

Research Article

The Effect of Fly Ash Nagan Raya on Geopolymer Mortar

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ABSTRACT

Industrial waste containing silica (Si), alumina (Al), and calcium (Ca) has potential as an alternative binder in concrete. These compounds form C-S-H and C-A-H gels in water-based systems, or Si-O-Si, Si-O-Al, N-A-S-H, and C-A-S-H gels in alkali-based geopolymer systems, enhancing strength and influencing setting time. One example is investigate FA from Nagan Raya (FANR) Coal-Fired Power Plantation in Aceh. This study evaluates its performance in geopolymer mortar through chemical and mechanical analysis. FANR is rich in Si and Al, improving mortar strength, while Ca content affects binding time. XRD analysis revealed crystalline phases in FANR and geopolymer binders, resulting in low reactivity. SEM analysis showed spherical particles with foggy surfaces, differing from typical glassy fly ash, which influences workability and alkali absorption. Mortar tests indicated the best performance at 8M NaOH and a $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio of 3.0, achieving 18.30 MPa compressive strength at 28 days. Higher alkali concentrations increased viscosity, reducing workability and final strength. Overall, FANR shows promise as a geopolymer binder with proper optimization of activator ratios.

Keywords: fly ash nagan raya; chemical analysis; workability; setting time; compressive strength

1. INTRODUCTION

The industrial waste-rich chemical Si, Al, and Ca content is an alternate substance for concrete. It is attributed to the chemical content of Si, Al, and Ca that react with water to produce C-S-H and C-A-H gels (Fauzi et al., 2016; Mulizar et al., 2020). Thus, industrial waste often partially replaces Portland cement's (OPC) application in concrete. In addition, industrial waste is able to replace all OPCs as binders in concrete (Gultom et al., 2024; Ikramullah et al., 2025; Shamsavari & Hwang, 2018). However, they did not use water to react with the content of the chemical compounds Si, Al, and Ca but used an alkaline solution. The reaction of the chemical content with an alkaline solution results in gels of Si-O-Si and Si-O-Al that enhance mechanical characteristics (Kwek et al., 2021; Y. S. Wang et al., 2019). This reaction also results in Gels C-A-S-H and N-A-S-H that contribute to the setting time. The reaction process is named the geopolymer system (Garcia-Lodeiro et al., 2011; Provis & Deventer, 2009).

Geopolymer systems were first discovered by Davidovits in 1980. He explained that geopolymers are alternative binders formed by inorganic polymers from solutions of alumina, silicate, and alkali. Alumina silicate is derived from an alternative material, while alkaline solution is derived from NaOH solution and Na_2SiO_3 solution combined in a certain ratio (Davidovits, 1991, 2018). Alternative materials used for concrete geopolymer must have a compound silica (Si), Alumina (Al), and calcium (Ca) content (Fauzi et al., 2023; Owaid et al., 2012). Fly ash is one of the alternative materials derived from Nagan Raya (FANR) Coal-Fired Power Plantation in Aceh. Particle fly ash (FA) is generally glass-shaped, finer than cement and lime, with sizes that range from less than 1 μm to a maximum of 150 μm , and is mostly gray or brown in color (Alterary & Marei, 2021). In addition, mechanically, FA particles that are finer than cement particles will fill the empty spaces (cavities) between the fine aggregate grains (Hardjito et al., 2005; Kosmatka et al., 2002).

In contrast to cement, fly ash is not able to bind. However, fly ash's silica oxide will chemically react with sodium hydroxide in the presence of water and generate a material with binding properties due to its tiny particle size. (Hardjito et al., 2005; H. Wang et al., 2021). Fly ash nagan raya is one of the industrial wastes in Aceh Province, which comes from the nagan raya coal-fired power plantation (PLTU). This serves as fuel for the nagan raya steam power plant (PLTU) to distribute electrical energy to districts/cities in Aceh Province. In general, fly ash nagan raya has a negative effect on the people of nagan raya and the surrounding environment (Raihan, 2023; Rezaei et al., 2021). So it has to be used as an additional material or substitute material in mortar (Rachman et al., 2021). This research was conducted to utilize fly ash nagan raya as a replacement material for geopolymer mortar.

