Compressive Strength and Efficiency Factor of Green Concrete

Mohammad Momeen Ul Islam[1,2], U. Johnson Alengaram[3], Mohd Zamin Jumaat[4]

[1]*BSc., Department of Civil Engineering, KUET, Bangladesh (momeen.structure.um@gmail.com)*
[2]*M.Eng.Sc, Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[3]*Associate Professor, Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[4]*Professor, Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*

Abstract

The efficacy of two palm oil industrial waste materials, namely palm oil fuel ash (POFA) and oil palm shell (OPS), as partial and whole replacement materials, respectively, for ordinary Portland cement (OPC) and conventional crushed granite aggregate on fresh and hardened concrete properties has been investigated and reported. OPC was partially replaced with POFA by weight proportion of 0%, 10%, 30%, and 50% cementitious material to produce the green concrete. The hardened concrete properties of the sustainable concrete developed through this research was investigated through ultrasonic pulse velocity (UPV) and cube compressive strength test. In addition, the efficiency factor was also calculated and reported. The compressive strength test was performed at 7-, 28-, 90- and 120-day for various concrete mixes, and the highest 28-day compressive strength of 40 MPa was found for the mix with 10% replacement of OPC POFA, hence could be categorized as lightweight concrete. The UPV values in the range of 3.89 to 4.09 km/s show quality of the concrete was good. Thus, the usefulness of POFA as partial cement replacement material in lightweight concrete with OPS as a whole replacement for conventional aggregate is feasible.

Keywords: *sustainable concrete materials; hardened concrete properties; ultrasonic pulse velocity (UPV); efficiency factor.*

1. Introduction

One of the research emphases is the utilization of industrial and agricultural waste materials as alternative concrete materials. Many researchers in developed and underdeveloped countries such as North America, Indonesia, Nigeria, and Malaysia are involved in research works to utilize locally available industrial and agricultural waste materials effectively. One of the significant research contributions from researchers in Malaysia, Indonesia, and Nigeria has been utilizing palm oil industrial wastes as construction material (Alengaram et al., 2013). Also, some of these countries have been engrained with profitable plants, such as coconut, tea, sugar can, rubber, paddy, cocoa, and oil palm, and the wastes generated could be utilized in the development of construction materials (Kanadasan & Razak, 2014). Presently, Malaysia is one of the leading exporting countries of palm oil. In 2011, it was reported 5 million hectares area of land was used for oil palm plantation (Alengaram et al., 2013). This resulted in enormous production of by-products such as empty fruit branches, fibers and oil palm shells (OPS), palm oil fuel ash (POFA) throughout the palm oil processing periods (Kanadasan & Razak, 2014). As such, a new window of prospect has opened up to utilize waste materials from the palm oil industry, namely POFA and OPS, and as replacement materials for conventional OPC and crushed granite aggregate in concrete production.

Various POFA contents were suggested to be used in concrete by previous researchers (Aldahdooh et al., 2014; Lim et al., 2013; Tangchirapat & Jaturapitakkul, 2010), however, generally, POFA was used up to 20% replacement level for OPC. As a pozzolanic material, the silicon dioxide content in POFA reacts with calcium hydroxide (CH) released from the hydration of OPC and produces more calcium silicate hydrate (CSH), which is a gel compound, as well as reducing the amount of CH. The later age compressive strength could be improved by up to 90% associating with the conventional concrete when the POFA was used in NWC as partial substitution of OPC (Tangchirapat & Jaturapitakkul, 2010). As detailed above, there had been researching works on the POFA as pozzolanic material in NWC; however, the use of POFA as cement replacement material in the development of lightweight concrete with another palm oil industrial waste, OPS as a lightweight aggregate for whole replacement of conventional crushed granite or normal weight aggregate hasn't been explored. This is crucial in view of vastly available local waste materials from the palm oil industry, which could be re-used in the production of lightweight concrete for environmental and financial advantages. Therefore, this study underlines the investigation of the effects of POFA as partial cement replacement from 0 to 50% and its effect on some engineering properties of OPSC. The variable investigated in this assessment is the POFA content. The hardened concrete properties through cube compressive strength, ultra-pulse velocity test, and efficiency factor have been studied and reported.

