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An Experimental Investigation of the Carbonation of Blended Portland Cement Palm Oil Fuel Ash Mortar in an Indoor Environment

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Abstract
In this research, palm oil fuel ash was utilized as a pozzolanic material in blended Portland cement mortar. The mortar was tested on the normal compressive strength and the negative effect of carbonation in indoor environment using the accelerated carbonation test of 5% CO_2 in 50% relative humidity. Three palm oil fuel ash fractions of different fineness, viz., coarse original palm oil fuel ash (CPOA), medium palm oil fuel ash (MPOA) and fine palm oil fuel ash (FPOA) were used for the study. Ordinary Portland cement (OPC) was partially replaced by these palm oil fuel ashes at the dosages of 20% and 40% by weight of binder. The results showed that the incorporation of the ashes affected the strength and the carbonation depths of mortars. The strengths of mortar slightly decreased with the increases in the dosage of the ash. The fineness of ash, on the other hand, improved the strength and the carbonation of the mortars. The mortars containing FPOA exhibited high strength and relatively low carbonation in comparison to those using coarser MPOA and CPOA. The use of FPOA resulted in a strong and dense mortar owing to the increased packing effect and pozzolanic reaction. It was therefore, demonstrated that the FPOA could be used as a pozzolanic material to replace part of Portland cement for use in the indoor environment.

Introduction

Manufacturing Portland cement requires high energy and releases a very large amount of green-house gas to the atmosphere. Approximately 13,500 million tonnes is produced from this process worldwide, which accounts for ~7% of the green-house gas produced annually [1].

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The use of pozzolans, especially waste pozzolans, to replace part of Portland cement is therefore receiving a lot of attention. Historically, "pozzolans" are named after the volcanic additives used in mortar by the Romans. Pozzolans are fine materials containing silica and/or alumina and while they do not have any cementing properties of their own in the presence of calcium oxide (CaO) or calcium hydroxide ($Ca(OH_2)$), silica and alumina in the pozzolans react and form cementitious materials [2]. Ash from some agricultural by-products such as rice husk ash, baggasse ash, and palm oil fuel ash have been shown to be good pozzolans [3–6]. Their uses are receiving more attention now since the properties of the blended cement concrete using them are generally improved. In addition, they can also save the cost of construction materials and reduce the negative environmental effects [7].

Palm oil fuel ash is one promising pozzolan and is available in many parts of the world. It is a by-product obtained from a small power plant, which uses the palm fiber, shells, and empty fruit bunches as a fuel which are burnt at $800-1000°C$ [6]. The main chemical composition of palm oil fuel ash is silica, which is the main ingredient of pozzolanic material. At present palm oil fuel ash is sent to landfill which is a problem for all power plants because it has not been proven useful yet and is treated as a waste.

The use of pozzolans to replace part of Portland cement improves the durability of concrete through the pore refinement and the reduction of calcium hydroxide in the cement paste matrix [8]. Resistance to chloride penetration, acid solution attack, and sulfate attack of the concrete containing pozzolans is generally enhanced [6,9,10]. The other important property, which also influences the performance of concrete is the carbonation which could induce corrosion in steel reinforcement [11]. The ingress of carbon dioxide into the cement matrix results in a reduction in the ability of the cement matrix to protect the steel reinforcement as the passive layer at the surface of the reinforcing bar is destroyed. The carbonation is usually severe in the high carbon dioxide environment and in the relatively dry or indoor environment of 50–60% RH [12]. In particular, when thin concrete sections, such as slab and thin walls, are involved, the concrete covering of the steel reinforcement is small and protection of the steel reinforcement by the cement matrix against penetration of carbon dioxide is much reduced. Although paint and other surface covering of the concrete surface can help reduce the carbonation, the modern designs using bare concrete surfaces are often preferred.

The use of these agricultural by-product ashes as pozzolans usually requires grinding to produce relatively fine pozzolans [6,13]. Their use reduces the bulk density of the concrete products as their specific gravity is usually around 2.0–2.3 which is much lower than the overall 3.15 of Portland cement. Other advantages are that the product is less stiff which gives better performance in terms of noise absorption and fire resistance [14]. The application of these materials in concrete for indoor use is therefore very attractive.

The fineness of the pozzolan is known to have a large influence on the properties of concrete through increases in the packing effect and pozzolanic activity. This ultimately improves the durability of the matrix through pore refinement and reduced $Ca(OH)_2$. The parameter used to quantify this is the Blaine number, a surface area measurement that has been used since the 1940s to determine cement quality.

