

Ultrafine Palm Oil Fuel Ash: From an Agro-Industry By-Product into a Highly Efficient Mineral Admixture for High Strength Green Concrete

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Abstract: Palm Oil Fuel Ash (POFA) obtained from palm oil mill was treated via. heat treatment to remove excess unburned carbon and then ground to a median particle size of about 2 μm using a ball mill. The resulting treated ultrafine POFA obtained was then utilized in the production of High Strength Green Concrete (HSGC) with POFA replacement levels of 0, 20, 40 and 60% by mass of ordinary portland cement. Concrete samples were prepared in order to investigate the influence of the ultrafine POFA inclusion on the strength and impermeability characteristics of the HSGC. The results show that the treatment processes undertaken results in a highly efficient pozzolan. In the case of compressive strength, the inclusion of the ultrafine POFA reduces early age strength of the HSGCs at 1, 3 and 7 days but enhances the strength at 28 days for all HSGCs containing POFA where strength exceeding 95 MPa was achieved for all the POFA-HSGCs. Whereas the impermeability characteristics as assessed via. rapid chloride permeability, gas permeability and water permeability tests were significantly improved with the inclusion of the ultrafine POFA with the HSGC containing 60% POFA exhibiting the greatest improvement at 28 days. Thus, the overall results prove that the ultrafine POFA which was originally an agro-industry by-product possesses significant potential as an efficient pozzolanic mineral admixture for the production of HSGC with promisingly superior strength and impermeability characteristics.

Key words: Agro-industry by-product, ultrafine palm oil fuel ash, efficient mineral admixture, high strength green concrete, strength, impermeability

INTRODUCTION

Palm oil is one of the major agriculture-based commodities in countries like Malaysia and Thailand. Indeed these 2 countries are the major producers of palm oil. The extraction of palm oil in the palm oil mills produces a large amount of wastes in the forms of empty fruit bunches, fibers and kernels. These by-products are normally utilized as fuel to heat up boiler for generation of electricity in palm oil mills and the ash derived from the combustion process is known as Palm Oil Fuel Ash (POFA) (Awal, 1998). Approximately 3 million tons of POFA was produced throughout Malaysia in 2007 (MPOB., 2010) while for the case of Thailand, it was estimated that more than 100,000 tons of POFA has been produced every year and the amount is expected to increase annually (Chindaprasirt *et al.*, 2007). Therefore, POFA is produced in vast quantity and it may contribute to future environmental problem if it is not disposed of

properly. Many researchers have attempted to utilize POFA in the production of concrete. Early study on the use of POFA in concrete indicated that POFA has low pozzolanic properties and it was suggested that POFA should not be used to partially replace cement at a quantity in excess of 10% by mass of the cement (Tay, 1990). This could be mainly attributed to the coarser particle size and high content of unburned carbon of the POFA used. Later, it was shown that that POFA has good potential to suppress expansion associated with alkali-silica reaction in concrete (Awal, 1998; Muthusamy and Azzimah, 2014). In addition, the utilization of POFA was also observed to enhance the potential chloride resistant performance of concrete (Chindaprasirt *et al.*, 2008), reduce heat development during cement hydration, increase resistance to acidic environment (Tay, 1990) as well as improve sulphate resistance of concrete (Jaturapitakkul *et al.*, 2007; Tangchirapat *et al.*, 2007). Furthermore, attempts have

been made to utilize POFA in the production of High Strength Concrete (HSC) where by the POFA was ground to a median particle size of approximately 10 μm and then used at replacement levels of 0, 10, 20 and 30% by mass of Portland cement (Sata *et al.*, 2004, 2007; Tangchirapat *et al.*, 2009; Mohammed *et al.*, 2014). Nonetheless, these studies somehow exhibited the limitation of the POFA used as the highest compressive strength was obtained at a POFA replacement level of 20% and the highest 28 days compressive strength achieved for the concretes containing POFA was in the range of 60-86 MPa.

Realizing this limitation and recognizing the potential pozzolanic property of POFA coupled with aims at alleviating the potential environmental problems associated with POFA disposal, reducing the negative implication normally linked with cement production especially emission of green house gasses as well as preserving the non-renewable resources for the production of cement, the present study attempts to utilize high volume of POFA as partial cement replacement in the production of High Strength Green Concrete (HSGC). In order to extend the potential of the POFA, post-treatment regimes were undertaken via grinding and heat treating the POFA obtained from palm oil mill and investigating the influence of the resulting ultrafine POFA on the strength and impermeability characteristics of HSGC containing high volume of the ultrafine POFA. It is part of an on-going research dealing with properties and performance of HSGC containing high volume of ultrafine POFA where by up to 60% of POFA is utilized in the concrete.