2. RESEARCH METHOD

This study uses fly ash from the nagan raya coal-fired power plantation in Aceh, Indonesia. Then Na_2SiO_3 solution and NaOH solution are combined to create the alkaline solution 4M, 6M, 8M, and 10M with a ratio ratio of 2.0, 2.5, 3.0, and 3.5 (Shamsah et al., 2025). NaOH and Na_2SiO_3 solutions are obtained from CV. Rudang Jaya, Medan, North Sumatra, Indonesia. Meanwhile, the proportion of fly ash to alkaline solution used is 1.1 (Ruhana et al., 2023).



Figure 1. Materials used: a) fly ash nagan raya, b) alkaline solution, c) sand.

Fly ash material was performed several tests, including chemical composition testing using XRF, then material crystal analysis testing using XRD tools, and finally SEM testing to indicate the shape and particle surface of fly ash nagan raya. As for the proportion of the mixture, it is designed based on the constituent materials of the geopolymer. The manufacture of cube-shaped geopolymer mortar test pieces with a size of 50 mm x 50 mm x 50 mm, the maintenance method carried out is by storing the test piece at lab temperature with a mortar test life of 28 days. The tests carried out in this study include: workability, setting time, and compressive strength (ASTM, 2002, 2003, 2008, 2009b, 2009a, 2010).

3. RESULTS AND DISCUSSION

3.1 Chemical Composition

The analysis of the chemical composition was investigated using fluorescence x-ray instruments as shown in Table 1. It can be seen that the Si, Al, and Ca content compounds in fly ash nagan raya is 48.04%, 27.62%, and 6.44%.

Table 1. The chemical composition of fly ash nagan raya

Si	Al	Fe	Ca	Mn	K	LOI
48.04%	27.62%	11.78%	6,44%	0,21%	0,98%	4,15%

Total content of Si + Al + Fe compounds found in fly ash nagan raya by 82.1%, this shows that fly ash the names used in this study are categorized into groups fly ash class F conforms to ASTM C 618 standard (ASTM, 2014). In general, low Ca content (less than 8%) results in N-A-S-H gel causing a long setting time, while high calcium content (over 12%) results in C-A-S-H gel causing a short setting time.

3.2 Material Crystal Analysis

The crystal identification of fly ash nagan raya (FANR) was investigated by XRD analysis. Figure 2. shows the peak dispersal area of fly ash nagan raya powder and binder which is in the angle range area of 20° to 30° 2θ . This indicates that the powder and the FANR binder are crystalline on Quartz (SiO_2), mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$, or $2\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$), hematite (Fe_2O_3) and magnetite (Fe_3O_4).

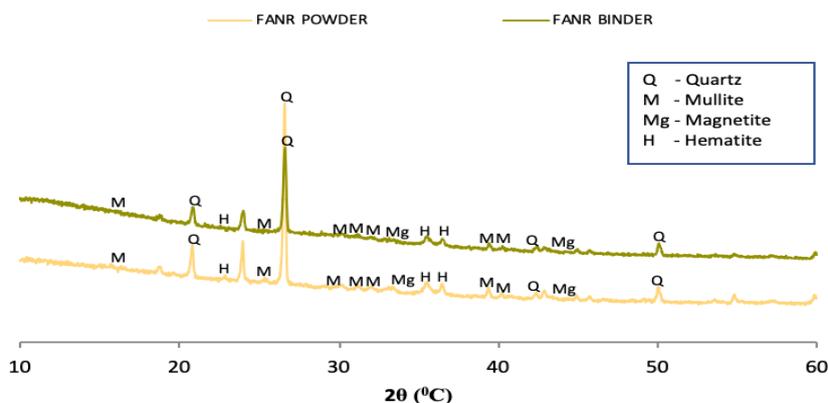


Figure 2. XRD pattern fly ash nagan raya

The XRD pattern of fly ash Nagan Raya on geopolymer binders can be seen in the main peak area of 25° to 27° 2θ . This demonstrates that the type of material from fly ash Nagan Raya is categorized as a material that has crystalline silica content, where materials that have crystalline silica content are not more reactive when compared to materials that have amorphous silica content. Furthermore, from Figure 2, it can appear that there is a similarity in the pattern between the powder and the FANR binder; this shows that FANR powder has a significant amount of geopolymerization in the formation of binders. The Si-O-Si and Si-O-Al are connected to this formation produced through the alkaline reaction and the elements Si and Al contained in fly ash Nagan Raya.

