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Palm Oil Fuel Ash (POFA) As a Cement Replacement Material: Compressive Strength of High Strength Concrete (HSC)

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Abstract:

***Purpose**: High strength concrete (HSC) contains higher cement content between 480 to 600 kg/m^2. This higher cement consumption leads to environmental impacts since approximately 650 to 900 kg of CO_2 will be produced per one ton of cement. Hence, a significant advantage over lowering carbon emissions is the ability to reduce cement consumption. Meanwhile in Malaysia, 100 tonnes of palm oil fuel ash (POFA), a waste product was produced and dumpedin the landfill. However, POFA has a high silica content and could be used as pozzolanic material to improve the cement hydration performance. Hence, this study focused on the compressive strength of the HSC while using palm oil fuel ash (POFA) as a cement replacementto produce a sustainable high strength concrete.*

***Methodology**: The characteristic strength of the concrete was designed to be 55 MPa at 28 days. Three design mixes with 0%, 20%, and 40% of POFA content were tested based on the guided literature review. A design mix with 100% OPC (0% POFA) was designed as a controlsample. The samples were assigned as OPC, POFA20, and POFA 40 according to the POFA replacement level. By using a compression machine, the compressive strength at 7 and 28 dayswas assessed following BS EN 206: Concrete Specification as a preferred standard.*

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***Result and Discussion**: The compressive strength of the HSC increases with the increased curing age indicating pozzolanic properties. However, the compressive strength had reduced with a further increment of POFA replacement. As 20% and 40% of POFA were utilized, the compressive strength of the HSC was reduced below the characteristic's strength of 55 MPa.*

This may be due to the use of untreated POFA in this study that has low silica content due to its higher unburned carbon content and loss-on-ignition (LOI) value.

***Conclusion and Recommendations**: The compressive strength of the HSC containing POFA increase with increasing curing age due to enhanced pozzolanic reaction which produced stronger concrete. However, raw POFA was not effective to improve the compressive strength.As 20% and 40% of POFA were utilized, the compressive strength of the HSC was reduced below the minimum characteristic's strength of 55 MPa. Thus, further treatment of POFA suchas heating at a higher temperature and grinding should be carried out, to improve the pozzolanic properties and therefore increase the strength of concrete.*

Keywords: *Palm Oil Fuel Ash, POFA, High Strength Concrete, Compressive Strength*

1. Introduction

Concerning alternative and sustainable uses, the rise in POFA disposal from industry is receiving a lot of attention. POFA's high silica content indicates that it has strong pozzolanic properties. Consequently, a thorough investigation into the potential use of POFA as cement materials in the construction industry was conducted (Tang et al., 2019).

Studies on high strength concrete (HSC) have demonstrated that the addition of POFA can result in HSC with compressive strengths of up to 46 to 105 MPa in just 28 days (Sumesh et al., 2019; Zeyad et al., 2019). It demonstrates that between 50% and 60% of POFA could be used to replace cement in high strength concrete (HSC), resulting in a reduction of high cement volumes (Zeyad et al., 2019; Alsubari et al., 2015).

This research aims to study the potential use of POFA to increase the compressive strength of HSC. POFA is agricultural waste with high pozzolanic properties, making it a material with a high potential for use as a cement replacement. Based on earlier studies, high volumes of POFA can be replaced with cement material for higher strength and durability of concrete. The ability to reduce cement consumption provides a significant advantage over lowering carbon emissions and takes care of the pressing issue of waste disposal (Hamada et al., 2018).

2. Literature Review

2.1 Pozzolanic Properties of POFA

The major chemical components of Ordinary Portland Cement (OPC) are calcium oxide, CaO while POFA contains a large amount of silica content, SiO_2. In the cement hydration process, cement with a lower content of silica will act as a limiting agent, therefore limiting the formulation of calcium silicate hydrate, C-S-H gel. As POFA has a higher silica content, it helps in the production of extra C-S-H gel. The silica content in POFA will combine with calcium hydroxide, $Ca(OH)_2$, or CH in cement to produce secondary hydration products of additional C-S-H and thus improves the microstructure of the concrete and its compressive strength (Hamada et al., 2020; Ismail & Feng, 2019; Philip et al., 2019; Sumesh et al., 2019; Bullard etal., 2011). The particles of POFA will act as a micro-filler, filling the gaps that will produce higher compressive strength, denser, and more durable concrete (Ismail & Feng, 2019; Philip et al., 2019; Sumesh et al., 2019; Alsubari et al., 2018).