MATERIALS AND METHODS

Constituent materials of concretes: The materials used for the HSGCs include Ordinary Portland Cement (OPC) complying the requirements of ASTM (2001), ultrafine POFA, natural river sand, crushed granite, water and a superplasticiser. The natural river sand used has a fineness modulus of 3.1, specific gravity of 2.7 and water absorption of 0.62% where as the crushed granite has a maximum size of 12.5 mm, specific gravity of 2.66, water absorption of 0.48% and dry-rodded unit weight of 1520 kg/m^3 . The high range water reducer used was a type F polymer based super plasticiser.

Treatment of POFA: POFA obtained from a near-by palm oil mill was first dried in an oven at $105\pm 5^\circ\text{C}$ for 24 h and then sieved passing a 300 μm sieve to remove coarser particles, fibers and kernels which were incompletely

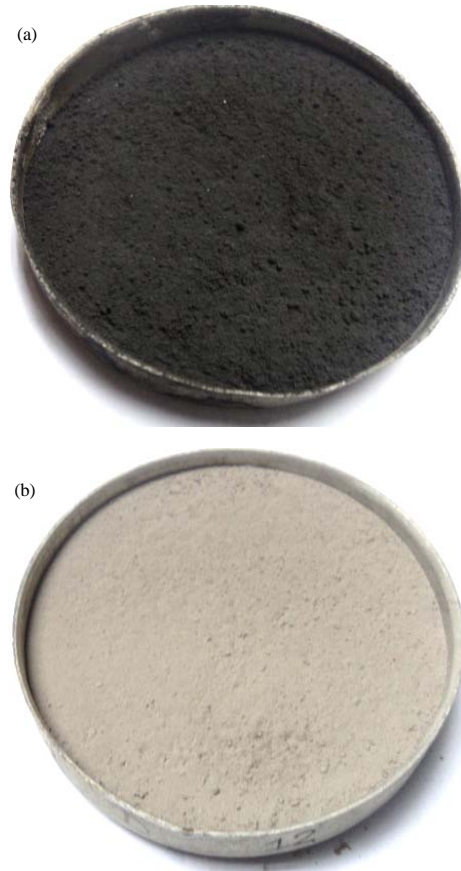


Fig. 1: a) POFA-before heat treatment and b) POFA-after heat treatment

burnt during the combustion in the palm oil mill. The POFA was then ground to a sufficient fineness using a laboratory scale ball mill to increase the efficiency of the heat treatment which follows. Subsequently, in order to remove excessive unburned carbon which will affect the potential pozzolanic properties, the POFA was heated at $500\pm 50^\circ\text{C}$ for 90 min in a gas furnace (Fig. 1). The same approach was previously utilized and reported to be effective in removing the excessive unburned carbon in POFA (Chandara *et al.*, 2010) but without the second stage grinding. Lastly, the heat treated POFA was subjected to further grinding via the same laboratory ball mill to obtain the treated ultrafine POFA.

Concrete mix proportions and samples preparation: The proportions for the control HSC mix were derived based on the method proposed by ACI Committee 211 (ACI, 1998) with a cement content of 550 kg/m^3 , water/binder ratio of 0.27 and superplasticiser dosage of 2.2% by mass of OPC.

Table 1: Concrete mix proportions

Materials	Materials (% of mass of cementitious material)					
	Binder of cementitious material		Fine aggregate	Coarse aggregate	Water	Superplasticizer
OPC	1.00	0.00	1.35	1.88	0.27	0.022
U-POFA20	0.80	0.20	1.35	1.88	0.27	0.022
U-POFA40	0.60	0.40	1.35	1.88	0.27	0.022
U-POFA60	0.40	0.60	1.35	1.88	0.27	0.022

For the HSGCs, the same binder content of 550 kg/m³ was utilized where the ultrafine POFA was used as a partial substitute of the OPC on mass-for-mass basis at substitution levels of 20, 40 and 60% while other ingredients remain the same. This was done to ensure that any change in the strength and impermeability characteristics of the HSGCs is due the partial substitution of the OPC with the ultrafine POFA. Owing to the lower specific gravity of the POFA in comparison to the OPC, the HSGC mixes are expected to have greater powder volume and binder paste volume in particular at higher POFA content. The mix proportions of the HSC used in this study are given in Table 1.

