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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

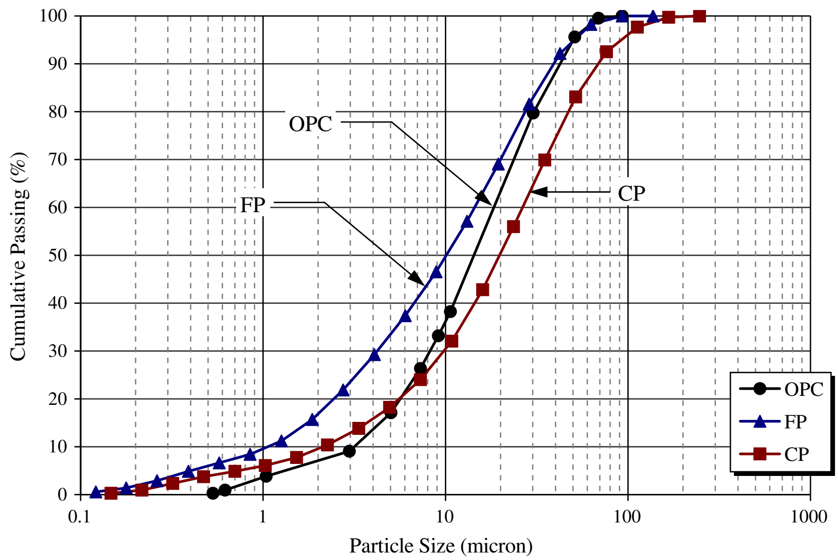

Fig. 1. Particle size distributions of the materials.

Table 3
Concrete mixture proportions.

Mixes	Mix proportion (kg/m^3)					W/B	Slump (mm)
	Cement	POFA	Sand	C. agg.	Water		
OPC	300	–	809	1031	210	0.70	65
CP10	270	30	804	1024	216	0.72	80
CP20	240	60	799	1018	219	0.73	75
CP30	210	90	794	1012	219	0.73	70
FP10	270	30	805	1026	204	0.68	55
FP20	240	60	801	1021	210	0.70	60
FP30	210	90	798	1016	213	0.71	60

flow rate (m^3/s), L is thickness of the concrete sample (m), P is water pressure (Pa), and A is the cross-sectional area of the concrete sample (m^2).

3. Results and discussion

3.1. Compressive strength

The relationships between the compressive strengths and the curing age of CP concretes are shown in Fig. 3a. The compressive strengths of CP concretes at an early-age were lower than that of OPC concrete, particularly for high cement replacement levels. At 7 days, the compressive strengths of CP10, CP20, and CP30 concretes were 22.9, 19.5, and 17.5 MPa, while that of OPC concrete was 24.0 MPa. The low compressive strength of the early-age concretes containing CP was due to the low cement content, resulting in a low C_3S content. At a later age, CP10 concrete had a higher compressive strength than OPC concrete, even though CP10 concrete had higher water to binder (W/B) ratio and the median

