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Effect of Lime Addition on Compaction and CBR Characteristics of Tropical Soft Clay

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Abstract

Soft clay soils present significant challenges in civil engineering due to their low bearing capacity, high compressibility, and susceptibility to moisture-induced volume changes. These characteristics make such soils unsuitable for direct use in foundation and pavement layers without stabilization. Although lime stabilization is a well-established method for improving soil strength and plasticity, its application to tropical clays, particularly in Indonesia, remains underexplored. This study investigates the effect of lime addition at varying percentages (15%, 20%, and 25% by dry weight) on the physical and mechanical properties of soft clay soil. Laboratory experiments were conducted without curing, using samples collected from Moncongloe, South Sulawesi, Indonesia. The soil was classified as A-7-6 under the AASHTO system and CL/OL under the USCS system, indicating high plasticity and low bearing capacity. Key tests included moisture content, Atterberg limits, compaction, and California Bearing Ratio (CBR). Results showed that increasing the lime content raised the optimum moisture content (OMC) from 21.89% to 26.39%. The maximum dry density peaked at 1.54 g/cm³ with 20% lime and decreased beyond that. CBR values also improved significantly with 20% lime (52.75%) but declined at 25% (46.57%), suggesting an optimum reaction threshold. The findings demonstrate that a 20% lime content yields the best improvement in both compaction and strength parameters under no-curing conditions. This study provides practical insights into the stabilization of tropical clays and supports the selection of effective lime treatment strategies in similar geotechnical environments.

Keywords: Soft clay, Lime stabilization, Soil compaction, CBR test, Tropical soil

1. Introduction

Soil is a primary component in civil engineering, serving as a supporting medium and construction material while simultaneously bearing the weight of the buildings that rest upon it. However, soil, as a natural product, has highly variable physical and mechanical properties that depend on its location and geological conditions. In various regions of Indonesia, including the northern coast of Java Island, the coast of Sumatra, Kalimantan, Sulawesi, and Papua, there is a widespread distribution of soft clay soils, which often presents a significant challenge in infrastructure development.

Soft clay soils are characterized by low bearing capacity, high compressibility, and significant volume changes due to fluctuations in moisture content. These properties make the soil less suitable for direct use as a basic layer of construction without prior repairs. Structural failure can occur when construction is built on this kind of land without adequate treatment.

Various methods have been developed and studied to enhance the characteristics of soft clay soils, which are often characterized by low strength, high compressibility, and susceptibility to changes in moisture. These methods often employ various additives and techniques to enhance the geotechnical properties of these soils, thereby making them more suitable for construction and other engineering applications.

One prominent approach is the use of stabilizing agents such as lime and fly ash. For instance, Zaini et al. demonstrated that mixing kaolinitic clay soil with lime and Palm Oil Fuel Ash (POFA) resulted in significant increases in undrained shear strength, particularly after prolonged curing times, with the maximum undrained shear strength reaching 32.68 kN/m^2 after 30 days of curing using an optimal mix [1]. Similarly, Islam et al. explored the effects of salt-lime stabilization on improving soil strength, emphasizing the challenges faced by geotechnical engineers when working with soft clay due to its heterogeneous nature [2]. The incorporation of organic materials, such as humic substances, has also been found beneficial, as these materials can significantly influence the engineering properties of clays, thereby improving their overall performance [3].

Another method that has garnered attention is the use of stone columns as reinforcement for soft clays. Salama et al. reported that increasing the area replacement ratio of stone columns improved the bearing capacity, reduced settlement, and minimized lateral movements in retaining wall systems constructed on soft clay [4]. These findings underscore the effectiveness of physical reinforcement methods in improving the load-bearing capabilities of soft soils.

Furthermore, advanced materials such as encapsulated polypropylene columns and nano-zeolite-modified cement have also been investigated for their effectiveness in stabilizing soft clay. Research by Aboalasaad et al. highlighted the potential of nano zeolites in enhancing the properties of soft clay, illustrating the continuing evolution of innovative materials for soil stabilization [5]. Additionally, methods that utilize agricultural waste, such as bagasse and rice husk ash, have been investigated for their potential to reduce the environmental impact of soil treatment while enhancing the engineering characteristics of soft soils [6].

