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Strength and chloride penetration of Portland cement mortar containing palm oil fuel ash and ground river sand

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Abstract This paper presents a study of the strength and chloride penetration of blended Portland cement mortar containing ground palm oil fuel ash (POA) and ground river sand (GS). Ordinary Portland cement (OPC) was partially replaced with POA and GS. Compressive strength, rapid chloride penetration test (RCPT) and chloride penetration depth of mortars were determined. The GS only asserted the packing effect and its incorporation reduced the strength and the resistance to chloride penetration of mortar. The POA asserted both packing and pozzolanic effects. The use of the blend of equal portion of POA and GS also produced high strength mortars, save cost and excellent resistance to chloride penetration owing to the synergic effect of the blend of POA and GS. For chloride depth, the mathematical model correlates well with the experimental results. The computer graphics of chloride depth of the ternary blended mortars are also constructed and can be used to aid the understanding and the proportioning of the blended system.

Keywords: palm oil fuel ash; ground river sand; strength; chloride; mortar.

1. Introduction

Palm oil fuel ash is one promising pozzolans and is available in many parts of the world (Rukzon and Chindaprasirt 2008). In Thailand alone, approximately 100,000 tons of palm oil fuel ash is produced annually (Chindaprasirt *et al*. 2007, Chindaprasirt *et al*. 2008). It is a by-product obtained from a small power plant using the palm fiber, shells and empty fruit bunches as a fuel and burnt at 800-1000°C. The main chemical composition of palm oil fuel ash is silica which is a main ingredient of pozzolan. Research indicates that ground palm oil fuel ash (POA) can be used as a pozzolan in normal and high strength concrete (Sata *et al.* 2007). In addition, partial replacement of OPC with POA helps improve permeability and sulfate resistance of concrete (Chindaprasirt *et al*. 2007).

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It is known that compressive strength of Portland cement mortar containing pozzolan is contributed by hydration reaction, packing effect and pozzolanic reaction. Hydration reaction is the chemical reactions between the reactive constituents of Portland cement, while the pozzolanic reaction is the reaction between the silica and/or alumina and the calcium hydroxide produced by the cement hydration reaction. The physical effect of the finer grains allows denser packing within the cement and pozzolan and reduces the wall effect in the transition zone between the paste and the aggregates (Poon *et al*. 1997, Chindaprasirt *et al*. 2005).

It is a generally accepted that incorporation of a pozzolan improves the resistance to chloride penetration and reduces chloride-induced corrosion initiation period of steel reinforcement. The improvement is mainly by the reduction of permeability, particularly to chloride ion transportation of the blended cement concrete (Thomas and Bamforth 1999, Bijen 1996, Tumidajski and Chan 1996). The use of the blend of pozzolan has been shown to be advantages owing to the synergic effects (Isaia *et al*. 2003, Rukzon and Chindaprasirt 2008). The objective of this research is to investigate the effect of pozzolanic reaction of POA on the strength and resistance to chloride penetration of mortars by comparing with the use of ground river sand (GS).

In this work, ordinary Portland cement, ground palm oil fuel ash and ground river sand are used as base materials for studying the ternary blended cement in order to reduce negative environmental effects, and landfill area required to dispose of waste ash and save cost. In addition, the mathematical model is performed on the results and is presented in the form of 3-D graphic to aid the understanding and the proportioning of the blended system.

2. Experimental details

2.1. Materials

Ordinary Portland cement (OPC) type I, palm oil fuel ash from a thermal power plant from the south of Thailand, river sand with specific gravity of 2.63 and fineness modulus of 2.82, and type-F superplasticizer (SP) were used. This river sand was used as a source material to produce ground sand. The D_{50} of ground river sand was 11 micron. The ground palm oil fuel ash (POA) and ground sand (GS) were obtained from ball mill grinding machine; the percentages retained on a sieve No. 325 were 1-3% (opening 45 μm) as well. The fineness, specific gravity and mean particle size of Portland cement and GS and POA are given in Table 1. The particle size distributions are given in Fig. 1 and the chemical constituents are presented in Table 2.

