

Mechanical Properties of Soft Soil Stabilized with Lime and Volcanic Ash

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Abstract. The nature of soft clay was identified from the unconfined compressive strength value through unconfined compressive strength (UCS) testing. Soft soil is improperly used as a construction base soil. The purpose of this study was to determine the increase in unconfined compressive strength and foundation-bearing capacity due to the addition of lime or volcanic ash to soft soil. Soft soil has an undrained shear strength of <25 kPa based on the unconfined compressive strength test. The unconfined compressive strength test was carried out on soil with lime or volcanic ash, each 3 to 12% of the dry soil weight. The highest unconfined compressive strength value was obtained on soil with 6% lime and 9% volcanic ash. The bearing capacity of the foundation on soil stabilized with 6% lime increased 13.7 times, while the bearing capacity of the foundation on soil with the addition of 9% volcanic ash increased the ultimate bearing capacity by 8.7 times the bearing capacity of the foundation on soft soil. The bearing capacity of the foundation on soil stabilized with lime is higher than that of the foundation on soil stabilized with volcanic ash.

Keywords: Soft clay, lime, volcanic ash, unconfined compressive strength, foundation-bearing capacity

INTRODUCTION

Soil with poor characteristics such as soft clay may cause problems for its low bearing capacity. Soft soil is cohesive soil that consists of tiny grains and has a dominant cohesion value (Waruwu et al., 2021). The soft soil layer has low shear strength, high compression, low permeability coefficient, and low bearing capacity.

Clay soil types tend to have impermeable properties, high cohesiveness, and low shear strength values. Meanwhile, sandy soil has a high shear strength value, and the attractive force between particles tends to be small. The properties of clay soil generally consist of fine grain size (less than 0.002 mm), low permeability, high capillary water rise, very cohesive, high shrinkage rate, and slow consolidation process (Hardiyatmo, 2002).

Soft soil is one type of soil that can cause long-term instability and settlement problems. Soft soil has low shear strength and high compression (Geotechnical Guide 4, 2002). Soft soil is divided into two, namely soft clay and peat. Clay soil generally has a high plasticity value with a plasticity index value greater than 17% as presented in Table 1 (Hardiyatmo, 2002).

Table 1.: Plasticity index value and soil type (Hardiyatmo, 2002)

PI (%)	Nature	Type of Soils	Cohesion
0	Non-plasticity	Sand	Noncohesive
< 7	Low plasticity	Silt	Partially cohesive
7 - 17	Medium plasticity	Silt clay	Cohesive
> 17	High plasticity	Clay	Cohesive

Based on Table 2, the nature of soft clay soil can be identified from the compressive strength (q_u) value. If the q_u value of the soil is less than 50 kPa, then the soil is classified as soft clay to very soft clay (Hardiyatmo, 2002). Soil with a CBR value of less than 9% is classified as soil that is not good for

construction-based soil (Waruwu, 2013). Soil that is classified as soft soil, high plasticity, and low unconfined compressive strength requires improvement by adding stabilization material.

Table 2.: Relationship between unconfined compressive strength (q_u) of clay soil and consistency (Hardiyatmo, 2002)

Consistency	Q_u (kPa)
Hard clay	> 400
Very stiff clay	200 – 400
Stiff clay	100 – 200
Medium clay	50 – 100
Soft clay	25 – 50
Very soft clay	< 25

The soil-bearing capacity is influenced by the water level and its density. Soft clay soil submerged in water provides a small bearing capacity (Dharmayasa, 2014). The bearing capacity of the foundation and the type of collapse are greatly influenced by the location of the hard soil and the type of soil layer (Fauzi & Ikhyia, 2016). The deeper the foundation is and the larger its width, the higher the bearing capacity of the foundation.

Soil cohesion can increase the bearing capacity of the footing foundation and reduce upward pressure (Manoppo, 2013). However, soft soil has a fairly low cohesion in undrained conditions. Soil improvement is needed to increase the cohesion value in undrained conditions. Soil improvement with fibrous materials such as coconut fiber can increase the bearing capacity of the foundation, but the increase is only 15% due to the addition of 1-2% coconut fiber (Fahriani & Apriyanti, 2017).

Soil improvement methods are a solution to overcome soft soil problems. Improvement of soft soil properties can be done by soil stabilization. Methods of soil stabilization are by compacting the soil, mixing the soil with granular materials, using reinforcement, excavation, and replacement of soil, and chemical soil improvement by mixing cement, lime, fly ash, asphalt, and other materials (Hardiyatmo, 2010).

Stabilization is needed to improve the soil properties, namely by mixing the soil with additional materials in a certain ratio. This kind of stabilization is known as chemical stabilization. Soil materials with a good classification such as low plasticity clay stabilized with cement or lime can be used as a foundation layer in road construction structures (Adha, 2009).

