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Oil palm shell as an agricultural solid waste in artificial lightweight aggregate concrete

Payam Shafigh\textsuperscript{a*}, Salmaliza Salleh\textsuperscript{b}, Hafez Ghafari\textsuperscript{c} and Hilmi Bin Mahmud\textsuperscript{d}

\textsuperscript{a}Department of Building Surveying, Faculty of Built Environment, University of Malaya, Kuala Lumpur 50603, Malaysia; \textsuperscript{b}Faculty of Engineering and Built Environment, SEGi University, Kota Damansara, Petaling Jaya, Selangor 47810, Malaysia; \textsuperscript{c}Sustainable Deliverable, 140 N Wilson Ave, Pasadena, CA 91106, USA; \textsuperscript{d}Department of Civil Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia

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The aim of this study was to produce a sustainable construction material by incorporating an agricultural solid waste, namely oil palm shell (OPS), in an artificial lightweight aggregate concrete. For this purpose, in a structural lightweight aggregate concrete made of expanded clay, the lightweight aggregate was substituted with OPS in 0, 25 and 50% by volume. Properties such as compressive strength under different curing conditions, as well as density, splitting tensile and flexural strengths, modulus of elasticity and drying shrinkage of expanded clay–OPS concretes were measured and discussed. The test results showed that partial substitution of expanded clay by OPS increased the density, compressive strength, specific strength (compressive strength to weight ratio), as well as splitting tensile and flexural strengths of lightweight concrete. However, it was observed that the modulus of elasticity decreased by about 4 and 13% in the 25 and 50% substitution levels, respectively. The expanded clay–OPS concretes showed greater drying shrinkage strain compared to expanded clay lightweight concrete. In addition, it was found that the sensitivity of compressive strength of concretes containing OPS to the lack of curing is due to high drying shrinkage and consequently micro-cracks formation in the interfacial transition zone of the concretes.

Keywords: lightweight concrete; oil palm shell; expanded clay; mechanical properties; green concrete

1. Introduction

There are two ways to improve the specific strength (strength/density ratio) of concrete: (1) reducing its density by developing lightweight concrete and (2) increasing the strength of concrete by developing high-strength concrete (Li, 2011). Structural lightweight concrete has been widely and successfully used in the construction of buildings and infrastructure since the 1920s (Li, 2011). The immediate benefit of using lightweight aggregate concrete is the reduction in dead weight, which, in turn, may lead to potential savings in reinforcement and prestressing steel, transportation and handling of aggregates and precast elements, reduced formwork and smaller foundations (CBDG, 2006).

In most cases, structural lightweight concrete is made using a lightweight aggregate as coarse aggregate and normal weight sand as fine aggregate. There are many types of
lightweight aggregate for producing structural lightweight aggregate concrete with a strength range of 20 to 40 MPa. Aggregates, such as Leca, Keramzite, Korlin (expanded clay); Agloporite, Haydite (sintered shale); Solite (expanded slate) and Lytag (sintered pulverised-fuel ash), are suitable for the production of concrete in this strength range (CEB/FIP manual of design & technology, 1997). Production of artificial lightweight aggregates such as Leca requires the combustion of fuels to provide high temperatures in the range of 1100 to 1200 °C by the rotary kiln process to melt raw materials such as clay (Bhatty & Reid, 1989; Harmon, 2007). Therefore, these types of lightweight aggregate are not economic and also ecologic materials (Ayhan, Gönül, Gönül, & Karakuş, 2011).

The use of artificial lightweight aggregates has various limitations: (1) the raw materials for heat-expanded aggregate are only available in certain limited geographic areas; (2) these aggregates are becoming less profitable due to the increasing costs for the raw materials, fuel and equipment, and they make relatively small amounts of product with poor uniformity (Glenn, Miller, & Orts, 1998). Hossain, Ahmed, and Lachemi (2011) suggest the use of natural lightweight aggregate instead of processed artificial lightweight aggregates in lightweight concrete, which leads to low-cost construction.

