Strength Development of Fly Ash-Perlite Based Geopolymer Mortar Using Recycled Waste Glass as Fine Aggregate

Methawee Sriwattanapong Photisan* and Onanong Sangphong

Department of Construction Engineering, Faculty of Industrial Technology, Nakhon Ratchasima Rajabhat University, Nakhon Ratchasima, 30000 Thailand

* Corresponding author. E-mail address: methawee.p@nrru.ac.th

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Abstract

In this paper, the synthesis of geopolymer mortars using fly ash and perlite with mixing recycled waste glass as a partial fine aggregate replacement was studied. Perlite was used to replace fly ash at weight percentages of 0 to 10, 20, 30, and 40. Waste glass was crushed with the size close to sand. Sand was replaced by waste glass at 20% by weight. Sodium silicate and 10 molar sodium hydroxide solutions were prepared as alkali activator. The workability, strength development, and fire resistance of geopolymer mortars were investigated. The results indicate that the flow and compressive strength of mortars decreased with an increase in perlite content. The strengths of fly ash-perlite geopolymer mortars at 28 days were in the range of 44 to 51 MPa, which is suitable for some engineering applications. The high strength for refractory applications was 95 MPa (70FA30PL), which increased as the sintering temperature increased.

Keywords: geopolymer, fly ash, perlite, waste glass, compressive strength, fire resistance

Introduction

Concrete is the most fundamental building material in the world, and cement is the primary ingredient used in its manufacturing. However, there is an urgent need to cut cement use, which accounts for 5-8 percent of world carbon dioxide emissions (Matalkah, Aqel, & Ababneh, 2020). Geopolymer has being explored as a viable replacement for traditional concrete (Haddad, Ashteyat, & Lababneh, 2018). The binding materials are mostly pozzolanic compounds and fairly priced alkali activators. The use of geopolymer is intended to alleviate environmental issues related with the emission of hazardous gases during the manufacturing of ordinary cement. The strength of geopolymer is comparable to that of regular ordinary Portland cement. Both the texture and appearance are similar. Furthermore, it is well known that geopolymer has good fire and acid resistance (Duxson et al., 2007).

Fly ash (FA) has been utilized as a precursor in the manufacturing of geopolymer cement and binder all over the world. The final chemical composition of fly ash may change depending on plant type and combustion temperatures. In this context, suitable fly ash characteristics for alkali activation have been proposed (Solouki, Viscomi, Lamperti, & Tataranni, 2020). The largest source of fly ash in Thailand is that produced by the Mae Moh coal-burning power plant in Lampang province. Mae Moh power station produces around 3 million tons of fly ash each year (Chindaprasirt, Chareerat, Hatanaka, & Cao, 2010). In Thailand, this fly ash has been utilized widely in concrete building as a partial replacement for ordinary Portland cement.

Perlite (PL) is a volcanic glass. Because it expands into a cellular substance when heated to 900°C, it is often used in construction as a lightweight aggregate or for insulation. Unexpended perlite, due to its amorphous form and the ratio between silica and alumina, is an effective natural pozzolan. These characteristics imply that perlite with alkaline solutions can be activated (Erdogan, 2015). The area with perlite in Thailand covers in Kanchanaburi and Lopburi provinces, with the capability of perlite production of over 10,000 tons annually (Sriwattanapong, Sinsiri, Pantawee, & Chindaprasirt, 2013). In a previous investigation, the productions of perlite geopolymer (Vance et al., 2009) and geopolymer foam insulation (Vaou & Panias, 2010) have been reported but the strengths achieved are very low. As such, the combination of fly ash-perlite should be usable with the necessary alkali activators for making strong geopolymer.

