Influence of palm oil clinker powder on the fresh and mechanical properties of masonry mortars

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Abstract. Masonry and rendering mortars are is well known oldest techniques in the building. A common idea is to use strong material as possible, and as a result mortars are often rich in cement. Not only this is unnecessary expensive, it has also technical disadvantages and harmful to environment. Hence, in this study focuses on utilisation of palm oil mills waste, namely palm oil clinker powder (POCP) and POCP influences on the fresh and mechanical properties of masonry mortars are analysed and comparison between cement–lime (CLM) and masonry cement mortar (MCM) are addressed. The masonry mortars were prepared using cement–lime and masonry cement as control masonry mortars christened as type ‘S’ mortar. The POCP used as cement replacement material in the masonry mortar mixture from 0-80% by volume in the preliminary study and ideal replacement of 40% was used in the final mixture of mortar for comparison. All specimens were cured in water and air curing regimes for 7, 28 and 56 days and the physical and mechanical properties were analysed. The results show that as replacement of cement with POCP increases, there is a reduction in fresh density with subsequent increase in air content. Further, the use of masonry cement with POCP (MCP) shows highly workable mix even at lower w/cm ratio compared to cement-lime mortar with POCP (CLP). Moreover, CLM, CLP obtained higher strength (28 & 20 MPa) than MCM and MCP (24 MPa & 11 MPa). on the contrary, the cement-lime mortar with POCP shows higher compressive strength compared to masonry mortar prepared with masonry cement-POCP.

1. Introduction

The masonry mortar is one of the most produced and widely used building materials in construction industry for laying of bricks and blocks or wall rendering etc. The performance level of these masonry mortars is not required to be very high, consequently allowing for the possibility of producing them with different combination of binders such cement- lime or masonry cement to achieve minimum strength and higher bonding capability. There is much confusion between cement/lime blends and masonry cements in the masonry market today [1]. However, these two products are mainly composed of limestones so the actual requirements of sustainability in construction promote the use of binding materials which cause lower impact on the environment than those of traditionally used [2].

The oil palm cultivation in Malaysia started almost century ago. At present Malaysia and Indonesia are the leading palm oil producers in the world and are supplying almost 90% of the global palm oil demand. On the contrary, Malaysian biomass wastes generated from palm oil industry accounts for
85.5% of the total biomass produced. This enormous amount of biomass wastes trigger a tremendous impact to the environment if they are not handled in an appropriate manner [3]. Approximately 75% of the wastes in the form of oil palm trunks and oil palm fronds are left rotten in the plantation for mulching and nutrient recycling purposes. The remaining 25% solid residues such like empty fruit bunch, palm kernel shell and mesocarp fibre are used in direct combustion to generate electricity in palm oil mills and at the same time reduce the dependency on fossil fuels [4]. As a result of this, the combustion process led to produce wastes such as palm oil fuel ash (POFA) and palm oil clinker (POC); and these two wastes cause problem to palm oil mill operators pertaining to disposal issue. Further, these operators face challenges towards sustainable development in handling the biomass wastes in compliance to environmental regulations, such as EQA 1974. In addition, the vicinity of many palm oil mills is filled with these wastes thereby causing land and air pollution.

There have been attempts by researchers to use POC as an alternative to conventional crushed granite aggregates in the development of lightweight concrete [5];[6], self-compacting concrete and supplementary cementitious material to enhance the strength of concrete [7];[8];[9];[10];[11]. Certain studies mainly on the manufacture of mortar, concrete and self-compacting concrete, have examined the use of POC powder (POCP) in mixtures taking advantage of highly pozzolanic reactive binder [12]. Studies on mortars and concrete manufactured with the addition of POCP have yielded positive results. POCP is potential pozzolanic material and development of this pozzolanic reaction with higher silica content can be positive in binder mixtures used in construction. Moreover, the quantities of free calcium oxide and magnesium oxides content are lower and this leads to their spontaneous reaction with cement.