Oil palm shell (OPS) or palm kernel shell (PKS) is a solid waste from the palm oil industry and has the characteristics of a lightweight aggregate (Okpala, 1990). This lightweight aggregate has been successfully used as a coarse aggregate for the manufacture of structural lightweight aggregate concrete with normal strength (Teo, Mannan, & Kurian, 2006) and high strength (Shafigh, Jumaat, & Mahmud, 2011). Mo, Visintin, Alengaram, and Jumaat (2016) and Yap, Alengaram, Jumaat, and Khaw (2015) have investigated the structural behaviour of OPS concrete beams to improve design guideline of this type of lightweight aggregate concrete beams. Acheampong, Adom-Asamoah, Ayarkwa, and Afrifa (2015) studied shear behaviour of reinforced concrete beams constructed with grade 20 PKS lightweight concrete. They reported that shear behaviour of PKS concrete beam is comparable to that of an equivalent normal concrete beam. OPS grains are hard and are not easily crushed, particularly when old OPS is crushed to smaller sizes of 5 to 8 mm (Shafigh, Jumaat, Mahmud, & Alengaram, 2011) whereas, an artificial lightweight aggregate, namely Leca is easily broken. Therefore, it is expected that lightweight concrete made of OPS aggregate has a better compressive strength compared to Leca lightweight concrete.

The aim of this study was to produce a greener structural lightweight aggregate concrete by incorporating OPS as partial replacement instead of Leca in a grade 20 sanded-Leca lightweight concrete. For this purpose, Leca was substituted with OPS in 0, 25 and 50% by volume. For all mixes, properties, such as compressive strength in different curing regimes, splitting tensile and flexural strengths, modulus of elasticity and drying shrinkage strain, were studied.

2. Research significance

The replacement of expanded clay with OPS has significant environmental importance. The process eliminates energy that is used and pollution that is discharged into the environment in production of expanded clay. The amount of energy used for crushing the naturally produced OPS is not comparable with the amount used for the production of synthetic products.

Recycling of agricultural solid waste as a construction material appears to be a viable solution, not only to the problem of pollution but also as an economical option.
to design green buildings (Raut, Ralegaonkar, & Mandavgane, 2011). OPS recycled as lightweight concrete material is indeed a potential source of pollution that is diverted from disposal sites and turned into a source of economical value for the community. In addition, the environmental benefits of this technique are recognised by most of sustainability and green building codes and rating systems. For instance, the United States Green Building Council’s (USGBC) Leadership in Energy and Environmental Design (LEED) (US Green Building Council, 2009), which is a globally recognised green building rating system, gives points to OPS concrete for using pre-consumer recycled material. Using this concrete can result in LEED points for a building in other categories including rapidly renewable material, recycled content and regional (locally available) materials.

The International Green Construction Code (IgCC), developed by the International Code Council (ICC), is intended to be adopted on a mandatory basis. It is the first model code to include sustainability measures for the entire construction project (ICC, 2012). The IgCC consists of minimum mandatory requirements and covers Material Resource Conservation and Efficiency in its fifth chapter. According to this chapter, 55% of the materials used in the construction project must be recycled, recyclable, bio-based or indigenous. In addition, the materials are permitted to have multiple attributes. As a bio-based and recycled material, OPS used as aggregate in concrete is eligible to be counted towards the percentage of this kind of material required by the code.

3. Materials and methods

3.1. Materials used

The binder used was ordinary Portland cement, which was obtained from a local cement company with a specific gravity, Blaine surface area, initial and final setting times of 3.14 g/cm³, 3510 cm²/g, 65 min and 140 min, respectively. A superplasticizer (SP) based on polycarboxylic ether (PCE) was used in all mixes.

Local mining sand with a fineness modulus of 2.45 was used as fine aggregate. Crushed old OPS and expanded clay with a maximum nominal size of 8 mm as well as crushed granite with a maximum nominal size of 12.5 mm were used as coarse aggregate in the concrete mixtures. The specific gravity and 24-h water absorption of OPS were 1.2 and 20%, respectively, while for expanded clay they were 0.66 and 28%, respectively.

