High volume cement replacement by environmental friendly industrial by-product palm oil clinker powder in cement – lime masonry mortar

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Abstract
Cement-lime based mortar is extremely popular for a wide range of construction around the world and conserving natural resources used in the production of such material is of capital importance. Identification of alternative materials from palm oil based industrial by-products enabled researchers to use palm oil clinker powder (POCP) as a cement replacement material; in this research work, POCP was used as cement replacement material in masonry mortar. The physical, chemical properties and SEM of POCP were analyzed to investigate the feasibility of utilizing POCP as cement replacement for up to 80%. Based on the feasibility study, final mortar mixes were prepared utilizing 40% of POCP. Further investigations were carried on fresh, mechanical and bond properties of mortar. The hardened properties for mechanical performance and ultrasonic pulse velocity (UPV) investigated in water and air cured regimes show that up to 40% of cement could be replaced to obtain the requisite compressive strength of 12.4 MPa for cement-lime mortar. Further, POCP ground to more number of cycles had minor impact on the mechanical properties. The investigation on the potential use of POCP as cement replacement confirmed the potentiality through energy saving, cost effective and cleaner environment.

1. Introduction
Lime based mortars has been used over 1000 years (Tate, 2005) especially the Greek - Roman empire used lime based mortars extensively and Roman architects provided basic guidelines for lime mortar mixes (Vitruvius, and De Architectu, 1931). Even now these are extremely popular for a wide range of construction around the world and considered as demanding construction material. Among lime based mortars, cement lime mortar is well known for its versatility for a wide range of masonry application. Based on field performances, studies have shown that cement lime mortar is having excellent workability, optimized cement hydration by lower water retentive, high levels of flexural bond strength and also proven durable in laboratory as well as in the field (Tate, 2005). However, high demand of cement in construction industry due to significant infrastructural changes in ASEAN, China and India as developing countries has led to negative impact on environment. Cement industry is one of the major polluters and accounts for approximately of 6% of the total global carbon dioxide emission (Zhang et al., 2014). Consequently, the environmental impact of carbon emission of cement – lime mortar is significant. Besides, demand for masonry construction is very high as lower to medium income group of people aspire to own a house in these countries at minimal cost. Recently, researchers from Centre for Innovation and Construction Technology, University Malaya, Malaysia constructed a model low cost house by using local waste materials such as palm oil clinker (POC), slag aggregates and palm oil clinker powder (POCP) as shown in Fig. 1 (News). In ASEAN region, palm oil is popular vegetable oil for cooking and food processing (Oosterveer, 2015) and Malaysia is the second largest exporter of palm oil in the world after Indonesia (Yusoff, 2006). As a result, a very significant amount of biomass (83 million tonnes of palm oil biomass generated in 2012) wastes including empty fruit branch, oil palm shell (OPS), palm oil fuel ash (POFA) and POC is generated every year and it is anticipated to

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generate about 100 million tonnes of solid biomass by 2020 (2011 National Biomass Strategy, 2020, 2011). For every kg of palm oil produced, approximately four kg of dry biomass is produced (Ng et al., 2012) in the form of by-products such as OPS, POFA and POC. Recently, Alengaram et al. (Alengaram et al., 2016) have shown that OPS can be used as whole replacement for coarse aggregate in blast resisting concrete due to its high impact resistance and it has superior performance compared to crushed granite aggregate. There has been number of past and ongoing research works that utilize the palm oil wastes such as POFA, POC & OPS as cement replacement and coarse aggregates, respectively (Mo et al., 2015), (Rahman et al., 2014a), (Kabir et al., 2017), (Kanadasan and Razak, 2015), (Mo et al., 2016), (Yew et al., 2014). The use of POFA and POC as cement replacement in normal and geopolymer concrete had shown stronger performance in terms of strength and durability (Kabir et al., 2017). On the other hand, POC has been used as both cement replacement and lightweight coarse aggregate (Kanadasan and Razak, 2014), (Ahnmad et al., 2016), (Ahnmad et al., 2017). Thus, the utilization of potential waste materials from palm oil industry could enhance the sustainability as well as pave way to safe disposal of these wastes (Al-Oqla and Sapuan, 2014).

Research works have been carried out on the utilization of wastes as cement replacement materials in mortars (Adesanya, 1996), (Barreca and Fichera, 2013), (Gleize et al., 2003), Gleize et al (Gleize et al., 2003) investigated microstructural effects of masonry mortars in which 10% of replacement of Portland cement by silica fume lowered total porosity. Adesanya (Adesanya, 1996) reported on using corn cob ash as a cost reducing additive in blended cement.