2. Experimental Programs

2.1 Materials

2.1.1 Cement

Type 1 Ordinary Portland cement, which meets the ASTM: C150/C150 M-12 specifications, was used in all mix proportions. The Blaine surface area and specific gravity of the cement were 346 m^2/kg, 3.14, respectively. Table 1 shows the chemical properties of OPC.

2.1.2 Palm Oil Fuel Ash (POFA)

POFA was used as partial cement replacement in this investigation. The un-processed POFA was collected from a local palm oil mill. The collected POFA was oven-dried at 100˚C for 24 hours and then sieved using a 300 μm size sieve to remove coarse particles. After that, the POFA was ground in a rotating drum for 30,000 cycles lasting 16 hours to achieve the targeted fineness (>66%). After grinding, the POFA passing through a 45 μm size sieve was collected. The total amount of POFA passing through the 45 μm was 87%. The POFA had specific gravity and surface area of 2.15 and 171 m^2/kg, respectively. Table 1 and Table 2 show the chemical and physical properties of POFA, respectively. Figure 1 shows the physical appearance of OPC and POFA.

2.1.3 Oil Palm Shell (OPS)

Crushed OPS of sizes between 2.36 and 9 mm were used as coarse aggregate. The OPS were soaked 24 hours prior to casting and then air-dried to achieve saturated surface dry condition before used for casting. Table 3 and Figure 2 show the physical properties and appearance of OPS, respectively.

2.1.4 Superplasticizer

A polycarboxylic-ether-based superplasticizer with a specific gravity of 1.20 was used in this study, and this was supplied by BASF Sdn Bhd. with a commercial name Glenium Ace 388.

2.1.5 Normal Sand

Normal mining sand was used as fine aggregate with maximum grain size, water absorption, specific gravity, and fineness modulus of 4.75 mm, 0.81 %, 2.79, and 2.88, respectively.

2.1.6 Water

The laboratory pipeline water free from contamination was used for all the mixes.

Table 1. Chemical properties of POFA and OPC by using X-ray Fluorescence (XRF) analysis.

Chemical composition	**Materials**	
	POFA (%)	**OPC (%)**
CaO	4.32	64.1
Al_2O_3	5.49	4.4
MgO	3.71	3.5
SiO_2	63.2	22.8
Na_2O	0.14	0.1
SO_3	0.92	2.6
P_2O_5	3.74	0.2
K_2O	6.37	0.8
MnO	0.17	0.8
Fe_2O_3	4.19	1.3
LOI	6.15	1.0

Table 2. Physical properties of POFA

Physical Properties	**POFA**
Specific surface area	171 m^2/kg
% Passing 45- µm sieve	87
Specific gravity	2.15
Color	dark

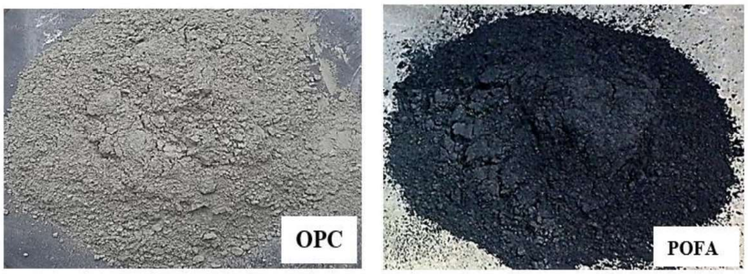

Figure 1. The contrast in color between ordinary Portland cement (OPC) and palm oil fuel ash (POFA).

Figure 2. The physical appearance of crushed oil palm shell (OPS).