The concrete specimens prepared include 100 mm standard cubes, 100 mm (diameter) by 200 mm (height) standard cylinders and 100×100×500 mm prisms. Mixing of concrete was done using a pan type mixer and casting of samples was done in three layers each layer was compacted using a vibrating table to achieve maximum compaction. The samples were demoulded 24 h after casting and then cured in water maintained at room temperature of 27±2°C until they are required for testing.

Test procedures

Tests for physical properties and chemical composition of POFA:

A laser diffraction particle size analyser was used to assess the specific gravity, particle size and surface area of the POFA. X-Ray Fluorescence (X-RF) was utilized to study the chemical compositions of the POFA and OPC. In addition, X-Ray Diffraction (XRD) analysis was used to identify the major phases in the POFA while Scanning Electron Microscope in combination with Energy Dispersive X-ray spectroscopy (SEM/EDX) was also utilized to quantify the changes in the physical properties and compositions of the POFA due to the treatment processes. These analyses were undertaken to ensure the efficiency of the treatment process as well as the uniformity of the resulting ultrafine POFA.

Tests for workability and setting times: Workability of fresh concrete was assessed by means of the slump test according to BS EN 12350-2 (BSI., 2000) while setting times were determined in accordance to ASTM C 403

(ASTM., 1999). For the setting times, the tests were performed using the proctor apparatus on mortar which was obtained by sieving freshly mixed concrete through a 5 mm sieve and measuring the force required for the proctor needle or plunger to penetrate 25 mm into the mortar.

Test for compressive strength: The compressive strength of the concrete cubes was determined using a 3000 kN concrete compression machine according to BSEN 12390-3 (BSI., 2002). The test was performed on 100 mm concrete cubes at the ages of 1, 3, 7 and 28 days.

Test for rapid chloride permeability: The Rapid Chloride Permeability Test (RCPT) was performed according to the recommendations given by ASTM 1202 (ASTM., 1997) on cylindrical concrete specimens with diameter of 100 and 50 mm thick using 60 V DC current for 6 h. The Total Charge Passed (TCP) was obtained and to be related to the resistance of the sample to chloride ion penetration.

Test for gas permeability: For the case of gas permeability, a gas permeameter similar to that developed by Cabrera and Lynsdale (1988) was used to measure the gas permeability of cylindrical concrete samples of 55 mm diameter and 40 mm thick. The coefficient of gas permeability, K was calculated using the modified Darcy’s Eq. 1 as proposed by Houst and Wittmann (1994):

$$K = \frac{2\mu P_{out} QL}{A (P_{in}^2 - P_{out}^2)} \tag{1}$$

Where:

- Q = Volume flow rate (m³/sec)
- L = Sample thickness (m)
- P_{in} = Pressure at inlet (bar)
- A = Cross-sectional Area of sample (m²)
- μ = The viscosity of the gas (Ns/m²)
- P_{out} = Putlet Pressure (1 bar)

Test for water permeability: Water permeability was performed using the same permeability cell used for the determination of gas permeability on similar cylindrical concrete samples of 55 mm diameter and 40 mm thick. The

procedure involved water penetrating the top surface and flowing through the sample under an applied pressure head of 2-4 bars. The coefficient of water permeability, K_w was calculated using Eq. 2 (Valenta, 1970):

$$K_w = \frac{d^2v}{2Th} \quad (2)$$

Where:

d = The depth of water penetration (m)

T = The Time of penetration (sec)

h = The applied pressure (m)

v = The total porosity (fraction)

Porosity, v was calculated by using Eq. 3:

$$v = \frac{m}{Adp} \quad (3)$$

Where:

m = Gain in mass (kg)

A = Cross-sectional Area of specimen (m²)

q = Density of water (1000 kg/m³)

RESULTS AND DISCUSSION

Physical properties and chemical composition of POFA:

The changes in the physical properties and chemical compositions of the POFA due to the treatment processes are shown in Table 2 and 3, respectively. The particle size distribution of the POFA at different stages of the treatment process and that of the OPC are shown in Fig. 2. The final ultrafine POFA recorded a median particle size of 2.06 μm with a specific surface area of 1.775 m²/g. Hence, in comparison to the original POFA that was sieved passing 300 μm sieve, the ultrafine POFA records >80% reduction in median particle size and more than 300% increase in surface area. In addition, the recorded median particle size is about 70% smaller than that of the OPC while the surface area is about greater than 120% that of the OPC used in the study. Thus, the ultrafine POFA has significantly smaller particle size and higher surface area than those of the original POFA and the OPC. Furthermore, the changes in the particle size of the POFA due to the treatment processes could also be clearly seen from the SEM micrographs shown in Fig. 3.

