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Scientific paper

Improving the Engineering and Fluid Transport Properties of Ultra-High Strength Concrete Utilizing Ultrafine Palm Oil Fuel Ash

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Abstract

Ground treated ultrafine-POFA obtained from palm oil industry was heat-treated to remove excess carbon. The varied proportion (17%, 30% and 40%) of UPOFA was incorporated into the ultra-high strength concrete (UHSC) to study its effects on the UPOFA-UHSC (U_x -UHSC) in comparison with OPC-UHSC (U_0 -UHSC) engineering and transport properties. The U_x -UHSC has an increasing workability tendency with a retarded setting times as compared to U_0 -UHSC. Besides, U_x -UHSC registered higher compressive strength than the U_0 -UHSC. The 90-d strength of 156 MPa was achieved in U_{17} -UHSC which was 4.7%, 7.5% and 12.2% higher than the values obtained for U_{30} -UHSC, U_{40} -UHSC and U_0 -UHSC, respectively. The U_{40} -UHSC exhibited the greatest improvement at 90 days in transport properties such as porosity, water absorption, initial surface absorption, rapid chloride permeability, gas permeability and water permeability while the highest strength was recorded with U_{17} -UHSC. Thus, the pozzolanic UPOFA is capable of improving the engineering and transport properties of UHSC.

1. Introduction

Palm oil industry is one of the major agro-industries in countries like Malaysia, Indonesia and Thailand, and this industry produces a large amount of waste in the form of empty fruit bunches, fibers and kernels. These by-products were normally used as fuel to heat up boiler for generation of electricity in palm oil factories. The ash derived from the process has been known as palm oil fuel ash (POFA) (Awal and Hussin 1997). In 2010, the Malaysian Palm Oil Board estimated the amount of POFA produced in Malaysia to be approximately 3.14 million tons (MPOB 2007). Very little of the POFA produced was actually used while some of it served as low-value material for backfill or fertilizers. The bulk quantity of the POFA was disposed as waste in landfills, causing environmental and other problems. However, many researchers found that POFA had pozzolanic properties and could be used as a replacement of cement in normal concrete, high strength concrete and even in the synthesis of alkaline activated binders (Yusuf *et al.*

2014a, Yusuf *et al.* 2014b). The test results on the performance of POFA revealed that it had a good potential in reducing the expansion due to alkali-silica reaction (Awal and Hussin 1997). The POFA has low pozzolanic reaction due to its large particle size and porous structure, which could be enhanced by means of grinding (Hussin and Awal 1996).

Some recent works have demonstrated that POFA can be used as a partial cement replacement material to produce high strength concrete with superior impermeability and increased durability. The demand for high strength construction materials was the main driving force behind the development of ultra-high strength concrete (UHSC). UHSC was generally characterized by its high cement content and very low water/binder ratio. Aggregate grading and high temperature curing need to be optimized to obtain superior mechanical and durability properties. Absence of coarse aggregates is a key aspect for the microstructure and performance of UHSC. Currently, UHSC seemed to be the promising material for special prestressed and precast concrete members. These materials can therefore be used for industrial and nuclear waste storage facilities (Tayeh *et al.* 2013b).

The main objective of this research is to investigate the effectiveness of varied proportions (0, 17, 30 and 40 wt.% of OPC) of ultrafine POFA on the engineering and fluid transport properties of ultra-high strength concrete (UHSC). Furthermore, this research is also aimed at reducing the consumption of cement with a view to lowering the construction costs and decreasing the solid wastes negative impacts on the environment.

