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Enhancement of Properties of Fly Ash Geopolymer Paste with Low NaOH Concentrations Using a Pressing Approach

Khamphee Jitchaiyaphum, Cherdsak Suksiripattanapong*

Department of Civil Engineering, Faculty of Engineering and Technology, Rajamangala University of Technology Isan, Nakhon Ratchasima, Thailand

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Abstract

Geopolymers are widely recognized as an eco-friendly alternative material. However, the impact of pressing stresses and low NaOH concentrations on their properties remains underexplored. This research aims to investigate the effects of pressing stresses on unit weight, porosity, water absorption, and compressive strength of high-calcium fly ash geopolymer paste with low NaOH concentrations. The low NaOH concentrations of 0.5, 1.0, and 2.0 M, pressing stresses of 10, 20, and 30 MPa, and liquid-to-binder ratios of 0.10, 0.12, 0.14, 0.16, 0.18, and 0.20 by weight are used. The specimens of geopolymer paste are oven-dried at 60°C for 24 hours before evaluation. The testing results show that the compressive strength of casted geopolymer paste is between 2 to 15 MPa, with higher compressive strength associated with lower porosity. The water absorption rate is between 11% and 21% by weight, which has a higher water absorption rate as the porosity increases.

Keywords: compressive strength, geopolymers, low molar, pressing approach

1. Introduction

In residential buildings in rural Thailand, hollow concrete blocks are considered an important alternative construction material because they are more economical than lightweight concrete blocks and fire clay bricks. Non-bearing hollow concrete blocks, most often used on unreinforced walls with a thickness of 70 mm, are unique among the materials available on the market as they are utilized extensively across the country. Generally, these blocks are made from cement mixed with small stones such as sand and rock dust in ratios of 1:2, 1:3, and 1:4 by weight, which provides different mechanical properties regarding unit weight and compressive strength. The blocks' production and characteristics are controlled per Thai Industrial Standards on TIS 58–2533, with a minimum compressive strength requirement of 2.5 MPa. However, ordinary Portland cement (OPC) is the main binder used to produce these blocks. The production of OPC significantly contributes to global CO_2 emissions [1], accounting for approximately 8 % of global greenhouse gas emissions [2-3].

Studying the properties of geopolymer materials as an OPC substitute has been a recent area of interest. Geopolymers are recognized as one of the new environmentally friendly alternative materials and are currently the focus of intensive development and research worldwide. They can be synthesized through geopolymerization from a solid aluminosilicate precursor leached with an alkaline activator, forming an amorphous and three-dimensional network structure at low temperatures [4-11].

* Corresponding author. E-mail address: cherdsak.su@rmuti.ac.th

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Coal fly ash-based geopolymers are an attractive and environmentally friendly option for various construction applications compared to OPC [12-18]. The coal fly ash (FA) is the main byproduct of the combustion process and is available in large quantities due to the lignite-fired power plants in Thailand [15]. Due to its high calcium content, FA provides rapid setting and high early strength compared to geopolymers made from other materials with low calcium content [19]. The workability and strength of geopolymer mortar from high calcium FA activated with sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were investigated, showing that the geopolymer mortar's flow rate and compressive strength ranged from 110 to 135 ± 5% and 10-65 MPa, depending on the Na_2SiO_3:NaOH ratio and NaOH concentration [20].

Moreover, the hydration processes of the high calcium FA-based geopolymer can transform sodium aluminosilicate hydrate (N-A-S-H) gels into calcium aluminosilicate hydrate (C-A-S-H) gels. The C-A-S-H gels effectively bind water to reduce permeability, resulting in a denser structure and higher strength performance than traditional low-calcium FA geopolymers [21].

However, the strength of geopolymers depends on many factors, such as the chemical composition and proportions of Si and Al. Inappropriate ratios can prevent the atoms from forming a continuous chain, resulting in low strength and inefficient leaching. Other factors include insufficient mixing time, the concentration of the alkaline solution used for leaching, moisture content within the geopolymer mixture, improper drying temperature, and too short drying time. These factors can cause the geopolymer framework to become unconnected. Zheng et al. [22] found that the compressive strength and microstructure of fly ash-based geopolymer were strongly influenced by the dosage of the alkaline activator and the Si/Al molar ratio. The highest strength was achieved at an intermediate alkaline activator dosage and Si/Al ratio, and the optimal Na/fly ash and Si/Al molar ratio was close to 2.8 mole/kg and 2.0, respectively. The higher alkaline activator dosage enhanced the structural disruption of the original aluminosilicate phases and a higher degree of polymerization of the geopolymer networks.

Takeda et al. [23] found that the weight of the FA geopolymer decreased as a result of water evaporation. The bonding mechanism of geopolymer particles was likely related to the presence of hydroxyl ions (OH) on each geopolymer particle. After being heated at 130 °C for 2 h, the particles containing OH can bond to each other by a dehydration reaction, releasing water to form a larger particle in three dimensions. The dense geopolymer with a high compressive strength was obtained. Ramujee and Potha Raju [24] found that the fly ash-based geopolymer concrete cured at moderate temperatures, between 60 °C and 90 °C, has strong durability and high initial mechanical properties.