In summary, enhancing the characteristics of soft clay involves a multifaceted approach that utilizes various stabilization techniques. While traditional methods remain prevalent, emerging materials and techniques continue to expand the possibilities for effectively addressing the challenges posed by soft clay in construction and engineering.

Although the use of lime has been shown to be effective in improving soil quality, its application to soft clay soils in tropical regions, such as Indonesia, remains limited. Therefore, this study was conducted to evaluate the effect of adding lime with varying levels of 15%, 20%, and 25% on the physical and mechanical properties of soft clay soils, particularly in terms of density and carrying capacity, as measured by the California Bearing Ratio (CBR) test.

The purpose of this study is to determine the physical classification of the clay soils used, evaluate the changes in characteristics resulting from lime mixing, and determine the optimal lime content that yields the most effective stabilization results. This research is expected to contribute to the development of local soil improvement methods and become a technical reference for foundation planning on problematic soils.

2. Research Method

This study is classified as experimental research and was carried out in the Soil Mechanics Laboratory of the Department of Civil Engineering and Planning, Faculty of Engineering, Universitas Negeri Makassar. The soil samples used in this research were collected from the Moncongloe area, Maros Regency, South Sulawesi, Indonesia. The research was conducted over three months, encompassing material preparation, laboratory testing, and data analysis.

This study is designed to observe the changes in the characteristics of clay soils resulting from the addition of lime with varying concentrations. The research design involved two main groups: untreated native clay soils (referred to as Norman soils) and clay soils stabilized with the addition of lime. In the original soil (0% lime), a series of laboratory tests were carried out to obtain basic parameters, including moisture content, liquid limit, plastic limit, filter analysis, hydrometer analysis, specific gravity, compaction test, and California Bearing Ratio (CBR) test. The second group consists of soil mixed with lime in three percentage variations: 15%, 20%, and 25% of the soil's dry weight. In each of these variations, the same tests were conducted on the original soil to assess the impact of lime on changes in the physical and mechanical properties of the soil. The results of these two groups were then compared to determine the effectiveness of stabilization and identify the optimum lime content that provided the best improvement to soil quality.

3. Results and Discussion

Results

- **Soil Classification**

Soil classification is a crucial first step in planning and implementing civil engineering projects, as the physical properties of the soil directly impact the stability and bearing capacity of the structure. Based on the results of laboratory tests conducted on the original soil samples, classification was carried out using two commonly used systems: the USCS (Unified Soil Classification System) and the AASHTO (American Association of State Highway and Transportation Officials) system.

- Atterberg Boundary Test

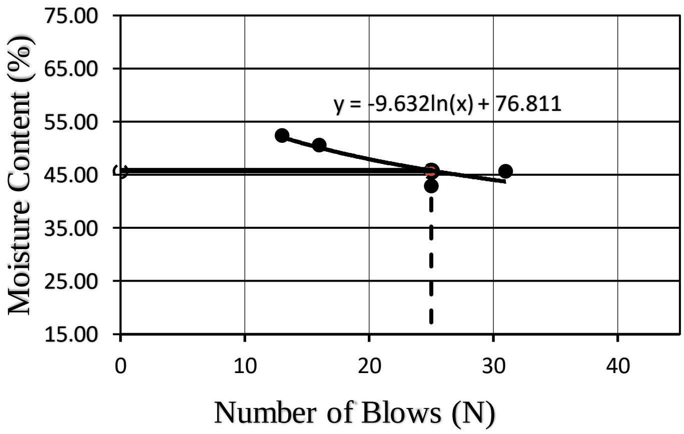
Table 1: Soil Liquid Limit Test Results

Description		Liquid Limit			
Test No.		1	2	3	4
Number of Blows		13	16	25	31
Weight of Wet Soil + Tare, (A)	gr	31.70	57.30	28.00	28.40
Weight of Dry Soil + Tare, (B)	gr	24.00	49.70	22.50	22.50
Weight of Tare (C)	gr	9.30	34.70	9.70	9.60
Weight of Water, D = A - B	gr	7.70	7.60	5.50	5.90
Weight of Dry Soil, E = B - C	gr	14.70	15.00	12.80	12.90
Water Content, F = (D / E x 100)	%	52.38	50.67	42.97	45.74
Average		52.38	50.67	42.97	45.74

This table presents the results of the soil Liquid Limit test using the Casagrande method, based on four tests with variations in the number of impacts. Each test displays the moisture content value obtained by subtracting the weight of the water from the dry weight of the soil after the drying process has been completed. The moisture content is calculated as the ratio of the weight of water to the dry weight of the soil, then expressed as a percentage.