In today's rapidly expanding society, waste management has emerged as a critical concern. The world's population is continually rising, resulting in unprecedented amounts of waste. In Thailand generated 23.93-27.40 million tons of municipal solid waste in the year from 2008 to 2017 (Warnphen, Supakata, & Kanokkantapong, 2019). Glass is non-biodegradable, which is disposed of in landfills and dumped as waste material and this causes environmental pollution. Fortunately, glass can be recycled and reused for various purposes. Due to the massive consumptions and widespread construction, the use of waste glass in building has attracted a great many interests worldwide. Many studies have been conducted to investigate the use of waste glass as a replacement for natural aggregate in concrete. Batayneh, Marie, and Asi (2007) examined the compressive strength of concrete mixes including 0-20% recycled waste glass as a proportion of aggregates, finding that as replacement for fine aggregates up to 20% of waste glass has proven to be the most efficient. Ali and Al-Tersawy (2012) also observed that as the waste glass content increased, the performance deteriorated; this was due to the internal structure, as there was insufficient contact between the cement paste and waste glass, resulting in excessive smoothness of the waste glass, which led to fractures.

From the viewpoint of locally available materials, this work aimed at studying the compressive strength and fire resistance of geopolymer mortars using fly ash and perlite as their powder binder and managing recycled waste glass used as a partial fine aggregate replacement in geopolymer mortar production.

Methods and Materials

Materials

The main materials used in this research were fly ash, perlite, alkali activator, river sand, and waste glass used as a fine aggregate.

Fly ash from power plant, in Thailand was used. Perlite was prepared by grinding in a laboratory ball mill in order to obtain mean particle size of about 36.5 µm. The chemical and physical characteristics are given in Table 1. Sodium silicate (Na_2SiO_3) and 10 molar (M) sodium hydroxide solutions (NaOH) were used as alkali activator.

River sand with specific gravity of 2.63 and water absorption of 0.20% was used for making geopolymer mortars. Waste glass was crushed with the size close to sand, having specific gravity of 2.51 and water absorption of 0.16%. The particle size distribution curves of the materials are shown in Figure 1 (Photisan & Sangphong, 2021). In this study, the waste glass came from clear and colored soda-lime bottles obtained after consumption.

Table 1 Chemical compositions and physical properties of fly ash and perlite

Chemical compositions (%)	Fly ash	Perlite
SiO_2	45.2	73.7
Al_2O_3	24.0	9.18
Fe_2O_3	10.6	2.75
CaO	12.6	1.72
MgO	2.92	1.09
K_2O	2.56	10.0
SO_3	1.58	0.02
LOI	0.53	1.02
Physical properties		
Mean particle size (µm)	25.6	36.3
Specific gravity	2.21	2.43

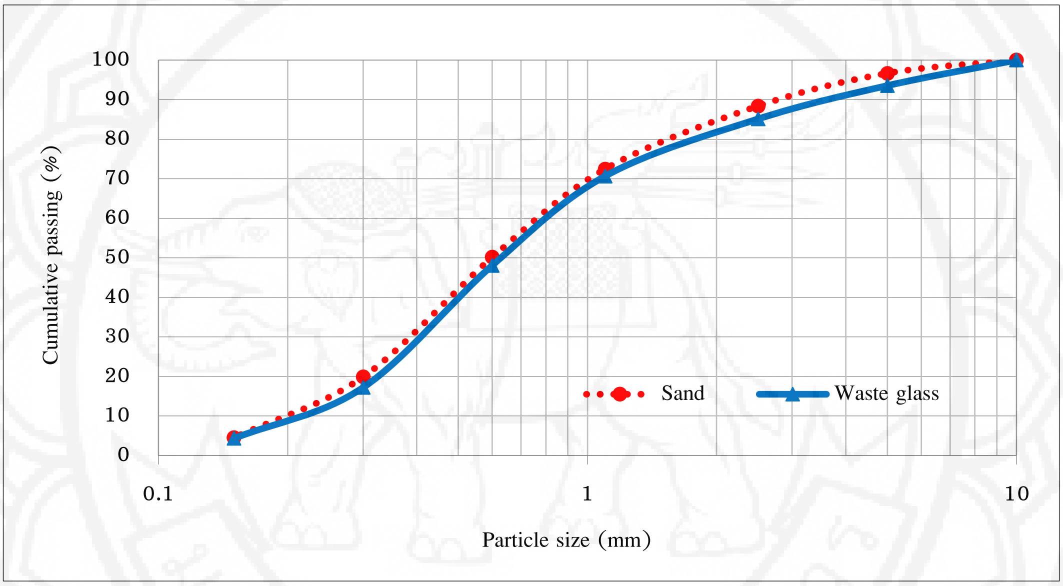

Figure 1 Particle size distributions of sand and waste glass

Methods

The geopolymer mortars used in the study were from a mixture of fly ash-perlite with a liquid alkali activator, which is a mixture of 10 molar sodium hydroxide solution and sodium silicate solution.