3.2. Mix proportions

The mix proportions for all mixes are shown in Table 1. All mixes included coarse lightweight aggregate and normal sand as fine aggregate. The control mix of L was designed according to the trial and error method to achieve a structural lightweight

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Cement (kg)</th>
<th>Water (kg)</th>
<th>SP</th>
<th>Sand (kg)</th>
<th>Expanded Clay (kg)</th>
<th>OPS (kg)</th>
<th>Granite (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>480</td>
<td>173</td>
<td>1.2</td>
<td>755</td>
<td>189</td>
<td>0</td>
<td>47</td>
</tr>
<tr>
<td>L25</td>
<td>480</td>
<td>173</td>
<td>1.5</td>
<td>755</td>
<td>142</td>
<td>86</td>
<td>47</td>
</tr>
<tr>
<td>L50</td>
<td>480</td>
<td>173</td>
<td>2.0</td>
<td>755</td>
<td>95</td>
<td>173</td>
<td>47</td>
</tr>
</tbody>
</table>
aggregate concrete to fulfil the requirements of the American concrete institute (ACI) standard (ACI 318–08, 2008). The type of lightweight aggregate was just expanded clay in this mix. By substitution of the expanded clay with 25 and 50% of crushed OPS by volume, mixes of L25 and L50 were produced, respectively. The slump value for all mixes was kept constant in the range of 50 ± 5 mm. Due to expanded clay aggregate is round, it helps to improve the workability. When such aggregate is substituted with OPS, the slump value decreases. Therefore, concretes containing OPS have a higher SP content than expanded clay concrete. Alengaram, Mahmud, and Jumaat (2010) reported that the use of SP in OPS concrete is required to obtain the desired workability.

It should be noted that due to the lower aggregate density, a structural lightweight aggregate concrete may have the same workability compared to normal weight concrete with a higher slump value (Kockal & Ozturan, 2011). Mehta and Monteiro (2006) reported that the workability of a structural lightweight aggregate concrete with a slump value of 50–70 mm may be the same as that of a normal weight concrete with a slump value of 100–125 mm. In this study, the workability of all mixes was suitable for good compaction by a vibration table.

3.3. Test methods

For the mixing of constituent materials, the cement, sand and coarse aggregate were blended in a rotary concrete mixer for 2 min. Then, mixing water was added to the mixture and mixing continued for another 3 min. The SP was added to the mixture to achieve the desired workability (slump value of 50 ± 5 mm). The slump test was then performed. Using steel moulds, the concrete specimens were cast in 100-mm cubes, cylinders of 100 mm diameter and 200 mm height, cylinders of 150 mm diameter and 200 mm height, and prisms of 100 × 100 × 500 mm³ for compressive strength, splitting tensile strength, modulus of elasticity and flexural strength tests, respectively. In addition, prism specimens with dimensions of 100 × 100 × 300 mm³ were used for measuring the drying shrinkage strain.

Specimens were compacted using a vibrating table and were demoulded one day after casting. Three specimens were prepared for obtaining the average for mechanical properties and two specimens were used for the drying shrinkage. The drying shrinkage test was performed on two prism specimens after 7-days curing. The shrinkage value for each age is the average of four readings. In addition, as shown in Table 2, six curing regimes were chosen to study the influence of curing conditions on the 28-day compressive strength of concretes.

<table>
<thead>
<tr>
<th>Curing code</th>
<th>Days in mould</th>
<th>Days in water</th>
<th>Days in air</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AC2</td>
<td>1</td>
<td>0</td>
<td>27</td>
</tr>
<tr>
<td>3 W</td>
<td>1</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>5 W</td>
<td>1</td>
<td>4</td>
<td>23</td>
</tr>
<tr>
<td>7 W</td>
<td>1</td>
<td>6</td>
<td>21</td>
</tr>
<tr>
<td>FW</td>
<td>1</td>
<td>27</td>
<td>0</td>
</tr>
</tbody>
</table>

1(%RH = 73 ± 5, T = 30 ± 3 °C)
2(%RH = 69 ± 2, T = 21 ± 1 °C).
4. Results and discussion

4.1. Density

OPS is about 80% heavier than expanded clay. Therefore, it is expected that the substitution of expanded clay with OPS in an expanded clay lightweight concrete increases the density of the concrete. Figure 1 shows the relationship between the substitution percentage of expanded clay with OPS and the dry density of concrete. This figure shows that the density of the concrete increased linearly from 1640 to 1770 kg/m$^3$ with increasing the OPS substitution level. Although the density of concrete increases using OPS instead of expanded clay, the density of concrete at the 50% substitution level still meets ACI and the European specifications for structural lightweight aggregate concrete. The European and the ACI specification for the air dry density of a structural lightweight concrete is 2000 and 1850 kg/m$^3$, respectively (Shannag, 2011). However, in practice, a concrete with a density less than 2160 kg/m$^3$ is considered lightweight concrete (Graybeal & Lwin, 2013). If it be assumed that normal weight concrete has a dry density of about 2300 kg/m$^3$, the L, L25 and L50 concretes are, respectively, about 29, 25 and 23% lighter than normal weight concrete.