Dinh et al. [25] found that in FA-based geopolymer, calcium (Ca) from ground granulated blast-furnace slag (GGBFS) and waste glass (WG) readily leaches out and reacts under both ambient and oven curing conditions, whereas Silicon (Si) only exhibits activity primarily in high-temperature environments. The reactivity of Ca from GGBFS and WG improved compressive strength and water absorption up to 50 % and 30 %, respectively. Moreover, based on the alkali leaching test, the most effective molar ratios (Si/Al = 3.5 – 4) demonstrated the highest compressive strength of 60 –70 MPa. Therefore, molding a geopolymer using a low alkali concentration under pressure is one option explored in this research.

This article aims to study the properties of geopolymer paste made from high-calcium FA activated with 0.5, 1.0, and 2.0 mole NaOH. The liquid-to-binder ratio (L/FA) of 0.12, 0.14, and 0.16 by weight were used. The specimens were formed with a jack under bearing stress of 10 MPa, 20 MPa, and 30 MPa per 10 cm thickness on a 10 × 10 cm cross-section, held for 1 minute, and dried at 60 °C for 24 hours. The porosity, compressive strength, and water absorption of the samples were evaluated. Furthermore, an equation was proposed to predict the compressive strength of FA geopolymer paste based on the known total porosity.

2. Materials and Methodology

Understanding the chemical and physical properties of the materials used, such as FA, Na_2SiO_3, and NaOH, was essential before analyzing the unit weight, porosity, water absorption, and compressive strength of high-calcium fly ash geopolymer paste with low NaOH concentrations.

2.1. Materials

Coal fly ash (FA) used in this study was high-calcium fly ash from a thermal power plant in Mae Moh District, Lampang Province, Thailand. It had a relatively spherical shape and smooth surface, as shown in the scanning electron microscopy (SEM) images in Fig. 1. According to Blaine's air permeability test, the FA had a specific gravity of 2.2, an average particle size of 14.10 µm, and a specific surface area of 4,050 cm^2/g.

The results of the chemical composition analysis by XRF of the FA are shown in Table 1. It was found that FA contains silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) of 42.94 % and 24.46 %, respectively. The sum of SiO_2, Al_2O_3, and ferric oxide (Fe_2O_3) is more than 70 % by weight, and FA is classified as class C FA. It also contains more than 10 % by weight of calcium oxide (CaO) and may be called high-calcium fly ash, according to ASTM C 618 [26]. In addition, it was found that FA had a loss on ignition (LOI) value of 1.48%, which was lower than the ASTM C 618 [26] that specified the LOI value not exceeding 6% w/w. The quantitative X-ray diffraction (XRD) analysis based on the Rietveld Method as the area below the curves which carried out using Bruker's TOPAS. The percentages of amorphous SiO2 of FA had a high amorphous content was 80.5% (by mass) or low crystallinity, as shown in Fig. 2.

The liquid sodium silicate (Na_2SiO_3) with 30 % SiO_2 and 9 % Na_2O was used at 1% by weight of FA. The sodium hydroxide (NaOH) used in this study was industrial-grade flake NaOH with a solid purity of 99%. Before the experiment, NaOH solution was prepared to achieve a purity of 100% by adding 1% NaOH and dissolving it in various water concentrations at a temperature of 23 ±2 °C, as shown in Table 2. The test results for preparing a NaOH solution or liquid (L) with a concentration level from 0.5 M to 14 M, dissolved in water within a flask with a volume of 1000 ml at a temperature of 23±2°C, are shown in Table 2. The relationship between the molar level and the liquid (NaOH + water) was linear. The equation for this linear function was y = 26.18x + 1051.6, with a multiple coefficient of determination (R^2) of 0.99, as shown in Fig. 3. This equation is used to calculate the proportions of liquid, NaOH, and water for different concentrations of NaOH solutions. It is also useful for determining the proportions of geopolymer paste mixtures.

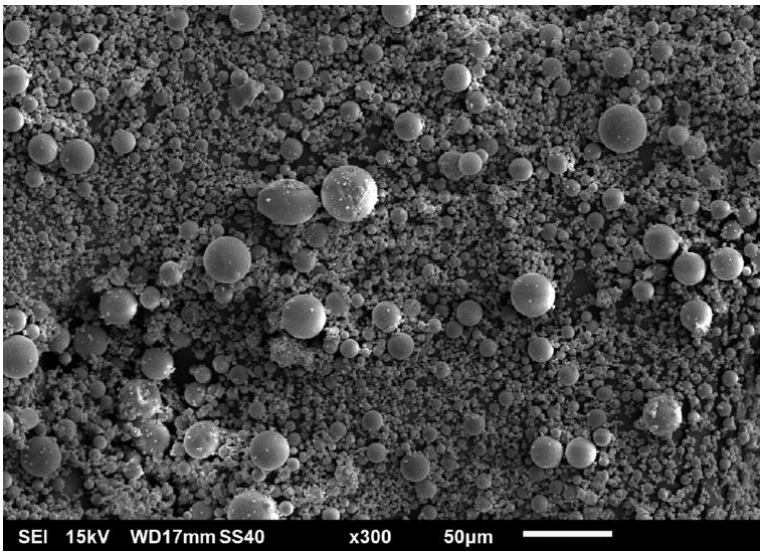


Fig. 1 SEM Image of FA

Table 1 Chemical composition in oxide form of FA

Chemical compositions	FA (% by mass)
SiO_2	42.94
Al_2O_3	24.46
Fe_2O_3	12.34
CaO	15.27
MgO	1.65
K_2O	1.33
SO_3	2.01
LOI	1.48

