Shear strength characteristic of geopolymer fly ash and egg shell powder stabilized clay soil

Willis Diana, Edi Wibowo Wahyu Eka, Weny Irma

Abstract

Geopolymers derived from solid waste encourage waste reduction, recycling, and safety while being an environmentally beneficial and sustainable green material [3]. When compared to PC, geopolymer-stabilized soils achieve high early strength more quickly. Because of their flexibility, geopolymer-stabilized soils can prevent cracking during construction, curing, and operation. The decreased shrinkage compared to PC can also help prevent the cracking damage caused by soil shrinkage. The cost problem can be solved by producing geopolymer from industrial waste or by-products [3]. The geopolymer was created by combining alkali silicate or hydroxide reactions to activate aluminosilicate binders with high pH concentrations [6]. According to the results of microstructural and mineralogical characterizations, the improvement in mechanical strength was attributed to the binding effect of geopolymer gels [2, 7, 8], which is dependent on the rapid dissolution of aluminosilicates and the release of $[SiO_4]^{-4}$ and $[AlO_4]^{-3}$ tetrahedral units in the solution. The dissolution can be attributed to the dissolution of the Si-O-Si and Si-O-Al bonds through a reaction with the OH ions in the alkaline activator. By redistributing ions and increasing their electronic density around silicon atoms, Hornibulsuk et al. [4] suggested adding 25% fly ash (FA) to the economic mix design. Because the amount of fly ash can equal 0.75 times the amount of cement, this suggestion can save up to 15.8% on the amount used. These materials can work as well as traditional cementitious binders in various situations, but they have the extra benefit of releasing much less greenhouse gas. Geopolymers can have different qualities and characteristics depending on the raw materials used and how they are processed. For example, they can have high compressive strength, low shrinkage, fast or slow setting, acid resistance, fire resistance, and low thermal conductivity. Even though geopolymers are often said to have a wide range of properties, not all geopolymers have all of these properties [5].

1 Introduction

The stability of geotechnical profiles depends on soil shear strength [1]. Due to reduced cohesion and friction between soft soil particles at a high moisture level, shear base failure is more likely to occur in soft soils than in granular structures. Various mechanical and chemical soil stabilization techniques are utilized to prevent such losses. The principle of mechanical approaches is to increase the friction between soil particles or transfer the internal stress of the soil into stronger elements. In contrast, chemical stabilization focuses on providing strong chemical bonding and surface tension between soil particles by utilizing binders. Geopolymer is a promising alternative to Portland cement (PC) due to its high strength, low cost, low energy consumption, and low CO$_2$ emissions during synthesis [2]. Geopolymers derived from solid waste encourage waste reduction, recycling, and safety while being an environmentally beneficial and sustainable green material [3]. When compared to PC, geopolymer-stabilized soils achieve high early strength more quickly. Because of their flexibility, geopolymer-stabilized soils can prevent cracking during construction, curing, and operation. The decreased shrinkage compared to PC can also help prevent the cracking damage caused by soil shrinkage. The cost problem can be solved by producing geopolymer from industrial waste or by-products [3].
the Si-O-Si bonds can be further weakened and more susceptible to rupture. These tetrahedral units are later joined in a process known as coagulation-condensation through the sharing of oxygen atoms rather than a polymeric precursor to form aluminosilicate hydrate (A-S-H) [9]. The alkaline metal that catalyzes the reaction during the dissolution phase functions as a structural component during the condensation phase [10].

The percentage of calcium in fly ash is an important but sometimes neglected factor. Coal combustion produces fly ash, which consists of inorganic matter that does not ignite. If sub-bituminous coal is utilized, the resulting ash is classified as type C due to its high calcium content [11]. This type of ash has self-cementing properties, which means that, in principle, only water is required to hydrate this material and form cementitious products comparable to those obtained from Portland cement. If bituminous coal is used, the resulting by-product is classified as class F fly ash (calcium content is typically less than 5 percent) with no self-cementing properties [12]. Even when no alkaline agent is added to improve its behavior, it is evident that the calcium percentage significantly affects the properties of fly ash as a building material.