It is believed that lightweight concrete is a relatively green building material (Cui, Lo, Memon, Xing, & Shi, 2012). Therefore, it can be said that the L25 and L50 mixes are a greener construction material due to the significant use of a solid waste instead of an artificial lightweight aggregate.

4.2. Compressive strength under moist curing and specific strength

Figure 2 shows the compressive strength of three types of lightweight aggregate concrete at different ages. It was observed that by incorporating OPS in expanded clay lightweight concrete, the compressive strength increased at all ages. A higher OPS content results the better compressive strength. The 28-day compressive strength of expanded clay lightweight concrete increased from about 22–24 and 27 MPa by incorporating 25 and 50% OPS aggregate, respectively, which showed an increase in the compressive strength of about 9 and 23%, respectively. Such an increase in the compressive strength shows that the OPS grains are stronger than expanded clay. Mehta and Monteiro (2006) reported that most structural lightweight concretes have a density in the range of 1600 to 1760 kg/m$^3$, and design strengths of 20 to 35 MPa are common.

Figure 1. Relationship between air dry density and percentage replacement of OPS.
can be seen that the density and 28-day compressive strength of the mixes containing OPS are in these ranges. It should be noted that in the case of mix L50 with higher density, 50% volume of lightweight coarse aggregate or about 14% of the total volume of lightweight concrete included OPS, which is a waste from the agricultural industry.

Although the substitution of the expanded clay with OPS increased the density of concrete, which is a negative effect of using this lightweight aggregate, due to the significant increase in the strength of concrete, more benefits can be achieved from the increase of the strength. This can be shown by the specific strength of the concrete (Li, 2011). The specific strength (strength/weight ratio) of the L, L25 and L50 mixes are 13,325, 13,986 and 15,271 N.m/kg, respectively. The specific strength of mix L increased by increasing the OPS content about 5 and 15% by incorporating 25 and 50% OPS aggregate, respectively.

4.3. Compressive strength under partial early moist curing

In practice, structural lightweight concrete elements are rarely moist cured for more than 7 days (Türkmen, 2003) and most codes of practice recommend 7-days moist curing for concrete (ACI 318–08, 2008; Haque, 1990).

Table 3 shows the 28-day compressive strengths for all the mixes under different curing environments. It can be seen that expanded clay lightweight concrete (mix L) under air drying and partial early curing regimes showed no reduction in the compressive strength compared to the moist curing condition, while the mixes containing OPS (L25 and L50 mixes) showed a reduction in the compressive strength. This shows that the inclusion of OPS in the concrete mixture makes it more sensitive to the lack of curing and that the higher the OPS content, the greater sensitivity to the lack of curing. However, it can be seen that when lightweight concrete containing OPS showed a

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Curing condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AC1</td>
</tr>
<tr>
<td>L</td>
<td>21.0</td>
</tr>
<tr>
<td>L25</td>
<td>21.0</td>
</tr>
<tr>
<td>L50</td>
<td>21.4</td>
</tr>
</tbody>
</table>

Figure 2. Compressive strength of concrete mixes (MPa).
significant reduction in the compressive strength under the air drying conditions (AC1 and AC2 curing conditions), even two days of moist curing (3W condition) significantly compensated for the reduction of the compressive strength.

According to the test results for the compressive strength, expanded clay lightweight concrete (mix L) does not need any special care after demoulding, while a minimum moist curing of 4 and 6 days is needed after demoulding for the L25 and L50 mixes, respectively. Tan and Gjorv (1996) investigated the effect of curing conditions on the strength and permeability of normal weight concrete. They observed that concretes with 2- and 6-days moist curing after demoulding have higher compressive strengths compared to those with 28 days of curing. They demonstrated that this may be due to the removal of moisture from the interlayer of cement gel. In this study, it was also observed that the expanded clay lightweight concrete (mix L) showed about 2–7% higher strength under partial early curing than for the 28-days moist curing condition. However, lightweight concrete containing OPS aggregate showed a 0–8.5% reduction in the compressive strength. These results show that the type of coarse aggregate has a significant effect on the performance of partial early curing on the compressive strength of concrete.