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2. Experimental work

2.1 Materials

2.1.1 Cement, aggregates and pozzolanic materials

Ordinary Portland cement (OPC) that complies with the requirements of ASTM 150 (ASTM-C150/C150M 2009) was used as the main binder. Palm oil fuel ash (POFA) from a palm oil mill plant in Nibong Tebal, Penang, Malaysia was used as a supplementary binder. The POFA was dried in an oven at $105 \pm 5^\circ\text{C}$ for 24 h, and then sieved through a $300\ \mu\text{m}$ sieve to remove larger particles, fibres and grains that underwent incomplete combustion in the palm oil mill. The POFA was then ground in a laboratory scale ball mill for 10 h to obtain ground POFA and to achieve improved efficiency of the subsequent heat treatment. To eliminate unburned carbon, particle agglomeration and crystallization of glassy phase which affect pozzolanic properties, the ground POFA (G-POFA) was heated at $500 \pm 50^\circ\text{C}$ for 90 min in a gas furnace. The heat treated POFA (T-POFA) was then subjected to further grinding via the same laboratory ball mill for 4 h to obtain the ultrafine POFA (UPOFA) as shown in Fig. 1. This process was similar to that reported previously by Zeyad *et al.* (2013) and also by Chandara *et al.* (2010) but without the second stage grinding. The physical properties and chemical compositions of OPC and UPOFA are provided in Table 1 and Table 2, respectively. Figure 2 shows the micrographs or microstructure of the POFA, GPOFA, TPOFA and UPOFA accordingly.

Natural river sand with particle size ranging from $100\ \mu\text{m}$ to $1180\ \mu\text{m}$, specific gravity of 2.72 and water absorption of 0.82% was used as fine aggregate. The fine sand was washed to remove all clay and organic material and left to dry in the laboratory before being used. Polycarboxylic ether (PCE) based superplasticizer was used to obtain high workability at low water content.

2.1.2 Mix proportions and sample preparation

Ultra-high strength concrete can be produced using a wide range of mixture compositions. The mix proportions were arrived based on the recommendations given by Tayeh *et al.* (Tayeh *et al.* 2013a). Besides, a series of estimates, calculations, and trials mixes were carried out by varying the percentage of superplasticizer and wa-

ter/binder ratio (w/b), in order to obtain a concrete having high strength and an acceptable workability.

The properties of different combinations of the basic constituents (cement, sand, water and superplasticizer) were compared in trial batches. The target of this investigation was to produce ultra-high-strength concrete with the compressive strength higher than 120 MPa at the age of 28 days. Workability of fresh concrete and compressive strength after 28 days were evaluated. Mix proportions of the UHSC used in this study are as provided in Table 3. The control UHSC (U_0 -UHSC) mix has the cement content of $1128\ \text{kg/m}^3$, water/binder ratio of 0.16 and superplasticizer dosage of 4.8% by mass of binder. The mixes U_{17} -UHSC, U_{30} -UHSC and U_{40} -UHSC were developed to study the effect of 17% POFA, 30% POFA, 40% UPOFA replacement in UHSC mixture. Mixing of all the mixtures were done using a pan type mixer.

Dry ingredients that comprise cement and the pozzolanic materials were mixed for initial 5 minutes be-

Table 1 Physical properties of OPC and.

Materials	Specific gravity	Median particle size, d_{50} (μm)	Specific surface area (m^2/g)
OPC	3.16	6.79	0.379
UPOFA	2.56	2.06	1.775

Table 2 Mineral compositions of the materials OPC, UPOFA.

Compositions	OPC (%)	POFA (%)	UPOFA (%)
SiO_2	19.01	46.00	65.01
Al_2O_3	4.68	3.10	5.72
Fe_2O_3	3.20	2.45	4.41
CaO	66.89	8.46	8.19
MgO	0.81	4.40	4.58
P_2O_5	0.08	3.95	4.69
K_2O	1.17	4.08	6.48
SO_3	3.66	0.30	0.33
TiO_2	0.22	0.13	0.25
MnO	0.19	4.40	0.11
Na_2O	0.09	0.13	0.07
C	--	26.44	0.09
LOI	2.48	21.06	2.53
$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$	--	51.55	75.17

POFA

GPOFA

UPOFA

Fig. 1 Different grades of POFA.

Fig. 2 Scanning electron microscope micrographs of post treated POFA.

Table 3 Mix proportions of UHSC used in the present study.

Materials (kg/m ³)	U ₀ - UHSC	U ₁₇ - UHSC	U ₃₀ - UHSC	U ₄₀ - UHSC
OPC	1128	936	789.6	677
UPOFA	--	192	338.4	451
River sand (1.18-0.6)mm	775	775	775	775
River sand (0.6-0.3)mm	259	259	259	259
Water	181	181	181	181
Superplasti- cizer	55	55	55	55

fore adding water which contained 50 wt.% of total superplasticizer (SP) and then slowly mixed for 2 mins. The remaining SP was added to premix and then homogeneously mixed for 5 mins. The mixing process was continued until the mixtures changed from a dry powder to a thick paste.

