

Strength development and thermal conductivity of POFA lightweight geopolymer concrete incorporating FA and PC

Satakhun Detphan¹⁾, Chattarika Phiangphimai¹⁾, Akaraphol Wachum¹⁾, Sakonwan Hanjitsuwan²⁾, Tanakorn Phoo-ngernkham^{*1)} and Prinya Chindaprasirt^{3, 4)}

¹⁾Sustainable Construction Material Technology Research Unit, Department of Civil Engineering, Faculty of Engineering and Architecture, Rajamangala University of Technology Isan, Nakhon Ratchasima 30000, Thailand

²⁾Program of Civil Technology, Faculty of Industrial Technology, Lampang Rajabhat University, Lampang 52100, Thailand

³⁾Sustainable Infrastructure Research and Development Center, Department of Civil Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002, Thailand

⁴⁾Academy of Science, The Royal Society of Thailand, Dusit, Bangkok 10300, Thailand

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Abstract

In this study, the compressive strength, water absorption, and thermal conductivity of palm oil fuel ash (POFA) lightweight geopolymer concrete (LWGC) incorporating high-calcium fly ash (FA) and Portland cement (PC) are reported. The POFA was replaced by FA or PC at the dosages of 60% by weight of binder. The wet density of POFA-based LWGC incorporating FA and PC was designed at 1000 kg/m³, based on ASTM C796. Test results found that the incorporation of FA and PC in POFA-based LWGC could significantly improve the strength development of LWGC. The reactive Ca ions could react with SiO₂ from POFA, leading to the additional formation of reaction products within the LWGC. The thermal conductivity of LWGC showed an excellent option for reducing the temperature change in the wall section during a day. It was positive effects on the building's electricity cost. A combination of POFA-based LWGC with PC met the 28-day strength and water absorption requirements as per TIS.2601-2556. Therefore, POFA-based LWGC incorporated with PC can be used as the non-load-bearing brick masonry units.

Keywords: Sustainable masonry unit, Lightweight geopolymer concrete, Strength development, Palm oil fuel ash, High-calcium fly ash, Portland cement

1. Introduction

Lightweight concrete has been widely used in the construction work because of its low density and low thermal conductivity. [1]. The air voids in lightweight concrete could produce by perlite, blast furnace slag, volcanic ash, and coal bottom ash, so on. Nowadays, cellular lightweight concrete (CLC) is getting more attention for applications in the concrete industry. CLC is a mixture of Portland cement, pozzolan, tap water, and foaming agents that produce a homogeneous void or cellular structure [2].

The advantages of good thermal and acoustic insulation, satisfactory workability, and self-flowing properties make the CLC a popular choice for building construction material [2]. However, CLC is still obtained from Portland cement (PC). Nagi and Jang [3] reported that every ton of PC production released approximately 0.82 tons of CO₂ into the atmosphere. To solve this issue, industrial by-products have been used to replace part of PC in order to reduce the CO₂ footprint [4-8]. A number of researchers [4-8] have studied the environmental friendly alternative to normal PC. This material called "Geopolymer binder" [9]. Geopolymer binder is generally produced by fly ash and high alkali solutions [10]. The main reaction product is sodium aluminosilicate hydrate (NASH) gel. For the system with high-calcium content, the main reaction products are calcium silicate hydrate (CSH) and/or calcium aluminosilicate hydrate (CASH) gels [10, 11]. The coexistence of NASH and CSH gels resulted in a high-strength alkali-activated binder [5, 12].

Palm oil fuel ash (POFA) is one of the pozzolanic material that contains large amounts of silica like FA. This POFA is obtained from palm oil residues, such as palm fiber and shells, burned at about 800–1000° C to produce steam for electricity generation in biomass thermal power plants [13, 14]. In Thailand, the annual output of POFA is approximately 100,000 tons. This POFA can be used as the precursor for making geopolymer; however, the strength development of POFA geopolymer is very low [15]. The temperature curing at around 60-70°C could improve its reaction degree [16, 17]. However, heat curing is not a good option for the construction industry, except in the precast industry.

