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Strength, drying shrinkage, and water permeability of concrete incorporating ground palm oil fuel ash

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ABSTRACT

In this study, palm oil fuel ash (POFA) was used as a pozzolanic material in concrete. The POFA was ground to obtain two different finenesses: coarse (CP) and fine (FP). A portion of ordinary type I Portland cement (OPC) was replaced by CP and FP at 10%, 20%, and 30% by weight of binder to cast concrete. Compressive strength, modulus of elasticity, drying shrinkage, and water permeability of concretes containing ground POFA were measured. The results showed that the compressive strength of the concrete increased with the fineness of the POFA. With 10% and 30% replacement of OPC by CP and FP, respectively, the compressive strength of the resulting concrete was as high as that of OPC concrete at 90 days. Moreover, the use of 10–30% of FP as a cement replacement in concrete reduced its drying shrinkage and water permeability. Finally, there was also a strong correlation between the compressive strength and the water permeability of ground POFA concrete.

1. Introduction

Palm oil fuel ash (POFA) is a by-product from biomass thermal power plants where oil palm residues are burned to generate electricity. In Thailand, it had been estimated that 2.1 million tons of biomass was used as fuel in 2001, producing about 100,000 tons (5%) of biomass ash [1]. Since palm oil is one of the major raw materials used to produce bio-diesel, it is likely that the production of POFA will increase every year. Very little of the POFA produced is actually used. While some of it serves as low-value material for backfill or fertilizers, most of the POFA is disposed as waste in landfills, causing environmental and other problems.

The durability of concrete is one of its most important properties, aside from its compressive strength, because distresses in concrete are mostly due to durability failures rather than insufficient strength. Permeability is considered to be one of the most important properties affecting concrete durability because many concrete degradation mechanisms are a function of the rate of water or solution flow through the concrete [2].

Drying shrinkage, one of the main causes of cracks that directly affect the strength and durability of concrete, usually occurs in hot and dry environments due to the loss of internal water in the concrete to the environment. This results in the reduction of concrete volume and leads to crack formation in hardened concrete. Furthermore, most of this drying shrinkage cannot be regained by rewetting the concrete.

Partial replacement of Portland cement by pozzolanic materials such as fly ash and silica fume increases not only the ultimate strength of the concrete but also significantly improves its durability [3–5]. This is due to the pozzolanic reaction that leads to the refinement of pore structures and results in a highly impermeable and denser concrete, thus increasing its compressive strength and durability [6,7]. Previous researches have shown that POFA has a high SiO_2 content, and it has recently been accepted as a pozzolanic material [8–10]. Even so, the durability properties (i.e., water permeability and drying shrinkage) of concrete containing POFA have not been thoroughly investigated.

In this study, POFA was used as a partial cement replacement in concrete. The influence of POFA and its degree of fineness on the compressive strength, modulus of elasticity, drying shrinkage, and water permeability of concrete was investigated. If POFA can improve the compressive strength, and reduce the drying shrinkage and water permeability of concrete, it can be used as a pozzolanic material for concrete production, leading to reduced cement usage and reduced cost while also helping the environment. Moreover, the use of POFA as a cement replacement will also encourage further research into the use of other by-product materials from biomass power plants, leading to ways of solving energy problems and reducing agro-waste ash that would otherwise be discarded.

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2. Experiments

2.1. Materials

2.1.1. Cement

Tables 1 and 2 show the physical and chemical properties, respectively, of the ordinary type I Portland cement (OPC) used in this study.

2.1.2. Aggregate

Local river sand with a fineness modulus of 2.68 was used as a fine aggregate. Crushed limestone was used as a coarse aggregate with maximum size of 20 mm. The fine and coarse aggregates had specific gravities of 2.60 and 2.71, and water absorptions of 0.63% and 0.47%, respectively.

2.1.3. Palm oil fuel ash (POFA)

The POFA used in this study was collected from the palm oil industry in the south of Thailand. The POFA received directly from the power plant had a low pozzolanic reaction due to its large particle size [1,9], thus the POFA was ground with a ball-mill into two different finenesses to improve its reactivity, one that was higher fineness than that of the OPC and the other one that was lower fineness. The designations CP and FP were used to identify the ground POFA as coarse and fine, respectively.

The physical properties of the ground POFA are shown in Table 1. Fig. 1 shows the particle size distribution of OPC and all ground POFA. It was found that CP had specific gravity of 2.17 with the median particle size (d_{50}) of 19.9 μm. The specific gravity and median particle size of FP were 2.33 and 10.1 μm, respectively. The percentage of particles retained on a 45-μm (No. 325) sieve of CP and FP were 17.1 and 1.5% by weight, respectively. The grinding process increased not only the fineness of POFA, but also its specific gravity. This is because the porous particles, which usually have low specific gravity values, are crushed into smaller particles with lower porosity [11,12].