Soil stabilization is the mixing of soil with certain materials to improve the technical properties of the soil to meet certain technical requirements. The soil stabilization process includes mixing soil with other soils to obtain the desired gradation, or mixing soil with manufactured materials so that the technical properties of the soil become better. The technical properties of the soil can be in the form of bearing capacity, compressibility, permeability, ease of work, expansion potential, and sensitivity to changes in water content.

There are several methods for soil improvement such as soil replacement, reinforcement to increase soil strength and stiffness, soil improvement, stone columns, and poles, and mixing chemicals such as cement and lime (Kazemian et al., 2011). Soft soil improvement can be done by using a horizontal reinforcement system (Waruwu, et al., 2022). The mixture ratio depends on the desired quality of the mixture. If the mixing is only intended to change the gradation and plasticity of the soil, and then worked on, then only a little additive is needed. However, if stabilization is intended to change the soil to have high strength, then more additives are needed.

According to Suaryana and Fransisko (2018), two-stage stabilization of clay soil using lime and cement can increase the unconfined compressive strength value from 1.9 kg/cm² to 9.05 kg/cm² with a lime content of 6% in the first stage, with an increase in unconfined compressive strength from 9.05 kg/cm² to 14.55 kg/cm² with a cement content of 8%.

The mixture of subgrade stabilization and soil-cement foundation layers must be in the range of 3% to 8% of the original soil weight in an oven-dry state (Directorate General of Highways, 2018). The use of 20-30% volcanic ash with 5% lime shows improvements in the properties of soft soil (Nasarani et al., 2019). The addition of 9% volcanic ash and 6% lime shows a significant increase in unconfined compressive strength in clay soil (Waruwu, et al., 2022).

Soil stabilization using lime is suitable for subgrade in road construction and is usually mixed with 2-6% lime content by weight (Hardiyatmo, 2014). Mixing volcanic ash and lime as a stabilization material for expansive clay soil can increase soil density, reduce water content, increase soil shear value, and the characteristics of clay soil expansion are reduced with the addition of non-plastic volcanic ash (Latif et al., 2017). Expansive clay soil can be stabilized with quenched lime, the improvement in the soil plasticity index is quite significant at an addition of 6% (Sutikno & Damianto, 2009). The same thing was found in the increase in the CBR value of expansive clay soil stabilized with 6% quenched lime, the CBR value of the soil above 6% lime did not increase significantly. According to SNI 03-3437-1994, the amount of lime used in the mixture is between 2-15% calculated against the dry weight of the soil.

The materials used for soil improvement vary widely, this is adjusted to the availability of materials in areas that require soil improvement. This can increase the involvement and participation of local communities in providing materials (Sianturi et al., 2019). In addition to lime, cement, and coal fly ash, there is also volcanic ash. The addition of 9% volcanic ash can increase the compressive strength value by 36.6% and the CBR of clay soil by 6.15% (Triputro & Rahayu, 2016). Initially, the compressive strength value of clay soil was only 76 kPa increasing to 120 kPa with the addition of 9% volcanic ash. The same thing was found in the increase in CBR value from 1.3156% to 1.4027% after the clay soil was added with 9% volcanic ash. Mixing volcanic ash and lime as a stabilization material for expansive clay soil can increase the bulk density of the soil, reduce the water content, increase the shear value of the soil, and the characteristics of clay soil expansion are reduced with the addition of non-plastic volcanic ash (Latif et al., 2017). The characteristics of soft soil can change into very stiff clay with the addition of 9% volcanic ash (Waruwu et al., 2021). The research study was carried out by selecting soft clay soil by testing its characteristics, then continued with improvements using stabilization materials from lime and volcanic ash. The soil parameters to be sought are an increase in compressive strength and a decrease in soil plasticity. Based on the compressive strength value, the soil cohesion value is obtained in undrained conditions. The bearing capacity of the foundation on the cohesive soil can be determined.

The purpose of this study was to determine the change in the consistency of soft clay soil due to stabilization, to determine the percentage of lime or volcanic ash addition in producing the highest free compressive strength value, and to determine the bearing capacity of the footing foundation on soil stabilized with lime or volcanic ash. The paper also finds that the practicability of space utilization promotes passive recreation while creating social relationship among the communities due to the bearing capacity and soft clay soil (Ramzi, 2019).

