EVALUATION OF THE ENGINEERING PROPERTIES OF FLY ASH-BASED GEOPOLYMER BRICKS

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ABSTRACT

This paper is aimed to evaluate the engineering properties of fly ash-based geopolymer bricks. Four geopolymer brick mixtures were designed with a constant solution-to-binder ratio of 0.40 and various concentrations of sodium hydroxide solution. The engineering properties of fly ash-based geopolymer bricks consisting of compressive strength, unit weight, water absorption, water permeability, and ultrasonic pulse velocity were investigated. The microstructure of fly ash-based geopolymer bricks was also investigated by using the scanning electron microscope (SEM). Test results indicated that the compressive strength, unit weight, and ultrasonic pulse velocity (UPV) of geopolymer bricks increased, while the water absorption and water permeability of geopolymer bricks reduced with increasing NaOH concentration. Moreover, brick samples with high NaOH concentration showed a higher geopolymeric reaction of fly ash than brick samples with low NaOH concentration. All geopolymer brick samples produced in this study showed a good quality with compressive strength of above 10.1 MPa, water absorption of below 9.4%, water permeability of below 1.84 L/m².h, and UPV of above 2500 m/s.

Keywords: brick, compressive strength, fly ash, geopolymer, sodium hydroxide, ultrasonic pulse velocity, water absorption, water permeability.

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1. INTRODUCTION

Cement-based products are well-known as the second most used material in the world after water [1]. A large quantity of cement-based products, as well as cement, is annually generated, and it is still increasing due to the growth of population and human living conditions. However, the production of cement consumed an intensive amount of energy and released a large volume of greenhouse gases, significantly negatively impacting the environment. It was also a cause for the depletion of natural resources. Recently, geopolymer products have been found as an alternative solution to replace cement-based products [2-5]. It was concluded that geopolymer products had comparable or even better properties and lower

global warming potential than cement-based products. Those were also considered as cost-effective and green construction materials [6]. One of the potentials to replace cement is fly ash, a by-product of coal power plants. With a high content of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), fly ash is suitable utilization as an alkali-activated binder instead of cement in construction materials. Furthermore, the store of fly ash is large enough for the construction industry. In Vietnam, it is projected that 29 million tons of fly ash and bottom ash are released annually [7]. In which, amount of fly ash is a majority with about 80 percentages. Such amount of these ash stockpiled on landfills caused many problems related to air and water pollutions, agricultural land loss, and human health. Thus, the reuse of fly ash as a construction material gives both benefits in economics and the environment.

The use of fly ash as an alkali-activated binder was attractive to many researchers. With the activation of sodium hydroxide, Memon et al. [8] have successfully used fly ash as a binder material in self-compacting concrete. The application of fly ash in the mortar was also investigated in previous studies [9-11], in which fly ash was activated by a combination of sodium hydroxide and sodium silicate. It is worth noting that the compressive strength of mortar can reach to 50 MPa [11] if using a suitable ratio between the sodium hydroxide and sodium silicate solutions. Similarly, fly ash was also utilized to produce geopolymer pastes [10, 12-16]. Test results indicated that it was possible to produce a geopolymer paste incorporating fly ash with a compressive strength of 56 MPa [12]. The compressive strength and flexural strength of geopolymer pastes containing both fly ash and ground granulated blast furnace slag can reach to 100 MPa [15]. However, the different results were found for the influence of NaOH concentration on the compressive strength of pastes. Most of the studies stated that the compressive strength of geopolymer pastes increased with increasing NaOH concentration [10, 12, 13], whereas Somna et al. [16] reported that NaOH concentration exceeding 14M led to a reduction in compressive strength of paste. That may be due to the various quality of fly ash used in those studies [17-18].