The concrete specimens prepared include 100 mm standard cubes, (100 mm diameter × 200 mm height) standard cylinders and 100×100×500 mm beams. After mixing was carried out, all specimens were cast in three layers; each layer was compacted using a vibrating table and then cast in the relevant moulds. All the specimens were stored in a humid environment and demoulded after 24 h. After demoulding, the specimens were placed

in steam curing at 90 °C for 48 h (Tayeh *et al.* 2012a) to achieve faster hydration process. Next, the specimens were cured in water at room temperature 27 ± 2 °C until the day of testing.

2.2 Test procedures

2.2.1 Workability and viscosity

Flow characteristics for each mix was measured by a simple flow table test as per ASTM; C-1437 prior to casting. Specifications for the flow table and truncated flow cone was in accordance to ASTM: C-230 (ASTM-C230M 1998).

In the case of viscosity, it was performed according to ASTM: C-1611 (ASTM-C1611 2005) standard test method for slump flow of self-consolidating concrete. The rate of flowability was determined by measuring the T500, which represents the elapsed time from the time the slump cone was lifted to the time the concrete reaches a 500 mm mark on the testing plate under free flow conditions. The relative viscosity influences the flow rate of the mix and this can be determined by the T 500 time, where high values of T 500 indicate greater viscosity.

2.2.2 Setting times

The setting times of the U_x-UHSC mixtures were determined using the proctor apparatus on mortar in accordance to ASTM: C-403 (ASTM-C403/C403/M

1995). The test was obtained by measuring the force required for a needle to penetrate 25 mm into the mortar. In order to minimize the effect of ambient temperature variation, the samples were kept in a controlled environment of 20 ± 2 °C and $65 \pm 5\%$ relative humidity throughout the test duration. Initial and final setting times were defined as the times at which the penetration resistance reaches values of 3.5 MPa (500 psi) and 27.6 MPa (4000 psi), respectively.

2.2.3 Compressive strength

In this investigation, the compressive strength of the concrete cubes was determined using a 3000 kN concrete compression machine according to BS EN 12390-3 (B.S. 2002). The test was performed on 100 mm concrete cubes at the ages of 3, 7, 28 and 90 days. The maximum load capacity of the mean of the three specimens was recorded and the compressive strength of the concrete was calculated.

2.2.4 Porosity

Total porosity of concrete was determined by a vacuum saturation method developed by RILEM CP 113 (RILEM-CP113, 1984) on 55 mm diameter $\times$ 40 mm thick concrete core samples. The tests were carried out to determine the effect of the inclusion of the POFA on the porosity of the U_x-UHSC. The porosity was calculated using the following equation:

$$P = \frac{w_{ssd} - w_d}{w_{ssd} - w_{ssw}} \times 100 \quad (1)$$

where; P is the total porosity in percentage, w_d is mass of oven dry sample; w_{ssd} is mass of sample in saturated and surface dry condition in air; w_{ssw} is mass of sample in water.

2.2.5 Initial surface absorption

The test was carried out to obtain data to indicate the water flow into the surface of a dry and flat concrete surface. Initial surface absorption test was performed on 100 mm concrete cube according to the recommendations given in BS 1881: Part 208 (1996).

2.2.6 Rapid chloride permeability

The rapid chloride permeability test (RCPT) was performed in accordance with the procedures prescribed by ASTM: C-1202 (ASTM-C1202 1997). The test monitored the amount of electrical current passing through 50 mm thick slices of 100 mm nominal diameter cored cylindrical specimens. A direct current of 60 V was applied across the specimen, and the resultant current was recorded at 5 min intervals covering a total period of 6 h. The total charge passed (TCP) was obtained and used in the determination of resistance of the sample to chloride ion penetration.

