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# Study of Mechanical Behavior of Expansive Clay due to the Addition of Nano Silica Dioxide ($SiO_2$)

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## ABSTRACT

Expansive clay which is a problematic soil is spread almost all over the world, including Indonesia. In various regions in Indonesia, expansive clay has damaged the infrastructure above, causing high maintenance costs. Expansive clay often becomes a problem when infrastructure is built on it, due to its large swell and shrink properties. Improved stabilization of expansive clay is required to improve mechanical behavior (shear strength, compressive strength and modulus of elasticity). In this study, the effect of increasing shear strength, unconfined compressive strength and modulus of elasticity of expansive clay added with $SiO_2$ nano material will be investigated. $SiO_2$ nanomaterial can be produced from processing waste from geothermal power plants. The percentage of $SiO_2$ nanomaterial mixture used in this research is 0%; 1%; 2% and 3% compared to dry soil weight. The increase in shear strength, unconfined compressive strength and modulus of elasticity will affect the mechanical behavior of expansive soil. This increase in mechanical behavior also means increasing the bearing capacity of the soil and this is very influential in stabilizing expansive clay. From laboratory substantiation that have been carried out, the laboratory test results show an increase in modulus of elasticity of 17%. An increase in shear strength of 64% and an increase in UCS stress of 91%, which occurs at the optimum mixing nano $SiO_2$ ratio.

**Keywords:** $SiO_2$ nano material; mechanical behavior; expansive clay; shear strength; unconfined compressive strength; modulus of elasticity.

## INTRODUCTION

Soil has a very important role in building work, either as a building material such as embankments and dams or as a support for buildings such as roads, railways and buildings. One type of problematic soil in civil construction is expansive clay. The properties of expansive clay soil are not good for buildings, including very low strength and quite large swelling and shrinkage, so that the soil physically and technically does not meet the requirements for building work. Therefore, to obtain stable basic soil, soil stabilization is required.

This research was conducted in Indonesia, according to data from the Ministry of Energy and Mineral Resources (ESDM) in 2016, Indonesia has total geothermal energy potential of 29,543.5 MW. Some of this geothermal potential has been utilized as a geothermal power plant. The operation of this geothermal power plant produces waste that contains a lot of silica which can be processed into nano silica dioxide (nano $SiO_2$). Geothermal waste contains a lot of silica ($SiO_2$), with other accompanying ingredients such as a number of potassium (K), magnesium (Mg). This silica waste has great potential to be processed into nano silica (nano $SiO_2$) which can be utilized into a product with high economic value. [1] The more geothermal power plants that will be built and operated, the more silica waste will be produced. Considering this, this research is projected to be able to provide an alternative solution for utilizing geothermal power plant waste as a stabilization material for expansive clay.

By adding nano $SiO_2$ to expansive clay, it is intended to fill the lattice between expansive clay particles. As a result, it will encourage water to come out of the expansive clay lattice. Thus the amount of water contained in expansive clay will be limited. Subsequently the shear strength can be expected to increase. Likewise, by inserting $SiO_2$ nano material into the cavities or spaces between expansive clay particles, it will increase the shear strength. Several previous studies have used nanomaterials to be used as expansive clay mixtures with the aim of improving mechanical behavior. Another use of nano material is nano alumina $Al_2O_3$, [2] [3] nano copper (CuO). [3] In this research $SiO_2$ is used because this material is 60% of the constituent elements of earth's rocks and processing it into nano materials is easier.

## RESEARCH METHODS

### Soil

Expansive clay samples used in this research were obtained from Karawang district, West Java, Indonesia. according to the geological map, the area is included in the TMS2 rock type. Tertiary rocks, Miocene series and Subang 2 rock formation. Table 1 shows the physical properties of the expansive clay (samples) used in this research. The liquid limit value of 110.13% and plastic limit of 44.20% indicates that the soil contains the mineral montmorillonite. [4] [5] It can also be seen that the soil according to the USCS classification is classified as CH (high plasticity).