4.4. Splitting tensile and flexural strengths

Table 4 shows the 28-day splitting tensile and flexural strengths for all mixes. Similar to the compressive strength, incorporating OPS in concrete increased the tensile strength. The greater contribution of OPS results in better tensile strength. The increase in the flexural strength was more than for the splitting tensile strength. By incorporating 25 and 50% OPS in the artificial lightweight aggregate concrete (mix L), the splitting tensile strength increased 0 and 16.8%, respectively, while an increase of about 13.2 and 28.8% was observed in the flexural strength, respectively. In most cases, the splitting tensile strength of a lightweight concrete with a cube compressive strength of 20–30 MPa ranges from 1.4 to 2.7 MPa, with the splitting tensile-to-compressive strength ratio ranging from 6 to 10% (CEB/FIP manual of design & technology, 1997).

It can be seen that the splitting tensile strength and its ratio to the compressive strength for all mixes is in the normal range of lightweight concrete. However, in the case of mix L50, the splitting tensile strength is close to the upper limit.

Among many prediction equations for the splitting tensile strength from the compressive strength, it was found that there are two appropriate equations for predicting the splitting tensile strength of the L, L25 and L50 mixes from their compressive strength. The first equation was suggested by CEB-PIP (1993) (Equation (1)) while the second was recommended by Khan and Lynsdale (2002) (Equation (2)). They found the equation from a series of data that include various cementitious systems and water-to-binder ratios. The compressive strength and splitting tensile strength in their investigation varied between 15–110 MPa and 2–8.5 MPa, respectively.

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Splitting tensile strength (MPa) ($f_t$)</th>
<th>Flexural strength (MPa) ($f_r$)</th>
<th>$f_t/f_{cu}$ (%)</th>
<th>$f_r/f_{cu}$ (%)</th>
<th>$f_r/f_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>1.96</td>
<td>3.26</td>
<td>9.0</td>
<td>15.0</td>
<td>1.66</td>
</tr>
<tr>
<td>L25</td>
<td>1.96</td>
<td>3.69</td>
<td>8.2</td>
<td>15.4</td>
<td>1.88</td>
</tr>
<tr>
<td>L50</td>
<td>2.29</td>
<td>4.20</td>
<td>8.5</td>
<td>15.6</td>
<td>1.83</td>
</tr>
</tbody>
</table>
where \( f_t \) is the splitting tensile strength (MPa), and \( f_{cu} \) and \( f_{cy} \) are the cube and cylinder compressive strengths (MPa), respectively. The use of Equations (1) and (2) gives, on average, about a 6 and 2% overestimate for all mixes, respectively.

There are several equations for predicting the flexural strength of lightweight concrete from their compressive strength. The ACI standard (ACI 318–08, 2008) recommends Equation (3) for lightweight concrete. If this equation is used for predicting the flexural strength of the L, L25 and L50 mixes, the predicted amount is significantly (on average about 37%) lower than the experimental results. However, Equations (4–7) give a closer estimation to the experimental results. Equation (4) (Lo, Cui, & Li, 2004) is recommended for expanded clay lightweight concrete. The use of this equation is only appropriate for mix L and mix L25, with an average error of about 4%, while this equation gives about a 14% underestimate error for mix L50. Equation (5) (Shetty, 2004) is recommended by the Indian standard. This equation, similar to Equation (4), is more appropriate for expanded clay lightweight concrete as well as for expanded clay lightweight concretes containing low percentages of OPS aggregate. However, Equations (6) (Zhang & Gjorv, 1991) and (7) (Short & Kinnburgh, 1978) are the best prediction equations for expanded clay lightweight concrete as well as for lightweight concrete containing expanded clay and with a high volume (up to 50%) of OPS aggregate. The use of this equation gives an estimated value with an error less than 10%. Therefore, if a general equation prediction for the flexural strength be considered as \( f_r = k \times f_{cu}^{0.5} \), \( k \) is a constant in the range of 0.73–0.76. It should be noted that the flexural strength of normal weight concrete is often approximated as 0.7–0.8 times the square root of the compressive strength in MPa (Kosmatka, Kerkhoff, & Panarese, 2002).

