Taylor & Francis
Taylor & Francis Group

JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT
ISSN 1392-3730 print/ISSN 1822-3605 online
2011 Volume 17(2): 234–247
doi:10.3846/13923730.2011.574450

UTILIZATION OF PALM OIL FUEL ASH IN CONCRETE: A REVIEW

Md. Safiuddin[1], Md. Abdus Salam[2], Mohd Zamin Jumaat[3]

[1]*Department of Civil and Environmental Engineering, Faculty of Engineering, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, Canada N2L 3G1*
[2, 3]*Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*
E-mails: [1]*msafiudd@engmail.uwaterloo.ca (corresponding author);* [2]*masalam@siswa.um.edu.my;* [3]*zamin@um.edu.my*

Received 3 Mar. 2010; accepted 3 Sept. 2010

Abstract Uncontrolled dumping of palm oil fuel ash (POFA) not only occupies valuable land but also creates environmental pollution and health hazard. These problems can be reduced to a large extent by using POFA in concrete. A number of research works have been carried out to investigate the potential of POFA for use as a supplementary cementing material in normal, high strength, high performance, and aerated concretes. This paper presents a review on the use of POFA in different types of concrete. It firstly discusses the physical and chemical properties of POFA. Then the emphasis has been given on the effects of POFA on the fresh and hardened properties, and durability of concrete. This paper shows that both ground and unground POFA increase the water demand and thus decrease the workability of concrete. However, ground POFA has shown a good potential for improving the hardened properties and durability of concrete due to its satisfactory micro-filling ability and pozzolanic activity. In addition to discussing the benefits of POFA, this study has identified certain gaps in the present state of knowledge on POFA concrete, and listed several research needs for future investigation. The findings of this study would encourage the use of POFA as a supplementary cementing material for concrete.

Keywords: concrete, fineness, micro-filling ability, palm oil fuel ash, strength activity index, supplementary cementing material.

1. Introduction

Palm oil fuel ash (POFA) is a by-product of palm oil industry. It is generated from the combustion of palm oil plant residues. The Elaeis Guineensis tree, commonly known as palm tree, was first introduced in Malaysia as an ornamental plant in 1970. It is now a leading agricultural cash crop in Malaysia and other tropical countries, such as Indonesia and Thailand. The palm oil industry has expanded rapidly in Malaysia since 1980 (Tay 1990). At present, there are more than three million hectares of palm oil plantation in Malaysia (Lim 2000). In total, about 90 million metric tons of trunks, shells, husks, palm press fibers, and empty fruit bunches are produced every year. After the extraction of the oil from the fresh palm fruit, both husk and shell are burnt as boiler fuel in palm oil mill at a temperature of 800–1000°C to produce steam, which is used in turbine for supplying electrical energy to the whole mill for milling operation and domestic or estate use (Abdullah *et al.* 2006; Tangchirapat *et al.* 2009). The burning process results in an ash, which is referred to as POFA. After combustion in the steam boiler, about 5% POFA by weight of solid wastes is produced (Sata *et al.* 2004). This POFA causes a nuisance to the environment. Since the tropical countries are continuously increasing the production of palm oil, the quantity of POFA is also increasing and thus creating a large environmental load (Abdullah *et al.* 2006). In Malaysia, an investigation was carried out to examine the potential of POFA to be used as a fertilizer for the agricultural purpose so that the environmental load can be minimized (Yin *et al.* 2008). However, due to the absence of sufficient nutrients required for a fertilizer, POFA is mostly dumped in open field near palm oil mills without any profitable return, thus causing environmental pollution and health hazard (Sumadi and Hussin 1995; Tonnayopas *et al.* 2006). In order to resolve these problems, several studies were conducted to examine the feasibility of using POFA in concrete. It has been found that the properly processed POFA can be used successfully as a supplementary cementing material for the production of concrete.

The use of POFA in Malaysia as a supplementary cementing material for concrete first started in 1990 (Tay 1990). Tay (1990) used unground POFA to partially replace ordinary portland cement (OPC) and showed that it had a low pozzolanic property, and therefore recommended that POFA should not be used with a content higher than 10% of cement by weight. Later many researchers showed that ground POFA can be successfully used as a supplementary cementing material in concrete due to its good pozzolanic property (Chindaprasirt *et al.* 2007; Hussin and Awal 1997; Sukantapree *et al*. 2002; Tangchirapat *et al.* 2003). Tonnayopas *et al.* (2006) used

5–30% ground POFA by weight of OPC and found that the incorporation of POFA in concrete decreased the strength at early ages (3 to 21 days) but the strength achieved at and after 28 days for the concretes with 5–15% POFA met the ASTM C618 requirement (ASTM C618-08a 2008). Chindaprasirt *et al.* (2007) used ground POFA in concrete and found that POFA has a good potential for concrete production. They observed that the partial replacement of OPC by ground POFA resulted in a higher water demand for a given workability of concrete. Moreover, they observed that the compressive strength of concrete with 20% ground POFA was as high as OPC concrete. The strength decreased when the POFA content became higher than 20%. A POFA content higher than 20% also increased the permeability of concrete. Hence, the optimum POFA content found by Chindaprasirt *et al.* (2007) was 20%. In addition, Hussin and Ishida (1999) used 20–40% ground POFA by weight of OPC in concrete. They determined the compressive strength, modulus of elasticity, Poisson's ratio, shrinkage and creep of concrete, and found that, up to 30% POFA content, the aforementioned properties of hardened concrete are comparable to those of OPC concrete. Hussin and Awal (1996, 1997) also studied the strength properties of concrete containing ground POFA at various cement replacement levels of 10–60% by weight. They have shown that it is possible to use 40% POFA in concrete without affecting the strength; however, the maximum strength gain occurs when the POFA content is 30%. Not only good strength, the POFA concrete has also shown satisfactory durability. Many laboratory investigations showed that POFA can be used in producing strong and durable concrete due to its adequate pozzolanic property (Awal and Hussin 1997a, 1999; Hussin and Awal 1996). According to Sumadi and Hussin (1995), POFA can be used up to 20% cement replacement level without any adverse effect on the strength characteristics and with a durability factor at least comparable to that of OPC concrete. POFA has also shown a good potential in suppressing the expansion due to sulfate attack (Awal and Hussin 1997b; Jaturapitakkul *et al.* 2007) and alkali-silica reaction (Awal and Hussin 1997a).

POFA has been used not only in normal concrete but also in special concretes such as high strength, high performance, and aerated concretes. Several researchers reported that the ground POFA can be used to produce high strength and high performance concretes (Awal and Hussin 1999; Sata *et al.* 2004, 2007; Tangchirapat *et al.* 2009). Ground POFA provides much higher compressive strength than unground POFA due to significant differences in particle size and fineness. The ground POFA with high fineness is a reactive pozzolanic material and therefore can be used in making high strength and high performance concretes (Awal and Hussin 1999; Sata *et al.* 2004). Sata *et al.* (2004) made high strength concrete with POFA replacing 10–30% cement by weight and showed that the concrete containing up to 30% ground POFA provides a higher compressive strength than OPC concrete at 28 days. However, 20% POFA produced the optimum strength in concrete. Awal and Hussin (1999) used POFA to produce high performance concrete with reasonably a good durability. In addition, Abdullah *et al.* (2006) used 10–50% ground POFA in aerated concrete and found that the increased POFA content decreases the compressive strength of aerated concrete. However, they observed that the replacement of cement by 10–40% ground POFA exhibits a significant improvement in the compressive strength of aerated concrete from 7 days to 28 days. Hussin and Abdullah (2009) also used ground POFA in aerated concrete. They observed that the aerated concrete can produce a similar strength like OPC concrete at 30% POFA content, but provides the maximum strength at the cement replacement level of 20%. Thus the published literature shows that POFA has a good potential for the production of different types of concrete. However, the use of POFA in self-consolidating normal strength, high strength and high performance concretes is very limited.

The present paper reviews the potential use of POFA as a supplementary cementing material for concrete. It firstly discusses the physical and chemical properties of POFA. However, this paper emphasizes the effects of POFA on the fresh and hardened properties, and durability of concrete. Above all, the existing gaps in the current state of knowledge on POFA concrete were sought to identify the future research needs.

2. Properties of POFA

2.1. Physical properties

The physical properties of POFA are greatly influenced by the burning condition, particularly burning temperature (Abdullah *et al.* 2006). A number of physical properties of unground and ground POFA used in various studies are shown in Table 1. These properties are briefly discussed below.

Table 1. Physical properties of OPC and POFA

Properties	OPC	Unground POFA	Ground POFA
Color	Grey	Light grey/whitish	Dark grey
Specific gravity	3.14–3.28	1.78–1.97	2.22–2.78
Median particle size, d_{50} (μm)	10–20	54.3–183	7.2–10.1
% Passing through 45-μm sieve (% mass)	–	5.6–58.8	97–99
Specific surface area, Blaine (m^2/kg)	314–358	796	882–1244
Strength activity index (%)	–	–	78.6–115
Soundness, Le Chatelier expansion (mm)	0.45–1	0.5–2.6	1

2.1.1. Color

Generally, unground POFA is light grey in color. This is due to the unburnt carbon content left at relatively low burning temperature. The unburnt carbon content becomes very low when the burning temperature is high. Unground POFA can be whitish in the absence of unburnt carbon (Abdullah *et al.* 2006). The color becomes dark grey in case of ground POFA.