Many researchers [5-7] reported that reactive CaO as additives in low-calcium geopolymer binder could enhance its strength development. For instance, PC and calcium carbide residue were used to replace bottom ash for producing the geopolymer binder [5]. Nowadays, high-calcium FA from the Mae Moh power station has been widely used as the precursor in Thailand. This FA showed suitable precursor materials for producing the geopolymer binder as reported by previous studies [8, 18]. The other interesting calcium-rich material is PC, although PC production released the CO₂ into the atmosphere. The PC content in geopolymer generated heat from

*Corresponding author. Tel.: +66 4423 3000

Email address: Tanakorn.ph@rmuti.ac.th

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the exothermic reaction of PC hydration, as highlighted by Phoo-ngernkham et al. [19]. Therefore, this paper investigates the compressive strength, water absorption, and thermal conductivity of POFA lightweight geopolymer concrete (LWGC) incorporated with high-calcium FA and PC. The obtained knowledge would be instrumental for applying lightweight geopolymer concrete (LWGC) as an alternative masonry unit.

2. Experimental details and testing analysis

2.1 Materials

The precursors used in this study are palm oil fuel ash (POFA), high-calcium fly ash (FA), and Portland cement (PC). The POFA had specific gravity of 2.27, the median particle size of 41.4 μm , and Blain fineness of 6,850 cm^2/g . The FA had specific gravity of 2.69, the median particle size of 15.3 μm , and Blain fineness of 4,300 cm^2/g . While, PC had specific gravity, median particle size, and Blain fineness of 3.15, 14.6 μm , and 3,500 cm^2/g , respectively. The SEM images of POFA and FA are illustrated in Figure 1. Table 1 shows the chemical compositions of POFA, FA, and PC. The POFA mainly consisted of SiO_2 , K_2O with some other minor elements. FA mainly consisted of SiO_2 , Al_2O_3 , Fe_2O_3 , CaO with some other minor elements. The sum of SiO_2 , Al_2O_3 , and Fe_2O_3 is 57.62%, with 25.79% of CaO contents; thus, this FA confirmed Class C FA per ASTM C618-15 [20]. Besides, the PC comprised of CaO and SiO_2 . Fine aggregate with specific gravity of 2.63 and fineness modulus of 1.80 in saturated surface dry (SSD) condition was used for producing the LWGC.

Table 1 Chemical compositions of POFA, FA and PC

Materials	Chemical compositions (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
POFA	42.94	2.22	0.69	5.19	4.55	22.45	0.49	6.10	9.30
FA	29.32	12.96	15.64	25.79	2.94	2.93	2.83	7.29	0.30
PC	20.80	4.70	3.40	65.30	1.50	0.10	0.40	2.70	0.90

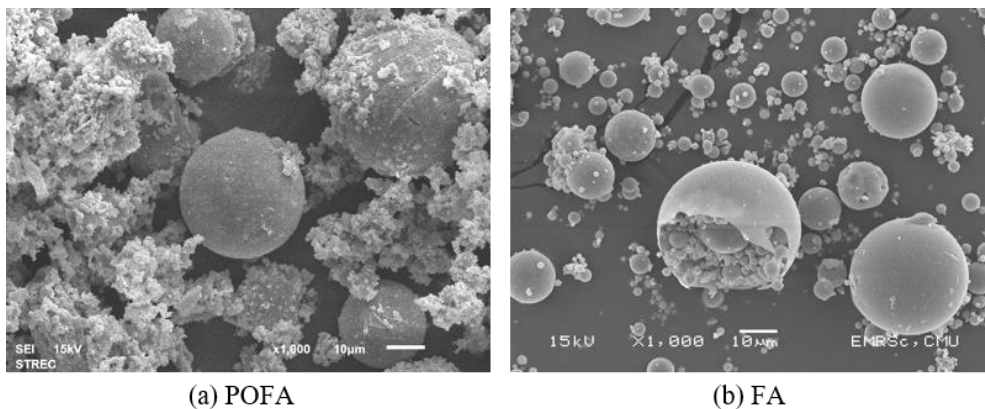


Figure 1 SEM Images of POFA and FA

For the foaming agent, it was used to make air foam for manufacturing the LWGC. The air foam was prepared by mixing the foaming agent with water at a ratio of 1:30 by volume. This ratio was based on the recommendation of manufacturer.