**Table 1.** Physical Properties of the Expansive Clay

| Properties of Sample | Categories/Content | |
|---|---|---|
| USCS Index | | CH |
| Clay Content | % | 41,19 |
| Silt Content | % | 19,78 |
| Sand Content | % | 38,53 |

X-Ray diffraction testing is required to determine the mineral content in expansive clay. The test implementation has been carried out according to test standards. The test results can be seen in the figure below.

| Phase | Pattern | Compound Name | Formula | % |
|---|---|---|---|---|
| Phase 1 | PDF 00-058-2034 | Muscovite | $KAl_2(Si,Al)_4O_{10}(OH)_2$ | 7.59% |
| Phase 2 | PDF 00-009-0453 | Halloysite | $Al_2Si_2O_5(OH)_4$ | 12.88% |
| Phase 3 | PDF 00-058-2008 | Montmorillonite-calcian | $Ca_{0.2}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot xH_2O$ | 36.19% |
| Phase 4 | PDF 04-010-4800 | Kaolinite | $Al_2Si_2O_5(OH)_4$ | 17.19% |
| Phase 5 | PDF 01-085-0865 | Quartz | $SiO_2$ | 26.15% |

**Figure 1.** Mineral Composition Based on X-Ray Diffraction Test on Sample Material

From the table above it can be seen that montmorillonite is the dominate mineral with a percentage of 36%. So based on this test, the sample soil used was expansive clay.

### Nano $SiO_2$

Nanoparticles are defined as dispersed particulates or solid particles with a particle size of 10 – 100 nm. Nanoparticles have physical characteristics, including a large surface area. The surface area determines the size, structure, and aggregation size of the particles. [6] Silica nano particles have several, advantagesmong other a large surface area.

**Table 2.** Physical Properties of Nano $SiO_2$.

| Soil Properties | Attribute |
|---|---|
| Model No | 150/200/300 |
| Standard EINECS No | 215-684-8 |
| Purity | 99,8% |

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| Soil Properties | Attribute |
|---|---|
| Country of Origin | China |
| MF | $SiO_2$ |
| Grade Standard | Hydrophobic |
| Performance | White, Nanoscale |
| Surface Area ($m^2$ $g^{-1}$) | 150-380 |

### Methods

The testing proceures carried out in this research can be explained in the chart below:

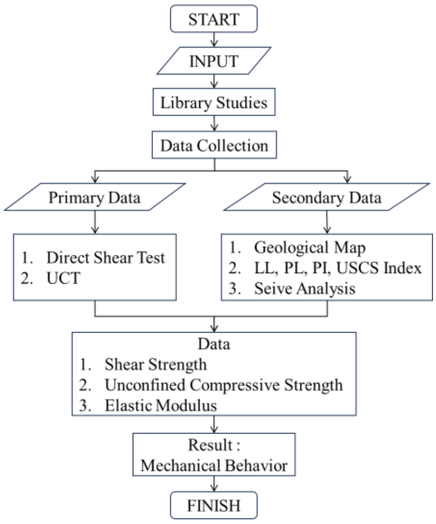


**Figure 2.** Research Flowchart

Testing is carried out in the laboratory. Implementation and experiment steps implemented are in accordance with applicable international standards. The following are the test standards that have been carried out:

1. Sieve Analysis (ASTM D 422-02)
2. Hydrometer Analysis (AASHTO-T-193-81)
3. Specific Grafity (ASTM D 854-02)
4. Standard Proctor (ASTM D 698-07)
5. Direct Shear (ASTM D 3080-04)
6. Unconfined Compressive Test (ASTM D 2166-06)

All soil samples to be used for experiments must be dried and pass sieve number 20. Then dried in an electric oven at a temperature of 100°C for 24 hours. The mixing ratio for the additional nano $SiO_2$ material is based on the percentage of dry soil weight. Without going through this process, sample homogeneity will be difficult to obtain. After the mixture reaches the expected homogeneity, then mixed with water according to the standard proctor test results.

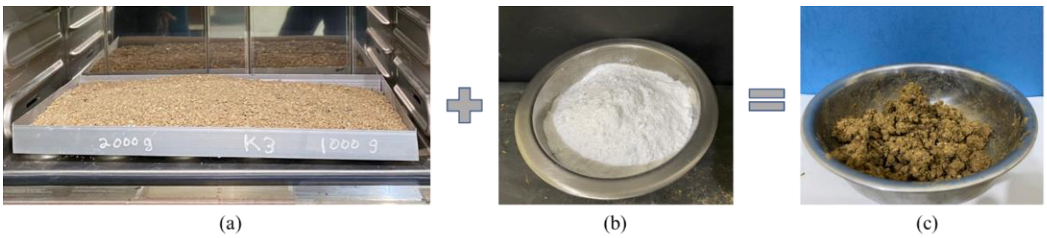


**Figure 3.** The Process of Forming Soil Samples (a) Expansive clay that has been dried in an oven (b) Nano $SiO_2$ (c) Soil mixture with nano $SiO_2$ at optimum water content

### Standard Proctor Test

Standard Proctor test are usually expressed as a curve of the relation between dry weight unit and water content.

