Performance evaluation of palm oil clinker as coarse aggregate in high strength lightweight concrete

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Abstract

The enhancement in the mechanical properties of high strength lightweight concrete (HSLWC) utilizing palm oil clinker (POC) as a replacement for oil palm shell (OPS) as lightweight coarse aggregate has been investigated and reported. A series of concrete mixes was prepared with 25%, 50%, 75% and 100% replacement of coarse aggregate by POC in HSLWC, while setting other parameters as constant. The parameters investigated include slump value, compressive strength, stress-strain behaviour, modulus of elasticity and its normalization, ultrasonic pulse velocity (UPV) and failure modes. The results showed that the replacement of OPS by POC as coarse aggregate has significant positive impact on compressive strength, modulus of elasticity and UPV. The highest compressive strength of about 63 MPa obtained for the mix with POC was about 43% higher than the control mix. Moreover, the enhancement in modulus of elasticity up to 2.5 times could significantly control the deflection.

1. Introduction

High strength and lightweight concretes are commonly desired for different structural applications including slabs and joists in high rise buildings, offshore and marine structures, and bridge decks in highway bridge structures (Malier, 1992). In the case of construction using conventional concrete, self-weight represents a significant proportion of the total load of the structure; however, a reduction in the density of the concrete would reduce the overall dead load to the foundation that could result in subsequent reduction in construction cost. Al-Khaiat and Haque (1998) reported that structural lightweight concrete has obvious advantages – higher strength/weight ratio, better tensile strain capacity, lower coefficient of thermal expansion, and superior heat and sound insulation – due to air voids in the lightweight aggregate. In addition, Topçu (1997) reported that the reduction in the dead load of a construction by the use of a lightweight aggregate in concrete could result in a decrease in the cross section of columns, beams, slabs and foundations. Since the load due to earthquake is proportional to the mass of civil engineering structures and buildings, reducing the mass of the structure or building is of utmost importance in the design of structural elements (Kılıç et al., 2003). In line with the design of structures using lightweight aggregate, high strength lightweight concrete (HSLWC) is one of the most important research areas in concrete materials and structural engineering. A decrease in the density of the concrete for the same strength category permits a saving in the dead load in the structural design and foundation. For producing HSLWC, different types of natural and artificial materials can be used as coarse aggregate including expanded clay, Leca, Lytag, basaltic-pumice, etc. Moreover, in recent times, agricultural waste, such as oil palm shell (OPS) (Mo et al., 2015b), palm oil clinker (POC) (Kanadasan and Razak, 2015) and coconut shell (Gunasekaran et al., 2013) have been used as the replacement aggregate instead of conventional crushed granite aggregate in the development of lightweight concrete.

Malaysia is the second largest palm oil producing countries in the world and hence the production of palm oil results in many waste products. The wastes from palm oil industries are OPS, empty fruit bunches, palm oil fibres and palm oil fuel ash. Research works on the use of OPS as lightweight coarse aggregate in the development of lightweight aggregate concrete has been well established...
since 1984 (Abdullah, 1984). However, POC is relatively a new sustainable material in the development of lightweight concrete. It is an industrial waste material available produced mainly in palm oil industries in South East Asia. In order to run the generator to produce electricity in palm oil industries, palm oil fibre and OPS are burnt at 850 °C. Generally, the proportion of palm oil fibre and oil palm shell is 70: 30. POC (Shafigh et al., 2014) is available in boulders of sizes ranging from 100 to 300 mm. These boulders are then crushed into suitable sizes as required in the development of lightweight concrete.

