Effect of binder content and water-binder ratio in mortar developed using partial replacement of cement with palm oil clinker powder

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Abstract. The manufacture of cement leads to almost 5 to 7% of the total production of carbon dioxide which causes greenhouse effect. So, it is vital to replace the ordinary Portland cement by the other binders which have the similar or better properties than cement. Besides, the recent interests on the palm oil industrial wastes in the development of mortar led to research works on usefulness of these wastes in construction materials. The palm oil industry produces many wastes such as oil palm shell, palm oil fuel ash (POFA) and palm oil clinker powder (POCP). In this research work, an experimental study was conducted to investigate the effects of different binder contents, and water-binder (w/b) ratio on the development of mortars. Conventional ordinary Portland cement was replaced with 40% of POCP and the total binder contents of 450, 500 and 550 kg/m³ with w/b ratios of 0.45, 0.35 and 0.32 used. The properties of mortars were evaluated for fresh and hardened properties; XRD characteristic was also studied. Test results showed that the strength of mortar specimens improved as the binder content increased with subsequent decrease in w/b ratio. POCP mortar specimens with binder content of 550 kg/m³ with cement replacement of 40% produced 28-day compressive strength of 45.3 MPa, compared to 65.12 MPa for control cement mortar (CM). The value of flow diameter of 40% replacement of POCP mortar was 108.51 mm and this was 16.6% lower compared to control mortar. Though POCP based mortar produced a strength reduction of about 36.6%, its usefulness in achieving acceptable strength and sustainable aspect of reducing 40% of conventional cement could be considered significant.

1. Introduction

CO₂ reduction by minimizing the use of Portland cement has recently recognized; the use of cementitious materials such as fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBS) and metakaolin as partial replacements for cement were efforts taken seriously by the cement industry to decrease the consumption of cement. Agro-industrial by-products such as rice husk ash (RHA) and palm oil fuel ash (POFA) are available in abundance in the South-East Asia; countries like Indonesia, Thailand, Vietnam, Philippines and Malaysia produce these wastes and many researchers focus on utilizing the above products as cement replacement material. Waste from the palm oil industry is not limited to POFA, but includes empty fruit bunches (EFB), oil palm shells (OPS) and palm oil clinker [1]. Malaysia being the world’s second largest palm oil producer has abundance of industrial by-products such as kernel shell, mesocarp fibre and empty fruit bunches. Many researchers focused on the feasibility and sustainability of transforming palm oil industry wastes into bio-based construction materials [2]. Palm oil clinker (POC) which is obtained as a final by-product from the incineration process of OPS and mesocarp fibre is usually landfilled in the vicinity of plantation or used as a cover
for potholes on the roads leading to the estates. The POC is available in large chunks from the mill and is much lighter in nature. Crushing POC into appropriate sizes provides an ideal alternative source to make as aggregate. Besides, POC has also been ground into fine powder, known as palm oil clinker powder (POCP) which can be used as a binder material to enhance the self-consolidating behaviour [3]. The challenge faced by ordinary Portland cement (OPC) producers is to minimize carbon footprint from Portland cement clinker production as well as to meet up to the increasing demand of cement for ever increasing construction activities in the world. The cement industry is responsible for 5–8% of the total global CO2 emission and with more developmental activities, the reduction in green house gases requires rapid action from industry players [4-6]. On the other hand, the scarcity of more reactive supplementary cementitious materials (SCMs), such as FA and GGBS motivated the researchers to use the local wastes from palm oil industries. Alengaram et al. [7] investigated the use of OPS as whole replacement for conventional crushed granite aggregate in the development of OPS concrete slab and reported its superior blast resistance characteristics compared to conventional concrete. The incorporation of OPS in concrete would lead to an effective usage of local industrial by-product into construction materials and many research works have been carried out on utilizing OPS as coarse aggregates. The pozzolanic activity and subsequent strength development of POCP based mortar was investigated by researchers [8-10] using X-ray diffraction (XRD) analysis. The pozzolanic activity of POFA and POCP depends on chemical composition and particle size. The development of the hydration products enhance due to the pozzolanic activity of fine particles [11]. Moreover, the replacement of binder by fines particles will contribute to reducing CO2 emissions generated by cement production [1].