2.1.2. Specific gravity

The specific gravity of unground POFA generally varies in the range of 1.78–1.97, which is about 40% lower than the specific gravity of OPC (Tay 1990). After the grinding process, the specific gravity of POFA increases and is found to be in the range of 2.22–2.78 (Sata *et al.* 2004; Tangchirapat *et al.* 2009). This is because the grinding process decreases the porosity with reduced particle size.

2.1.3. Particle shape and size

The particle shape and size of ground and unground POFA are different. From scanning electron microscopy, it was found that the unground POFA particles are mostly large, spherical and porous, as shown in Fig. 1(b). In contrast, the ground POFA generally consists of crushed particles with irregular and angular shape similar to that of portland cement (Chindaprasirt *et al.* 2007), as can be seen from Figs 1(a) and 1(c).

The unground POFA has larger particles than OPC. However, the ground POFA has smaller particles than OPC. The typical particle size distributions of POFA and OPC are shown in Fig. 2. The median particle size (d_{50}) of unground POFA varies in the range of 54.3–183 μm, which is larger than that of OPC (10–20 μm). After grinding, the median particle size of POFA can be reduced to 7.2–10.1 μm (Sata *et al.* 2004; Chindaprasirt *et al.* 2008).

2.1.4. Fineness

Fineness is a vital property of cement and supplementary cementing materials. The rate of hydration and pozzolanic reaction depends on the fineness of particles. For the rapid development of strength, a high fineness is necessary. The unground POFA is coarser than OPC but the ground POFA becomes finer than OPC, as evident from Table 1 and Fig. 2. The particle size of POFA can be reduced by the grinding process in ball mills (Sata *et al.* 2007; Tangchirapat *et al.* 2007; Tangchirapat *et al*. 2009). POFA may also be ground in a Los Angeles abrasion machine using mild steel bar (12 mm diameter and 800 mm long) instead of steel ball (Abdullah *et al.* 2006; Awal and Hussin 1999; Hussin and Awal 1996). The grinding process reduces not only the particle size but also the porosity of POFA (Kiattikomol *et al.* 2001). After grinding, POFA can be less porous with smaller particles (Paya *et al*. 1996).

The fineness of supplementary cementing material is generally measured with respect to the specific surface area of particles. The fineness of POFA can also be expressed with regard to the percent mass passing through

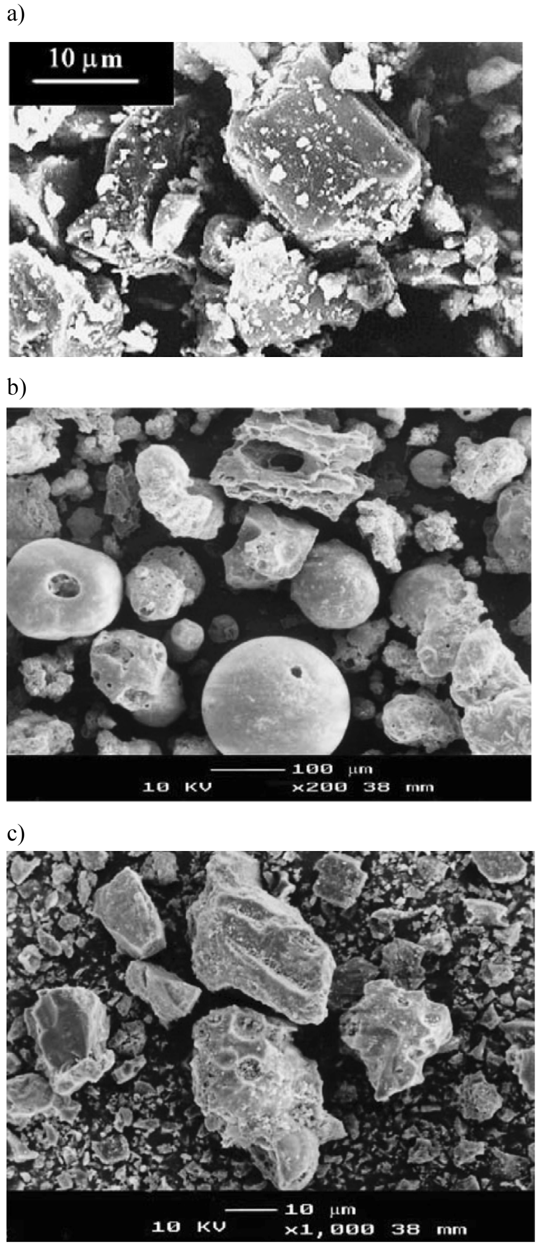

Fig. 1. Scanned electron micrographs (SEMs): a) OPC (Chindaprasirt *et al.* 2007); b) unground POFA (Jaturapitakkul *et al.* 2007); c) ground POFA (Jaturapitakkul *et al.* 2007)

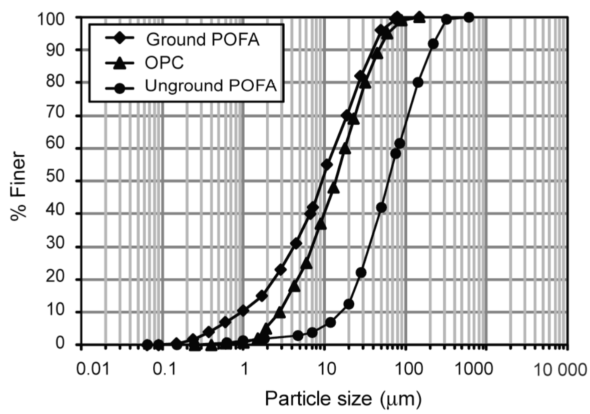

Fig. 2. Particle size distribution of OPC, and unground and ground POFA (adapted from Sata *et al.* 2004)

or retained on sieve No. 325 (45 μm opening). The specific surface area of ground POFA is higher than that of OPC, as can be seen from Table 1. In addition, the percent mass passing sieve No. 325 can be in the range of 5.6–58.8% for unground POFA whereas it can be 97–99% for ground POFA. Both specific surface area and percent mass passing sieve No. 325 reveal that the surface area of POFA becomes higher after grinding.

2.1.5. Strength activity index

The strength activity index expresses the reactivity of supplementary cementing material for pozzolanic reaction. It can be determined by testing the compressive strength of 50-mm mortar cubes with and without supplementary cementing material (ASTM C311-07 2007). POFA is generally used as a supplementary cementing material like fly ash. According to ASTM C618-08a (2008), the specified minimum strength activity index of fly ash is 75%. This requirement can also be applied for POFA to be a pozzolanic supplementary cementing material. The strength activity index of POFA greatly depends on its silica content, particle size distribution, and surface area. It can be improved significantly by increasing the fineness of POFA through grinding process (Sukantapree *et al.* 2002). Therefore, ground POFA possesses a good strength activity index, as can be seen from Table 1.

2.1.6. Soundness

There is limited literature on the soundness of POFA. The soundness of POFA can be determined according to the procedure mentioned in ASTM C311-07 (2007). It can also be examined based on the Le Chatelier accelerated test as mentioned in BS 12 (1991). Tay (1990) as well as Tay and Show (1995) used the Le Chatelier apparatus to examine the soundness of POFA. They observed that the expansion of POFA blended cement paste increases with the increase in ash content, as evident from Fig. 3. However, the expansion results of the soundness test for various percentages of unground POFA blended with cement were much below the maximum limit (10 mm) specified in BS 12 (1991), thus indicating that the POFA concrete will be free from undue expansion (Tay 1990; Tay and Show 1995). According to Awal and Hussin (1999), and Hussin and Awal (1996), the ground POFA has been found equally sound as OPC.

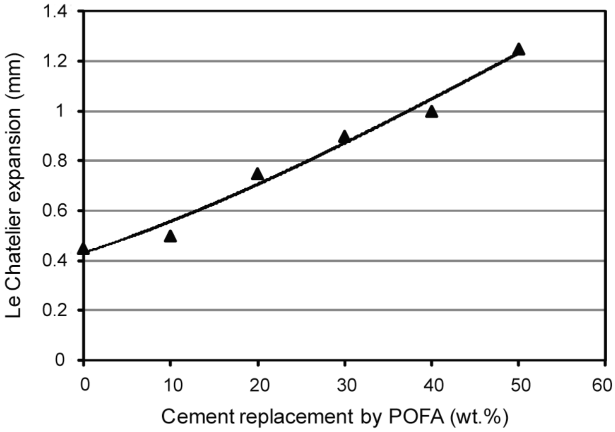

Fig. 3. Effect of unground POFA on the soundness of blended cement (adapted from Tay 1990)

2.2. Chemical composition

The chemical composition of POFA reported in various studies is summarized in Table 2.

