Thai Environmental Engineering Journal Vol. 38 No. 3 (2024) : 1-10
www.eeat.or.th

Environmentally Friendly Manufacturing of Fly Ash Geopolymer Mortar

Thanudkij Chareerat[1], Sarawut Chaungchot[1], Santiphap Bussabin[1], Vatwong Greepala[2] and Krit Sriworamas[1*]

[1]Faculty of Engineering, Ubon Ratchathani University, Ubon Ratchathani 34190, Thailand
[2]Faculty of Science and Engineering, Kasetsart University, Sakon Nakhon 47000, Thailand
[*]E-mail : krit.s@ubu.ac.th

Article History; *Received: 24 July 2024, Accepted: 4 October 2024, Published: 24 December 2024*

Abstract

This research presents the environmentally friendly manufacturing (green manufacturing) of geopolymer mortar, focusing on the unit weight and compressive strength of geopolymer made from Mae Moh fly ash from Lampang Province. Graded sand in a dry condition was used in this investigation. The fly ash/sand ratio was set at 1:2.75. Sodium hydroxide (NaOH) and potassium hydroxide (KOH) solutions were used at concentrations of 2.5, 5, and 7.5 molars (M), respectively. The ratios of Na_2SiO_3/NaOH and Na_2SiO_3/KOH were controlled at 0.5:1, 1:1, and 2:1, respectively. The solution/fly ash ratio was set at 0.6. The temperatures for curing the geopolymer mortar were controlled at 30°C and 60°C, respectively. The compressive strength test of geopolymer mortar was conducted at the ages of 7, 28, and 56 days, respectively. Tap water was used to mix the geopolymer mortar, similar to that used in cement mortar for strength comparison.

The results indicated that the concentration of the alkaline solution can affect the rate of polymerization. Higher concentrations can lead to faster polymerization such as at a NaOH concentration of 7.5 M and a Na_2SiO_3/NaOH ratio of 1:1, a maximum compressive strength of 210 ksc was obtained at 56 days of testing (after 1 day of curing at 60°C). Similarly, at a KOH concentration of 7.5 M and a Na_2SiO_3/KOH ratio of 1:1, a maximum compressive strength of 240 ksc was obtained at 56 days of testing (after 1 day of curing at 60°C). Comparatively, the compressive strength of samples mixed with KOH solution was a bit higher than those mixed with NaOH solution. Furthermore, elevated curing temperatures can accelerate the geopolymerization process, enhancing strength in a shorter time frame. As it was clearly found that heat curing at 60°C provided higher compressive strength than curing at room temperature (30°C). Nevertheless, due to the aspect of environmentally friendly manufacturing of geopolymer mortar, a curing temperature close to room temperature (approximately 30°C) can yield a reasonable compressive strength within the range of 160-220 ksc, when stored in air for duration of 56 days, therefore, lengthening the curing time results in higher strength, as it allows more complete polymerization which contributes to the density and interconnectivity of geopolymer structure.

Keywords : Geopolymer; unit weight; strength; fly ash

Introduction

Geopolymers are materials that resemble cement but are produced from non-fossil fuel raw materials. They utilize materials containing silica and alumina in the form of industrial waste, such as fly ash from coal combustion or blast furnace slag from steel manufacturing. Additionally, alternative natural materials, such as metakaolin or natural pozzolans, are also available. Geopolymers have found applications in various industries, including construction, the production of environmentally friendly building materials, and waste management.

Geopolymers are environmentally friendly due to their use of recycled materials and generates significantly lower CO_2 emissions than traditional cement due to the lower calcination temperatures [1], exhibit superior resistance to chemical attacks, including acids and sulfates, making them ideal for harsh environments [2], and typically demonstrate high compressive strength comparable to or exceeding traditional cement-based materials. Studies have shown that strength can be influenced by factors such as raw material composition, curing temperature, and age [3]. However, challenges and concerns surrounding geopolymers include limited knowledge and research, leading to potential misuse due to inadequate education and training. Additionally, there are questions about their long-term durability and stability, necessitating further investigation. Lastly, while geopolymers are environmentally friendly, high production costs may impede their competitiveness in certain markets.