2.2.7 Gas permeability

Gas permeability was commonly used to evaluate dura-

bility characteristics of concrete. In this study, the test was similar to that developed by Cabrera and Lynsdale (1988). The test method was performed on cylindrical concrete samples of 55 mm diameter and 40 mm thick to measure the gas permeability. The specimens were placed in the permeability cell and gas pressure of 5 bars was applied for 10 min to reach steady state. The time of the gas flow was measured using the appropriate bubble flow meter. The coefficient of gas permeability was calculated using the modified Darcy's equation (Eq. 2) as proposed by Grube and Lawrence (1984):

$$K = \frac{2\mu p_{out} QL}{A(p_{in}^2 - p_{out}^2)} \quad (2)$$

where; K is intrinsic permeability, L is length of specimen (m), Q is the volume flow rate (m^3/s), P_{in} is pressure at inlet (bar), and A is cross-sectional area of sample (m^2), μ is the viscosity of the gas ($N s/m^2$), and outlet pressure, $P_{out} = 1$ bar.

2.2.8 Water permeability

In case of water permeability test, it was performed on the same permeability cell used in the determination of gas permeability, and similar cylindrical concrete specimens having diameter of 55 mm and 40 mm thick were utilized. The procedure involved water penetrating the top surface and flowing through the specimen under an applied pressure of 5 bar. Coefficient of water permeability, K_w , was calculated using the following equation (Valenta 1970):

$$K_w = \frac{d^2 v}{2ht} \quad (3)$$

where ; d is the depth of water penetration (m), t the time of penetration (s), h the applied pressure (m) and v is the total porosity (fraction), which was calculated using the following equation:

$$v = \frac{m}{Ad\rho} \quad (4)$$

where; m is the gain in mass (kg); A the cross-sectional area of specimen (m^2), ρ is the density of water (1000 kg/m^3).

3. Results and discussion

3.1 Workability

The results of slump test are shown in **Table 4**. The test showed that the inclusion of the UPOFA improved the workability of UHSC and the workability increased with the increase in the percentage of UPOFA replacement when compared to OPC. This phenomenon could be partially attributed to the greater effective superplasticizer dosage relative to the weight of cement. Besides, the higher binder paste volume also contributed to this increase of the U_x-UHSC especially at higher UPOFA

Table 4 Influence of UPOFA on setting times, workability and viscosity of UHSC.

Concrete mix	Initial set (min)	Final set (min)	Slump (mm)	T500 (Second)
U ₀ -UHSC	420	615	210	12
U ₁₇ -UHSC	450	669	215	14
U ₃₀ -UHSC	540	810	225	19
U ₄₀ -UHSC	612	918	230	22

content (due to the lower specific gravity of UPOFA).

An increase in workability was observed at higher UPOFA content when compared to the control mix with only OPC. It was also found that the excess paste volume of UPOFA-UHSC in comparison to the OPC-HSGC could have provided better roles of filling the voids among the particles of aggregates. Thus, coating the particles of aggregates, and providing lubrication for aggregate particles to move during the slump test, hence increasing the workability (Megat Johari *et al.* 2012). The results of viscosity for T500 (in second) under free flow condition are given in **Table 4**. The high values of T500 indicate greater viscosity. The results showed that U_x-UHSC has higher viscosity than U₀-UHSC and this increased with higher UPOFA content. These values accounted for 12, 14, 19 and 22 second for OPC, U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively. This increase in viscosity could be attributed to the greater volume of the cement paste containing UPOFA as well as to the greater surface area of the UPOFA in comparison to OPC.

3.2 Setting times

The initial and final setting times of the UHSC were determined using the penetration resistance test in accordance with ASTM C 403 (ASTM-C403/C403/M 1995). The results of this test are given in **Table 4** and **Fig. 3**. From the results, it was clear that the inclusion of the UPOFA retards both the initial and final setting times of the UHSC as compared with OPC mix, with greater retarding effect at higher UPOFA content. U_x-UHSC records a relative initial setting time of 107%, 128% and 145% of the OPC mix for U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively. Thereafter, the relative final setting time records an increase of 109%, 132% and 150% of the OPC mix for U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively. The highest retar-

Fig. 3 Influence of UPOFA on the penetration resistance of UHSC.

dation of the setting times occurred at U₄₀-UHSC, which resulted in 612 min. for the initial setting time and 918 min. for the final setting time. The delay in setting times can be mainly attributed to the combined effect of a higher UPOFA content (UPOFA/cement ratio) and a higher effective superplasticizer dosage relative to the weight of cement which started the initial hydration that prompted the setting of the binder.