Results of X-RF analysis in Table 3 exhibit that the heat treatment utilized significantly reduces the carbon content of the POFA from about less than 19 to 1% and lowers the Loss on Ignition (LOI) from 21.60-2.53%. The recorded reduction in carbon content is generally in agreement with the results of SEM/EDX analysis provided in Fig. 3. For POFA that has not been subjected to heat treatment, the SEM/EDX micrographs show that carbon element could easily be detected in relatively high

Table 2: Physical properties of OPC and POFA

Materials	Specific gravity (kg/m ³)	Median particle size, d ₅₀ (μm)	Specific surface area (m ² /g)
OPC	3.10	6.79	0.785
POFA	2.42	15.76	0.435
G-POFA	2.50	2.45	1.694
T-POFA	2.50	2.99	1.438
U-POFA	2.56	2.06	1.775

POFA refers to original POFA which has been sieved passing 300 μm sieve; G-POFA refers to Ground POFA; T-POFA refers to POFA which has been pre-ground and subjected to heat Treatment and U-POFA refers to Ultrafine POFA

Table 3: Chemical component of OPC and POFA based on X-RF analysis

Chemical components	OPC	G-POFA (weight)	U-POFA
SiO ₂	19.01	51.18	65.01
Al ₂ O ₃	4.68	4.61	5.72
Fe ₂ O ₃	3.20	3.42	4.41
CaO	66.89	6.93	8.19
MgO	0.81	4.02	4.58
P ₂ O ₅	0.08	4.10	4.69
K ₂ O	1.17	5.52	6.48
SO ₃	3.66	0.36	0.33
TiO ₂	0.22	0.19	0.25
MnO	0.19	0.09	0.11
Na ₂ O	0.09	0.06	0.07
C		19.05	0.09
LOI	2.48	21.60	2.53
SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃		59.21	75.14

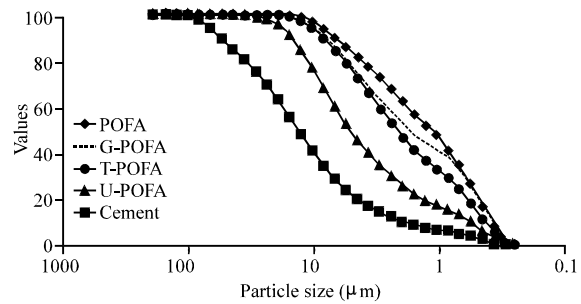


Fig. 2: Particle size distribution of POFA and OPC

intensity. Nonetheless for the heat treated POFA, carbon element could still be detected but in significantly lower intensity. Concomitantly, as a result of the reduced carbon content and LOI, the other chemical compositions in particular the SiO₂ increase except for the case of SO₃. It is also interesting to note that the heat treatment process changes the sum of SiO₂, Al₂O₃ and Fe₂O₃ from about 59% for the ground POFA to about 75% for the ultrafine POFA. Hence, the ultrafine POFA is deemed appropriate to be classified into mineral admixture class F, according to ASTM C618 (ASTM., 2005). For the case of the ground POFA, it could be grouped into mineral admixture class C based on the sum of SiO₂, Al₂O₃ and Fe₂O₃ but the high LOI value of 21.6% is way outside the stipulated maximum limit of 6%. Therefore, the heat treatment process is very much required to ensure compliance of the POFA with the LOI requirement specified in ASTM C618.