Table 3. Physical properties of OPS

Physical Properties	**Crushed OPS**
Bulk density (compacted) (kg/m^3)	684
Fineness modulus	5.94
Specific gravity	1.25
Water absorption (30 min) (%)	9.65
Water absorption (24 h) (%)	18.7

2.2 Mix Proportion

The variable in the mix design of the study is the amount of cement replacement with POFA. The ground POFA was used as partial cement replacement at 0%, 10%, 30%, and 50% by mass of binder, and their mix designations are christened as M0, M10, M30, and M50, respectively. In this investigation, a fixed binder, sand, OPS, and water contents of 565, 960, 368, and 170 kg/m3, respectively, were used. The superplasticizer was used to 0.6 to 1.1% to maintain the slump value within a specific range. The mix proportions (kg/m^3) are given in Table 4.

Table 4. Mixture Proportions of concrete (kg/m^3)

Mix No.	**Cement**	**POFA**	**Water**	**Super-plasticizer**	**Sand**	**Coarse aggregate (OPS)**
M0	565	0	170	3.4	960	368
M10	508	57	170	3.4	960	368
M30	395	170	170	4.9	960	368
M50	283	282	170	6.2	960	368

2.3 Mixing procedure

Both OPS and sand were mixed in a drum mixer for 2 min followed by binder materials (cement and POFA) which were further mixed for 3 minutes. Then, half of the mixing water was added for mixing of 2 minutes, followed by the addition of the remaining mixing water and superplasticizer. The mixing procedure continued for a further 2 minutes before a slump test was performed to check the workability of the fresh concrete mix. The concrete specimens were cast in 100-mm cubes to determine the density, ultrasonic pulse velocity, and compressive strength. The specimens were de-moulded after 24 hours and water cured for 28-days and then removed from the water curing tank and exposed to the laboratory condition with a temperature of 30˚± 2C and relative humidity of 85 ± 3% for the determination of concrete properties at ages of 90- and 120-day.

2.4 Test method

The UPV test was done on 100 mm cube specimens. A portable ultrasonic non-destructive digital indicating tester with adjoining transducers was used to measure the traveling time for pulse between the ends of specimens. The UPV is calculated by dividing the length of pulse travel by the time measured. The compressive strength test was done following the standard method BS EN 12390-3: 2002 (BS EN 12390-3, 2002).

3. Result and Discussion

3.1 Ultrasonic pulse velocity (UPV)

The ultrasonic pulse velocity (UPV) denotes the soundness of concrete and the variation in the structure of the concrete due to aging and curing (Mannan et al., 2002). Figure 3 shows the variation of the UPV values of all mixes up to a period of 120-day. Generally, for all mixes and curing regimes, the UPV increased as the curing age is increased. The range of UPV values obtained was 3.89-4.09 km/s at the age of 120-day. According to the UPV value classification (Mannan et al., 2002), all OPSC and POFA based OPSC exhibited good quality type concrete.

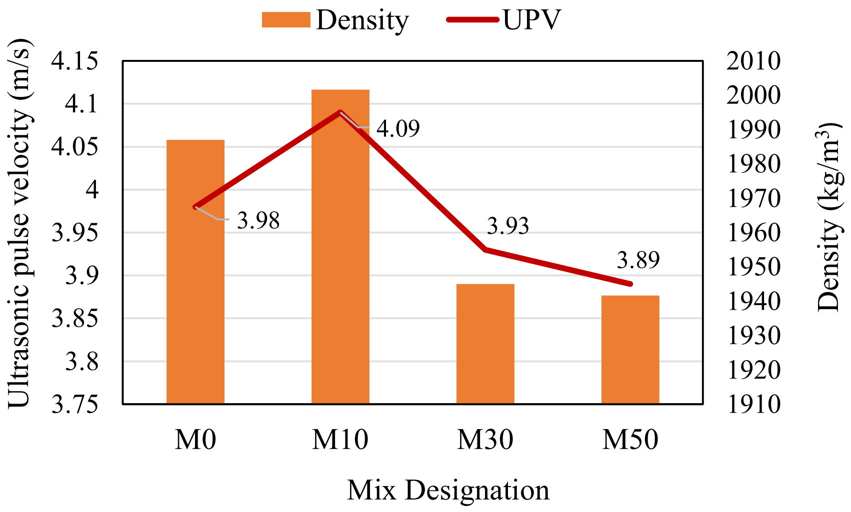

Figure 3. Variation of UPV and density with % replacement of cement by POFA.

