulus of elasticity of OPS concrete were approximately 0.52, 0.38, 0.58 and 0.27 of the granite concrete, respectively.

To show the potential use of OPS concrete in actual projects, a small footbridge of 2 m in span and a low-cost house with a floor area of 59 m², both using OPS concrete were constructed on the campus of the University of Malaysia Sabah (UMS) [27]. To encourage the use of OPS concrete in construction industry, more research is needed to reveal potential applications of this agricultural solid waste. The use of OPS LWC as a construction material is interesting since the cost of artificial LWA production is high due to the energy costs associated with their production [28]. Therefore, successful use of OPS aggregate in the production of OPS structural lightweight concrete with acceptable mechanical properties can be an alternative way to produce LWAC. In the process, the environmental impact and energy consumption can be simultaneously reduced, thereby achieving energy savings and reducing waste disposal issues.

This study is another effort to show the potential engineering performance of OPS concrete. Compared to the other previous studies, OPS of different shapes was used as a coarse aggregate in this study. OPS was obtained by crushing large sizes of old OPS. The use of crushed OPS is new and this shape of OPS was not used in previous studies. Compressive strength, splitting tensile strength and flexural strength of LWC containing crushed OPS were evaluated. Different curing regimes were chosen for evaluating their effect on the strength of different mixtures of crushed OPS concrete. Normal weight concrete with crushed granite as coarse aggregate was cast to compare its properties with that of crushed OPS concrete.

2. Experimental programme

2.1. Materials used

The materials used in this study were, potable water; ASTM type I ordinary Portland cement (OPC) with a specific gravity of 3.14 and Blaine specific surface area of 3510 cm²/g; local mining sand with specific gravity, fineness modulus, water absorption and maximum grain size of 2.68, 2.65, 0.94% and 4.75 mm, respectively. Sika visconcrete superplasticizer, supplied by Sika in conformity with EN 934-2, was used in the range of 0.8–1.8% of cement weight.

Crushed old OPS were used as coarse aggregate. Old OPS imply that they have been discarded for more than 6 months in the palm oil mill area. Some oil coating and fibre exist on the surface of freshly disposed OPS. When disposed OPS are left outdoors for 2 months, no oil traces are present on the shells [29]. The fibres on the surface of OPS increase the demand for water and cause a weak bond between OPS and cement paste. When OPS are left outdoors for more than 6 month, most of these fibres are removed from their surfaces [30]. Old OPS were used in this study. They were washed and sieved using a 9.5 mm sieve. OPS grains above this sieve were collected and crushed with a stone crushing machine. After crushing, the crushed OPS aggregates were sieved using a 2.36 mm-sieve to remove OPS aggregates of less than 2.36 mm. They were weighed in dry room conditions, and then immersed in water for 24 h. Subsequently, they were air dried in the laboratory to obtain approximately saturated surface dry conditions. For comparison, normal weight concrete contains crushed granite, with grading similar to OPS aggregate and specific gravity of 2.66 was also cast. The physical properties and grading of OPS as well as crushed granite are shown in Tables 1 and 2, respectively. The crushed OPS and granite aggregates are shown in Fig. 1.

2.2. Mix proportions

The mix proportions, slump and density values are shown in Tables 3 and 4, respectively. From the experience of developing high strength OPS concrete [30], mix P1 which has a high workability was chosen and designed. Because of the high workability of this mix, it was possible to reduce the water/cement ratio of this mix for designing another mix, namely, P2 mix. To maintain the high workability of this mix, more superplasticizer content was needed. Compared to the P1 mix, 20% of the fine aggregate was replaced with crushed granite aggregate with a maximum size of 12.5 mm in the P2 mix to reduce the total surface area, and maintain workability similar to the P1 mix. P3 mix has the highest recommended cement content for high strength sanded-LWC as recommended by ACI 213R-87 [31]. This mixture was designed with a higher OPS content with an acceptable workability level for LWAC. P4 mix has a cement content of 360 kg/m³, which is lower than the previous studies [17,27,32–34]. In the N mix, all proportions are similar to the P1 mix, but OPS were replaced in the same volume with crushed granite.