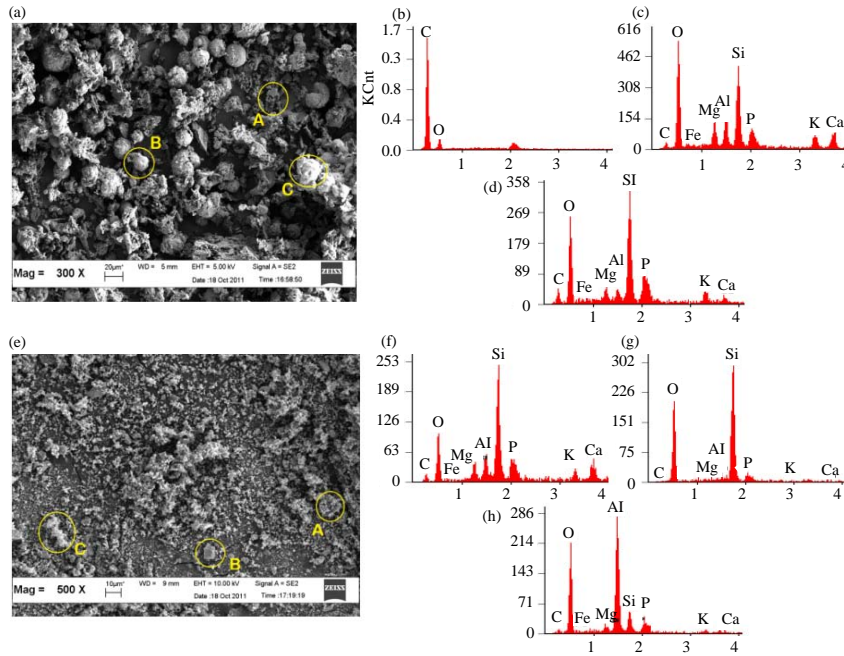


Fig. 3: SEM micrographs with EDX analysis of POFA: a-d) POFA after sieving through 300 µm sieve and e-h) Treated ultrafine POFA

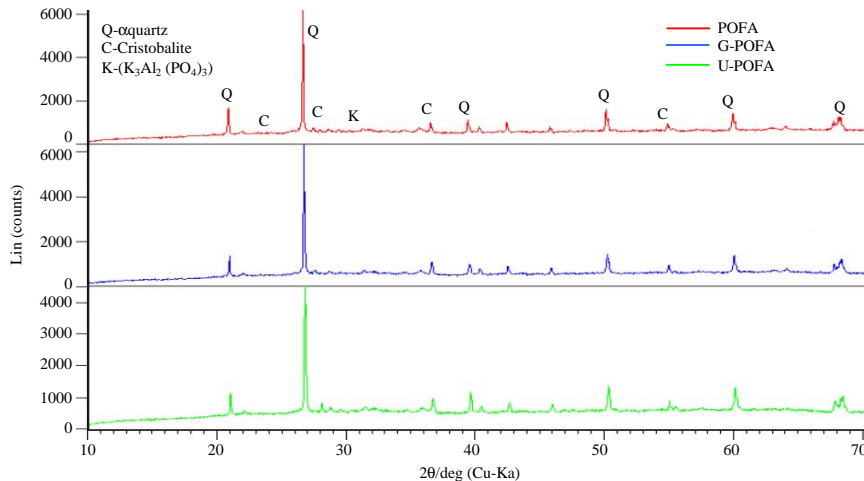


Fig. 4: X-RD diffractograms of POFA

Figure 4 shows the X-RD diffractograms for the original POFA, ground POFA as well as the ultrafine POFA. It is clear that all the three diffractograms exhibit very much similar and consistent pattern with α -quartz (SiO_2) as the major crystalline phase while cristobalite (SiO_2) and Potassium Aluminium Phosphate ($\text{K}_3\text{Al}_2(\text{PO}_4)_3$) represent the minor crystalline phases.

Thus, the treatment process which includes ball milling and heat treatment did not modify the phases of

the POFA. Similar findings was previously reported by Chandara *et al.* (2011) and they found that the POFA consisted of high amorphous content of about 70%, based on semi quantitative X-RD analysis. Hence, on the basis of similarity in the X-RD pattern and the observed phases of the POFA with those of earlier studies (Chandara *et al.*, 2010, 2011), it is expected that the POFA used in the present study should also have high amorphous content. Therefore, owing to the small particle

Table 4: Influence of ultrafine POFA on workability and setting times

Concrete mix	Slump (mm)	Initial setting time (min)	Final setting time (min)
OPC	190	140	285
U-POFA20	210	230	385
U-POFA40	225	270	460
U-POFA60	230	350	555

size, large surface area, low carbon content and LOI as well as high amorphous content, all of which contribute to superior pozzolanic properties, the ultrafine POFA is expected to have significant influence on the strength and impermeability characteristics of the HSGCs.