On the other hand, the fresh and hardened properties of mortar, water content plays an important role. Water is often considered to improve the workability and finishability of concrete in construction site. The easy mixing and workability would be achieved when additional water added to the concrete but leads to increase the porosity. The higher the porosity results in degradation of concrete and affects the durability and structural performances. In addition to that the added water causes segregation of aggregates and reduction in strength. The higher water added to the concrete the more would be activation of hydration for the same amount of cement content. However, the reduction of strength and deterioration of concrete happens because of the formation of more pores in cement paste [12]. Also, the addition of super-plasticizer (SP) increases the strength of mortar [13].

In view of the above, the aim of this study is to develop a mortar incorporating POCP as the partial replacement of cement and to investigate the effects of different binder contents and water-binder ratios (w/b). There are very few literatures on the comparative study of mortar incorporating palm oil industrial wastes. Hence, there is need for further investigation on the use of POCP as pozzolanic material in the development of mortar. Thus, this paper presents the material characterization of POCP and flow, compressive strength, microstructural characteristics of mortar along with the reactivity of POCP.

2. Experimental programme

2.1 Materials

OPC Type I used in this investigation according to the requirements of ASTM C150-07. The chemical composition of OPC and POCP as determined by X-ray florescence (XRF) is shown in Table 1. The physical properties of OPC and POCP are provided in Table 2.
The POC was obtained from a palm oil mill in the vicinity of Kuala Lumpur, Malaysia. The raw POC is not feasible to use directly as received due to impurities of foreign materials and uncombusted palm fibers, large particle size and moisture content. In order to remove the moisture content the raw POC was oven dried at 105 ±5 °C for 24 h and then sieved using 300 µm sieve. The sieved portion of these POC was then ground in a Los Angeles abrasion machine. The process of grinding was carried out for 30,000 (30K) cycles for POCP. The morphology of the POC was examined by scanning electron microscope (SEM) and the micrograph is shown in Figure 1. The POCP particles have porous structure and irregular and angular particles (Figure 1). Figure 2 shows the results of particle size

### Table 1: Chemical composition of OPC and POCP.

| Chemical compositions (%) | OPC     | POCP    |
|---------------------------|---------|---------|
| SiO₂                      | 13.34   | 59.12   |
| Al₂O₃                     | 3.03    | 5.72    |
| Fe₂O₃                     | 2.98    | 5.27    |
| SiO₂ + Al₂O₃ + Fe₂O₃      | 19.35   | 70.11   |
| CaO                       | 54.03   | 3.98    |
| MgO                       | 1.61    | 4.20    |
| P₂O₅                      | 0.03    | 3.78    |
| K₂O                       | 0.15    | 7.24    |
| SO₃                       | 3.83    | 0.31    |
| TiO₂                      | 0.11    | 0.10    |
| MnO                       | 0.08    | 0.12    |
| Na₂O                      | 0.02    | 0.20    |
| CuO                       | -       | 0.04    |
| ZnO                       | 0.03    | 0.01    |
| Rb₂O                      | -       | 0.05    |
| SrO                       | 0.02    | 0.01    |
| Y₂O₃                      | 0.00    | -       |
| ZrO₂                      | 0.01    | 0.01    |
| Cl                         | 0.01    | 0.07    |
| Cr₂O₃                     | -       | 0.01    |
| NiO                       | -       | 0.02    |
| Loss on ignition (LOI)    | 2.01    | 3.68    |

### Table 2: Physical properties of OPC and POCP.

| Properties                                 | OPC     | POCP    |
|--------------------------------------------|---------|---------|
| Specific gravity                           | 3.14    | 2.52    |
| Median particle size (µm)                  | 22.96   | 47.85   |
| Specific surface area (m²/kg)              | 353     | 424     |
| Particle passing on 45 µm sieve (%)        | 78.5    | 49      |
distributions of OPC and POCP. It can be seen from the Table 2 and Figure 2 that the median particle size of POCP has higher than OPC. Local mining sand was used as fine aggregate with a maximum particle size of 2.36 mm including all the fines. The specific gravity and fineness modulus of fine aggregate was determined as 2.66 and 2.88, respectively. A polycarboxylate-based super-plasticizer (SP) (Sika ViscoCrete) was used with a quantity of 3% of the mass of binder in all the mixtures.