As outlined earlier, the utilization industrial by-products in ASEAN countries is gaining momentum. The pozzolanic activity of POCP shows its potential and it has been utilized as cement based material. Studies (Karim et al., 2017a), (Karim et al., 2016a), (Kanadasan and Razak, 2015), proved that based on the chemical composition, the pozzolanic activity of POCP is higher than ground POFA. Fresh and hardened concrete properties of POCP based lightweight concrete have been investigated (Kanadasan and Razak, 2015), (Ahnmad et al., 2017), with the dosage of 15% POCP by mass of the total cementitious material produced optimum results in terms of strength and water absorption. Thermal activation effects on POCP and influence on the strength development have also been reported (Karim et al., 2016b). Investigations on self-compact concrete with POCP as additional cementitious material along with POC as coarse and fine aggregates show that the particle packing of POCP affects the fresh and hardened properties of concrete (Kanadasan and Razak, 2014).

Though the use of POCP as filler or additional cementitious material in concrete and self-compacting concrete has been reported, there is no existing work on the development of cement – lime masonry mortar solely employing POCP as high-volume cement replacement material. This is particularly impactful for geographical regions in the world exposed to anthropogenic pollution due to booming construction sector (Rahman et al., 2014b), (Taaffe et al., 2014).

This research work reports the experimental study conducted on POCP based cement-lime mortar; POC was utilized up to 80% as cement replacement and its effects on fresh, mechanical and bond properties have been investigated and reported. In addition, the carbon emission, cost and energy analysis of mortars using POCP also elaborated towards environmental sustainability.

2. Experimental program

2.1. Materials and their properties

Cementitious materials as shown in Fig. 2 were used in the development of cement – lime mortar consists of ordinary Portland cement, natural hydrated lime, and POCP.

2.1.1. Ordinary Portland cement (OPC) and hydrated lime (HL)

Ordinary Portland cement (CEM I 42.5) based on ASTM: C150/ C150M – 14 (ASTM C150-14, 2014) was used in the development of mortar. Hydrated lime (Ca(OH)2) was used in this study based on ASTM C207-14 (ASTM C207-14, 2014).

2.1.2. Palm oil clinker powder (POCP)

It is by-product of the combustion of palm oil shells and fibers in palm oil industry. During combustion in the boiler, most of the palm oil shells and fibers are burnt and in the process, the fused material cools and solidified into irregular shapes of chunks called palm oil clinker (POC). The POC in the boiler are fused in suspension and carried away from the combustion boiler and dumped in the factory yard causing land and air pollution. In this study, POC obtained from the factory was crushed and ground to obtain POCP and used as cementitious material. The POC particles of sizes below 2.36 mm were ground in a Los Angeles abrasion machine for 30,000 at 150 rpm to obtain POCP. The process of POCP preparation is depicted in Fig. 3. This study also focuses on ultra POCP (UPOCP) ground in Los-Angele's Machine for 60000 cycles at 150 rpm to on the effect of particle size (Karim et al., 2016a). The physical properties of POCP are given in Table 1.

![Fig. 1. Low cost house constructed using local waste materials and SCM in University Malaya, Malaysia (News).](image-url)
2.1.3. Physical and chemical characteristics

The particle size analysis of CM was investigated according to ASTM B822-14 (ASTM B822-14, 2014). The morphology of CM observed based on ASTM E986-14 (ASTM E986-14, 2014). The chemical composition of CM was determined in accordance with ASTM D4326-14 (ASTM D4326-14, 2014). Loss on ignition (LOI) was measured based on ASTM C114-14 (ASTM C114-14, 2014).

Fig. 4 shows the scanning electronic microscopic (SEM) images of cementitious materials. It was observed that most of POCP or UPOCP particles were found to be irregular shaped particles with small pores and hollow cenospheres whereas ground materials OPC and HL (90% of CaO) have amorphous solid angular particles. HL has spherical shaped fine particle of size of about 14 µm as stated in Table 1.

The particle sizes of UPOCP vary from 1.72 µm to more than 132 µm with the typical particle size measuring below 32.83 µm and only about 29% of the particles are larger than 45 µm. Coarser particles of average size of about 47.85 µm were found in POCP compared to UPOCP due to different grinding cycles (Table 1).

As shown in Fig. 4, identical particle size distribution was noticed in all three cementitious materials—OPC, POCP, UPOCP and HL.

Table 2 shows the chemical composition of OPC, HL and POCP and it can be observed that POCP is primarily consisting of 60.29% of silica. Based on the SiO₂ + Al₂O₃ + Fe₂O₃ (SAF) contents, POCP could be classified under Class-F pozzolan material (min. 70% of SAF, less than 5% of SO₃ and LOI is less than 12%) ASTM C618-14 (ASTM C618-14, 2014). Additionally, the chemical contents of POCP shows that soluble contents of silica and alumina in POCP were within requirement ASTM C618-14 (ASTM C618-14, 2014).

2.1.4. Local mining sand

Local mining sand was used for the cement-lime mortar (CLM). An experimental analysis was carried out to determine whether sand complies with the ASTM C128-14 (ASTM C128-14, 2014) & ASTM C136-14 (ASTMC136-14, 2014). The values of specific gravity and fineness modulus of local mining sand were found as 2.59 and 2.27, respectively. Fig. 6 shows well-graded local mining sand.