Workability and setting times: The results for workability assessed by means of the slump test and setting times determined via the penetration resistance test are given in Table 4. In the case of workability, it is clear that the inclusion of the ultrafine POFA improves the workability of the HSGC with higher workability at higher POFA content. The observed increase in workability could be partly attributed to the greater binder paste volume of the HSGCs, especially at higher POFA content as a result of the lower specific gravity of POFA in comparison to that of OPC. The excess paste volume in comparison to the OPC HSC could have provided better roles of coating the particles of aggregates, filling the gaps between the particles of aggregates as well as providing lubrication for aggregate particles to move during the slump test, hence, increasing the workability. This increase is despite the fact that the ultrafine POFA is having smaller particle size and greater surface area than the OPC as well as constant water/binder ratio and superplasticiser dosage used in all concrete mixes. Thus, this could be translated into a lower dosage of superplasticiser to obtain constant workability.

For the case of setting times, the results in Table 4 clearly exhibit that the inclusion of the ultrafine POFA retards both the initial and final setting times of the HSGC, with greater retarding effect at higher substitution levels. The observed retardation could be attributed to dilution effect for the HSGC containing POFA as part of the cement was replaced by the ultrafine POFA, particularly at higher POFA content. Similar finding was previously reported (Tangchirapat *et al.*, 2007; Safiuddin *et al.*, 2013) on concrete containing POFA with different particle sizes and on HSC containing different mineral admixtures (Brooks *et al.*, 2000; Safiuddin *et al.*, 2012a, b, 2011). This retarding effect could be utilized to full advantage for hot weather concreting to moderate the effect of hot weather on setting and probably also on workability retention of concrete.

Compressive strength: Figures 5 and 6 demonstrate that the inclusion of the ultrafine POFA reduces the early age

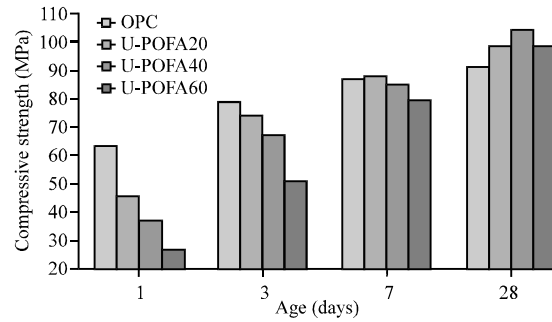


Fig. 5: Influence of ultrafine POFA inclusion on compressive strength development of HSGC

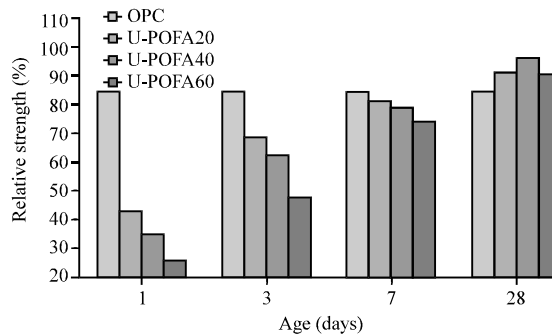


Fig. 6: Relative strength of HSGC containing different U-POFA content

compressive strength of the HSGC with greater reduction at higher POFA content. This could be attributed to the dilution effect as part of the cement was replaced by the POFA. At 1 day, the HSGC containing the ultrafine POFA records a relative compressive strength of 71.3, 57.5 and 41.1% of the OPC mix for POFA 20, 40 and 60, respectively (Fig. 6). The relative compressive strength increases to 93.4, 84.6 and 64.1% at 3 days and 100.6, 97.7 and 91.4% at 7 days for POFA 20, 40 and 60, respectively. Subsequently with prolonged water curing period of 28 days, the POFA-HSGCs exhibit greater compressive strength than the OPC concrete with a compressive strength value of 91.4, 98.3, 104.2 and 98.1 MPa for OPC, POFA20, 40 and 60, respectively with the POFA40 exhibiting the highest 28 days compressive strength. Hence, all of the POFA-HSGC mixes achieve greater compressive strength than the OPC concrete at 28 days with an increase of 7.5, 14 and 7.3% for POFA20, 40 and 60, respectively. This could be attributed to the pozzolanic reaction between the ultrafine POFA and $\text{Ca}(\text{OH})_2$ to produce secondary Calcium-Silicate-Hydrate (C-S-H) (Tayeh *et al.*, 2013; Yusoff, 2006; Zeyad *et al.*, 2016; Safiuddin *et al.*, 2012a), densifying the concrete microstructure, resulting in higher compressive strength.