The results displayed showed moisture content of 52.38%, 50.67%, 42.97%, and 45.74% for the number of collisions of 13, 16, 25, and 31 times respectively. The moisture content value tends to decrease as the number of impacts increases, which follows the principle of the liquid limit testing method. The average value of the four tests was 47.94%, which was used as an estimate of the soil liquid limit value. This pattern of decreasing moisture content to the increase in the number of impacts illustrates the transition point of the soil from a liquid state to a plastic state.

Figure 1: Relationship between Impact Amount and Moisture Content for Liquid Limit Determination



The graph shows the relationship between the Number of Blows and the Moisture Content of the soil in the liquid limit test using the Casagrande tool. The data points represent the moisture content values obtained at various collision speeds, and logarithmic regression curves are used to model the trend of the relationship.

It can be observed that the moisture content tends to decrease as the number of impacts increases, in line with the characteristics of the soil, which transitions from a more liquid to a more plastic state when compacted more intensively. The regression equation obtained was $y = -9.632\ln(x) + 76.811$, which shows a negative logarithmic relationship. On the graph, the dotted vertical line indicates the number of standard hits, which is 25 times, serving as the reference point for determining the liquid limit value. Based on the position of this line against the curve, the soil melt limit value is approximately 47–49%, which is the moisture content when the soil requires 25 impacts to close the standard 12.7 mm wide test groove.

Table 2: Soil Plastic Limit Test Results

Description		**Liquid Limit**	
Test No.		**1**	**2**
Number of Blows		U	TK
Weight of Wet Soil + Tare, (A)	gr	35.50	37.10
Weight of Dry Soil + Tare, (B)	gr	35.30	36.70
Weight of Tare (C)	gr	34.40	34.40
Weight of Water, D = A - B	gr	0.20	0.40
Weight of Dry Soil, E = B - C	gr	0.90	2.30
Water Content, F = (D / E x 100)	%	22.22	17.39
Average		19.81	

This table presents the results of the soil Plastic Limit test, which indicates the minimum moisture content at which the soil exhibits plastic properties and can be rolled into a 3 mm diameter thread without being crushed. The test was carried out in two trials. Each row shows wetland, dryland, and tare weight data, which is used to calculate water weight and dry soil weight.

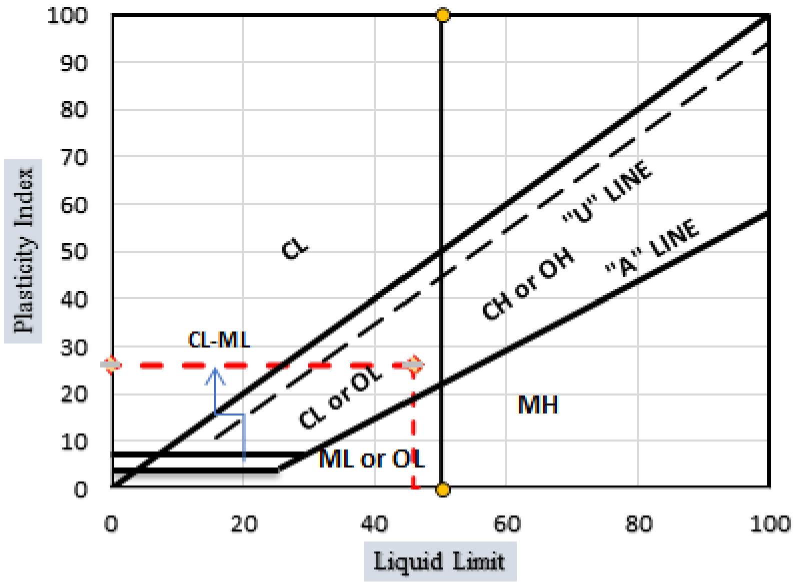
From these calculations, the moisture content value was obtained at 22.22% and 17.39%, respectively. The average of the two values is 19.81%, which is set as the limit value of the soil plastic. This value indicates the moisture content at which the soil begins to lose its plastic consistency and is approaching a semi-solid state. The difference between the two tests is quite slight and is still within acceptable limits for geotechnical laboratory standards.