2.3. Test methods and curing regimes

As for the mixing procedure, the cement, sand and OPS were blended in a pan mixer for 1 min. Then, the SP and about 70% of the mixing water were added. After 3 min of mixing, the remaining water was added and the mixing was continued for 2 min. The mix proportions, slump and density values are shown in Tables 3 and 4, respectively. From the experience of developing high strength OPS concrete [30], mix P1 which has a high workability was chosen and designed. Because of the high workability of this mix, it was possible to reduce the water/cement ratio of this mix for designing another mix, namely, P2 mix. To maintain the high workability of this mix, more superplasticizer content was needed. Compared to the P1 mix, 20% of the fine aggregate was replaced with crushed granite aggregate with a maximum size of 12.5 mm in the P2 mix to reduce the total surface area, and maintain workability similar to the P1 mix. P3 mix has the highest recommended cement content for high strength sanded-LWC as recommended by ACI 213R-87 [31]. This mixture was designed with a higher OPS content with an acceptable workability level for LWAC. P4 mix has a cement content of 360 kg/m³, which is lower than the previous studies [17,27,32–34]. In the N mix, all proportions are similar to the P1 mix, but OPS were replaced in the same volume with crushed granite.

Table 1

<table>
<thead>
<tr>
<th>Physical property</th>
<th>OPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>1.22</td>
</tr>
<tr>
<td>Fineness modulus</td>
<td>5.72</td>
</tr>
<tr>
<td>Bulk density (compacted) (kg/m³)</td>
<td>683</td>
</tr>
<tr>
<td>Water absorption (10 and 30 min)</td>
<td>7.65 and 9.70</td>
</tr>
<tr>
<td>Water absorption (1 and 24 h) (%)</td>
<td>10.20 and 18.73</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Cumulative % by weight passing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OPS</td>
</tr>
<tr>
<td>12.5</td>
<td>100</td>
</tr>
<tr>
<td>8.5</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>27.9</td>
</tr>
<tr>
<td>4.75</td>
<td>27.9</td>
</tr>
<tr>
<td>3.35</td>
<td>10.0</td>
</tr>
<tr>
<td>2.36</td>
<td>0.4</td>
</tr>
</tbody>
</table>
The 28-day compressive strength of OPS and normal weight concrete in dry and moist skin conditions, in continuously moist curing (FW), no curing regime (AC) and initial water curing conditions, is summarized in Table 5.

### 3. Results and discussion

#### 3.1. Compressive strength

The 28-day compressive strength of OPS and normal weight concrete in dry and moist skin conditions, in continuously moist curing (FW), no curing regime (AC) and initial water curing regimes (3 W, 5 W and 7 W) are summarized in Table 5.

#### 3.1.1. Continuously moist curing

The 28-day compressive strength and the oven dry concrete density of OPS concrete varied from 34 to 53 MPa and from 1790 to 1922 kg/m³, respectively. On average, the OPS concrete produced in this study is approximately 21% lighter than normal weight concrete (N mix). The test results of Chen and Liu [36] on LWAC made with expanded clay with particle size ranging from 5 to 15 mm showed that this concrete with 28-day compressive strength ranges from 43 to 53 MPa and has a dry density approximately 36% lighter than normal weight concrete. The present investigation shows that LWAC made with OPS (as an agricultural solid waste) is approximately 23% heavier than a LWAC made with expanded clay (as an artificial lightweight aggregate) in the same range of strength. However, it can be observed that by using this agricultural solid waste a significant saving in the self-weight of concrete can be achieved.

Yasar et al. [3] reported that LWAC made with crushed Scoria aggregate (as a natural lightweight aggregate) had air-dry density of 1860 kg/m³ and 28-day compressive strength of 28 MPa for a standard concrete cylinder. Its density is similar to that of P3 mix. The P3 mix has a 28-day concrete compressive strength of 43 MPa. If a coefficient of 0.8 is used to convert cube strength to standard cylinder strength [37], OPS concrete exhibited approximately 23% higher strength than Scoria concrete of the same density.

The highest 28-day compressive strength achieved in this study was 53 MPa, which is much higher than previous studies. This is about 15% higher than OPS high strength concrete made with uncrushed old OPS aggregate of 9.5 mm maximum grain size conducted by Shafigh et al. [30]. Alengaram et al. [38] reported that most of the previous studies have shown that OPS concrete produced cube compressive strength of approximately 25 MPa. They mentioned that one of the reasons for such low strength of OPS concrete is the weaker bond between the OPS and the cement matrix.