3.3 Surface of Fly Ash

Figure 3a shows a surface image of the Fly ash Nagan Raya (FANR). It describes the surface shape of the FANR particle, which is spherical and foggy. The surface of FANR particles is different from the usual form of fly ash, where fly ash generally has a smooth spherical surface. The foggy surface of the FANR has an impact on workability. The foggy surface causes more absorption of alkaline solutions in the fresh SCGM mixture in a short time, thus causing a decrease in the workability of the fresh geopolymer mixture. Figure 3b, shows an image of fly ash Nagan Raya geopolymer binder, where it can be seen that the alkaline solution's absorption contributes to the gel density generation in the FANR binder. FANR materials that react with alkaline solutions form a gel inside the binder. Meanwhile, FANR material that does not react will become filler inside the binder.

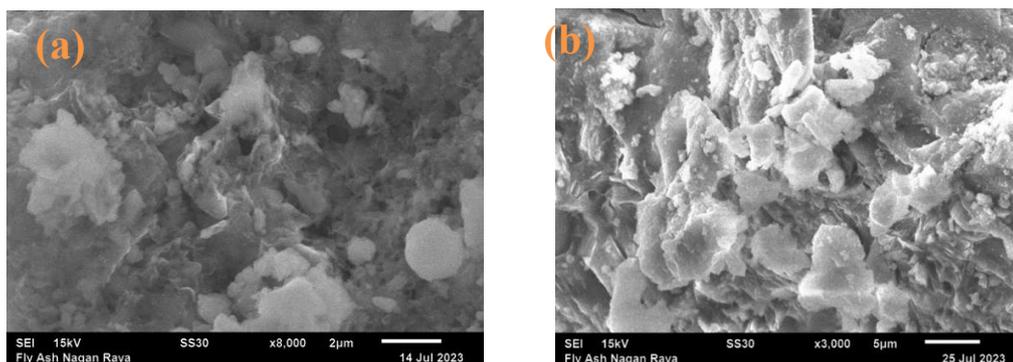


Figure 3. Material surface of (a) FANR powder and (b) FANR binder

3.4 Workability

The surface shape of the material particles and the composition of the alkaline solution greatly affect the performance of fresh geopolymer mortar mixtures. As is known, an alkaline solution consists of a certain ratio between NaOH solution and Na_2SiO_3 solution. With the increase in molarity concentration from 4M to 10M, workability decreases, as shown in Figure 4. This is due to the increased concentration, which results in increased viscosity, or viscosity, in the newly made geopolymer mortar mixture. As is known, when the NaOH solution reacts with the Na_2SiO_3 solution and forms an alkaline solution, this solution will release OH-ions. The higher the molarity concentration of the NaOH solution, the more OH- ions are released, which dissolve the catalyst from the Na_2SiO_3 solution and cause the alkaline solution bonds to become more viscous. As a result, fresh geopolymer mortar mixtures are more cohesive than regular mortar mixtures. In addition, Figure 4, shows the variation in the ratio of Na_2SiO_3 to NaOH of 2, 2.5, 3, and 3.5 in relation to decreased workability. High viscosity will result from the high ratio of Na_2SiO_3 to NaOH. This is because more Na_2SiO_3 solutions are used if there is a ratio of Na_2SiO_3 to NaOH. As is known, Na_2SiO_3 solution has catalytic properties as well as high viscosity properties. So, a large amount of Na_2SiO_3 solution will also become more viscous. Therefore, the use of a combination of high NaOH solution concentration and a large amount of Na_2SiO_3 solution will result in higher viscosity and lower workability. Figure 4 shows how the NaOH solution's concentration and the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ solution ratio to workability are related to each other.