Figure 1. Scanning electron microscopy image of POCP.

Figure 2. Particle size distribution of POCP.

2.2 Mixing proportions

There were two main set of mortars with 100% OPC referred as control specimens and POCP used as cement replacement at the replacement level of 40%. The binder contents and w/c ratios of 450, 500 and 550 kg/m$^3$ and 0.45, 0.35 and 0.32, respectively, used to investigate the effect of variations in binder contents and w/c ratios on the mortars. The mortar specimens were cast in 50 mm cube steel molds in three layers of equal height and vibrated. The mix designation of mortars was designated as ‘CM’ for control specimens and for POCP mixes, ‘40C’ refers to the replacement level of 40% of POCP and ‘C’ denotes POCP mix. The mix proportions of mortar mixes are given in the Table 3.

| Mix designation | Total Binder Content (kg/m$^3$) | Water-binder ratio | OPC (kg/m$^3$) | POCP (kg/m$^3$) | Sand (kg/m$^3$) |
|-----------------|-------------------------------|-------------------|----------------|-----------------|----------------|
| CM-1            | 450                           | 0.45              | 450            | 0               | 1350           |
| CM-2            | 500                           | 0.45              | 500            | 0               | 1500           |
| CM-3            | 550                           | 0.45              | 550            | 0               | 1650           |
| CM-4            | 450                           | 0.35              | 450            | 0               | 1350           |
| CM-5            | 500                           | 0.35              | 500            | 0               | 1500           |
| CM-6            | 550                           | 0.35              | 550            | 0               | 1650           |
| CM-7            | 450                           | 0.32              | 450            | 0               | 1350           |
| CM-8            | 500                           | 0.32              | 500            | 0               | 1500           |
| CM-9            | 550                           | 0.32              | 550            | 0               | 1650           |
| 40C-1           | 450                           | 0.45              | 270            | 180             | 1350           |
| 40C-2           | 500                           | 0.45              | 300            | 200             | 1500           |
| 40C-3           | 550                           | 0.45              | 330            | 220             | 1650           |
| 40C-4           | 450                           | 0.35              | 270            | 180             | 1350           |
The sand to binder ratio of 3:1 used for all mortar mixes and dry mixing method was adopted in this study. The OPC and POCP were mixed in a mixer for 2 min. The dry mix powder was added to the sand and proceeded mixing for another 3 min. Then, 70% mixing water was added to the mixture and further mixed for 5 min. The rest of the water added with SP and mixing continued for another 3 min and then the flow table test was performed. The flow table test was done in accordance with the standard ASTM C1437-15 to determine the workability of the fresh mortar. The fresh mortar filled up in the mould and tamped for 20 times. Then, the mould was lifted away and the table was dropped 25 times in 15 s. Compressive strength test of cube specimens was carried out in accordance with BS EN 12390-03:2009. The water cured specimens of 1-, 3-, 7-, and 28-d were tested with a consistent load at the rate of 0.9 kN/s.

3. Results and discussions

3.1 Workability of fresh mortar

The workability of fresh mortar for control mortar mixtures and 40% replacement of OPC with POCP mixtures are shown in Figure 3 & 4. It can be seen from the Figure 3 & 4 that the flow diameter values reduced with lower w/c ratio and higher binder content. As can be seen from the figure, the CM-1 mortar mixture showed the highest workability of 155 mm and this is attributed due to the higher w/c ration as well as lower binder content. For CM-9 mix, the flow diameter value was 133 mm, which is the lowest flow value among the control mortar mixtures (Figure 3). This is because of the low w/c ration as well as higher cement content of 550 Kg/m\(^3\) and hence the lack of water in the mix causes low workable mortar.

![Figure 3. Flow diameter of control mortar mixtures (100% OPC).](image)

In the case of 40% replacement mortar mixtures (Figure 4), It can be seen that the all the mortar mixtures with low flow diameter values as compared to control mortar mixtures. This could be due to the porous nature of POCP as compared to OPC and hence, 40% of POCP in the mix tends to absorb...
the added water during the mixing [11]. Therefore, the flow values are reduced for POCP based mixtures. The target flow was confirmed in accordance with standard ASTM C109–02 and all the mortar mixtures stratified the minimum requirement of 110±5 mm.

