The Properties of Blended Cement Containing Palm Oil Fuel Ash

Asnidah Arif¹, Hidayati Asrah¹, Ahmad Nurfaidhi Rizalman¹ and Salinah Dullah¹

¹Civil Engineering Program, Faculty of Engineering, Universiti Malaysia, Sabah, Malaysia

Email: hidayati@ums.edu.my

Abstract. Burning of the palm oil fibres and palm oil shells at the palm oil plantation mill has generated abundant amount of palm oil fuel ash (POFA). Recycling and reuse of POFA through thermal activation to produce a new Portland POFA cement (PPC) is one alternative that can be proposed to reduce the environmental problems due to improper POFA disposal. This paper reports on the chemical and physical properties, and the pozzolanic reactivity of POFA heated at 700°C for 1 hour, which interground and blended together with the Ordinary Portland Cement (OPC) in order to produce the PPC cement at 20, 40, and 50% of POFA replacement level. To investigate the physical and chemical properties of the PPC, the specific gravity, soundness, density, and LOI tests were conducted. The flowability and compressive strength were also determined to identify its effect on the pozzolanic reactivity. The results showed that the PPC has high compressive strength due to its high pozzolanic reaction. The flowability is higher than the OPC, signifying that PPC has low water requirement. The compressive strength and pozzolanic reactivity increased with increasing of TGP content (up to 50%). The findings showed that there is a possibility of using POFA in producing blended POFA cement which is environmental green product for use in the concrete construction.

1. Introduction

The cement industry consumes about 12-15% of the total industrial energy use [1]. To produce energy for the cement production, as high as 1450°C temperature is maintained in the kiln to burn the coal, fossil fuels, fuel oils and petroleum coke [2]. However, this has released approximately 0.97 tonne of carbon dioxide (CO₂) for each tonne of clinker produced [3]. Therefore, the cement production process is classified as the second biggest source that is responsible for high CO₂ emission in the world. This has consequently contributed to the environmental pollution and increase in the carbon footprint. Nevertheless, despite of having high carbon footprint, demand on the cement is still higher due to increase in the urbanization and population growth. Hence, production of a greener cement is possibly one of the alternatives to reduce the cement’s carbon footprint in the cement manufacturing industry.

Palm oil fuel ash (POFA) is a secondary type of wastage, which obtained by burning the palm oil fibers and palm oil shells as fuel in the palm oil mill boilers. About 85% fibers and 15% shells are usually burned at very high temperature between 800 - 1000°C [4], which produced 5% of POFA wastes [5]. It was estimated that the amount of POFA in Malaysia is about 2% of the total palm oil wastes generated yearly. With no economical benefit, these ashes are usually dumped to open fields causing environmental hazards [6].
Many attempts have been done to use POFA in concrete construction. The most popular method is by replacing cement with POFA in concrete. However, there is very limited information on the use of POFA as pozzolan to produce blended cement. Recently, it was reported that the treated POFA was able to improve the engineering and durability properties of concrete due to its high pozzolanic reactivity and low loss on ignition (LOI) value \([7]\). In previous research, it was confirmed that the activation of POFA at 500°C and 800°C has given significant improvement in its pozzolanic reactivity \([7–9]\). This information gives an indication that POFA might be potential to be exploited in the production of new blended cement, either by calcining and intergrind the POFA and raw materials for cement making, or by intergrinding and blending POFA with the OPC to produce Portland POFA cement (PPC). Recycling and reused of POFA to produce PPC is one alternative that can be proposed in order to save the earth and reduce the landfills. Hence, this research investigates the possibility of using POFA to produce Portland POFA Cement through the intergrinding and blending with the OPC.

2. Materials and Methods

2.1. Materials

The materials used in this study were ordinary Portland cement (OPC), river sand, and POFA. POFA was collected from the Lumadan Palm Oil Mill in Beaufort, Sabah, Malaysia. It was pre-treated through the drying process at 110°C for 24 hours to reduce the moisture. The dried POFA was then sieved using the 300 µm sieve. Materials that retained on the sieve were discarded. POFA passing the sieve was known as unground POFA. Subsequently, the unground POFA was heated in the furnace at 700°C for 1 hour and then ground using the planetary grinding ball mill for two (2) hours. The treated ground POFA (TGP) produced was stored in an airtight container to prevent from the moisture.

The mineral phase of TGP and chemical compositions of OPC and TGP are shown in figure 2 and table 1, respectively. To produce the POFA Portland Cement (PPC), the OPC was replaced with the TGP at 20, 40, and 50% (by weight of the cement). Both OPC and TGP were interground and blended together for 10 minutes using the planetary grinding ball mill. The PPC mixes were identified as PPC20 (20% TGP), PPC40 (40% TGP) and PPC50 (50% TGP) (figure 1).

2.2. Methods

The properties of the PPC were investigated based on the fineness, soundness, specific gravity, chemical composition (XRF), X-Ray Diffraction (Phillips X’pert Pro), and the loss on ignition (LOI) tests. Meanwhile, the engineering properties of the PPC were the density, flowability, compressive strength and strength activity index. The strength activity index was calculated based on the average of the compressive strength of the sample and expressed as % of the compressive strength of control mix. The compressive strength of the PPC was determined after 3, 7 and 28 days of curing.