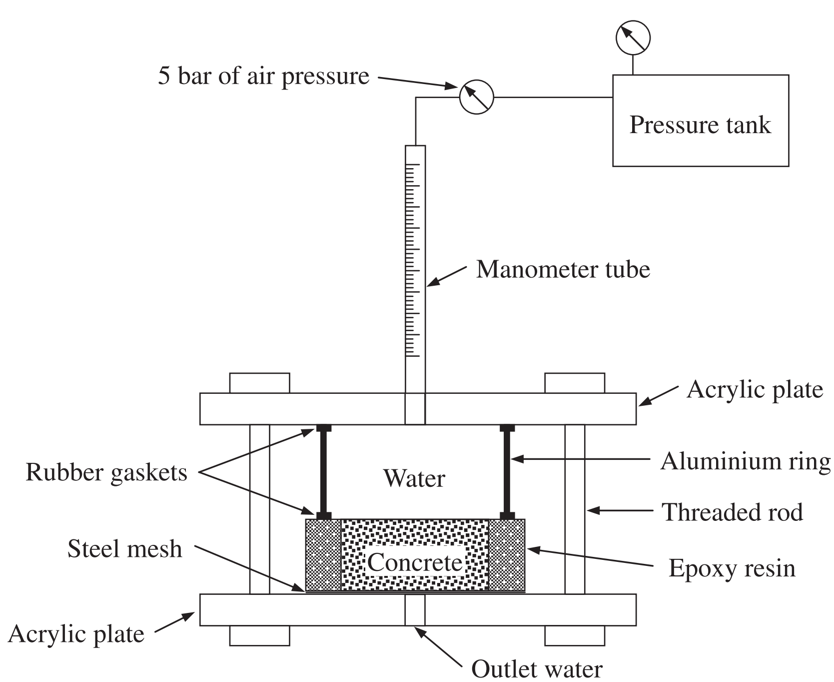

Fig. 2. Experimental setup for testing the water permeability of concrete.

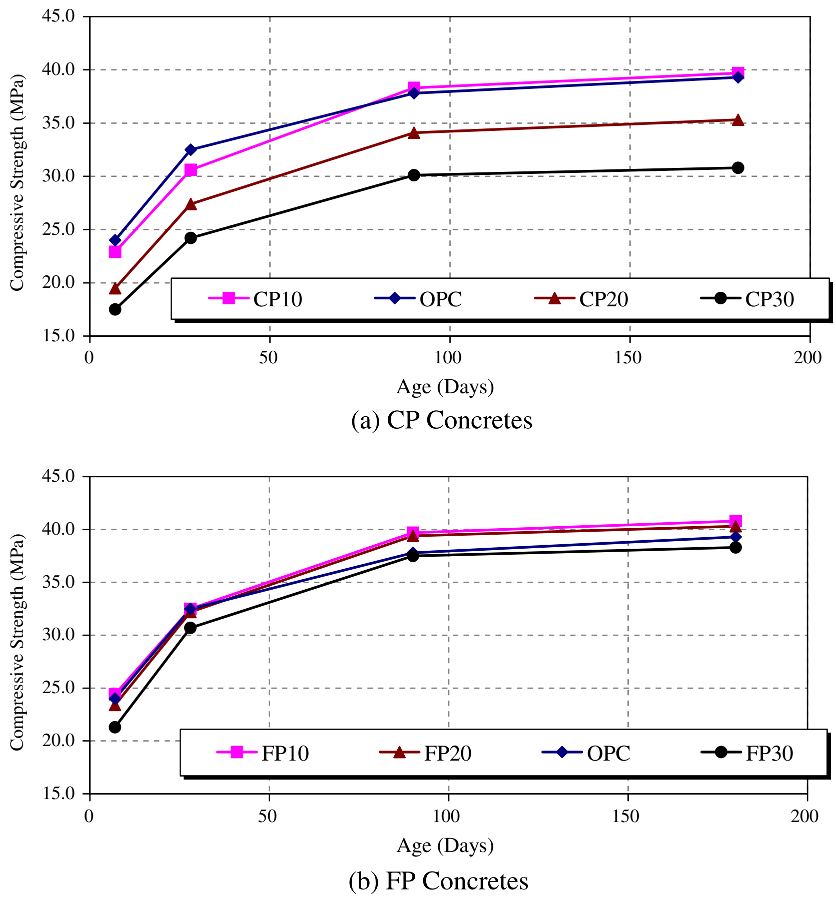

Fig. 3. Compressive strength of concrete.

particle size of CP (19.9 μm) was larger than that of OPC (14.6 μm). The compressive strengths of CP10 concrete at 90 and 180 days were 38.3 and 39.7 MPa, respectively, or about 101% of the OPC concrete value. This result is different than that obtained by Tay [19], who found that POFA had low pozzolanic properties and should not be used as a cement substitute in any quantity higher than 10% by weight of binder. The low pozzolanic property of palm oil fuel ash in Tay's work is due to the large particles (the weight mean diameter of the ash was more than twice the diameter of the cement) that resulted in a very low rate of pozzolanic reaction.