According to the Cement manufacturing process which significantly contributes to environmental pollution by emitting gases that exacerbate the greenhouse effect (Green House Gas; GHG), totaling 13,500 million tons per year, or approximately 7% of all global emissions. Consequently, there is an effort to reduce the use of Portland cement. This includes the development of concrete with high pozzolan content or the production of cementitious material that entirely eliminates Portland cement. One such alternative is geopolymer material [4-5]. Geopolymer is a type of cementitious material made from pozzolans, such as fly ash and calcined kaolin (metakaolin), which are rich in silica (Si) and alumina (Al). The fundamental principle of geopolymer involves a chemical reaction between silica and alumina to form polymer chains. This reaction is facilitated by a highly alkaline solution. When mixed with an alkali hydroxide solution and sodium silicate solution, and catalyzed with heat or thermal stimulation, a strong cementitious material is produced [6-8]. This material can achieve the same strength as conventional cement. The development of geopolymer not only represents an engineering advancement but also helps mitigate environmental pollution and combat global warming, a critical issue today.

This research, therefore, presents the environmentally friendly manufacturing of geopolymer mortar using Mae Moh fly ash as the primary local raw material. The study investigates the effects of varying concentrations of two types of alkali hydroxide solutions i.e. sodium hydroxide and potassium hydroxide on the unit weight and compressive strength of geopolymer mortar. The mortar was cured at room temperature (30°C) without heat energy consumption and at elevated temperature (60°C) with heat energy consumption.

Methodology

Fly ash from the Mae Moh Power Plant in Lampang Province, characterized by an average particle size of 30.4 microns and a specific gravity (S.G.) of 2.23, was utilized in this study. The Mae Moh fly ash exhibited a brownish-gray coloration and displayed a solid spherical morphology with a smooth surface [9-10]. The chemical composition of the fly ash, as analyzed using X-ray Fluorescence (XRF), revealed that it consists primarily of SiO_2, Al_2O_3, Fe_2O_3, and CaO, which collectively account for approximately 88 percent of its total composition. Furthermore, when focusing specifically on the primary compounds, SiO_2, Al_2O_3, and Fe_2O_3 constitute about 69 percent. Consequently, this fly ash is classified as Class C fly ash according to the ASTM C 618 standards. The detailed chemical composition of Mae Moh fly ash is presented in Table 1.

Table 1 Chemical composition of fly ash analyzed by X-ray fluorescence (XRF)

Chemical composition of fly ash	
Silicon Dioxide, SiO_2 (%)	32.10
Aluminum Oxide, Al_2O_3 (%)	19.90
Iron Oxide, Fe_2O_3 (%)	16.91
Calcium Oxide, CaO (%)	18.75
Magnesium Oxide, MgO (%)	3.47
Sodium Oxide, Na_2O (%)	0.69
Potassium Oxide, K_2O (%)	2.38
Sulfur Trioxide, SO_3 (%)	2.24
Loss On Ignition, LOI (%)	0.07

Test Method

1. Calculation of molarity (molar)

Molarity, often referred to as molar concentration, is a unit that quantitatively expresses the concentration of a solute in a solution. It is defined as the ratio of the number of moles of solute to the volume of the solution in liters (L). Molarity is denoted by the symbol 'M' and is expressed in units of moles per liter (mol/L), as represented by the following formula:

$$\text{Molar (M)} = \frac{\text{Number of moles of solute (mol)}}{\text{Volume of solution (L)}}$$

2. Manufacturing of geopolymer mortar

The mix proportions of the geopolymer are detailed in Tables 2 and 3, respectively. The process for manufacturing geopolymer mortar and procedure for mixing geopolymer mortar samples using a mortar mixer is outlined as follows [11]:

1) Place the measured quantities of fly ash and sand into the mixer, and mix for a duration of 2-3 minutes.
2) Mix the sodium hydroxide solution, as prepared in Table 4, with added water thoroughly for an additional 2 minutes. Subsequently, incorporate the sodium silicate solution and continue mixing for a further 5 minutes.
3) Replace the sodium hydroxide solution with potassium hydroxide solution, and then repeat steps 1 and 2.

3. Casting of geopolymer mortar

1) Pour the fresh geopolymer mortar into the test mold in two layers. The first layer should be approximately 25 mm thick. Subsequently, stir the mixture 16 times within a period of 10 seconds, and then pour the remaining geopolymer mortar into the mold. Repeat the aforementioned process for the second layer.
2) Utilize a steel trowel to remove any excess fresh geopolymer mortar that has overflowed onto the edges of the mold, ensuring that the surface is smooth.