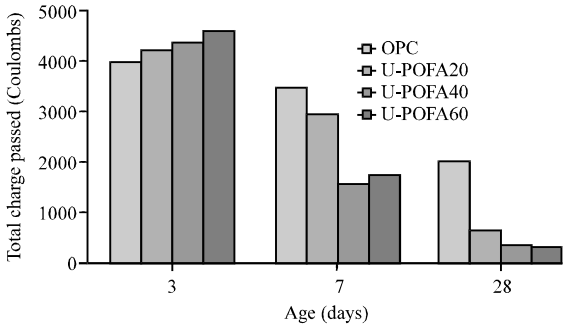


Fig. 7: Influence of ultrafine POFA inclusion on rapid chloride permeability of HSGC

By utilizing a binder content of 560 kg/m³, water/binder ratio of 0.28 and POFA replacement levels of 10, 20 and 30% in the production of HSC (Sata *et al.*, 2004) reported 28 days compressive strength values of 77.5, 81.3, 85.9 and 79.8 MPa for OPC, POFA10, 20 and 30, respectively. In a study on HSC containing POFA using binder content of 550 kg/m³ and water/binder ratio of 0.32 (Tangchirapat *et al.*, 2009) obtained 28 days compressive strength of 58.5, 59.5, 60.9 and 58.8 MPa for OPC, POFA10, 20 and 30, respectively. Hence, the results of these earlier studies somehow portrayed the limitation of POFA when used in HSC where by the maximum compressive strength obtained was 85.6 MPa at a replacement level of 20%. This could be mainly due to the coarser particle size and greater LOI of POFA used in these studies. Therefore, the findings of the present study clearly indicate that the ultrafine POFA with median particle size of about 2 μm is a much more efficient pozzolanic mineral admixture and also allows the POFA to be used at higher replacement levels of 60% and yet, achieving higher 28 days compressive strength than the OPC-HSC (Safiuddin *et al.*, 2012a).

Rapid chloride permeability: The RCPT was used to assess the potential chloride resistant performance of the HSGC and the results are shown in Fig. 7. It is obvious that in comparison to the OPC-HSC, the TCP values generally increase for the POFA-HSGCs at 3 days. Nonetheless, at longer water curing periods of 7 and 28 days, the TCP values of the POFA-HSGCs significantly reduce in comparison to the OPC-HSC. In fact, at 28 days there is a clear and consistent trend that the TCP values reduce with increasing POFA content with TCP values of 2038, 648, 363 and 327 coulombs for OPC, POFA20, 40 and 60, respectively. This shows that the POFA-HSGCs exhibit a reduction in TCP of 68, 82 and 84%, respectively for POFA20, 40 and 60. The significant reduction in TCP could potentially be translated into superior chloride

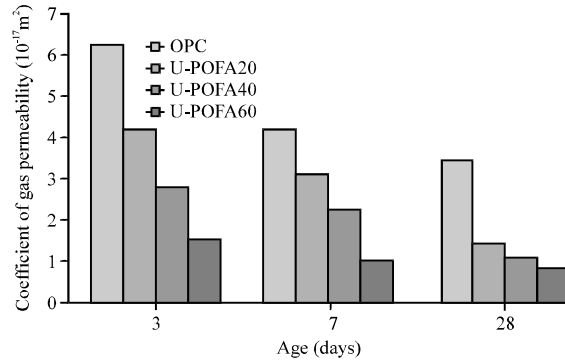


Fig. 8: Influence of ultrafine POFA inclusion on gas permeability of HSGC

resistant performance of the POFA-HSGC. Similar, trend was previously observed by Chindaprasirt *et al.* (2008) in particular for concrete using finer POFA. This could be attributed to reaction between the ultrafine POFA and Ca(OH)₂ to produce secondary C-S-H and part of ultrafine POFA working as filler which led to a reduction in charge passed.

Gas permeability: For the case of gas permeability, the test results obtained in the form of coefficient of gas permeability are shown in Fig. 8. Figure 8 clearly shows that the inclusion of the ultrafine POFA tremendously reduces the coefficient of gas permeability of the HSGC at all testing ages. At 3 days, the OPC, POFA20, 40 and 60 record a coefficient of gas permeability of 6.58, 4.36, 2.89, 1.55×10⁻¹⁷ m², respectively while at 28 days the coefficient of gas permeability reduces to 3.67, 1.48, 1.14 and 0.88×10⁻¹⁷ m², respectively. Hence, in comparison to the OPC-HSC, the effect of the ultrafine POFA is to consistently reduce the 28 days coefficient of gas permeability of the POFA-HSGCs by 60, 69 and 76% for POFA20, 40 and 60, respectively. This could be attributed to reaction between the ultrafine POFA and Ca(OH)₂ to produce secondary C-S-H and part of ultrafine POFA working as filler which led to reducing the coefficient of gas permeability.