Table 1 Physical properties and oxides of OPC, GS and POA

Physical properties	OPC	GS	POA
Median particle size (μm)	15.0	11.0	7.2
Retained on a sieve No. 325 (%)	-	1-3	1-3
Specific Gravity (g/cm^3)	3.14	2.65	2.25
Blaine Fineness (cm^2/g)	3600	3200	11,800

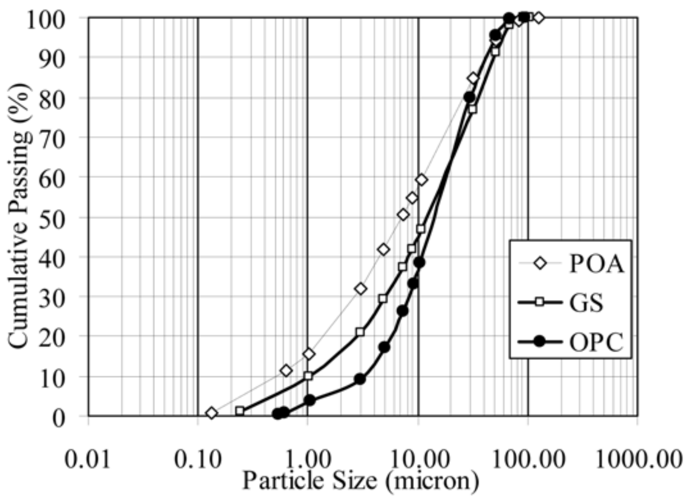

Fig. 1 Particle size distribution of POA, GS and OPC

Table 2 Oxides of OPC, GS and POA

Oxides (%)	OPC	GS	POA
SiO_2	21.0	93.5	63.6
Al_2O_3	4.7	5.0	1.5
Fe_2O_3	3.3	NA	1.5
CaO	65.5	NA	7.6
MgO	1.3	NA	3.9
Na_2O	0.2	NA	0.1
K_2O	0.4	NA	6.9
SO_3	2.7	NA	0.2
LOI	0.9	NA	9.6
$SiO_2 + Al_2O_3 + Fe_2O_3$	-	98.5	66.6

2.2. Mix proportions and curing

OPC was partially replaced with POA and GS at the dosage of 0%, 20% and 40% by weight of cementitious materials. In addition to normal replacement, a blend of equal weight portion of POA and GS (BPGS) was also used to study the combined effect of the POA and GS. Sand-to-binder ratio of 2.75 by weight and water to binder (OPC+POA+GS) ratio of 0.5 were used. Superplasticizer (SP) was incorporated in order to obtain mortar mixes with similar flow of 110±5%. The cast specimens were covered with polyurethane sheet and damped cloth and placed in a 23±2°C chamber. They were demoulded at the age of 1 day and cured in water at 23±2°C until the test age. The mortar mix proportions are given in Table 3.

Table 3 Mortar mix proportions

Mix. ID	OPC	POA	GS	SP (%*)
OPC	100	-	-	1.9
20POA	80	20	-	2.1
40POA	60	40	-	3.3
20GS	80	-	20	1.3
40GS	60	-	40	1.9
20BPGS	80	10	10	1.4
40BPGS	60	20	20	1.7

Note * percentage of cement + POA + GS

2.3. Compressive strength

The cube specimens of size 50×50×50 mm were used for the compressive strength test of mortar. They were tested at the ages of 7, 28 and 90 days. The test was done in accordance with the ASTM C109 (2001). The reported results were the average of three samples.

2.4. Chloride penetration

Cylindrical specimens of 100 mm in diameter and 200 mm in height were prepared in accordance with ASTM C39 (2001). They were demoulded at the age of 24 hours. After being cured in water until the age of 27 days, they were cut into 50 mm thick slices and the 50 mm ends discarded. The 50 mm slices were epoxy coated around the cylinder. The samples were used for the determination of rapid chloride penetration test (RCPT) and chloride immersion test (IMT).

2.4.1. Rapid chloride penetration test (RCPT)

For RCPT, the epoxy-coated specimens of 100 mm in diameter and 50 mm in height were conditioned and tested at the age of 28 days in accordance with the method described in ASTM C1202 (2001). The charge passed (Coulomb) was determined by applying voltage of 60 V dc. The reported results were an average of two samples.

