Research Article

Utilization of Palm Oil Fuel Ash as Binder in Lightweight Oil Palm Shell Geopolymer Concrete

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Traditionally fly ash (FA) has been used to replace cement as binder in the geopolymer concrete. The utilization of palm oil industrial waste materials known as palm oil fuel ash (POFA) and oil palm shell (OPS) that are abundantly available in South East Asia as binder and coarse aggregate in geopolymer concrete would give an added advantage in both the environmental and economic aspects. The mechanical properties of the OPS geopolymer concrete (OPSGC) through the use of POFA, FA, and OPS are investigated and reported. A total of ten OPSGC mixtures were prepared with varying percentages of POFA and FA such as 0, 10, 20, 40, and 100%. The specimens prepared with two alkaline solution to binder (AK/B) ratios of 0.35 and 0.55 were oven cured at 65°C for 48 hours. The experimental results showed that the highest compressive strength of 30 MPa was obtained for the mix with 20% replacement of FA by POFA and AK/B ratio of 0.55, which underwent oven curing. Further, the mix of up to 20% POFA (with AK/B ratio of 0.55) can be categorized as structural lightweight concrete. An increase of the POFA content beyond 20% decreases the mechanical properties, and hence this mix is recommended to be used.

1. Introduction

Cement is an indispensable material in the development of concrete even though the conventional concrete is made of composite materials such as fly ash, ground granulated blast furnace slag, and silica fume. The use of ordinary Portland cement (OPC) was not environmental friendly and caused adverse effect, resulting from the energy intensive and greenhouse effects [1]. Davidovits [2] was the pioneer in introducing binders other than cement that could be produced by the reaction between alkaline solution (AK) and source materials that are rich in silica (SiO_2) and alumina (Al_2O_3), commonly known as geopolymerization. In comparison with the normal concrete, the geopolymer concrete has more factors that affect its properties due to the use of AK. Sathonsaowaphak et al. [3] reported that the geopolymer mortar with AK/B ratios of 0.43–0.71 achieved compressive strength of 42–52 MPa by using FA and bottom ash as binders. Furthermore, geopolymer concrete could achieve high early compressive strength when oven cured, instead of undergoing ambient curing [4].

Since Malaysia is the second largest palm oil producer, the leftover agricultural wastes have been cumulative and caused land and air pollution in the vicinity of the palm oil factories. Many researchers have taken the initiative to utilize the palm oil industrial wastes, such as OPS and POFA, to develop sustainable construction material. Shafigh et al. [5] reported that by crushing the larger original OPS aggregate, a high 28-day compressive strength of 53 MPa of oil palm shell concrete (OPSC) can be obtained. Additionally, by adding foam in the OPSC to reduce its density, a structural lightweight concrete (LWC) can be produced with a 39% of reduced thermal conductivity compared to the conventional brick [6]. Moreover, Yap et al. [7] investigated that the addition of polypropylene and nylon fibres in the OPSC enhanced the postfailure compressive strength. Depending on the fineness and percentage of cement replacement, POFA as cement replacement enables longer initial and final setting times [8].

Sata et al. [9] reported that replacing POFA, as cement of up to 30% can produce high strength concrete of about 86 MPa.

Furthermore, the use of geopolymer technology in concrete, which incorporates waste materials such as FA, POFA and OPS, will be an added advantage in construction industry especially in terms of environmental and economic aspects. Raden and Hamidah [10] made an effort to utilize waste paper sludge ash as a source material to develop foamed geopolymer concrete (FGC). The density and the compressive strength of FGC were found to be approximately 1800 kg/m^3 and 3 MPa, respectively. Kupaei et al. [11] produced a structural grade of 30 MPa by incorporating OPS as lightweight aggregate (LWA) in geopolymer concrete. Ariffin et al. [12] reported that the geopolymer concrete using FA and POFA as binders is more durable when exposed to the sulphuric acid, compared to the OPC concrete. The abundance of the agricultural wastes such as POFA and FA in South East Asia enables researchers to utilize these materials as binders in the development of geopolymer concrete by using OPS as LWA. There has been no research carried out in the past incorporating POFA and OPS in the geopolymer concrete.

This research work aims to develop geopolymer concrete by utilizing the local industrial wastes such as FA and POFA as binders and the OPS as coarse aggregate. This novel geopolymer concrete is christened as oil palm shell geopolymer concrete (OPSGC). The variables investigated are the percentages of POFA and FA and the curing regimes, namely, oven and ambient curing; the other variable investigated includes the AK/B ratios (0.35 and 0.55) by mass. The compressive strengths at different ages of 3, 7, 14, and 28 days were tested and reported in this investigation. In addition, the 28-day splitting tensile and flexural strengths of the OPSGC are also reported.