Method

This study was conducted at the Soil Mechanics Laboratory, Civil Engineering Department, Simalungun University. Clay soil samples were obtained from Deli Serdang, North Sumatra (see Figure 1). Soil was taken from a depth of 60 to 150 cm for lumps for disturbed samples, while undisturbed samples were stored in tubes. Disturbed samples were dried in the sun before being tested (Figure 2). The dried samples were sieved with a No. 40 sieve. The initial testing was carried out to determine the water content, specific gravity, consistency limits (Atterberg limits), grain size distribution, and compressive strength of undisturbed soil. The results are presented in Table 3. These tests are needed to ensure that the soil studied is clay with high plasticity based on the plasticity index value and soft clay based on the undisturbed compressive strength value. Plasticity properties are tested with Atterberg limits.



Figure 1. Soil sampling process



Figure 2. Soil sample drying process

The improved properties of this clay soil are soil consistency properties as reflected in the unconfined compressive strength (q_u) value. These properties are improved by adding lime and volcanic ash from Mount Sinabung (Figure 3). The lime and volcanic ash content is 3%, 6%, 9%, and 12% of the dry soil weight, respectively. The amount of additional material used in this study is close to 3 to 8% of the original soil weight in an oven-dry state recommended (Directorate General of Highways, 2018). The results of the study showed that 9% volcanic ash and 6% lime provided optimal improvement in clay soil (Waruwu, et al., 2022).



Figure 3. (a) Chalk and (b) Volcanic ash

The water content required in mixing soil samples for unconfined compressive strength testing was obtained from the results of standard compaction testing. Compaction test samples were carried out on each mixture of 3%, 6%, 9%, and 12% of both lime and volcanic ash. In addition to the optimum water content, the maximum dry volume weight was obtained from the standard compaction test.

Unconfined compressive strength test

The main test to determine the unconfined compressive strength value and consistency properties was carried out using a compressive strength tester (Figure 4). Soil and a mixture of lime or volcanic ash materials are mixed with a percentage of 3%, 6%, 9%, and 12% using the amount of water from the optimum water content of the compaction test results. The weight of each mixture is obtained from the multiplication of the percentage by the dry weight of the required soil sample.



Figure 4. Unconfined compressive strength test

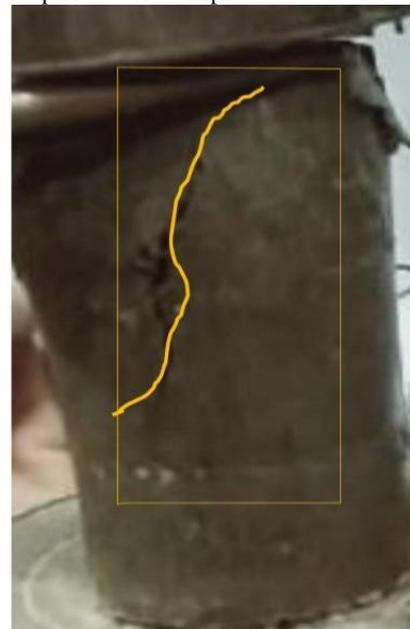


Figure 5. Typical collapse pattern of soil + 3% lime from unconfined compressive strength test.

The unconfined compressive strength value is obtained at the time of maximum stress marked by the soil sample experiencing collapse (Figure 5). The water content of the sample used to test the unconfined

compressive strength is based on the results of compaction tests, both on the original soil and samples mixed with improvement materials.

Analysis of foundation-bearing capacity

Cohesion in undrained conditions (c_u) is determined from the results of the unconfined compressive strength test on stabilized soil, as described in Equation 1.

$$c_u = q_u/2 \quad (1)$$

c_u is cohesion in undrained conditions (kPa) and q_u is the undrained compressive strength (kPa)

Based on the cohesion in undrained conditions (c_u), the ultimate bearing capacity (Q_u) of clay soil can be determined using the Skempton 1951 theory (Hardiyatmo, 2011). The method for determining the ultimate bearing capacity (Q_u) is as described in Equation 2. The bearing capacity value studied here is obtained from the results of the unconfined compressive strength test.

$$Q_u = c_u \times N_c \quad (2)$$

where, Q_u is the ultimate bearing capacity (kPa), N_c is the bearing capacity factor (Figure 6), D is the foundation depth (m), B is the foundation width (m).

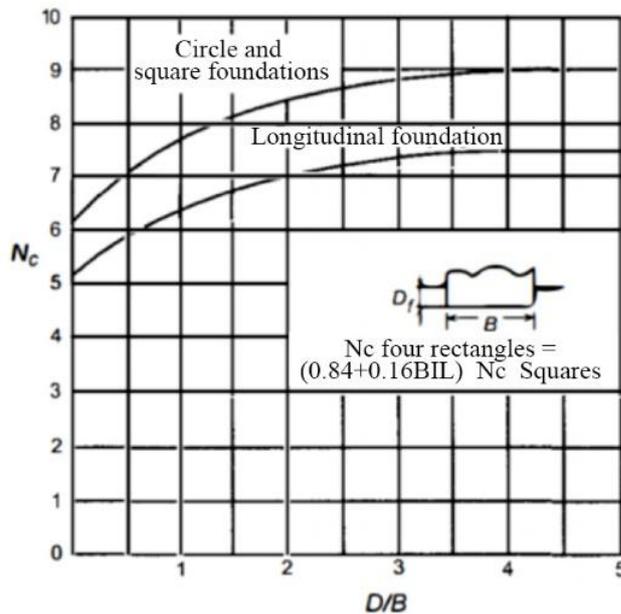


Figure 6. Bearing capacity factor N_c (Hardiyatmo, 2011)