Shafigh et al. (2012) obtained a maximum compressive strength of 53 MPa using OPS as the aggregate in lightweight concrete; however, the modulus of elasticity (MOE) obtained was only 18.46 GPa, and the $\frac{MOE_{f_{c}}}{MOE_{f_{c}}} \text{ratio was only 348. The structural behaviour of OPS concrete (OPSC)}$ has been analysed with respect to flexure by researchers (Alengaram et al., 2008); although OPSC is structural lightweight concrete, in the case of doubly reinforced beams, it exceeds the code limit for deflection, as shown by Teo et al. (2006). The deflection of reinforced concrete flexural members depends on numerous factors, including the strength of the concrete, the tensile reinforcement ratio balanced reinforcement ratio ($p/p_{n}$), the amount of longitudinal compressive reinforcement and the amount of lateral tie steel (Ahmad and Shah, 1985; Shin et al., 1989). Therefore, it is necessary to enhance the mechanical properties of OPS lightweight concrete as well as the MOE. In contrast, using POC as the lightweight aggregate in concrete, Mohammedi et al. (2011) showed that the ratio of $\frac{MOE_{f_{c}}}{MOE_{f_{c}}}$ was in the range of 480–670 and with the increase in the concrete strength, the ratio improves. Also, the deflection of a POC concrete beam is less than the desired code limit, as shown by Mohammedi et al. (2014). Consequently, POC aggregate improves the properties of lightweight concrete compared to the OPS lightweight concrete.

The aim of this study is to enhance the mechanical properties of HSLWC incorporating waste POC for producing novel lightweight concrete. The variable studied includes different percentages of POC as a replacement for OPS coarse aggregate. The mechanical properties investigated include the compressive strength, stress-strain behaviour, modulus of elasticity of HSLWC. Moreover, the internal bonding property of concrete has been studied by the ultrasonic pulse velocity test.

### 2. Materials used

As the study aims to enhance the mechanical properties of high strength lightweight concrete, the effect of POC replacement for OPS as coarse aggregate in different proportions as indicated in the mixture proportion was investigated. Details of the materials used in the study and experimental works performed to achieve the objectives are given in the subsequent sections.

#### 2.1. Cement

Type I 42.5 grade ordinary Portland cement (OPC), with a specific gravity of 3.14 g/cm³, was used in the preparation of the test specimens. The Blaine’s specific surface area of the cement was 3510 cm²/g. In lightweight concrete, this OPC acts as the binder material and fills the pores of the coarse and fine aggregates.

#### 2.2. Superplasticiser (SP)

A high range water-reducing admixture, Sika ViscoCrete®-2199, had been found to be suitable for the concrete mixes in the present investigation. In accordance with BS 5075, the admixture is chloride free and is compatible with all types of Portland cement, including sulphate resistant cement. The use of SP content was kept constant at 1.74% of the cement weight.

#### 2.3. Aggregate

The fine aggregate comprises local mining sand with a specific gravity, fineness modulus, water absorption and maximum grain size of 2.66, 2.89, 11.7% and 4.75 mm, respectively. Moreover, OPS and POC coarse aggregates are considered as a renewable source of aggregate from waste materials. OPS, which, according to the existing literature (Alengaram et al., 2011a,b), consists of different shapes with a smooth convex and concave surfaces, was used as the coarse aggregate, as shown in Fig. 1.

The OPS collected from a local crude palm oil producing mill was washed to remove oil coating and then dried. The dry OPS was crushed using stone crusher and sieved using 4.75 mm and 12.5 mm sieves. The particles between 4.75 mm and 12.5 mm were considered to be suitable as coarse aggregate in the preparation of concrete. In contrast to the preparation of OPS, POC needs only crushing and similar size as that of the OPS. It should be noted that the OPS had low specific gravity of 1.22, but high 24 h water absorption of 23.52%. Its fineness modulus and compacted bulk density were found as 6.23 and 683 kg/m³. The measured range of shell thickness was between 0.62 and 6.08 mm, which was within the range as stated by Alengaram et al. (2013). The POC is the result of burning OPS and fibre during incineration process and obtained in boulders of sizes between 100 and 300 mm (Kanadasan and Razak, 2014). The crushed POC aggregate contains numerous pores and has a rough and undulated surface, as shown in Fig. 2.