2.2 Compressive strength of concrete

Compressive strength was defined as the maximum load sustained by the concrete before its failure. A compressive strength test is performed using a compression machine in accordance with BS EN 12390-3 at a loading rate of 0.9 kN to determine the compressive strength of concrete (Zeyad et al., 2019; Sumesh et al., 2019; Zeyad et al., 2017).

In a recent study by Sumesh et al., (2019), POFA can produce HSC with a compressive strength of 108.8 MPa in just 90 days. Meanwhile, in contrast with plain concrete, Zeyad et al., (2019) found that 30% POFA provided the highest compressive strength of up to 25%. Since the compressive strength of all samples containing up to 60% POFA is greater than that of controls. Therefore, up to 60% of POFA can be used as a cement replacement to produce HSC. Superior compressive strength achieved by Megat et al., (2012) with the increased compressive strength up to 100 MPa in 28 days at 40% of POFA replacement level. The increasing compressive strength may be due to micro-filter effect of POFA, which contributed to the early age strength by filling the voids between the particles and improved the overall strength of the concrete (Alsubari et al., 2015).

3. Methodology

3.1 First stage: Materials preparation

In this research, the materials that were used were Ordinary Portland Cement (OPC), Palm Oil Fuel Ash (POFA), river sand, coarse aggregate, tap water, and superplasticizer.

3.1.1 Ordinary Portland Cement (OPC)

The OPC used for this study was CEM 1 type with a minimum strength class 52.5 which compliance with EN 197: Part 1: Cement Composition and Specifications (British Standards, 2019).

3.1.2 Palm Oil Fuel Ash (POFA)

Before its use, POFA underwent heat treatment and sieved. Firstly, the raw POFA collected from the palm oil mill was dried in the oven at 105 ± 5 °C for 24 ± 1 hr to remove the moisture content. Next, POFA was sieved using a 300µm mesh according to ASTM C136: Test Method for Sieve Analysis of Fine and Coarse Aggregates, to remove the coarse particles that were incompletely combusted in the boiler (British Standards, 2005). The pictures of POFA and unwanted particles collected from the sieving process were shown in Figure 1.

Figure 1: Picture of raw POFA and unwanted particles

Source: Developed for this research.

3.1.3 Fine Aggregate (Sand)

The sand was sieved to pass through 5 mm sieve size following ASTM C136: Test Method for Sieve Analysis of Fine and Coarse Aggregates, to remove coarse particles and impurities (British Standards, 2005). Next, the sand with a particle size less than 5 mm was dried in the oven at 110 °C ± 5 for 24 hr and used in the sample preparation. The fine aggregates have complied with BS EN 12620: Aggregate for concrete (British Standards, 2013).

3.1.4 Coarse Aggregate (Gravel)

All aggregates should comply with BS EN 12620: Aggregate for concrete (British Standard, 2013). The aggregates were sieved following ASTM C136: Test Method for Sieve Analysis of Fine and Coarse Aggregates (British Standard, 2005). Figure 2 shows the crushed gravel used in the mixing process. The size of the coarse aggregates used was from 5 mm to a maximum size of 20 mm.

Figure 2: Coarse aggregate fraction 5 mm to 20 mm

Source: Developed for this research.

3.2 Concrete Mix Design

The proportion of the control sample was derived based on the DOE method with a water cement ratio, w/c of 0.35. The concrete was designed to have a characteristic strength of 55

MPa at 28 days. Three design mixes with 0%, 20%, and 40% of POFA content were tested and assigned as OPC, POFA20, and POFA40, respectively. A mixture with 0% of POFA was assigned as a control sample. The concrete admixture, superplasticizer (SP) was added not more than 5% of the cement content for the workability. Table 1 shows the details of the concrete mix design.

Table 1: Mix design using DOE Method

Materials	POFA (%)	OPC (kg)	POFA (kg)	Aggregates		Water (kg or liters)	SP (kg or liter)
				Fine (kg)	Coarse (kg)		
CONTROL	0	577.14	0	389.77	1285.33	195	28.9
POFA20	20	461.71	115.43	389.77	1285.33	195	28.9
POFA40	40	346.28	230.86	389.77	1285.33	195	28.9

Source: Developed for this research.