Results and Discussion

Results of physical and mechanical properties test of native soil

The results of the physical and mechanical properties test of soil are as in Table 3. Based on the physical properties test, the water content value was 78%, specific gravity 2.65, liquid limit 59.2%, plasticity index 21.2%, and the amount of fine-grained soil from passing sieve No. 200 was 97%.

Based on the results of sieve analysis and Atterberg limit on native soil, this soil is classified as high plasticity clay soil, because passing sieve No. 200 is greater than 50%, the search limit (LL) is greater than 50%, and the plasticity index (PI) is above 17% as in Table 1. The grain size curve of native soil can be seen in Figure 7.

Table 3.: Test results for original soil properties

Soil properties	Values	Unit
Water content (w)	78	%
Specific gravity (Sg)	2.65	-
Liquid limit (LL)	59.2	%
Plastic limit (PL)	38	%
Plasticity index (PI)	21.2	%
Pass sieve No. 200	97	%
Unconfined compressive strength (q_u)	34	kPa
Dry weight (γ_d)	1.3	Gr/cm ³

Optimum water content (w_{opt})	34	%
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The results of the undisturbed compressive strength test on undisturbed samples showed a q_u value of 34 kPa, thus this soil is classified as soft clay because its q_u less than 50 kPa as shown in Table 2.

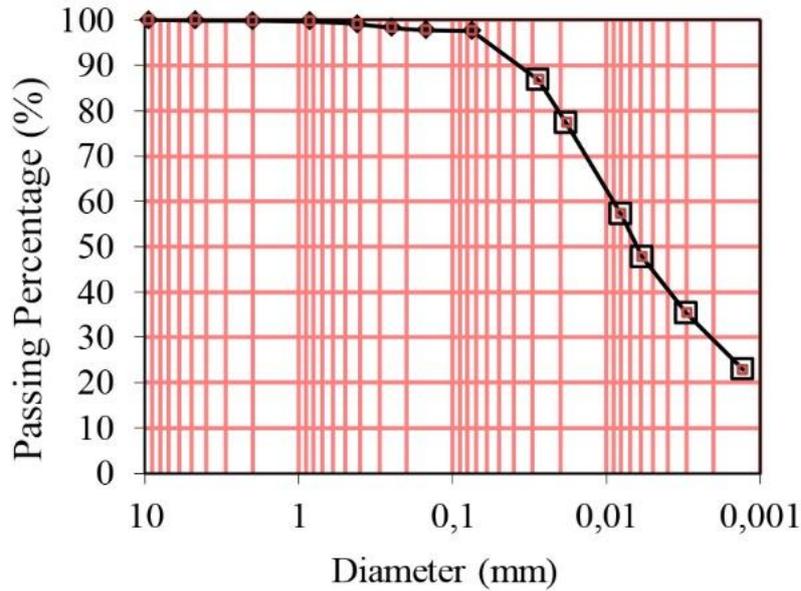


Figure 7. Grain size on native soil

Characteristics of properties and soil classification

Based on sieve analysis, hydrometer, and Atterberg limit tests as described in Table 3, the clay soil used in the study is classified according to the American Association of State Highway and Transportation Officials (AASHTO) M145 classification as a clay soil group A-7-5 (Passing sieve No. 200 > 36%, liquid limit (LL) > 41%, plastic index (PI) > 11%, and plastic limit (PL) > 30%).

The value of the soil plasticity index was obtained from the difference between the liquid limit and the plastic limit based on the results of the Atterberg limit test on soil with a mixture of lime and a mixture of volcanic ash shown in Figure 8. Both of stabilization materials showed a significant decrease in the plasticity index (PI) value.