Sukmak et al. [13] investigated the effects of fly ash geopolymers on clay soil with Na2SiO3/NaOH. They found that the optimal ratio of sodium silicate (Na2SiO3) and sodium hydroxide (NaOH) produced fly ash with the greatest strength at a ratio of 0.5, the greatest compressive strength at a ratio of 1.5, and geopolymerization can strengthen the soil and generate optimal results for the dispersion of fly ash and alkali activators in a specific ratio. Also, Abdullah and Shahin [14] investigated the geopolymer method for stabilizing clay soil and found that the UCS value of geopolymer-treated soil was higher than that of untreated soil. During the geopolymerization process, the compressive strength is also affected by the molarity ratio of the activator alkali. The higher the molarity, the higher the compressive strength [14].

Eggshells are a typical domestic waste product. It will increase each year if improperly disposed of. When eggshells are left in the garbage for an extended period, they can irritate the skin and emit offensive aromas. Numerous researchers have reported using eggshell powder as a geopolymerization precursor [15-21], and Sathiparan [22] has reviewed the use of Eggshell Powder (ESP) for a variety of purposes, including soil stabilization materials, cement replacement, and geopolymerization precursors. Chemical stabilization can be accomplished by introducing materials, such as eggshells, that initiate chemical reactions when added. Adding eggshell waste (powdered eggshells) to the eggshells, that initiate chemical reactions when added. can be accomplished.

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Research indicates that the geopolymer approach using FA can increase the tensile strength of soil [8]. Due to the simultaneous influence of N-A-S-H or K-A-S-H, C-A-S-H, and C-S-H, precursors with high amorphous content and specific area perform better. In contrast, Ca-based precursors provide robust alkali binder structures [23]. The compressive strength of the soil can be increased by incorporating ESP into the geopolymerization of FA. Literature indicates that the optimal activator concentration for eggshell powder and fly ash-based geopolymers is 2.0 M with 10 M sodium hydroxide [15]. It means that the compressive strength of eggshell powder and fly ash-based geopolymer increases proportionally to the quantity of fly ash but decreases proportionally to the amount of eggshell powder.

The test results of soil stabilization using geopolymers fly ash-eggshell powder geopolymer is still variable; in addition to the type and precursor content, soil minerals also generally influence soil stabilization. Additionally, published research and recommendations may serve as a general resource. The influence elements must be individually validated for each site [24]. This study uses UU triaxial testing to investigate the stress-strain behavior and shear strength parameters of clay soil treated with a fly ash-egg shell powder-based geopolymer. This study investigates the parameters, such as curing time and sodium hydroxide molarity, that influence soil stabilization using FA and ESP-based geopolymer. The results are compared to clay that has not been treated. This study was conducted to determine the role of ESP in replacing FA in improving the shear parameters of clay soil, as well as the possibility of using fly ash and eggshell to stabilize the soil.

2 Material and methods

2.1 Soil

High plasticity clay (CH) soil was used in this study. This disturbed soil was collected from Kasihan, Bantul, in the Yogyakarta Special Region. Table 1 summarizes the physical and mechanical parameters of the soil.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity, Gs</td>
<td>2.66</td>
</tr>
<tr>
<td>Atterberg limits:</td>
<td></td>
</tr>
<tr>
<td>Liquid limit, LL (%)</td>
<td>77.50</td>
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<tr>
<td>Plastic limit, PL (%)</td>
<td>33.60</td>
</tr>
<tr>
<td>Plasticity index, PI (%)</td>
<td>43.90</td>
</tr>
<tr>
<td>Particle-size distribution:</td>
<td></td>
</tr>
<tr>
<td>Clay (%)</td>
<td>68.77</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>24.77</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>6.46</td>
</tr>
<tr>
<td>USCS classification</td>
<td>CH</td>
</tr>
<tr>
<td>Maximum dry density, MDD (g/cm³)</td>
<td>12.68</td>
</tr>
<tr>
<td>Optimum moisture content, OMC (%)</td>
<td>34.83</td>
</tr>
<tr>
<td>Shear strength parameter (triaxial UU test)</td>
<td></td>
</tr>
<tr>
<td>Cohesion (kPa)</td>
<td>43.26</td>
</tr>
<tr>
<td>Internal friction angles (°)</td>
<td>2.35</td>
</tr>
</tbody>
</table>

The particle size analysis of the soil, as performed according to ASTM D7928 [25], The liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the soil were measured according to ASTM D 4318 [26]. The soil's optimum water content and maximum dry density by ASTM D 698 [27].