2. Experimental Procedures

2.1. Materials. The binders used in this experimental work are class-F FA and POFA, whose the chemical compositions are shown in Table 1 which conform to the ASTM C618 [13]. The POFA collected from the local palm oil mill was oven dried at $105 \pm 5°C$ for 24 hours, followed by sieving through $300\,\mu$m to remove any coarse foreign particles. Then, the POFA was ground to a mean particle size of $45\,\mu$m by using the Los Angeles (LA) abrasion machine for 30,000 cycles, to enhance the fineness and reactivity. The speed of the LA abrasion machine was about 33 revolutions per minute (rpm).

The use of POFA as binder satisfies the chemical requirement in ASTM C618 [13] as pozzolanic material by having loss on ignition (LOI) of less than 10%; thus, it could be beneficial in the manufacture of concrete. Sata et al. [9] and Hussin and Ishida [14] reported that the POFA concrete exhibited consistent strength development after 3 days, indicating no deterioration over time.

The crushed OPS of sizes between 2.36 and 9.5 mm with saturated surface dry (SSD) condition was used as the coarse LWA in this study. Table 2 shows the physical properties of the OPS. Mining sand with a specific gravity of 2.67, passing through 5 mm and retained on $300\,\mu$m, was used as the fine

Table 1: Chemical composition (%) of class-F FA and POFA.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	LOI
Class-F FA	57.6	28.9	5.8	0.2	0.9	0.9	0.2	3.6
POFA	63.4	5.5	4.2	4.3	3.7	6.3	0.9	6.0

Table 2: Physical properties of OPS.

Physical property	OPS
Specific gravity (saturated surface dry)	1.36
Bulk density (loose) (kg/m^3)	589
Bulk density (compacted) (kg/m^3)	652
Fineness modulus	5.90
Water absorption (24 h) (%)	24.39

Table 3: Variables investigated on the OPSGC.

Mixture	POFA (%)	FA (%)	AK/B	Curing method
M1	0	100	0.55	Oven
M2	10	90	0.55	Oven
M3	20	80	0.55	Oven
M4	40	60	0.55	Oven
M5	100	0	0.55	Oven
M2-A	10	90	0.55	Ambient
M1-2	0	100	0.35	Oven
M2-2	10	90	0.35	Oven
M3-2	20	80	0.35	Oven
M4-2	40	60	0.35	Oven
M5-2	100	0	0.35	Oven

aggregate. The fineness modulus of the OPS was determined in accordance with ASTM C136 [15]. Since the fineness modulus of OPS is uniform similar to the normal weight aggregate (e.g., granite), Alengaram et al. [16] reported that the OPS can be used as coarse aggregate.

As for the alkaline activator, a combination of sodium hydroxide (NaOH) in flake form and sodium silicate (Na_2SiO_3) solution was used in this investigation, where the molarity of the NaOH was kept constant at 14 M. The solution was prepared at least 1 day prior to its use to allow the exothermically heated liquid to cool to ambient temperature. The ratios of the Na_2SiO_3 solution to NaOH solution and the AK/B were 2.5 and 0.55 or 0.35 by mass, correspondingly. Additionally, a polycarboxylate ether (PCE) based superplasticizer (SP) was used at a dosage of 1.5% by mass of binders, to improve the workability. Potable water was used in all the mixes and the ratio of additional water to binders was maintained at 0.1.

2.2. Mix Proportions and Specimen Preparation. The variables that are investigated in this research are shown in Table 3, while the respective mixture proportions are shown in Table 4. The effect on OPSGC with different percentages of POFA and FA (0%, 10%, 20%, 40%, and 100%) is investigated and reported. Other than that, the curing methods (oven and ambient curing) and ratios of AK/B (0.55 and 0.35) by mass,

TABLE 4: Mixture proportions of the OPSGC.