The Atterberg limit test is used to determine the consistency and level of plasticity of fine soil by measuring three main parameters, namely the liquid limit (LL), the plastic limit (PL), and the plasticity index (PI). The test results showed that the soil liquid limit value was 49.81%, while the plastic limit was recorded at 19.81%. From these two values, a plasticity index of 26.00% was calculated based on the difference between the liquid limit and the plastic limit (PI = LL − PL). This plasticity index value indicates that the soil has a moderate to high level of plasticity, characteristic of active clay soils that are susceptible to volume changes due to variations in moisture content.

The LL and PI values are quite high, indicating that the soil has medium to high plasticity, which means it is able to undergo significant changes in shape due to changes in moisture content. Soils with a PI value above 17 generally include active clay that is susceptible to shrinkage.

- Classification Based on USCS

Figure 2: Soil Classification Chart Based on Liquid Limit and Plasticity Index (USCS System)

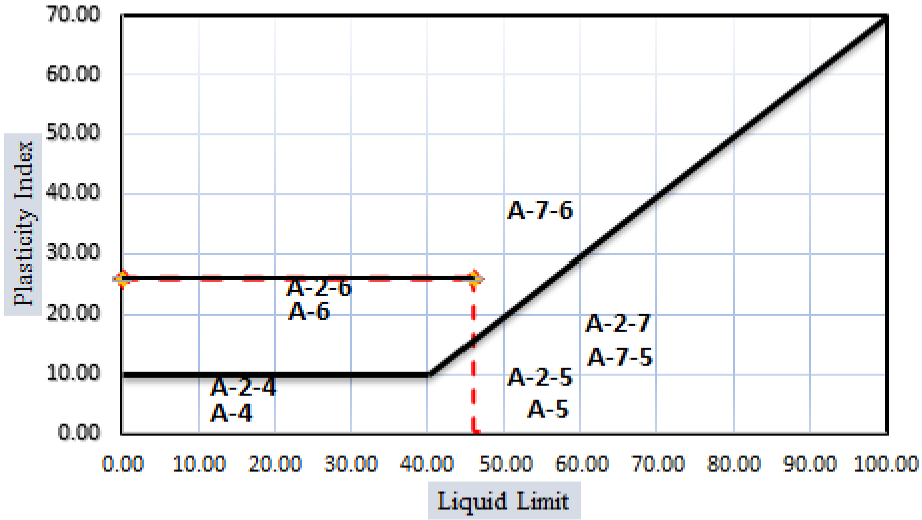


This image displays a soil classification graph based on the USCS (Unified Soil Classification System), which utilizes two primary parameters: the Liquid Limit and the Plasticity Index. This graph is divided into several classification zones, such as CL, ML, CH, MH, OL, OH, and transition areas in between, each of which represents a soil type based on its consistency.

Based on the results of laboratory tests, the soil tested had a Liquid Limit of 49.81% and a Plasticity Index of 26.00%, with 82.05% of the fine grains passing through sieve No. 200. This figure indicates that the soil is included in the category of fine-grained soil. When the values of LL and PI are plotted on the chart, they are located below the A-line and are within the CL or OL classification region. The CL zone refers to inorganic clay of low to medium plasticity, while the OL zone indicates the possibility of organic silt or clay of low plasticity. Thus, these soils can be categorized as low to medium-plasticity clay or organic clay, depending on the content of organic material.

- Classification Based on AASHTO

Figure 3: Land Classification Chart Based on the AAASHTO System (LL–PI Chart)



This image displays a soil classification graph based on the AASHTO (American Association of State Highway and Transportation Officials) system, which utilizes two primary parameters: Liquid Limit (LL) and Plasticity Index (PI). This graph divides soils into groups such as A-2-4, A-2-6, A-5, A-6, A-7-5, and A-7-6, based on their consistency and plasticity properties. This classification is beneficial in the field of civil engineering, especially for determining the feasibility of land as a road construction material.