2.1.5. Water

Portable tap water was used for mixing cement-lime mortar; the w/c or w/cm ratio was maintained to achieve minimum consistency of mortar according to ASTM C270-14 (ASTM C270-14, 2014).

2.2. Cement lime mortar mix design and composition

CLM with type ‘S’ was selected for the research and it was found suitable as it complies with ASTM: C270 - 14 (ASTM C270-14, 2014). The mix proportion used in the study was 1:0.5:4.5 (Cement: Hydrated lime: Sand). Table 3 shows nine mixes (1 control and 8 mixes with POCP) that were prepared to find the optimum amount of POCP to be used in CLM. Further, three more mixes were cast in order to compare the optimized content of 40% of each POCP and UPOCP (Table 4).

2.3. Preparation of cement lime mortar and testing methods

The materials cement, hydrated lime and sand were mixed for about 2–3 min using mortar mixer (see in Fig. 7) in order to obtain homogenous mixture. Then, POCP was added and mixed for about 2–3 min and then finally requisite water was added and mixing continued for another 4 min. Finally, slump flow and air content tests were conducted in accordance with ATSM C270-14 (ASTM C270-14, 2014) & ASTM C185-14 (ASTM C185-14, 2014), respectively.

Table 1

<table>
<thead>
<tr>
<th>Properties</th>
<th>OPC</th>
<th>POCP</th>
<th>UPOCP</th>
<th>HL</th>
</tr>
</thead>
<tbody>
<tr>
<td>D50 (µm)</td>
<td>22.96</td>
<td>47.85</td>
<td>32.83</td>
<td>14.67</td>
</tr>
<tr>
<td>D10 (µm)</td>
<td>00.90</td>
<td>02.79</td>
<td>01.72</td>
<td></td>
</tr>
<tr>
<td>D90 (µm)</td>
<td>72.36</td>
<td>180.92</td>
<td>132.07</td>
<td></td>
</tr>
<tr>
<td>Passing 10.48 µm</td>
<td>25.94</td>
<td>23.11</td>
<td>26.82</td>
<td>43.21</td>
</tr>
<tr>
<td>Passing 48.27 µm -Retained 10.48 µm (%)</td>
<td>55.18</td>
<td>34.00</td>
<td>34.40</td>
<td>29.60</td>
</tr>
<tr>
<td>Retained 48.27 µm (%)</td>
<td>18.88</td>
<td>33.29</td>
<td>29.00</td>
<td>20.19</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>3.15</td>
<td>2.55</td>
<td>2.53</td>
<td>2.30</td>
</tr>
<tr>
<td>Moisture Content (%)</td>
<td>0.18</td>
<td>0.83</td>
<td>0.59</td>
<td>0.13</td>
</tr>
</tbody>
</table>
the evaluation of flexural bond strength of CL mortars using a method developed by F. M. Khalaf (Khalaf).

The specimens prepared include 50 mm³ cubes for compression strength and UPV and performed in accordance with ASTM C109-14 (ASTM C109/109M-14, 2014) and ASTM C597-14 (ASTM C597-14, 2014), respectively; prisms of 40 x 40 x 160 mm were prepared and tested based on ASTM C348 e14 (ASTM C348-14, 2014) for flexural strength, and cylindrical specimens of 50 mm dia. X 100 mm height was prepared and tested for splitting tensile test, in accordance with BS EN 12390 e6: 2009 (BS EN 12390 -6, 2009) (Fig. 8). All the specimens were covered with plastic sheathing and demoulded after 24 h. The specimens were water cured till the day of testing; however, for optimized mixes- CL, CLP40 and CLPU40, the demoulded specimens were subjected to two types of curing, namely water and air curing-laboratory ambient condition (temperature and humidity of 25±2 °C and 60 ± 10% respectively).

2.3.1. Flexural bond strength (f_{fb})

The Z shaped specimens with two types of bricks (clay and cement based) were prepared and tested after 28 days of curing. The specimen test set up shown in Fig. 9.

The description of analysis and free-body diagrams is presented in Table. Two types of load distributions, namely linear and parabolic were used in analysis. F_{fb}, the total force represented by the stress distribution, is calculated from the area of a triangle: By substituting for R_A and F_{fb} using Eqn. 1a and 1 b and solving for F_{fb}.

The expressed notation is introduced in the initial stage and dimension of clay burnt bricks (CBB) and cement based bricks (CB), and their properties are given in Table 5.

Solving the equation by substituting dimensions of bricks into the expressions then obtained simplified equations for particular bricks for both distributions method is shown in Table 6.