Mixture	Mix proportions (kg/m^3)						
	POFA	FA	Sand	OPS	AK	Water	SP
M1	0.0	483.8	822.5	290.3	266.1	72.6	7.3
M2	48.7	437.9	827.2	291.9	267.6	73.0	7.3
M3	97.9	391.5	831.9	293.6	269.1	73.4	7.3
M4	297.0	198.0	841.5	297.0	272.2	74.3	7.4
M5	512.7	0.0	871.6	307.6	282.0	76.9	7.7
M2-A	48.7	437.9	827.2	291.9	267.6	73.0	7.3
M1-2	0.0	515.6	876.5	309.4	180.5	77.3	7.7
M2-2	51.9	466.8	881.8	311.2	181.6	77.8	7.8
M3-2	104.4	417.5	887.2	313.1	182.7	78.3	7.8
M4-2	211.3	317.0	898.1	317.0	184.9	79.2	7.9
M5-2	548.5	0.0	932.5	329.1	192.0	82.3	8.2

TABLE 5: Development of compressive strength.

Mixture	Compressive strength (MPa)				28-day oven-dry density (kg/m^3)
	3-day	7-day	14-day	28-day	
M1	25.2	25.8	26.4	28.1	1952.8
M2	26.0	27.1	27.5	28.4	1861.1
M3	22.4	25.7	25.8	30.1	1959.0
M4	9.7	12.7	14.0	16.4	1996.1
M5	8.4	8.8	9.2	10.0	2118.1
M2-A	5.1	16.6	21.6	25.8	1941.2
M1-2	15.7	16.5	16.8	17.3	1947.7
M2-2	5.5	10.1	13.1	16.4	1971.2
M3-2	4.3	8.3	12.3	14.6	1997.3
M4-2	7.8	8.7	9.2	9.7	1996.8
M5-2	5.6	8.1	8.2	8.6	2151.7

which affect the strength development of OPSGC, were also carried out.

The coarse and fine aggregates were first mixed in a rotary concrete mixer for about 2 minutes; this was followed by the addition of the binders (FA and POFA) with further mixing for about 3 minutes. Next, the water, AK, and SP were gradually added and mixed for another 6 minutes. The well-mixed concrete was then poured into the steel moulds and compacted with vibration table. The specimens were then covered with plastic sheets to avoid evaporation of the surface water. After that, the oven-cured (oven temperature of 65°C) and ambient-cured (laboratory temperature of about 30°C) specimens are cured for 48 hours before being demoulded and tested.

2.3. Test Methods. The concrete specimens were cast in 100 mm cubes for the compressive test, which was carried out at the ages of 3, 7, 14, and 28 days, in accordance with BS EN 12390-3 [17]. The tests on splitting tensile and flexural strengths were conducted based on ASTM C496 [18] and ASTMC78 [19], respectively. These tensile strength tests were carried out on cylinders of size 100 $\phi \times$ 200 mm and prism of size $100 \times 100 \times 500$ m, correspondingly.

3. Results and Discussion

3.1. Effect of POFA on Strength Development of OPSGC. The development of the compressive strength for all OPSGC mixtures is presented in Table 5. From Figure 1, it is seen that the 28-day compressive strength of the OPSGC increases as the replacement of FA with POFA up to 20% for 0.55 AK/B ratio by mass. This phenomenon is attributed to the higher content of silica (SiO_2) and higher fineness of POFA, which enhanced the geopolymerization of the binders. Sata et al. [9] found similar trend where POFA increases the production of calcium silicate hydrate (CSH) by reacting with calcium hydroxide ($Ca(OH)_2$), which improved the strength of the conventional concrete. The high fineness of POFA had greater pozzolanic reaction and acted as filler in voids; thus, it increased the compressive strength of the concrete [8]. On the other hand, the strength development showed a declining trend with a further replacement of FA with POFA (M4 and M5). Ariffin et al. [20] described that the low strength in the geopolymer concrete with high POFA content may be attributed to the incomplete geopolymerization due to its lower content of Al_2O_3. This is because Al_2O_3 tends to dissolve at higher rate during the early stage of geopolymerization. The low strength in the mixes M4 and M5, which
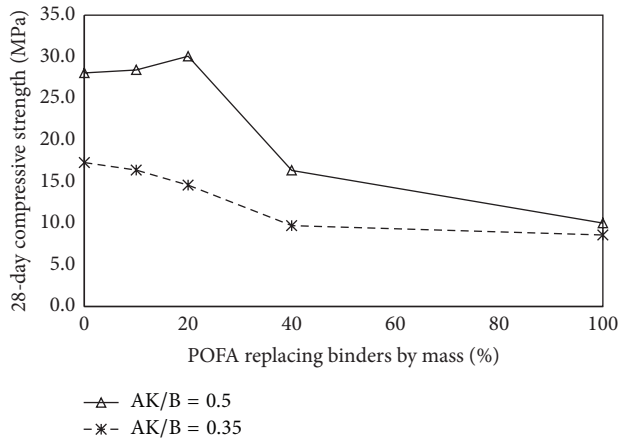
FIGURE 1: Effect of POFA on 28-day compressive strength.