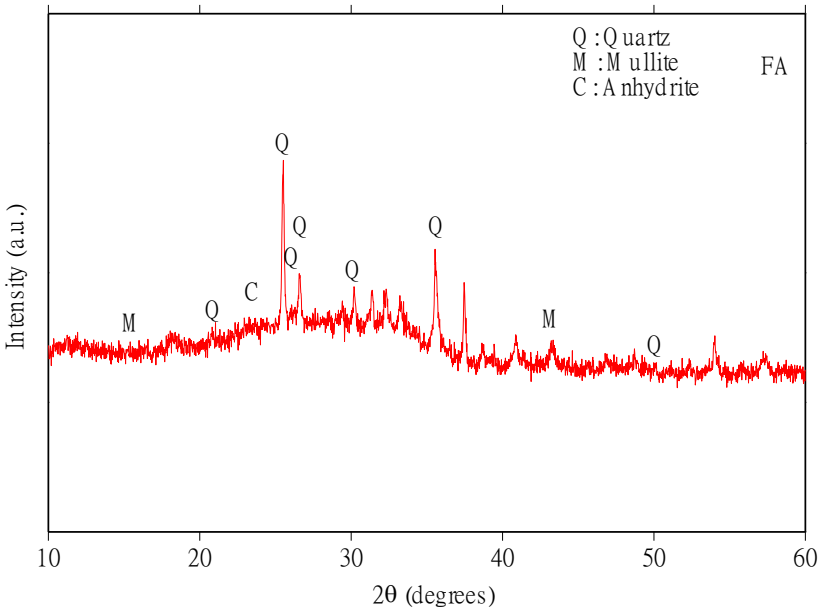


Fig. 2 XRD Pattern of coal fly ash

Table 2 Concentration of NaOH solution per 1 liter

Concentration of NaOH (mole)	100 % purity of NaOH (g)	Water (g)	Liquid (g)	The specific gravity of liquid at 23 ±2 °C
0.5	20.2	1057.6	1077.8	1.08
1.0	40.4	1046.5	1086.9	1.09
2.0	80.8	1025.2	1106.0	1.11
2.5	101.0	1015.0	1116.0	1.12
4.0	161.6	986.4	1148.0	1.15
5.0	202.0	969.0	1171.0	1.17
7.5	303.0	931.0	1234.0	1.23
10.0	404.0	901.0	1305.0	1.31
12.0	484.8	882.8	1367.6	1.37
14.0	565.6	869.7	1435.3	1.44

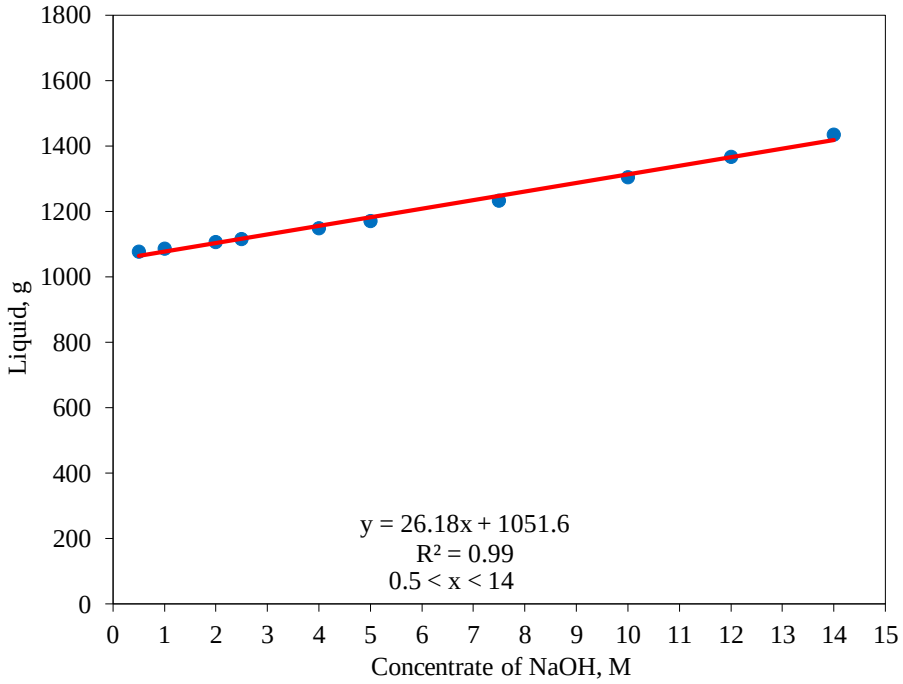


Fig. 3 Relationship between molarities and liquid

2.2. Mix proportions and testing

To obtain the optimum liquid content for preparing FA geopolymer paste, the FA with NaOH concentration of 0.5 M was dissolved using L/FA ratios of 0.10, 0.12, 0.14, 0.16, 0.18, and 0.20 and Na_2SiO_3 content was fixed at 1% by weight of the FA. Firstly, the FA dissolved with L for 10 minutes. Then, the fresh FA geopolymer paste was poured into 10 × 10 × 10 cm cube molds for three specimens, and a pressure jack on the top surface was used to apply a maximum bearing stress of 10 MPa for 1 minute. After pressing, the FA geopolymer paste was removed from the molds and sealed with plastic film before drying it at 60 °C for 24 hours. After drying, the samples were tested for compressive strength and dry unit weight.