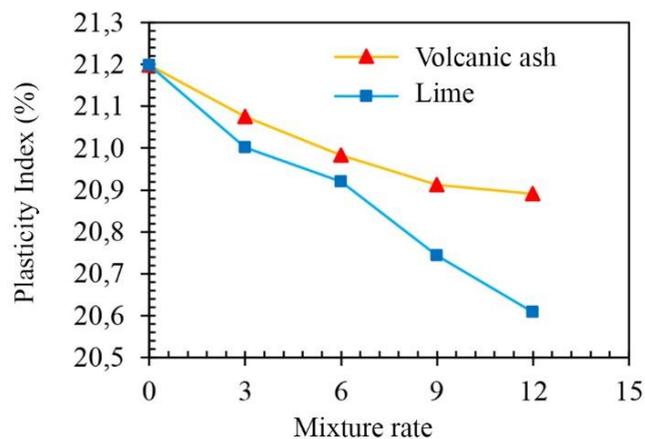


Figure 8. Changes in soil plasticity index

The plasticity index values of the soil improved with lime were 21%, 20.92%, 20.74%, and 20.61% for lime content of 3%, 6%, 9%, and 12%, respectively. Meanwhile, the plasticity index values of the soil improved with volcanic ash were 21.08%, 20.98%, 20.91%, and 20.89% for volcanic ash content of 3%, 6%, 9%, and 12%, respectively.

The improvement in the properties of the clay soil studied was revealed from the results of the Atterberg limit test on soil mixed with lime and volcanic ash. The properties in question are plasticity and

consistency. Based on the test results in Table 3, the soil studied was classified as soft clay with high plasticity.

Adding lime or volcanic ash can improve the plasticity properties of clay. It is obviously from the decrease in the value of the soil plasticity index with increasing levels of lime or volcanic ash mixture. The decline in soil plasticity index with lime is higher than volcanic ash.

Soil compaction test results

The optimum water content was obtained from the results of compaction tests of native soil and soil with a mixture of lime and volcanic ash (Figure 10). The optimum water content of the compaction test was used as the water content on the sample mixture for unconfined compressive strength test.

The water content of the soil with a mixture of volcanic ash tended to decrease in line with the addition of the volcanic ash content. Meanwhile, the water content for soil with a mixture of lime tended to increase in line with the addition of the lime content. It is due to the nature of lime that easily absorbs the water. Thus, the more lime content used, the more water is needed for the mixture.

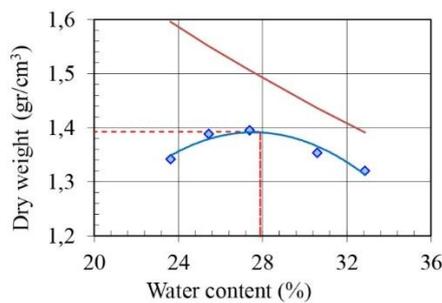


Figure 9. Relationship between dry unit weight and water content from standard compaction test results on soil with 12% volcanic ash.

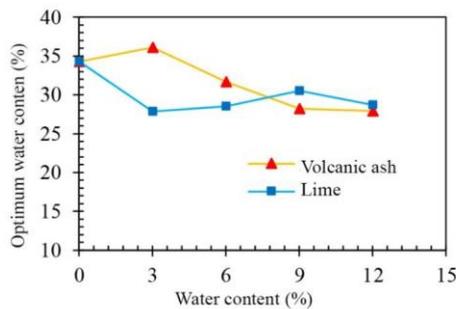


Figure 10. Optimum water content of mixtures

The relationship between the mixture content of lime and volcanic ash and the maximum dry bulk density from the compaction test results is presented in Figure 11. The highest dry bulk density values are 3 to 6% for lime and 9 to 12% for volcanic ash. The dry bulk density of 3-6% lime is higher than that of 3-6% volcanic ash, while for the 9-12% mixture, the dry bulk density of soil-volcanic ash is slightly higher than the dry bulk density of soil-lime.

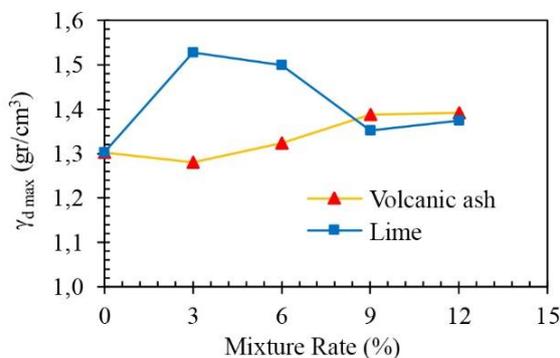


Figure 11. Maximum dry weight of each mixture

Unconfined compressive strength test results

The unconfined compressive strength (q_u) value is obtained from the unconfined compressive strength test. The results of the unconfined compressive strength test on undisturbed soil are shown in Figure 12. The original or undisturbed soil shows an unconfined compressive strength value of 34 kPa. This value is obtained at the maximum stress indicated when the soil sample collapses. The test results for the original soil show a slow and gentle increase in stress. It indicates that the tested soil is classified as soft soil with a q_u value = 34 kPa < 50 kPa as described in Table 2. The maximum strain value obtained is a maximum of 15%.