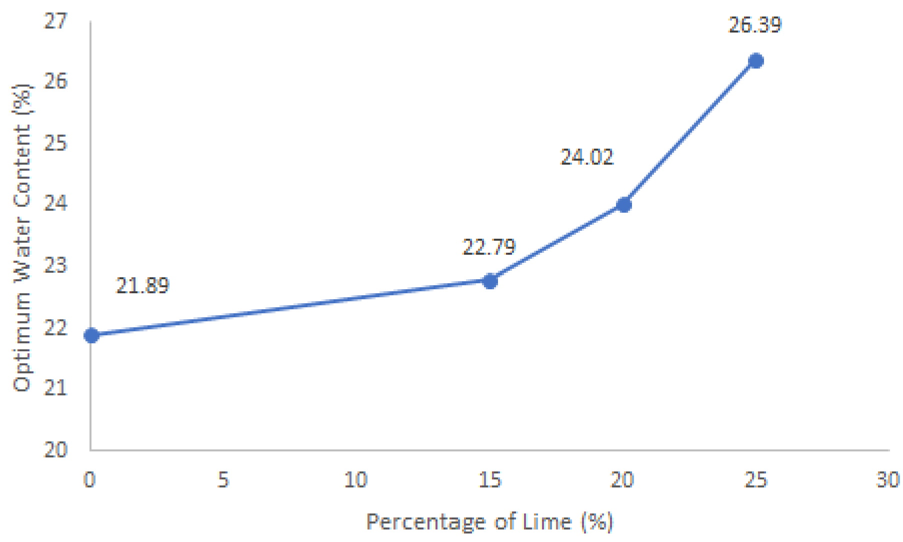
Based on the results of laboratory tests, the soil tested had a Liquid Limit (LL) value of 49.81% and a Plasticity Index (PI) of 26.00%. LL value that exceeds 41% and a PI that exceeds 11% indicates that the soil is in group A-7-6. This condition is reinforced by the position of the data points on the graph, which is located right in the A-7-6 classification zone.

Group A-7-6 represents high plastic clay soils that have low carrying capacity and are very sensitive to changes in moisture content. This type of soil typically undergoes shrinkage and volume expansion due to changes in humidity, making it unsuitable for use as a road pavement layer without prior treatment or stabilization.

- **Stabilization Test with Lime**
- Influence on Optimal Water Content (OMC)

The figure shows the relationship between the level of lime (%) added to the soil and the optimal moisture content (OMC) resulting from the compaction test. It can be seen that along with the increase in lime content, the OMC value also increases. In the original soil without lime, the organic matter content (OMC) was approximately 21.89%. After the addition of 15% lime, the OMC increased to about 22.79%. A more significant increase occurred in the lime content of 20% and 25%, with OMC values reaching 24.02% and 26.39%, respectively. This pattern depicts a consistent upward trend, indicating that the addition of lime affects the groundwater requirements in reaching maximum density. The graph line shows a sharper slope with the addition of lime above 15%, which indicates that the increase in OMC becomes more drastic at higher lime levels.

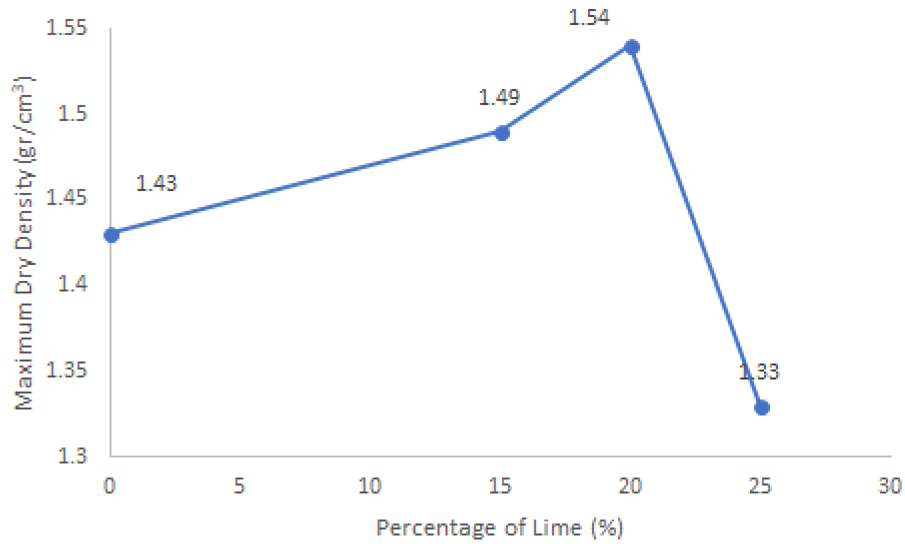
Figure 4: Effect of Lime Content on Optimal Water Content