3. Results and discussion

3.1. Effects on freshly mixed mortar

3.1.1. Workability, air content and fresh density

The effect of w/cm ratio on CL with POCP replacement was investigated and the results are shown in Table 7. Substitution of POCP in mortar resulted in more water demand to maintain slump flow value. Girish et al (Girish et al., 2010) reported that an increase in the paste volume elevates slump flow values for varying water content. As the replacement level increased then an increase in air...
content causing water to be repelled and air trapped on the surface results in subsequent reduction in fresh density of mortar as shown in Fig. 10. The flow and air contents obtained for the mixes fulfilled the requirement as stipulated in ASTM C 270 e14 (ASTM C270-14, 2014).

The fresh properties of optimized mixes are shown in Table 8. Based on the test results, it can be seen that the addition of POCP and UPOCP had less effect on the fresh properties compared to the control mix. Further observation on UPOCP shows that despite being ground to 60,000 cycles compared to 30,000 cycles for POCP, the former had slight influence on slump flow and this could be attributed to lower particle size of UPOCP compared to POCP.

### 3.2. Effects on hardened mortars

#### 3.2.1. Compressive strength ($\sigma$)

Fig. 11 shows the compressive strength obtained on CL and CLP samples. The measured compressive strength of cement lime mortar containing POCP is comparable with previous results reported (Kanadasan and Razak, 2015) for self-compacting mortar. Generally, the trend of the compressive strength shows that the addition of POCP reduced the strength; however, for the addition of 10% of POCP, the enhancement of compressive strength could be seen at all ages due to presence of amorphous phase which is

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**Table 3**

Mix proportion of cement lime mortar and substituted POCP at different levels.

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Replacement (%)</th>
<th>Sand (kg/m$^3$)</th>
<th>Lime (kg/m$^3$)</th>
<th>Cement (kg/m$^3$)</th>
<th>POCP (kg/m$^3$)</th>
<th>W/cm ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>0</td>
<td>1440</td>
<td>80</td>
<td>376</td>
<td>0</td>
<td>0.40</td>
</tr>
<tr>
<td>CLP 10</td>
<td>10</td>
<td>1440</td>
<td>80</td>
<td>338</td>
<td>38</td>
<td>0.49</td>
</tr>
<tr>
<td>CLP 20</td>
<td>20</td>
<td>1440</td>
<td>80</td>
<td>301</td>
<td>75</td>
<td>0.57</td>
</tr>
<tr>
<td>CLP 30</td>
<td>30</td>
<td>1440</td>
<td>80</td>
<td>263</td>
<td>113</td>
<td>0.57</td>
</tr>
<tr>
<td>CLP 40</td>
<td>40</td>
<td>1440</td>
<td>80</td>
<td>226</td>
<td>150</td>
<td>0.58</td>
</tr>
<tr>
<td>CLP 50</td>
<td>50</td>
<td>1440</td>
<td>80</td>
<td>188</td>
<td>188</td>
<td>0.58</td>
</tr>
<tr>
<td>CLP 60</td>
<td>60</td>
<td>1440</td>
<td>80</td>
<td>150</td>
<td>226</td>
<td>0.60</td>
</tr>
<tr>
<td>CLP 70</td>
<td>70</td>
<td>1440</td>
<td>80</td>
<td>113</td>
<td>263</td>
<td>0.60</td>
</tr>
<tr>
<td>CLP 80</td>
<td>80</td>
<td>1440</td>
<td>80</td>
<td>75</td>
<td>301</td>
<td>0.60</td>
</tr>
</tbody>
</table>

**Table 4**

Mix proportion of cement lime mortar and optimum replacement of POCP.

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Replacement (%)</th>
<th>Sand (kg/m$^3$)</th>
<th>Lime (kg/m$^3$)</th>
<th>Cement (kg/m$^3$)</th>
<th>POCP (kg/m$^3$)</th>
<th>W/cm ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>0</td>
<td>1440</td>
<td>80</td>
<td>376</td>
<td>0</td>
<td>0.58</td>
</tr>
<tr>
<td>CLP</td>
<td>40</td>
<td>1440</td>
<td>80</td>
<td>226</td>
<td>150</td>
<td>0.58</td>
</tr>
<tr>
<td>CLPU</td>
<td>40</td>
<td>1440</td>
<td>80</td>
<td>226</td>
<td>150</td>
<td>0.58</td>
</tr>
</tbody>
</table>

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**Fig. 7.** Preparation of mortar and flow test.

**Fig. 8.** Testing set-up for a. Slump flow; b. Ultrasonic pulse velocity; c. Compression test; d. Flexural test; e. Split tensile test.

**Fig. 9.** a. Flexural bond testing set up; b. Free body diagram of flexural bond strength test.
reactive on the basis of pozzolanic activity to form C–S–H gel for strength development leading to compact structure and thus enhancing the durability (Karim et al., 2016a). However, the compressive strength of mortar decreases and found lower than control specimens due to cement dilution effect and reduction in CaO to SiO₂ ratio’s as shown in Table 9 (Karim et al., 2016a).