Our results indicate that CP can contribute compressive strength via the pozzolanic reaction. The concrete with 20% CP had a compressive strength of 27.4 MPa, or 84% that of OPC concrete at 28 days, and increased to 34.1 MPa, or 90% that of OPC concrete at 90 days. CP30 concrete had a rather low compressive strength of 17.5 MPa at 7 days, 73% that of OPC concrete. However, it gained strength up to 30.1 MPa or 80% that of OPC concrete at 90 days. Moreover, the compressive strengths of concretes containing CP decreased when the percentage of CP was increased. This is due to the porosity of CP, which can cause the W/B ratio of the concrete to become higher than that of OPC concrete when the slump of fresh concrete is maintained in the same range, and thus results in a low compressive strength [20,21].

Fig. 3b shows the compressive strength of FP concrete. Concretes with 10% and 20% of the cement replaced by FP had compressive strengths as high as that of OPC concrete at 7 days. The compressive strengths of FP10 and FP20 concretes at 7 days were 24.4 and 23.4 MPa (102% and 98% that of OPC concrete), respectively. In addition, the compressive strength of FP30 concrete at 90 days was as high (about 99%) as that of OPC concrete (37.5 MPa). These results suggested that the higher fineness of POFA (FP) resulted in a greater pozzolanic reaction. This behavior is the same as that obtained using other pozzolanic materials, such as fly ash where a high fineness is very important in achieving high reactivity [22]. In addition, smaller particles fill in the voids in the concrete mixture, and thus contribute to an increased compressive strength [23,24].

The results of these compressive strength tests suggest that ground POFA is a pozzolanic material with high potential for use as a partial replacement of cement in concrete when it is ground very finely. This result confirms previous researches [1,9]. The optimum replacements of CP and FP were 20% and 30% by weight of binder, respectively, for which the compressive strengths of concretes containing CP and FP were more than 90% of OPC concrete after 90 days.

3.2. Modulus of elasticity

The modulus of elasticity was determined using the 100 × 200-mm concrete cylinders. The results are shown in Fig. 4. The modulus of elasticity values of ground POFA concretes at 28 days were in the range of 25.0–28.0 GPa, while that of OPC concrete was 27.5 GPa. The results showed that the use of ground POFA (either CP or FP) in concrete did not affect its modulus of elasticity compared to OPC concrete. Similar results were found in the concrete containing fly ash or silica fume [25,26]. This was due to the modulus of elasticity of concrete was usually related to the strength of aggregates rather than the strength of paste [27].

Fig. 4 shows the relationship between the modulus of elasticity and the square root of the compressive strength, and compares this

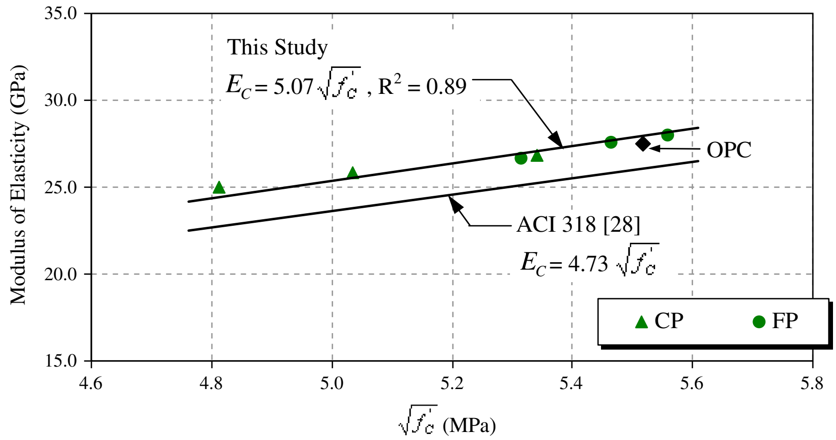

Fig. 4. Relationship between modulus of elasticity and compressive strength of concrete.