The major chemical component of POFA is SiO_2, which varies in the range of 44–66%. The other pozzolanic components are Al_2O_3 and Fe_2O_3. The loss on ignition (LOI) and SO_3 are in the range of 0.1–21.5% and 0.2–3%, respectively. In most cases, the LOI was much higher than the specified limit. In all cases, the amount of SO_3 was well below, but in some investigations, the amount of Na_2O was higher than the maximum limit. Sata *et al.* (2004; 2007) and Tangchirapat *et al.* (2009) stated that the chemical composition of POFA satisfies the requirement for Class N pozzolanic materials stated in ASTM C618-08a (2008), since the sum of SiO_2, Al_2O_3 and Fe_2O_3 was close to 70%, SO_3 was not higher than 4%, and LOI was close to 10% in their studies. In contrast, Tangchirapat *et al.* (2007) found that the total amount of SiO_2, Al_2O_3 and Fe_2O_3 of POFA can be lower than the minimum requirement for natural pozzolan as specified in ASTM C618-08a (2008). Therefore, they

Table 2. Chemical composition of OPC and POFA

Chemical component	OPC (% mass)	POFA (% mass)	ASTM C618-08a (2008) requirement		
			F*	C†	N‡
SiO_2	20–23.5	44–66	–	–	–
Al_2O_3	3–6	1.5–11.5	–	–	–
Fe_2O_3	2.5–3.5	1.5–5.5	–	–	–
SiO_2+ Al_2O_3+ Fe_2O_3	–	55–70	70 (min)	50 (min)	70 (min)
CaO	62–66	4–8.5	–	–	–
MgO	1–3	2–6.5	–	–	–
K_2O	0.3–1	2–8.5	–	–	–
Na_2O	0.1–0.3	0.10–3.50	1.5 (max)	1.5 (max)	1.5 (max)
SO_3	1.5–3.0	0.2–3.0	5 (max)	5 (max)	4 (max)
Loss on ignition (LOI)	1–3	0.1–21.5	6 (max)	6 (max)	10 (max)

*Class F fly ash, †Class C fly ash, ‡Raw or calcined natural pozzolan enforced that POFA cannot be classified as a natural pozzolan. According to Abdullah *et al*. (2006), POFA satisfies the requirement for a pozzolanic supplementary cementing material and therefore may be classified under Class F. The justification was made based on the percentage of CaO content of POFA, which they found as 4.12%. Nagataki (1994) mentioned that fly ash under Class F should have a CaO content less than 5%. Moreover, the total amount of SiO_2, Al_2O_3 and Fe_2O_3 in POFA was near to 70%, which is the minimum requirement for pozzolanic Class F ash. In addition, Hussin and Awal (1996), and Ahmed *et al.* (2008) reported that POFA satisfies the requirement to be a supplementary cementing material and may be classified under Class C according to the standard specification stated in ASTM C618-08a (2008). Thus, there are many arguments in justifying the classification of POFA based on its chemical composition. This is possibly due to the variability in the nature of product, and also because of various burning conditions. Hence, more study is needed to avoid this contradiction by establishing a proper classification.

3. Effects of POFA on the Properties of Concrete

3.1. Fresh properties

3.1.1. Workability

In various experimental studies, it was found that POFA does not cause any severe adverse effect on the workability of concrete. However, the workability decreased with the increase in POFA content (Eldagal 2008; Sata *et al.* 2007; Tay 1990; Tay and Show 1995), as can be seen from Table 3.

The higher content of POFA exhibits a lower slump and a lower degree of compaction (Eldagal 2008). POFA concrete needs more water than OPC concrete for lubrication to maintain the same workability (Chindaprasirt *et al.* 2007). This is due to high porosity of POFA particles, which absorb some water and thus reduce the free water content needed for workability. In addition, the water demand of ground POFA becomes greater than that of unground POFA due to increased specific surface area. The angularity and irregularity of ground POFA with some porous particles also contribute to increase the water demand of concrete for a given workability.

3.1.2. Setting time

Several studies showed that the use of POFA delays the setting of concrete, and therefore the initial and final setting times increase with the increased POFA content (Tay 1990; Tay and Show 1995; Tangchirapat *et al.* 2007), as can be seen from Table 4.

Tay (1990) and Tay and Show (1995) reported that the setting times of POFA concrete, though increased, still fulfilled the ASTM requirement (ASTM C150/ C150M-09 2009). In contrast, the other studies showed that the setting times of POFA concrete with various ash contents did not conform to the ASTM requirement (ASTM C150/C150M-09 2009). Nevertheless, the long setting times of POFA concrete are due to the pozzolanic reaction (reaction between POFA and calcium hydroxide evolved from cement hydration), which is usually slower than the hydration reaction of cement (Tangchirapat *et al.* 2007). In addition, porous POFA particles absorb some water, which cannot readily participate in hydration reaction, thus increasing the setting time of concrete. The setting time of POFA concrete varies with the degree of ash fineness and replacement level of cement. The ground POFA decreases the setting time of concrete as compared with the unground POFA (Tangchirapat *et al.* 2007), since it enhances the pozzolanic reaction due to increased

Table 3. Effect of POFA on the workability of concrete (Eldagal 2008; Sata *et al.* 2007; Tay 1990)

Cement replacement by POFA (wt.%)	Unground POFA		Ground POFA	
	Slump (mm)	Compacting factor (%)	Slump (mm)	Compacting factor (%)
0	150	0.975	200	0.970
10	150	0.970	200	–
20	140	0.960	185	0.950
30	130	0.955	185	0.930
40	130	0.950	–	–
50	120	0.950	–	–

Table 4. Setting times of POFA concrete (Chindaprasirt *et al.* 2008; Tay 1990)

Cement replacement by POFA (wt.%)	Initial setting time*		Final setting time†	
	Unground POFA	Ground POFA	Unground POFA	Ground POFA
0	2 hr 5 min	4 hr 10 min	3 hr 15 min	6 hr 30 min
10	2 hr 10 min	4 hr 25 min	3 hr 45 min	6 hr 35 min
20	2 hr 10 min	4 hr 35 min	4 hr 0 min	7 hr 00 min
30	2 hr 20 min	4 hr 50 min	4 hr 10 min	7 hr 25 min
40	2 hr 30 min	5 hr 10 min	4 hr 30 min	7 hr 40 min
50	2 hr 40 min	–	4 hr 40 min	–

*ASTM C150/C150M-09 (2009) requirement: not < 45 min; †ASTM C150/C150M-09 (2009) requirement: not > 6 hr 15 min surface area. Also, the higher replacement level of cement with POFA reduces the amount of tricalcium silicate (C_3S), and thus increases the setting time of concrete (Tangchirapat *et al.* 2007).

3.1.3. Segregation and bleeding

Limited studies investigated the effect of POFA on the segregation and bleeding of concrete. Few investigations reported that there was no segregation in the concretes with various POFA contents (Tay 1990; Tay and Show 1995). It was observed in the research carried out at the University of Technology, Malaysia that the use of POFA not only improves the workability with no segregation but also reduces the bleeding significantly (Hussin 2009). However, no studies were conducted to examine the effect of POFA on the segregation and bleeding in case of highly flowing or self-consolidating concrete.

3.1.4. Other fresh properties

Limited studies have been conducted to examine the effects of POFA on the plastic shrinkage, slump loss, and air content of concrete. The plastic shrinkage can cause early-age cracking in concrete, thus aggravating many durability problems. The slump loss significantly decreases the workability of concrete before it is properly placed. Both plastic shrinkage and slump loss may cause difficulties for concreting in hot countries. Also, the air content is an important factor for the freeze-thaw durability of concrete in cold countries. Hence, more studies are needed to investigate how these properties, particularly plastic shrinkage and slump loss, are affected in the presence of POFA. Furthermore, no studies have been carried out to examine the effect of POFA on the fundamental rheological properties, yield stress and plastic viscosity of concrete. These two properties should be investigated if POFA is intended to be used in highly flowing or self-consolidating concrete.

3.2. Hardened properties

3.2.1. Heat of concrete

Limited literature is available on the heat of POFA concrete. According to Sata *et al.* (2004), the increased content of ground POFA can reduce the peak temperature in concrete. The use of 30% ground POFA as a partial replacement of cement produces the lowest peak temperature and gives 15% lower temperature than OPC concrete (Sata *et al*. 2004). This is due to the reduction in cement content in the presence of POFA. The partial replacement of cement by ground POFA decreases the total heat released (Sata *et al.* 2004). According to Awal and Hussin (1999), the partial replacement of OPC by POFA is advantageous in controlling the temperature rise, particularly for the mass concrete where the thermal cracking due to excessive heat release is of great concern.