![Flow diameter of mortar mixtures (40% replacement of OPC with POCP).](image)

**Figure 4.** Flow diameter of mortar mixtures (40% replacement of OPC with POCP).

### 3.2 X-Ray Diffraction (XRD) analysis of mortar

The calcium hydroxide (CH) formed from the hydration of OPC reacted with the silica from POCP and formed (calcium silicate hydrate) C-S-H. The CH peaks clearly observed at 2θ of 18.85° and C-S-H were identified at 2θ of 29.3°, 39.99° & 51.13°. In the case of control specimens, the CH and C-S-H peaks were evidently seen in the Figure 5. Among all the mixtures, the higher peaks of CH and C-S-H were noticed for CM-9 mix; this is due to the high cement content in the mix produced more CH and C-S-H. The value of flow diameter of 40% replacement of POCP mortar was 155 mm and this was 18.7% lower compared to control mortar.

![XRD patterns of mortars (100% OPC mixes along with 40% replacement of OPC with POCP) at 28 day of curing.](image)

**Figure 5.** XRD patterns of mortars (100% OPC mixes along with 40% replacement of OPC with POCP) at 28 day of curing.

It can be evidently observed from Figure 5 that CH and C-S-H peaks intensities were higher for control specimens compared to the specimens of POCP with the replacement of 40%. The C-S-H peaks decreased when replace the OPC with 40% POCP. The reduction in the formation of CH is mainly due to the dilution effect when POCP is partially replaced with OPC. For POCP mixtures with high replacement level, the rate of the hydration process reduced. The POCP absorbed the added water
in the mix, at the same time when high level of replacement reduces the amount of CaO in the cement. This is known as dilution effect [11, 14]. The CaO content is very essential for the formation of CH.

3.3 Compressive strength of hardened mortar
The compressive strength of mortar specimens are shown in Figure 6 & 7. POCP mortar specimens with binder content of 550kg/m³ and cement replacement of 40% produced 28-day compressive strength of 45.3 MPa, compared to 71.45 MPa for control cement mortar (CM). It was observed form the Figure 6 & 7 that the compressive strength of all the mortar specimens increased with curing ages. In control mortar mixtures, the strength increased with increase in binder content and decrease in w/c ratio [15]. This is well supported with the XRD results (Figure 5). The highest compressive strength of 71.45 MPa was achieved for control mortar of CM-9 with binder content of 550 Kg/m³ and lower w/c of 0.32. In case of POCP based mortars (Figure 7), the mix 40C-9 produced a higher compressive strength of 45.3 MPa. Though, the mix 40C-9 shows a strength reduction 36.6% its usefulness in achieving acceptable strength and sustainable aspect of reducing 40% of conventional cement could be an effective approach.

![Figure 6](image1.png) Compressive strength of control mortar mixtures (100% OPC).

![Figure 7](image2.png) Compressive strength of mortar mixtures (40% replacement of OPC with POCP).

4. Conclusions
This research focused on critical examination of using POCP as additional cementitious material in cement mortar to achieve high strength and acceptable workability. The following conclusions are made based on the research findings:

- The workability and compressive strength are strongly influenced by different w/c ratio and binder content. Increasing binder content improved the compressive strength; it could be due to the more amount of cement reacted with water and formed CH and then the available silica and CH produced CSH gel.
- All the mortar mixtures achieved a minimum target flow of 110±5 mm in accordance with standard ASTM C1109–02 and the highest flow diameter of 155 mm was attained by a mortar mix with binder content of 450 Kg/m³ and w/c of 0.45. The higher w/c and lower binder content enhanced the workability of the mortar. On the other hand, the POCP mix has less
flow diameter compared to control specimens; which is mainly attributed to the water absorption of POCP due to the porous structure.

- Though POCP based mortar produced a strength reduction of about 36.6%, in terms of satisfactory strength, workability and sustainable aspect of reducing 40% of conventional cement could be considered significantly. The mortar mix with binder content of 550 Kg/m³ and w/c of 0.32 produced a desirable workability and strength.

Acknowledgments
The authors gratefully acknowledge the funding provided by University of Malaya through University of Malaya Research Grant (UMRG) with Project No. RP037C-15AET – Synthesis of Nano Silica, Alumina and TiO₂ in the Development of Geopolymer of Concrete using Local Waste.

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