The maximum UPV value was found for 10% replacement which was about 3% higher than mix M0. However, the addition of POFA has a negative effect on the UPV values as there was a slight reduction in UPV for mixes M30 and M50 compared to the control OPSC (M0). One possible explanation could be the use of lower cement content in OPSC. The use of the high amount of POFA might absorb water, and with the loss of water, the formation of C-S-H would be reduced, and the densification of concrete is also reduced. This is shown in Figure 3, where the UPV values showed a reducing trend with density.

3.2 Compressive Strength

The 7-, 28-, 56- and 120-day compressive strengths for various mix designs are shown in Figure 4. There is a clear trend of increasing compressive strength with an increase of age. The compressive strengths of 7-, 28-, 56-and 120-day ranged 21-39 MPa, 26-40 MPa, 31-41 MPa, and 38-41 Mpa, respectively. It was mentioned by Okafor (Okafor, 1988) that by using agricultural waste, the maximum compressive strength was about 25-35 MPa for lightweight concrete, which was within the range of typical structural lightweight concrete of 20-35 MPa. In this research work, the compressive strength of various mixes was similar or more of the range mentioned above. The rate of strength development for POFA based OPSC was lower at the initial curing stage rather than the later age curing. This similar case was also explained by (Shafigh et al., 2011). They reported that the development rate for pozzolanic material-based structural lightweight concrete at the early age is lower than the later curing age. This could be attributed to the hydration of cement and pozzolanic reactivity during the initial stage of curing. Conversely, the pozzolanic material POFA delayed the hydration process because POFA has more significant loss of ignition (LOI) than OPC, which was previously discussed and for the same reason, it increased the water demand to mix up with the concrete constituent materials. This increased demand for water hindered the hydration process inside the concrete and affected the strength development consequently. A similar reason was explained by researchers (Newman & Choo, 2003), and they found that pozzolanic materials like fly ash caused the lack of curing, which affected the final product because of delaying the hydration process. As seen from the results, the OPSC containing 10% POFA produced comparable results compared to the control mix.

Table 5 shows the increase of compressive strength till the age of 120-day. At the age of 7-day, the control mix M0 gained 97% of 28-day compressive strength, and other OPSC mixes containing POFA achieved 71-88% of 28-day compressive strength. Conversely, 10% replacement of cement with POFA produced maximum compressive strength than other mixes at 28-day. But at 56-day, a slight increase in compressive strength of about 2% was found in

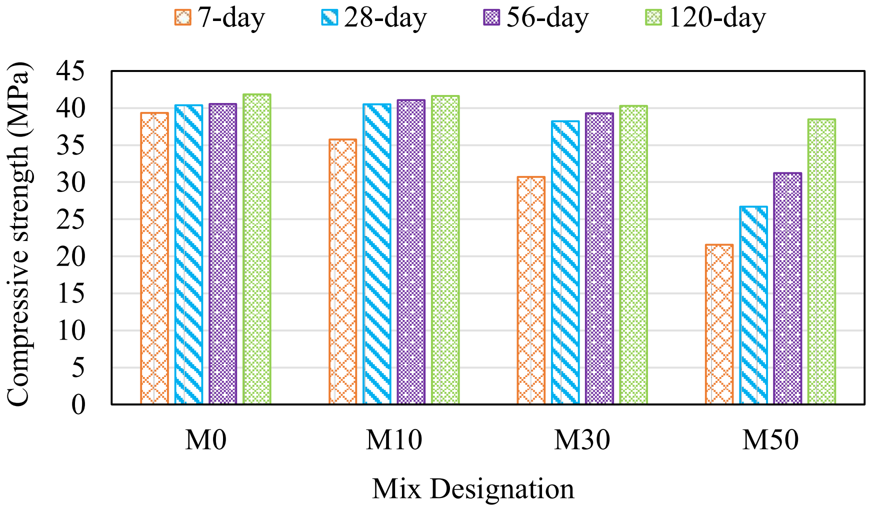

Figure 4. Variation of Compressive strength with different various mixes.