3.2.2. Compressive strength

Many studies were carried out to examine the effect of POFA on the compressive strength of concrete. Some studies (Tay 1990; Tay and Show 1995) revealed that the compressive strength of concrete decreases as the POFA content is increased. In contrast, some other researchers found that the concrete made with POFA exhibits a higher compressive strength than OPC concrete. According to Tay (1990), and Tay and Show (1995), the compressive strength of concrete decreased for the unground POFA content in the range of 20–50%. But the compressive strength of POFA concrete was similar to that of OPC concrete for 10% unground POFA as shown in Fig. 4.

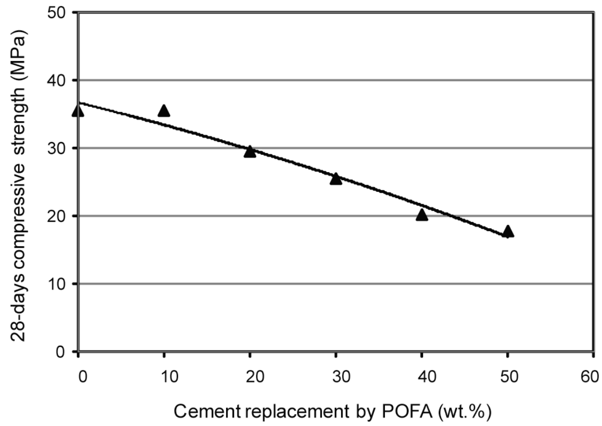

Fig. 4. Effect of unground POFA on the compressive strength of concrete at 28 days (adapted from Tay 1990)

The decrease in the compressive strength of concretes containing a greater amount of unground POFA was due to the large POFA particles with high porosity. The porous POFA particles increase the actual water/binder (w/b) ratio in concrete due to the absorption of water, and thus results in a lower compressive strength (Jaturapitakkul *et al.* 2007; Tangchirapat *et al.* 2007).

Tonnayopas *et al.* (2006) also showed that there can be a decrease in the concrete strength at the early age due to the slow pozzolanic activity of ground POFA. However, the later strength of POFA concrete was higher than that of OPC concrete. They also concluded that the optimum ground POFA content was 20% to obtain satisfactory concrete strength. Chindaprasirt *et al.* (2007) found that the compressive strength of concrete with 20% ground POFA was higher than OPC concrete. In contrast, they obtained that the compressive strength of concrete at 40% ground POFA was less than that of OPC concrete. Hussin and Awal (1996, 1997) reported that it is possible to use 40% ground POFA in concrete without any adverse effect on strength although the maximum strength gain occurs at 30%. Sata *et al.* (2007) observed that the compressive strength of concrete at the early ages ($\leq$ 7 days) was higher for 10% ground POFA. But they found that the compressive strength of concrete at later ages (> 28 days) was higher for 20% POFA. According to Ahmed *et al.* (2008), the optimum content of ground POFA was 15% to achieve the maximum gain in compressive strength.

The above-mentioned studies indicate that the effect of POFA on the compressive strength of concrete largely depends on its fineness. Tangchirapat *et al.* (2009) found that the concrete containing 10–30% ground POFA exhibits a higher compressive strength than OPC concrete at 28 days, as evident from Fig. 5. Also, Sata *et al.* (2007) observed that the concrete with 10–20% ground POFA provides a greater strength than OPC concrete, as obvious from Fig. 6. This is because of satisfactory micro-filling ability and pozzolanic activity of ground POFA.

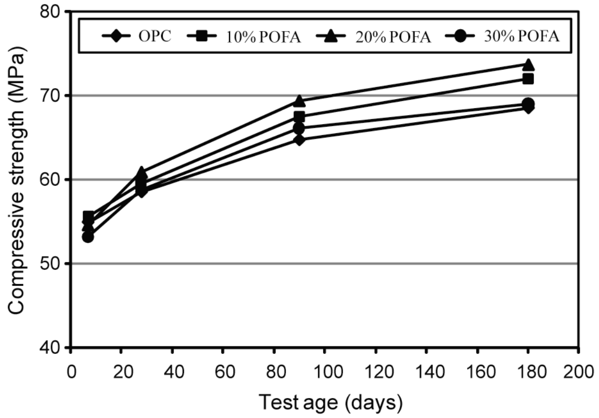

Fig. 5. Effect of ground POFA on the compressive strength of concrete at different curing ages (adapted from Tangchirapat *et al.* 2009)

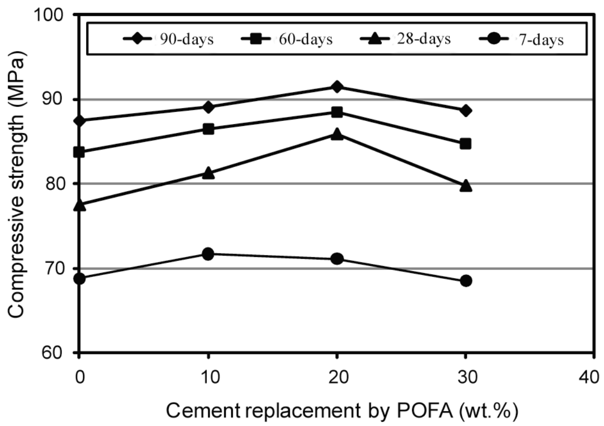

Fig. 6. Effect of ground POFA on the compressive strength of high strength concrete (adapted from Sata *et al.* 2007)

The ground POFA particles fill the micro-voids between cement particles due to smaller particle size (Isaia *et al.* 2003). The micro-filling ability mostly contributes to increase the compressive strength of concrete at the early ages. In addition, the SiO_2 of ground POFA reacts with the Ca $(OH)_2$ liberated from cement hydration in the presence of water (pozzolanic reaction), and forms additional or secondary calcium silicate hydrate (C–S–H). The pozzolanic reaction mainly contributes to increase the compressive strength of concrete at the later ages by improving the interfacial bond between paste and aggregate (Sata *et al.* 2007). However, both micro-filling ability and pozzolanic activity of POFA may depend on the w/b ratio of concrete. Alike other supplementary cementing materials, POFA can be more effective in these two mechanisms when used in concrete with a relatively low w/b ratio (Safiuddin 2008).

3.2.3. Flexural strength

Limited literature has been found on the flexural strength of concrete containing POFA. Eldagal (2008) used 20% and 30% POFA passing through 10-μm and 45-μm sieves for determining the flexural strength of high strength concrete. Those POFA concretes exhibited a lesser flexural strength than OPC concrete, but the reduction was lower for higher POFA content, as shown in Fig. 7. More research is necessary to examine the flexural capacity of concrete containing POFA.

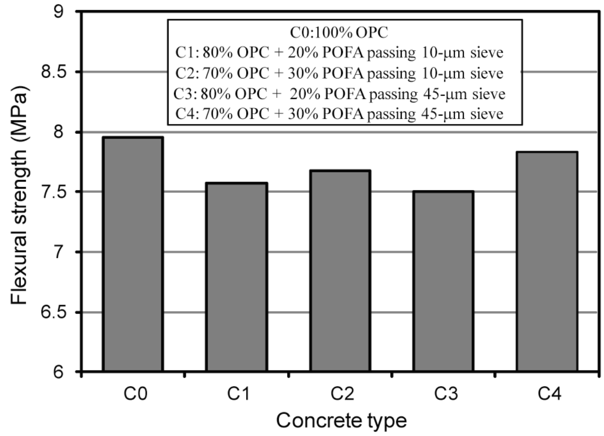

Fig. 7. Effect of ground POFA on the flexural strength of concrete (adapted from Eldagal 2008)

3.2.4. Splitting tensile strength

Few studies focused on the splitting tensile strength of concrete incorporating POFA. Sata *et al.* (2007) made high strength concretes using 10–30% ground POFA and tested their splitting tensile strength. They found that the splitting tensile strength of concretes with 20% and 30% POFA was slightly higher than that of OPC concrete as shown in Fig. 8. The highest value of splitting tensile strength occurred at 20% POFA content. The increase in

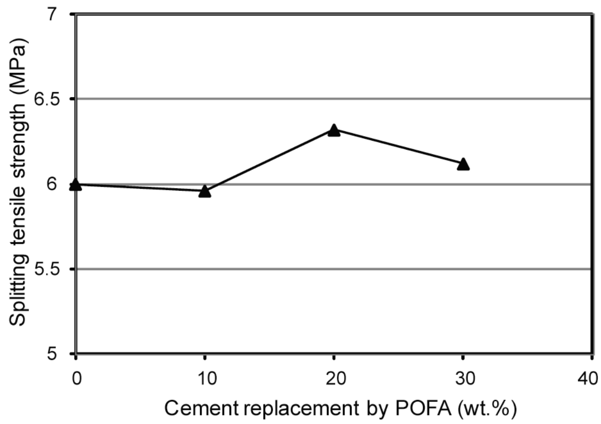

Fig. 8. Effect of ground POFA on the splitting tensile strength of concrete (adapted from Sata *et al.* 2007)

the tensile strength of concrete is possibly due to the pore refinement resulting from the micro-filling ability and pozzolanic activity of ground POFA. In contrast, Eldagal (2008) showed that the POFA concrete provided a lower tensile strength than OPC concrete. Hence, more investigation is necessary to examine how POFA influences the tensile strength of concrete.