Similar trend was previously reported on high strength green concrete (HSGC) containing different percentage of UPOFA, wherein an increase in setting time was observed at higher UPOFA content (Megat Johari *et al.* 2012). Also similar finding was previously reported by Tangchirapat *et al.* (Tangchirapat *et al.* 2007) on concrete containing UPOFA with different particle sizes. It showed that the longer setting times of UPOFA concrete was due to the pozzolanic reaction between pozzolan and calcium hydroxide Ca(OH)₂, which was usually slower than the hydration of OPC. On the other hand, Morin *et al.* (2001) reported that the overall effect of superplasticizer was to delay the setting times of concrete and the extent of delay depended largely on the type and dosage of superplasticizer, type of cement and temperature.

3.3 Compressive strength

Figure 4 presents the results of the compressive strength of the UHSC mixtures. The lowest compressive strength of 131.4 MPa was recorded by U₄₀-UHSC at 3 days, while the highest compressive strength of 156 MPa was achieved by U₁₇-UHSC at 90 days. It is clear from the overall results that the inclusion of UPOFA has significant influence on strength and strength development characteristics of the UHSC mixes when compared with the control mix with only OPC. The results showed that the compressive strength of U_x-UHSC decreased as the percentage of UPOFA replacement increased. **Figure 5** showed the strength of U_x-UHSC relative to U₀-UHSC. At 3 days, the U_x-UHSC recorded a relative strength of 109.6%, 103.3% and 99.5% of the OPC mix for U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively. The relative strength increased to 110.3%, 104.9% and 100.9% of the OPC mix at 7 days and later to 111.8%, 106.5% and 103.3% for U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively at 28 days. Thereaf-

Fig. 4 Influence of ultrafine UPOFA on compressive strength development of UxHSC.

Fig. 5 Strength variation of UxHSC with age.

ter, after 90 days, the POFA-UHSC exhibit greater strength than the OPC-UHSC, with strength value 139, 156, 149, and 145 MPa for OPC, U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively.

In addition, as the age increased, the compressive strengths of POFA-UHSC also increased and UHSC with 17% replacement of POFA had the highest strength at all ages compared with 30% and 40% replacement of UPOFA. This is similar to the findings of other researchers (Sata *et al.* 2004; Tangchirapat *et al.* 2009b; Budiea *et al.* 2010). Excessive UPOFA composition beyond the optimum caused the breaking down of chains within the primary or secondary structural unit of C-S-H already formed due to attachment of excessive Si from the additional UPOFA beyond the optimum. Thus, it appears that the optimum UPOFA that enhanced the effective secondary hydration was 17%.

Moreover, all POFA-UHSC mixes recorded higher compressive strength than U₀-UHSC at 7, 28 and 90 days. The increase in the compressive strength of U_x-UHSC could be attributed to the high fineness of UPOFA particles as reflected by SEM micrograph (Fig. 2), which filled the voids between the cement and the fine aggregates thereby serving as the reinforcement or enhancing the packing effect within the microstructural matrices. Besides, the SiO₂ contained in UPOFA reacted with the Ca (OH)₂ generated by the hydration process of cement to form secondary calcium-silicate-hydrate (C-S-H). The aggregate packing effect and enhancement of microstructural density through secondary hydration of UPOFA effect enhanced the compressive strength (Tayeh *et al.* 2013c).

3.4 Porosity

The test results of porosity are presented in Fig. 6. The porosity values were found to be in range of 0.93 to 2.64 %. The results showed that the inclusion of UPOFA significantly reduced the porosity when compared to the control mix with only OPC. The recorded porosity at 3 days was 2.64%, 1.54%, 1.49% and 1.63%, while at 7 days was 2.48%, 1.37%, 1.23% and 1.25% for OPC, U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively. The porosity reduced to 2.4%, 1.22%, 1.13% and 1.08% at 28 days and later to 2.3%, 1.1%, 0.99% and 0.93% for OPC, U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, re-

spectively at 90 days.