The geopolymer paste had a dry density ranging from 1,367 to 1,760 kg/m³, with an average of approximately 1,559 kg/m³, as shown in Table 3. The L/FA ratio of 0.16 resulted in the lowest compressive strength and dry unit weight values. Meanwhile, the optimum compressive strength was found at an L/FA ratio of 0.20. However, the mixture with an L/FA ratio of 0.10 had poor compression molding efficiency due to the small amount of liquid, making the mixture dry and stiff. Conversely, the mix with an L/FA ratio of 0.20 tended to leak out of the mold during casting at 10 MPa pressure. For this reason, the L/FA ratios used in this research ranged from 0.12-0.16.

Table 3 Compressive strength and dry unit weight of FA geopolymer paste with 0.5 M NaOH and pressing of 10 MPa

No.	L/FA	Compressive strength (MPa)	Dry unit weight (kg/m^3)
1	0.10	0.96	1,617
2	0.12	0.64	1,537
3	0.14	0.98	1,493
4	0.16	0.55	1,367
5	0.18	1.63	1,577
6	0.20	3.64	1,760

The geopolymer paste mix proportions are provided in Table 4. All ingredients were used with L/FA ratios of 0.12, 0.14, and 0.16. The NaOH solutions contained 0.5, 1.0, and 2.0 mole (M). Na_2SiO_3 content was added to all mixtures in 1% by weight of the FA. Before mixing the geopolymer paste, the materials were prepared by weighing the FA, Na_2SiO_3, and NaOH

solution of various concentrations, as shown in Table 4. Then, pour the FA into the mixing tank, followed by the NaOH solution. Continue mixing for at least 10 minutes to dissolve the FA effectively. Next, the Na_2SiO_3 was added and then mixed until a uniform paste. The fresh FA geopolymer paste samples were poured into the cube molds and slightly tamped on the outside. Then, they were either compacted by hand or covered with a 10 mm thick steel plate. For compacting with a hydraulic press, the samples were compressed at maximum bearing stresses of 10 MPa, 20 MPa, and 30 MPa and held for 1 minute.

The pressed geopolymer sample was used in this study because it exhibited higher strength than the cast geopolymer [27] and successfully withstood bearing stresses of 15 and 20 MPa, as reported by Alshaaer [28] and Prasanphan et al. [29]. However, for comparison, the control mixture (CON) was compacted by hand. The fresh FA geopolymer paste was removed from the molds and sealed with plastic film. The samples were then dried in an oven at 60 °C for 24 hours. Afterward, 10 cm × 10 cm × 10 cm specimens were used for compressive strength, water absorption, unit weight, and total porosity tests. Fig. 4 shows the compressive strength test setup of the sample.

Table 4 Proportions of geopolymer paste mixture in 1 cubic meter

Mix No.	Symbol	FA (kg)	NaOH		Water (kg)	Liquid, L (kg)	Na_2SiO_3 (kg)	L/FA
			Molar	(kg)				
1	CON	1,800	0.5M	4.7	247.3	252	18	0.14
2	0.12FA0.5M	1,800	0.5M	4.0	212.0	216	18	0.12
3	0.12FA1.0M	1,800	1.0M	8.0	208.0	216	18	0.12
4	0.12FA2.0M	1,800	2.0M	15.8	200.2	216	18	0.12
5	0.14FA0.5M	1,800	0.5M	4.7	247.3	252	18	0.14
6	0.14FA1.0M	1,800	1.0M	9.4	242.6	252	18	0.14
7	0.14FA2.0M	1,800	2.0M	18.4	233.6	252	18	0.14
8	0.16FA0.5M	1,800	0.5M	5.4	282.6	288	18	0.16
9	0.16FA1.0M	1,800	1.0M	10.7	277.3	288	18	0.16
10	0.16FA2.0M	1,800	2.0M	21.0	267.0	288	18	0.16

Fig. 4 Compressive strength test setup of sample

2.3. Compressive strength test

The method for testing the compressive strength of samples follows EN 196-1. This is done by pressing the sample to determine the ultimate compressive force before failure at a pressure rate between 0.11 and 0.27 MPa per second. The compressive strength is measured in MPa and calculated by dividing the ultimate compressive force by the cross-sectional area, as shown below.

$$\text{Compressive strength (MPa)} = \frac{P}{A} \tag{1}$$

2.4. Water absorption test

The water absorption of samples was tested by soaking 10 × 10 × 10 cm cubes (3 samples) in water for 24 hours. After soaking, the samples were removed from the water, and excess surface water was absorbed with a cloth. The samples were then weighed within 30 seconds. The recorded weight included the samples and the water that had permeated it. The samples were dried at 110 ±5°C for 24 hours and cooled to room temperature. The water absorption value was calculated as the average of 3 samples according to ASTM C 642, as shown below.

$$\text{Water absorption (\%)} = \frac{W_{sat} - W_{dry}}{W_{dry}} \times 100 \tag{2}$$

where W_{sat} = the weight of the saturated sample and W_{dry} = the weight of the dried sample.

2.5. Dry unit weight test

The dry unit weight of the samples was determined after drying for 24 hours. This was done by weighing the samples in kilograms (kg) and dividing by their volume in cubic meters (m^3). The results are presented as the averages of three samples, expressed in kilograms per cubic meter (kg/m^3), as shown below.