The optimum water content is obtained in the following item: from 6 samples with different water contents we can calculate the $\gamma_d$ for each samples. After that, it is depicted using the usual scale $w$ (%) as the x-axis and $\gamma_d$ as the y-axis, so that a curved compaction curve will be obtained. This curve also depicts $z_{av}$ and the curve at the degree of saturation s=80%. From the top of the compaction curve, vertical and horizontal lines are drawn until they intersect the curve axes. From the horizontal line the maximum $\gamma_d$ value will be obtained, while from the vertical line the $w_{opt}$ (optimum water content) will be obtained.

**Table 3.** Test Result of Standard Proctor

| Specimen | | OMC (%) |
|---|---|---|
| Expansive Clay (EC) | | 32,0 |
| EC + $SiO_2$ | 1% | 30,2 |
| EC + $SiO_2$ | 2% | 29,1 |
| EC + $SiO_2$ | 3% | 30,8 |

### Direct Shear Test

This experiment is intended to specify the magnitude of the shear strength of the soil directly. The aim is to determine the relationship between the magnitude of the shear force and the normal load which is presented in the graph. To determine the cohesion parameters ($c$) and internal friction angle ($\phi$). To examine the shear strength parameters of expansive clay mixed with nano $SiO_2$, the direct shear tests, subjected to loading using 3 variations in normal loads: 3,2 kg, 6,4 kg, and 9,6 kg.

### Unconfined Compressive Test

To evaluate the increase in UCS (Unconfined Compressive Strength) of expansive clay due to addition of nano-$SiO_2$, a set of Unconfined Compression Tests (UCT) was conducted on expansive clay mixed with nano $SiO_2$ and original specimens. The laboratory experiments were carried out with different ratios of nano-$SiO_2$ (0%, 1%, 2%, and 3% of soil dry weight). The Unconfined Compression Test (UCT) is a method carried out in the laboratory to measure how much the soil's bearing strength accepts the compressive strength applied until the soil separates from its grains and also the strain of the soil due to this pressure.

### Data Analysis

Direct Shear Test

From this test, shear strength parameters were obtained for expansive clay mixed with nano $SiO_2$. Shear strength for expansive clay is cohesion: 25,48 kPa and internal shear angle: 18,43°. For expansive clay mixed with nano $SiO_2$ 1% respectively is cohesion: 29,72 kPa and internal shear angle: 23,63°. For expansive clay mixed with nano $SiO_2$ 2% respectively is cohesion: 34,44 kPa and internal shear angle: 26,57°. For expansive clay mixed with nano $SiO_2$ 3% respectively is cohesion: 41,05 kPa and internal shear angle: 34,51°. The results are shown in the figure below:

| Parameter of Shear Strength | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Expansive Clay (EC) | | | EC + Nano $SiO_2$ 1% | | | EC + Nano $SiO_2$ 2% | | | EC + Nano $SiO_2$ 3% | | |
| c | 25,48 | kPa | c | 29,72 | kPa | c | 34,44 | kPa | c | 41,05 | kPa |
| ϕ | 18,43 | deg | ϕ | 23,63 | deg | ϕ | 26,57 | deg | ϕ | 34,51 | deg |

**Figure 4.** Direct Shear Test Result

The stress-strain curve resulting from the Direct Shear Test is shown in the figure below:

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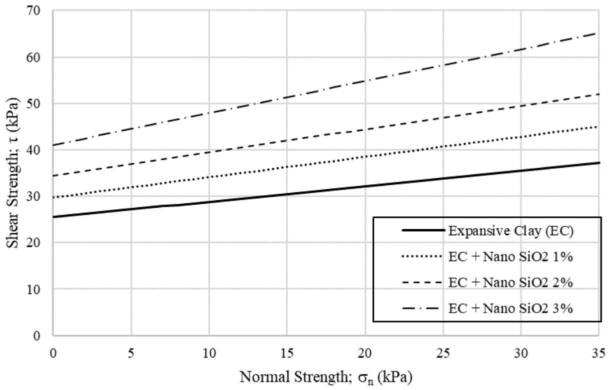


**Figure 5.** Stress – Strain Curve Result of Direct Shear Test

Documentation of the Direct Shear Test carried out can be seen in the image below :