FIGURE 2: Effect of curing methods on the strength development.

FIGURE 3: Effect of ratio of AK/B by mass on the strength development.

contain high level of POFA, may also be attributed to the deficiency of the filler effect of POFA and the low availability of Al_2O_3 content for geopolymerization.

As seen in Table 5, the 3-day compressive strength of M2 is higher than that of both M1 and M3, which may be due to the higher efficiency of filler effect by POFA and higher dissolution rate of FA compared to that of POFA that contributes to a higher early strength. Tonnayopas et al. [21] reported that the lower early compressive strength is due to the slow pozzolanic activity of POFA. However, M3 with 20% of POFA content produced the highest 28-day compressive strength and similar finding has been reported by Sata et al. [9]. Further, Table 5 shows that all the mixtures of the OPSGC fulfil the requirement for LWC as the oven-dry densities are lower than 2000 kg/m^3 as per the BS EN 206-1 [22] except for the M5 and M5-2. The use of 100% POFA in the mixes M5 and M5-2 exhibited the highest density.

3.2. Effect of Curing Methods on Strength Development of OPSGC. It is clearly seen from Figure 2 that the oven-cured OPSGC, M2, exhibited higher compressive strength than the ambient-cured OPSGC, M2-A. Nevertheless, the main observation is the high early (3-day) compressive strength gained by M2, which is about 91% of its 28-day compressive strength; however, the mix M2-A achieved only about 20% of its 28-day compressive strength. This denotes that the rate of the geopolymerization is accelerated by elevated temperature at early stage [23]. However, the strength of M2 does not develop exponentially compared to the strength of M2-A; this could be attributed to the high rate of geopolymerization during 48 hours of oven curing and this rate reduces after 48 hours. Similarly, Kusbiantoro et al. [24] reported that the oven-cured geopolymer concrete at 65°C exhibited superior mechanical properties compared to the other curing methods—ambient and external exposure. They reasoned that this could be attributed to the oven curing as the suitable condition to accelerate the dissolution and polycondensation of aluminosilicate gel in geopolymer framework.
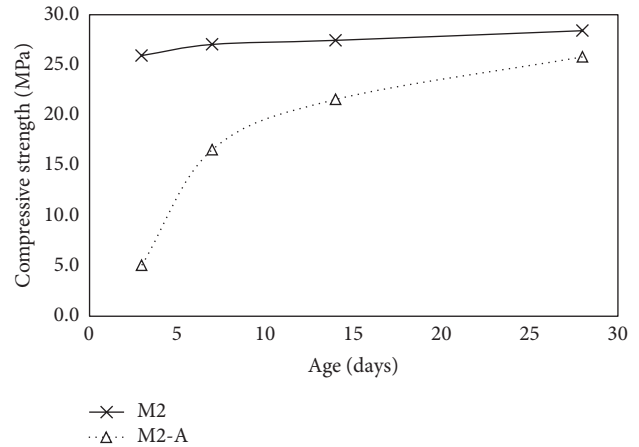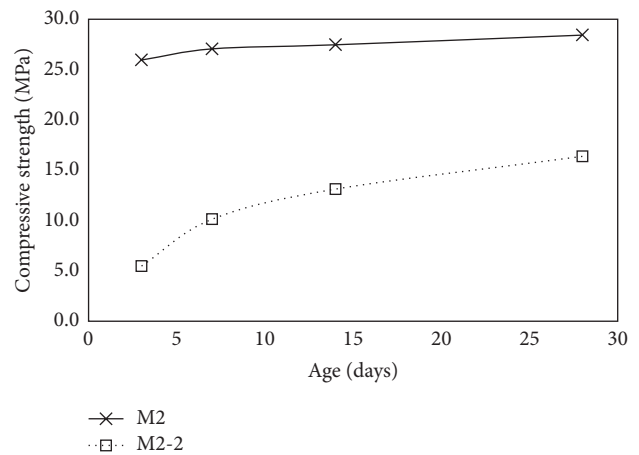
3.3. Effect of Alkaline Solution to Binders Ratio by Mass on Strength Development of OPSGC. Figures 1 and 3 show that in general all the mixes with AK/B ratios of 0.55 are of higher strength compared to the mixes with low AK/B ratio of 0.35. The increase of the ratio of AK/B by mass increases the ratio of SiO_2/Al_2O_3 that results in higher rate of geopolymerization and formation of denser structure, which leads to a higher compressive strength. Abdullah et al. [25] investigated that the ratio of AK/B of 0.5 by mass produces higher compressive strength than the ratio of 0.67 and 0.4. Sathonsaowaphak et al. [3] found that a very low compressive strength of 8 MPa was achieved for the mix with the AK/B ratio of 0.325 by mass; however, they reported that the high compressive strengths were in the range of 42 to 52 MPa as the ratios of AK/B by mass were varied between 0.429 and 0.709.