The ground perlite was used to replace fly ash at percentages of 0, 10, 20, 30, and 40 by weight, designated as 100FA, 90FA10PL, 80FA20PL, 70FA30PL, and 60FA40PL, respectively. Waste glass used as a partial replacement for river sand at 20% by weight was prepared.

The geopolymer mortars were prepared using Na_2SiO_3-to-10 M NaOH solution ratio of 1.50 and alkali activator solution-to-binder ratio of 0.67. The workability of fresh mortars was controlled by keeping the percentage flow of 110±5%. The fine aggregate-to-binder ratio in all geopolymer mortars was 1.50. Table 2 shows the mixture proportions by weight used in the geopolymer mortars.

Table 2 Mixture proportions of the fly ash-perlite geopolymer mortars

Sample	Content of materials (kg/m^3)					
	Fly ash	Perlite	Sand	Waste glass	Na_2SiO_3	NaOH
100FA	888	-	1066	266	357	238
90FA10PL	799	89	1066	266	357	238
80FA20PL	710	178	1066	266	357	238
70FA30PL	622	266	1066	266	357	238
60FA40PL	533	355	1066	266	357	238

The mixing procedures, fly ash and perlite were completely combined dry to produce a homogeneous powder. The mixture was then added with an alkali activator solution for 7 minutes. This was followed by the incorporation of fine aggregate with a final mixing of 3 minutes. Immediately upon mixing, the flow value of fresh geopolymer mortars was measured in accordance with ASTM C1437.

After the determination of flow, the fresh mortar was molded into 50-mm test cubes. Two-layer placing and tamping were used to compact the mortar specimens. To prevent moisture loss, the specimens were wrapped in polyethylene foil. The mortar samples were removed from the mold after 24 hours and then kept in the controlled room under ambient conditions with the temperature of 23°C and 65% relative humidity until the testing age. The compressive strength tests were performed at the ages of 1, 7, and 28 days as described in ASTM C109. The findings of strength were the mean of three samples.

After 28 days of curing, the fire resistance tests were carried out. The mortar specimens were heated to 500 and 1000°C in an electric furnace at a rate of 5°C/min. Once the required temperatures were reached, the mortar samples were kept cooling at the same rate to room temperature for 60 minutes in the furnace.

Results and Discussion

Workability of mortar

The results of the workability of fly ash-perlite fresh geopolymer mortars containing amounts of waste glass up to 20% as fine aggregate are shown in Table 3. The flow of geopolymer mortar decreased with increasing content of perlite. The flow of 60FA40PL mortar was 103%, which was less than 110±5% prescribed by ASTM C1437, whereas the others were in the range of 109 to 114%. In general, fly ash improves fresh concrete by lowering the amount of water required for mixing and enhancing the flow behavior (Chindaprasirt et al., 2010). Fly ash particles with spherical shapes function as tiny ball bearings inside the concrete mix, giving a lubricant effect (American Coal Ash Association, 2003). For this perlite, it has been observed that the application of perlite after the grinding process was only limited if it is of an irregular shape, indicating the particle form has a significant impact on the workability of geopolymer mortars; further research is required to provide evidence for such transformations.

Table 3 Workability of the fly ash-perlite geopolymer mortars

Specimen	100FA	90FA10PL	80FA20PL	70FA30PL	60FA40PL
Flow of mortar (%)	114	114	112	109	103

Compressive strength

The effect of the fly ash-based geopolymer mortars incorporated with perlite prepared with mixing 20% waste glass on strength development is presented in Figure 2. The compressive strength ranged from 17 to 51 MPa, with the highest value achieved from 90FA10PL geopolymer mortar, which had dropped by 15% at 28 days when compared to the mortar without perlite (100FA). With an increasing perlite percentage, the strength clearly reduced. The compressive strength of the specimens increased with curing time, as predicted.