In addition, it was clear that at 3 days, UPOFA with 40% had higher porosity than U₁₇-UHSC and U₃₀-UHSC. However, at 7 and 28 days, the opposite trend was observed but it can be clearly observed porosity reduced with increasing UPOFA content as all U_x-UHSC mixes showed lower porosity than control mix. The reduction in porosity for all concrete mixes from 3 to 90 days indicated that the U₀-UHSC, U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC observed reduction in porosity by 12.8%, 28.5%, 33.5% and 43% respectively. This implies that as the development of microstructural density with time influenced the porosity of the product. Hence, the higher the UPOFA content, the greater was the reduction in porosity especially at the extended period of curing. There is consensus among several researchers that with partial replacement of cement with pozzolans prompts decreases in porosity of concrete (Güneyisi *et al.* 2007; Megat Johari *et al.* 2012)).

3.5 Initial surface absorption

The results for initial surface absorption test (ISAT) were determined at time sequence of 10 min, 30 min, 60 min and 120 min. The ISAT values for time interval of 120 min was found to be in the range of 2.24 to 18×10^{-3} ml/m²/s. It is clear that the inclusion of pozzolanic materials such as UPOFA significantly reduced the ISAT values when compared with control mix having only OPC.

Figure 7 shows the effect of UPOFA on the initial surface absorption at time sequence of 10, 30, 60 and 120 min at 90 days. At 90 days, the recorded ISAT val-

Fig. 6 Influence of UPOFA on the porosity of UxHSC.

Fig. 7 Influence of UPOFA on initial surface absorption of UHSC with different time at 90 days.

Fig. 8 Influence of UPOFA on initial surface absorption development of UHSC for time interval of 120 min at 90 days.

ues with 10 min was 8.8, 6.4, 5.04 and 4×10^{-3} ml/m²/s for U₀-UHSC, U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively. In addition, at 30 min the recorded ISAT values were 6.8, 5.2, 4.16 and 3.44×10^{-3} ml/m²/s and at 60 mins the values were 5.28, 4.32, 3.44 and 3×10^{-3} ml/m²/s for U₀-UHSC, U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively. However, results at 120 min. showed a significant reduction in ISAT values 5.12, 3.92, 2.56 and 2.24×10^{-3} ml/m²/s for OPC, U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively at 90 days. The results indicated that U₄₀-UHSC had the lowest ISAT values in all even with OPC-based (U₀-UHSC).

Figure 8 shows the influence of UPOFA on the initial surface absorption development of UHSC for time interval of 120 min. At 3 day, the recorded ISAT values were 18, 17, 6 and 3.9×10^{-3} ml/m²/s for U₀-UHSC, U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively. Further, at 7 days the ISAT values reduced to 12.6, 8, 4.4 and 3.5×10^{-3} ml/m²/s and later to 6.4, 4.9, 3.2 and 2.8×10^{-3} ml/m²/s for U₀-UHSC, U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively at 28 days. The ISAT values for all concrete mixes at 90 days exhibited a reduction of 23.4%, 50% and 56.2%, respectively for U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, when compared to OPC (U₀-UHSC) mix. Besides, it was observed that all U_x-UHSC mixes showed lower ISAT values than control mix and the ISAT values decreased as the percentage of UPOFA replacement increased with longer period of curing.

On the other hand, Voo and Foster (Voo and Foster 2010) recoded that UHPC had initial surface absorption less than 0.7 and 0.2 at 10 min and 120 min, respectively and this is in agreement with the findings of this study. Therefore, it can be argued that the inclusion of UPOFA up to 40% enhanced the tortuosity due to the presence of more particles of reduced diameter that prevent fluid transmission. This reduction in the porosity of U₄₀ suggests that high Si content in it probably constitutes either the cross linking effect to the already formed C-S-H thereby enhancing the tortuosity or filling of the pores better than U₁₇ and U₃₀. However, this requires further microstructural investigation into the resulting binder of UHSC.

3.6 Rapid chloride permeability

The test results are shown in **Fig. 9**. Rapid chloride permeability test (RCPT) values were found to be in the range of 1757 to 16 Coulombs, which can be described as “low” to “negligible” chloride ions penetrability, according to ASTM: C-1202 designation. It was evident that the inclusions of UPOFA significantly reduced the total charge passed (TCP) values when compared to U₀-UHSC.

The results showed that U_x-UHSC with 40% UPOFA recorded the lowest TCP values at all ages. Besides that, all POFA-UHSC mixes showed lower TCP values than control mix and TCP values reduced with increasing UPOFA content. At 3 days, the recorded TCP values were 1757, 480, 95.5 and 56 Coulombs for U₀-UHSC, U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively. In addition, it was clear that at 3 days, U₄₀-UHSC has lower TCP value than U₁₇-UHSC and U₃₀-UHSC.