2.4.2. Immersion test (IMT)

The immersion test of mortar was performed using 3% NaCl solution. The test set-up shown in Fig. 2 was similar to that described in RTA T263 (RTA 2001, Chindaprasirt *et al*. 2008). The samples were prepared in the same manner as the RCPT samples. The specimens of 100 mm in diameter and 50 mm in height were used. Apart from coating the epoxy around the cylindrical surface, its top surface was also epoxy-coated. At the ages of 28 days the specimens were immersed for 30 days. The specimens were then split and the chloride penetration depths were determined using 0.1 M $AgNO_3$ solutions (Otsuki *et al*. 1993).

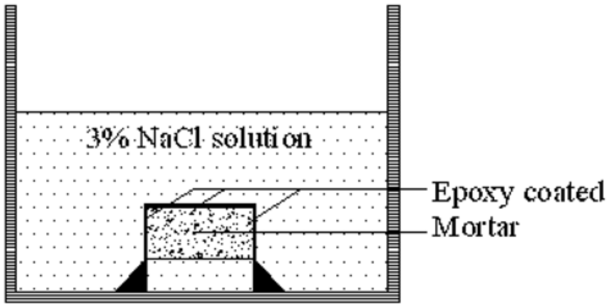

Fig. 2 Immersion of mortar specimen in 3% NaCl solution

3. Results and discussions

3.1. Superplasticizer (SP) content

The results of SP requirement of the mortar mixes to produce a similar flow are shown in Table 3. The incorporation of POA increased the SP requirement comparing to the normal OPC mortar. The SP content of the OPC mortar was 1.9%. The SP content of 20POA only slightly increased to 2.1%, but that of 40POA mixes significantly increased to 3.3%. The incorporation of GS had a small effect in the SP requirement of the mix. The SP contents of 20GS and 40GS mixes containing were 1.3% and 1.9%. The results indicated that the use of up to 20% of POA and 40% of GS produced mixes with similar SP requirement to the OPC mixes. POA particles are very irregular with cellular surface and high surface area (Chindaprasirt *et al*. 2008). This significantly increases the SP requirement of the mix to produce similar flow. On the other hand, the GS particles are solid and angular which are similar to the shape of the cement particles. The additions of GS, therefore, had little effect to the SP requirement of the mixes.

3.2. Results of compressive strength

The compressive strength of mortars is given in Table 4. The 7, 28 and 90 days strengths of OPC mortars were 43.5, 57.0 and 60.0 MPa respectively. At replacement dosages of 20% and 40%, the

Table 4 Compressive strength and normalized of mortar

Mix. ID	Compressive strength (MPa), (normalized)		
	7 d	28 d	90 d
OPC	43.5 (100)	57.0 (100)	60.0 (100)
20POA	43.5 (100)	57.5 (101)	62.0 (103)
40POA	32.5 (75)	53.5 (94)	61.5 (103)
20GS	40.5 (93)	47.5 (83)	51.5 (86)
40GS	24.0 (55)	34.5 (61)	38.0 (63)
20BPGS	40.5 (93)	48.5 (85)	53.0 (88)
40BPGS	32.5 (75)	47.5 (83)	52.0 (87)

Note *normalized* = % of OPC mortar strength strengths of GS mortars were and 55-93% of those of OPC mortars. At the 20% replacement level, the strengths were between 83-93% of the strengths of the OPC mortar. The reductions were slightly less than the reduction in the OPC content of 20%. For the 40% replacement level, the strengths were between 55-63% of the OPC mortar strengths. The reductions were on the average the same as the reduction in the OPC content of 40%. The strength reduction was, therefore, due to the reduced OPC content and the GS acted as inert filler and only exerted the packing effect.