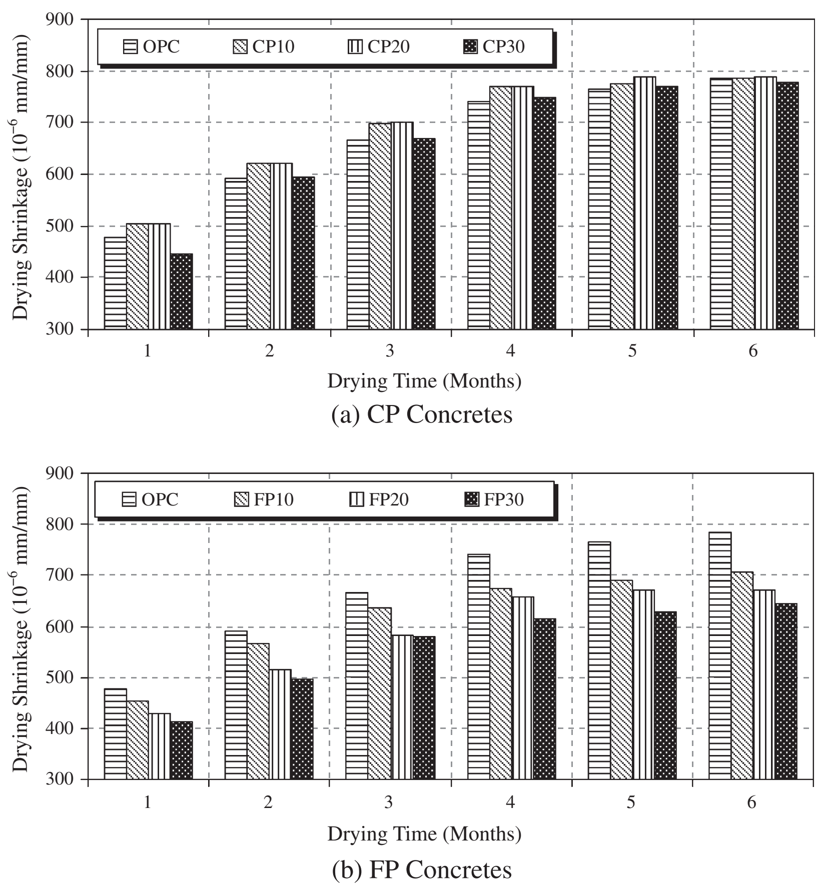

Fig. 5. Drying shrinkage of concrete.

to the values suggested by ACI 318 [28]. The equation suggested by ACI 318 was obtained from data on light-weight and normal-weight concretes with compressive strengths between 21 and 83 MPa, which cover the compressive strengths measured in this study (24.2–30.9 MPa). The modulus of elasticity of concrete incorporating ground POFA can be predicted using

$$E_C = 5.07\sqrt{f_C'} \tag{2}$$

where E_C and $\sqrt{f_C'}$ are expressed in GPa and MPa, respectively.

The modulus of elasticity of concrete obtained in this study was about 7% higher than that predicted by ACI 318 [28]. This may cause from two reasons, the differences in size of testing specimens and type or source of coarse aggregate [27].

3.3. Drying shrinkage

The drying shrinkage of CP concrete is shown in Fig. 5a. The drying shrinkage of all concrete specimens increased very quickly during the first 3 months, but only slightly after that. The drying