![Figure 1](image-url)  
**Figure 1.** The OPC (a) and POFA Portland Cement (PPC) at 20 (b), 40 (c), and 50% (d) of TGP
Table 1. Chemical composition of OPC [11] and treated POFA

| Chemical composition (%) | OPC   | TGP   |
|--------------------------|-------|-------|
| SiO₂                     | 13.80 | 55.88 |
| Al₂O₃                    | 3.34  | 8.77  |
| Fe₂O₃                    | 3.83  | 5.80  |
| CaO                      | 56.89 | 7.98  |
| MgO                      | 1.88  | 6.54  |
| Na₂O                     | 0.13  | 0.35  |
| K₂O                      | 1.08  | 8.31  |
| SO₃                      | 3.51  | 0.42  |
| P₂O₅                     | 0.04  | 5.55  |
| S + A + F                 | N/A   | 70.45 |

Figure 2. The XRD pattern of TGP

3. Results and discussion

3.1. Physical and chemical properties of POFA Portland cement (PPC)

3.1.1. Chemical composition and mineral phase. The chemical compositions of OPC and TGP are shown in table 1. From table 1, it is clear that TGP (7.98%) has lower lime content compared to the OPC (56.89%), indicating its no inherent binding ability. However, with high silica content, TGP is able to react with lime from the cement to produce a material having cementitious properties through the formation of extra Calcium Silicate Hydrate (CSH). On the other hand, the XRD analysis (figure 2) shows that TGP has silica as its main chemical composition, which is in agreement with table 1. The presence of halo peak observed between 15° to 40° indicates that TGP has higher ratio of the amorphous silica. The minor phases such as cristobalite and plagioclase were also observed in the sample.

3.1.2 Fineness. Figure 3 shows the fineness of OPC, TGP, and PPC at various percentages of TGP replacement. With fineness of 89.3%, TGP has shown higher fineness than the OPC, indicating its finer size due to the grinding effect. Blending and intergrinding both OPC and TGP have produced PPC20, PPC40, and PPC50 with 85.1%, 86.2%, and 86.9% of fineness, respectively. Due to its high fineness, increasing the TGP replacement content has increased fineness of the PPC cements.
3.1.3 Specific gravity. Table 2 shows the specific gravity of the OPC, TGP, and PPC cements. The results revealed that the specific gravity decreased with increasing amount of TGP replacement in the PPCs. With a specific gravity of 2.84 g/cm$^3$, PPC50 was less dense than the PPC20 (3.02 g/cm$^3$) and PPC40 (2.87 g/cm$^3$). The amount of TGP affects the specific gravity of PPC due to their lower specific gravity (2.66 g/cm$^3$) than the OPC (3.42 g/cm$^3$).

![Figure 3. Fineness of the OPC, TGP and POFA Portland cements (PPCs)](image)

| Materials | OPC | TGP | PPC20 | PPC40 | PPC50 |
|-----------|-----|-----|-------|-------|-------|
| Specific Gravity (g/cm$^3$) | 3.42 | 2.66 | 3.02 | 2.87 | 2.84 |

3.1.4 Soundness. The destructive expansion in the cement is caused by excessive amounts of free lime or calcium oxide (CaO) or magnesium oxide (MgO). Cements showing excessive dimensional instability are said to be unsound and can lead to cracking in concrete. From table 3, the OPC has an expansion of 1.5 mm, which is less than the maximum specified value of 10 mm. This signifies that OPC is sound. Meanwhile, it was observed that the expansions of PPC20 and PPC40 have increased slightly by 4 mm and 3 mm, respectively. PPC50 has the lowest expansion with 1 mm. Formation of a higher strength matrix possibly one of the factors responsible for the increase in soundness.. Development of stronger matrix has better resistant to the expansive force due to the formation of extra CSH [12]. Hence, diminution in the expansion of PPC50 may be attributed to higher compressive strength of PPC50 as compared to OPC, PPC20 and PPC40. With a sufficient amount of TGP, the PPC cement is actually has the ability to retain its volume after hardened. Therefore, the PPCs were sound for the intended use.

![Table 3. Soundness of the OPC, TGP, and POFA Portland cements (PPCs)](image)

| Materials | OPC | PPC20 | PPC40 | PPC50 |
|-----------|-----|-------|-------|-------|
| Soundness (mm) | 1.5 | 4 | 3 | 1 |

