Unconfined compressive strength test on geopolymer fly ash stabilized clay shale

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**Abstract.** This paper discusses the problem of clay shale in construction and the need for its improvement. The use of geopolymer as a sustainable and environmentally friendly solution for soil stabilization is presented as an alternative to cement-based stabilization. Geopolymers are inorganic aluminum-silicates formed by silicon and aluminum and can be easily found in materials such as fly ash mixed with sodium hydroxide and sodium silicate. The successful use of geopolymer as a soil stabilizer has been reported in several studies, and the alkali activators used significantly impact the mechanical properties and durability of the geopolymer-stabilized soil. This paper aims to explore how geopolymer works for soil stabilization and its corresponding unconfined compressive strength value. The study's findings indicate that the concentration of the alkali activator had a significant influence on the stabilized soil's compressive strength, brittleness index, and secant modulus. The research identified an optimal range of 12-14 M for Na\(_2\)SiO\(_3\)+NaOH mixtures in fly ash-based geopolymers, and emphasized the importance of the alkali activator ratio in stabilizing soil with geopolymer materials. However, the study suggests that further research is necessary to investigate the impact of different ratios and molarities of alkali activator on stabilized soil properties.

**1 Introduction**

As a type of mudrock, clay shale is a big problem in construction due to its unstable properties. The clay shale formed by finely-grained soft rock [1] contains the smectite and montmorillonite minerals. Those minerals collapse clay shale easily when exposed to the atmosphere and water [2]. The study regarding the clay shale was done by numerous researchers, such as mentioned by Agung et al. [3]; Alatas et al. [4], Ilori et al. [5]; Al-Maamori et al. [6]. Most of those studies were trying to examine the clay shale's strength and show that the wetting and drying process decreases the strength.

Land use problems, illegal digging, and cutting off the land surface might cause the clay shale exposed. A landslide in the Cipularang Toll Road exemplifies the clay shale problem in the geotechnical field after exposure [7]. Moreover, the study from Alatas et al. [4] shows how the landslide happened at the Hambalang Sports Center when the clay shale layer was exposed. In a few decades ago, a clay shale layer was also found at the heavy landslide in 1973 at Ciganea, Purwakarta, Indonesia [8]. Those cases conclude that clay shale is a big problem that should be solved.

Smectite minerals dominate the cause of weathering in clay shale and will occur faster when compared to clay shale dominated by kaolinite and illite minerals [9]. Therefore, mechanical treatment is needed to improve clay shale.

Soil-stabilized with chemical matter is widely used nowadays, where most use cement bases. The effect of cement on soil-stabilized cement has been investigated by Stavridakis [10]. The result shows the cement works effectively and has increased the soil's unconfined compressive strength and resistance value. However, cement implementation is one of the main emitters of carbon dioxide, so it is not environment friendly [11].

Among the chemical stabilization alternatives that can be used is the geopolymer. The material used in geopolymer manufacturing is an environmentally friendly solution. The materials could be kaolinite, zeolite, slag, POFA (Palm Oil Fuel Ash), rice husk ash, and fly ash [12-15].

Abdullah et al. [16] successfully used a fly ash-based geopolymer as a soil stabilizer binder. This innovative solution eliminates the need for Ordinary Portland Cement (OPC) and enables the recycling of industrial by-products. At the same time, Yiping et al. [17] evaluated the environmental impact of geopolymer-stabilized soil and found that it had a lower carbon footprint than traditional cement stabilization. This technology shows great potential for sustainable soil stabilization applications in the construction industry. Thus, in this paper how the geopolymer works for soil stabilization and corresponding to the unconfined compressive strength value would be explained further.

### 1.1 Geopolymers for soil stabilisation

Geopolymer has been widely used worldwide. Geopolymer for soil stabilization is one of the alternatives as a sustainable and environment-friendly
material [18]. According to Qomaruddin et al., [19] geopolymer is an inorganic aluminum-silicate that are formed by Silicon (Si) and aluminum (Al). Those materials can be found easily in daily life, such as from fly-ash mixed sodium hydroxide (NaOH) and sodium silicate (Na$_2$SiO$_3$).

American Standard Testing and Material (ASTM) C 618 (2013) classified fly ash into three types: N, F, and C. However, the most used are the F and C types. The F fly ash type has pozzolanic properties with CaO less than 10% and contains more than 70% of the SiO$_2$+Al$_2$O$_3$ + Fe$_2$O$_3$, where it does come from coal. In comparison, Type C fly ash has pozzolanic and self-cementing properties. Those properties appear without any limes [19].

The application of geopolymer as a soil stabilization treatment using geopolymer method has been carried out by many researchers with various variations. Horpibulsuk et al. [20] carried out a significant result when using geopolymer as their addiction material for soil stabilization, where the unconfined compressive strength was increased during the stabilization process. Similarly, the result from Kusuma et al. [21] shows the soil stabilized geopolymer is proven in terms of soil improvement. The results show that the more time the curing takes, the more yield increases.