4. Curing and storage method

The cast geopolymer mortar should be wrapped in plastic film and subsequently maintained at room temperature (30°C) for duration of 1 hour. Following this initial period, certain samples of the geopolymer mortar were cured at room temperature (30°C) for an additional 24 hours, while others were subjected to heat in an oven at 60°C for the same duration. After the 24-hour curing period, the geopolymer mortar samples were removed from the molds and stored at room temperature (30°C) until they were tested for compressive strength at 7, 28, and 56 days of age, respectively.

5. Compressive strength test of geopolymer mortar

The compressive strength was evaluated following ASTM C109 standard; compressive strength tests determine the load-bearing capacity of the mortar using a compressive strength testing machine at 7, 28, and 56 days, resulting in a total of 324 samples. These samples were categorized into two groups: 162 samples derived from sodium hydroxide (NaOH) solution (with 81 samples cured at 30°C and 81 samples cured at 60°C) and 162 samples derived from potassium hydroxide (KOH) solution (with 81 samples cured at 30°C and 81 samples cured at 60°C).

Table 2 Mix proportions of geopolymer using sodium hydroxide solution with 1,650 g of sand and 600 g of fly ash

Concentration (M)	Na_2SiO_3 (g)	NaOH (g)	Added water (g)	Na_2SiO_3/NaOH solution ratio	Solution to fly ash ratio
2.5	120	240	69	0.5	0.6
	180	180	71	1	0.6
	240	120	124	2	0.6
5	120	240	98	0.5	0.6
	180	180	97	1	0.6
	240	120	138	2	0.6
7.5	120	240	127	0.5	0.6
	180	180	123	1	0.6
	240	120	153	2	0.6

Table 3 Mix proportions of geopolymer using potassium hydroxide solution with 1,650 g of sand and 600 g of fly ash

Concentration (M)	Na_2SiO_3 (g)	KOH (g)	Added water (g)	Na_2SiO_3/ KOH solution ratio	Solution to fly ash ratio
2.5	120	240	69	0.5	0.6
	180	180	71	1	0.6
	240	120	124	2	0.6
5	120	240	98	0.5	0.6
	180	180	97	1	0.6
	240	120	138	2	0.6
7.5	120	240	127	0.5	0.6
	180	180	123	1	0.6
	240	120	153	2	0.6

Table 4 Weight of substances used in each concentration

Substances	Concentration / solution 1 liter		
	2.5 M	5 M	7.5 M
Sodium hydroxide	100 g	200 g	300 g
Potassium hydroxide	140 g	280 g	420 g

Results and Discussion

1. Unit weight test

Based on the conducted tests, it was found that the ratios of sodium silicate solution to sodium hydroxide solution, as well as the ratios of sodium silicate solution to potassium hydroxide solution, at concentrations of 2.5, 5, and 7.5 M had minimal impact on the unit weight of the geopolymer. In contrast, the variables that significantly influenced the unit weight of the geopolymer were the testing age and the curing temperature. As illustrated in Figure 1, the unit weight measurements taken during the first 7 days indicated an average value of 2.23. However, upon examination at 28 days, the unit weight value decreased slightly to 2.22, with subsequent measurements showing minimal further reduction. Notably, curing at room temperature produced a higher unit weight compared to curing at elevated temperatures of 60 °C. An overall results of this investigation yielded average geopolymer unit weight of 2.22.

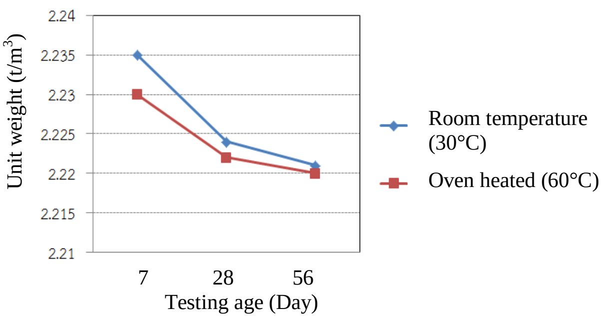

Figure 1 Relationship between unit weight and testing age of geopolymer

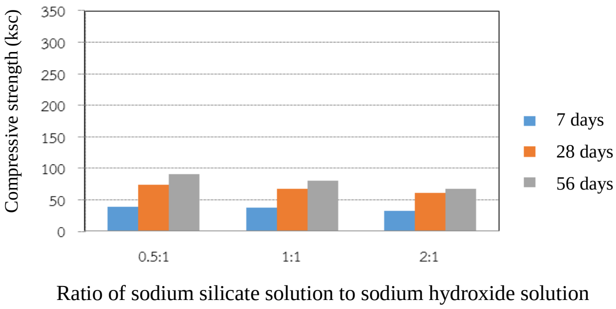

Figure 2 Relationship between compressive strength and the ratio of sodium silicate solution to sodium hydroxide solution cured at 30°C