As seen from the Fig. 12, the addition of 80% of POCP reduced the compressive strength by about 81% and 84%, respectively for control and mix with 10% of POCP. The CLP40 produced the required
mortar strength of 12.4 MPa as required under ASTM C270-14 guideline for mortar. Though the compressive strength produced by CLP50 is close to that of CLP40, it was decided to utilize CLP40 for further investigation as variation in the particle size, amorphousness, chemical & mineral composition and water demand could be expected depending on the sources and process of POCP produced in the palm oil mills. Apparently, the water demand for mortar mixes increases as replacement of POCP increases. The mixes with more than 50% of POCP produce lower strength than 12.4 MPa required to be classified as type S mortar.

Fig. 13 shows the failure pattern of the tested specimens-CL, CLP and CLPU under compression. The results of compressive strength of these specimens are displayed in Fig. 14 for two curing regimes-air and water curing. Though the strength enhancement between CLP and CLPU is not appreciable at the early age of 7 day, the later age strengths of CLPU specimens at 28, 56, and 90-day were found 16–20% higher than the corresponding strengths of CLP. This could be attributed to the fineness and water demand of the CLPU and possible reaction between silicon di-oxide and CH in the presence of water to form cementitious hydration products; on the contrary, the comparison between the CL and CLP & CLPU shows that though the control-CL mix developed higher strength of about 30 MPa with a cement content of 376 kg/m³ as per the type “S” mortar based ASTM C270, the strength achieved by CLP and CLPU specimens were satisfactory as per the minimum requirement of 12.4 MPa; nonetheless, the saving of cement of about 40% through the use of POCP as cement replacement material is noteworthy; though the use of UPOCP of 40% also resulted in higher strength than the corresponding POCP mixes in CLP, the grinding for UPOCP requires more energy and hence it is recommended the use of POCP as cement replacement material. The amount of hydrated lime added in control and POCP mixes were constant and influence of hydrated lime on mortar mixes gives mortar its workability and ability to hold water for longer time (Walker and Pavía, 2011).

On the effect of curing regimes on compressive strength, it was observed that in all mortars the compressive strength decreases from water curing to air curing. When mortar samples were immersed in water, then it was open to reactive to hydration phase whereas non-reactive in air curing. In air curing, it was observed that the absence of water resulted in failure to produce cementing compounds and in effective, the compounds contribution for filling capillary voids was not appreciable (Sajedi and Razak, 2011).

### Table 9

<table>
<thead>
<tr>
<th>POCP replacement level (%)</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO (C)</td>
<td>68.14</td>
<td>61.65</td>
<td>55.17</td>
<td>48.68</td>
<td>42.19</td>
<td>35.71</td>
<td>29.23</td>
<td>22.74</td>
<td>16.25</td>
</tr>
<tr>
<td>SiO₂ (S)</td>
<td>16.86</td>
<td>21.2</td>
<td>25.55</td>
<td>29.89</td>
<td>34.24</td>
<td>38.53</td>
<td>42.88</td>
<td>47.26</td>
<td>51.6</td>
</tr>
<tr>
<td>C/S Ratio</td>
<td>4.04</td>
<td>2.91</td>
<td>2.16</td>
<td>1.63</td>
<td>1.23</td>
<td>0.93</td>
<td>0.68</td>
<td>0.48</td>
<td>0.31</td>
</tr>
</tbody>
</table>

![Fig. 12](image1.png)

**Fig. 12.** Relationship between Compressive Strength and curing ages.

![Fig. 13](image2.png)

**Fig. 13.** Failure pattern of compressive strength cubes.

![Fig. 14](image3.png)

**Fig. 14.** Compressive strength of CL, CLP, CLPU mortars with different curing regimes.
3.2.2. Ultrasonic pulse velocity (UPV)

Fig. 15 depicts UPV test results of both water and air cured specimens and it can be seen that water cured specimens show higher UPV values than air cured for all mixes and at all ages as expected. As mentioned in the compressive strength discussion, the water cured CL mixes enabled hydration and resulted in compact specimens that resulted in the highest 28-day UPV value of 4.2 km/s and this could be categorized as “good”. The compaction decreases the porosity and improves the durability in terms of less water absorption and lower shrinkage; the excellent category for CL specimens was achieved at the age of 90-day. The water cured CLP and CLPU specimens also produced “good” quality with the UPV values of 3.5–4.2 km/s (σ-0.35, CV- 0.09); due to low pozzolanic activity and changes in relative humidity and temperature in varying curing condition in air cured specimens, both CLP and CLPU specimens produced lower UPV values compared to water cured specimens and achieved ‘medium’ quality; thus, lack of water affects the hydration process and would lead to less compact specimens as compared to water curing specimens. Therefore air cured specimens are susceptible to higher water absorption and drying shrinkage and henceforth would compromise on the durability performance of the mortar. From the results, it is evident that the mortar substituting cement by POCP has a positive effect on the UPV values of mortar.