However, at 7 and 28 days identical trend was observed with a recorded TPC value of 1360, 324, 67 and 42 Coulombs and subsequently at 28 days it was 995, 129, 27 and 18.3 Coulombs for OPC, U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC, respectively. The reduction in TCP values for all concrete mixes at 90 days exhibit a reduction in TPC of 84%, 96.6% and 97.6%, respectively for U₁₇-UHSC, U₃₀-UHSC and U₄₀-UHSC when compared with OPC mix. Hence, higher the POFA content, greater would be the reduction in the chloride permeability with longer period of curing in UPOFA blended UHSC (Megat Johari *et al.* 2012).

Similarly, chloride penetration of mortar improved considerably with partial replacement of OPC with POFA. The resistance to chloride penetration was higher with an increase in the replacement level POFA (Chindaprasirt *et al.* 2008) while the different between the compressive strength achieved for different UPOFA replacement were found insignificant with the values generally less than 600 Coulombs.

3.7 Gas permeability

For the case of gas permeability, the test results were zero for all U_x-UHSC mixes at all testing ages. This could be due to the ultra-dense structure of U_x-UHSC on account of the low water/binder ratio and the fine materials used. This is advantageous for sealing and

Fig. 9 Influence of UPOFA on rapid chloride permeability development of UHSC.

durability properties of the U_x -UHSC samples. Similar trend was previously reported by Tayeh *et al.* and Vernet where the gas permeability coefficient was recorded as zero value and extremely low, respectively (Tayeh *et al.*, 2012b, Vernet, 2004). The permeability of UHPC to oxygen was found to be less than ($1 \times 10^{-20} \text{ m}^2$). By comparison, the oxygen permeability of UHPC was 10 times ($1 \times 10^{-19} \text{ m}^2$) and 100 times ($1 \times 10^{-18} \text{ m}^2$) smaller than what was observed in HPC and normal concrete, respectively.

3.8 Water permeability

The water permeability values were found to be in the range of 2 to $5.2 \times 10^{-13} \text{ m/s}$. The test results for gas permeability in the form of water permeability coefficient are presented in Fig. 10. It can be clearly seen from the figure that, inclusions of UPOFA greatly reduced the coefficient of water permeability when compared to U_0 -UHSC. The results also indicate that the coefficient of water permeability was reducing with the increasing UPOFA content. Besides, all U_x -UHSC mixes showed lower water permeability than control mix. At 3 days of curing, the recorded values of coefficient of water permeability were 5.2×10^{-13} , 3.4×10^{-13} , 3.6×10^{-13} and $4.3 \times 10^{-13} \text{ m/s}$ for U_0 -UHSC, U_{17} -UHSC, U_{30} -UHSC and U_{40} -UHSC, respectively. In addition, it was clear that at 3 days, U_{40} -UHSC had the highest water permeability than U_{17} -UHSC and U_{30} -UHSC. However, at 7 and 28 days, the opposite trends were observed with a recorded water permeability of 4.7, 3, 3.15 and $3.17 \times 10^{-13} \text{ m/s}$ at 7 days and subsequently at 28 days 4.5, 2.7, 2.66 and $2.6 \times 10^{-13} \text{ m/s}$ for U_0 -UHSC, U_{17} -UHSC, U_{30} -UHSC and U_{40} -UHSC, respectively were observed. Nonetheless, after prolonged period of water curing of 90 days, the recorded coefficient of water permeability was 4.1, 2.3, 2.2 and $2 \times 10^{-13} \text{ m/s}$ for U_0 -UHSC, U_{17} -UHSC, U_{30} -UHSC and U_{40} -UHSC, respectively.

The reduction in water permeability for all concrete mixes from 3 to 90 days indicates that the U_0 -UHSC, U_{17} -UHSC, U_{30} -UHSC and U_{40} -UHSC recorded a reduction in water permeability by 21%, 32.4%, 38.8% and 53.4%, respectively. Hence, the higher the UPOFA content, the greater the reduction in the coefficient of

Fig. 10 Influence of UPOFA on water permeability development of UHSC.

water permeability in UHPC. This implies that there is no significant difference in the water permeability properties for the UPOFA inclusion of U_{17} to U_{40} as the recorded values were not more than 20% increment in water permeability for the specimen cured for 7 to 28 days. The closeness in values of samples cured for 90 days reveals the fact that prolong curing reduced the microstructural pores through the continuous hydration processes within the microstructure. The insignificant difference between the 17% substitution and others further establishes the optimum content of UPOFA in U_x -UHSC to be 17%.