This present work, studied on two types of masonry mortars such as cement – lime and masonry cement mortars, both are prepared with POCP for sustainability and comparison of fresh and mechanical properties of mortars was studied. It aims to obtain mixtures that have similar levels of performance to conventional masonry mortars, albeit with POCP as partial cement replacement material.

2. Materials and Methods

2.1. Materials and their properties

2.1.1. Cementitious materials: Ordinary Portland cement (CEM I/42.5), hydrated lime (HL) and masonry cement (MC). The particle size distribution of cementitious materials is shown in Figure 1. The chemical composition and physical properties of cementitious materials (CM) is shown in Table 1. Palm oil clinker powder (POCP) used in this study as cementitious material was processed from POC that was obtained from palm oil mill in Selangor, Malaysia. The large size chunks of POC transported from the palm oil mill were dried and then crushed using a jaw crusher. The 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 sum of SAF for POCP is about 70 % and LOI is 5.23, and hence it could be classified as class ‘F’ based on ASTM C618 -14 [13]. Mining sand obtained from local supplier was used as fine aggregate; the values of specific gravity and fineness modulus of local mining sand were found as 2.59 and 2.27, respectively. Portable tap water was used in mortar; the according to ASTM C270-14 [14].
Figure 1. Particle size distribution of cementitious materials

Table 1. Chemical composition and physical properties of cementitious materials

| Oxides (%) | Cementitious Materials |  
|---|---|---|---|
|  | OPC | POCP | MC | HL |
| SiO₂ | 16.86 | 60.29 | 9.43 | 0.29 |
| Al₂O₃ | 3.83 | 5.83 | 2.23 | 0.14 |
| Fe₂O₃ | 3.76 | 4.71 | 2.27 | 0.33 |
| CaO | 68.14 | 3.28 | 53.8 | 93.1 |
| MgO | 2.04 | 4.2 | 1.94 | 4.71 |
| P₂O₅ | 0.04 | 3.78 | 0.03 | 0.02 |
| K₂O | 0.21 | 7.24 | 0.18 | 0.40 |
| SO₃ | 4.84 | 0.31 | 3.01 | 0.97 |
| TiO₂ | 0.14 | 0.10 | 0.08 | - |
| MnO | 0.11 | 0.12 | 0.08 | 0.06 |
| Na₂O | 0.03 | 0.20 | 0.01 | - |
| SAF | 70.83 |  |
| LOI | 2.01 | 5.23 | 1.52 | 0.09 |
| Specific Gravity | 3.15 | 2.55 | 2.90 | 2.30 |
| Moisture Content (%) | 0.18 | 0.83 | 0.48 | 0.13 |

2.2. Mix proportioning and methods

Masonry mortars with type ‘S’ was selected for the research and it was found suitable as it complies with ASTM: C270 – 14 [14]. The mix proportion used in the study was 1:0.5:4.5 (Cement: Hydrated lime: Sand) for cement – lime mortar (CL) and 1: 3 (masonry cement: sand) for masonry cement mortar (MC). Table 2 shows 9 mixes (1 control and 8 mixes with POCP) that were prepared to find the optimum amount of POCP to be used for further study. Further, 3 more mixes were cast in order to compare the optimized content of 40% of POCP in CL and MC. The materials, cement, hydrated lime and sand were mixed for about 2-3 min using mortar mixer 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 [14] and ASTM C185-14 [15], respectively. The specimens prepared include 50 mm³ cubes for compression strength test [ASTM C109-14] and UPV test were performed in accordance with ASTM C109-14 [16] ASTM C597-14 [17]. The flexural test was performed on prism of 40 x 40 x 160 mm in accordance with ASTM C348 – 14[18]. Finally, cylindrical specimens of 50 mm dia. x 100 mm height were prepared for splitting tensile test. BS EN 12390 - 6: 2009 [19]. All the specimens were covered with plastic sheathing and demoulded after 24 hours. The specimens were water cured till the day of testing; however, for optimized mixes- CL, MC, CLP and MCP, the demoulded specimens were subjected to two types of curing, namely water and air curing in the laboratory environment (temperature and humidity of 29±2°C and 60±10% respectively) for all the tests.