The OPS was replaced with POC as coarse aggregate at 0%, 25%, 50%, 75% and 100% by volume. Furthermore, POC had a specific gravity of 2.08 which is higher than that of OPS; similarly, its fineness modulus and compacted bulk density of 6.29 and 782.10 kg/m³ were also found higher compared to OPS. In contrast, the lower 24 h water absorption of 3.56% obtained for POC aggregates is much lower compared to very high water absorption of about 24% for OPS. Table 1 illustrates the chemical composition of the POC and OPS waste materials.

#### 2.4. Mix proportions

Five concrete mixes were prepared to investigate the enhancement of the mechanical properties of HSLWC containing OPS and POC as coarse aggregates. The cement content and water to cement ratio for those mixtures were kept constant at 466 kg/m³ and 0.353, correspondingly. A control mix with only OPS as coarse aggregate was cast for comparison purpose. Since the control concrete contained no POC, this mix was designated as P0 (no partial replacement POC as coarse aggregate). The other four mixes contained POC coarse aggregate by volume replacement of OPS coarse aggregate at 25%, 50%, 75% and 100% is named as POC based HSLWC, which were

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**Fig. 1.** Smooth (a) concave and (b) convex surface of waste OPS aggregate.
designed based on the particle packing concept of concrete mix design (Kanadasan and Razak, 2014). The mixes are referred to as P25, P50, P75 and P100. The details of the concrete mixes with slump are presented in Table 2.

2.5. Specimen preparation

Concrete cube specimens of 100 mm in size were used for the determination of the ultrasonic pulse velocity (UPV), oven dry density and compressive strength. A cylinder of 100 mm diameter and 200 mm length was used to determine the modulus of elasticity. After casting, these specimens were covered with plastic and 28-d. Three concrete specimens were prepared and tested for each test condition to obtain average values.

3. Results and discussion

In this work, for the improvement of the mechanical properties of lightweight concrete, the partial replacement of the OPS lightweight coarse aggregate with the POC as lightweight coarse aggregate was at 0%, 25%, 50%, 75% and 100% by volume. Table 2 shows the mix proportions and slump values. Though the surface of POC is rougher compared to OPS, the slump values of all the mixes show consistent values. It can be seen from the slump values that the required workability is achieved in the range of site applied lightweight concrete (Mehta and Monteiro, 2006) for all the mixes with the use of water to cement ratio of 0.353 and SP content of 1.7% of cement weight. The results on improved hardened concrete properties of HSLWC are discussed in the following sub-sections.

3.1. Compressive strength of hardened OPS and POC based HSLWC

The compressive strength of the concrete mixes in water curing up to 56-d is provided in Table 3. As shown in Table 3, the increase in the POC content enhanced the compressive strength of the concrete. The gradual replacement of OPS with POC by 25%, 50%, 75% and 100% is reflected in the 28-d compressive strength as these increments enhanced in the sequence of 14.7%, 19.8%, 28.5% and 43.1%, compared to the strength of the control mix P0. Moreover, the highest 28-d cube compressive strength of 61.67 MPa for the mix P100 with a 100% replacement of OPS by POC in contrast to mix P0, which shows the effect of POC as coarse aggregate.

Table 1
Chemical composition of POC and OPS waste materials (Ahmmad et al., 2014).

<table>
<thead>
<tr>
<th>Oxides</th>
<th>SiO₂</th>
<th>K₂O</th>
<th>CaO</th>
<th>P₂O₅</th>
<th>MgO</th>
<th>Fe₂O₃</th>
<th>Al₂O₃</th>
<th>SO₃</th>
<th>Na₂O</th>
<th>TiO₂</th>
<th>Cr₂O₃</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>POC</td>
<td>59.63</td>
<td>11.66</td>
<td>8.16</td>
<td>5.37</td>
<td>5.01</td>
<td>4.62</td>
<td>3.7</td>
<td>0.73</td>
<td>0.32</td>
<td>0.22</td>
<td>–</td>
<td>0.58</td>
</tr>
<tr>
<td>OPS</td>
<td>46.61</td>
<td>9.88</td>
<td>14.76</td>
<td>1.95</td>
<td>2.91</td>
<td>10.19</td>
<td>3.33</td>
<td>7.84</td>
<td>1.15</td>
<td>–</td>
<td>1.38</td>
<td>–</td>
</tr>
</tbody>
</table>