3.3 Sample Preparation

The preparation of the sample was following BS EN 12390: Part 2: Making and curing specimens for strength tests (British Standard, 2019). The procedure for sample production was as follows:

1) The quantities of each material were measured by using a weighing scale and pour into a concrete mixer until uniform.
2) The entire mould was cleaned and coated with a lubricant before the concrete was poured into the mould for easier concrete cube removal from the mould after the concrete has been hardened.
3) The fresh concrete was poured into the molds in three layers. To eliminate air void and preventing honeycomb within the concrete, each layer was tamped by a steel rod 25 times.
4) To create a smooth surface, excessive concrete was trimmed with a trowel.
5) Finally, the concrete samples have been covered with sheets of plastic for 24 hours and placed between 20 ° C and 25 ° C at room temperature.
6) After 24 hours the concrete sample was taken out of the mould and immersed in the water tank where the temperature was controlled to be constant at 23 °C. These concrete samples were cured for 7 and 28 days.

3.4 Compressive Strength Test Procedure

A compressive strength test is performed using a compression machine in accordance with BS EN 12390: Part 3: Method for Compressive Strength (British Standard, 2019).

Three 100 mm^3 cube samples per mixture would be used in the test and the strength value would be the average of the samples. The concrete sample was cleaned from surface water and weighed before being placed on the compression machine as shown in Figure 3. The surface of the testing machine was removed from the dirt and the sample was centred on the lower plate. The loading rate was set at 0.6 ± 0.2 MPa/s ($N/mm^2 \cdot s$) and continuously increased in the rate ± 10% until the sample failed. This test has been conducted at 7 days and 28 days of curing age.

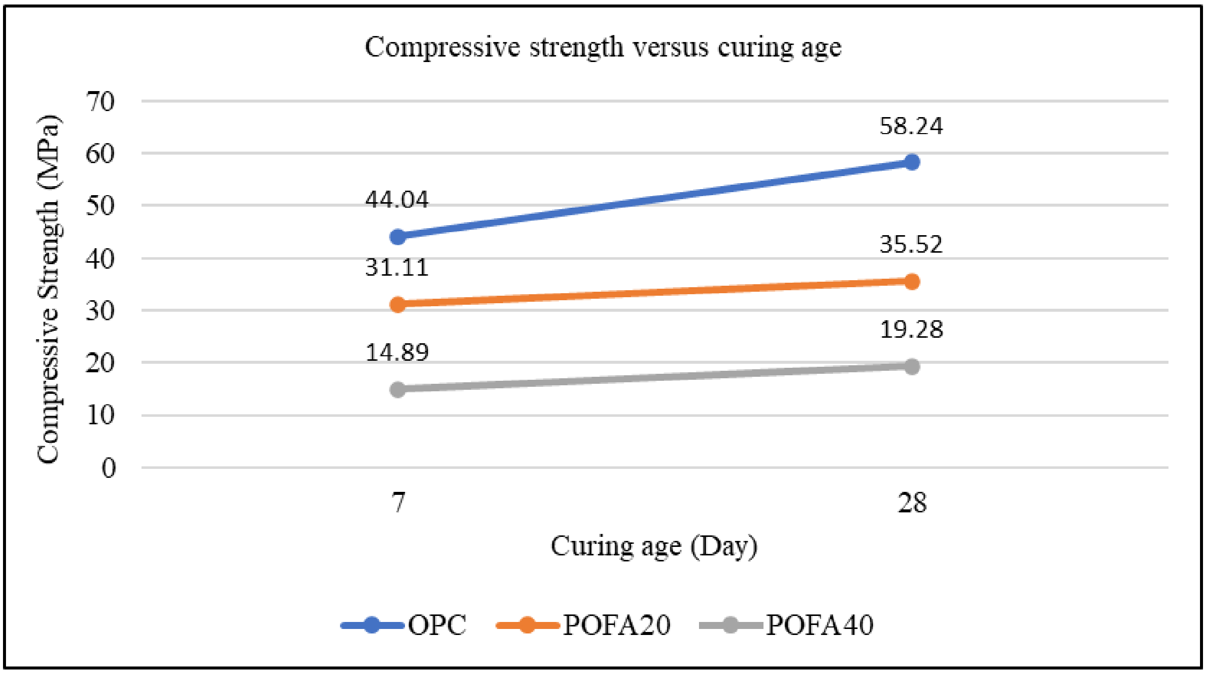
Figure 3: The compression machine

Source: Developed for this research.