Table 2. Mix proportions for optimization and ideal mixes

| Phase     | Mix ID | Replacement (% ) | Sand (kg/m³) | Lime (kg/m³) | Cement (kg/m³) | POCP (kg/m³) | w/cm Ratio |
|-----------|--------|------------------|--------------|--------------|----------------|--------------|------------|
| Optimisation | CL   | 0                | 1440         | 80           | 376            | 0            | 0.4        |
|            | CLP 10| 10               | 1440         | 80           | 338            | 38           | 0.49       |
|            | CLP 20| 20               | 1440         | 80           | 301            | 75           | 0.57       |
|            | CLP 30| 30               | 1440         | 80           | 263            | 113          | 0.57       |
|            | CLP 40| 40               | 1440         | 80           | 226            | 150          | 0.58       |
|            | CLP 50| 50               | 1440         | 80           | 188            | 188          | 0.58       |
|            | CLP 60| 60               | 1440         | 80           | 150            | 226          | 0.6        |
|            | CLP 70| 70               | 1440         | 80           | 113            | 263          | 0.6        |
|            | CLP 80| 80               | 1440         | 80           | 75             | 301          | 0.6        |
| Ideal     | CL   | 0                | 1440         | 80           | 376            | 0            | 0.58       |
|            | CLP 40| 40               | 1440         | 80           | 226            | 150          | 0.58       |
|            | MC   | 0                | 1440         | 0            | 420            | 0            | 0.58       |
|            | MCP 40| 40               | 1440         | 0            | 252            | 168          | 0.58       |

3. Results and Discussion

3.1. Fresh properties

3.1.1. Slump flow, air content and fresh density

The importance of workability is apparent when one considers that workmanship is the key element in achieving quality in masonry construction. Therefore, fresh properties such as workability, air content and fresh density were investigated and tabulated in Table 3. The w/cm ratio used in the optimization phase ranged from 0.46 to 0.60 to maintain slump flow of 110±5% based on ASTM C270 – 14 [14]. In, the POCP replacement with cement was varied from 0 to 80%, whereas the amount of hydrated lime remained unchanged. It was noticed that total w/cm ratio was increased as the POCP replacement increased; subsequently, this influenced the air content of mortar mixes to the range of 4.19 – 7.17% and the fresh density decreased from 2298 – 2015 kg/m³ due to the presence of POCP particles. Thus, the POCP particles with low specific gravity could lower the stress effect and this would ease the
movement of flow of mortar [20]. In ideal phase of study, the w/cm ratio for all mortar mixes maintained at 0.58. The test results of air content and fresh density of masonry mortar (MC) were found higher than cement-lime blend mortar (CL); this is due to the incorporation of plasticizers in MC blends that helps in workability, but cause density variation due to water retentivity [1]. Similar results were obtained for mortar mix with POCP; however POCP substituted mortars produced lower density and higher air content than the control mortars due to irregular shaped porous particles of POCP that would create voids in the mortar [9];[7].

**Table 3. Fresh properties of optimization and ideal mortar mixes**

| Phase | Mix ID | Replacement level (%) | w/cm Ratio | Slump Flow (mm) | Fresh Density (kg/m³) | Air Content (%) |
|-------|--------|-----------------------|------------|-----------------|-----------------------|-----------------|
| Optimisation | CL | 0 | 0.46 | 108 | 2298 | 4.19 |
| | CLP10 | 10 | 0.49 | 115 | 2185 | 3.74 |
| | CLP20 | 20 | 0.57 | 113 | 2135 | 3.99 |
| | CLP30 | 30 | 0.57 | 106 | 2120 | 4.39 |
| | CLP40 | 40 | 0.57 | 112 | 2095 | 5.24 |
| | CLP50 | 50 | 0.57 | 110 | 2060 | 6.56 |
| | CLP60 | 60 | 0.60 | 112 | 2035 | 6.78 |
| | CLP70 | 70 | 0.60 | 108 | 2022 | 7.09 |
| | CLP80 | 80 | 0.60 | 111 | 2015 | 7.17 |
| Ideal | CL | 0 | 0.58 | 115 | 2248 | 4.25 |
| | CLP | 40 | 0.58 | 114 | 2154 | 4.41 |
| | MC | 40 | 0.58 | 113 | 2378 | 5.25 |
| | MCP | 40 | 0.58 | 110 | 2208 | 5.98 |