3.2.5. Modulus of elasticity

Some research works reported the effect of POFA on the modulus of elasticity of concrete. According to Hussin and Ishida (1999), the modulus of elasticity of concrete containing ground POFA was lower than that of OPC concrete at the early age (7 days) due to the lower compressive strength of POFA concrete. At later ages, the modulus values were comparable to those of OPC. Moreover, 20% POFA produced a higher elastic modulus than OPC at the age of 365 days as illustrated in Fig. 9. This is mainly due to the improvement of interfacial transition zone between aggregate and cement paste caused by the pozzolanic activity of ground POFA that increases the compressive strength of concrete (Hussin and Ishida 1999). In general, POFA concrete shall provide a higher modulus of elasticity if it gives a greater compressive strength than OPC concrete. However, the effect of POFA on the modulus of elasticity also depends on the aggregate content of concrete. According to Sata *et al.* (2004), the ground POFA content in the range of 10–30% slightly decreases the modulus of elasticity of concrete due to a reduction in coarse aggregate content. They also mentioned that POFA has a little effect on the modulus of elasticity of high strength concrete as compared with OPC concrete.

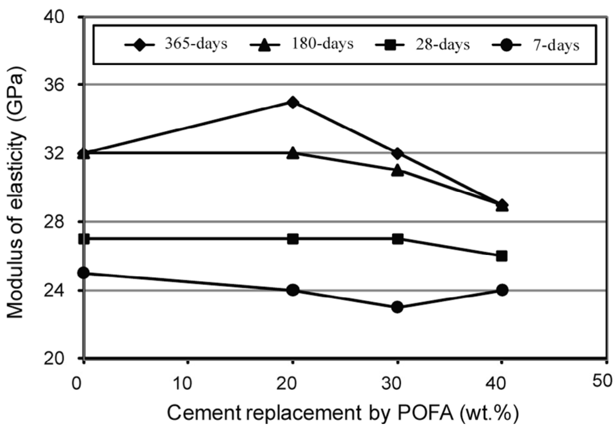

Fig. 9. Effect of ground POFA on the modulus of elasticity of concrete (adapted from Hussin and Ishida 1999)

3.2.6. Drying shrinkage

Drying shrinkage is caused by the evaporation of internal water from hardened concrete. According to Tay (1990), the drying shrinkage of concrete with unground POFA increases slightly after 28 days if the ash content is increased. It was also found that the drying shrinkage of concrete with 10% POFA is comparable to that of OPC concrete. Moreover, Hussin and Ishida (1999) produced concretes with 10–40% ground POFA and found that 40% POFA exhibits the highest shrinkage, while 20% and 30% POFA provide a similar shrinkage developed in OPC concrete. In contrast, Tangchirapat *et al.* (2009) observed that high strength concrete with ground POFA produced lower drying shrinkage than OPC concrete for any amount of POFA, as shown in Fig. 10. The lower value of drying shrinkage in high strength POFA concrete is due to the densification of pore structure. The incorporation of ground POFA decreases the pore sizes in concrete due to pore refinement (Haque and Kayali 1998). The transformation of large pores into fine pores decreases the evaporation of water from concrete surface and thus reduces the drying shrinkage.

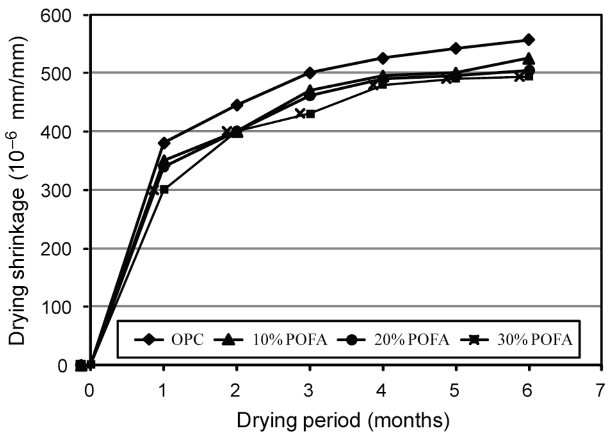

Fig. 10. Effect of ground POFA on the drying shrinkage of concrete (adapted from Tangchirapat *et al.* 2009)

3.2.7. Creep

The creep of concrete refers to the deformation of hardened concrete caused by a long-term sustained load. Limited studies have been conducted on the creep of concrete containing POFA. According to Hussin and Ishida (1999), the specific creeps of the concretes with and without ground POFA were almost the same. After 180 days, the specific creep of POFA concrete was only about 5% lower than that of OPC concrete. They mentioned that a similar creep occurred for both OPC and POFA concretes due to the equivalent improvement in strength under the same curing condition. However, more research is needed to investigate the effect of POFA on the creep of concrete.

3.2.8. Water absorption

Limited research has been conducted on the water absorption of POFA concrete. Tay (1990), and Tay and Show (1995) found that the water absorption of concrete increased with the increase in unground POFA content, as shown in Fig. 11. They mentioned that the POFA concrete exhibits a more porous nature with higher unground POFA content. It indicates that the concrete with a higher unground POFA content tends to absorb more water due to greater porosity (Tay and Show 1995). But the water absorption of concrete can be reduced in case of ground POFA because of its satisfactory micro-filling ability and

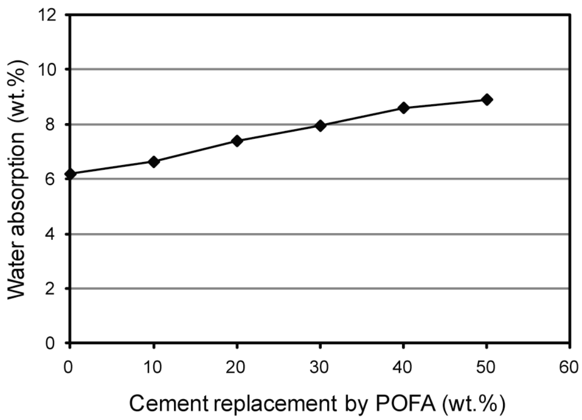

Fig. 11. Effect of unground POFA on the water absorption of concrete (adapted from Tay and Show 1995)

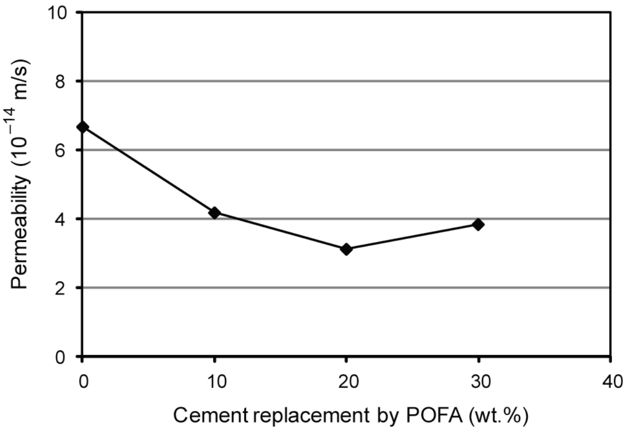

Fig. 12. Effect of ground POFA on the water permeability of concrete (adapted from Tangchirapat *et al.* 2009)

pozzolanic activity leading to a pore refinement. However, more research is required to investigate the water absorption of concrete containing ground POFA.

3.2.9. Water permeability

The water permeability of concrete containing POFA depends on the content and fineness of POFA. Sumadi and Hussin (1995) investigated the water permeability of concrete with ground POFA. They found that the permeability of POFA concrete decreased with increased age due to the formation of additional gel from the pozzolanic reaction of ash. Chindaprasirt *et al.* (2007) made concrete incorporating 20–55% ground POFA by weight of cement and found that the water permeabilities of POFA concrete at both 28 and 90 days were lower than that of OPC concrete, except the concrete made with 55% POFA. Their results also showed that the concrete made with 20% and 40% ground POFA provided the lower permeability than OPC concrete even though the w/b ratios of these two concretes were higher than OPC concrete. In contrast, the permeability of concrete made with 55% ground POFA rapidly increased and was higher than that of OPC concrete. This is attributed to the low cement content and high w/b ratio of the concrete made with 55% ground POFA. According to Tangchirapat *et al.* (2009), the concrete containing 20% ground POFA produced the lowest water permeability as compared with the other ash contents, as shown in Fig. 12. In addition, all high strength concretes containing ground POFA provided 50% lower water permeability than OPC concrete (Tangchirapat *et al.* 2009). This is due to the reason that the ground POFA increases the impermeability of concrete by pore refinement and porosity reduction.