The ratio of the flexural-to-splitting tensile strengths of the mixes is in the range of 1.66–1.88. Reports (Bhanja & Sengupta, 2005; Zhou, Barr, & Lydon, 1995) show that this ratio for normal weight concrete varies between 1.35 and 1.65. It can be seen that the ratio in this study is more than normal weight concrete. The greater ratio obtained for OPS concretes in this study shows that although flexural and splitting tensile strengths of lightweight concrete is less than normal weight concrete; however, the splitting tensile strength is weaker compared to the flexural strength.

### 4.5. Modulus of elasticity

The modulus of elasticity of the L, L25 and L50 mixes were measured at 15.8, 15.1 and 13.8, respectively. The modulus of elasticity reduced about 4.4 and 12.7% when the...
expanded clay lightweight aggregate in mix L was substituted with OPS in percentages of 25 and 50% (by volume), respectively.

The estimation equation for the modulus of elasticity of standards, such as BS 8110 (1997) (Equation (8)) and ACI 318 (ACI-318, 318R, 2009) (Equation (9)), shows that the modulus of elasticity could be estimated from the compressive strength and density of concrete.

\[
E = 0.0017w^2f_{ck}^{0.33} \quad 1400 < w < 2320
\]  
\[
E = 0.043w^{1.5}f_c^{0.5} \quad 1500 < w < 2500, \quad fc < 41
\]

These estimation equations show that if the strength and density of concrete increase, the modulus of elasticity also increases. However, according to the results of this study, the conclusion from such equations is not always correct. For example, in mix L, when a part of the expanded clay was substituted with OPS, the density and compressive strength increased while the modulus of elasticity decreased. Compared to mix L, Mix L50 had 23.9 and 8.1% greater compressive strength and dry density, respectively. According to the predictions of BS 8110 and ACI equation, it is expected that this concrete (mix L50) should have a modulus of elasticity of about 25% higher than mix L, while the modulus of elasticity for this concrete is 12.7% less than mix L. Therefore, when a lightweight concrete is made of two or more types of lightweight aggregate, the accuracy of the equation prediction should be well-studied. This is because different types of lightweight aggregate have different properties. In addition, the performance and fracture mechanisms of different types of lightweight aggregate may be different.

Anwar Hossain (2004) reported that the modulus of elasticity is affected by several factors, such as the compressive strength, stiffness and volume of lightweight aggregate, interfacial zone between the aggregate and the paste, as well as the elastic properties of the constituent materials. When all of these factors are considered, it can be seen that the stiffness of OPS is more than for the expanded clay aggregate. Therefore, while it was expected that the modulus of elasticity should be increased in the mixes containing OPS, it reduced. The total volume of lightweight aggregate and all other materials were similar for all mixes. Therefore, it seems that the main reason for the modulus of elasticity results could be due to interfacial transaction zone (ITZ).

Moravia, Gumieri, and Vasconcelos (2010) showed that the cement paste can penetrate inside the shell of the surface pores of the expanded clay aggregate (Figure 3), which increases the bond by mechanical interlocking. In addition, Lo and Cui (2004) reported that because the surface of expanded clay lightweight aggregate is porous, it provides a dense and uniform interfacial zone. They showed that the interfacial zone is much smaller than that of normal aggregate. However, in the case of OPS aggregate, because the concave and convex faces of OPS are smooth, the bond between the OPS and the cement matrix is weak. Such a weak bond causes the lower mechanical properties of OPS concrete (Shafigh, Mahmud, & Jumaat, 2012). Previous studies (Alengaram, Mahmud, & Jumaat, 2011; Shafigh et al., 2012) showed that by improving the bonding of the interfacial zone, the compressive strength and modulus of elasticity improve. Alengaram et al. (2011) reported that the outer surface of OPS has micro-pores with sizes varying from 16 to 24 μm. They reported that if silica fume and fly ash are used in the concrete mixture, the matrix can penetrate into the pores and improve the mechanical interlocking. This causes a significant enhancement in the modulus of elasticity. In addition, Shafigh et al. (2012) reported that to produce high-strength OPS
concrete with the highest modulus of elasticity compared to previous studies, crushed OPS should be used in the concrete mixture instead of original OPS. This is because crushed OPS aggregate has a rougher surface texture than that of the original. The rough surface of the aggregate results in a better bond and better mechanical properties compared to a smooth surface texture (Li, 2011).