Table 1. Geotechnical properties of soil.
2.2 Geopolymer material

The alkaline activator consisted of sodium hydroxide and sodium silicate. The ratio of sodium silicate to sodium hydroxide is 1 to 1. Based on the soil strength parameter, Phummpihan et al. [28] suggested that a Na2SiO3:NaOH ratio of 1:1 is the optimal constituent whose Unconfined Compression strength (UCS) meets the requirements for heavy traffic. This ingredient is also the most cost-effective, as NaOH is considerably less expensive than Na2SiO3. In this study, the molarity of the sodium hydroxide solution was varied at 5 M and 10 M. At the same time, the ratio of the alkalai activator to optimum water was fixed at 1 (34.82% by weight). According to Andini et al. [29] and Hanjitsawan et al. [30], the optimal concentration of sodium hydroxide is between 4.5 and 18 molar.

The coal-burning PLTU Tanjung Jati in Jepara was the type F fly ash source. The fly ash is dried for at least 16 hours in an oven heated to 100 °C. The fly ash is pulverized until it passes a 200-mesh sieve. The FA content used is 20% of the weight of the mixture.

The eggshells were sourced from industrial suppliers and waste bakeries near Universitas Muhammadiyah Yogyakarta. The eggshell is cleaned, and the white membrane is separated, sun-dried, and pulverized until it passes through a No. 200 sieve (0.074 mm). The ESP was heated and calcinated for two hours at 900 °C to facilitate its interaction with soil when mixed with soil. In this study, the ESP was used 5% by weight of the mixture to substitute for FA.

2.3 Specimens preparation

The specimens were cylindrical, with a diameter of 3.5 cm. The ratio of height to diameter was 2 (7 cm height). The proportion of the samples displayed in Table 2. As FA type F contains less than 10% CaO, the addition of ESP is anticipated to accelerate the specimen's setting time. Variations of 5% ESP additions are supplied to replace and add more CaO to the geopolymer.

<table>
<thead>
<tr>
<th>Precursor types</th>
<th>NaOH Molarity</th>
<th>Material composition</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Soil (%)</td>
</tr>
<tr>
<td></td>
<td>5 M</td>
<td>10 M</td>
</tr>
<tr>
<td></td>
<td>10 M</td>
<td>20 M</td>
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</tbody>
</table>

The soil is desiccated in an oven at 105°C for twenty-four hours and pulverized to pass a No. 40 sieve. The geopolymerization process was created by mixing and thoroughly blending all the dry precursor materials (FA and ESP) until the color was uniform. A predetermined quantity of an alkaline liquid solution containing sodium hydroxide (NaOH) and sodium silicate (Na2SiO3) was mixed. The soil was added after the precursor (fly ash and ESP), and liquid alkaline activator had been mixed. The liquid activator percentage was identical to the OMC percentage (34.83%). When a liquid alkali activator and the precursor are applied to the soil, it must be stored in a covered container for at least 16 hours before compaction.

2.4 Specimens compaction dan curing

The specimens were prepared by compacting at least three layers of material using a circular cross-section mold with dimensions meeting the specifications. Specimens should be compacted to the desired density (same as MDD 12.68 g/cm3) by tamping each layer until the accumulative mass of soil formed in the mold is compacted to a known volume; the top of each layer must be sacrificed before the addition of material for the next layer. The tamper diameter used for compacting the material must match the diameter of the mold. Remove the mold and ascertain the specimen's mass and dimensions after a specimen has been formed with perpendicular ends to the longitudinal axis. The water content measurements were performed on excess sample preparation material. Fig. 1 shows the mold and the specimens. The sample was cured between 7 and 28 days. The specimens were cured in dry condition, and wrapped in plastic film in the temperature room. After the samples had cured, they were taken out of their wrappings and put through triaxial UU testing. Fig. 2 shows the curing specimens.
2.5 Unconsolidated undrained triaxial test

The Unconsolidated Undrained (UU) Triaxial Test is performed according to ASTM Standard D2850-03a [31]. The unconsolidated undrained triaxial test determines the strength and stress-strain relationships of a cylindrical sample of remolded cohesive soil. In a triaxial chamber, specimens are subjected to confining fluid pressure (σc). During the test, no drainage of the specimen is permitted. The specimen is sheared in compression without drainage (strain-controlled) at a constant rate of axial deformation. The UU triaxial test provides information for determining soils' undrained strength properties and stress-strain relationships. This method measures the total stresses applied to the specimen; pore-water pressure is not considered. Consequently, the resultant strength depends on the pressure developed in the pore fluid during loading.