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Table 2
Mix proportion (kg/m^3) and basic property of concrete.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Cement</th>
<th>Water</th>
<th>W/C</th>
<th>SP</th>
<th>Fine aggregate</th>
<th>Coarse aggregate</th>
<th>Slump (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0 (OPS)</td>
<td>466</td>
<td>166</td>
<td>0.353</td>
<td>8.1</td>
<td>847</td>
<td>OPS</td>
<td>373</td>
</tr>
<tr>
<td>P25 (POC)</td>
<td>466</td>
<td>166</td>
<td>0.353</td>
<td>8.1</td>
<td>847</td>
<td>OPS</td>
<td>280.5</td>
</tr>
<tr>
<td>P50 (POC)</td>
<td>466</td>
<td>166</td>
<td>0.353</td>
<td>8.1</td>
<td>847</td>
<td>OPS</td>
<td>187</td>
</tr>
<tr>
<td>P75 (POC)</td>
<td>466</td>
<td>166</td>
<td>0.353</td>
<td>8.1</td>
<td>847</td>
<td>OPS</td>
<td>93.5</td>
</tr>
<tr>
<td>P100 (POC)</td>
<td>466</td>
<td>166</td>
<td>0.353</td>
<td>8.1</td>
<td>847</td>
<td>POC</td>
<td>565</td>
</tr>
</tbody>
</table>

Table 3
Compressive strength of OPS and POC based HSLWC at different ages.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Cube compressive strength (f_{cu}) at different ages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-d</td>
</tr>
<tr>
<td>P0</td>
<td>28.37</td>
</tr>
<tr>
<td>P25</td>
<td>29.35</td>
</tr>
<tr>
<td>P50</td>
<td>31.60</td>
</tr>
<tr>
<td>P75</td>
<td>32.10</td>
</tr>
<tr>
<td>P100</td>
<td>41.85</td>
</tr>
</tbody>
</table>

In this research, OPSC was prepared using a combination of crushed OPS and POC as the aggregate in different mix proportions; hence, the correlation between the initial age (1-, 3-, 7-d) strength and 28-d strength, as shown in Fig. 5 is important. Generally, the linear correlation gives high values of coefficient between the initial and 28-d compressive strength. All the mixes produced 87–97% of their 28-d strength at the age of 7-d and similar correlation of 82–90% was reported (Lo et al., 2004) for LWAC using expanded clay as the coarse aggregate. On the other hand, Wilson and Malhotra (1988) reported lower correlation of 76–87% for high strength lightweight concrete using expanded shale aggregate. The ratio observed for 1- and 3-d compressive strength to 28-d strength, was 57–67% and 79–87%, respectively. The equations showing the relationship between 1-, 3-, and 7-, and 28-d compressive strengths are given below:

\[
\frac{f_{cu}}{f_{cu}} = 1.16 (f_{cu})_1 + 14.2
\]

\[
\frac{f_{cu}}{f_{cu}} = 1.13 (f_{cu})_3 + 2.06
\]

\[
\frac{f_{cu}}{f_{cu}} = 1.43 (f_{cu})_7 - 16.62
\]

where \((f_{cu})_1, (f_{cu})_3, (f_{cu})_7\) and \((f_{cu})_{28}\) are the 1-, 3-, 7- and 28-d compressive strength for OPS concrete, correspondingly.