4. Result and Discussion

The compressive strength of HSC at 7 and 28 days of curing age was illustrated in Figure 4. From the result, the compressive strength at day 7 and 28 of curing age was recorded as 44.04 MPa and 58.24 MPa, respectively. Since the compressive strength of OPC at 28 days was higher than 55 MPa, the design mix thus meets the characteristic strength requirement for HSC. At an early age of 7 days, for HSC containing POFA replacement, all the compressive strength was lower than the OPC sample. This may be due to the delayed formation of C-S-H gel due to high silica content over cement. A similar lower early strength trend recorded by Megat et al., (2012), Philip et al., (2019), and Zeyad et al., (2018). At the early age of 7 days, the compressive strength was recorded at 31.11 MPa and 14.89 MPa for POFA20 and POFA40, respectively. However, at the later age of 28 days, the compressive strength of POFA20 and POFA40 increased to 35.52 MPa and 19.28 MPa, respectively. This shows that along with the curing age, a further pozzolanic reaction takes place between the silica in POFA and calciumhydroxide in cement to produce extra secondary calcium-silicate-hydrate (C-S-H), thus improved the microstructure of the concrete and therefore increase the compressive strength ata later age (Sata et al., 2004; Sumesh et al., 2019; Zeyad et al., 2017, Zeyad et al., 2019).

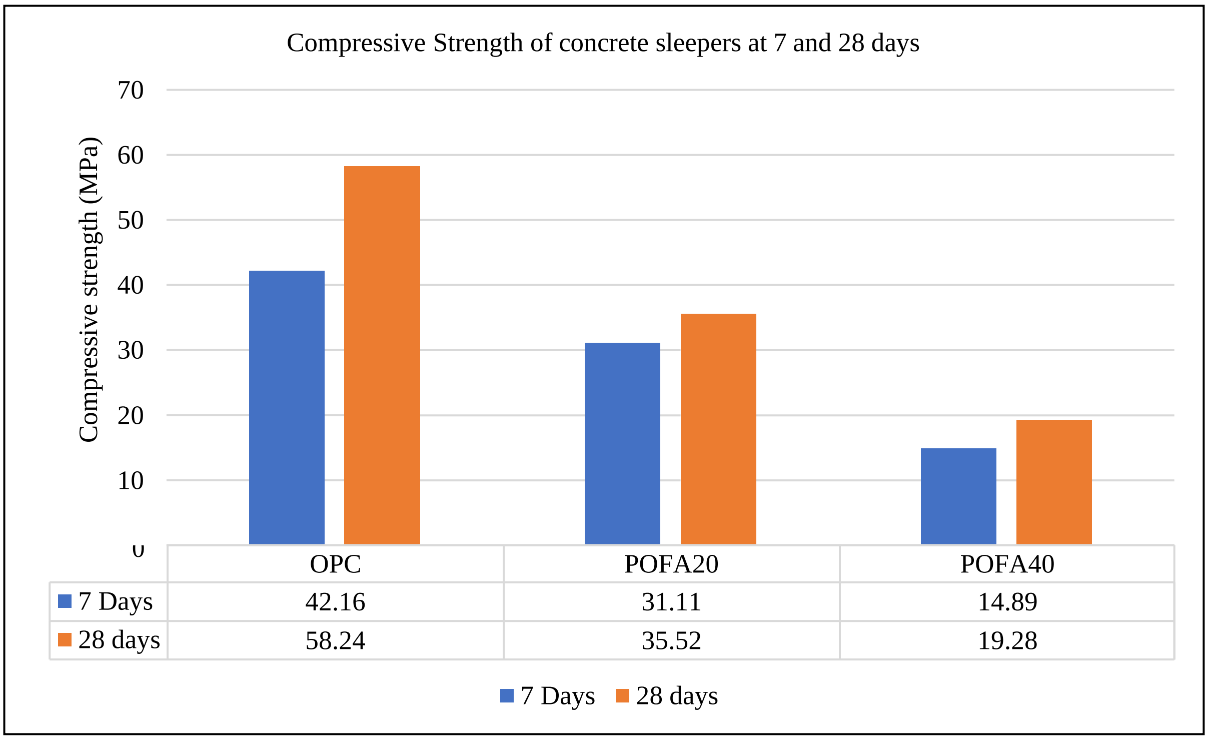
Figure 4: Compressive strength (MPa) versus curing age (Day)



Source: Developed for this research.