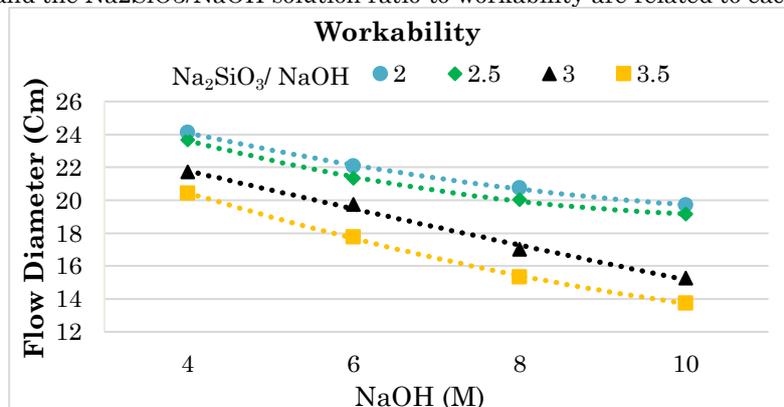


Figure 4. Workability Impact of NaOH Concentration and $\text{Na}_2\text{SiO}_3/\text{NaOH}$ Ratio

3.4 Setting Time

The results of the geopolymer mortar setting time test are shown in Figure 5, with NaOH concentrations of 4M, 6M, 8M, and 10M, the Na₂SiO₃/NaOH ratios are 2.0, 2.5, 3.0, and 3.5, respectively. The results obtained showed that the setting time would be longer if the NaOH concentration solution increased. This is because the molarity of NaOH will make the geopolymer reaction of the released OH⁻ ions increase. In addition, the setting time is affected by ratio of Na₂SiO₃/NaOH solution increased. This is because there is an increase in the concentration of Na₂SiO₃ in the alkaline solution, which makes the fresh geopolymer mortar mixture more viscous, making it stiffer and speeding up the setting time process. Previous research by Balczár in 2015 showed that the setting time of fresh geopolymer mortar mixtures is proportional to workability (Balczár et al., 2015). However, in this study, setting time was not proportional to workability, with longer setting times due to higher molarity. This is because the reaction solution rate between the alkaline solution and the crystalline FANR material is not affected by the increase in the NaOH solution's concentration or the Na₂SiO₃ ratio to NaOH in the fresh geopolymer mortar mixture. The results are in accordance with the analysis obtained from the XRD test, which shows that the FANR material is categorized as a material containing crystalline silica and is not amorphous.