The UPV values can be correlated with corresponding cubes compressive strength obtained for mortar mixes as shown in Fig. 16. Eq (1). Shows the relationship between the compressive strength and UPV values.

\[ y = 0.0733x + 2.5673 \]  

3.2.3. Flexural strength (\( f_{fl} \))

Fig. 17 depicts the failure pattern of the flexural specimen and it can be seen from the failure the cup and cone pattern of failure at applied point load on prism; Fig. 18 shows the flexural test results of CL, CLP, CLPU mortars. The highest 28-day flexural strength of about 7.70 MPa obtained for CL mix was about 30–35% higher than CLP and CLPU mixes, respectively; however, the achievement of 5.28–5.4 MPa (σ-0.78, CV-0.22) of flexural strength by CLP and CLPU mixes was about 70% of CL mix; in addition, the comparison between the 28-day flexural and the corresponding compressive strengths show that CLP and CLPU mixes achieved about 34 and 38% of the compressive strengths. The addition of UPOCP hasn’t had much influence on the flexural strength as observed in the compressive strength. The use of POCP as pozzolanic material has been reported (Kanadasan and Abdul Razak, 2015) in different mortar and concretes and the finding of flexural strength from this research shows similar trend.

As explained in Section 3.2.1, the effect of air curing didn’t have much impact on the flexural strength; on the contrary, the air cured specimens produced about 90% of the flexural strength as that of the water cured specimens. The trend of both water and air cured specimens show an increase in the strength development at later ages, albeit low for air cured specimens.

Fig. 19 illustrates regression analysis of correlation between compressive strength and flexural strength with a correlation coefficient of \( R^2 \). The \( R^2 \) value by the linear Eq. (2), was found to be 0.9073.

\[ y = 0.2607x + 1.0522 \]  

3.2.4. Splitting tensile strength

Fig. 20 shows the specimens that compile with JSIR – 5201–1997 and BS EN 12390–6: 2009 (BS EN 12390 -6, 2009). A correction factor of 1.10 due to the difference in specimen sizes was found and this correction factor was used to correct the values of the strength of the specimens of 50 mm dia. & 100 mm height based on the strength obtained for 100 mm dia. & 200 mm height cylinder specimens.

Fig 21 shows the results of splitting tensile strength of CL, CLP and CLPU mortars and it shows similar behavior as that of flexural strength.

At 28-days of curing, the highest splitting tensile strength of about 3.57 MPa (σ-0.33, CV-0.15) obtained was for CL mix whereas CLP and CLPU mixes achieved about 68% and 76% of splitting tensile strength of control CL mix. In addition, the CLPU mix obtained splitting tensile strength around 3.5% and 11.7% more as compared to CLP mortar in air cured and water cured respectively. The splitting tensile strength of CL, CLP and CLPU mixes were found 13%, 17% and 17% of compressive strength and 45%, 46% and 50% of flexural strength of mortar mixes; it was observed that as compressive strength increases then flexural and splitting tensile strength also increases.
3.2.5. Flexural bond strength

Poor bonding and low bond strength are the major weaknesses of brickwork. One of the salient features of the sustainable mortar developed by using local waste materials is to apply it on bricks and to test for flexural bond strength. In this research work POCP used as pozzolan and the reactivity of pozzolans affects interface bond development. The high reactive pozzolans will allow early formation of the CSH gel and these strong hydrates will provide the mechanical interlock between the unit and the mortar by enhancing bond strength (Taha and Shrive, 2001). The method used in the investigation based on F. Khalaf (Khalaf) is simple to adapt compared to traditional method; the adapted method enables to differentiate through linear and parabolic load distributions. Fig. 20 shows the results of flexural bond strengths of mortars tested for flexural bond strength on burnt clay and cement bricks. The experimental flexural bond strengths obtained are comparable with previous study conducted using natural hydraulic lime mortar (Pavía and Hanley, 2010).

Fig. 22 shows the flexural bond strength of clay burnt and cement based bricks by using linear and parabolic stress
distribution methods. Based on the parabolic stress distribution of flexural bond strengths of mortars, the control CL mortar with clay burnt bricks obtained about 0.45 MPa (σ-0.1, CV-0.08), whereas CLP and CLPU mortars with clay burnt bricks achieved about 0.30 MPa (σ-0.12, CV-0.09), and 0.20 MPa (σ-0.2, CV-0.10), respectively. The lower bond strength observed in CLPU mix might be due to decrease in active binder content and the effect of water absorption by clay and cement bricks could play role on the bond development of CLPU mortar; generally, more water is required for CLPU mortar compared to CLP due to its finer particle size. On the other hand, in CLP mix average particle size larger than CLPU mix thus this would contribute with the existing mortar particles to form a dense packing particle system that will help to reduce the wall effect between the mortar particles at unit interface (Taha and Shrive, 2001) and could improve bond strength.