3.2.10. Chloride penetration

Several experimental investigations (Awal and Hussin 1999; Chindaprasirt *et al.* 2008; Rukzon and Chindaprasirt 2009a) revealed that the ground POFA can be used alone or with other supplementary cementing materials to produce concrete possessing a better resistance to chloride penetration than OPC concrete. The depth of penetration of chloride ions into POFA concrete is much lower than that in OPC concrete as illustrated in Fig. 13. The POFA particles increase the nucleation sites for the production of hydration products, consume $Ca(OH)_2$, and produce pozzolanic products. The pozzolanic products fill in the pores in bulk binder paste and transition zone. Consequently, POFA decreases the permeability of concrete, and thus increases the resistance to chloride penetration.

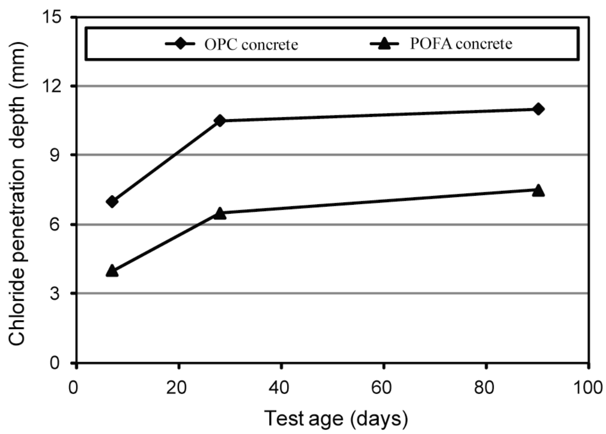

Fig. 13. Effect of ground POFA on the chloride penetration resistance of concrete (adapted from Awal and Hussin 1999)

3.2.11. Porosity and density

Concrete with a greater unground POFA content may possess a higher porosity because of the porous nature of POFA. Moreover, the density of concrete can be decreased due to the absorption of water by porous POFA particles. According to the investigations of Tay (1990), and Tay and Show (1995), the oven-dry, saturated surface-dry and air-dry densities of concrete made with unground POFA decreased with the increase in ash content, as shown in Fig. 14. However, Tangchirapat *et al.* (2009) reported that the ground POFA refines the pore size and reduces the porosity in concrete, and thus results in a dense concrete. Jaturapitakkul *et al.* (2007) also mentioned that the use of ground POFA decreases the $Ca(OH)_2$ content of hydrated cement and reduces the voids between aggregates and hydration products, thus producing a denser concrete.

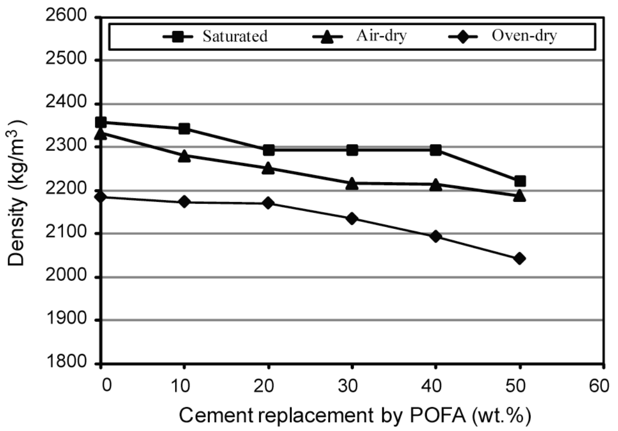

Fig. 14. Effect of unground POFA on the density of concrete (adapted from Tay and Show 1995)

3.2.12. Other hardened properties

In published literature, there are limited reports on several important hardened properties of POFA concrete such as shear, bond, impact and fatigue strengths, oxygen permeability and diffusion, autogenous shrinkage, and electrical resistivity. The POFA concrete should be examined for its shear, bond, impact and fatigue strengths before applying in structural member. The autogenous shrinkage and electrical resistivity are also important for the durability of POFA concrete. In addition, the oxygen permeability and diffusion of POFA concrete should be assessed to ensure adequate corrosion resistance leading to a good durability.

3.3. Durability

3.3.1. Resistance to sulfate attack

Several research works investigated the effect of unground and ground POFA on concrete's resistance to sulfate attack (Hussin and Awal 1998; Jaturapitakkul *et al*. 2007; Kiattikomol *et al.* 2001). The sulfate attack was simulated using 10% $MgSO_4$ solution. In general, the expansion of concrete due to sulfate attack decreased with the increased content of unground POFA (Jaturapitakkul *et al.* 2007), as shown in Fig. 15. However, high strength concrete containing ground POFA showed a better resistance to sulfate attack (Tangchirapat *et al.* 2009), indicating that the fineness influences the sulfate resistance of concrete – the finer the POFA, the lower is the expansion of concrete due to sulfate attack. However, more research is needed to investigate the sulfate resistance of POFA concrete.

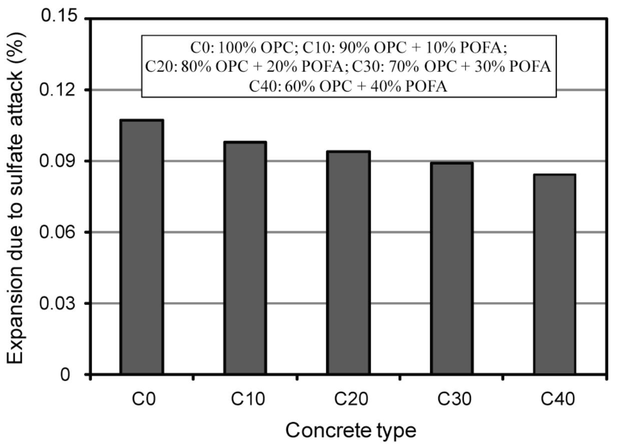

Fig. 15. Effect of ground POFA on the sulfate resistance of concrete (adapted from Jaturapitakkul *et al*. 2007)

3.3.2. Resistance to acid attack

Limited research was carried out to evaluate the acid resistance of POFA concrete. Awal and Hussin (1999), and Hussin and Awal (1996) determined the weight loss of the concrete containing 30% ground POFA along with non-POFA concrete continuously submerged in 5% hydrochloric acid solution to measure the resistance to acid attack. They found that the weight loss of POFA concrete after 1800 hours was less than that of OPC concrete, as shown in the Fig. 16. It was also observed that POFA concrete showed a better surface condition than OPC concrete after exposure to acid solution. The high acid resistance of POFA concrete was attributed to the pozzolanic property and low lime content of POFA. In the presence of POFA, the amount of porous $Ca(OH)_2$ was less due to a low lime content. Moreover, secondary hydration product (additional C–S–H gel from pozzolanic reaction) was produced at the expense of $Ca(OH)_2$. As a result, the microstructure of concrete became dense with a reduction in porosity. This led to a reduced penetration of acid solution into the interior of concrete. Nevertheless, the above studies neither differentiated the effects of unground and ground POFA nor determined their optimum contents. Hence, more research is required for various contents of unground and ground POFA.

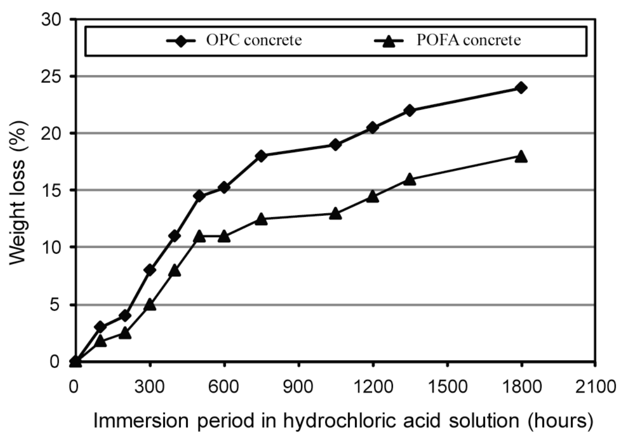

Fig. 16. Effect of ground POFA on the acid resistance of concrete (adapted from Awal and Hussin 1999)

3.3.3. Resistance to alkali-silica reaction

Limited research has been carried out to investigate the effect of POFA on concrete's resistance to alkali-silica reaction. Awal and Hussin (1997) used ground POFA in concrete as a supplementary cementing material and showed that a reduction in expansion occurred with an increased ash content. After 12 days of exposure, about 25% reduction in expansion was obtained for the concrete containing 10% POFA. In addition, they reported a substantial reduction in expansion for 50% POFA. Furthermore, the total alkali content (as equivalent Na_2O) in their study was much higher than that specified in ASTM C150/C150M-09 (2009). Despite the higher alkali content, ground POFA was very effective in reducing the expansion due to alkali-silica reaction. The reason is that the pozzolanic POFA particles react rapidly with the alkalis present in cement because of their reactive nature, thus leaving very little unreacted alkalis for the later reaction with reactive aggregate. However, more research is needed to confirm the beneficial effect of POFA in reducing alkali-silica reactivity.