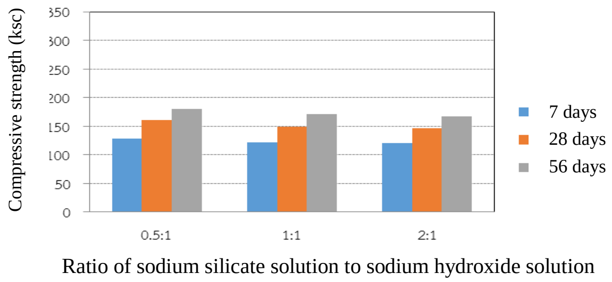

Figure 3 Relationship between compressive strength and the ratio of sodium silicate solution to sodium hydroxide solution cured at 60°C

2. Compressive strength test

2.1 Sodium silicate to sodium hydroxide solution ratio

From the initial seven days of testing, it was observed that the compressive strength values of the ratios 0.5:1 and 1:1 were comparable, both achieving a strength of 40 ksc, while the ratio of 2:1 exhibited the lowest compressive strength at 32 ksc. Further assessment of compressive strength conducted at 28 and 56 days revealed that the 0.5:1 ratio yielded the highest compressive strength at 91 ksc. When comparing the solution ratios of 1:1 and 2:1, both cured at 30°C, as illustrated in Figure 2, it was noted that the trends in compressive strength development remained similar when the geopolymer was subjected to testing at 60°C. Specifically, the 0.5:1 ratio consistently provided the highest compressive strength, while the 2:1 ratio produced the least, as depicted in Figure 3. Consequently, the optimal ratio of the geopolymer synthesized from sodium hydroxide solution was determined to be 0.5:1 to 1:1. This finding aligns with the research conducted by Chindaprasirt et al. (2007) [12], which investigated the fundamental properties of workability and compressive strength of geopolymers derived from high-calcium fly ash. Their study noted that the flow capacity ranged from 105% to 140%, and recommended a ratio of sodium silicate solution to sodium hydroxide solution between 0.67 and 1.0 to achieve satisfactory compressive strength.

2.2 Sodium silicate to potassium hydroxide solution ratio

Development of compressive strength in geopolymer over a period of 7 days, utilizing ratios of 0.5:1, 1:1, and 2:1, revealed a consistent trend in compressive strength development across the different formulations. Further testing conducted at intervals of 28 and 56 days indicated that the geopolymer mixture with a ratio of 1:1 exhibited the highest compressive strength, while the 2:1 ratio resulted in the lowest compressive strength, as illustrated in Figure 4.

Moreover, compressive strength testing of the geopolymer cured at 60°C demonstrated that its performance during the first 7 days surpassed that of samples cured at room temperature (30°C), yielding a difference of approximately 90 ksc. Evaluating the compressive strength values at 28 and 56 days post-curing revealed that the 1:1 geopolymer ratio consistently provided the highest compressive strength. In contrast, the compressive strength values for the 0.5:1 and 2:1 ratios were comparable, as depicted in Figure 5.

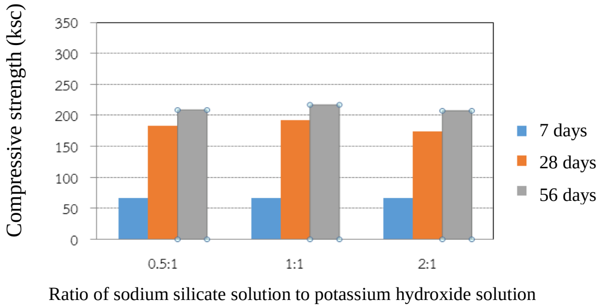

Figure 4 Relationship between compressive strength and the ratio of sodium silicate solution to potassium hydroxide solution cured at 30°C

Therefore, it can be concluded that the optimal ratio for the geopolymer synthesized from potassium hydroxide solution, based on the results obtained during this study, is 1:1. This finding aligns with the research conducted by Hardjito and Tsen (2008) [13], who explored geopolymers synthesized from fly ash using potassium silicate and potassium hydroxide solutions. Their findings indicate that the effectiveness of potassium hydroxide solution as a stimulant for compressive strength is contingent upon the concentration of the solution, similarly to the effects observed with high-concentration sodium hydroxide solutions. Hardjito and Tsen recommended that the ratio of potassium silicate solution to potassium hydroxide solution should be maintained within the range of 0.8 to 1.5 to ensure optimal compressive strength performance.