Other studies have reported on the successful use of geopolymer as a soil stabilizer, such as the work by Zhang et al. [22] and Disu and Kolay [18], who investigated the mechanical properties of geopolymer-stabilized soil. Another study by Sreelakshmi [23] evaluated the long-term stability of geopolymer-stabilized soil and found that it performed better than traditional cement stabilization.

Alkali activators play a crucial role in the formation of geopolymers, and their selection and dosage significantly impact the mechanical properties and durability of geopolymer-stabilized soil. A wide range of Alkali activators has been investigated for geopolymer production, including sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium silicate (Na$_2$SiO$_3$), and potassium silicate (K$_2$SiO$_3$).

1.2 Alkali activators mixed geopolymer

Alkali activators are required to initiate geopolymer reactions. In general, binding materials such as aluminum silicates activated by silica under high pH conditions can be classified as geopolymers. The chemical and physical properties of each will determine the properties and value of the geopolymer [24]. The research on alkali activator has been done by Abdullah et al. [25], where NaOH as the activator influence soil physical change.

Another study has investigated the effect of alkali activators on geopolymer-stabilized soil, such as the work by Mousavinjad and Sammank [26], who evaluated the effect of NaOH and Na$_2$SiO$_3$ dosage on the mechanical properties of geopolymer-stabilized soil. Another study by Odeh et al. [27] investigated the influence of alkali activators on the strength and durability of geopolymer-stabilized soil.

Sodium hydroxide (NaOH) has been studied as an Alkali activator in geopolymer for soil stabilization, such as Cithambaram et al. [28] investigated the influence of NaOH concentration on the unconfined compressive strength of geopolymer-stabilized soil.

Moreover, the use of NaOH can also reduce the carbon footprint associated with soil stabilization. Kaya and Mehmet [29] studied the effect of NaOH on the carbon footprint of geopolymer-stabilized soil and found that it significantly reduced carbon emissions compared to conventional cement stabilization. Another study by Hamidi et al. [30] investigated the use of NaOH as an activator in fly ash-based geopolymer for soil stabilization and found that it improved the strength and durability of the stabilized soil.

In summary, the use of NaOH as an Alkali mixed geopolymer for soil stabilization has shown promising results. The optimization of NaOH concentration and curing conditions is crucial for the successful application of geopolymer-stabilized soil. Furthermore, the use of NaOH as an activator can lead to a reduction in carbon emissions and contribute to sustainable soil stabilization practices.

2 Materials and experimental method

2.1 Soils

The study used clay shale soil collected from the Semarang-Bawen Toll Road. The Clay shale in the form of chunks is then pulverized to pass sieve No.4. The clay soil used in this study is shown in Fig. 1.

![Image](https://example.com/image1.png)

Fig. 1. The clay-shale formed along the Semarang-Bawen Toll Road.

2.2 Geopolymer

Fly-ash mixed alkali activator was used as the basic material of the geopolymer. Those two materials combine 65% fly ash and 35% Alkali activator. At the same time, the comparison between soil and geopolymer is 75% and 25%, respectively. The curing time was also configured to know the optimum result.
2.2.1 Fly ash

Fly ash is a fine powder that is a by-product of burning pulverized coal in power plants. It is often used as a supplementary cementitious material in concrete due to its pozzolanic properties, which means it reacts with calcium hydroxide in the presence of water to form—cementitious compounds. The fly ash contains chemical compounds, including cadmium, chrome, lead, copper, silver, zinc, boron, cyanide, fluoride, nitrate, and nitrite. This study used fly ash type F as the soil stabilizer.

2.2.2 Alkali activator

The Alkali activator is needed as an alternative to Portland cement. The alkali-activated cement was combined with fly ash to create an alternative to Portland cement. It combines sodium hydroxide (NaOH) and sodium silicate (Na2SiO3). The sodium hydroxide (caustic soda) was NaOH in solid form, then diluted with distilled water to generate 12 molar of NaOH. This test has conducted a ratio of sodium silicate to sodium hydroxide of 1 to 2.5 and molarity from 8M to 14M. Fig. 2 shows the Alkali activator used in this research.

![Image](a.png) ![Image](b.png)

**Fig. 1.** The alkali activator: (a) sodium hydroxide (NaOH) and (b) sodium silicate (Na2SiO3).

2.2.3 Mix design

The proportions used for the clay shale to geopolymer and fly ash to Alkali activator ratios were 65% to 35%, respectively. After determining these ratios, the next step involved determining the weight of fly ash and the alkali activator required. The alkali activator was formulated using NaOH and Na2SiO3 based on the specified ratios, starting from 1 to 2.5 ratio.