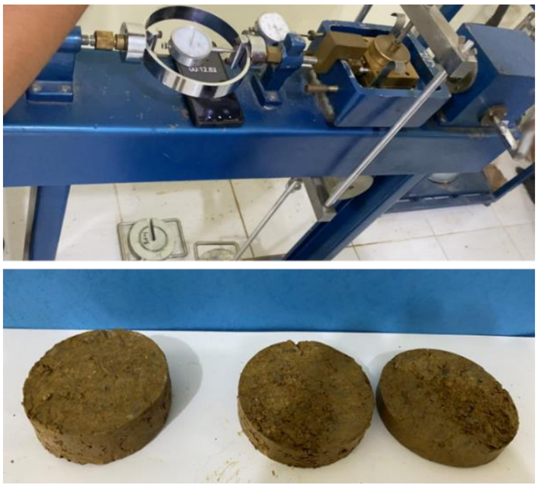

**Figure 6.** Direct Shear Testing Documentation

Unconfined Compression Test (UCT)

Unconfined Compression Test (UCT) is a method carried out in the laboratory to measure how much bearing capacity of the soil has to accept a given compressive force, until the soil separates from its grains and also the strain of the soil due to this pressure. [7] From the UCT test for expansive clay + variations of $SiO_2$ which was carried out in the laboratory, the results of strength of UCS for each mixture ratio were:

| No. | Sample | Unconfined Compressive Strength ($q_u$), kg/cm$^2$ | Cohesion ($c_u$), kg/cm$^2$ |
|---|---|---|---|
| 1 | Expansive Clay (EC) | 2,48 | 1,24 |
| 2 | EC + Nano $SiO_2$ 1% | 3,82 | 1,91 |
| 3 | EC + Nano $SiO_2$ 2% | 4,47 | 2,24 |
| 4 | EC + Nano $SiO_2$ 3% | 4,74 | 2,37 |

**Figure 7.** Unconfined Compressive Test Result

The stress-strain curve resulting from the Unconfined Compressive Test is shown in the figure below:

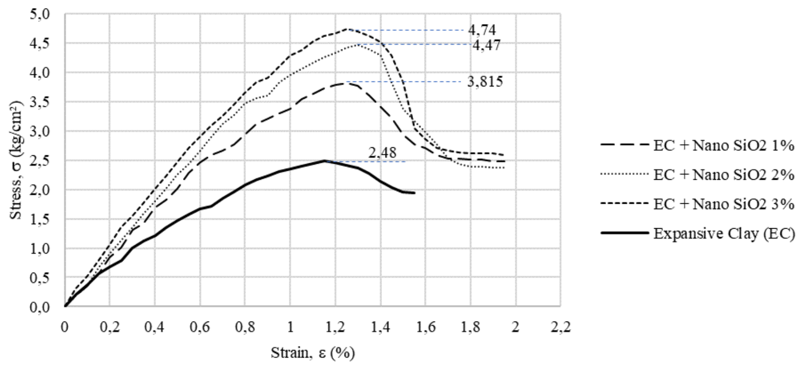


**Figure 8.** Stress – Strain Curve Unconfined Compressive Test

Documentation of the Unconfined Compressive Test carried out can be seen in the image below:

**Figure 9.** Unconfined Compressive Test Documentation

**Modulus Elasticity**

In the Unconfined Compressive Test (UCT) that have been carried out, the modulus of elasticity (E) is obtained from the stress-strain relation curve. In the stress-strain curve, the value $E=E_0$ is obtained which is defined as Young's Modulus, while the $E_{50}$ value is the Secant's Modulus value which is obtained from the value $\sigma_{50}/\varepsilon_{50}$. In other terms, the 50% modulus of elasticity ($E_{50}$) is an modulus of elasticity value of 50% of the initial modulus of elasticity value ($E=E_0$). [8] From drawing a line on the stress-strain curve, the value of the 50% elasticity modulus ($E_{50}$) is obtained as follows.

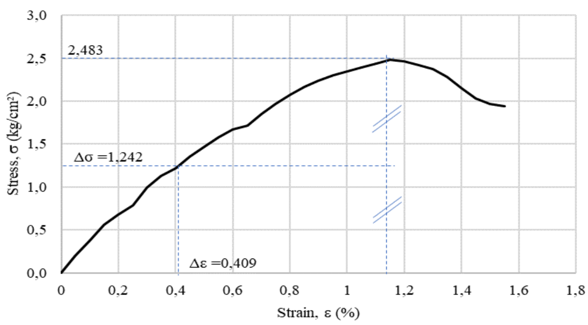


**Figure 10.** Modulus of elasticity Determination from Unconfined Compressive Test Curve

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Determine the modulus of elasticity of soil using the formula $E_{50} = \frac{\Delta\sigma}{\Delta\varepsilon}$ for expansive clay $E_{50}$ = 1,242/0,409 = 3,04 kg/cm$^2$ or 297,63 kN/m$^2$. So it can be seen that the modulus of elasticity of the expansive clay soil has an modulus of elasticity of 297,63 kN/m$^2$. Using the same formula, the modulus of elasticity for expansive clay mixed with varying nano $SiO_2$ ratios are shown in the figure below.