2.3 Concentration of sodium hydroxide solution

Based on the test results of geopolymers exposed to sodium hydroxide solutions at concentrations of 2.5 M, 5.0 M, and 7.5 M, it was observed that the compressive strength of the geopolymer exhibited direct variation relationship with the concentration of the solution. In compressive strength tests conducted on geopolymers aged for 7 days, the lowest compressive strength was recorded at a concentration of 2.5 M, whereas the highest compressive strength was observed at a concentration of 7.5 M. However, the difference in compressive strength between these concentrations was minimal, amounting to only 5 ksc. Upon evaluating the compressive strength of geopolymers aged 28 days, it was reaffirmed that the solution concentration of 7.5 M yielded the highest compressive strength. Similarly, after testing geopolymers aged 56 days, the concentration of 7.5 M once again resulted in the highest compressive strength, particularly when cured at 30°C, as illustrated in Figure 6. Furthermore, when subjected to heating at 60°C, it was determined that geopolymers tested after 7 days exhibited higher compressive strength across all solution concentrations compared to those cured at 30°C, with the values obtained from samples aged 28 and 56 days corroborating this finding. Notably, the geopolymer produced at a concentration of 7.5 M displayed higher compressive strength when compared to those at concentrations of 2.5 M and 5.0 M, as demonstrated in Figure 7.

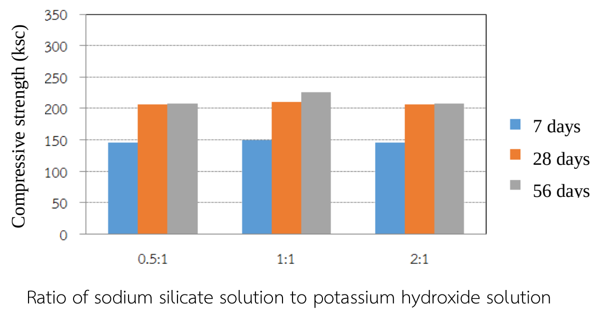

Figure 5 Relationship between compressive strength and the ratio of sodium silicate solution to potassium hydroxide solution cured at 60°C

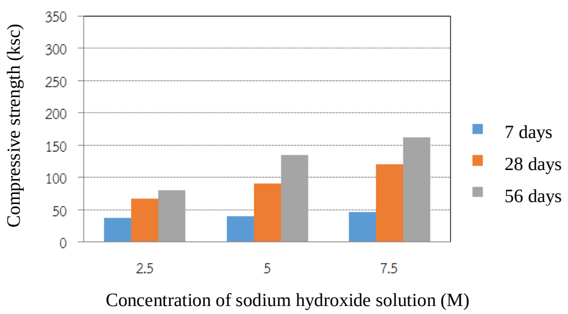

Figure 6 Relationship between compressive strength and concentration of sodium hydroxide solution at 30°C

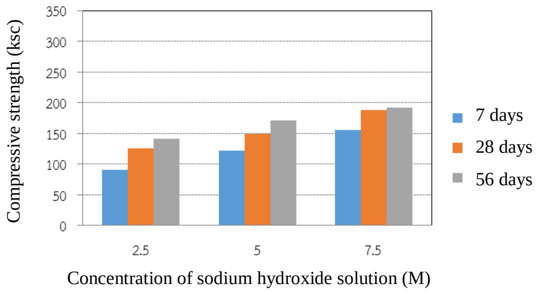

Figure 7 Relationship between compressive strength and concentration of sodium hydroxide solution at 60°C

2.4 Concentration of potassium hydroxide solution

Based on the test results of geopolymer constructed with potassium hydroxide solutions at concentrations of 2.5, 5.0, and 7.5 M, it was observed that the variation in compressive strength over the initial 7 days of testing was minimal in comparison to the concentration of the potassium hydroxide solution. The compressive strength values were similar, averaging approximately 65 ksc. However, during the curing periods of 28 days and 56 days, the trends indicated that compressive strength exhibited a direct variation relationship with increasing concentrations of potassium hydroxide solution, particularly at a concentration of 7.5 M. The sample cured for 56 days at 30 °C achieved a maximum compressive strength of 217 ksc, as illustrated in Figure 8. In contrast, samples cured at a temperature of 60 °C demonstrated consistently superior compressive strength across all concentrations, with the highest compressive strength recorded at 240 ksc, as shown in Figure 9. For comparison purposes, a sodium silicate to sodium hydroxide solution ratio of 1:1 and a solution to fly ash ratio of 0.6 were utilized.