Many researches have been conducted to investigate the role of the silica-to-alumina ratio and its relationship to the mechanical characteristics of geopolymer. The silica-to-alumina ratio and the strength of a geopolymer have a strong correlation (Davidovits, 1991). It has been demonstrated that the strength of geopolymer is related to its composition and nanostructure. In this section of the work, the silica-to-alumina ratios and compressive strength of fly ash-perlite geopolymer mortars are plotted in Figure 3. The compressive strength of fly ash-based geopolymer mortars decreased from 60 to 44 MPa when the ratio of silica-to-alumina increased from 1.88 to 2.75. The obtained results supported the suggestion that the metakaolin-based geopolymer with a silica-to-alumina ratio less than 1.40 had a highly porous matrix, resulting in low compressive strength. When the ratio of silica to aluminum was increased by more than 1.65, the strength of the geopolymer improved before declining again at the maximum silica-to-alumina ratio of 2.15. The increase was ascribed to the geopolymer's homogeneous microstructure, whereas the decrease in strength for high silica-to-alumina ratio mixtures was caused by unreacted material, which was soft and acted as a defect in the binder phase (Duxson et al., 2005). Furthermore, the results also indicate that the fineness of the binders has an influence on the strength development of the geopolymer mortar. Fly ash dissolving in sodium silicate and sodium hydroxide solutions was faster and more effective for finer particle size fly ash (Sinsiri, Teeramit, Jaturapitakkul, & Kiattikomol, 2006).

It should be noted that the geopolymer mortar can attain appropriate later age strength. The strengths of fly ash-perlite geopolymer mortars at 28 days were in the range of 44 to 51 MPa which are acceptable for some engineering applications.

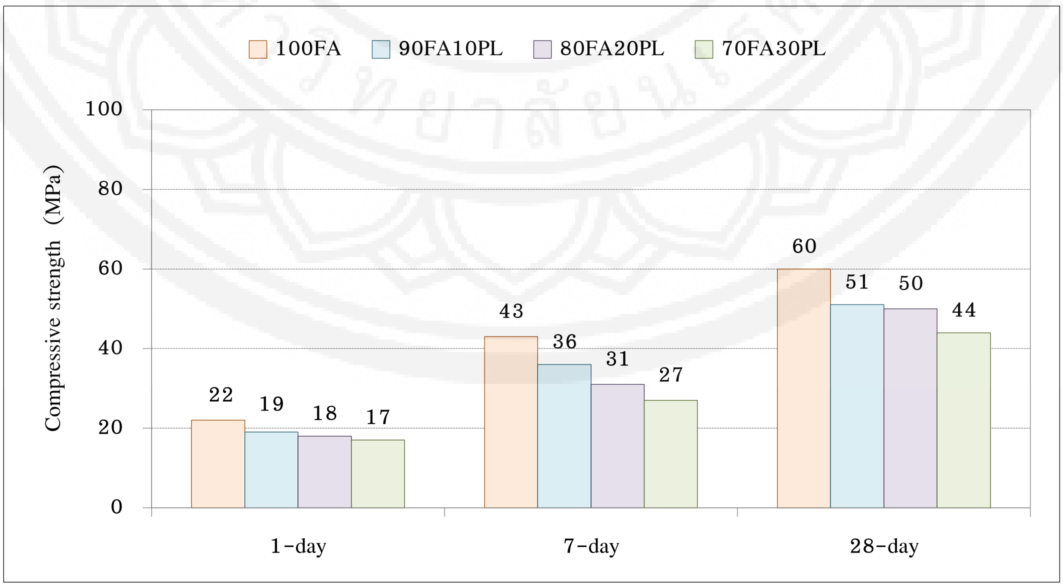

Figure 2 Compressive strength of fly ash-perlite geopolymer mortars at different ages of curing up to 28 days