In the present work, mortars from blended Portland cement and ground palm oil fuel ash with various finenesses were studied. The results could be beneficial to the understanding of the mechanisms involved as well as for future applications of these materials in the indoor environment.

Materials and Methods

Materials

Palm oil fuel ash from a small power plant in the south of Thailand, ordinary Portland cement (OPC), a river sand with specific gravity of 2.63 and fineness modulus of 2.82, and type-F superplasticizer (SP) were the materials used in this study. The grading analysis (particle size distribution), scanning electron microscopy (SEM), and X–ray diffraction (XRD) were performed on palm oil fuel ash. Three fineness grades of palm oil fuel ash were used:

(1) Coarse original palm oil fuel ash (CPOA) with 70% retained on a sieve No. 325 (opening 45 m).
(2) Medium palm oil fuel ash (MPOA) obtained from ball mill grinding with the percentage retained on a sieve No. 325 of 15%.
(3) Fine palm oil fuel ash (FPOA) obtained from ball mill grinding with the percentage retained on a sieve No. 325 of 3%.

Mix Proportions and Curing

Palm oil fuel ashes were used to replace OPC at dosage levels of 20 and 40% by weight of binder. Sand-to-binder (cement + palm oil fuel ash) ratio of 2.75 by weight and water to binder ratio (W/B) of 0.5 were used. SP was

Table 1. Mortar mix proportions

Mix	OPC	CPOA	MPOA	FPOA	SP (%)
OPC	100	–	–	–	1.9
20POAO	80	20	–	–	3.7
20POA1	80	–	20	–	3.1
20POA2	80	–	–	20	2.8
40POAO	60	40	–	–	3.9
40POA1	60	–	40	–	3.5
40POA2	60	–	–	40	3.3

Note: Sand-to-binder ratio 2.75, W/B = 0.5, flow 110 ± 5%.

incorporated to increase the workability of the mortar and in order to obtain mortar mixes with similar flow of 110 ± 5%. The cast specimens were covered with polyurethane sheet and damped cloth in a 23 ± 2°C chamber. They were demolded at the age of 1 day. The mix proportions of the mortars are given in Table 1.

Compressive Strength

The 50 × 50 × 50 mm cube specimens were used for the compressive strength test of mortar. They were moist cured in a 23 ± 2°C chamber. They were tested at the age of 7, 28, and 90 days in accordance with the ASTM C109 [15]. The reported results are the average of three samples.

Carbonation Test

The carbonation test was done using 40 × 40 × 160 mm mortar bars in accordance with the procedures given in the RILEM CPC18 [16]. The specimens were moist cured in a 23 ± 2°C chamber. At the age of 28 days, the mortar bars were put in the accelerated carbonation environment of 5% CO_2 at 50% R.H. at 23 ± 2°C. After carbonation for the periods of 3, 7, 14, 28, and 60 days, the bars were broken at one end and phenolphthalein solution was sprayed onto the fresh surface to identify the carbonation depth. The average depth of the carbonation was determined using digital photography of the identified surface.

Results and Discussion

Characteristics of OPC and POA

The surface areas as measured by the Blaine fineness of OPC, MPOA, and FPOA are 3600, 7500, and 11,800 cm^2/g, respectively (Table 2). The specific gravity of the OPC, CPOA, MPOA, and FPOA were 3.14, 1.95, 2.15, and 2.25, respectively. The chemical characteristics of Portland cement and palm oil fuel ash are given in Table 3.

Table 2. Physical properties of OPC, CPOA, MPOA, and FPOA

Sample	Median particle size (μm)	Retained on a sieve No. 325 (%)	Specific gravity	Blaine fineness ($cm^2 \cdot g^{-1}$)
OPC	15.0	N/A	3.14	3600
CPOA	55.0	70	1.95	–
MPOA	20.0	15	2.15	7500
FPOA	7.2	3	2.25	11,800

Table 3. Chemical composition of OPC, CPOA, MPOA, and FPOA

Oxides (%)	OPC	CPOA	MPOA	FPOA
SiO_2	20.9	64.5	62.8	63.6
Al_2O_3	4.8	1.6	1.7	1.4
Fe_2O_3	3.4	1.6	1.8	1.5
CaO	65.4	7.8	7.7	7.6
MgO	1.3	3.7	3.6	3.9
Na_2O	0.2	0.2	0.1	0.1
K_2O	0.4	6.6	6.5	6.9
SO_3	2.7	0.1	0.3	0.2
LOI	1.0	9.4	9.7	9.6
$SiO_2 + Al_2O_3 + Fe_2O_3$	–	67.7	66.3	66.5