3.3.4. Resistance to carbonation

Several studies were conducted to investigate the effect of POFA on the carbonation of cement paste (Chindaprasirt and Rukzon 2009) and mortar (Rukzon and Chindaprasirt 2009b). Chindaprasirt and Rukzon (2009) showed that the carbonated POFA paste possesses a lower total porosity than non-carbonated POFA paste due to the deposition of $CaCO_3$, which forms from the reaction of CO_2 with $Ca(OH)_2$. In their study, the reduction in total porosity was very marginal in case of carbonated OPC paste although it had a full supply of $Ca(OH)_2$. As a reason, they pointed out that the advanced stage of carbonation may produce an increased total porosity due to the formation of silica gel from CO_2 attack on C–S–H. This effect can be minimized in POFA concrete due to the reduced amount of $Ca(OH)_2$. Also, Rukzon and Chindaprasirt (2009b) used coarse, medium and fine POFA in mortars and investigated their resistance to carbonation. They found that the presence of POFA decreased the carbonation depth in mortar and the lowest carbonation depth occurred in case of fine POFA. Similar effects are expected in case of POFA concrete. However, very few studies focused the effect of POFA on the carbonation resistance of concrete. Awal and Hussin (1999) investigated concrete's resistance to carbonation with and without ground POFA. They found that there is a little difference between the carbonation values of OPC and POFA concretes. They also mentioned that the results are not truly conclusive because POFA concrete appears to be more sensitive to the exposure condition – the dryer the concrete, the deeper the carbonation. Nevertheless, further research is needed to investigate the carbonation resistance of POFA concrete.

3.3.5. Other durability properties

In published literature, there is no information about the effects of POFA on the freezing and thawing resistance, de-icing salt scaling resistance, and corrosion resistance of concrete. In addition, no study was conducted to examine the abrasion resistance of POFA concrete. The performance of POFA regarding these durability properties needs to be investigated before use in concrete.

4. Research Needs

POFA can be used as a supplementary cementing material up to a certain replacement level of cement without causing any adverse effect on the strength and durability of concrete. However, more research is needed to confirm the beneficial effects of POFA on several properties and durability of concrete. In this context, the following research needs have been identified for further investigation to encourage the use of POFA in concrete:

- Proper classification of POFA as a supplementary cementing material for concrete;
- Investigation of the effects of POFA on the plastic shrinkage, slump loss, and air content of concrete;
- Investigation of the effects of POFA on the segregation and bleeding characteristics of highly flowing or self-consolidating concrete;
- Investigation of the effects of POFA on the rheological properties, yield stress and plastic viscosity of concrete;
- Examination of the effects of POFA on the tensile, flexural, shear, impact, fatigue, and bond strengths of concrete;
- Investigation of the effects of POFA on the creep, autogenous shrinkage, water absorption, electrical resistivity, and oxygen permeability and diffusion of concrete;
- Further investigation of the effects of POFA on concrete's resistance to sulfate attack, acid attack, alkali-silica reaction, and carbonation;
- Assessment of the effects of POFA on the durability performance of concrete with respect to freeze-thaw, de-icing salt scaling, corrosion, and abrasion resistances;
- Investigation on the potential use of POFA to produce self-consolidating normal strength, high strength and high performance concretes.

5. Conclusions

The following salient conclusions can be drawn based on the findings from the review on the utilization of POFA in concrete:

- The use of POFA as a supplementary cementing material in concrete can solve the environmental and health problems caused by the ash generated in palm oil industry;
- The physical and chemical properties of POFA are favorable for concrete production. Properly processed POFA can be used to replace a significant amount of portland cement without affecting the properties and durability of concrete;
- POFA can be used as a supplementary cementing material with a content up to 40% by weight of cement. However, the optimum POFA content is 20–30%. A POFA content higher than 40% may adversely affect the properties and durability of concrete;

- The fineness of POFA plays an important role in concrete. The high fineness of POFA improves its micro-filing ability and pozzolanic activity, and thus contributes to improve the hardened properties and durability of concrete;
- POFA concrete shows a comparable and sometimes a better performance than OPC concrete in resisting acid attack, sulfate attack, and alkali-silica reaction;
- Further research should be carried out to confirm the beneficial effects of POFA on several concrete properties and durability issues, and thus to encourage the use of POFA in concrete;
- Additional research should be conducted to extend the use of POFA in self-consolidating normal strength, high strength and high performance concretes.

Acknowledgment

The authors appreciatively acknowledge the financial support from the University of Malaya, Kula Lumpur, Malaysia to conduct the research.

References

Abdullah, K.; Hussin, M. W.; Zakaria, F.; Muhamad, R.; Hamid, Z. A. 2006. POFA: a potential cement replacement material in aerated concrete, in *Proc. of the 6th Asia-Pacific Conference on Structural Engineering and Construction*, Kuala Lumpur, Malaysia, September 5–6, 2006, B132–B140.

Ahmed, M. H.; Omar, R. C.; Malek, M. A.; Noor, N. M.; Thiruselvam, S. 2008. Compressive strength of palm oil fuel ash concrete, in *Proc. of the International Conference on Construction and Building Technology,* Kuala Lumpur, Malaysia, June 16–20, 2008, 297–306.

ASTM C150/C150M-09 Standard specification for portland cement. Annual Book of ASTM Standards, Vol. 04.01, American Society for Testing and Materials. Philadelphia, USA, 2009. 10 p.

ASTM C311-07 Standard test methods for sampling and testing fly ash or natural pozzolans for use as a mineral admixture in portland cement concrete. Annual Book of ASTM Standards, Vol. 04.02, American Society for Testing and Materials. Philadelphia, USA, 2007. 10 p.

ASTM C618-08a Standard specification for fly ash and raw or calcined natural pozzolan for use as a mineral admixture in portland cement concrete. Annual Book of ASTM Standards, Vol. 04.02, American Society for Testing and Materials. Philadelphia, USA, 2008. 3 p.

Awal, A. S. M. A.; Hussin, M. W. 1997a. The effectiveness of palm oil fuel ash in preventing expansion due to alkali-silica reaction, *Cement and Concrete Composites* 19(4): 367–372. doi:10.1016/S0958-9465(97)00034-6

Awal, A. S. M. A.; Hussin, M. W. 1997b. Effect of palm oil fuel ash on durability of concrete, in *Proc. of the 5th International Conference on Concrete Engineering and Technology*, University of Malaya, Malaysia, May 5–7, 1997, 299–306.

Awal, A. S. M. A.; Hussin, M. W. 1999. Durability of high performance concrete containing palm oil fuel ash, in *Proc. of the 8th International Conference on the Durability of Building Materials and Components*. Ed. by M. A. Lacasse, D. J. Vanier, D. R. Payer. Vancouver, British Columbia, Canada, 30 May–3 June, 1999, 465–474.

BS 12 Specification for portland clement. British Standard Institution, London, England, 1991. 5 p.

Chindaprasirt, P.; Homwuttiwong, S.; Jaturapitakkul, C. 2007. Strength and water permeability of concrete containing palm oil fuel ash and rice husk-bark ash, *Construction and Building Materials* 21(7): 1492–1499. doi:10.1016/j.conbuildmat.2006.06.015

Chindaprasirt, P.; Rukzon, S.; Sirivivatnanon, V. 2008. Resistance to chloride penetration of blended portland cement mortar containing palm oil fuel ash, rice husk ash and fly ash, *Construction and Building Materials* 22(5): 932–938. doi:10.1016/j.conbuildmat.2006.12.001

Chindaprasirt, P.; Rukzon, S. 2009. Pore structure changes of blended cement pastes containing fly ash, rice husk ash and palm oil fuel ash caused by carbonation, *Journal of Materials in Civil Engineering* ASCE 21(11): 666–671. doi:10.1061/(ASCE)0899-1561(2009)21:11(666)

Eldagal, O. E. A. 2008. *Study on the behaviour of high-strength palm oil fuel ash (POFA) concrete*. MSc Thesis, Skudai, Malaysia: Universiti Teknologi Malaysia. 60 p.

Haque, M. N.; Kayali, O. 1998. Properties of high-strength concrete using a fine fly ash, *Cement and Concrete Research* 28(10): 1445–1452. doi:10.1016/S0008-8846(98)00125-2

Hussin, M. W.; Abdullah, K. 2009. Properties of palm oil fuel ash cement based aerated concrete panel subjected to different curing regimes, *Malaysian Journal of Civil Engineering* 21(1): 17–31.

Hussin, M. W.; Awal, A. S. M. A. 1996. Influence of palm oil fuel ash on strength and durability of concrete, in *Proc. of the 7th International Conference on the Durability of Building Materials and* Components. Vol. 1. Ed. by C. Sjostrom. May 19–23, 1996, Stockholm, Sweden. London, UK: E & FN Spon, 291–298.

Hussin, M. W.; Awal, A. S. M. A. 1997. Palm oil fuel ash: a potential pozzolanic material in concrete construction, *Journal of Ferrocement* 27(4): 321–327.

Hussin, M. W.; Awal, A. S. M. A. 1998. Influence of palm oil fuel ash on sulfate resistance of mortar and concrete, in *Proc. of the 6th CANMET/ACI/JCI International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*: ACI SP-178. Vol. 1. Ed. by V. M. Malhotra. May 31–June 5, 1998. Bangkok, Thailand. Michigan, USA: American Concrete Institute, 417–430.