Moreover, fly ash was also applied to produce geopolymer bricks. The paving blocks produced from fly ash and red mud under activation of NaOH solution had a compressive strength of above 16 MPa and water absorption of 6.0-7.0% [19]. Freidin [20] investigated the use of fly ash, bottom ash, and water glass as an alkaline activator to produce pressed blocks. The experimental results showed that the compressive strength and water absorption of pressed blocks ranged from 1.5-15.6 MPa and 5.8-38.4%, respectively. Furthermore, the geopolymer method was used to produce unfired building bricks containing fly ash, ground and unground rice husk ash, and sand under activation of sodium silicate and sodium hydroxide solutions [21-23]. Test results indicated that the engineering properties of those bricks conformed to the Vietnamese standard for unfired building bricks with compressive strength of above 20 MPa. The fly ash and NaOH of 10 M were used as activated-binder materials to produce unfired building bricks incorporating chippings and unground rice husk ash [7]. The compressive strength and water absorption of these bricks were 1.5-29 MPa and 3.7-31.9%, respectively.

Recycling fly ash as a binder material into geopolymer products such as concrete, mortar, paste, and brick has been studied by many researchers as mentioned above; however the database for geopolymer bricks is still limited. The objective of this study is to investigate the use of fly ash for the production of geopolymer bricks. The physical, mechanical, durable properties and microstructure of geopolymer bricks were examined. The influence of sodium hydroxide concentrations on engineering properties of fly ash-based geopolymer bricks was also investigated.

2. MATERIALS AND EXPERIMENTAL PROGRAMS

2.1. Materials

Geopolymer bricks in this study were manufactured from fly ash, chippings, and sodium hydroxide solution. Fly ash was locally sourced from a coal power plant in Thanh Hoa province of Viet Nam. The chemical composition and density of fly ash are shown in Table 1. According to ASTM C618 [24], it is classified as Class-F because of the total amount of silicon dioxide, aluminum oxide, and iron oxide greater than 70%. The scanning electron micrograph of fly ash is shown in Figure 1. The spherical shapes in various sizes are fly ash particles, while irregular shapes maybe are unburnt impurities. It is explained for high loss on ignition of fly ash (15.9%).

Chippings, which is a by-product from the process of stone crushing, was used as a fine aggregate in this study. The specific gravity, dry rodded weight, maximum size, fineness modulus, and water absorption of chippings are 2.69, 1.62 T/m³, 5 mm, 3.39, and 1.08%, respectively. Figure 2 shows the gradation curve of chippings. The sodium hydroxide solution was utilized to activate the fly ash. The concentrations of sodium hydroxide solutions are 5, 8, 10, and 12 M corresponding to their densities of 1.20, 1.28, 1.33, and 1.38 T/m³.

Table 1 Chemical composition and density of fly ash

Composition (wt.%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Others	LOI	Density
Fly ash	51.5	20.2	7.07	1.99	1.23	2.16	15.9	2.16

*LOI = Loss on ignition

Figure 1. Scanning electron micrograph image of fly ash

Figure 2. Gradation curve of chippings

2.2. Brick Mixtures

Table 2 shows mixture proportions for all fly ash-based geopolymer bricks. Four mixtures were designed with a fixed sodium hydroxide solution-to-binder ratio (S/B) of 0.4, referred to B40 in the nomenclature of mixtures. These numbers 5, 8, 10, and 12 following B40 denote concentrations of NaOH solution. The purpose of this design is to investigate the influence of NaOH concentrations on the engineering properties of fly ash-based geopolymers bricks. It is noticed that the amount of fly ash and NaOH solution were fixed to ensure a constant S/B ratio of 0.4, whereas the chippings content in each mixture varied to remain the total volume of all ingredients in one cubic meter. That is due to the various density of NaOH solution corresponding to different NaOH concentrations.