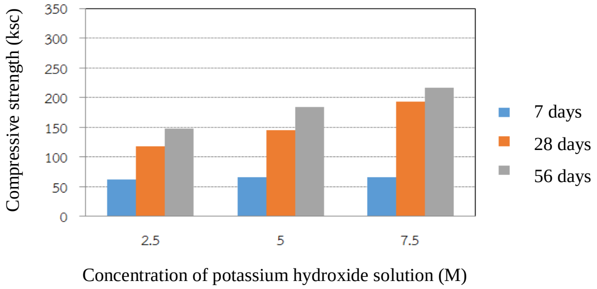

Figure 8 Relationship between compressive strength and concentration of potassium hydroxide solution at 30°C

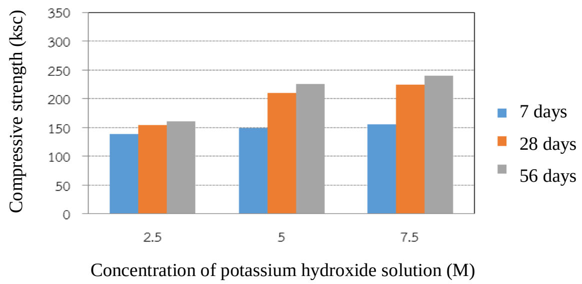

Figure 9 Relationship between compressive strength and concentration of potassium hydroxide solution at 60°C

2.5 Development of compressive strength of geopolymer using sodium hydroxide solution as a catalyst

Based on the testing, it was found that the compressive strength of geopolymer mortar developed with a 2.5 M concentration exhibited the lowest compressive strength, while a sodium hydroxide solution with a concentration of 7.5 M provided the highest compressive strength across all curing durations, as illustrated in Figure 10. The samples exhibiting the highest compressive strength during each curing period are illustrated in Figure 10, which compares the performance of samples with a sodium silicate solution to sodium hydroxide solution ratio of 1.0 and a solution to fly ash ratio of 0.6.

Curing the samples at a temperature of 60°C significantly accelerated the reaction, leading to improved compressive strength compared to curing at 30 °C. Notably, the rate of compressive strength development was most pronounced at 7 days of age when compared to the samples cured at 30°C, with a subsequent decrease in strength gain observed at 28 days testing. After 28 days, the increase in compressive strength was less pronounced, as depicted in Figure 11, which compares samples with a sodium silicate solution to sodium hydroxide solution ratio of 1:1 and a solution to fly ash ratio of 0.6.

2.6 Development of compressive strength of geopolymer using potassium hydroxide solution as a catalyst

Based on evaluations conducted using potassium hydroxide solution as a catalyst, the findings indicate that the development of compressive strength in geopolymer mortar is influenced by the concentration of the catalyst.

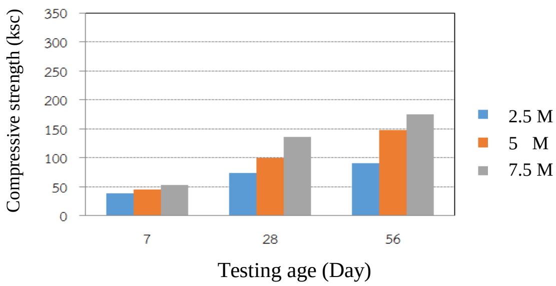

Figure 10 Relationship between compressive strength and testing age of geopolymer using sodium hydroxide solution at curing temperature of 30°C

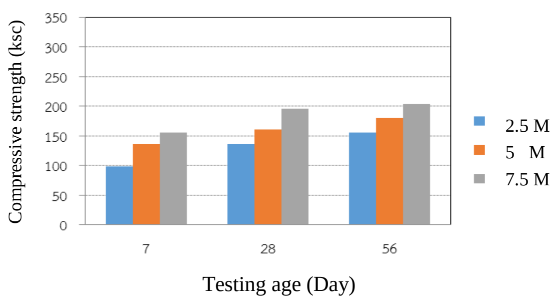

Figure 11 Relationship between compressive strength and testing age of geopolymer using sodium hydroxide solution at curing temperature of 60°C