3.2. Mechanical properties

3.2.1. Hardened density and ultrasonic pulse velocity (UPV)

The relationship between the hardened density and UPV mean values of ideal mixes and their evolution over time is shown in Figure 2. The effect of curing regimes of the four mortar types (2 control and 2 mixes with POCP) showed significant influence on the hardened density and UPV. The hardened densities of water cured CL and MC mortar mixes obtained were in the range of 2250 - 2285 kg/m³ and 2248 - 2270 kg/m³, respectively. The fresh density of MC mix was found higher than the CL mix, but due to the evaporation of water in the air voids, the hardened density was lower than CL. It is worth noting that hydrated lime in CL mortar has an added advantage as it holds moisture inside the mortar for hydration, thus developing good bond between hydrated cement and sand. The comparison of densities of CL and CLP shows slight reduction for the latter and this could be attributed to the lower specific gravity of POCP. Similar reduction in the density was observed in MC and MCP mixes. The comparison between all the air and water cured specimens of both mortar types also shows a reduction of about 50 kg/m³.
The UPV values obtained for CL and MC mixes were in the range of 4.00 – 4.50 km/s and 3.50– 4.25 km/s, respectively; the UPV values of CLP and MCP mixes were found in the range of 3.50 – 4.25 km/s and 3.00 to 3.70 km/s, respectively. The CL, MC and CLP mortars achieved threshold value of 3.5 km/s—which could be categorized as ‘Good’ quality mortar whereas MCP fall shorter than threshold value and categorized as ‘Medium” quality mortar[21];[20]. In CL and CLP mixes the very fine lime particles combined with coarser POCP particles produce slightly lower UPV values compared to the control CL mixes. In general, the MC and MCP mixes produced acceptable UPV values.

![Figure 2. Relationship of mortars type v/s hardened density and ultrasonic pulse velocity (UPV) at different ages](image)

3.2.2. Compressive strength

Figure 3 shows the relationship of compressive strength of all mortars at 7, 28, 56 and 90 days for different curing conditions. The test was carried out in accordance with ASTM C109 – 14. The CL mix produced the highest 28-day compressive strength of 28 MPa. Though the MC mixes produced lower early age strength the 90-day strength was found closer to that of CL mix. The porous particles of POCP with less density produced lower compressive strength compared to control mix. However, CLP mortar achieved requisite compressive strength of 12.40 MPa based on ASTM C270 – 14, but MCP failed to achieve the requisite strength under both curing regimes. In the case of air cured condition, all mixes produced lower strength due to lack of water for hydration and subsequent carbonation process occurs in air curing mortars; however the strength contribution from carbonation is lower than hydraulic components [22]. Furthermore, water and air cured MC mixes didn’t show any significant difference in the strength. It is noteworthy to mention that except MCP mixes, all other mixes irrespective of curing regimes achieved the requisite compressive strength to be classified as type ‘S mortar based on ASTM C270 – 14.

The comparison between 28 and 90-day strength of CL mortar didn’t show much difference between these two strengths. Due to hydrated lime content in CL mortar, the mortar hardens due to excess water lost and at the same time, the carbonation process of transforming portlandite (Ca(OH)$_2$) into calcite (CaCO$_3$) starts [23] as seen in XRD results presented in Figure 4. Further, alite (C$_3$S) is formed before the peak of calcite. However, certain of amount of portlandite remained uncarbonated in all the mortars[23]. On the contrary, MC mortar needs much longer period than that of CL mortar. However, at 90 days of curing MC mortar achieved equivalent strength to CL mortar and the both curing regimes
had not much influence on MC mortar, but CL mortar achieved lower compressive strength in air cured condition. The composite mortars of CLP and MCP followed Figure 3. Relationship of mortars type v/s compressive strength at different age similar trend as that of the controlled mortar and the strength obtained was found lower than that of the control mortars at all ages of curing.