Table 2 Mixture proportions for sample preparation

Mixture	S/B	Ingredient proportions (kg/m ³)		
		Fly ash	Chippings	NaOH solution
B40-5	0.40	400.0	1833	160
B40-8			1856	
B40-10			1868	
B40-12			1880	

2.3. Samples Preparation and Test Programs

To produce geopolymer brick samples, fly ash was firstly mixed with sodium hydroxide solution to form a geopolymer paste. After that, chippings were added to the paste and continued mixing until the mixture becomes homogeneous. A steel mold with dimensions of 160×85×40 mm was used to form brick samples. A pressure of around 0.5 MPa was used during the process of sample forming. Brick samples were stored in the laboratory in natural conditions. The engineering properties of fly ash-based geopolymer bricks including compressive strength, unit weight, water absorption, and water permeability were tested complying with TCVN 6477 [25]. The uniformity of brick samples was assessed through the ultrasonic pulse velocity test (UPV). The microstructure of brick samples was evaluated by using the scanning electron microscope. It is noticed that the compressive strength and UPV of bricks were tested at 3, 7, 14, and 28 days, whereas others were conducted at 28 days. The average value of three measurements is used as the reported value in this study. The reported compressive strength values were multiplied by the shape adjustment coefficient of 0.7 as stipulated by TCVN 6477 [25].

Based on TCVN 6477 [25], the water permeability was calculated by the following equation:

$$H = \frac{V}{S \times T}$$

In which, H =water permeability (L/m².h); V =the volume of water absorbed through the brick sample (L); S =surface area of the brick sample contacted with water (m²); T =testing time (h). It is noticed that a brick sample was saturated in water before the water permeability test. The experiment of water permeability was conducted under pressure of 25 cm water column height.

3. RESULTS AND DISCUSSION

3.1. Compressive Strength

Figure 3 shows the compressive strength of fly ash-based geopolymer brick samples, which was developing over time due to the process of geopolymerization. The 28-day compressive strength of bricks ranged from 10.1 MPa to 25.2 MPa. It is noticed that compressive strength of around 7.5 MPa is used in real practice. It means that all fly ash-based geopolymer bricks produced in this study have a compressive strength of above 10 MPa, classifying as a high grade of brick [7]. In addition, as an increment in NaOH concentration, the compressive strength of brick samples increased. This result is in line with results from previous studies [10-13]. The high concentration of NaOH solution encouraged the dissolution rate of silicon and aluminum ions, thus enhancing the formation of aluminosilicate in geopolymerization [10, 12]. That resulted in improving the compressive strength of geopolymer brick samples. It is worth noting that the 28-day compressive strength of brick samples is higher than 25 MPa when using NaOH solution of 12 M as an alkaline activator. This strength value is as high as the strength of normal hardened concrete. This is demonstrated for the use of fly ash even with a high loss on ignition to produce geopolymer bricks.

3.2. Unit Weight

Figure 4 shows the unit weight of fly ash-based geopolymer bricks corresponding to NaOH concentrations. The unit weight of brick samples changed from 2.1 to 2.2 T/m³, which values are similar to that of practical cement concrete bricks manufactured in Vietnam. When NaOH concentration increased, the unit weight of brick samples slightly increased. This is due to the higher amount of chippings and a higher density of NaOH in brick mixtures with high NaOH concentration (Table 1). As mentioned above, NaOH solutions with concentrations of 5, 8, 10 and 12 M have densities of 1.20, 1.28, 1.33, and 1.38 T/m³, respectively.

Figure 3. Compressive strength of fly ash-based geopolymer bricks

Figure 4. Unit weight of fly ash-based geopolymer bricks

3.3. Water Absorption

As well as compressive strength, water absorption is an important property of building bricks. Because it is associated with water permeability and chemical attack resistance of bricks. That is why the Vietnamese standard for concrete brick limiting the maximum water absorption of lower than 14% [25]. The effect of NaOH concentration on the water absorption of fly ash-based geopolymer bricks is shown in Figure 5. As an increment of NaOH concentration, the water absorption of brick samples reduced. As mentioned above, the high NaOH concentration enhanced the formation of aluminosilicate, which leads to increasing in compressive strength and reducing in water absorption of geopolymer bricks.