However, a contradictory trend was observed by other researcher who reported that, the coefficient of water permeability increased at higher POFA content of 30%. The difference in trend between Tangchirapat *et al.* observation and the present study could be due to the potentially more reactive nature of the UPOFA used in the present study (Tangchirapat *et al.*, 2009a). It should also be noted that further treatment POFA which contained high LOI (~26%) to achieve UPOFA caused the reduction in its LOI (~2%). LOI increases with organic impurity and with water absorption of POFA-based product. These facts could be responsible for the discrepancy in the results reported.

3.9 Relationship between water permeability and porosity

Figure 11 shows the relationship between the water permeability and porosity for the U_x -UHSC mixes. The results indicate that the water permeability generally increased when the porosity increased at all ages. Besides, UHSC with moderate UPOFA (17%) compositions recorded perfect correlation between the permeability and porosity than others. The Figure also shows a perfect correlation for U_{17} than other samples (U_{30} and U_{40}). The general reduction in the UPOFA-based UHSC could be added to reduced capillary pore diameter prompted by microfilling or reinforcement of the finer UPOFA particle and secondary hydration that accompanies cement hydration reaction. This significantly influenced the permeability and porosity properties while difference in the Si composition that increases with quantity could be identified as the reason why U_{40} performs better than U_{17} in the longer time transport properties of the UHSC. It is expected that the lesser the

Fig. 11 Relationship between water permeability and porosity.

Fig. 12 Relationship between initial surface absorption and chloride permeability.

volume of pores, the denser the microstructure, the higher the compressive strength of UHSC and the better the transport properties and better the durability performance of the product when compared with OPC-based.

3.10 Relationship between initial surface absorption and chloride permeability

The relationship between the initial surface absorption for time interval of 120 min. and chloride penetration can be seen in Fig. 12. It showed that the variation was similar for both test conditions. In both cases, the initial surface absorption increased with the increase in chloride penetration. In addition, UHSC with higher UPOFA content recorded significant reduction in ISA and TCP values at the prolonged curing durations. Though the concrete performance in terms of initial surface absorption appears to be better when the UPOFA replacement in UHSC is 40% despite its less strength values when compared with 17% replacement. This could be probably due to increase in the volume of fines present in the matrices. In other words, as the strength development grows outwardly from the core of the specimens, the unreacted excesses probably play the filling role especially at the periphery of the specimen (U₄₀-UHSC) thereby preventing surfacial infiltration.

4. Conclusions

Based on the results obtained from the study on engineering and transport properties of UHSC containing high volume of UPOFA (U_x-UHSC), the following conclusions can be drawn:

- Palm oil fuel ash being a waste material, can be a good pozzolanic material on account of its higher silica content especially when it is subjected to further treatment.
- The inclusion of UPOFA tends to increase the workability and viscosity of the ultra-high strength concrete (U_x-UHSC).
- UPOFA retarded both the initial and final setting times of the U_x-UHSC and the highest retardation of the setting times occurred at 40% of UPOFA replacement (U₄₀-UHSC).

- All mixes of UPOFA-UHSC (U_x-UHSC) registered higher compressive strength than the OPC-UHSC (U₀-UHSC) while the compressive strength of U_x-UHSC decreased with the increase in UPOFA replacement level such that 17% UPOFA (U₁₇-UHSC) exhibited the highest compressive strength of 156 MPa at 90 days compared to U₃₀-UHSC and U₄₀-UHSC.
- The U_x-UHSC in comparison with U₀-UHSC recorded lower porosity, initial surface absorption, rapid chloride permeability and water permeability at longer curing period. The transport properties performance increased with the content of UPOFA and this could be translated into potential superior durability performance in comparison with U₀-UHSC.
- All U_x-UHSC mixes recorded zero or negligible gas permeability due to its ultra-dense structure as a result of the fineness of the materials used.

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