For the POA, the 7 and 28 day strengths of 20POA mortar were approximately the same as those of OPC mortars at the same age. The higher strengths of POA mortars as compared to the GS mortars confirmed that the POA exerted the pozzolanic effect and contribute to the strength development of the mortars. For higher replacement level of 40%, the strengths of POA mortar were 75%, 94% and 103% of those of OPC mortar. Again, the strengths of the POA mortars were significantly higher than the GS mortars. The low early strength and the later age strength development are the common feature of the pozzolans (Chindaprasirt *et al*. 2008). In addition, the SP requirement at 20% POA replacement level was low. For the 40% POA replacement level, the SP requirement was high and also affected the strength of mortars.

For the use of blend of POA and GS, the strengths of 20BPGS mortar were excellent at 85–93% of those of OPC mortar. For the higher replacement level of 40%, the strengths of the 40BPGS mortar were still high at 74-87% of those OPC mortar at the same age. The rather good performance of mortar containing the blend of POA and GS in term of strength was associated with the synergic effect of the two fine materials in the cementitious system (Chindaprasirt *et al*. 2008, Isaia *et al*. 2003). The synergic effect was very significant especially at the early age and at the high replacement level. At the age of 7 days, the strength development of the 40BPGS mortar was 75% of that of OPC mortar in comparison to 55-75% when single GS or pozzolan was used. At the age of 28 and 90 days, the strength developments of the 40BPGS mortar were still good at 83% and 87% of those of OPC. These strengths were higher than the average between the 40POA and the 40GS mortar strengths.

3.3. Chloride penetration of mortar

3.3.1. RCPT results

Usually there is a risk of temperature rise in using RCPT test for mortar specimens. For this experiment, the temperature rise is not large, as the strength of mortar used is reasonably high at around 25-60 MPa. The results of the RCPT as shown in Fig. 3 indicated that the resistance to chloride penetration of the OPC mortar was intermediate at 7400 Coulombs at the age of 28 days. The replacements of OPC by GS greatly reduced the resistance to chloride penetration and the reductions were more with increases in the percentage of replacements. At the age of 28 days, incorporations of 20% and 40% of GS increased the charge passed to 11600 and 13200 Coulombs. The reduction in the resistance to chloride penetration was a result of the reduced OPC and the reduced hydration products. The incorporation of the GS acted as filler and caused only the packing effect and hence reduced both the strength and the resistance to chloride penetration of mortars.

The replacement of OPC with POA, on the contrary, greatly improved the resistance to chloride penetration of the mortars. At the age of 28 days, incorporations of 20% and 40% of POA reduced the charge passed to 1900 and 1050 Coulombs. The improvement was associated with the filling effect and the increased nucleation sites and pozzolanic reaction of the fine POA particles with high surface area and the much reduced $Ca(OH)_2$ of the mortars (Chindaprasirt *et al*. 2008).

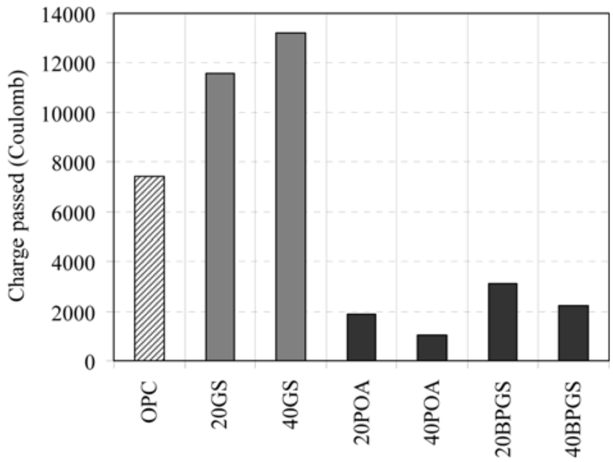

Fig. 3 Charges passed of rapid chloride penetration test (RCPT)