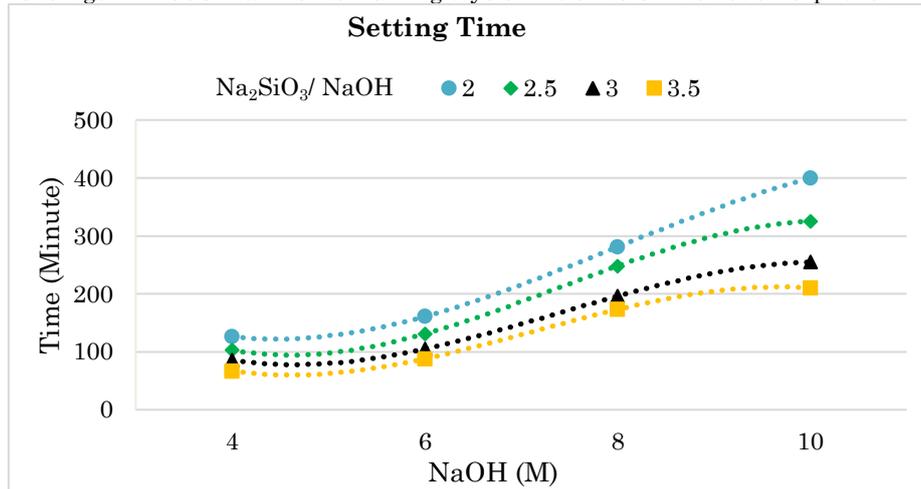


Figure 5. Setting Time Impact of NaOH Concentration and Na₂SiO₃/NaOH Ratio

3.5 Compressive Strength

The compressive strength relationship of geopolymer mortar to the ratio of Na₂SiO₃/NaOH is 2.0, 2.5, 3.0, and 3.5, according to the concentration of NaOH of 4M, 6M, 8M, and 10M for 28 days. The results showed that geopolymer mortars with a concentration of 8M NaOH and a Na₂SiO₃/NaOH ratio of 3.0 had the best compressive strength, with an average of 18.30 MPa. However, when NaOH concentrations of more than 8M are used, the compressive strength decreases. In addition, as shown in Figure 6, the Na₂SiO₃/NaOH ratio of 3.0 is the best ratio that can be used in a geopolymer mortar mixture to achieve maximum compressive strength. Na₂SiO₃/NaOH ratio of 3.0 consistently provides maximum compressive strength to the overall Na₂SiO₃/NaOH ratio.

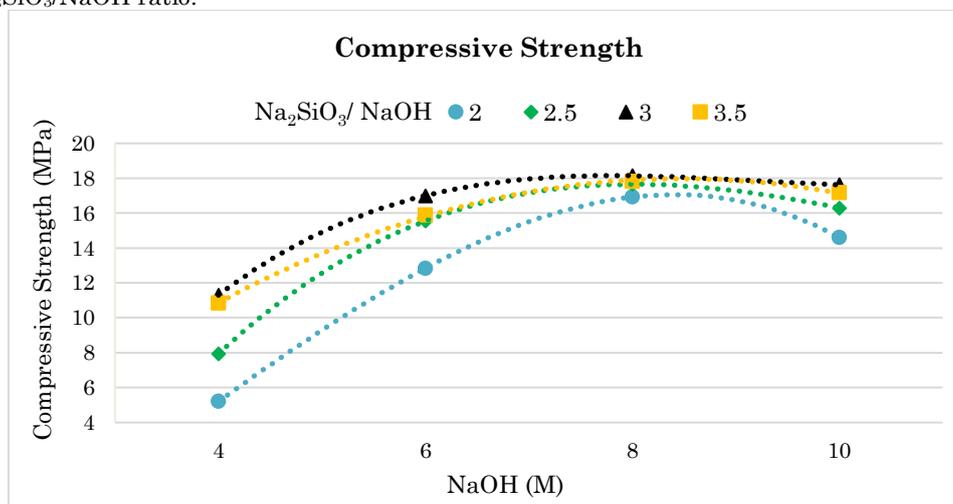


Figure 6. Compressive Strength Impact of NaOH Concentration and Na₂SiO₃/NaOH Ratio

This is caused by excessive hydroxide ions produced by high concentrations of NaOH. In the initial stage, the aluminosilicate gel settles, which stops the process of polycondensation. Furthermore, the ratio of Na₂SiO₃/NaOH greater than 3.0 will make the geopolymer mortar solution more viscous, which stops the process of forming alumina silicate gel.

4. CONCLUSION

Based on the results of the study, the increase in NaOH concentration from 4M to 10M caused a decrease in workability due to increased viscosity of the mixture. In addition, the higher Na₂SiO₃/NaOH ratio also decreases workability due to the high viscosity nature of Na₂SiO₃. Furthermore, setting time testing showed that the increase in NaOH concentration from 4M to 10M tended to extend the initial binding time of the geopolymer mortar. Then the ratio of Na₂SiO₃/NaOH of 3.0 at the concentration of NaOH 8M results in the optimum compressive strength of the geopolymer mortar of 18.30 MPa. The concentration of NaOH exceeding 8M and the Na₂SiO₃/NaOH ratio above 3.0 decreases the compressive strength due to interference in the polycondensation process and the increase in viscosity of the mixture.

RECOMMENDATIONS

Further analyses were conducted to evaluate concrete performance using FANR as a partial replacement of cement, considering the rheology, mechanical properties, and durability.

AUTHOR'S CONTRIBUTIONS

All authors discussed the results and contributed to from the start to final manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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