3.2. Strength to density ratio

The additional benefit of using crushed POC aggregate as replacement to conventional crushed granite aggregates would enable lower dead load in structural elements. Another aspect of the oven dry density (ODD) is the strength to density ratio (Table 4) of the POC based concrete; this ratio for POC based concrete was found in the range of 27–31 × 10^−3 MPa/kg/m^3 and this is higher compared to previously published values of 17–22 × 10^−3 MPa/kg/m^3 for OPS based concrete (Mo et al., 2015a). In addition, the comparison between POC based concrete and conventional crushed granite concrete shows that the former has superior performance. Conventional concrete has the lowest value in the range of 14–19 × 10^−3 MPa/kg/m^3 (Mo et al., 2015a) due to high density. However, the reduction in the density of POC based concrete shows about 63% higher strength to density ratio compared to conventional concrete. Though both the mixes P0 and P100 fall under lightweight category, the later mix shows superior ratio compared to the former and this could be attributed to the stronger bond between the aggregate and matrix that enabled the concrete to produce higher strength. Also, the POC based mixes (P25–P100) show higher ratio of about 40% compared to the published strength to density ratio of 17–22 × 10^−3 MPa/kg/m^3 for OPSC.

3.3. Strength increasing factor at 28-d

One of the strength characteristics of concrete is the aggregate proportion in concrete. This characteristic was analytically calculated based on the proportion of POC in the mixes and the strength enhancement is reported as factor. The strength increasing factor (SIF) is the ratio of the compressive strength of the mixes P25, P50, P75 and P100 containing different proportions of OPS and POC with the compressive strength of the control concrete mix P0 as given in Eqn. (4).

\[
SIF = \frac{\text{Strength of concrete}}{\text{Strength of control concrete}}
\]

(a) OPS embedded in concrete  
(b) Failure mode of OPS

Fig. 3. Failure pattern of concrete containing OPS.
Using Eqn. (4), the SIF for the mixes obtained were 1.15, 1.20, 1.28 and 1.43 for the POC replacement as the coarse aggregate by 25%, 50%, 75% and 100%, respectively. SIF is used here to quantify the increase in the compressive strength as higher the SIF greater the strength of the concrete. The SIF increases gradually with the increase in the POC content in the concrete.

By regression analysis, experimental data were used to establish a valid relationship between the SIF and the consumption of POC, \( p \), as shown in Eqn. (5) established from Fig. 6.

\[
SIF = 0.004p + 1.0124
\]

where, \( p \) is the percentage of OPS replacement by POC.

### 3.4. Stress–strain relationship of OPS and POC based HSLWC

Fig. 7 shows the stress–strain relationships for all the specimens of OPS and POC based HSLWC containing different proportions of OPS and POC aggregates. The value of the strain is presented with the increase in the compressive load. Domagala (2011) reported that for normal weight concrete (NWC) the linear stress-strain curves stretches up to 30–45% of its ultimate strength. Akbar (2008) showed that for NWC the strain at the peak stress was in the range of 0.0015–0.002. From the experimental values, the strain at maximum stress in the range of 0.00173–0.00401 was found higher than the NWC. It was found that the specimen of the mix P0 showed more cracks compared to the other specimens. On contrary, the addition of more amount of POC as coarse aggregate reduced the number of cracks and this could be attributed to the brittle nature of the POC aggregate. Usually, LWAC tends to be more inelastic than the NWC, which causes sudden failure after the ultimate load (Balendran et al., 2002). The brittleness of the POC aggregate is one of the limitations of the lightweight concrete. However, the OPSC mixes containing 50% of OPS or more as the coarse aggregate showed a higher strain rate than the NWC, and this could be advantageous to overcome the temperature and shrinkage cracks on the structural element.

Fig. 7 also shows that the effectiveness of the ultimate load carrying capacity increased with the increase in the POC as replacement for the OPS aggregate. It can be seen that an increase in the POC coarse aggregate content increased the ultimate stress as well as the slope of the stress vs. strain curve. However, the \( \varepsilon \) value decreased due to the increase in the POC aggregate content. In the stress-strain diagram, it is seen that the strains at the failure point of the P100 and P75 specimens were found very close to maximum stress. However, in the HSLWC with up to 50% of replacement of OPS by POC aggregate, the failure occurred steadily as seen from the Fig. 7.

![Fig. 5. Relationship of short-term (1-, 3- and 7-d) compressive strength with long-term (28-d) compressive strength.](image)

**Table 4**

Strength to density ratio and modulus of elasticity (MOE) of OPS and POC based HSLWC.