Water permeability: Similarly, as in the case of gas permeability, the inclusion of the ultrafine POFA significantly reduces the water permeability of the HSGCs (Fig. 9) especially at longer water curing of 28 days. After 3 days of curing, a coefficient of water permeability of 5.05, 3.42, 4.58 and 4.92×10⁻¹¹ msec was recorded for OPC, POFA20, 40 and 60, respectively. This shows that the ultrafine POFA lowers the coefficient water permeability albeit the seeming trend of higher coefficient of water permeability at higher POFA content which could be

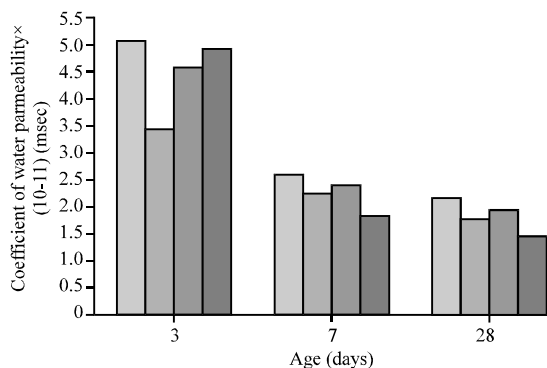


Fig. 9: Influence of ultrafine POFA inclusion on water permeability of HSGC

attributed to dilution effect. Nonetheless, after prolonged period of water curing of 28 days, the recorded coefficient of water permeability is 2.16, 1.77, 1.65 and 1.45×10^{-11} msec for OPC, POFA20, 40 and 60, respectively, indicating a consistent reduction in the coefficient of water permeability with higher POFA content. In comparison to the OPC-HSC, the POFA-HSGCs exhibit a reduction in coefficient of water permeability of 18, 24 and 33% for POFA20, 40 and 60, respectively at 28 days. Tangchirapat *et al.* (2009) reported that HSC containing 20% POFA provided the lowest coefficient of water permeability and the coefficient of water permeability increased at higher POFA content of 30% which is contradicting the finding of the present study. The different trend could be due to the potentially more reactive nature of the ultrafine POFA used in the present study, enabling it to reduce the water permeability of the HSGC at much higher POFA content of 60%. This could be attributed to the reaction between the ultrafine POFA and $\text{Ca}(\text{OH})_2$ which led to producing additional gel of C-S-H in addition to filling in the micro-voids in the matrix, resulted in reducing the coefficient of gas permeability (Salam *et al.*, 2013; Zeyad *et al.*, 2013).

CONCLUSION

Based on the results presented earlier on the strength and impermeability characteristics of HSGC containing high volume of ultrafine POFA, the following conclusions are offered.

The ultrafine POFA could be classified into mineral admixture class F, according to ASTM C618. For the case of the ground POFA, it could be grouped into mineral admixture class C based on the sum of SiO_2 , Al_2O_3 and Fe_2O_3 but the high LOI value of 21.6% is way outside the stipulated maximum limit of 6%. Hence, the heat treatment process is very much required to ensure compliance of the POFA with the specified LOI requirement.

The inclusion of the ultrafine POFA tends to reduce the water demand of the HSGC which leads to higher workability at constant water/binder ratio and superplasticiser dosage with higher workability at higher POFA content. This could be translated into lower dosage of superplasticiser to obtain constant workability.

The effect of the ultrafine POFA is to retard both the initial and final setting times of the HSGC with greater retardation at higher POFA content which could be advantages for hot weather concreting.

The POFA-HSGC exhibits lower compressive strength at 1, 3 and 7 days especially at higher POFA contents but the opposite trend is shown after 28 days of water curing period whereby all POFA-HSGCs register higher compressive strength than the OPC-HSC with the POFA40 HSGC exhibiting the highest compressive strength of 104 MPa at 28 days. In addition, even at 60% substitution level, the POFA-HSGC exhibits higher 28 days strength than the OPC-HSC.

The POFA-HSGC records lower rapid chloride permeability, gas permeability and water permeability in particular at higher POFA content and at longer water curing period. This could be translated into potentially superior durability performance.

The treated ultrafine POFA with smaller particle size, greater surface area, lower carbon content and LOI as well as high amorphous content proves to be a highly efficient pozzolan which significantly enhances the strength and impermeability characteristics of the HSGC, therefore, it is possible to produce HSGC utilizing high volume of ultrafine POFA with promisingly superior properties and durability performance.

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