The triaxial chamber assembled with the specimen in the rubber membrane sealed to the specimen cap and base. Contact the specimen cap repeatedly to sit and align the axial load piston properly. Position the chamber in the axial loading device. To avoid lateral strain on the piston during testing, align the axial load measuring device, axial load measuring device, and triaxial chamber. Fill the chamber with confining liquid and attach the pressure-measuring equipment. Adjust the chamber pressure and apply pressure to the chamber fluid. Allow the specimen to stabilize under chamber pressure for 10 min before using the axial force.

The axial load is applied to produce axial strain at approximately 1%/min to attain maximal deviator stress at 3 to 6% strains. At these rates, maximum deviator stress will be reached in 15 to 20 minutes. Continue loading to 15% axial strain, except when the deviator stress has peaked and declined 20% or when the axial strain has exceeded the strain at which the deviator stress peaked by 5%. Record load and deformation values to three significant digits at approximately 0.1, 0.2, 0.3, 0.4, and 0.5% strain; then at increments of about 0.5% strain to 3%; and finally, every 1%. Take enough readings to define the stress-strain curves; therefore, more frequent readings may be required at the beginning of the test and as failure approaches.

Deviator stress (Δσ) was plotted as the ordinate, and axial strain (ε) (in percent) was plotted as the abscissa to create a graph representing the relationship between principal stress difference (deviator stress) and axial strain. The compressive strength and failure axial strain was selected.

The interparticle cohesion (c) and friction angle (f) values were determined using triaxial tests and the Mohr-Coulomb criterion as described in Equation 1. This Equation represents the normal stress acting on the surface of failure.

\[
\tau = c + \sigma \tan \phi
\]

In unconsolidated undrained triaxial tests, specimen drainage is not permitted at any stage (consolidation or shear). After applying the chamber-confining pressure (σc), the deviator stress (Δσ) is increased until failure occurs. Total major principal stress (σm) = (σc + Δσ), and total minor principal stress= σn. The p-q diagram is a technique for facilitating the analysis of triaxial and other commonly used stress data in soil mechanics, where p=1/2(σm+σn) and q=1/2(σm−σn). The p-axis was set as the abscissa (x-axis) and the q-axis as the ordinate (y-axis) to obtain the failure line.

Two components can be used to evaluate soil shear behavior in more detail: cohesion or physicochemical bonds and interparticle friction. Matrix suction and effective cohesion contribute to the cohesion of the entire structure. A combination of negative pore water pressure and surface tension within the water film promotes the former. In contrast, the latter results from interparticle bonds (physicochemical attractions), including cementation and adhesion due to compaction and electrostatic attractions. Internal friction is determined primarily by the normal stress working on the failure surface and the geometrical properties of the particles [32, 33].

3 Result and discussion

Fig. 3 and Fig. 4 show the stress (deviatoric stress) - strain curve for the specimen at 28 days of curing, with a variation of 20% FA and 15% FA + 5% ESP and 5-molar and 10-molar sodium hydroxide concentrations, respectively. Fig. 5 shows the maximum deviatoric stress for confining pressure of 98, 1 kPa, 196,2 kPa, and 294,3 kPa, for each NaOH concentration of 5 M and 10 M at a curing time of 28 days.

![Fig. 3. Stress-strain curves of NaOH concentrations at 28 days of curing](https://doi.org/10.1051/e3sconf/202342904024)
However, specimens treated with 20% FA were 1381.46 kPa, 1672.47 kPa, and 1718.90 kPa. The maximum deviatoric stress of specimens treated with 15% FA + 5% ESP was between 16% and 25% greater than that of specimens treated with 20% FA. The maximum deviatoric stress was between 1.6 and 2.1 times greater in specimens treated with 10 molar NaOH than in specimens treated with 5 molar.

Greater stress requires more energy to damage the specimen before its failure. The amorphous aluminosilicate gel is the primary product of geopolymerization, which enhances mechanical strength. Incorporating calcium-rich ESP can also be advantageous for forming a calcium silicate gel in an alkaline medium. Few sources [28] [34] confirm the formation of C–S–H, C–A–H, C–A–S–, and N–A–S– from alkali-activated class C FA, which has high calcium, in this study, high calcium was obtained from ESP. The addition of calcium-rich ESP increased the amount of geopolymerization products in addition to aluminosilicate gel [17]. Therefore, the lower percentage of calcium in the silica and alumina source used for soil improvement through alkaline activation positively affects mechanical behavior over the medium to long term (more than 28 days). In contrast, a strength at curing period of 7 days gain is faster in calcium-based materials such as fly ash C, cement, or lime [6]. Furthermore, small amounts of ESP, according to the research of Anoop et al. [35], can enhance the strength-increasing pozzolan reactions on treated soils.