the Mix M10 compared to 28-day compressive strength; however, POFA based mixes achieved higher strength increment in the range of 101-108% of 28-day compressive strength. The rate of development of compressive strength from 7-day to 28-day was 2-40%. At 120-day, the compressive strength of mix M0 was higher than M10. This could be due to inadequate hydration in the mixes with POFA. The overall strength for all mixes was increasing proportionally with the curing age; it was also observed that the compressive strength for mixes M30 and M50 was found lower at every curing age compared to other mixes. The drop of compressive strength for mix M30 and M50 could be due to poor pozzolanic reaction. In pozzolanic reaction, portlandite from OPC reacts with the major chemical composition SiO_2 of POFA and the by-products help to increase the strength; but with the increase of POFA, the portlandite due to lower OPC content hampers the pozzolanic reaction with SiO_2 to produce the by-product and hence it causes a reduction in the compressive strength. Such phenomenon was also found when pozzolanic materials content increased like fly ash in OPSC (Basri et al., 1999). But the rate of development of strength for these two mixes M30 and M50, were 24% and 44%, respectively, from 7-day to 120-day, which was much higher than the other two mixes M0 and M10. As the POFA is available in alumina oxides and silica where lime is absent almost, and the hydraulic properties cannot progress without the hydrated lime (Mertens et al., 2009). The main function of hydrated lime is to accelerate the hydration process for making the natural pozzolans acting as binding materials like OPC. But in the case of POFA, the reactive silica is readily dissolved in the matrix as $Ca(OH)_2$ becomes available during the hydration process. These pozzolanic reactions lead to the formation of additional C-S-H with binding properties. Simply, this reaction can be schematically represented as follows:

$$Ca(OH)_2 + H_4SiO_4 \rightarrow Ca^{2+} + H_2SiO_4^{2-} + 2\ H_2O \rightarrow CaH_2SiO_4 \cdot 2\ H_2O$$

or summarized in the abbreviated notation of cement chemists:

$$CH + SH \rightarrow C\text{-}S\text{-}H$$

The product of the general formula ($CaH_2SiO_4 \cdot 2\ H_2O$) formed is a calcium silicate hydrate, also abbreviated as C-S-H in cement chemistry notation which contributes to the enhancement of the compressive strength. Figure 5 shows the failure pattern after the cube compressive strength test, and it shows in the cube specimens of mixes M30 and M50, there is more breakdown of the bond between mortar and OPS compared to the mixes M0 and M10. This could be due to a slower hydration process between 28 and 120 days as the specimens were kept in the air. The slow hydration process might have hampered the development of strength and C-S-H, which in turn resulted in poor bonding between OPS and mortar. It was reported that the low compressive strength of the OPSC could be attributed to a weaker bond between the OPS and cement matrix (Alengaram et al., 2013; Shafiq et al., 2007).

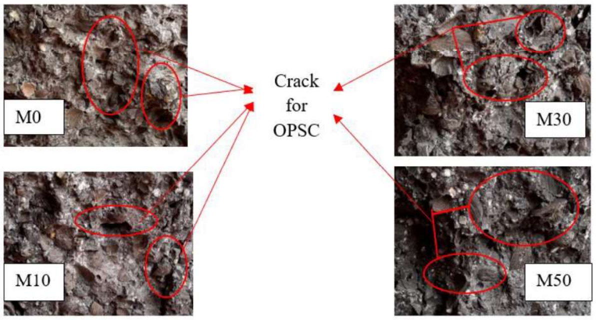

Figure 5. Failure pattern for A) M0, B) M10, C) M30, and D) M50 mix after compressive strength test at 120-day.

Table 5. Comparison of 28-day compressive strength with 7-, 90- and 120-day compressive strength.