2.2 Mix proportions

The mix proportions of POFA-based LWGC incorporating FA and PC are summarized in Table 2. The wet density of POFA-based LWGC incorporating FA and PC was designed at 1000 kg/m^3 , based on ASTM C796 [21]. The 15M sodium hydroxide solution (NH) and commercial-grade sodium silicate solution (NS) with 11.67% Na_2O , 28.66% SiO_2 , and 59.67% H_2O were used as liquid activators with a constant NS-to-NH of 0.50. The 15M NH solution was selected for this study because it provided a high degree of geopolymerization as reported by Hanjitsuwan et al. [22]. The constant liquid alkaline-to-binder ratio of 0.40 and sand-to-binder ratio of 1.0 were used.

For mixing of the LWGC, precursors and sand were dry mixed first until the mixture was almost uniformly mixed, which took approximately 60s. Then, the NS and NH solutions were added to the mixture, and the mixing was continued again for another 30s. Then, the foaming agent was added and the mixing was done for 90s. The fresh POFA-based LWGC incorporated with FA and PC is shown in Figure 2.

Table 2 Mix proportions of POFA-based LWGC incorporated with FA and PC

Symbol	Mix proportions (kg/m^3)							
	POFA	FA	PC	Sand	Foaming agent	Tap water	NH	NS
100POFA	450	-	-	450	0.91	27.4	240	120
40POFA60FA	198	275	-	450	0.97	29.0	240	120
40POFA60PC	198	-	275	450	0.99	29.7	240	120
40POFA30FA30PC	198	137	137	450	0.98	29.4	240	120



Figure 2 Fresh LWGC

2.3 Testing procedure

The fresh LWGC was placed into a 75x150 mm cylinder mold for the compressive strength test (see Figure 3). The preparation of the sample was done as described in ASTM C39 [23]. After the casting of samples, all samples were protected the moisture loss by using the vinyl sheet for 3 days in a room at $25\pm 2^\circ\text{C}$. Then, they were de-molded with immediately wrapped by the vinyl sheet and kept in a room at $25\pm 2^\circ\text{C}$ until testing ages of 7, 14, 28, and 60 days. The reported results are the average of the three samples. The test set-up of compressive strength specimens is shown in Figure 4.



Figure 3 LWGC Samples



Figure 4 Test set-up of compressive strength test



Figure 5 Water absorption test

The water absorption test was adapted from TIS.2601-2556 [24] using a 100x100x100 mm cube mold (see Figure 5). The water absorption of the LWGC samples was examined at a curing period of 28 days. The reported results are the average of the three samples. Eq. (1) was used to calculate the water absorption value of LWGC [24].

$$WA (\%) = \left(\frac{W_a - W_d}{W_d} \right) \times 100 \quad (1)$$

Where WA is water absorption (%), W_a is the weight in air of saturated sample (g), and W_d is the weight of the dried sample (g).

The ISOMET2114 instrument was used to measure the thermal conductivity of LWGC. For the sample preparation, the fresh LWGC was placed into a 100x200 mm cylinder mold. After that, the samples were de-molded after 3 days and wrapped with the vinyl sheet for a 28-day curing period in a room at $25 \pm 2^\circ\text{C}$. Three samples were tested to calculate the thermal conductivity value. The measurement details were reported in the work of Wongsu et al. [25]. The test set-up of thermal conductivity specimens is shown in Figure 6.



Figure 6 Thermal conductivity test

3. Results and discussion

3.1 Compressive strength

Table 3 shows the results of the compressive strength of POFA-based LWGC incorporating FA and PC. According to Table 3, the strength development of LWGC is remarkably increased as the replacement levels of FA and PC increased. The compressive strength of the 100POFA is very low because of the low reaction process at ambient temperature and high K_2O content. High K_2O content could delay the setting time of the geopolymer binder, similarly to the dissolution of the NH solution [22]. When the mix incorporated with FA, the strength development of the 40POFA60FA mix was higher than that of the 100POFA mix. The reactive SiO_2 and CaO from FA helped speed up the geopolymerization, leading to an increase in its compressive strength. Sun and Li [10] demonstrated that the CaO from FA reacted with SiO_2 from POFA and FA. Hence, the formation of CSH and NASH gels were formed [10].