On the average, palm oil fuel ash consisted mainly of 63.5% silica (SiO_2), 7.7% CaO and 9.5% loss of ignition (LOI). The high silica content indicated that a relatively good natural pozzolan had been used. The LOI is an indicator of the burning condition. The LOI of 9.5% suggested that the palm oil fuel ash was reasonably well burnt. The particle size distributions shown in Figure 1 revealed that the particle size distribution of MPOA was similar to that of OPC. The mean particle sizes of the material used from the finest to the coarsest were as follows: FPOA = 7 μm, OPC = 15 μm, MPOA = 22 μm, and CPOA = 55 μm. The SEM photos shown in Figure 2 showed that palm oil fuel ash consisted of irregular-shaped particles with a sizable fraction showing porous cellular structure. After grinding, palm oil fuel ash consisted mainly of fine irregular-shaped particles. The XRD pattern of palm oil fuel ash shown in Figure 3 confirmed that it contained mainly amorphous silica, which was more reactive than the crystalline silica.

SP Requirement

The results of the SP requirements of mortar mixtures to produce similar flow are shown in Table 1. The SP requirement of mortar containing palm oil fuel ash as a cement replacement increased in comparison with the control OPC mortar. This was due to the high fineness and porous surface of palm oil fuel ash [6]. The SP requirement of mix with MPOA and FPOA were lower than that of

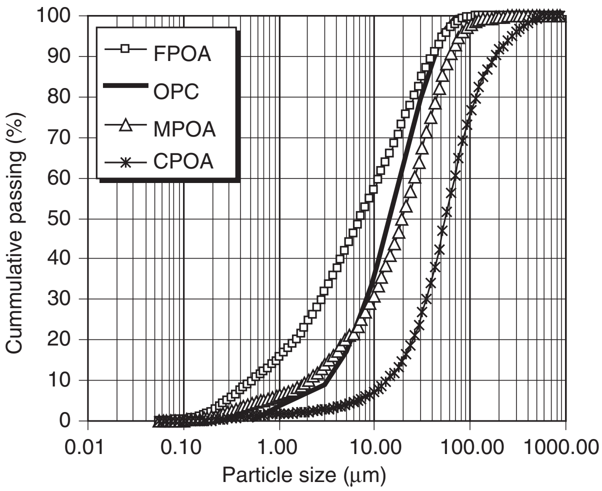

Fig. 1. Particle size distributions of OPC, CPOA, MPOA, and FPOA.

mortar containing CPOA. The increase in fineness of palm oil fuel ash decreased the SP demand of the mix as the porous cellular structure of the palm oil fuel ash surface was broken down. The requirement of the SP also increased with an increase in the replacement level of palm oil fuel ash [6,7].

Results of Compressive Strength

The results of compressive strength of mortars are given in Figure 4. The strength development of OPC mortar was rather good. The 7, 28, and 90 days strengths of OPC mortars were 43.5, 57.0, and 60.0 MPa. The compressive strengths of mortars containing CPOA and MPOA were lower than those of OPC mortars at the same age as shown in Figure 4. The compressive strength reduction was greater with an increase in dosage of palm oil fuel ash. The results also showed that the strength of mortar increased with the increases in the palm oil fuel ash fineness. The increase in compressive strength was due to the filler effect and the higher pozzolanic reaction of the FPOA [6,7].

The high compressive strength of FPOA mortar was due to the high reactivity of the fine FPOA and a decrease the SP requirement. The strength development increased with age as shown in Figure 4. The increase in strength could be attributed to the reduced SP content and the filler effect and the higher pozzolanic reaction of the FPOA. The results of SP requirements and strengths of mortars conformed to results found in other investigations [7,17,18].

Carbonation Depth

The results of the carbonation depths of the mortar specimens subjected to accelerated testing condition are shown in Figure 5. An incorporation of palm oil fuel ash in place of Portland cement increases the carbonation depth in comparison with those of normal OPC mortars. The depth of carbonation after a period of 60 days in the