There was slight enhancement of the flexural bond strength obtained for CL mortar with cement bricks as it produced about 0.50 MPa; similarly, the flexural bond strengths for CLP and CLPU were found higher compared to the clay bricks and this could be attributed to high water absorption of clay bricks; in addition, the rough surface of cement bricks enables stronger bond compared to smooth surface of clay bricks. Based on the published result (ASTM C150-14, 2014), it was shown that the parabolic distribution of flexural bond is more precise than the linear stress distribution and henceforth parabolic stress distribution is recommended, though it shows lower values.

3.3. Carbon emission

Carbon di-oxide emission from cement plant is divided into two categories namely, combustion and calcination. As known, the manufacture of every tonne of cement produces about 0.88 tonne of CO₂. Further, concrete has relatively large environmental footprint and manufacture of 1 m³ of standard concrete mix is responsible for emitting about 178 kg of embodied CO₂ (Spencer, 2015).

In this research work, cement was replaced by non-combustive SCM. The estimation of CO₂ emission factor for the mining sand is taken from the previous study conducted by Azizul et al. (Islam et al., 2015). The CO₂ emission of POCP was considered as zero as there is no combustion process in the production. The emission factors (CO₂-e) for the manufacture of mortar are shown in Table 10 and Table 11, respectively. The processes of decomposition of lime, grinding, and heating kiln, as well as transportation were considered in the calculation (Collins, 2010).

Fig. 23 shows the estimated CO₂-e for CL and CLP of POCP replacement up to 80% of mortar mixtures. It can be seen that 8–68% CO₂-e reduction for CLP mortars with 10–80% POCP compared to CL; for the optimum level of 40% of POCP addition, 32% reduction of CO₂-e was found. Thus, a significant reduction of CO₂-e was observed in development of cement lime mortar incorporating POCP as SCM.

3.4. Cost efficiency

The use of POCP also results in cost saving. The cost factor of materials by weight is based on the market rate as shown in Table 12. The cost of POCP can be considered as “minimum to zero” as its disposed off as a waste material with no economic value (Kanadasan and Abdul Razak, 2015). The cost of transportation, electricity and manpower are not included in the study.

Fig. 24 shows the comparison of mix proportion for one conventional CL and eight CLP mixes used in this investigation. As the quantity of POCP substitution level increases, the cost of the mix reduces the utilization of CLP80 significantly reduced the cost of mortar by 50% of total cost compared to control mortar. However, in this research work adopted 40% of POCP as optimum replacement to meet the requisite standard for type ‘S’ cement lime mortar and thus the cost reduction is 20% of total cost as compared to control mortar.

The current trend focusses on sustainability in terms of the substitution of the conventional materials by introducing industrials by-product as environmental friendly resource which may help to implement cost saving and use green product. The utilisation of industrial by-product will help to reduce landfilling and potential dangerous effects to the environment (Ljungberg, 2007).

Table 10

<table>
<thead>
<tr>
<th>Mortar producing materials</th>
<th>Emission factor (t CO₂-e/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>0.88</td>
</tr>
<tr>
<td>HL</td>
<td>0.72</td>
</tr>
<tr>
<td>POCP</td>
<td>0</td>
</tr>
<tr>
<td>Mining Sand</td>
<td>0.0139</td>
</tr>
</tbody>
</table>

Fig. 22. Flexural bond strength and mortar type of clay burnt and cement based bricks.
Another important consideration has to be given to the energy in the sustainability development. The POC used in this research work was obtained as completely burned final product that could be used directly but to meet the standard requirement as aggregate or binder materials requires minimum energy for crushing and grinding to convert into powder form. Kanadasan and Razak (Kanadasan and Abdul Razak, 2015) reported that production of POC aggregate will be three times higher compared to gravel for the same crushing energy used. To convert into powder form, the machinery is used for grinding POC and the running time of machinery is directly proportional to energy consumption. The running time of machinery for POC was shortened compared cement and this will consequently reduce the energy consumption. Thus, a significant amount of energy saving for large amount of production of POC. Considering the production of binder material for construction purposes, the utilisation of the abundantly available POCP from POC provides an ideal choice because it consumes less energy, lower carbon emission and provides cost effective mortar or concrete.