P2 and N mixes have similar proportions but used different types of coarse aggregate. The 28 and 56-day compressive strength of mix P2 is approximately 63% and 65% of the N mix, respectively. Basri et al. [39] reported that OPS concretes have lower compressive strength than ordinary concrete by 42–55% and 41–50% at 28 and 56 days, respectively, depending on the curing environment. Mannan et al. [40] reported that OPS concretes have approximately 52% lower compressive strength than crushed stone concrete. In these two studies, the OPS concretes have strength in the normal range of structural lightweight concrete (17–35 MPa). Therefore, it can

### Table 3

<table>
<thead>
<tr>
<th>Mix no.</th>
<th>Cement (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>Water/cement ratio</th>
<th>Superplastiziser</th>
<th>Coarse aggregate</th>
<th>Fine aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>550</td>
<td>1923</td>
<td>0.350</td>
<td>4.4</td>
<td>333</td>
<td>891</td>
</tr>
<tr>
<td>P2</td>
<td>550</td>
<td>168</td>
<td>0.305</td>
<td>6.0</td>
<td>333</td>
<td>713</td>
</tr>
<tr>
<td>P3</td>
<td>500</td>
<td>177</td>
<td>0.354</td>
<td>6.1</td>
<td>435</td>
<td>726</td>
</tr>
<tr>
<td>P4</td>
<td>360</td>
<td>161</td>
<td>0.448</td>
<td>6.5</td>
<td>381</td>
<td>826</td>
</tr>
<tr>
<td>N</td>
<td>550</td>
<td>170</td>
<td>0.309</td>
<td>6.8</td>
<td>0</td>
<td>713</td>
</tr>
</tbody>
</table>

### Table 4

Slump value and densities of mixtures.

<table>
<thead>
<tr>
<th>Mix no.</th>
<th>Slump (mm)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Demoulded</td>
</tr>
<tr>
<td>P1</td>
<td>230</td>
<td>1938</td>
</tr>
<tr>
<td>P2</td>
<td>205</td>
<td>2016</td>
</tr>
<tr>
<td>P3</td>
<td>65</td>
<td>1893</td>
</tr>
<tr>
<td>P4</td>
<td>33</td>
<td>1927</td>
</tr>
<tr>
<td>N</td>
<td>185</td>
<td>2373</td>
</tr>
</tbody>
</table>

It known that surface moisture affects the strength of concrete [35]. Therefore, to determine the skin effect on the 28-day compressive strength of OPS concretes, three cube specimens of each mixture were placed out of the water and put in the lab environment 24 h prior to testing.

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>28-day compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Continuously moist curing</td>
</tr>
<tr>
<td>P1</td>
<td>41.38</td>
</tr>
<tr>
<td>P2</td>
<td>53.05</td>
</tr>
<tr>
<td>P3</td>
<td>43.25</td>
</tr>
<tr>
<td>P4</td>
<td>34.29</td>
</tr>
<tr>
<td>N</td>
<td>84.45</td>
</tr>
</tbody>
</table>
be seen that the difference between OPS concrete and conventional coarse aggregate concretes reduces for high strength OPS concrete.

3.1.2. Effect of curing conditions on 28-day compressive strength

Haque [41] reported that to negate skin effects, all specimens in his study were placed outside the fog room (23 ± 2 °C and RH of 95 ± 5%) 24 h prior to testing. It has been reported [42] that air dried specimens have 20–25% higher strength than specimens in a saturated condition.

It can be seen from Table 5 that the specimens of the P1, P2, P3 and P4 mixes in dry skin condition have 8.7%, 2.4%, 2.3% and 6.9% higher strength than moisture skin condition, respectively. As shown in Table 5, if the dry skin condition of FW curing condition is considered all OPS mixtures show a strength loss under AC. The strength loss is 18.5%, 11.6%, 8.1% and 5.6% for P1, P2, P3 and P4 mixes, respectively. It can be seen that the sensitivity of OPS concrete in poor curing decrease by a reduction in the water/cement ratio, higher OPS content or lower cement content. The P2 mix shows 6.9% lower strength loss than the P1 mix. Therefore, it can be concluded that by reducing the water/cement ratio of OPS concrete the sensitivity in poor curing will reduce.