3.1.5 Loss on ignition. As shown in table 4, the TGP has a lower LOI value than the OPC, indicating less presence of unburned carbon content due to the 700ºC heat treatment. From table 4, it was observed that the PPC50 (2.67%) has lower LOI than PPC20 (3.67%) and PPC40 (3.47%). Since TGP has low LOI value, increasing the amount of TGP replacement in the PPC has reduced the LOI due to lower OPC content. Nevertheless, the LOI of the PPC cements varied at 2.67% and 3.67%, which fall within the requirement for Portland Pozzolan cement, which limited at 5.0% [13]. Reduction of the unburned carbon is important because carbon is able to interrupt the hydration process and reduce the workability [14]. Hence, the heat treatment process prior of grinding of POFA has given beneficial effect in improving the use of TGP in the PPC production.
Table 4. LOI of the OPC, TGP, and POFA Portland cements (PPCs)

| Materials | OPC | TGP | PPC20 | PPC40 | PPC50 |
|-----------|-----|-----|-------|-------|-------|
| LOI (%)   | 4.3 | 1.33| 3.67  | 3.47  | 2.67  |

3.2. The engineering properties of POFA Portland cement (PPC)

3.2.1 Flowability. Figure 4 shows that all PPC samples have higher flowability compared to OPC (110%) with 115%, 112%, and 112% for PPC20, PPC40 and PPC50, respectively. Grinding has reduced porosity of the TGP, hence, less water requirement was needed to fluidify the mixes [12]. In addition, the finer particles of TGP had acted as ball bearing and improved lubrication of the mixes. Hence, the flowability was improved when the TGP was added to produce the PPC. However, it was also noticed that the flowability decreased with the increasing of TGP content. This is due to more water is required to lubricate the mix and wet the surface at higher TGP content.

![Figure 4. Flowability of the OPC and POFA Portland cements (PPCs)](image)

3.2.2 Density. OPC has the highest density compared to the PPC samples with 1915 kg/m³ (figure 5). The density of the fresh mortar constantly decreased with the increasing amount of TGP in the mixes. As shown in figure 5, the densities of the PPC samples decrease with 1909 kg/m³ for PPC20, 1905 kg/m³ for PPC40 and 1863 kg/m³ for PPC50 due to the increasing amount of TGP replacement in the PPC. This is because OPC has a higher specific gravity than the TGP, which means that the cement particles are heavier and denser (table 2). Hence, replacement of TGP reduced the density of the PPC samples, particularly at the higher replacement level.

![Figure 5. The density of the OPC and POFA Portland cement (PPC) mortars](image)
3.2.3 Strength activity index (SAI). Figure 6 shows the strength activity (SAI) of OPC, PPC20, PPC40, and PPC50. At 7 days of curing, both PPC40 and PPC50 had shown higher SAI compared to the OPC. This indicates that with high TGP content, the pozzolanic activity occurs rapidly between TGP and OPC to produce extra CSH within the samples. Although previous researchers reported slower SAI of POFA at the early age of curing [13], improvement in the pozzolanic reactivity of PPC observed in this research might be due to the effect of the heat treatment and grinding of the TGP. Production of amorphous TGP, which characterized with high fineness and low carbon content (low LOI) helped to improve its pozzolanic reactivity for strength gain. In addition, heat treatment increases the amorphous or glassy phase of POFA, which activates the POFA reactivity [14]. At the later ages (28 days), the pozzolanic reaction of both PPC40 and PPC50 continue to occur due to the availability of TGP to produce extra CSH for strength development process. Meanwhile, PPC20 has shown reduction in its SAI activity, possibly caused by the deprivation of the TGP.

Figure 6. Strength activity index of the OPC and POFA Portland cements (PPCs)

3.2.4 Compressive strength. The compressive strength values of PPC mortar samples are shown in figure 7. These values were obtained from the average of three specimens. It was found that at 28 days, the average compressive strengths of OPC, PPC20, PPC40 and PPC50 mortars were 29.9, 27.6, 34.3, and 34.8 MPa, respectively, which were higher than the 25 MPa strength required for Portland Pozzolona Cement [13]. The increase in compressive strength, particularly for PPC40 and PPC50 could be attributed by the higher pozzolanic reaction in the PPC mortars. The increasing amount of pozzolona with OPC has given higher strength at the later age because TGP was able to sustain the continuous pozzolanic reaction at increasing silica content [18]. This has improved the pozzolanic reaction between excessive Ca(OH)₂ (from the cement) with silica (SiO₂) of POFA and produced more CSH gels so that the strength development of the PPC mortars was continuously occurred even at the longer age of testing. In addition, the finer particles of TGP were able to fill voids within the mortar samples, hence the strength improved. The results also revealed that the TGP can be used up to 50% to produce the PPC without degrading the strength properties of the mortar produced.
4. Conclusion
Based from the results, it can be concluded that:

- Intergrinding and blending of the TGP with OPC had produced PPC with high fineness, particularly at 50% TGP replacement level.
- Higher TGP content improved soundness of the PPC cements.
- Replacement of OPC with the TGP at higher level reduced the LOI content of the PPC cements.
- The PPC mortars demonstrated better flowability compared to the control mortar. However, the flowability decreased with increasing of the TGP content.
- The TGP has lower specific gravity than the OPC. Hence, replacement of OPC with TGP reduced density of the mortar samples.
- PPC40 and PPC50 showed higher pozzolanic reaction at the age of 28-days compared to PPC20 and OPC. Higher TGP content ensures continuous pozzolanic reaction occurrence for the production of CSH at the later ages. Therefore, the compressive strength for both samples were also high.

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