### Table 11
Total carbon emission of mortar at different POCP replacement level.

<table>
<thead>
<tr>
<th>Mix</th>
<th>CM content (kg/m³)</th>
<th>CO₂ e/t from CM</th>
<th>Fine Aggregate (kg/m³)</th>
<th>eCO₂/t from fine aggregate</th>
<th>Water</th>
<th>Total eCO₂/t/m³ of mortar</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>376.0</td>
<td>80</td>
<td>0.3667</td>
<td>1440</td>
<td>0.0200</td>
<td>0.000047</td>
</tr>
<tr>
<td>CLP10</td>
<td>338.4</td>
<td>80</td>
<td>0.3358</td>
<td>1440</td>
<td>0.0200</td>
<td>0.000055</td>
</tr>
<tr>
<td>CLP20</td>
<td>300.8</td>
<td>80</td>
<td>0.3049</td>
<td>1440</td>
<td>0.0200</td>
<td>0.000063</td>
</tr>
<tr>
<td>CLP30</td>
<td>263.2</td>
<td>80</td>
<td>0.2740</td>
<td>1440</td>
<td>0.0200</td>
<td>0.000063</td>
</tr>
<tr>
<td>CLP40</td>
<td>225.6</td>
<td>80</td>
<td>0.2430</td>
<td>1440</td>
<td>0.0200</td>
<td>0.000063</td>
</tr>
<tr>
<td>CLP50</td>
<td>188.0</td>
<td>80</td>
<td>0.2121</td>
<td>1440</td>
<td>0.0200</td>
<td>0.000063</td>
</tr>
<tr>
<td>CLP60</td>
<td>150.4</td>
<td>80</td>
<td>0.1812</td>
<td>1440</td>
<td>0.0200</td>
<td>0.000066</td>
</tr>
<tr>
<td>CLP70</td>
<td>112.8</td>
<td>80</td>
<td>0.1501</td>
<td>1440</td>
<td>0.0200</td>
<td>0.000066</td>
</tr>
<tr>
<td>CLP80</td>
<td>75.20</td>
<td>80</td>
<td>0.1194</td>
<td>1440</td>
<td>0.0200</td>
<td>0.000066</td>
</tr>
</tbody>
</table>

### Table 12
Cost factor of materials by weight.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Cost (RM/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>0.44</td>
</tr>
<tr>
<td>Sand</td>
<td>0.08</td>
</tr>
<tr>
<td>POCP</td>
<td>0.02</td>
</tr>
<tr>
<td>HL</td>
<td>0.40</td>
</tr>
</tbody>
</table>

### 3.5. Energy efficiency

Another important consideration has to be given to the energy in the sustainability development. The POC used in this research work was obtained as completely burned final product that could be used directly but to meet the standard requirement as aggregate or binder materials requires minimum energy for crushing and grinding to convert into powder form. Kanadasan and Razak (Kanadasan and Abdul Razak, 2015) reported that production of POC aggregate will be three times higher compared to gravel for the same crushing energy used. To convert into powder form, the machinery is used for grinding POC and the running time of machinery is directly proportional to energy consumption. The running time of machinery for POC was shortened compared cement and this will consequently reduce the energy consumption. Thus, a significant amount of energy saving for large amount of production of POC. Considering the production of binder material for construction purposes, the utilisation of the abundantly available POCP from POC provides an ideal choice because it consumes less energy, lower carbon emission and provides cost effective mortar or concrete.

### 4. Conclusions

- The water content is increasing as POCP content increases in cement-lime mortar (CL) due to consistency requirement and the highest cement replacement of 80% POCP necessitates w/cm ratio of about 0.6. Thus, high water content slightly increases the air content in the mortar which subsequently reduced the fresh density.
- The addition of POCP up to 50% as SCM in CL mortar fulfills the requirement as far the compressive strength of 12.4 MPa is concerned; nevertheless, the use of POCP up to 40% is recommended due to the factors of consistency, air content and fresh density.
- The significant observation on curing regime is noteworthy as the air curing produced the requisite compressive strength for type ‘S’ cement-lime mortar due to presence of hydrated lime which has ability to hold water for longer time and helps during hydration in air cured mortar. Both the water and air cured specimens produced enhancement of compressive strength until the age of 90 days.
- The UPV test results show that both water and air cured specimens achieved ‘good’ quality (Malhotra, 1976).
- Flexural strength shows that CLP and CLPU mixes achieved about 70% of CL mix due to pozzolanic effects of POCP; in addition, the comparison between the 28-day flexural strength and the corresponding compressive strengths shows that CLP and CLPU mixes achieved about 34 and 38% of the compressive
strengths. Curing regime proves similar behaviour as that of compressive strength.

- In splitting tensile strength, comparison between JSIR – 5201–1997 and EN 12390–6 was made. The noticeable factor was that the specimen size had no measurable impact on split tensile strength. The results show that CLP and CLPU mixes achieved about 68% and 76% of split tensile strength of CL mortar at 28 days of curing. There was significant enhancement in split tensile strength until 90 days of curing due to pozzolanic reactivity of POCP at later ages (Karim et al., 2017b).

- Incorporation of POCP achieved 70% of flexural bond strength as that of control mortar; the use of parabolic stress distribution is recommended as it is more precise compared to linear stress distribution. The finer particles in CLPU mortar produced lower bond strength as compared to that of CLP mortar in both the clay and cement bricks which could be attributed to water absorption and particle size.

- Incorporation of POCP could significantly reduce carbon footprint by about 32% compared to conventional mortar; further, cost saving of 20% and potential energy saving could also be envisaged.

- Despite slight enhancement in mechanical properties, the production of UPOC is energy intensive and hence the use of up to 40% of POCP is recommended for cost effectiveness, and environmental sustainability.

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References