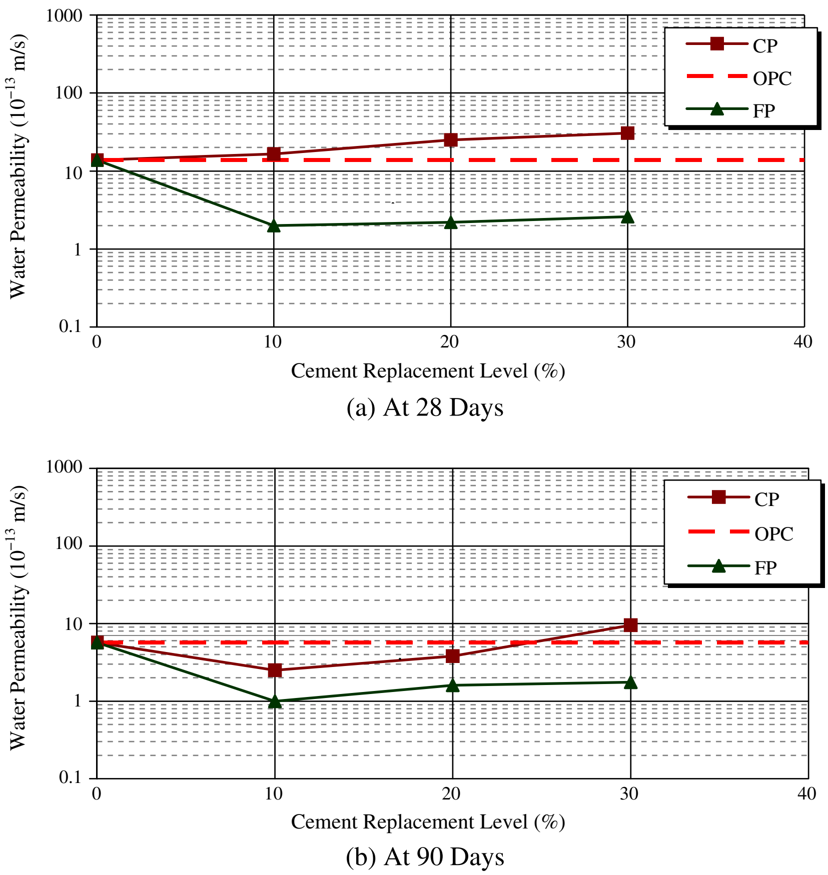

Fig. 6. Relationship between water permeability of concrete and cement replacement level.

shrinkage values at 6 months of CP concretes were varied between 778×10^{-6} and 787×10^{-6} mm/mm, while the value for OPC concrete was 785×10^{-6} mm/mm. Therefore, for this long-term period, CP concretes exhibited drying shrinkage values that were the same as that of OPC concrete. This result suggests that the use of CP to replace Portland cement by up to 30% by weight of binder cannot reduce the drying shrinkage of concrete.

The drying shrinkage values of FP concretes are shown in Fig. 5b. It is clear that the use of 10–30% FP as a cement replacement can reduce the drying shrinkage of concrete, and the cement replacement rate of 30% seems to be the most effective. At 6 months, FP10, FP20, and FP30 concretes had drying shrinkage values of 707×10^{-6}, 670×10^{-6}, and 645×10^{-6} mm/mm, respectively. Therefore, FP concrete had lower drying shrinkage than OPC concrete. FP exhibited a good pozzolanic reaction and a high packing effect [24]. These effects assisted in transforming large pores into fine pores. This pore refinement reduced the loss of water, and thus reduced the drying shrinkage of concretes containing FP. This behavior is similar to that of pozzolanic materials such as fly ash or silica fume that can be used to reduce drying shrinkage of mortar and concrete [18,29,30].

3.4. Water permeability

The values of water permeability of concretes containing ground POFA at 28 and 90 days are shown in Figs. 6a and b for CP and FP concretes, respectively. OPC concrete had water permeability values at 28 and 90 days of 13.8×10^{-13} and 5.7×10^{-13} m/s, respectively. The values of water permeability of CP10 concrete at 28 and 90 days were 16.5×10^{-13} and 2.5×10^{-13} m/s while those of CP20 concrete were 25.0×10^{-13} and 3.8×10^{-13} m/s, respectively. Therefore, at 28 days, CP10 and CP20 concretes had higher values of water permeability than OPC concrete, but much lower values by 90 days. This means that CP10 and CP20 concretes were better at reducing water permeation than OPC concrete. CP30 concrete had higher water permeability than OPC concrete at both testing ages. At 28 days, the water permeability of CP30 concrete was 30.6×10^{-13} m/s, and this declined to 9.5×10^{-13} m/s by 90 days. This indicates that the use of CP up to 30% will not produce more impervious concrete. The high values of water permeability of CP30 concrete because the mixture requires more mixing water to maintain the slump of fresh concrete in the same range (CP30 concrete had a W/B ratio of 0.73 while OPC concrete had a W/B ratio of 0.70). Furthermore, the high replacement percentage of Portland cement produced concrete with low compressive strength (CP30 concrete had compressive strengths at 28 and 90 days of 74% and 80% that of OPC concrete, respectively), and had many voids that resulted in high water permeability values.