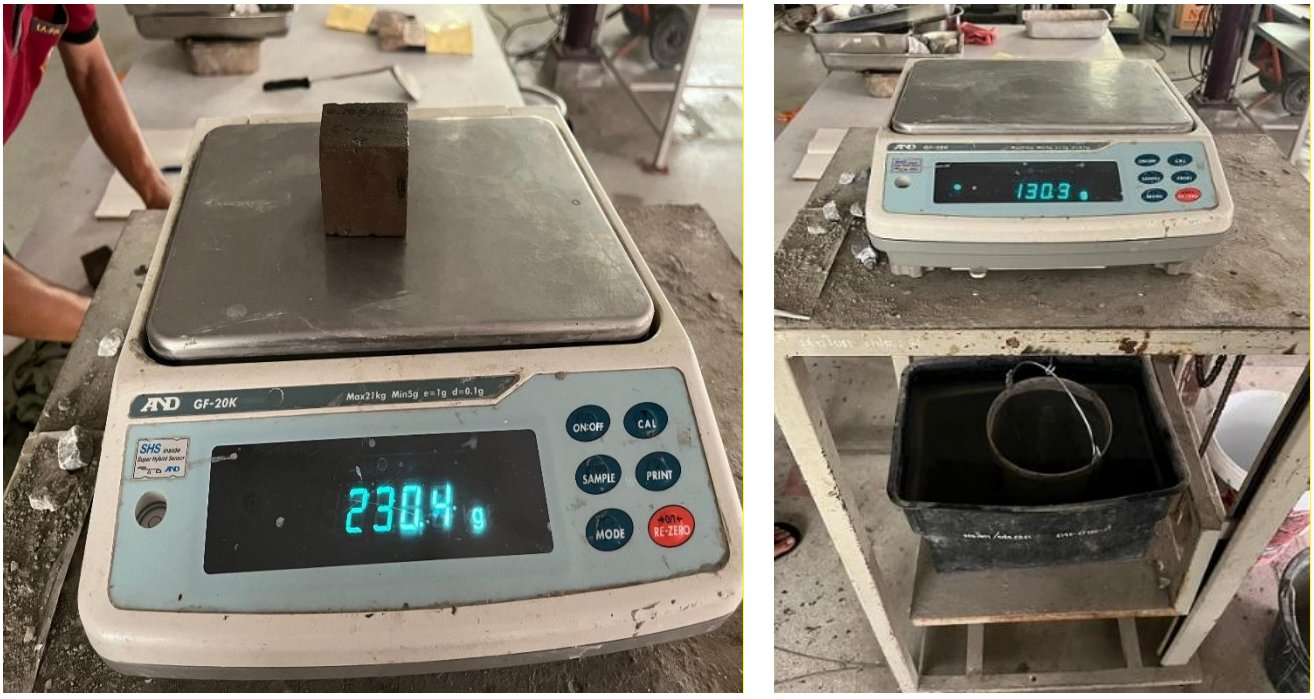
$$\text{Dry density } (kg/m^3) = \frac{M}{V} \tag{3}$$

2.6. Total porosity test

The porosity of the samples was determined using the Saturation Apparatus developed by Cabrera and Lynsdale at the University of Leeds. Porosity measurements were conducted on 5 cm cube slices drilled out of the center of a 10 cm cube. The slices were dried at 110±5°C until a constant weight was achieved. They were then placed in a desiccator under vacuum for at least 3 hours, after which the desiccator was filled with de-aired, distilled water, as shown in Fig. 5. The porosity was calculated using below.

$$P\ (\%) = \frac{W_{sat} - W_{dry}}{W_{sat} - W_{wat}} \times 100 \tag{4}$$

where P is saturation porosity, W_{sat} is the weight in air of the saturated sample, W_{wat} is the weight in water of the saturated sample, and W_{dry} is the weight of the oven-dried sample.



(a) Measurement of the weight of the oven-dried sample

(b) Measurement of weight in water of the saturated sample

Fig. 5 porosity test of the sample

2.7. X-ray diffraction (*XRD*)

Dried FA sample powder was sifted through a No. 100 sieve (150 μm openings). A sample of powder weighing approximately 1 g was used for XRD analysis. The XRD scans were performed for 2θ between 10° and 65° with an increment of 0.02°/step at a scan speed of 0.5 sec/step. A quantitative XRD analysis determined the amorphous FA phases using Bruker's TOPAS software.

3. Results and Discussion

The effects of low NaOH concentrations (0.5, 1.0, and 2.0 M), pressing stresses (10, 20, and 30 MPa), and liquid-to-binder ratios (0.10, 0.12, 0.14, 0.16, 0.18, and 0.20 by weight) on high-calcium fly ash geopolymer paste were evaluated. Additionally, the unit weight, porosity, water absorption, and compressive strength of high-calcium fly ash geopolymer paste with low NaOH concentrations are discussed in the following sections.

3.1. Compressive strength

Fig. 6 illustrates the compressive strength of FA geopolymer paste compacted by hand and pressed with a hydraulic jack under bearing stress of 10 MPa, 20 MPa, and 30 MPa. The liquid-to-binder ratio (L/FA) of 0.12, 0.14, and 0.16 and the NaOH concentrations of 0.5 M, 1.0 M, and 2.0 M were used. It was found that the control mix (CON) used NaOH of 0.5 M as a leaching FA and compacted it with the hand, giving a compressive strength of 24 MPa.