The strength loss of the P3 mix is significantly lower than the P1 mix. This might be due to the higher OPS content in the P3 mix, which causes a higher degree of hydration of cement because of better internal curing. The benefits of internal curing include increased hydration and strength development, reduced autogenous shrinkage and cracking, reduced permeability and increased durability [43]. Another reason may be due to the lower cement content of P3 mix compared to P1 mix. The effect of cement content on the strength loss of OPS concrete is clearer when it can be observed that the strength loss of the P4 mix is lower than the other mixtures. The P4 mix has 35% lower cement and 14% higher OPS content than the P1 and P2 mixes. The strength loss of this mix is significantly lower than the P1 and P2 mixes.

It was reported [30] that under air curing (AC), OPS concrete made with uncrushed OPS aggregate with 9.5 mm maximum size and with 28-day compressive strength of 42–48 MPa, has strength loss in the range of 14–26%. In the present study the strength loss for OPS concrete with 28-day compressive strength of 41–53 MPa was 6–11%. It can be seen that the sensitivity of OPS concretes made with crushed OPS in poor curing conditions (AC) is lower than that of uncrushed OPS concrete.

The 28-day compressive strength of OPS concrete under initial water curing (7 W, 5 W and 3 W) showed that there is little difference between the strength of OPS concretes under these curing conditions. This means that although 7 W curing is recommended for ASTM type-I cement [44], for OPS concrete made with crushed OPS, 3 W curing is comparable to 7 W curing. Therefore, the cost of curing can significantly be reduced.

The average strength of the P1, P2, P3 and P4 mixes under initial curing conditions is 40.2, 52.4, 42.8 and 36.7 MPa, respectively. Compared to FW curing with dry skin, these mixes show strength loss of approximately 11%, 4%, 3% and 0%, respectively. These results imply that when the water/cement ratio is reduced, the OPS content is increased or the cement content is reduced in OPS concrete, then the initial curing can significantly reduce the strength loss of OPS concrete.

Moreover, for different curing conditions, a noticeable finding was observed in the P4 mix. In this mix, the 28-day compressive strength under 3 W curing regime was similar to FW curing. This result shows that when the cement content in the OPS concrete is in the usual range, even 2 days moist curing of specimens after demoulding will be sufficient.

A comparison between the P1 and N mixes reveals that the strength loss of OPS concrete without any curing (AC) is almost twice as high as granite concrete. However, under initial water curing conditions, the P1 mix has lower strength loss than the N mix.

3.2. Splitting tensile strength

Fig. 2 shows the relationship between the compressive and splitting tensile strength of OPS concrete. It can be observed that the splitting tensile strength increases with increasing compressive strength. The measured 28-day splitting tensile strength is in the range of 2.85–3.54 MPa. Previous studies [25,27,45,46] showed that the 28-day splitting tensile strength of OPS concrete in moist curing is in the range of 1.10–2.41 MPa. It can be seen that the splitting tensile strength measured in this study is significantly higher than previous studies. In most cases, the splitting tensile strength of LWC of cube compressive strengths of 30, 40 and 50 MPa is in the range of 1.8–2.7, 2.2–3.3 and 2.5–3.8 MPa, respectively [4].

The 28-day splitting tensile strength of crushed OPS concretes was 6.7–8.1% of the compressive strength. Generally, the splitting tensile strength of concrete is 8–14% of the compressive strength [47]. Compared to normal weight concrete (NWC), the tensile/compressive strength ratio is lower for LWAC of equivalent grade [48]. However, the tensile/compressive strength ratio of OPS concrete measured in this study is comparable with LWAC made with an artificial LWA, namely, Lytag of an equivalent grade, as reported by Haque et al. [48]. Furthermore, it was reported that for high strength lightweight concrete, in continuously moist cured; the splitting tensile strength is generally 6–7 percent of the compressive strength [49]. It can be seen that the ratios obtained for OPS high strength concrete in this study is within this range.