For all confining pressures and NaOH concentrations, 15% FA + 5% ESP treated specimens exhibit higher peak stresses than 20% FA specimens. At a 10 molar NaOH concentration and a curing time of 28 days, the maximum deviatoric stress of specimens treated with 15% FA + 5% ESP was 1738.76 kPa, 1953.12 kPa, and 2141.44 kPa for confining pressures of 98.1 kPa, 196.2 kPa, and 294.3 kPa, respectively.
20% FA exhibited cohesion values of 144.73 kPa and 355.68 kPa, with internal friction angles of 18.05° and 28.80°, respectively.

Fig. 7. The cohesion of a treated soil.

Fig. 8. The friction angles of treated soil.

To compare the shear strength behavior of the various treated specimens, the shear strength parameters of the treated clay (cohesion and angle of internal friction) were normalized to values corresponding to untreated clay. Fig. 9 shows the normalized cohesion and friction angles.

According to Fig. 9, specimens treated with 15% FA+5% ESP at concentrations of 5 and 10 molar NaOH produced cohesion that was 5,3 and 9.9 times greater than untreated soil, whereas soil treated with 20% FA produced cohesion that was 3.3 and 8.2 times greater than untreated soil. The cohesion obtained from soil treated with 15% FA + 5% ESP was higher than that obtained from soil treated with 20% FA.

Similar results were obtained for the internal friction angle parameter, with the internal friction angle in the soil treated with 15% FA + 5% ESP being greater than the internal friction angle in the soil treated with 20% FA by 6.2 times, 8.8 times, and 12 times for 5 molar and 10 molar NaOH, respectively.

The formation of the N-A-S-H and C-A-S-H artificial cementitious products resulted from the combination of fly ash and eggshell powder, resulting in a relatively solid structure. The cementitious material bonds the particles and forms a cohesive network within the soil matrix, resulting in greater internal friction angles. Additionally, the hydrating of the geopolymer over time can increase the rigidity and stiffness of the stabilized clay, increasing the internal friction angle.

Fig. 9. Effects of Sodium hydroxide concentration on shear strength parameter of clay soils.

The concentration of NaOH influences the dissolution of aluminium and silicon in clay particles, thereby influencing the formation of geopolymers and then the strength of geopolymers. A relatively high degree of geopolymerization can be obtained with a high concentration of NaOH. Due to the low base concentration and reduced silica and alumina leaching from the source material, geopolymerization is low at low concentrations [30, 36]. Abdullah et al.[37] and Onutai et al. [38] also demonstrated comparable research findings.

Fig. 10 presents the progress of normalized cohesion against curing time. At seven days, soil cohesiveness stabilized with geopolymer fly ash and increased 1-2 times more than soil cohesiveness without treatment. At 28 days, cohesion increased to 4 times more than untreated soil. Increasing the curing period might increase the shear strength of the stabilized soil as the geopolymerization process continues to proceed. The reaction between the fly ash and the alkaline activator that generates the geopolymer matrix that holds the soil particles together is known as geopolymerization: the more time the geopolymer matrix must form and strengthen, the longer the curing period. Jallu [39] also stated the similar results that the specimens that cured 28 days improved mechanical strength and stiffness significantly, resulting in lower permanent deformations.

The parameters of the increase in cohesion and friction angle in soils treated with 15% FA + 5% ESP tended to be higher at 7 and 28 days of curing than in soils treated with 20% FA.

These analyses provided no insight into the relationship between soil mineralogy and soil plasticity...
and stabilization results. Notably, soil mineralogy and plasticity are known to have a significant impact on soil stabilization effectiveness. Further research requires mineral, plasticity analysis and Scanning Electron Microscope (SEM) on treated soil, to determine changes in the microstructure and minerals in the treated by FA and ESP geopolymer.

4 Conclusion

This study examined the parameters of the strength of geopolymer-stabilized clay using the Unconsolidated Undrained triaxial test. The molarity concentration of NaOH considerably influence shear strength characteristics, the amount of fly ash and eggshell powder, and the curing time. The maximal deviatoric stress is significantly increased by substituting 5% FA with ESP. The 15% FA and 5% ESP precursor increase cohesion and the internal friction angle. Increasing molarity and curing time enhanced shear strength, as predicted. ESP has the potential to replace some of the fly ash as a precursor in geopolymers for soil stabilization.

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References