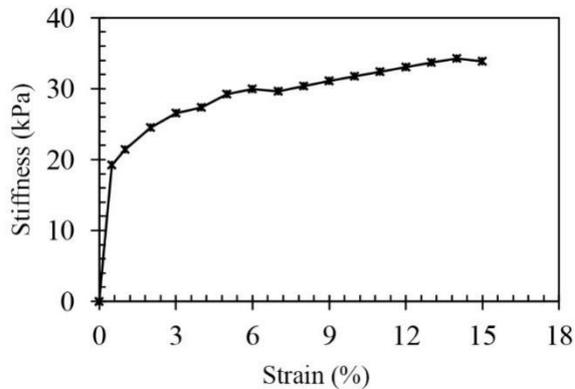


Figure 12. Unconfined compressive strength test of original soil

The results of the unconfined compressive strength test were shown in the relationship between stiffness and strain. Figure 13 shows the relationship between stress and strain in soil with a mixture of lime. The addition of 3% and 6% lime showed a fairly high increase in stress, but the unconfined compressive strength produced at 6% lime was still higher than 3% lime. The test results for 9% and 12% lime were still quite high compared to the test results on the original soil without a mixture of lime. This increase was influenced by the density of the soil that followed the density of the compaction test results and the effect of the addition of lime.

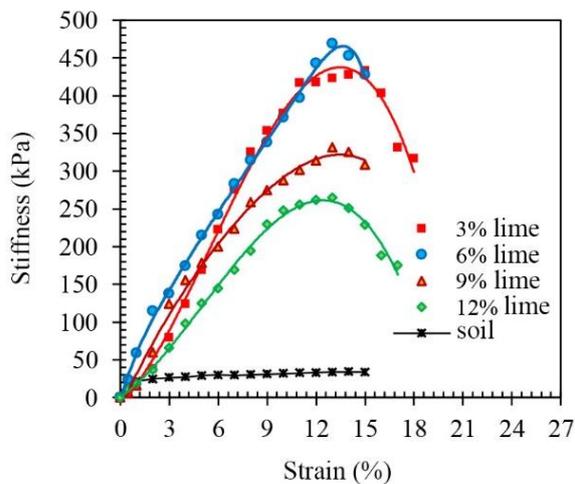


Figure 13. Stress - strain of soil with lime

The unconfined compressive strength value is obtained at the maximum stress followed by soil collapse. Soil collapse occurs at a strain between 12% to 15%. The maximum strain is obtained below 18%. The unconfined compressive strength value of soil improved with lime is obtained at 433 kPa, 469 kPa, 331 kPa, and 265 kPa for lime content of 3%, 6%, 9%, and 12%, respectively.

Figure 14 shows the relationship between stress and strain in soil stabilized with volcanic ash. Unlike the mixture of lime in the soil, volcanic ash showed an increase in stress at 6% and 9%, while for 3% and 12% volcanic ash still showed higher stress values than the original soil. The strain when the collapse occurred varied greatly between 8% and 15%. The maximum strain was obtained less than 18%. The unconfined compressive strength values of soil improved with volcanic ash were obtained at 160 kPa, 274 kPa, 299 kPa, and 214 kPa for volcanic ash content of 3%, 6%, 9%, and 12%, respectively.

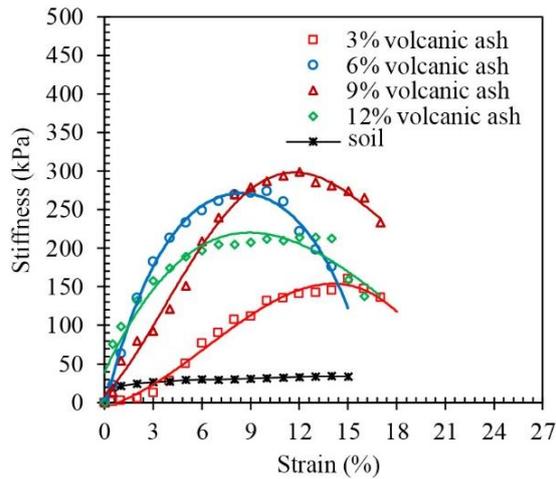


Figure 14. Stress-strain of soil with volcanic ash

The best compressive strength value for soil with lime stabilization was obtained in a mixture of 3% and 6%, while soil with a mixture of volcanic ash was obtained in the addition of 6% and 9% of volcanic ash. The comparison of these two soil stabilization materials can be seen in the stress and strain relationship shown in Figure 15.

The maximum stress on soil with a mixture of 6% showed the highest value compared to other mixtures. Soil with a mixture of 9% looked slightly higher than 6% and 9% volcanic ash. It is indicated that lime still has a better effect than volcanic ash. The use of 9% volcanic ash is close to the same as 9% lime.