The water absorption of geopolymer bricks in this study ranged from 3.1% to 9.4%, much lower than the maximum value stipulated by TCVN 6477 [25]. Both water absorption and compressive strength are related to NaOH concentration, thus they also have a relationship. Figure 6 shows the relationship between water absorption and compressive strength, it is described as a linear equation of $y = -0.42x + 12.86$ with $R^2 = 0.91$.

Figure 5. Effect of NaOH concentrations on water absorption of brick samples

Figure 6. Relationship between water absorption and compressive strength

3.4. Water Permeability

As well as water absorption, water permeability directly reflects the durable properties of bricks related to chemical attack resistance. The lower water permeability, the greater resistance to chemical attack. Therefore, the Vietnamese standard also limits the value of water permeability below 16 L/m².h [25]. The water permeability of geopolymer brick samples corresponding to various NaOH concentrations is illustrated in Figure 7. The water permeability reduced as increasing NaOH concentration. This is attributable to the high formation of aluminosilicate, preventing water absorbed through the brick sample. The water permeability of brick samples in this study varied from 0.23 to 1.84 L/m².h, significantly lower than the allowance value stipulated by TCVN 6477 [25] as mentioned above.

3.5. Ultrasonic Pulse Velocity

The relative quality of fly ash-based geopolymer bricks in this study was evaluated based on the ultrasonic pulse velocity (UPV) test. The UPV values of all brick samples are shown in Figure 8. At 28 days, the UPV values of brick samples ranged from 2500 m/s to 4521 m/s corresponding to NaOH concentration changed from 5 M to 12 M. In other words, the quality of geopolymer brick enhanced with increasing NaOH concentration. Similarly, this result is associated with the formation of aluminosilicate in the process of geopolymerization. That resulted in increasing compressive strength, reduction in water absorption and water permeability values as aforementioned. Based on results from previous studies, the UPV values of bricks ranged from 1700-2100 m/s and 2060-3150 m/s corresponding to the compressive strength of 6.0-15.0 MPa and 7.7-26.3 MPa [26-27]. In this study, brick samples with UPV values of 2500-4521 m/s had the compressive strength values of 10.1-25.2 MPa. It means that all geopolymer brick samples produced in this study are classified as good quality.

Figure 7. Effect of NaOH concentrations on water permeability of brick samples

Figure 8. Ultrasonic pulse velocity of fly ash-based geopolymer bricks

3.6. SEM Observation

Figure 9 shows the scanning electron micrograph images of all brick samples with a magnification of 2000 times. Many free fly ash particles as seen in spherical shapes and many voids were observed in brick samples with NaOH concentrations of 5 and 8 M. It means that with a low concentration of NaOH solution, fly ash is not effective to joint in geopolymeric reaction. For geopolymer brick samples using NaOH of 10 and 12 M, free fly ash was fewer and geopolymer formations were seen as large textures. This finding is related to other properties of fly ash-based geopolymer bricks as reported above.

Figure 9. SEM micrographs of fly ash-based geopolymer brick samples

4. CONCLUSION

In this study, the fly ash and sodium hydroxide solution were used as alkaline-activated materials to produce geopolymer bricks. Based on the obtained results, the following conclusions may be drawn:

- All geopolymer brick samples manufactured in this study were classified as good quality with compressive strength of above 10.1 MPa, water absorption of below 9.4%, water permeability of below 1.84 L/m².h, and ultrasonic pulse velocity of above 2500 m/s.
- As an increment in NaOH concentration, the compressive strength, unit weight, and ultrasonic pulse velocity of geopolymer bricks increased. The adverse trend was obtained for the water absorption and water permeability of geopolymer bricks.
- As observed in SEM images, the use of high NaOH concentration encouraged the fly ash joining in geopolymeric reaction, enhancing the properties of geopolymer bricks.

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