<table>
<thead>
<tr>
<th>Mix no.</th>
<th>( f_{cu} ) at 28-d (MPa)</th>
<th>Oven dry density at 28-d, ( \rho ) (( \text{kg/m}^3 ))</th>
<th>Strength to density ratio ( \left( f_{cu}/\rho \right) ) at 28-d (( \times 10^{-1} ) MPa/( \text{kg/m}^3 ))</th>
<th>MOE ( \left( \text{GPa} \right) )</th>
<th>( \text{MOE}/f_{cu} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0</td>
<td>43.09</td>
<td>1787</td>
<td>24.11</td>
<td>14.1</td>
<td>327.2</td>
</tr>
<tr>
<td>P25</td>
<td>49.45</td>
<td>1833</td>
<td>26.98</td>
<td>16.4</td>
<td>331.6</td>
</tr>
<tr>
<td>P50</td>
<td>51.62</td>
<td>1879</td>
<td>27.47</td>
<td>20.9</td>
<td>404.9</td>
</tr>
<tr>
<td>P75</td>
<td>55.37</td>
<td>1925</td>
<td>28.76</td>
<td>27.6</td>
<td>498.5</td>
</tr>
<tr>
<td>P100</td>
<td>61.67</td>
<td>1971</td>
<td>31.29</td>
<td>34.8</td>
<td>564.3</td>
</tr>
</tbody>
</table>

![Fig. 6. SIF with increase of POC content in concrete.](image)
3.5. Modulus of elasticity (MOE) of OPS and POC based HSLWC

The modulus of elasticity and compressive strength of the HSLWC increased with the increase of the POC content as seen from Fig. 8. The highest MOE of about 34.8 GPa was obtained for the mix P100 and it is higher than previous studies (Gao et al., 1997; Kayali et al., 2003) in HSLWC. Though MOE of structural LWC is in the range of 10–24 GPa, (FIP, 1983) the mix P100 with whole replacement of OPS with POC shows significant improvement and this is vital in the design of structural elements in serviceability limit state. Furthermore, the values of MOE of P50, P75 and P100 were higher compared to the previous study (Shafigh et al., 2012) of OPS based HSLWC. Generally, stiffness of lightweight concrete is less compared to normal weight concrete (Zhang and Poon, 2015). The use of POC increased the stiffness of OPS based lightweight concrete and resulted in lower deflection as observed by Alengaram et al. (2008).

The modulus of elasticity of the concrete could also be correlated with the compressive strength of the concrete (Alengaram et al., 2011a,b). The relationship between the MOE and the cube compressive strength of HSLWC using POC aggregate is shown in Fig. 9 and compared with the equation previously used to predict the modulus of elasticity of lightweight concrete in CEP/FIP manual (Short and Kinniburgh, 1978) (Eqn. 6) and ACI code (ACI 318, 2008) (Eqn. 7).

\[
E_s(\text{pre}) = \left[ \frac{\rho}{2400} \right]^2 \left(\frac{f_{cu}}{C138} \right)^3 \times 9.1
\]  

where, \(E_s(\text{pre})\) (kN/mm²), \(f_{cu}\) (N/mm²) and \(\rho\) (kg/m³) are the predicted elastic modulus, cube compressive strength and air-dry density.

\[
E_s(\text{pre}) = 0.043W_1^{1.5} \sqrt{f_c'}
\]  

where, \(E_s(\text{pre})\) (kN/mm²), \(f_c'\) (N/mm²) and \(\rho\) (kg/m³) are the predicted elastic modulus, cylinder compressive strength and air-dry density, respectively.

From Fig. 9, it is observed that CEB/FIP manual and ACI code underestimated the MOE of the POC based HSLWC in case of mixes P75 and P100 containing higher amount of POC. Also, these equations overestimate MOE in the case of mixes P0 and P25 containing lower amount of POC. An equation is proposed to predict the MOE based on the compressive strength from the experimental data and it is shown below:

\[
E_s(\text{pre}) = 0.0005f_{cu}^{2.69}
\]  

where, \(E_s(\text{pre})\) (kN/mm²) is the predicted elastic modulus, and \(f_{cu}\) is the cube compressive strength.