The casted geopolymer paste samples were dried at 60 °C for 24 h. The compressive strength increased with increasing bearing stress and NaOH concentration. For example, the compressive strengths of FA geopolymer paste were 0.7 MPa, 0.9 MPa, and 1.4 MPa for bearing stress of 10 MPa, 20 MPa, and 30 MPa, respectively. Additionally, for a bearing stress of 10 MPa, the compressive strengths of FA geopolymer paste were 0.7 MPa, 0.9 MPa, and 1.4 MPa for 0.12FA0.5M, 0.12FA1.0M, and 0.12FA2.0M, respectively. This result is due to the influence of NaOH concentration on FA leaching, which, combined with extrusion, brought geopolymer particles closer together, forming chemical bonds of silicate and aluminosilicate that linked to create a chain polymer structure [30].

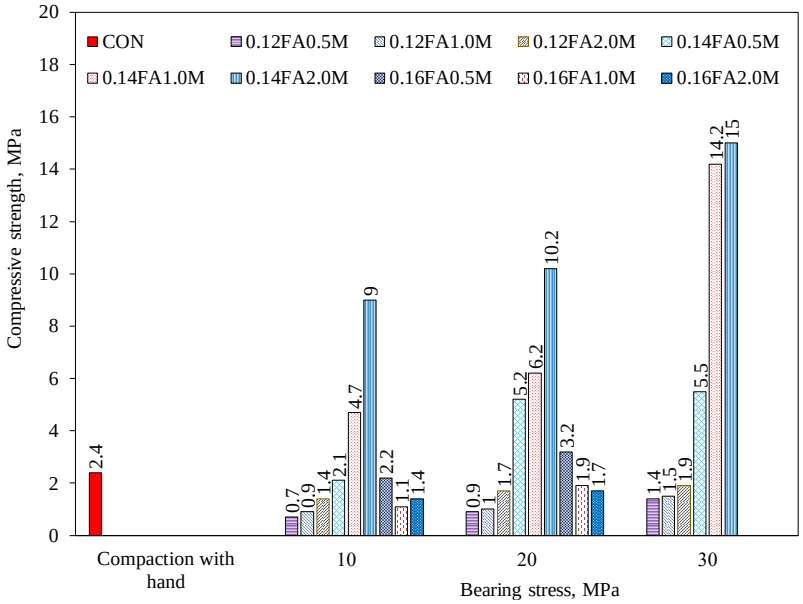


Fig. 6 Compressive strength of FA geopolymer paste

Table 5 Relative compressive strength of FA geopolymer paste

Mix No.	Symbol	Pressing stress (MPa)	Compressive strength (MPa)	Relative compressive strength (%)
1	CON	-	2.4	100
2	0.12FA0.5M		0.7	29
3	0.12FA1.0M	10	0.9	38
4	0.12FA2.0M		1.4	58
5	0.12FA0.5M		0.9	38
6	0.12FA1.0M	20	1.0	42
7	0.12FA2.0M		1.7	71
8	0.12FA0.5M		1.4	58
9	0.12FA1.0M	30	1.5	63
10	0.12FA2.0M		1.9	79
11	0.14FA0.5M		2.1	88
12	0.14FA1.0M	10	4.7	196
13	0.14FA2.0M		9.0	375
14	0.14FA0.5M		5.2	217
15	0.14FA1.0M	20	6.2	258
16	0.14FA2.0M		10.2	425
17	0.14FA0.5M		5.5	229
18	0.14FA1.0M	30	14.2	592
19	0.14FA2.0M		15.0	625
20	0.16FA0.5M		2.2	92
21	0.16FA1.0M	10	1.1	46
22	0.16FA2.0M		1.4	58
23	0.16FA0.5M		3.2	133
24	0.16FA1.0M	20	1.9	79
25	0.16FA2.0M		1.7	71
26	0.16FA0.5M		-	-
27	0.16FA1.0M	30	-	-
28	0.16FA2.0M		-	-

This result differs from Takeda et al. [23], who observed that high-density pure-phase geopolymers formed within a few hours using a warm-pressing technique. Their study achieved compressive strengths as high as 149 MPa by pressing at 200 MPa and 130 °C for 1 hour, with heat and pressure accelerating the geopolymerization and hardening of the fly ash, sodium

hydroxide, and water glass (sodium silicate) raw materials. Additionally, a sample with a high NaOH concentration of 14 M and pressing at 25 MPa achieved a compressive strength of 37.3 MPa, as reported by Shee Ween et al. [27]. Compared to the compressive strength of concrete blocks (2.5 MPa) specified in TIS 58–2533, the FA geopolymer paste with a L/FA ratio of 0.14, an NaOH concentration of 2.0 M, and a bearing stress of 30 MPa exhibited a maximum compressive strength of 15 MPa, meeting the standard requirement.

Table 5 shows the relative compressive strength of FA geopolymer paste compacted by hand and pressed with hydraulic jack under bearing stress of 10 MPa, 20 MPa, and 30 MPa. The L/FA of 0.12, 0.14, and 0.16 and the NaOH concentrations of 0.5 M, 1.0 M, and 2.0 M were used. It was found that casting the mixture with a liquid-to-binder ratio of 0.16 under a bearing stress of 30 MPa was not feasible, as the mixture leaked out of the mold and caused it to break. This failure occurred because the higher liquid content increased the mixture's flowability and reduced its viscosity, making it more prone to leakage through gaps. Additionally, excessive pressing stress generated higher excess pore water pressure, further contributing to the mold's failure.