Specifically, a potassium hydroxide concentration of 2.5 M resulted in the lowest compressive strength, while a concentration of 7.5 M yielded the highest compressive strength. After a testing of 7 days, compressive strength values were found to be quite similar across all concentrations, averaging approximately 61 ksc, as illustrated in Figure 12. These samples were compared using a sodium silicate solution to sodium hydroxide solution ratio of 1.0, along with a solution to fly ash ratio of 0.6.

Curing the samples at 60°C accelerated the chemical reactions, leading to an enhancement in compressive strength compared to the ambient temperature of 30 °C. The rate of compressive strength development was notably higher at 7 days in case of curing at 60°C compared to those cured at 30°C, although this rate experienced a decline when the samples were tested at 28 days. After 28 days, the increase in compressive strength diminished, with the maximum compressive strength reaching 240 ksc. Samples incubated for 56 days at a concentration of 7.5 M demonstrated this improvement, as depicted in Figure 13. The analyses conducted also involved comparing samples based on a sodium silicate solution to sodium hydroxide solution ratio of 1.0 and a solution to fly ash ratio of 0.6.

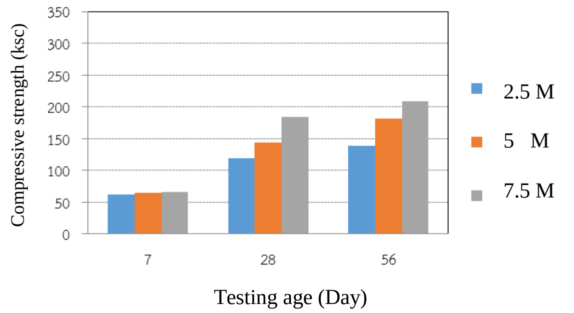

Figure 12 Relationship between compressive strength and testing age of geopolymer using potassium hydroxide solution at curing temperature of 30°C

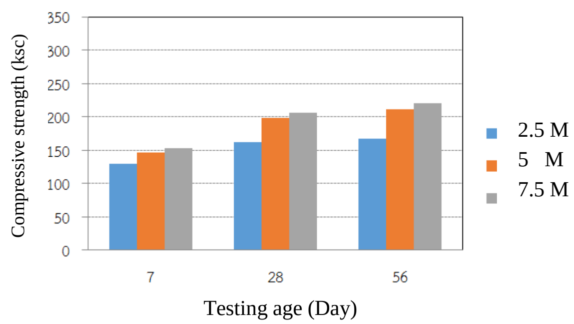

Figure 13 Relationship between compressive strength and testing age of geopolymer using potassium hydroxide solution at curing temperature of 60°C

2.7 Comparison of compressive strength between geopolymer mortars made from sodium hydroxide solution and potassium hydroxide solution and cement mortar

The test results indicated that the compressive strength of geopolymer mortar formulated with sodium hydroxide solution is approximately 10% lower than that of geopolymer mortar produced with potassium hydroxide solution. Furthermore, when comparing the geopolymer mortar with the highest compressive strength to cement mortar, it was demonstrated that the geopolymer mortar achieved approximately 80% of the maximum compressive strength of the cement mortar. This is illustrated in Figure 14, which presents the comparison of a sodium silicate solution ratio to a sodium hydroxide solution of 0.5, a sodium hydroxide solution concentration of 7.5 M, as well as a sodium silicate to potassium hydroxide solution ratio of 1.0, with a potassium hydroxide solution concentration also set at 7.5 M, yielding the highest compressive strength among the geopolymer samples.

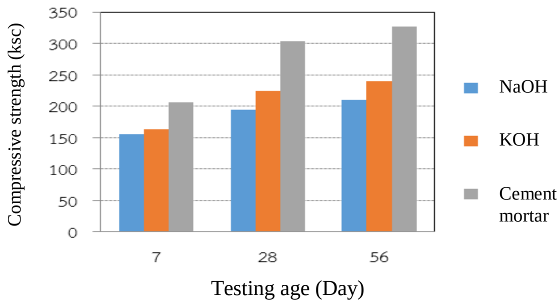

Figure 14 Relationship between compressive strength and testing age of geopolymer and cement mortar

Conclusions

Sodium hydroxide and potassium hydroxide solutions with concentrations of 2.5, 5, and 7.5 M exhibited varying in compressive strengths. The results indicated that compressive strength increased with higher concentrations of the solutions. The optimal compressive strength was achieved with a 1:1 ratio of sodium silicate solution to both sodium hydroxide and potassium hydroxide solutions.