| No. | Sample | Elasticity Modulus, ($E_{50}$) kg/cm$^2$ |
|---|---|---|
| 1 | Expansive Clay (EC) | 3,04 |
| 2 | EC + Nano $SiO_2$ 1% | 4,05 |
| 3 | EC + Nano $SiO_2$ 2% | 4,52 |
| 4 | EC + Nano $SiO_2$ 3% | 4,53 |

**Figure 11.** Modulus of Elasticity Test Result

The highest modulus of elasticity for expansive clay with a nano $SiO_2$ mixture occurred at a mixture ratio of 3%. The difference in modulus of elasticity between the highest nano $SiO_2$ and expansive clay is 92 kN/m$^2$ or about 17%.

## RESULT AND DISCUSSION

From the results of the UCT test, the modulus of elasticity value can be calculated or determined. The modulus of elasticity in this study uses the $E_{50}$ value. From the test results it can be seen that stabilization with $SiO_2$ nanomaterial results in an increase modulus of elasticity.

It can be seen that the more nano $SiO_2$ inclusions, the higher modulus of elasticity will be obtained. The addition of 3% nano $SiO_2$ shows an modulus of elasticity value of 4,53 kc/cm$^2$. This shows that the addition of nano $SiO_2$ will increase the elastic modulus. This also means increasing the bearing capacity of the soil and improving the mechanical properties of expansive clay. The addition or increase in the modulus of elasticity is not linear, but resembles a hyperbolic curve. The figure below shows the increasing trend in the modulus of elasticity.

Soil elastic modulus, is a soil elastic parameter and a measure of soil stiffness. Defined as the ratio of stress along an axis to strain along that axis within the range of elastic behavior of soil. The use of the soil elastic modulus value for soil structure design uses the $E_{50}$ value, where $E_{50}$ is the elastic modulus value of the soil at a stress of 50% of the maximum stress.

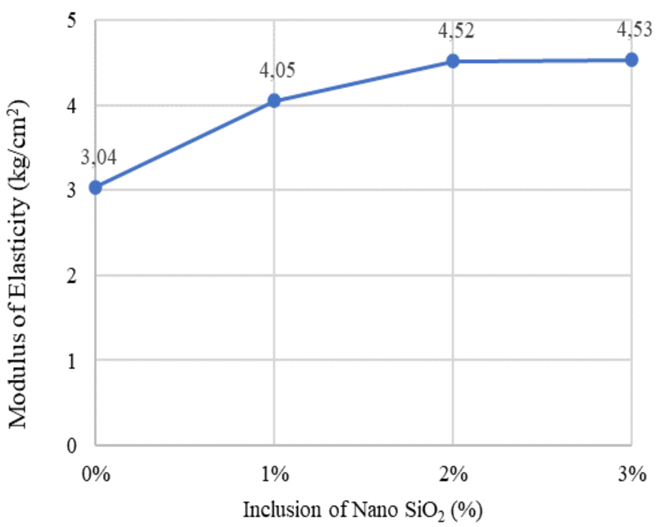


**Figure 12.** Modulus of elasticity Increase Curve

## CONCLUSION

From a series of tests that have been carried out, it can be interpreted that nano $SiO_2$ can be used as a stabilization material for expansive clay. The inclusion of nano $SiO_2$ on expansive clay will improve the mechanical behavior of expansive clay. It is clear that its addition will increase the elastic modulus. This increase in the modulus of elasticity is described as resembling a hyperbolic curve. Increasing the modulus of elasticity of expansive clay means increasing the carrying capacity and stability of expansive clay which has caused many problems for the infrastructure above it. In this study, it can be interpreted that the method of expansive clay stabilized with nano $SiO_2$ is a significantly applied method of field application of ground improvement, which increases the shear strength, the UCS, and the elastic modulus of expansive clay. Because of this, it increases the stability of structures. Field applications can be applied to reduce the cost of repairing infrastructure damaged due to the problematic properties of expansive clay.

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