Hussin, M. W.; Ishida, T. 1999. Study on basic properties of hardened concrete containing palm oil fuel ash as partial cement replacement material, in *Summaries of Technical Papers of Annual Meeting.* Tokyo, Japan: Architectural Institute of Japan, 179–180.

Hussin, M. W. 2009. Blended cement concrete – potential without misuse (a public lecture), in *UTM Today* [online], [cited 4 January 2010]. Available from Internet: <HTTP://WEB.UTM.MY/TODAY>.

Isaia, G. C.; Gastaldini, A. L. G.; Moraes, R. 2003. Physical and pozzolanic action of mineral additions on the mechanical strength of high-performance concrete, *Cement and Concrete Composites* 25(1): 69–76. doi:10.1016/S0958-9465(01)00057-9

Jaturapitakkul, C.; Kiattikomol, K.; Tangchirapat, W.; Saeting, T. 2007. Evaluation of the sulfate resistance of concrete containing palm oil fuel ash, *Construction and Building Materials* 21(7): 1399–1405. doi:10.1016/j.conbuildmat.2006.07.005

Kiattikomol, K.; Jaturapitakkul, C.; Songpiriyakij, S.; Chutubtim, S. 2001. A study of ground coarse fly ashes with different fineness from various sources of pozzolanic materials, *Cement and Concrete Composites* 23(4–5): 335–343. doi:10.1016/S0958-9465(01)00016-6

Lim, B. A. 2000. Feature on palm oil fuel ash, in *The New Straits Times*, Thursday, December 28, 2000. Malaysia, 3–4.

Nagataki, S. 1994. Mineral admixture in concrete: state of the arts and trends, in *Proc. of the V. Mohan Malhotra Symposium on Concrete Technology: Past, Present and Future:* ACI SP–144. Ed. by P. K. Mehta. 21–23 March, 1994, University of California, Berkeley. Michigan, USA: American Concrete Institute, 447–482.

Paya, J.; Monzo, J.; Borrachero, M. V.; Mora, E. P.; Lopez, E. G. 1996. Mechanical treatment of fly ashes part II: particles morphology in ground fly ashes (GFA) and workability of GFA-cement mortars, *Cement and Concrete Research* 26(2): 225–235. doi:10.1016/0008-8846(95)00212-X

Rukzon, S.; Chindaprasirt, P. 2009a. Strength and chloride resistance of blended portland cement mortar containing palm oil fuel ash and fly ash, *International Journal of Minerals, Metallurgy and Materials* 16(4): 475–481. doi:10.1016/S1674-4799(09)60083-2

Rukzon, S.; Chindaprasirt, P. 2009b. An experimental investigation of the carbonation of blended portland cement palm oil fuel ash mortar in an indoor environment, *Indoor and Built Environment* 18(4): 313–318. doi:10.1177/1420326X09336554

Safiuddin, M. 2008. *Development of Self-consolidating High Performance Concrete Incorporating Rice Husk Ash.* PhD. Thesis, Waterloo, Ontario, Canada: University of Waterloo. 359 p.

Sata, V.; Jaturapitakkul, C.; Kiattikomol, K. 2004. Utilization of palm oil fuel ash in high-strength concrete, *Journal of Materials in Civil Engineering* ASCE 16(6): 623–628. doi:10.1061/(ASCE)0899-1561(2004)16:6(623)

Sata, V.; Jaturapitakkul, C.; Kiattikomol, K. 2007. Influence of pozzolan from various by-product materials on mechanical properties of high-strength concrete, *Construction and Building Materials* 21(7): 1589–1598. doi:10.1016/j.conbuildmat.2005.09.011

Sumadi, S. R.; Hussin, M. W. 1995. Palm oil fuel ash (POFA) as a future partial cement replacement material in housing construction, *Journal of Ferrocement* 25(1): 25–34.

Sukantapree, S.; Namarak, C.; Jaturapitakkul, C. 2002. Use of calcium carbide residue and palm oil fuel ash in concrete, in *Proc. of the Annual Conference of the Engineering Institute of Thailand*. Bangkok, Thailand, 20–23 June, 2002, 191–199.

Tay, J. H. 1990. Ash from oil-palm waste as concrete material, *Journal of Materials in Civil Engineering* ASCE 2(2): 94–105. doi:10.1061/(ASCE)0899-1561(1990)2:2(94)

Tay, J. H.; Show, K. Y. 1995. Use of ash derived from oil-palm waste incineration as a cement replacement material, *Resources, Conservation and Recycling* 13(1): 27–36. doi:10.1016/0921-3449(94)00012-T

Tangchirapat, W.; Tangpagasit, J.; Waew-kum, S.; Jaturapitakkul, C. 2003. A new pozzolanic material from palm oil fuel ash, *KMUTT Research and Development Journal* 26: 459–473.

Tangchirapat, W.; Saeting, T.; Jaturapitakkul, C.; Kiattikomol, K.; Siripanichgorn, A. 2007. Use of waste ash from palm oil industry in concrete, *Waste Management* 27(1): 81–88.

Tangchirapat, W.; Jaturapitakkul, C.; Chindaprasirt, P. 2009. Use of palm oil fuel ash as supplementary cementitious material for producing high-strength concrete, *Construction and Building Materials* 23(7): 2641–2646. doi:10.1016/j.conbuildmat.2009.01.008

Tonnayopas, D.; Nilrat, F.; Putto, K.; Tantiwitayawanich, J. 2006. Effect of oil palm fiber fuel ash on compressive strength of hardening concrete, in *Proceedings of the 4th Thailand Materials Science and Technology Conference, Pathumthani, Thailand, March 31-April 1,* 2006, 1–3.

Yin, C. Y.; Kadir, S. A. S. A.; Lim, Y. P.; Syed-Ariffin, S. N.; Zamzuri, Z. 2008. An investigation into physicochemical characteristics of ash produced from combustion of oil palm biomass waste in a boiler, *Fuel Processing Technology* 89(7): 693–696. doi:10.1016/j.fuproc.2007.12.012

PALMIŲ ALIEJAUS KURO PELENŲ NAUDOJIMAS BETONE. APŽVALGA

Md. Safiuddin, Md. A. Salam, M. Z. Jumaat

Santrauka

Nekontroliuojami palmių aliejaus kuro pelenų (POFA) sąvartynai ne tik užima vertingus žemės plotus, bet ir teršia aplinką bei kelia pavojų sveikatai. Šios problemos gali būti sumažintos POFA naudojant betone. Daug mokslinių tyrimų buvo atlikta siekiant ištirti POFA potencialą, kad juos būtų galima naudoti kaip papildomą normalių, didelio stiprio, aukštos kokybės ir poringųjų betonų cementavimo medžiagą. Šiame straipsnyje apžvelgiama, kaip POFA naudojami įvairių tipų betonams. Visų pirma aptariamos fizinės ir cheminės POFA savybės. Tuomet dėmesys atkreipiamas į šviežio ir sukietėjusio betono savybes bei betono ilgaamžiškumą. Šis straipsnis parodo, kad tiek malti, tiek nemalti POFA padidina vandens poreikį ir blogina technologines charakteristikas. Tačiau malti POFA parodė potencialą gerinant betono atsparumo ir ilgaamžiškumo savybes, nes jie pasižymi geromis mikroužpildų savybėmis ir pucolaniniu aktyvumu. Be to, aptarta POFA nauda, nustatytos tam tikros šiuo metu turimų žinių apie POFA betoną spragos ir išvardyta daugelis tyrimų, kurie turėtų būti atlikti ateityje. Šio darbo išvados turėtų paskatinti naudoti POFA kaip papildomą rišamąją betono medžiagą.

Reikšminiai žodžiai: betonas, mikroužpildas, palmių aliejaus kuro pelenai, stiprio rodikliai, papildoma rišamoji medžiaga.

Md. SAFIUDDIN. Post-doctoral fellow in the Department of Civil and Environmental Engineering, University of Waterloo, Canada. He is a member of American Concrete Institute, American Society of Civil Engineers, Bangladesh Environmental Network, and Institution of Engineers, Bangladesh. His research interests include concrete materials, high strength and high performance concretes, self-consolidating concrete, green concrete, and repair and rehabilitation of concrete structures.

Md. Abdus SALAM. PhD. candidate and graduate research assistant in the Department of Civil Engineering, University of Malaya, Malaysia. He is a member of Institution of Engineers, Bangladesh. His research interests include concrete materials, self-consolidating concrete, and green concrete.

Mohd Zamin JUMAAT. Professor in the Department of Civil Engineering at the University of Malaya, Malaysia. He is a council member of Institution of Engineers, Malaysia and a member of the Drafting Code Committee for reinforced concrete structures. His research interests include behaviour of reinforced concrete structural elements, concrete materials, self-consolidating concrete, lightweight concrete, and green concrete.