The water permeability values of FP concretes were lower than those of CP concretes and OPC concrete at both testing ages. At 28 days, the values of water permeability of FP10, FP20, and FP30 concretes were 2.8×10^{-13}, 4.4×10^{-13}, and 6.2×10^{-13} m/s, respectively, and this declined to 1.2×10^{-13}, 1.5×10^{-13}, and 1.8×10^{-13} m/s at 90 days. This result showed that the higher fineness of ground POFA resulted in lower water permeability values. The low water permeability of concrete containing FP was affected by the pozzolanic reaction and packing effect of small particles, which produced concrete with a denser matrix and low permeation [22]. Similar results have also been reported when fly ash or silica fume has been used to replace Portland cement; that concrete had increased resistance to chloride ions and low permeability [31,32].

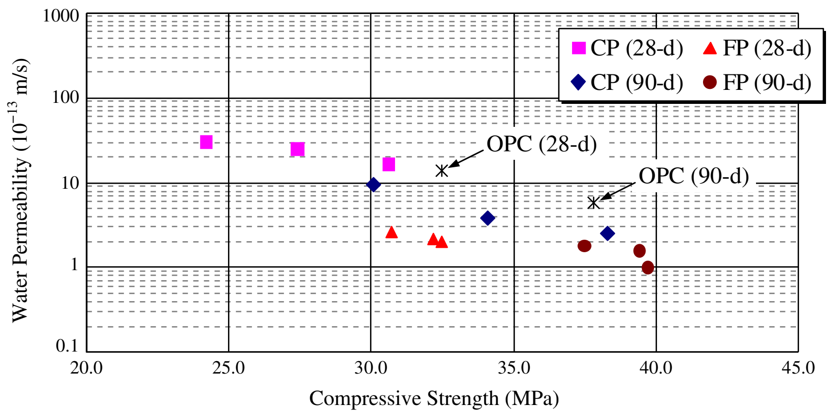

Fig. 7. Relationship between compressive strength and water permeability of concrete.

The relationship between the compressive strength and water permeability of concrete at 28 and 90 days is illustrated in Fig. 7. As Fig. 6 clearly indicates, the values of water permeability of OPC concrete and ground POFA concretes decreased as the compressive strength increased. On the other hand, the higher compressive strength of concrete significantly reduced the water permeability value. For the same compressive strength, ground POFA concretes had lower water permeability than OPC concrete. For example, FP30 concrete had a compressive strength of 37.5 MPa and a water permeability of 1.8×10^{-13} m/s at 90 days, while OPC concrete had a compressive strength of 37.8 MPa and a water permeability of 5.7×10^{-13} m/s at the same age. Moreover, CP30 concrete had a lower compressive strength and higher W/B ratio than OPC concrete, while the water permeability was lower than OPC concrete. This behavior could be explained from two causes; (1) ground POFA had a pozzolanic reaction that led to denser concrete and (2) the specific gravity of ground POFA was much lower than that of OPC, so ground POFA concrete had more volume of paste and less aggregate than OPC concrete, which resulted in lower water permeability.

4. Conclusions

The following conclusions can be drawn based on the experimental results of this study.

1. POFA is a reactive pozzolanic material with high potential for use as a partial replacement for cement in concrete. The compressive strength of concrete containing ground POFA depended on the fineness of the POFA and the amount of cement replacement. The optimum replacements of CP and FP (particles retained on a 45-μm (No. 325) sieve of 17.1% and 1.5% by weight, respectively) in concrete were 20% and 30% by weight of binder, respectively, which produced compressive strengths higher than 80%, 84%, and 90% that of OPC concrete after 7, 28, and 90 days, respectively.
2. The use of CP and FP did not change the modulus of elasticity of concrete. The modulus of elasticity of ground POFA concrete increased with the increase of compressive strength and was about 7% higher than that predicted by ACI 318 [28].
3. Concrete incorporating CP did not have a reduced drying shrinkage because it had a higher water to binder ratio than OPC concrete. However, concretes containing 10–30% of FP exhibited 10–17% lower drying shrinkage than OPC concrete.
4. The use of 10–30% of CP and FP as a cement replacement in concrete exhibited a good result in water permeability, depending on the cement replacement level and the concrete age. The water permeability of ground POFA concrete decreased as the compressive strength increased. In addition, there was a good correlation between the compressive strength and the water permeability of ground POFA concrete.

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