- Effect on Maximum Dry Density (γdry max)

The graph above shows the relationship between **the level of lime (%)** added to the soil and **the maximum dry density value (gr/cm^3)** resulting from the compaction test. It was observed that the maximum dry density increased from the original soil (0% lime) to a lime content of 20%. The initial value of 1.43 g/cm^3 in the original soil increased to 1.49 g/cm^3 at a 15% lime content and peaked at 1.54 g/cm^3 when the lime content reached 20%. However, with the addition of 25% lime, there was a sharp decrease in the maximum dry density to 1.33 gr/cm^3. The graph pattern forms an upward curve to the optimum point at 20% of the lime, then drops drastically, indicating that there is a specific limit at which the addition of lime no longer has a positive effect on soil compaction.

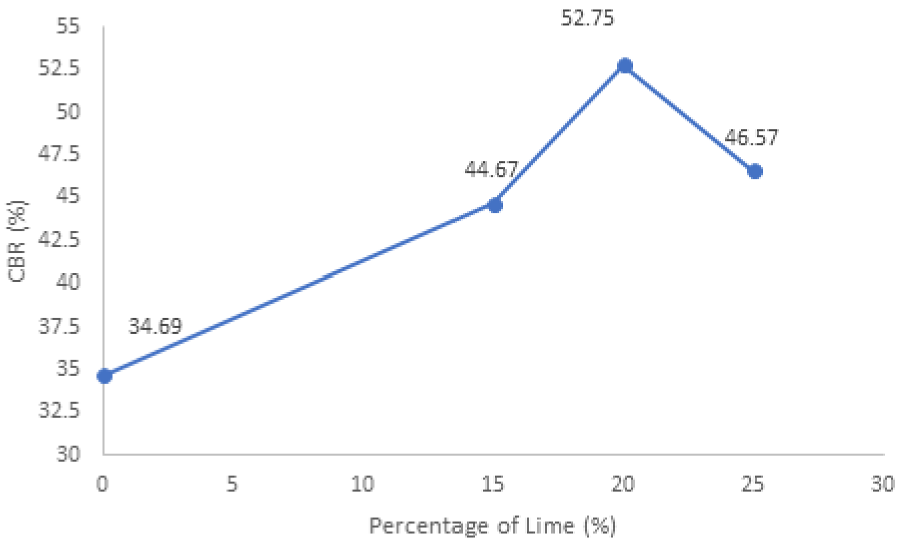
Figure 5: Effect of Lime Content on Maximum Dry Density



- Influence on CBR Value

The graph shows the relationship between the level of lime (%) added to the soil and the average CBR value (%) generated from laboratory tests. It was seen that the addition of lime up to 20% resulted in a significant increase in CBR value. The initial value of CBR on the original soil, at 34.69%, increased to 44.67% at 15% lime and reached its highest value of 52.75% at 20% lime. However, the addition of lime up to 25% results in a decrease in the CBR value to 46.57%. This graph pattern forms a curve that rises to a peak and then decreases again, illustrating the optimum point of lime content in increasing the bearing strength of the soil, as indicated by the CBR value.

Figure 6: Effect of Lime Content on CBR Value



Discussion

Soil stabilization with lime additives aims to improve the technical properties of clay soils, which naturally have low bearing capacity and high plasticity. In this study, variations in lime content (15%, 20%, and 25% of the dry soil weight) were mixed without a curing time and tested to determine their effect on the physical and mechanical characteristics of the soil.

- **Influence on Optimal Water Content (OMC)**

The results of the compaction test showed that the addition of lime increased the optimal moisture content. The optimum moisture content increased from 21.89% in natural soil to 26.39% in the addition of 25% lime. This condition is caused by the initial reaction between lime and water in the soil, which absorbs water through hydration and pozzolan reactions. In addition, changes in the structure of soil grains due to flocculation also cause the soil to require more water to reach maximum density.

The addition of lime causes an increase in the optimal moisture content (OMC) as the lime content increases. This condition follows the principle of an initial hydration reaction, in which lime reacts with water and absorbs moisture from the soil. A study by [7] demonstrated that the addition of lime resulted in an increase in the optimal moisture content of up to 23.5% during the stabilization of soft clay soils. This condition supports the findings of this study, which show a similar trend, from 21.89% to 26.39%.