Table 3 Compressive strengths of POFA-based LWGC incorporating FA and PC

Symbol	Compressive strength (MPa)			
	7d	14d	28d	60d
100POFA	0*	0*	0*	0.15
40POFA60FA	0.92	0.76	1.54	1.71
40POFA60PC	2.22	2.98	3.33	3.62
40POFA30FA30PC	1.14	1.55	2.01	2.55

* = very low strength.

For the mix with PC content (40POFA60PC mix), the strength development of LWGC is similar to that of the 40POFA60FA mix. These results are consistent with the findings of Phoo-ngernkham et al. [19] and Pangdaeng et al. [7]. The readily available Ca ions from PC reacted with SiO_2 from POFA and then formed the formation of CSH gel, in which coexisted with NASH gel. Also, the reaction products within the matrix were accelerated by the hydration process [19]. This led to high strength development of the LWGC. According to Table 3, it is noticed that the strength development of POFA-PC blends and POFA-FA-PC blends is higher than that of POFA-FA blends. This agrees with the works of Chindaprasirt et al. [12] and Hanjitsuwan et al. [5]. The tricalcium silicate (C_3S) and dicalcium silicate (C_2S) existing in PC were high reaction degree compared to calcium oxide (CaO) existing in FA [12].

According to Table 3, the 28-day strength of the 40POFA60PC mix meets the 28-day strength requirement (>2.5 MPa) as per TIS.2601-2556 [24]. Therefore, POFA-based LWGC incorporated with PC satisfies the strength requirement for the non-load-bearing brick masonry units.

3.2 Water absorption

The results of water absorption of POFA-based LWGC incorporating FA and PC are shown in Figure 7. For the 100POFA mix, the sample could not be tested because the sample was still unhardened like the case of strength test. The water absorption of the

40POFA60FA, 40POFA60PC, and 40POFA30FA30PC mixes are 27.8, 12.3, and 26.4%, respectively. As reported, the water absorption of the 40POFA60PC mix was lower than those of the 40POFA60FA and 40POFA30FA30PC mixes. Yip et al. [26] reported that the increasing amount of Ca content modified its microstructure through the increase in CSH gel. This also agreed with Chindapasirt et al. [12] that the pore structures of LWGC were modified due to the C_3S and C_2S existing in PC reacted with SiO_2 from POFA and hence the pozzolanic reaction in POFA-PC blends was formed [5]. This helped the strength development and refined the pore structure of GFC.

According to Figure 7, the 28-day water absorption of the 40POFA60PC mix meets the 28-day water absorption requirement ($<23\%$) as per TIS.2601-2556 [24]. Therefore, POFA-based LWGC incorporated with PC cured at ambient temperature satisfies the water absorption requirement for the non-load-bearing brick masonry units.