As can be seen in Fig. 3, the 28-day splitting tensile and compressive strength of OPS concrete in this study revealed that
the splitting tensile/compressive strength ratio decreases as the compressive strength increases. This trend was reported by Neville [24], who mentioned that, as the compressive strength increases, the tensile strength also increases but at a decreasing rate. Caldarone [50] reported that the relationship between the splitting tensile strength and the compressive strength of NWCs, having measured compressive strengths of up to 84 MPa at 28 days, showed that at low strengths, the splitting tensile strength may be as high as 10% of the compressive strength but at higher strengths, it may reduce to 5%.

A comparison between the splitting tensile strength of the P2 and N mixes showed that with the same mortar, LWAC made with crushed OPS has a tensile strength of about 28% lower than NWC made with crushed granite.

The proposed equation based on the results of the present study provided a parabolic relationship between the compressive strength and the splitting tensile strength is given by:

\[ f_{st} = 0.4887 \sqrt{f_{cu}} \]  \hspace{1cm} (1)

where \( f_{st} \) is splitting tensile strength and \( f_{cu} \) is cube compressive strength, both in MPa.

Fig. 4 shows the comparison of the experimental values of splitting tensile strength with those predicted by the various equations given by Oluokun [51] for NWC (Eq. (2)), Shafiqi et al. [14] for OPS concretes with a cube compressive strength ranging from 17 to 37 MPa (Eq. (3)), Smadi and Migdady [52] for natural Tuft LWAC with high strength (Eq. (4)), Neville [24] for pelletized blast furnace slag LWAC with cube compressive strength ranging from 10 to 65 MPa (Eq. (5)), Slate et al. [53] for high strength lightweight concrete (Eq. (6)), Gesoglu et al. [54] for cold-bonded fly ash LWAC with a cube compressive strength ranging from 20 to 47 MPa (Eq. (7)), and Babua et al. [55] for lightweight expanded polystyrene aggregate concretes (Eq. (8)).

\[ f_{st} = 0.20 f_{cy}^{0.7} \]  \hspace{1cm} (2)

\[ f_{st} = 0.20 \sqrt[3]{f_{cu}}^{2} \]  \hspace{1cm} (3)

\[ f_{st} = 0.46 \sqrt{f_{cy}} \]  \hspace{1cm} (4)

\[ f_{st} = 0.23 \sqrt[3]{f_{cu}} \]  \hspace{1cm} (5)

\[ f_{st} = 0.51 \sqrt{f_{cy}} \]  \hspace{1cm} (6)

\[ f_{st} = 0.27 \sqrt[3]{f_{cu}} \]  \hspace{1cm} (7)

From Eqs. (2)–(8), Eq. (7) predicts the splitting tensile strength from the cube compressive strength very close to the experimental results of this study, with an average of 3.2% overestimating error. Eq. (6) predicts the splitting tensile strength from cylinder compressive strength with an average of 6.7% underestimating error. It should be noted that an accurate prediction of tensile strength of concrete will help in mitigating cracking problems, improve shear strength prediction and minimize the failure of concrete in tension due to inadequate methods of tensile strength prediction [56,57].

### 3.3. Flexural strength

The 28-day flexural strength of the OPS concrete in this study ranged from 4.42 to 6.99 MPa. Previous studies [11,17,20,25,46,58] revealed that OPS concretes have flexural strength in the range of 2.13–4.93 MPa. The 28-day flexural strength was, on average, 13.7% of the 28-day compressive strength, ranging from 12.9% to 14.8%. It was reported [42] that the flexural strength of NWC with a compressive strength of 34–55 MPa is in the range of 5–6 MPa and a flexural/compressive strength ratio is in the range of 11.6–13.5%. Therefore, it can be concluded that OPS concretes tested in this study have a similar or higher flexural strength and flexural/compressive strength ratio than NWC of the same compressive strength. It was also reported [49] that the flexural strength of high strength lightweight aggregate concrete (HSLWAC) under continuous moist curing, is generally in the range of 9–11% of the compressive strength. The test results of the present study show that OPS concretes with high strength have a higher flexural/compressive strength ratio than the value mentioned for HSLWAC. The ratio of splitting/flexural strength ratio for P1, P2, P3 and P4 mixes was found to be 51%, 51%, 72% and 64%, respectively. These values show that this ratio increases with increasing OPS content in the mixture.