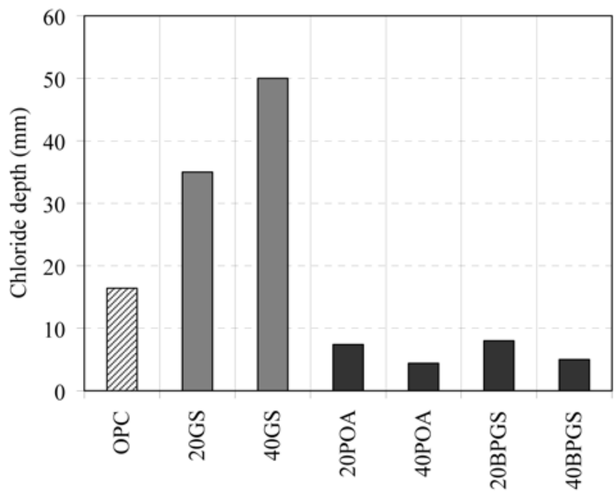

Fig. 4 Chloride depths after 30 days immersion in 3% NaCl (IMT)

For the use of blend of POA and GS, the charges passed of mixes containing blend of POA and GS were very low in comparison with OPC mortar. The charges passed at the age of 28 days of 20BPGS and 40BPGS mortars were relatively low at 3100 and 2220 Coulombs. These Coulomb charge values were very low considering the percentage replacements of POA were only 10% and 20% with the same amount of GS. It should be noted here that for the replacement of 20% POA alone, the charges passed were also at 1900 Coulombs. As already shown, the blend of POA and GS exerted some beneficial effect in term of strength. More significantly was the effect on improvement of the resistance to chloride penetration of mortar.

3.3.2. IMT results

The results of chloride penetration test of mortar immersed in 3% NaCl solution for 30 days as shown in Fig. 4 were similar to that of RCPT. The chloride depths of GS mortars were higher than those of OPC mortars at the same age. At the age of 28 days, the chloride depths of 20GS and 40GS mortars were 35 and 50 mm as compared to 16.5 mm of OPC mortar. For mortar with POA, the chloride depths of mortars were significantly lower than those of OPC and GS mortars. The chloride depths of 20POA and 40POA mortars were 7.5 mm and 4.5 mm. This is consistent with the results of RCPT which also give rather low charges passed of 1050-1900 Coulomb for these mortars.

For the use of the blend of POA and GS, the chloride depths of mortars were also very low in comparison with those of the OPC mortar at the same age. The chloride depths of 20BPGS and 40BPGS mortars at the age of 28 days were only slightly higher than those of the POA mortar at the same replacement level at 8 and 5 mm. The results confirm the synergic effect of the blend of POA and GS in reducing the chloride penetration of mortars (Chindaprasirt *et al.* 2008, Isaia *et al.* 2003). The tests were based on the actual immersion tests and hence gave the direct measure of the chloride penetration depth. The same trend of results thus reinforced the excellent resistance to chloride penetration of mortars containing POA or the blend of POA and GS.

3.4. Mathematical modeling

The second order polynomial mathematical analysis method using POA and GS contents were used to calculate the chloride depth of the mortar. The model of chloride depth could be expressed as follows:

$$C_d = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \tag{1}$$

where C_d = chloride depths,
x_1 = POA content by % replacement,
x_2 = GS content by % replacement.

$\beta_0, \beta_1, \beta_2, \beta_{11}, \beta_{22}$ and β_{12} were the regression coefficients obtained after the best fit to models using the least squares method.

The results were analyzed with two-parameter polynomial model at 30 days in 3% NaCl solution (after being cured in water until the age of 27 days). The equation for chloride depths based on the results of 7 mixes is obtained as shown in Eq. (2) with the coefficients, R^2 of 0.98. This equation was used to calculate the strength and porosity of the cement based materials successfully (Rukzon and Chindaprasirt 2008).

$$C_d = 16.5000 - 0.8560 x_1 + 0.7560 x_2 + 0.0140 x_1^2 + 0.0020 x_2^2 - 0.0430 x_1 x_2 \tag{2}$$

From the chloride depth equations, the chloride depth of ternary blended mortars could be calculated using two factor variables or proportion of POA and GS for two experimental variables. Where C_d was chloride depth (mm) at 30 days in solution; x_1 was the amount of POA as partial cement replacement (%); x_2 was the amount of GS as partial cement replacement (%). The calculated chloride depths are agreed well with the experimental data (Fig. 5).