As known, OPS has smooth surface and low specific gravity (Teo et al., 2007) and hence it produces low MOE. However, the increased stiffness (Guo et al., 2014) of POC along with more POC content, the stiffness of the concrete increases. This is evident in the MOE values as it increases from 16 to 34 GPa for whole replacement of OPS. The comparison of MOE between P0 and P100 shows the mix with whole replacement of OPS has 140% increase compared to the mix with OPS. Similar trend could be seen between the mixes P25 and P100, as the later shows 100% increase in the MOE. Another important aspect of material characteristics is the normalization of the material properties; thus, the ratio between the MOE and the corresponding compressive strength shows (Table 4) the increasing trend as the POC content increases. Based on the previously published data, the \(MOE/f_{cu}\) ratio for high strength OPSC was found in the range 329–360 (Yew et al., 2014). Due to superior MOE values, the conventional concrete shows higher \(MOE/f_{cu}\) ratio of 390–450 (Sandemir, 2013) compared to high strength OPSC. However, the POC based mixes (P50, P75 and P100) with \(MOE/f_{cu}\) ratio in the
range of 400—560 is higher than the OPS based concrete. The MOE/f<sub>cu</sub> ratios of P75 and P100 show these mixes could structurally perform similar to that of conventional concrete with lower deflection.

4. Non-destructive test

4.1. Ultrasonic pulse velocity (UPV) of OPS and POC based HSLWC

UPV is a non-destructive test that is conducted to evaluate the consistency and quality of concrete to specify the existence of pores, cracks and to determine the crack depth in the concrete. The UPV values of control mix along with POC based HSLWC is shown in Table 5. The concrete with UPV values between 3.66 and 4.58 km/s is termed as ‘good’ (Leslie and Cheesman, 1949). The concrete within the above said range is considered as having no large voids or cracks that reduce the structural integrity. Shafgh et al. (2011) showed the failure in OPSC arising at the interfacial zone between the aggregate and mortar because of the leaky mortar at the interface. Therefore, UPV is the essential method for detecting large pores in the aggregate-mortar interface. The UPV values for all the mixes investigated in this research were found higher than 3.66 km/s from the age of 1-d and above.

The trend of increase in the UPV with the increasing age of concrete could be attributed to the bonding between the mortar and aggregate; this enables the concrete to enhance its strength with reduced pores in the solid skeleton of concrete. It is also important to note that the increase in the POC content resulted in enhanced UPV values. The rate of increase in the UPV values shows slower trend due to slow rate of hydration after 3-d.

In addition the above mentioned points, it is important to discuss the correlation between short and long term UPV values and the relationship between the compressive strength and UPV. These are explained in the following sub-sections.

Table 5
Ultrasonic pulse velocity (UPV) of OPS and POC based HSLWC.

<table>
<thead>
<tr>
<th>Mix</th>
<th>UPV at different ages in km/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-d</td>
</tr>
<tr>
<td>P0</td>
<td>3.68</td>
</tr>
<tr>
<td>P25</td>
<td>3.78</td>
</tr>
<tr>
<td>P50</td>
<td>3.81</td>
</tr>
<tr>
<td>P75</td>
<td>3.87</td>
</tr>
<tr>
<td>P100</td>
<td>4.02</td>
</tr>
</tbody>
</table>

4.1.1. Correlation between short term (1-, 3-, 7- d) and long term (28-d) UPV

The comparison between 1-, 3-d and 28-d UPV values show 87—95% of UPV values was achieved at early ages. Further, all the mixtures produced 96—99% of their 28-d UPV values at the age of 7-d.

The correlation between the UPV values at the ages of 1-, 3-, and 7-d and 28-d of the concrete mixes is shown in Fig. 10. As seen, all the mixes show linear correlation between early and later age UPV values.