Alengaram et al. [46] reported that this ratio for OPS concrete is between 60% and 70%.

Fig. 5 shows the relationship between the 28-day cube compressive strength and the flexural strength of crushed OPS LWC. Using linear regression analysis of the data, Eq. (9) was obtained for compressive strength in the range of 34.8 and 53 MPa:

\[ f_{fr} = 0.12 f_{cu}^{0.03} \]  \hspace{1cm} (9)

where \( f_{fr} \) is flexural strength and \( f_{cu} \) is compressive strength in MPa.

Fig. 6 shows a comparison between the predicted values for flexural strength based upon known compressive strength using Eq. (10) as reported by Alengaram et al. [46] for OPS concretes with compressive strength ranging from 15 to 37 MPa; Eq. (11) as reported by Lo et al. [37] for expanded clay lightweight aggregate concrete with cube compressive strength ranging from 29 to 43 MPa; Eq. (12) [4] was suggested for lightweight concrete made

![Fig. 4. Experimental and theoretical 28-day splitting tensile strength of OPS concrete.](image-url)

![Fig. 5. Relationship between 28-day compressive and flexural strength of crushed OPS concrete.](image-url)
with expanded shale and clay aggregates with a cube compressive strength ranging from 20 to 60 MPa; and Eq. (13) [52] was suggested for lightweight concrete made with Tuff lightweight aggregate.

\[
f_r = 0.30 \sqrt{f_{cu}}
\]  
(10)

\[
f_r = 0.69 \sqrt{f_{cu}}
\]  
(11)

\[
f_r = 0.46 \sqrt{f_{cu}}
\]  
(12)

\[
f_r = 0.58 \sqrt{f_{cu}}
\]  
(13)

From Fig. 6, it can be observed that Eq. (10), which was suggested for OPS concretes, gives a very low underestimate of the flexural strength based upon known compressive strength and is not appropriate for crushed OPS concrete. From Eqs. (10)–(13), only Eq. (12) gives a closer estimate to the present experimental results. The 28-day flexural strength of the N mix was 8.4 MPa. The flexural/compressive strength ratio of this mix was 59%. In the present study, it was found that if crushed OPS is used instead of crushed granite aggregate (as in P2 mix), then the flexural strength and flexural/compressive strength ratio are reduce by about 17% and 8%, respectively.

4. Conclusions

Based on the experimental results of this study the following conclusions can be drawn:

(1) The density of crushed OPS concrete was found to be approximately 23% higher than artificial LWA concrete of the same strength. However, this concrete has a 28-day compressive strength that was approximately 23% higher than a natural LWA concrete of the same density.

(2) All OPS specimens made with crushed OPS showed a strength loss of approximately 6–11% when not subjected to any curing (AC), which is significantly lower than for uncrushed OPS concrete. The sensitivity of OPS concrete in poor curing conditions decreases by reducing the water/cement ratio, increasing the OPS content or lowering the cement content.

(3) There is no considerable difference between the 28-day compressive strength of OPS concretes under initial water curing conditions (7 W, 5 W) and (3 W). Therefore, 3 W curing instead of 7 W curing condition can be sufficient, which can reduce curing cost. When the water/cement ratio is reduced or the OPS content is increased, or the cement content is low, the initial water curing can significantly reduce the strength loss of OPS concrete.

(4) Although OPS concrete in poor curing conditions has higher strength loss (approximately two times) compared to granite concrete, by providing initial water curing the strength loss of OPS concrete can be lower than granite concrete.

(5) The 28-day splitting tensile strength of crushed OPS concrete was measured in the range of 2.85–3.54 MPa. These values are significantly higher than previous studies and are in the usual range for LWC.

(6) The tensile/compressive strength ratio of OPS concrete is lower than normal concrete. However, it is comparable with LWAC made with artificial LWA of an equivalent grade.

(7) The 28-day flexural strength ranges from 4.4 to 7.0 MPa, which is 12.9–14.8% of the 28-day compressive strength. This ratio increases with increasing OPS content in the mixture. These ratios are comparable or even higher than normal weight concrete.

(8) The 28-day compressive strength, splitting tensile and flexural strength of OPS concrete was found to be 38%, 28% and 17% lower than that of granite concrete.

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References