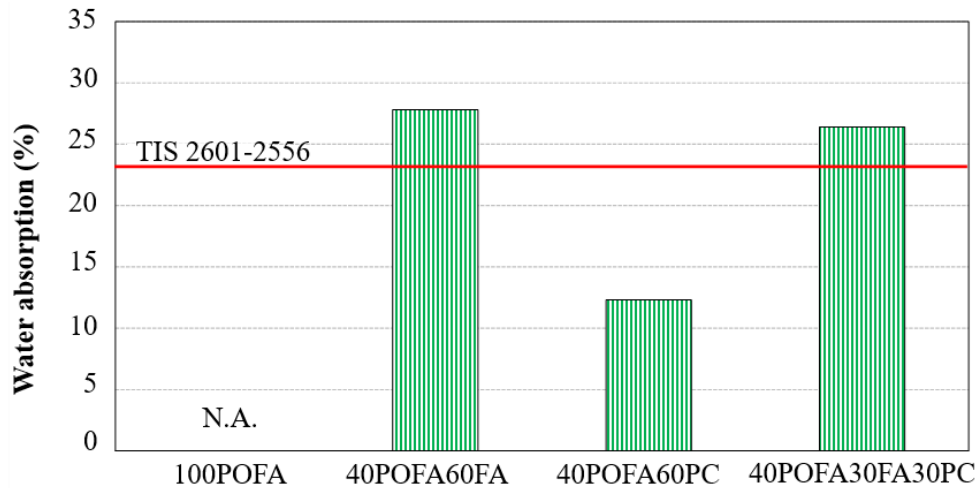


Figure 7 Water absorption of POFA-based LWGC incorporating FA and PC

3.3 Thermal conductivity

The results of thermal conductivity of POFA-based LWGC incorporating FA and PC are shown in Figure 8. The thermal conductivity of LWGC in this study ranges between 0.551-0.647 W/m.K. As shown in Figure 8, the thermal conductivity values of this study were higher than that of insulating lightweight concrete (CLC and AAC brick), as reported in ASTM C332-17 [27]. The thermal conductivity values of CLC and AAC brick were approximately 0.15 and 0.43 W/m.K, respectively [27]. However, they were lower than that of clay brick, about 1.15 W/m.K. Besides, the results of thermal conductivity of LWGC were higher than that of LWGC with crumb rubber that ranged between 0.235-0.30 W/m.K [25]. According to Figure 8, it can be concluded that the non-load-bearing brick masonry unit made from POFA-based LWGC incorporating FA and PC is lovely to reduce the temperature change in the wall section during a day. It corresponds to reduce the electricity cost of the building.

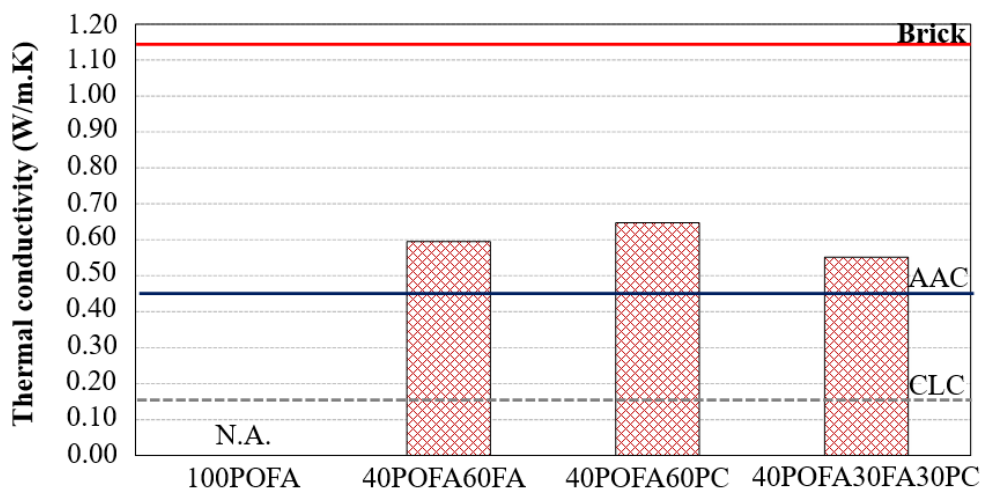


Figure 8 Thermal conductivity of POFA-based LWGC incorporating FA and PC

4. Conclusions

From the results obtained, the following conclusions are drawn:

1. The incorporation of FA and PC in POFA-based LWGC could significantly improve the strength development of LWGC. High Ca content existing in FA and PC could react with SiO_2 from POFA and FA, resulting in the additional formation of reaction products within the matrix.
2. The water absorption of POFA-based LWGC with PC was lower than those of POFA-based LWGC incorporated with FA. The reactive C_2S and C_3S existing in PC would react with SiO_2 from POFA, leading to the refinement of pore structure of LWGC.

3. The thermal conductivity values of LWGC were higher than both of CLC and AAC bricks; however, they were lower than that of clay brick. A reduction of temperature change in the wall section during a day would reduce the building's electricity cost.

4. The POFA-based LWGC with PC is recommended due to its great improvement on strength development, water absorption, and thermal conductivity of LWGC when compared with that of POFA-based LWGC with FA.

5. A mixture of 40%POFA and 60%PC for producing the LWGC met the 28-day strength and water absorption requirements as per TIS.2601-2556. Therefore, POFA-based LWGC incorporated with PC can be used as the non-load-bearing brick masonry units.

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