Furthermore, geopolymer constructed using potassium hydroxide solution demonstrated approximately a 10% higher compressive strength compared to those made with sodium hydroxide solution across all tested ages. Additionally, curing at a temperature of 60°C resulted in a more rapid increase in compressive strength than curing at 30°C. Nevertheless, due to the aspect of environmentally friendly manufacturing of geopolymer mortar, a curing temperature close to room temperature (approximately 30°C) can yield a reasonable compressive strength within the range of 160-220 ksc, when stored in air for duration of 56 days.

In conclusion, the manufacturing of fly ash geopolymer mortar employs environmentally friendly practices by managing waste through the utilization of fly ash from the Mae Moh electricity manufacturing Power Plant, which reduces industrial waste. It enhances energy efficiency by activating geopolymer at a low room temperature of 30°C, decreasing energy consumption compared to traditional methods. Additionally, it minimizes environmental impact by using lower concentrations of sodium hydroxide (2.5-5.0 M) instead of the typical 10-15 M [12], thereby reducing chemical hazards. Furthermore, advocating for geopolymer mortar as a sustainable alternative to traditional cement can significantly lower the carbon footprint in construction, promoting more sustainable building practices.

Acknowledgments

The researchers would like to express their gratitude to the Faculty of Engineering, Ubon Ratchathani University on their support of this research.

References

[1] Davidovits, J. 2011. Geopolymer chemistry and applications. Geopolymer Institute.

[2] Duxson, P., et al. 2007. Geopolymer technology: The current state of the art. Journal of Materials Science. 42(9): 3023-3035.

[3] Wang, H., et al. 2021. Mechanical properties of geopolymer composites: A review. Journal of Composites Science. 5(3): 78.

[4] Charin Senawong, Kietsuda Somna and Wichian Charlie. 2010. Compressive strength and bonding strength of geopolymer concrete from fly ash. Burapha Science Journal. 15: 13-22.

[5] Thanakorn Phungernkham. 2010. Study of compressive strength of geopolymer mortar from fly ash mixed with diatomite perlite and natural zeolite. Master of Engineering, Thesis in Civil

Engineering, School of Engineering, Suranaree University of Technology.

[6] Wichian Charlie and Ubonlak Rattanasak. 2009. Study of durability properties of geopolymer materials. From the ash bottom of the stove. Burapha Science Journal. 14(1): 47-55.

[7] Weeraphong Phikunprayong and Wanchai Yodsudjai. 2009. Properties of geopolymer mortar to develop into a repair material. 14th National Civil Engineering Conference, Suranaree University of Technology: 1801-1805.

[8] Thiensak Klapprasit, Samit Songpiriyakit and Chai Jaturapitakkul. 2006. Study of compressive strength of geopolymer paste made from rice husk ash and tree bark ash mixed with coal ash. Academic conference 2nd Annual Concrete, Udon Thani: MAT 53-58.

[9] Prinya Chindaprasirt and Chai Jaturapitakkul. 2004. Cement, pozzolan and concrete. Bangkok: Thai Concrete Association.

[10] Prinya Chindaprasirt and Intharachai Horwichit. 2005. Portland cement mixed with Mae Moh fly ash. Office of Technology for Rural Affairs. Faculty of Engineering, Khon Kaen University.

[11] Prinya Chindaprasirt, Thanudkij Chareerat, Waraporn Kunawanakit and Anuchart Luenansaksiri. 2005. Preliminary study of geopolymer production from Mae Moh fly ash. 1st Annual Concrete Academic Conference, Rayong: 13-18.

[12] Chindaprasirt, P., Chareerat, T. and Sirivivatnanon, V. 2007. Workability and strength of coarse high calcium fly ash geopolymer. Cement and Concrete Composites. 29(3): 224-229.

[13] Hardjito, D. and Tsen, M.Z. 2008. Strength and thermal stability of fly ash based geopolymer mortar. The 3rd International Conference - ACF/VCA. 144-150.