Fig. 6 presents the isoresponse curves of chloride depth showing the interaction of POA and GS for the domain studied in the ternary system. The computer graphic revealed the difference contribution to chloride depth between POA and GS. POA contribution to the chloride depth of the ternary system was larger than that of the GS as the region of high chloride depth lied close to the zero GS content axes. It should be reminded here that the POA used in this study was fine palm oil

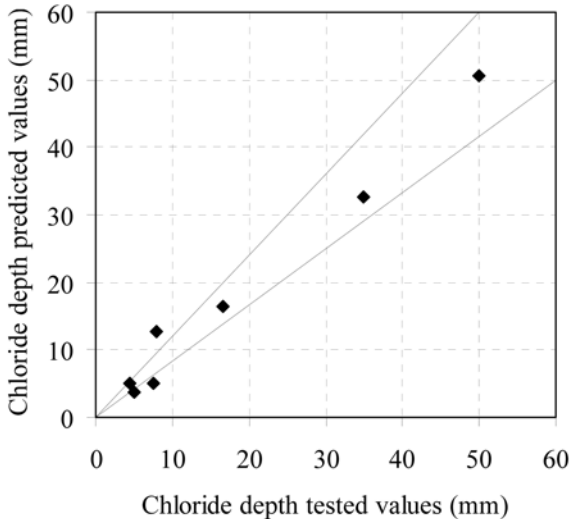

Fig. 5 Relationship between experimental and predicted values of chloride depth

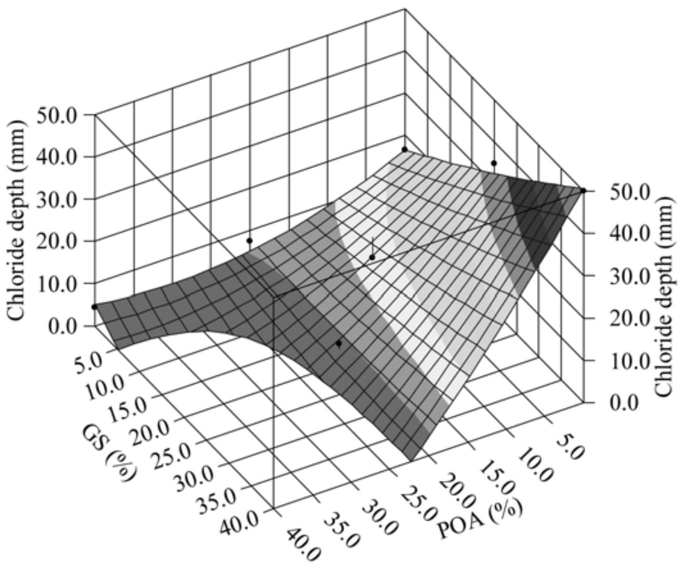

Fig. 6 Isoresponse curve for chloride depth (mm) of mortars

fuel ash and hence its properties and its effect on the strength and resistance to chloride penetration were better than the GS. The zone of minimum chloride depth is located high level of POA replacement and low level of GS replacement. The use of blend of GS and POA also produced mortars with excellent resistance to chloride penetrations as a result of the synergic effect of POA and fine particles of GS.

4. Conclusions

From the tests, it could be concluded that the resistance to chloride penetration of mortars was increased with the incorporation of POA and the blend of POA and GS. The use of GS to replace part of OPC in the mortar resulted in a filler effect and the strength and the resistance to chloride penetration were greatly reduced. For the incorporation POA, the relatively high compressive strengths were maintained owing to the pozzolanic reaction of POA while the resistances to chloride penetration as measured by RCPT and IMT tests were significantly improved. The improvement was associated with the filling effect and the pozzolanic reaction of the fine POA particles and the much reduced $Ca(OH)_2$ of the mortars.

The use of blend of GS and POA also produced mortars with relatively good strength and excellent resistance to chloride penetrations as a result of the synergic effect of POA and fine particles of ground sand. The results encourage the use of POA and GS, as a base material for cement replacement in concrete, which reduce the cost of cement, environmental effects, and the landfill area required for disposed of waste ash. Computer graphic in the form of isoresponse curves are easily formed and used to aid the understanding and the mix proportioning of the ternary OPC, POA and GS system.

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