2.3 Material Strength

2.3.1 Brittleness index

The Brittleness Index (IB) is an essential parameter in soil stabilization, and its value can be used to determine the ductility of a soil specimen. The IB measures the ductility of a specimen, and its value can be used to determine whether a soil specimen is ductile or brittle. In soil stabilization, a soil specimen exhibiting a high IB value is considered brittle and may be more prone to cracking and fracturing. On the other hand, a soil specimen that has a low IB value is ductile and has a higher ability to withstand stress and deformation. The IB can be calculated using Equation 1.

\[ I_B = \frac{q_u - q_r}{q_u} \]  

where:
- \( I_B \) = Brittleness Index value
- \( q_u \) = ultimate stress
- \( q_r \) = residual stress

2.3.2 Secant modulus

The determination of the secant modulus (E50) involves calculating the slope of the stress-strain curve between the starting point (0.0) and the stress-strain at 50% of the qu value [31]. According to Muntohar [32], the axial compressive strength and strain relationship can be used to establish the secant modulus using Equation 2.

\[ E_{50} = \frac{q_{50}}{e_{50}} \]  

where:
- \( E_{50} \) = Secant modulus (kPa)
- \( q_{50} \) = 50% of the compressive strength value (kPa)
- \( e_{50} \) = strain on \( q_{50} \) (%)

3 Result and discussion

The different variations of the alkali-activators ratio through the curing time have been examined as the contribution of different alkali-activator concentrations.

3.1 Relationship of compressive strength and molarity

In general, the test results showed an increase in strength with curing time (see Fig. 3). In the alkali-activator with one of ratio, each sample showed an increase in compressive strength as the curing days increased. However, at the 14 molar level, the compressive strength tends to decrease when compared to other levels, both at 7 days, 14 days, days, and 28 days of curing time. Likewise, in samples with 1.5 and 2 of ratio, in general, the decreasing in compressive strength showed in 14M content. However, a difference behaviour was found in the 2.5 ratio sample. An increase in compressive strength occurred in the 14M sample, although a decrease occurred when the sample at 28 days old in compared to 12 M. The effect of the molarity of Na2SiO3+NaOH mixtures on the compressive strength of geopolymer has been studied by many researchers like Abdullah et al. [16, 33], and Affandhiea et al. [12]. The optimum molarity was found to be around 12-14 M for fly ash-based geopolymer.
3.2 The relationship of curing time and brittleness

3.2.1 Index

Fig. 4 shows the effect of curing time and alkali-activator concentration on the brittleness index. The results show that the curing time and alkali activator concentration are quite influential in terms of changes in the brittleness index. In the sample with 1 of ratio, the brittleness index increased simultaneously to the additional time and the addition of alkali-activator content. However, fluctuating results were obtained in the 1.5 ratio, 2 ratio, and 2.5 ratio samples with 8M and 12M levels. No correlation was found between the curing time, molarity content, and brittleness index at these levels. It can be concluded that the ratio of Alkali activator on soil stabilized geopolymer plays an important role. Both results indicate the important role of alkali activator concentrations in mixing geopolymer materials [34]. The studies found that varying he Na$_2$SiO$_3$/NaOH ratio and NaOH molarity affects the compressive strength of fly ash-based geopolymer mortar. Higher molarities of NaOH generally lead to higher compressive strength, while the effect of the Na$_2$SiO$_3$/NaOH ratio is more complex and depends on the specific ratio used [35].

3.2.2 The relationship of curing time and secant modulus

The findings presented in Fig. 5 demonstrate the effects of using geopolymer to stabilize soil, with varying ratios of alkali activator, on the secant modulus of the resulting stabilized soil. The results indicate that unstable outcomes were observed with alkali activator ratios of 1.5 and 2.5. The results further reveal that when using a ratio of 2, an increase in the secant modulus occurred during the 28-day curing period.

4 Result and discussion

This study focused on investigating the effect of varying alkali activator ratios on the performance of soil-stabilized geopolymers. The results showed that alkali activator concentration had a significant impact on the compressive strength, brittleness index, and secant modulus of the resulting stabilized soil. The study found that the optimum molarity for the Na$_2$SiO$_3$+NaOH mixtures in fly ash-based geopolymer was around 12-14 M, and the ratio of alkali activator played an important role in stabilizing soil with geopolymer materials. However, the results also showed that the effect of molarity content on the properties of stabilized soil was complex and depended on the specific ratio used. The study suggests that further research is needed to
investigate the effect of different ratios and molarities of alkali activator on the properties of stabilized soil. Overall, the findings of this study could provide useful insights for the development of more efficient and sustainable soil stabilization techniques using geopolymers.

Fig. 4. The brittleness index of clay shale stabilized geopolymer in different NaOH molarities. (a) is 8 M, (b) is 10M, (c) is 12M, and (d) is 14M.

Fig. 5. The secant modulus of 28 days curing period.

References


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