Mix	**Compressive strength (MPa)**			
	7-day	**28-day**	**56-day**	**120-day**
M0	39.35 (97.5%)	40.38	40.55 (101.16%)	41.87 (103.70%)
M10	35.78 (88.32%)	40.51	41.10 (101.57%)	41.63 (102.77%)
M30	30.72 (80.38%)	38.22	39.30 (102.20%)	40.30 (105.43%)
M50	21.56 (71.87%)	30.70	31.25 (108.1%)	34.35 (113.34%)

3.3 Efficiency factor

The efficiency factor is the strength (MPa) to weight (kg/m^3) ratio of concrete which has a very vital role in determining the behavior of concrete in structure. Figure 6 shows the variation of efficiency factor with the reduction of cement for some specific percentages by POFA under 7-, 28-, 90- and 120-day curing ages. Likewise, the efficiency factor of lightweight structural concrete has an outstandingly greater impact than NWC at the similar compressive strength, and it was found that the efficiency factor for OPSC was 17,000-22,000 N M/kg for the 28-day compressive strength of 30-45 MPa (Shafigh et al., 2014). The calculated efficiency factor of this study varies 11,000 -21,000 N M/kg for 28-day compressive strength of 26-40 MPa, where mixes M30 and M50 showed lower efficiency factors as the compressive strength of these mixes was also lower. But mixes M0 and M10 showed higher efficiency factors as these mixes developed higher compressive strengths than mix M30 and M50.

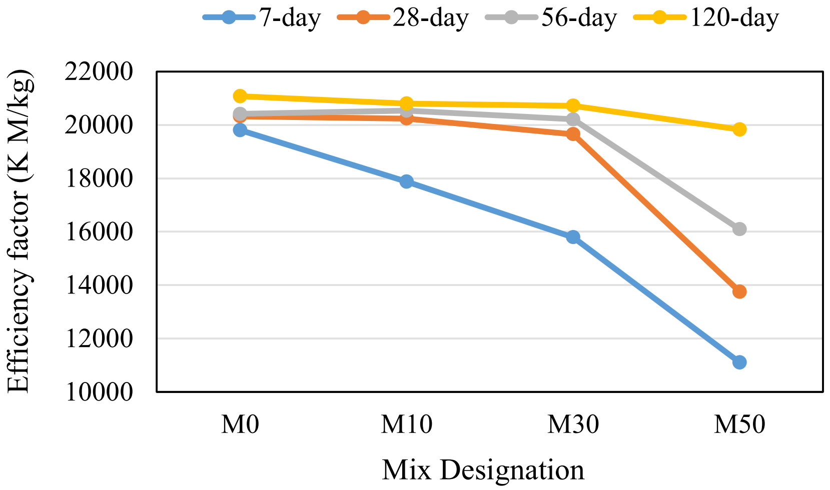

Figure 6. Replacement of cement by POFA vs efficiency factor (K M/kg) under 7-, 28-, 90- and 120-day curing age.

4. Conclusions

1. Ultrasonic pulse velocity showed all concrete mixes are of good quality category.
2. Compressive strength for higher POFA based OPSC was lower at the initial curing condition but found to increase with later curing age. At 7-day, the minimum compressive strength was found 21.5 MPa for 50% POFA content in OPSC, which surpassed the minimum strength 17 MPa requirement for the structural lightweight concrete as specified in ACI 213R. The maximum compressive strength was found for 10% replacement of OPC by mass with POFA at 120-day. But the strength development rate from 28-day to 120-day for higher percentage like 30% and 50% POFA content in OPSC was higher than the mix without POFA based OPSC.
3. As aggregate covers about 60–80% of the volume of the concrete, the replacement of industrial waste as a complete or fractional replacement for conventional aggregate may subsidize considerably in energy saving, cost-effectiveness, and modification of the environmental effect through construction diligence. Given the current criteria for sustainable related environmental benefits, green building rating systems, infrastructure, and concrete using industrial wastes like POFA and OPS as aggregate can benefit in creating the concrete industry environmentally friendly.

5. Acknowledgements

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