The following equations indicate linear relationship between 1-, 3-, 7- d and 28-d UPV values and the 28-d UPV values can be predicted using this equation:

\[(UPV)_{28} = 1.0746(UPV)_{1}^{0.0372} \quad (9)\]

\[(UPV)_{28} = 1.0478(UPV)_{3}^{0.0017} \quad (10)\]

\[(UPV)_{28} = 0.5384(UPV)_{7}^{1.4393} \quad (11)\]

where \((UPV)_{1}, (UPV)_{3}, (UPV)_{7}\) and \((UPV)_{28}\) are the 1-, 3-, 7- and 28-d UPV of OPS concrete, respectively.

4.1.2. Relationship between compressive strength and UPV

Although there is no unique correlation with UPV and the compressive strength of the concrete (Neville, 2005), the hardened mortar depends on the water/cement ratio and subsequently the UPV values is affected. When the voids are filled with water, the UPV travels faster than when the voids are filled with air (Neville, 2005), which indicates that the moisture also affects the UPV of the concrete. However, the strength of the concrete can be assessed using the UPV test. Moreover, with the change in the coarse aggregate in the concrete, the strength property of the concrete is changes. The relationship between the compressive strength and UPV of the concrete containing various proportions of OPS and POC coarse aggregate has been developed. Fig. 11 shows the correlation between the cube compressive strength and UPV of the OPSC mixes. From the figure, it is seen that the relationship between the compressive strength and UPV of OPSC is exponential. From the relationship, the following equation is developed:

\[f'_c = 0.1982(UPV)^{3.79} \quad (12)\]
5. Conclusion

The effect of replacement of lightweight OPS aggregate with another industrial waste material, POC at various percentages to develop HSLWC was investigated. The properties investigated include slump, ODD, compressive strength, stress-strain behaviour, MOE and UPV. Based on the investigation, the following conclusions can be drawn:

1. Generally the replacement of OPS with POC shows positive influence on both the workability and the compressive strength. The enhancement in the compressive strength with the replacement of 25%, 50%, 75% and 100% aggregate volume in OPSC by POC coarse aggregate shows 14.7%, 19.8%, 28.5% and 43.1%, respectively higher than the control mix.

2. The strength to density ratio of POC based HSLWC is in the range of 27–31 × 10^3 MPa/kg/m^3 and it is about 40% and 63% higher compared to OPS based lightweight concrete and normal weight concrete, correspondingly. This increasing strength to density ratio indicates, POC based HSLWC reduce the weight of structure significantly compared to previous OPS based lightweight concrete and normal weight concrete.

3. The failure in HSLWC containing OPS as the aggregate shows two types of failure mode – debonding between the aggregate-mortar interface and the breaking of the aggregate. On the contrary, the concrete containing POC fails due to the crushing of the aggregate.

4. The strain of OPS and POC based HSLWC at maximum stress in the range of 0.00173–0.00401 was found higher than the NWC, which indicate it may have more shrinkage crack resisting capacity compared to normal weight concrete.

5. The increase in the MOE of POC based HSLWC by about 2.5 times compared to the control mix (P0) could be attributed to stronger bond between the mortar and aggregate. The normalization of MOE shows that an increase in the POC content enhances the MOE/\(e_{c0}\) values. The highest MOE of 34.8 GPa achieved for the mix with whole replacement of OPS with POC (P100) is about 66% higher than the mix with 50% partial replacement of OPS with POC. Though MOE of structural LWC is in the range of 10–24 GPa, the mix P100 with whole replacement of OPS with POC shows significant improvement and this is vital in the design of structural elements in serviceability limit state.

6. The increment of POC in the mixes shows improvement in UPV values with the mix with whole replacement of OPS with POC showing about 9% higher value than the control mix. Although the increment in UPV shows only about 9%, the compressive strength improvement 43% could be attributed to good interlocking between POC and mortar.

7. The regression analysis between UPV and the compressive strength shows good correlation between these two with the R^2 value of 0.97.

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