- **Effect on Maximum Dry Density (γdry max)**

The addition of lime resulted in an increase in maximum dry density of up to 20%, from 1.43 g/cm^3 in the native soil to 1.54 g/cm^3. However, at 25% lime, there was a decrease in the γdry max value to 1.33 gr/cm^3. This condition indicates that at a 20% level, the chemical reaction of lime effectively improves the structure of soil particles, allowing them to fill the pore space more efficiently. In contrast, the addition of excess lime tends to result in coarse aggregates and rigid particles that are not perfectly solid, thus lowering the total density.

The addition of lime up to 20% increases the γdry max, but the decrease occurs at a lime content of 25%. This condition shows that there is an optimal limit in the process of flocculation and agglomeration of soil grains. [8] reported that a mixture of soil and lime formed a denser microstructure through the pozzolan process and matrix locking after 7 days of curing, resulting in increased initial strength and density. Although no curing was done in this study, a similar phenomenon occurred at 20% levels.

- **Influence on CBR Value**

The CBR value increased significantly with the addition of lime to a level of 20%, from 34.69% in the original soil to 52.75%. However, there was a decrease in the CBR value to 46.57% at a lime content of 25%. This condition indicates that the pozzolanic reaction between calcium from lime and silica/alumina in soil occurs most effectively at a lime content of 20%. This reaction produces calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which strengthen the bonds between soil grains. The decrease in CBR value at 25% is likely due to an excess of lime that does not react effectively, forming a rigid material that does not contribute optimally to the soil's strength.

The increase in the CBR value from 34.69% (native soil) to 52.75% (20% lime) was followed by a decrease at 25% lime, indicating that the optimum level of lime was around 20%. A study by Pancar&Akpınar (2016) [9]showed that the CBR value of plastic clay increased by more than 5 times after stabilization with 5–6% lime but decreased when the lime content was excessive. This condition is consistent with the theory that excess lime reduces strength due to the formation of non-reactive residues.

- **Optimal Lime Rate**

According to the analysis results, a lime content of 20% can be considered the optimum level for this soil, as it yields the best CBR value and maximum density. At this level, the mechanical properties of the soil continue to decrease. This condition aligns with the basic principle of lime stabilization, where determining the optimum level is essential for the chemical reaction to occur efficiently without excess material.

He et al. (2024) [10]assert that stabilization with lime results in three main compounds: *calcium silicate hydrates (C-S-H),calcium aluminate hydrates (C-A-H),* and *calcium sulfoaluminate hydrates*, all of which strengthen the soil's aggregate structure.

4. Conclusion

Based on the results of laboratory tests and analysis of stabilized clay soils using variations in lime content of 15%, 20%, and 25%, the following can be concluded:

- Based on the USCS classification system, the soil in this study is categorized as CL or OL, which is clay with low to medium plasticity or organic clay. Meanwhile, according to the AASHTO classification, soils belong to groups A-7-6, which indicates soils with high plasticity and low carrying capacity. Soil with these characteristics has high cohesion and is highly sensitive to changes in moisture content, so it requires stabilization treatment to improve its engineering properties and make it suitable for use as a basic construction material.
- The addition of lime to the soil causes an increase in the optimum moisture content (OMC), from 21.89% in natural soils to 26.39% in soils mixed with 25% lime. The maximum dry density value (γdry max) increased to 20% lime, reaching a value of 1.54 g/cm^3, but decreased to 1.33 g/cm^3 at 25%. This decrease indicates that the addition of too high lime can result in the soil structure becoming too rigid or not bonding efficiently, so the density formed decreases.
- The CBR value of the soil shows a significant increase after the addition of lime, especially at the 20% level, where the CBR value reaches 52.75%. However, at a 25% lime content, the CBR value decreased to 46.57%. This increase indicates the occurrence of a pozzolanic reaction between the lime and soil minerals, which strengthens the bonds between particles and enhances the soil's ability to carry water. The decrease in CBR values at higher limescale levels is caused by excessive chemical reactions that no longer contribute effectively to the increase in soil strength.
- Among all the parameters tested in this study, the lime content of 20% yielded the best results in terms of increasing soil density and strength, as indicated by CBR values. Therefore, this level can be recommended as the optimal lime content for this type of clay soil stabilization process, especially in conditions without curing treatment.

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