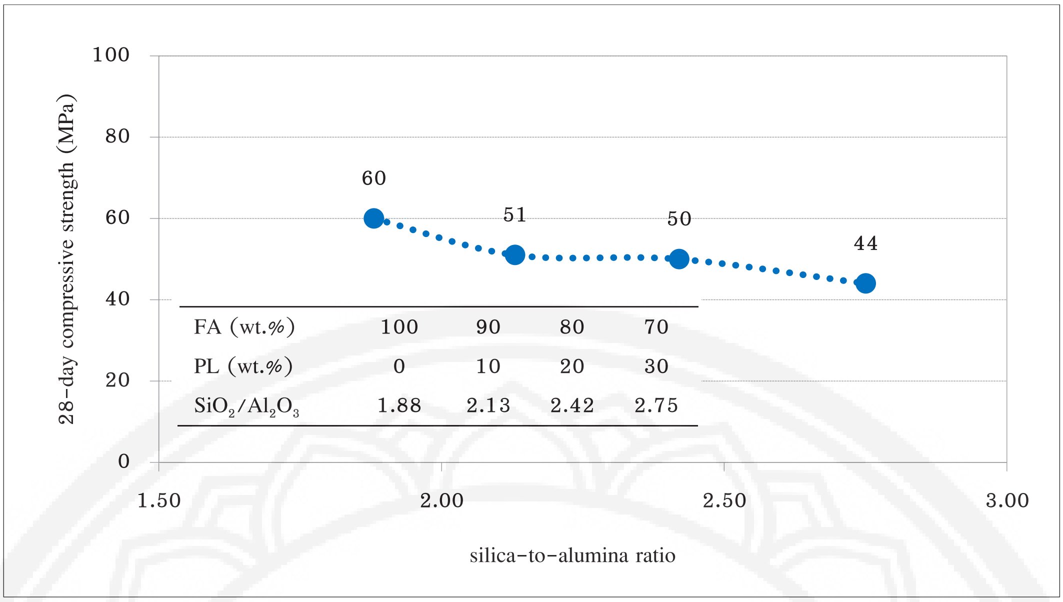

Figure 3 Compressive strength development of fly ash-perlite geopolymer mortars at different silica-to-alumina ratios

Fire resistance

Physical observation

Photographs of the physical observation of the exposed fly ash-perlite geopolymer mortars, including waste glass to the elevated temperatures of 500 and 1000°C, are illustrated in Figure 4. Fly ash has a dark grey color and is the main source material used in this work; mixing the fly ash content causes the specimens to become darker before being exposed to high temperatures. The mortars, however, became lighter after being exposed to high temperatures. The mortars had a light gray to yellowish brown color with smooth surface. Hager (2013) suggested that color changes in the geopolymer mixtures are comparable to those seen following high temperature exposures in ordinary Portland cement mixtures, mainly due to gradually dehydrated geopolymer binders and microstructural alterations within the aggregate. At higher temperatures, the fly ash-perlite geopolymer mortars did not exhibit volume changes and their shapes up to 1000°C.

(a) after exposed to 500°C (b) after exposed to 1000°C

Figure 4 Photographs of fly ash-perlite geopolymer mortars after exposed to (a) 500°C and (b) 1000°C

Compressive strength

The compressive strength results before and after elevated temperature exposures for fly ash-based geopolymer mortars prepared using perlite with 20% waste glass used as a partial fine aggregate replacement are presented in Figure 5. The results showed that the geopolymer samples gained their strength after heating to 500°C. It can be seen that the compressive strength of the geopolymer mortars increased by 48% on average of ambient compressive strength. This was due to the increase in polymerization reactions and high-temperature sintering (Abdullah et al., 2013). Once heated at 500 °C, 70FA30PL reached 95 MPa, which is the highest among the three fly ash-perlite geopolymer mortar mixtures. This trend is consistent with Pan and Sanjayan (2012), they found that all geopolymer samples tested at high temperatures improved significantly in compressive strength. They hypothesized that the geopolymer with low initial strength has more unreacted materials. At high temperatures, these unreacted materials will be transformed into reaction products by geopolymer reactions. The higher content of unreacted materials the higher strength increase, which is due to the high extent of geopolymer reactions. However, thermal incompatibility between geopolymer paste and fine aggregate had an effect on strength (Bhowmick & Ghosh, 2012). After being exposed to an elevated temperature of 1000°C, the mortars showed a very poor strength; the strength dropped by 88 %. Pan, Sanjayan, and Rangan (2009) also concluded that geopolymer mortars' strength trends after exposure to high temperatures rely on two factors: (1) further geopolymerization of the unreacted raw materials and/or sintering process resulting to increased strength; (2) thermal incompatibility damages leading to decreased strength. These two opposed processes take place simultaneously at elevated temperatures in geopolymer mortars and whether the strength increases or decreases is determined by the dominant process.