Chi, Huang, Yang, and Chang (2003) investigated the effect of water-to-cement ratio and aggregate properties on the compressive strength and modulus of elasticity of three types of lightweight aggregate concrete. The lightweight aggregates were cold-bonded pelletised with different properties. They reported that when the lightweight aggregate volume fraction (defined as the coarse aggregate volume divided by the total concrete volume) is 18%, the compressive strength and modulus of elasticity of the concrete are independent on the type of aggregate and are mainly affected by the water-to-cement ratio of the paste, while in higher volume fractions (i.e. 24, 30 and 36%), the property of lightweight aggregate is a key factor. However, according to this study, an additional point the cement matrix-aggregate interlock should be considered when the lightweight aggregate used in concrete originates from different sources.

It is worth noting that although the immediate benefit from the use of lightweight aggregate concrete is the reduction in dead weight, an additional benefit arises from the lower modulus of elasticity. Generally, the modulus of elasticity of lightweight aggregate concrete is about 30% less than for normal weight concrete of the same strength class, which accommodates more strain. More strain capacity of concrete reduces the risk of strain-induced cracking, e.g. due to drying shrinkage (CBDG, 2006). A previous study (Shafigh et al., 2012) showed that the strain capacity of OPS concrete is significantly more than normal weight concrete and expanded clay lightweight concrete for the same mix proportions.

4.6. Drying shrinkage strain
The developing of the drying shrinkage strain with time for all mixes is shown in Figure 4. The drying shrinkage strain of all concrete specimens was measured after
7 days moist curing. It is seen that by partial incorporation of OPS in expanded clay lightweight concrete, the drying shrinkage strain increases. The increase in drying shrinkage strain is significant up to 56 days. After 56 days, the increase in the rate for all mixes reduced. The reduction of the increase in the rate for mix L was more significant than for the L25 and L50 mixes. After five months, the drying shrinkage strain was almost constant for all mixes. It can be seen in Figure 4 that the drying shrinkage strain of both mixes containing OPS are similar for all ages.

Chandra and Berntsson (2002) reported that drying shrinkage depends upon the type of cement and its contents, water-to-binder ratio and the aggregate. They reported that the drying shrinkage of lightweight aggregate concrete is mostly affected by the properties of the lightweight aggregate and the aggregate content. This is because almost 75% of the volume of concrete is made up of aggregate. Mehta and Monteiro (2006) also reported that aggregate content in concrete is the most important factor affecting drying shrinkage and creep. Zhang, Zakaria, and Hama (2013) have shown that the characteristics of aggregate have significant effect on the drying shrinkage of concrete. In addition, it was reported (Mehta & Monteiro, 2006) that the modulus of elasticity of the aggregate is a more important factor than the other aggregate characteristics. The modulus of elasticity of aggregate can control the deformation of concrete. For example, when an aggregate with a high modulus of elasticity was substituted in a concrete with an aggregate with a low modulus of elasticity, both the drying shrinkage and the creep of concrete increased 2.5 times (Mehta & Monteiro, 2006). Alengaram (2009) reported that the drying shrinkage strain of OPS concrete is relatively high. He reported that the drying shrinkage strain of OPS concrete with a 28-day compressive strength in the range of 22–38 MPa is 160–520, 300–990 and 540–1300 microstrain at 28, 56 and 90 days, respectively. He stated that the high shrinkage of OPS concrete is due to the high cement and OPS (as coarse aggregate) content.

Compared to mix L, the higher drying shrinkage of the L25 and L50 mixes explains the lower modulus of elasticity of these mixes. Gao, Lo, and Tam (2002) have shown that the main reason for the reduction in the relative dynamic modulus of elasticity of a high-performance lightweight aggregate concrete is the formation of micro-cracks during the hardening of the cement paste of concrete. A micro-crack pattern in a high-performance lightweight aggregate concrete, reported by Gao et al. (2002), is shown in Figure 5. Due to the higher drying shrinkage of the L25 and L50 mixes, as well as the weakness of the OPS-cement paste interlocking, it seems that the micro-cracks form in ITZ, and consequently, the modulus of elasticity reduces. In addition, it can also be
explained that due to the formation of such micro-cracks in ITZ, the compressive strength of concrete containing OPS is more sensitive to the lack of curing. The higher OPS content the weaker ITZ areas, and therefore, more cracks due to drying shrinkage. Such cracks cause a greater reduction in the compressive strength. Previous studies (Shafigh, Johnson Alengaram, Mahmud, & Jumaat, 2013; Shafigh, Jumaat, Mahmud, & Alengaram, 2013; Shafigh, Jumaat, Mahmud, & Hamid, 2012; Shafigh et al., 2011) revealed that OPS concrete with normal and high strength is sensitive to the lack of curing, particularly, when cementitious materials, such as fly ash or ground granulated blast furnace slag, are used in the concrete mixture (Shafigh, Johnson Alengaram, et al., 2013; Shafigh, Jumaat, et al., 2013).