The strength activity index of ground POFA was higher than the minimum value specified by ASTM C618 (75%) [13] and were 90%, 89% and 90%, 95% at 7 and 28 days for CP and FP, respectively. It should be noted that the strength activity index, which was an indirect method for measurement of pozzolanic activity, was used in this study to evaluate the pozzolanic property of ground POFA. However, Donatello et al. [14] reported that the Frattini test, a direct method used to measure the pozzolanic activity, has a good significant correlation with the strength activity index test.

The chemical composition of the ground POFA is shown in Table 2. The major chemical composition of ground POFA (FP) is 65.3% of SiO_2 and the total amount of SiO_2, Al_2O_3, and Fe_2O_3 is 69.7%. The LOI and SO_3 are within the limit of 10.0% and 4.0%, respectively. Awal and Hussin [15] found that the sum of SiO_2, Al_2O_3, and Fe_2O_3 was 59.7% and LOI and SO_3 were 18.0% and 2.8%, respectively. The difference in chemical composition of POFA was due to the burning condition and the source of materials. Although POFA is not a natural pozzolan, according its chemical composition it may be classified as Class N (natural) pozzolan according to ASTM C618 [13].

Table 1
Physical properties of type I Portland cement (OPC) and ground POFA (CP and FP).

Physical properties	OPC	CP	FP
Specific gravity	3.14	2.17	2.33
Retained on a 45 μm sieve (No. 325) (%)	N/A	17.1	1.5
Median particle size, d_{50} (μm)	14.6	19.9	10.1
Strength activity index (%)			
At 7 days	–	90	89
At 28 days	–	90	95

Table 2
Chemical composition of materials (%).

Component	OPC	POFA (FP)
Silicon dioxide (SiO_2)	20.9	65.3
Aluminium oxide (Al_2O_3)	4.7	2.5
Iron oxide (Fe_2O_3)	3.4	1.9
Calcium oxide (CaO)	65.4	6.4
Magnesium oxide (MgO)	1.2	3.0
Sodium oxide (Na_2O)	0.2	0.3
Potassium oxide (K_2O)	0.3	5.7
Sulfur trioxide (SO_3)	2.7	0.4
Loss on ignition (LOI)	0.9	10.0
$SiO_2 + Al_2O_3 + Fe_2O_3$	–	69.7

2.2. Mix proportion and test specimens

The ground POFA was used to replace a portion of the OPC at 10%, 20%, and 30% by weight of binder. Table 3 summarizes the mixture proportions of the OPC concrete and concretes containing ground POFA. The compressive strength of the OPC concrete was designed to be about 30 MPa at 28 days with slump of fresh concrete in the range of 50–100 mm. The ratio of fine to coarse aggregate was maintained at 45:55 by volume. The water to binder (cement plus ground POFA) ratio of the concrete was adjusted by varying the amount of water to maintain the slump of the fresh concrete at the same value as that of the OPC concrete (50–100 mm).

Concrete cylinders 100 mm in diameter and 200 mm in height were cast. The concrete samples were removed from the molds 24 h after casting and cured in tap water. They were tested to determine the compressive strengths at 7, 28, 90, and 180 days. The modulus of elasticity values of concretes containing ground POFA were tested at 28 days.

Prismatic concrete specimens with a cross-section of 75×75 mm^2 and a length of 285 mm were used to determine the drying shrinkage. Each specimen was fitted with a stainless steel stud at both ends. The specimens were removed from the molds 24 h after casting and cured in water for another 48 h. At the age of 3 days, the specimens were removed from the water, wiped with a damp cloth, and immediately measured; this was considered the initial length of the concrete specimens. Then the specimens were placed in an air storage cabinet with a controlled temperature of 23 ± 2 °C and a relative humidity of 50 ± 5%, as specified by ASTM C 596 [16]. The drying shrinkage of all specimens was monitored for up to 6 months.

The first step in the water permeability test was to saw a 40-mm-thick slice from the middle of the 100×200-mm concrete cylinder. The circumference of the concrete slice was covered with 25 mm of epoxy resin that was allowed to harden for 24 h. The specimen was placed in a permeability housing cell, as shown in Fig. 2, and water pressure of 0.5 MPa (5.0 bar) was applied to the cell. This pressure was recommended and used by Chan and Wu [17] and Chindaprasirt et al. [18] in their research. The amount of water flowing through the concrete specimen was measured by reading the reduction of the water level in a manometer tube. The result was plotted as a graph of the cumulative amount of water flowing as a function of the cumulative time to determine the steady-state flow. The steady flow rate was used to determine the coefficient of permeability using Darcy's law and the equation of continuity [7],

$$K = \frac{\rho L g Q}{PA} \tag{1}$$

where K is the coefficient of water permeability (m/s), ρ is density of water (kg/m^3), g is acceleration due to gravity, 9.81 (m/s^2), Q is