3.4. Tensile Strength of OPSGC. The results of the splitting tensile and flexural strengths of all the OPSGC mixtures are shown in Table 6. The results of the tensile strength showed a comparable trend with the results of 28-day compressive strength. The mix, M3, produced the highest splitting tensile

TABLE 6: Tensile strength of OPSGC.

Mixture	Tensile strength (MPa)	
	Splitting tensile	Flexural
M1	2.12	3.55
M2	2.13	3.70
M3	2.41	3.74
M4	1.62	3.11
M5	1.27	1.95
M2-A	2.03	3.31
M1-2	1.66	2.65
M2-2	1.62	2.55
M3-2	1.53	2.36
M4-2	1.25	1.93
M5-2	1.17	1.85

and flexural strengths of 2.41 and 3.74 MPa, respectively. The oven curing of the specimens combined with high AK/B ratio of 0.55 by mass may have aided the dissolution and polycondensation process of the geopolymer framework. This could have led to enhancing the rate of production of amorphous aluminosilicate gel and hence improved the mechanical properties. The ratio of splitting tensile strength to compressive strength (f_t/f_{cu}) of M1, M2, M3, and M2-A is varied from 0.075 to 0.08, which showed comparable results reported by Alengaram et al. [26]. Alengaram et al. [27] also stated that the low ratio of f_t/f_{cu} could be due to the porous OPS. Conforming to ASTM C330 [28], the mixes M1, M2, and M3 meet the requirement as structural LWC. Furthermore, (1) proposed by Neville [29] to estimate the splitting tensile strength for LWAC with the compressive strength of 10 to 65 MPa can be used for OPSGC since it gives close results. Consider

$$f_t = 0.23 \sqrt[3]{f_{cu}^2}, \tag{1}$$

where f_t is the 28-day splitting tensile strength of the test specimen (MPa) and f_{cu} is the 28-day compressive strength of the test specimen (MPa).

The percentages of flexural strength to compressive strength (f_r/f_{cu}) found in this investigations ranged from 12.4 to 21.5%. Similar to splitting tensile strength results, a comparable ratio of f_r/f_{cu} with the results reported by Shafigh et al. [30] is only applicable to few mixtures such as M1, M2, M3, and M2-A. Further, the flexural strength of 3.74 obtained for the mix M5 shows the significance of the percentage of POFA used in the mixes. The increase of the POFA content up to 20% increases the strength for both 0.35 and 0.55 of AK/B ratios. However, any further replacement of FA with POFA decreases the strength, which could be attributed to the lower void ratio to occupy the fine particles.

4. Conclusions

Based on the experimental results obtained from this research, the following conclusions can be drawn.

(i) The OPSGC mixture with POFA content of up to 40% could be considered as LWC as the oven-dry density is found to be lower than 2000 kg/m^2 for both mixtures which contain 0.55 and 0.35 as AK/B ratios. However, an increase of the POFA content beyond 40% increases the concrete density.

(ii) The compressive and tensile strengths of the OPSGC increased with the POFA content up to 20% and further replacement of POFA showed a significant reduction in the strength.

(iii) The oven curing enhanced the early strength of the OPSGC up to 91%; however, there is a higher strength gain over time for the ambient-cured OPSGC.

(iv) The use of AK/B ratio of 0.55 by mass contributes to dissolution and polycondensation in geopolymer framework that produced higher compressive strength of OPSGC compared to mixes with low AK/B ratio of 0.35.

(v) The mix, M3, with 20% of POFA content along with AK/B ratio of 0.55 and oven curing is recommended as optimum mix as it produced the highest strength among others.

(vi) The minimum requirement of 2.0 MPa of the splitting tensile strength was achieved for the mixes with low POFA content of less than 20%.

(vii) Both the splitting and flexural tensile strengths of the OPSGC showed acceptable values for LWAC.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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