It was seen in the 28-day compressive strength test results that OPS concrete under continuous moist curing had the highest compressive strength compared to the other types of curing regime. In addition, the reduction in the compressive strength of concrete containing OPS under air drying as well as partial early curing regimes was significantly more than the control concrete (mix L). This is because concretes under standard curing were tested almost immediately after removal from the water, and therefore, no drying shrinkage took place in the concrete specimen. In contrast, under air drying (AC) and partial early curing conditions (3W, 5W and 7W), the specimens were under air drying, and consequently, under drying shrinkage for several days, which, as discussed earlier, led to the occurrence of micro-cracks in ITZ.

In summary, from the test results of this study, it can be said that compared to expanded clay lightweight concrete, because of the higher drying shrinkage strain of concretes containing OPS, micro-cracks formed in ITZ between the OPS and the cement matrix. The forming of these micro-cracks causes the modulus of elasticity to decrease; in addition, it causes that the compressive strength of OPS concretes is more sensitive in poor curing regimes.

5. Conclusion

The process of producing artificial lightweight aggregates (i.e. Leca) from raw materials (i.e. clay) is high energy consumption and is not environmentally friendly. In addition, manufacturing of lightweight concrete using these types of lightweight aggregates is costly for countries that these lightweight aggregates are imported materials. In this study, to reduce the volume of an artificial lightweight aggregate, namely Leca, in mix proportions of structural lightweight aggregate concrete, this lightweight aggregate was
substituted with OPS which is a waste from palm oil industry. The substitution was 0, 25 and 50% (by volume). Generally, the test results showed the significant benefits contributed by the OPS in the Leca lightweight concrete in terms of the engineering properties and environmental aspects. The following specific conclusions can be drawn from the results of this experimental study:

(1) Partial replacement of expanded clay with OPS increased the density of concrete. However, even at the 50% replacement level, the density of the lightweight concrete still meets the ACI and the European specifications for structural lightweight aggregate concrete.

(2) The use of OPS as partial replacement with expanded clay in expanded clay lightweight concrete increases its compressive strength. The increasing in the compressive strength was significant at the 50% replacement level.

(3) The specific strength (strength/weight ratio) of the expanded clay–OPS blended lightweight aggregate concrete is more than when the lightweight concrete was made of just expanded clay lightweight aggregate.

(4) The compressive strength of lightweight aggregate concretes containing OPS is sensitive to the lack of curing. The greater contribution of OPS in lightweight concrete makes it more sensitive, therefore, expanded clay–OPS lightweight concrete needs a longer moist curing period than a lightweight concrete made of just expanded clay.

(5) By substitution of expanded clay with OPS, the splitting tensile and flexural strengths of concrete increase. The increasing in the tensile strength was significant at the 50% substitution level. The enhancement of the flexural strength was more significant than for the splitting tensile strength.

(6) The estimation equation for the modulus of elasticity, as recommended by the BS 8110 and ACI 318 standards, shows that an increase in compressive strength, and density of concrete increases the modulus of elasticity. However, the test results of this study showed that although the density and compressive strength of expanded clay–OPS lightweight concrete are more than for the expanded clay lightweight concrete, the modulus of elasticity reduced by about 4.4 and 12.7% by substituting expanded clay with OPS in percentages of 25 and 50%, respectively. This shows that the type of lightweight aggregate(s) used in the lightweight concrete is a key factor that influences the modulus of elasticity.

(7) The drying shrinkage strain of expanded clay–OPS mixes is about 65% more than that of expanded clay lightweight concrete after nine months exposure to the air drying condition.

(8) The higher drying shrinkage strain of concretes containing OPS causes micro-cracks to occur in ITZ between the OPS aggregate and the cement matrix. The formation of such cracks causes the expanded clay–OPS concretes to be more sensitive to the lack of curing, and consequently, there is a greater reduction in the compressive strength when these concretes are cured under air drying or partial early curing conditions.

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