3.2. Water absorption

The average water absorption of geopolymer paste compacted by hand and pressed with hydraulic jack under maximum pressing stress of 10 MPa, 20 MPa, and 30 MPa is shown in Fig. 7. It was found that the control mix (CON), which used 0.5 M NaOH and was compacted by hand, exhibited a water absorption rate of 17%. The pressed FA geopolymer paste at a stress of 10 MPa showed water absorption rates of 29%, 28%, and 25% for the 0.12FA0.5M, 0.12FA1.0M, and 0.12FA2.0M mixtures, respectively. At a 20 MPa stress, the water absorption rates were 21%, 24%, and 20% for the same mixtures, respectively. At 30 MPa, the rates were 21%, 23%, and 19%, respectively. Overall, water absorption rates decreased as pressing stress increased.

The water absorption rate also decreased as NaOH concentration increased under compression stresses up to 10 MPa. The additional water reduced the molarity in the aqueous phase, decreasing the extent of polymerization and preventing the formation of a compact gel, as suggested by Singh et al. [9]. Furthermore, excessive liquid caused excess water to evaporate, leaving voids in the geopolymer brick and consequently increasing water absorption. However, differences in NaOH concentration did not noticeably affect water absorption at stresses between 20 and 30 MPa. The liquid-to-binder ratio of 0.14 produced a lower water absorption rate than ratios of 0.12 and 0.16, as the optimal liquid content allowed for higher compacting efficiency, reducing voids and lowering water absorption [7-8].

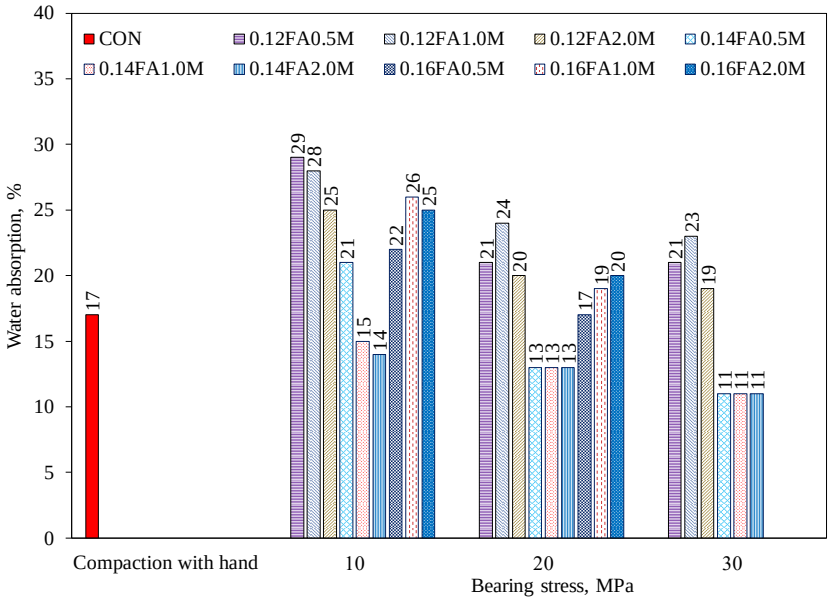


Fig. 7 Water absorption of FA geopolymer paste

3.3. Dry unit weight

The average dry weight of FA geopolymer paste compacted by hand and pressed with hydraulic jack under maximum pressing stress of 10 MPa, 20 MPa, and 30 MPa is shown in Fig. 8. It was found that the control mix (CON) had a dry weight of 1,735 kg/m³. The dry unit weight of FA geopolymer paste increased with higher compression stress and NaOH concentration. For example, FA geopolymer paste pressed with stresses of 10 MPa, 20 MPa, and 30 MPa yielded dry unit weights of 1,624 kg/m³, 1,660 kg/m³, and 1,704 kg/m³, respectively, for the 0.12FA0.5M mixture; 1,651 kg/m³, 1,700 kg/m³, and 1,776 kg/m³ for the 0.12FA1.0M mixture; and 1,695 kg/m³, 1,778 kg/m³, and 1,810 kg/m³ for the 0.12FA2.0M mixture.

Compression molding at maximum pressing stresses of 10 and 20 MPa yielded optimal dry unit weights, particularly for the 0.14FA2.0M mixture. However, at maximum pressing stress of 30 MPa, slightly different optimal dry unit weights were observed for the 0.14FA0.5M, 0.14FA1.0M, and 0.14FA2.0M mixtures, as shown in Fig. 7. This is because the liquid content and pressing stress influence the unit weight of geopolymer formation, consistent with the findings of Shee-Ween et al. [27].