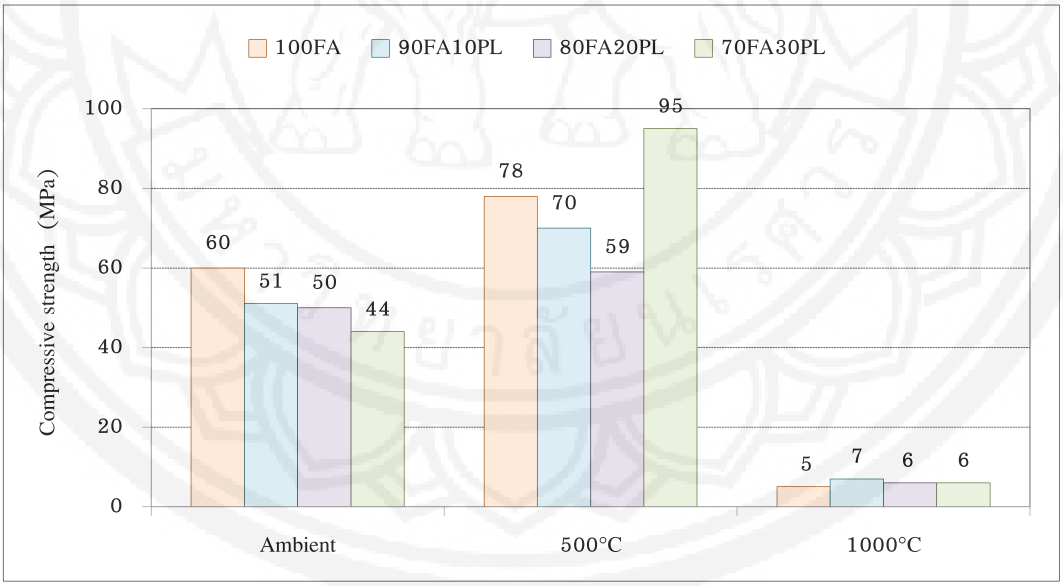

Figure 5 Compressive strength of fly ash-perlite geopolymer mortars at various temperatures

Conclusions

The compressive strength development of the geopolymer mortars using fly ash and perlite as their powder binder made with waste glass as a partial fine aggregate replacement has been investigated as well as their resistance to high temperatures. Main conclusions which can be drawn from this research are as follow:

1. Fly ash and perlite with mixing waste glass as a partial fine aggregate replacement can be used to produce geopolymer mixtures. Compressive strengths of 44-51 MPa after 28 days can be achieved.

2. Increasing perlite leads to loss of workability and reduce compressive strength; the maximum percentage replacement is 30%.

3. Silica-to-alumina ratio is crucial for compressive strength. The compressive strength of fly ash-perlite geopolymer mortars decreases from 60 to 44 MPa when the ratio of silica-to alumina increases from 1.88 to 2.75.

4. After exposure to high temperatures, the fly ash-perlite geopolymer mortars have a light gray to yellowish brown colour with smooth surface. Up to 1000°C, the mortars keep their forms with no deformation, peeling, or cracking on the surface.

5. The fly ash-perlite geopolymer mortars lose their strength after exposure to temperature of up to 1000°C, however, the mortars gain strength at 500°C. Hence, the geopolymer mortar strength can either be increased (sintering process) or reduced (thermal incompatibility) depending on the dominant process.

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