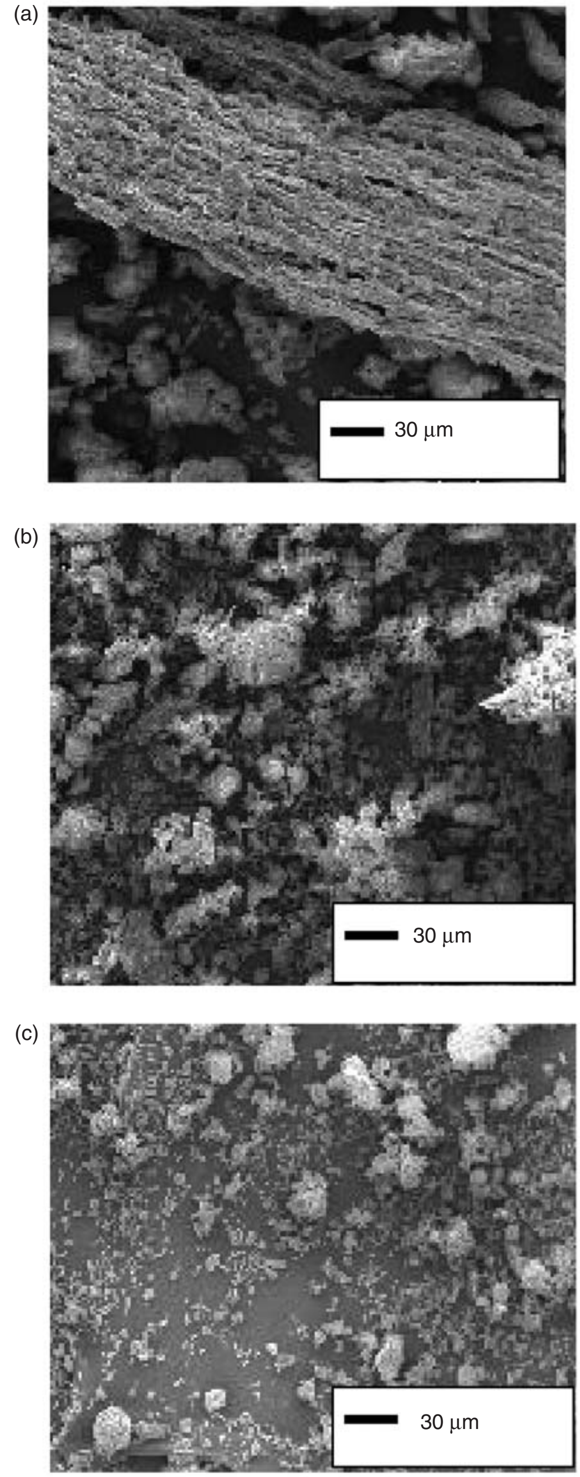

Fig. 2. SEM of palm oil fuel ash of various finenesses: (a) CPOA, (b) MPOA, and (c) FPOA.

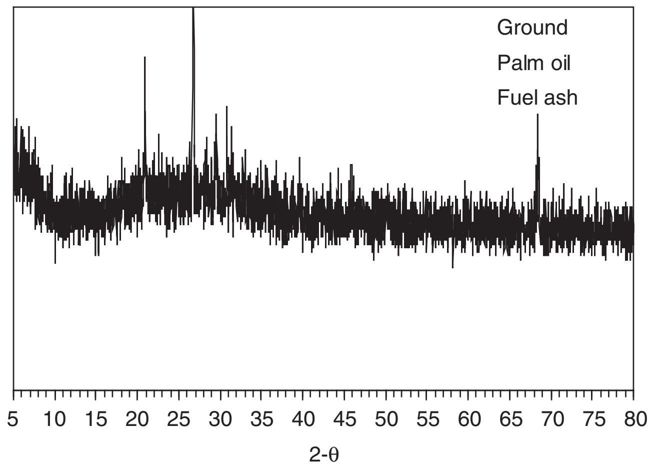

Fig. 3. XRD patterns of ground palm oil fuel ash.

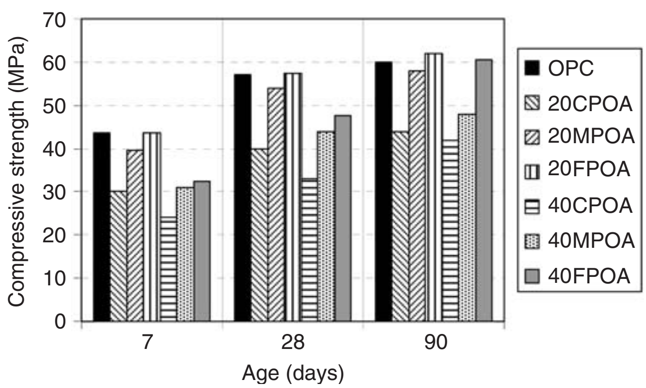

Fig. 4. Compressive strength of mortars (MPa).