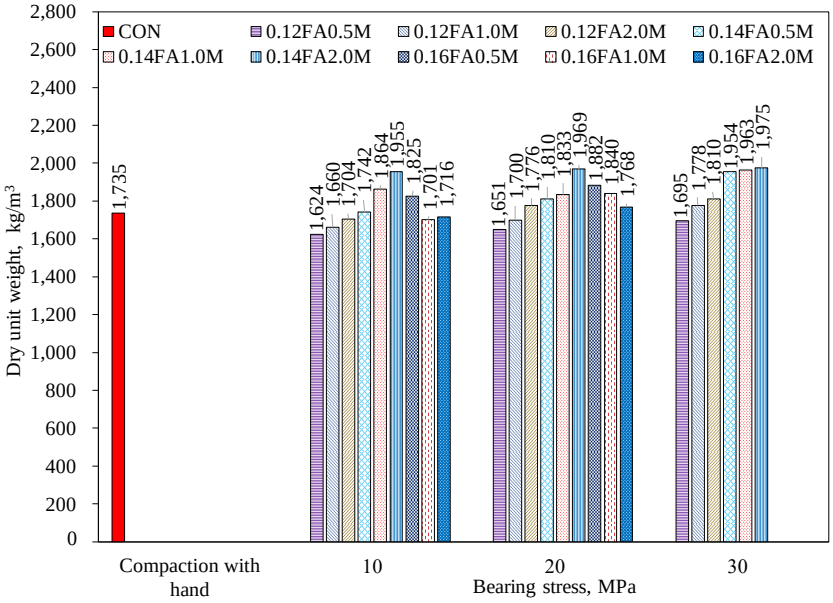


Fig. 8 Dry unit weight of FA geopolymer paste

3.4. Relationship between compressive strength and total porosity

Fig. 9 shows the average total porosity of FA geopolymer paste compacted by hand and pressed with a hydraulic jack under stresses of 10 MPa, 20 MPa, and 30 MPa. Liquid-to-binder ratios (L/FA) of 0.12, 0.14, and 0.16 and NaOH concentrations of 0.5 M, 1.0 M, and 2.0 M were used. The control mix (CON) had a total porosity of 35%. The total porosity of the FA geopolymer paste decreased as pressing stress increased. For example, the 0.12FA0.5M FA geopolymer paste pressed at 10 MPa, 20 MPa, and 30 MPa showed total porosities of 39%, 36%, and 33%, respectively. The correlation between compressive strength and total porosity of FA geopolymer paste decreased with increasing porosity. It was found that an exponential function in the form of $y = 479.61e^{-0.101x}$, with a multiple coefficient of determination (R^2) of 0.95, best describes the relationship, where x represents the total porosity of FA geopolymer paste. Similar results have also been reported by other researchers [23].

FA geopolymer paste provided high compressive strength due to its low porosity, achieved through casting under high pressure. This effect depended on the L/FA ratio. A high L/FA ratio reduced viscosity, increased fluidity, and caused geopolymer paste leakage during high-pressure molding, resulting in increased porosity. This study found that the optimum L/FA ratio for all pressures was 0.14.

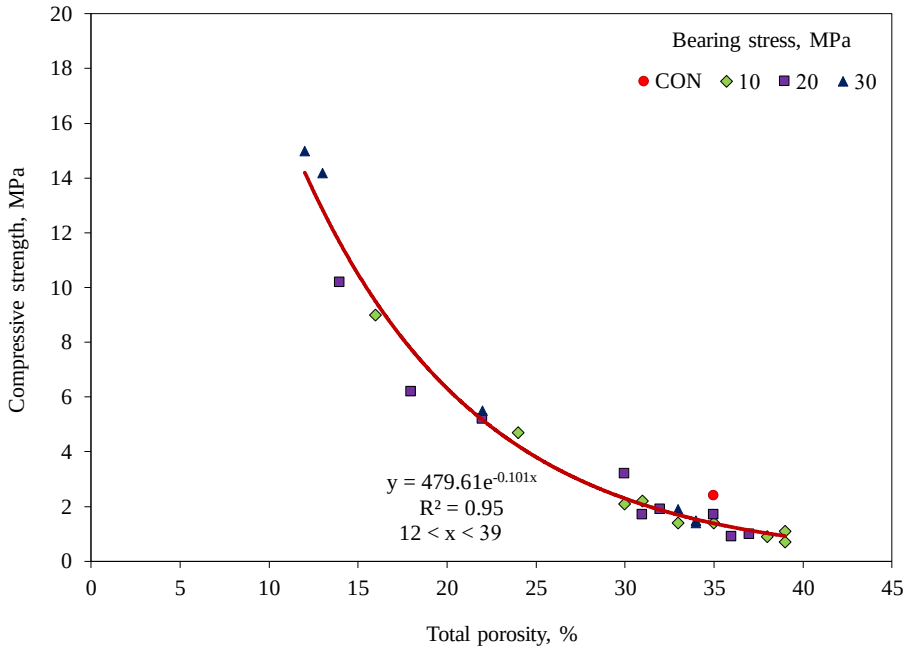


Fig. 9 Relationship between compressive strength and total porosity

4. Conclusions

The physical and mechanical properties of fly ash geopolymer paste with low NaoH concentrations using a pressing approach were evaluated in this study. The findings can be summarized as follows:

(1) The increasing NaOH concentration and bearing stress significantly enhance the compressive strength of FA geopolymer paste. The improved strength is attributed to NaOH-facilitated FA leaching and closer particle alignment during extrusion, which promotes the formation of a robust silicate and aluminosilicate polymer network.

(2) The increasing pressing stress and NaOH concentration generally reduced water absorption rates in FA geopolymer paste. Additionally, a liquid-to-binder ratio of 0.14 minimized voids, further decreasing water absorption.

(3) The study shows that higher compression stress and NaOH concentration increase the dry unit weight of FA geopolymer paste, with optimal weights observed at specific liquid-to-binder ratios.

(4) The increasing compressive strength in FA geopolymer paste is associated with reduced porosity, achieved through high-pressure compaction and an optimal L/FA ratio of 0.14. The FA geopolymer paste in this research provided higher compressive strength than ordinary Portland cement concrete blocks (2.5 MPa), as specified in TIS 58–2533. Future research should focus on microstructural properties, such as SEM with EDS analysis or FT-IR analysis, to investigate the effects of casting pressure on the compressive strength of fly ash geopolymer paste with low NaOH concentrations.

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Conflicts of Interest

The authors declare no conflict of interest.

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