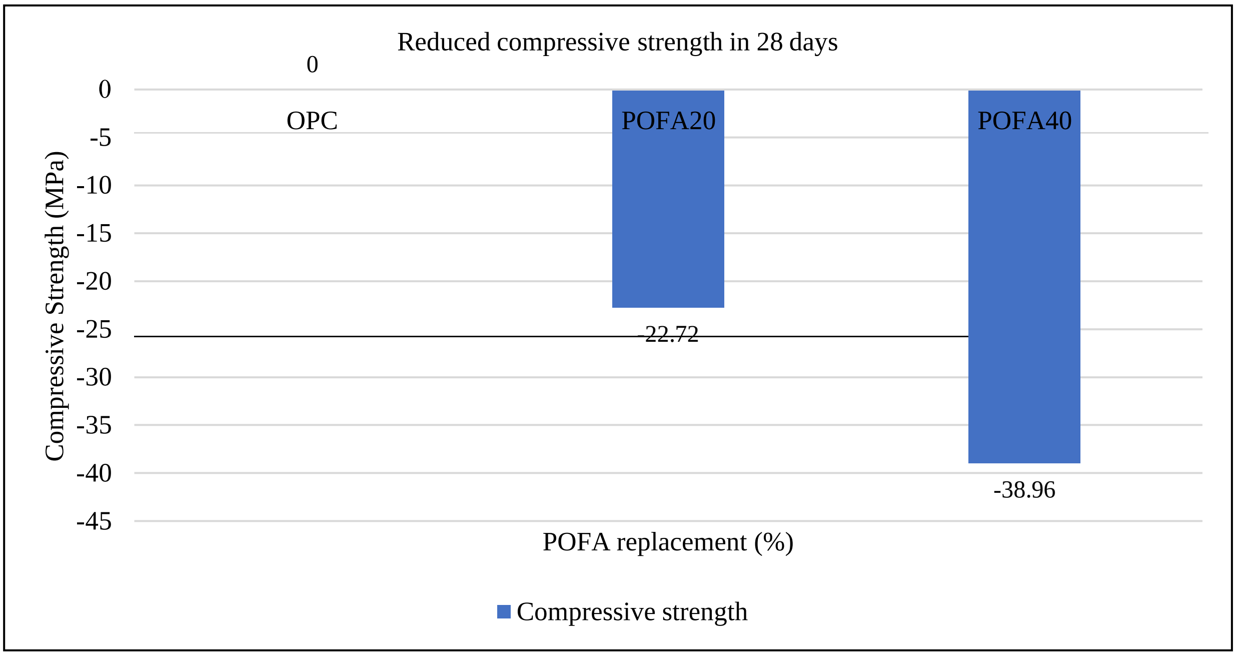
Although the compressive strength of the HSC increases with the increased curing age, the compressive strength had reduced with a further increment of POFA replacement. Figure 5 and Figure 6 shows the relationship between the compressive strength of the HSC and the POFA replacement content. From the results, the compressive strength was inversely proportional to POFA replacement content. As the percentage of POFA increase, the compressive strength reduced by 39% for POFA20 and 67% for POFA40. Similar trend reported by Sumesh et al., (2019) where the compressive strength of HSC decreases gradually as the POFA content increase. This may be due to the use of untreated POFA in this study that has low silica content due to its higher unburned carbon content and loss-on-ignition (LOI) value (Karim et al., 2020; Tang et al., 2019; Hassan et al., 2019; Hamada et al., 2019; Alsubari et al., 2018). Thus, higher POFA content in POFA20 and POFA40 along with reduced cement content, therefore, limit the reaction to cement and produce lower strength concrete than OPC (Ismail & Feng, 2019; Sumesh et al., 2019). Furthermore, a higher LOI value in POFA would cause excessive water absorption during the hydration process. As the result, the HSC with higher POFA content would losses their strength (Sumesh et al., 2019). In terms of its physical properties, the POFA may have low pozzolanic properties due to its large particle size and porous structure (Alsubari et al., 2018; Hassan et al., 2019; Karim et al., 2020; Tang et al., 2019).

Figure 5: Compressive strength (MPa) versus the percentage of POFA replacement (%)



Source: Developed for this research.

Figure 6: Relationship between compressive strength (MPa) versus POFA replacement (%)



Source: Developed for this research.

5. Conclusion

The compressive strength of the HSC containing POFA increase with increasing curing age due to enhanced pozzolanic reaction which produced stronger concrete. However, raw POFA was not effective to improve the compressive strength. As 20% and 40% of POFA were utilized, the compressive strength of the HSC was reduced below the minimum characteristic strength of 55MPa. Thus, further treatment of POFA such as heating at a higher temperature and grinding should be carried out, to improve the pozzolanic properties and therefore increase the strength of concrete.

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