![Figure 3](image3.png)

**Figure 3.** relationship between mortars type and compressive strength (MPa)

![Figure 4](image4.png)

**Figure 4.** XRD results of mortars

### 3.2.3. Flexural strength
Figure 5 shows the relationship between mortar types and flexural strength at 28, 56 and 90 days of specimens cured in different conditions. The flexural strength of CL and MC mortars was found in the range of 6.00 – 8.00 MPa and 4.00 – 7.90 MPa respectively. The small increase in the flexural strength of CL at the later ages of 56 and 90 days could be due to lime rich, [24]. The wide variation in the MC mortar could be due to cement rich binder [24]. The flexural strengths of POCP incorporated CLP and MCP mortars were found in the range of 4.00 to 6.02 MPa and 2.00 – 4.30 MPa, respectively. However, CLP and MCP mortars produced up to 75% and 55% strength relative to control mortars. It was important to notice that the cement replacement materials-POCP in the CL mix achieved satisfactory results compared to the corresponding MC mortar. The flexural strengths of CL and CLP mortars achieved 1/3 of compressive strength. In general, the flexural strength shows an increment between 28 and 90 days in both curing regimes [23].

![Figure 5. Flexural strength of mortars](image)

3.2.4. Splitting tensile strength

Figure 6 shows the relationship between mortars type and splitting tensile strength. The splitting tensile strengths of CL and MC mortars obtained at different ages (28-90 days) were in the range of 3.50 – 3.70 MPa and 2.80 – 3.20 MPa, respectively. As expected the water cured specimens produced higher strength compared to air cured due to hydration and strong bond at the interface [25]. In general, the air cured specimens produced (%) compared to the water cured specimens. Though the replacement of POCP reduced the splitting tensile strength, the requisite strength of 2 MPa was achieved in all mortars except in MC (air cured) and MCP mixes (both curing conditions). The bond between the aggregate and different cement types and POCP interface could provide some indication concerning the effectiveness of POCP in these types of mortar and substantially this result will influence on the bonding and load capacity of structure. In general, both flexural and splitting tensile strengths have good correlation with the compressive strength. As far as mechanical properties are concerned, in mortars with lime rich binder (CL,CLP) carbonation predominates during the hardening process, so the mechanical strength increases in parallel with the carbonation process [26]. The cement- rich binder (MC, MCP) shows the higher variation in the mechanical properties, but the curing conditions had insignificant influence on strength [27].
4. Conclusions
To reduce carbon emission and enhance the sustainability, it is vital to preserve natural resources; thus, it is highly recommended to use industrial waste by-products in the masonry construction, especially in mortar. Based on the research, it can be concluded that POCP would be an ideal choice to replace cement up to 40% without compromising on strength.

- The comparison between CL and MC mortars shows, the former has higher fresh density, lower air content. The CL mortar performed better than MC mortar though MC mortar is more workable.
- The influence of POCP on CL and shows that POCP achieved relatively acceptable performance with CL blended mortar compared to MC mortar. Based on the results, it can be concluded that replacing cement with POCP will significantly improve the long-term strength of well-cured mortars.
- Despite replacing 40% of cement, POCP, CLP mortar produced the requisite compressive strength of 12.40 MPa as stipulated in ASTM C270 – 14; further both the compressive and flexural strengths were found to be 75% of the control mortar (CL). In addition, CLP mortar achieved 70% of splitting tensile strength of the control mortar.
- The CLP results show acceptable performance as that of MC mortar; however, MCP failed to achieve the requisite compressive strength of 12.40 MPa.

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