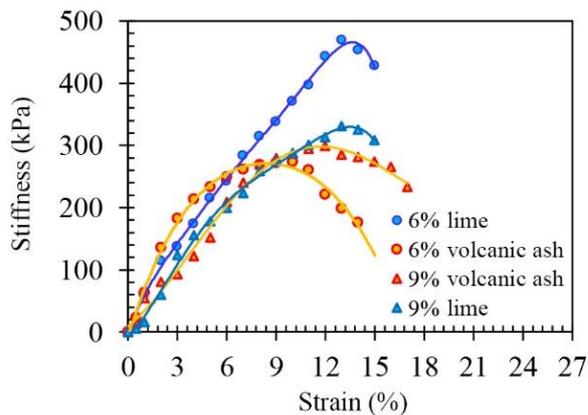


Figure 15. Comparison of soil - lime and soil - volcanic ash

DISCUSSION

The improvement of the properties of the clay soil studied can be seen from the results of the Atterberg limit test and the unconfined compressive strength of the soil mixed with lime and volcanic ash. The properties in question are plasticity and consistency.

Based on the test results in Table 3, the soil studied is classified as soft clay with high plasticity. The addition of lime and volcanic ash can improve the plasticity properties of clay, this can be seen from the decrease in the value of the soil plasticity index with increasing levels of lime and volcanic ash mixture Figure 8. This occurs because the addition of coarser volcanic ash further reduces the plastic properties of the clay soil. In addition to decreasing the value of the soil plasticity index, the addition of lime and volcanic ash also affects the consistency properties of clay soil.

Table 4.: Consistency of soft clay soil with lime

Lime mixture	C_u (kPa)	Consistency
0	17	Soft clay
3	217	Hard clay
6	234	Hard clay
9	166	Stiff clay

12	132	Stiff clay
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Table 4 shows the unconfined compressive strength (q_u) values of soil stabilized with lime. The addition of 3% to 6% lime changes the consistency of clay soil into hard clay. However, with a q_u value above 400 kPa, but a lime content of 9 to 12%, the clay consistency decreases slightly to very stiff. The highest q_u value is obtained in a mixture of soil with 6% lime. The soft clay changes into hard clay when mixed with 6% lime.

The C_u value in the 12% lime mixture decreased compared to the 9% lime mixture. This is because the addition of lime in large quantities will increase coarse grains and water absorption from clay grains so that the adhesive properties of the clay are reduced. Improvement in soil consistency due to the addition of volcanic ash is shown in Table 5. The addition of 3% volcanic ash immediately changes the consistency of soft clay soil to stiff clay.

The addition of 6 to 12% volcanic ash can change the consistency of soft clay soil into very stiff clay. The highest q_u value in soil stabilized with volcanic ash was obtained at 299 kPa for a mixture of 9% volcanic ash, then the soil consistency became very stiff.

Lime is much better in terms of improving the consistency properties of clay soil compared to volcanic ash. This is because lime is coarser-grained than volcanic ash. Finer clay soil with coarser grains will have an impact on increasing shear strength. Volcanic ash appears to be able to improve soft properties to become stiff to very stiff but not to hard clay as with the addition of lime. It was revealed from the increase in the q_u value of the soil along with the increasing levels of the lime and volcanic ash mixture. The addition of lime produces a maximum q_u value at a lime content of 6%, while volcanic ash reaches a maximum q_u value at a volcanic ash content of 9%. Thus, these two materials are better used as soil stabilization materials at additions below 9%. The use of 6% lime provides the highest compressive strength value, while 9% volcanic ash is needed to produce the maximum compressive strength value.

Table 5.: Consistency of soft clay soil with volcanic ash

Volcanic ash mixture	C_u (kPa)	Consistency
0	17	Soft clay
3	80	Stiff clay
6	137	Very stiff clay
9	149	Very stiff clay
12	107	Very stiff clay

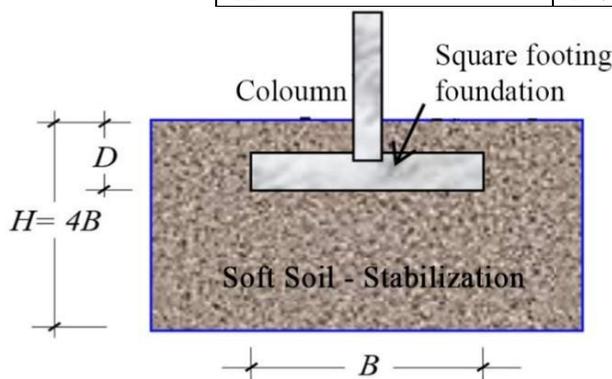


Figure 16. Application on footing foundation

Soft soil stabilization improvement on the foundation base can be done on the footing foundation. This study is applied to a square footing foundation with a width of B and a depth of D . The thickness of the stabilized soil is planned to a depth of $4B$. The planned cross-section of the foundation can be seen in Figure 16.