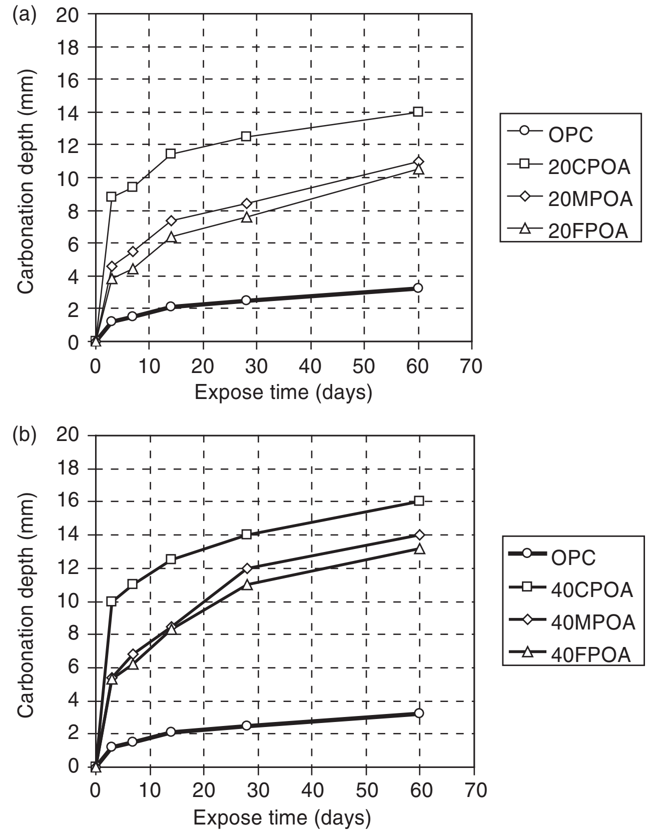

Fig. 5. Carbonation depth of mortars with: (a) 20% replacement and (b) 40% replacement.

5% CO_2 environment of 20 CPOA (mortar containing 20% CPOA as partial replacement in the cementitious material), 20 MPOA and 20 FPOA mortars were 14.0, 11.0, and 10.5 mm, respectively, while the depth of carbonation at the same age of OPC mortar was only 3.2 mm. The depth of carbonation after a period of 60 days in the 5% carbon dioxide chamber of 40 CPOA, 40 MPOA, and 40 FPOA mortars were 16.0, 14.0, and 13.2 mm. Similar findings on the increase in the carbonation depth owing to an incorporation of pozzolans have been reported [7,19,20]. The increases in carbonation were less with an increase in the fineness of palm oil fuel ash. In other words, the carbonation decreases when the FPOA was used. Furthermore, it has been shown that the average pore size of the paste of fine pozzolan is smaller than that of the coarser pozzolan and OPC mortars [7]. The reduction in the average pore size together with the reduction in the SP reduced the carbonation of the mortar. It should be noted here that the use of FPOA resulted in an increase in hydration in comparison with the use of the coarser CPOA and MPOA. The increase in hydration resulted in an increase in the consumption of calcium hydroxide in the matrix and thus could lead to an increase in carbonation of mortar [19]. However, the increase in the hydration together with the packing effect produced denser and stronger matrix and so lowered the carbonation. The carbonation depth of the CPOA mortar is clearly higher than in the MPOA and FPOA mortars. This suggested that the carbonation of the mortar was clearly affected by the palm oil fuel ash fineness. The use of FPOA resulted in a lower carbonation in comparison to the CPOA and MPOA owing to the better dispersion and filler effect of the FPOA despite the higher pozzolanic activity. This made the mortar denser and, hence better able to resist the ingression of carbon dioxide.

Conclusions

There is a serious concern for carbonation of the concrete products using palm oil fuel ash to partially replace OPC in mortar. The study indicated that the use of fine palm oil fuel ash resulted in lower carbonation depth than the use of coarser palm oil fuel ash. The fine FPOA reduced the amount of SP requirement and improved the strength of mortar as compared to the coarser CPOA and MPOA. Partial replacement of OPC with palm oil fuel ash increased the carbonation of mortar as a result of a decrease in the $Ca(OH)_2$ content of the hydration products of the cement. The use of FPOA results in a relatively low carbonation in comparison with the use of CPOA and MPOA owing to the better dispersion and filler effect despite an increase in the pozzolanic reaction. FPOA can be used as a good pozzolan to replace part of Portland cement in making mortar with relatively high strength and low carbonation depth. The hydration reaction and pozzolanic activity were enhanced by the incorporation of FPOA. Therefore, palm oil fuel ash has a high potential to be developed to be a good pozzolanic material. These results should encourage the use of palm oil fuel ash as a pozzolanic material for cement replacement in mortar and concrete for indoor use. This will reduce the cost of the concrete, have a positive effect on environmental problems, and reduce the landfill areas required for the disposal of waste ash.

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