The ultimate bearing capacity is determined using Equation 1. The N_c value is determined based on Figure 6, by taking the square foundation curve. The cohesion value in undrained conditions (c_u) is taken from Table 4 and Table 5. The bearing capacity of the square foundation on lime-stabilized soil is shown in Figure 17. The ultimate bearing capacity of the foundation increases significantly on lime-stabilized soil. The highest increase was found with the addition of 6% lime. The addition of 3% lime appears to approach the bearing capacity of the foundation on 6% lime-stabilized soil.

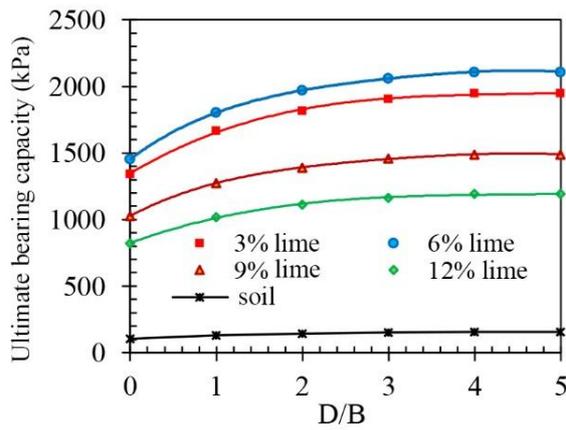


Figure 17. Bearing capacity of square foundation on limestone soil

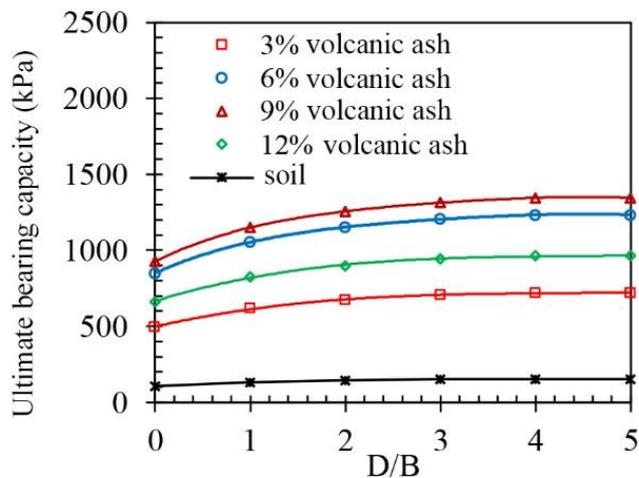


Figure 18. Bearing capacity of square foundation on volcanic ash soil

The bearing capacity of a square foundation on volcanic ash-stabilized soil is shown in Figure 18. The ultimate bearing capacity of soil stabilized with volcanic ash shows a fair good increase with the addition of 9%.

The ultimate bearing capacity of a foundation on lime-stabilized soil is much higher than the ultimate bearing capacity of a volcanic ash-stabilized soil foundation. The addition of 6% lime can increase the ultimate bearing capacity by 13.7 times for the bearing capacity of the foundation on soft soil, while the addition of 6% volcanic ash increases the ultimate bearing capacity by 8 times. The ultimate bearing capacity of a foundation on 6% lime-stabilized soil is 1.7 times higher than the bearing capacity of a foundation on 6% volcanic ash-stabilized soil.

CONCLUSION

Based on the results and discussion, several conclusions can be drawn. The soil studied is classified as soft clay, because it has a free compressive strength (q_u) value of 34 kPa to 50 kPa. The free compressive strength value of soil mixed with lime is still higher than that of soil mixed with volcanic ash.

Soil mixed with lime produces a q_u value of 265 to 469 kPa, while the q_u of soil with volcanic ash is 165 to 299 kPa. Lime is much better in terms of improving the consistency of clay compared to volcanic ash. A mixture of 6% lime in the soil can produce hard clay, while 9% volcanic ash can only change soft clay into very stiff clay. The free compressive strength of the soil increases significantly with the addition of 6% lime and 9% volcanic ash.

The increase in the free compressive strength value of the soil is obtained from the free compressive strength value (q_u) that increases to 6% lime or 9% volcanic ash. The addition of 6% lime can increase the bearing capacity of the square footing foundation by 13.7 times the bearing capacity of the foundation on soft soil, while the addition of 9% volcanic ash increases the ultimate bearing capacity by 8.7 times

the bearing capacity of the foundation on soft soil. The ultimate bearing capacity of the foundation on lime-stabilized soil is higher than the bearing capacity of the foundation on volcanic ash-stabilized soil.

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