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Original Research Article

The Influence of Lime Variations on the Unconfined Compressive Strength of Inorganic Clay Soil Stabilized with a Combination of Nickel Slag and Aluminum Hydroxide

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Abstract

Soil stabilization is a ground improvement technique aimed at enhancing the strength and bearing capacity of soil, particularly in road construction projects. The combination of multiple stabilization materials allows for achieving better improvements in soil bearing capacity. The use of industrial waste materials offers an eco-friendly solution while repurposing materials that are typically discarded. This study focuses on the engineering application of adding limestone as a natural pozzolanic material. The research involves laboratory testing to measure the unconfined compressive strength (UCS) of stabilized clay soil samples. The addition of stabilization materials is based on weight ratios, where the ratio of nickel slag to aluminum hydroxide is 1,5, and limestone is added in varying proportions of 2%, 4%, and 6%. The curing of the test specimens is carried out over periods of 3, 7, 14, and 28 days to examine the influence of curing time on the improvement of soil UCS values. The results indicate that the addition of nickel slag and aluminum hydroxide significantly enhances the soil's UCS. Furthermore, variations in limestone content show that increasing its concentration up to 6% yields optimal results in improving soil strength. This study concludes that the combination of waste materials and limestone can effectively enhance the mechanical characteristics of soil, providing a sustainable and environmentally friendly solution for soil stabilization in various infrastructure projects.

Keywords: Soil Stabilization, Lime, Nickel Slag, Alumunium Hydroxide, Inorganic Soil.

INTRODUCTION

Soil serves as the foundation for any construction, whether it is building structures or roadworks. When subjected to loads, soil absorbs vertical and horizontal forces transmitted by the foundation or the structure above it. Unstable soil can lead to structural failures, foundation damage, or soil deformation, requiring significant remediation [1]. Therefore, the stability of a construction project heavily depends on the condition of the soil as its foundation. Different types of soil inevitably exhibit varying behaviors and strengths.

Poor soil conditions are generally characterized by low bearing capacity, significant volume changes, and high plasticity [2]. These issues present major challenges in various construction projects, including highways, bridges, and buildings. Consequently, chemical soil stabilization methods are often chosen to improve the physical and mechanical properties of soil, making it more stable and capable of supporting construction loads. Fundamentally, soil stabilization aims to enhance soil strength, bearing capacity, and resistance to external factors such as weather and mechanical loads [3].

In chemical soil stabilization, a commonly used approach is the addition of stabilizing materials such as lime, cement, or other chemical substances. However, the use of these conventional materials is considered environmentally unfriendly due to the high carbon dioxide emissions generated during their production, contributing to greenhouse gas effects [4]. With the growing awareness of the importance of sustainable development, there is increasing attention on the use of alternative materials that are more environmentally friendly and cost-effective. In this context, the utilization of industrial waste offers a viable alternative for meeting the needs of soil stabilization materials, such as rice husk ash (RHA), slag, fly ash, bottom ash, and cement kiln dust, which generally exhibit pozzolanic properties.

Chemical stabilization is one of the most effective methods for improving the mechanical properties of soil. This process involves a pozzolanic reaction between the stabilizing material and soil minerals, resulting in the formation of new compounds with greater stability and strength. These chemical reactions often involve pozzolanic materials, such as lime or cement, which interact with the silica and alumina in the soil to form calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH)—two compounds that play a crucial role in enhancing soil strength and durability [5]. In this study, the use of nickel slag and aluminum hydroxide is expected to produce similar reactions, where the chemical interaction between these materials and soil particles improves the microstructure of the soil. The addition of limestone as an auxiliary stabilizing material also contributes to accelerating the chemical reactions, ultimately enhancing the soil's load-bearing capacity through improved mechanical properties.

North Maluku is one of Indonesia's largest nickel producers, ranking second in the country. The nickel ore extraction process generates by-products such as nickel slag, nickel sludge, fly ash, and bottom ash. Research by Rauf *et al*., (2024) [6] highlights that these nickel waste by-products have significant potential for use as environmentally friendly advanced materials. Specifically, the mineral composition of nickel slag has shown promise for development as a stabilization material for soft soils in construction applications [7]. The utilization of these by-products offers several advantages. Compared to conventional materials, nickel slag is not only abundant but also more cost-effective, providing an economical solution for large-scale infrastructure projects. Additionally, the use of nickel slag can help mitigate the environmental impacts of industrial waste, which, if left unutilized, could pollute the environment.

The utilization of nickel slag as a stabilization material for clay soils has demonstrated significant improvements in mechanical properties. In organic soils with high plasticity (OH), the use of nickel slag at concentrations ranging from 3% to 12% can increase the unconfined compressive strength of the soil by 40% to 68% [8]. Furthermore, research conducted by Fatahilla (2024) [9], revealed that the addition of aluminum hydroxide to nickel slag in soil stabilization resulted in UCS improvements of up to 700%. Although these studies indicate substantial enhancements in soil strength, the application of this stabilization method remains primarily limited to the subgrade layer in road construction.

The combination of multiple stabilization materials often yields better results compared to the use of a single material [10, 11]. According to the Federal Highway Administration (FHWA) [12], the reasons for using a combination of stabilization materials for soil include: (a) Improving the technical characteristics of a specific type of soil to make it more optimally usable, (b) Allowing one material to compensate for the weaknesses of another in addressing specific aspects or properties of the soil, and (c) Economic or environmental considerations. Each stabilization material possesses unique chemical and physical properties, and when combined, they can complement each other to enhance the overall mechanical properties of the soil. Therefore, efforts to further develop the use of nickel slag are still necessary to expand its applications in other construction fields, such as its use in sub-base road layers, brick production, and more.

The use of lime in soil stabilization is a long-established technique due to its ability to react with soil minerals and enhance particle cohesion [13]. Lime alters soil structure by reducing plasticity and improving its geotechnical properties through pozzolanic reactions [14, 15], forming pozzolanic compounds such as calcium silicate hydrate (CSH), calcium aluminate hydrate (CAH), and calcium silico-aluminate hydrate. These compounds strengthen the soil. Lime not only acts as an additional binding agent but also improves the initial strength of the soil after stabilization. Thus, the addition of lime is expected to contribute positively to soil performance, both in the short and long term.

This study aims to evaluate the effect of varying lime combinations added to soil stabilized with nickel slag and aluminum hydroxide. The focus is on improving mechanical properties, particularly the unconfined compressive strength (UCS). The research explores various lime additions to identify the optimal combination that delivers the best results in enhancing soil performance. Additionally, the study emphasizes the potential of industrial waste as an alternative stabilization material that is more environmentally friendly and economical. By utilizing waste materials, this research not only contributes to improving the efficiency of soil stabilization but also supports sustainability efforts within the construction industry.

RESEARCH METHODE

This study aims to evaluate the effect of the combination of nickel slag, aluminum hydroxide, and limestone on the stabilization of inorganic soil, with a focus on unconfined compressive strength. To achieve this goal, the study was conducted through several stages, including: material sampling, preparation of test specimens, and the execution of laboratory testing.

Location of Materials Quarry

The material samples in this study are locally sourced from the North Maluku Province. The clay soil sample was obtained from a quarry of stockpiled material located on Ternate Island, nickel slag was sourced from a nickel ore processing industry on Bacan Island, limestone was taken from Morotai Island, while aluminum hydroxide was purchased in powdered form from the market.

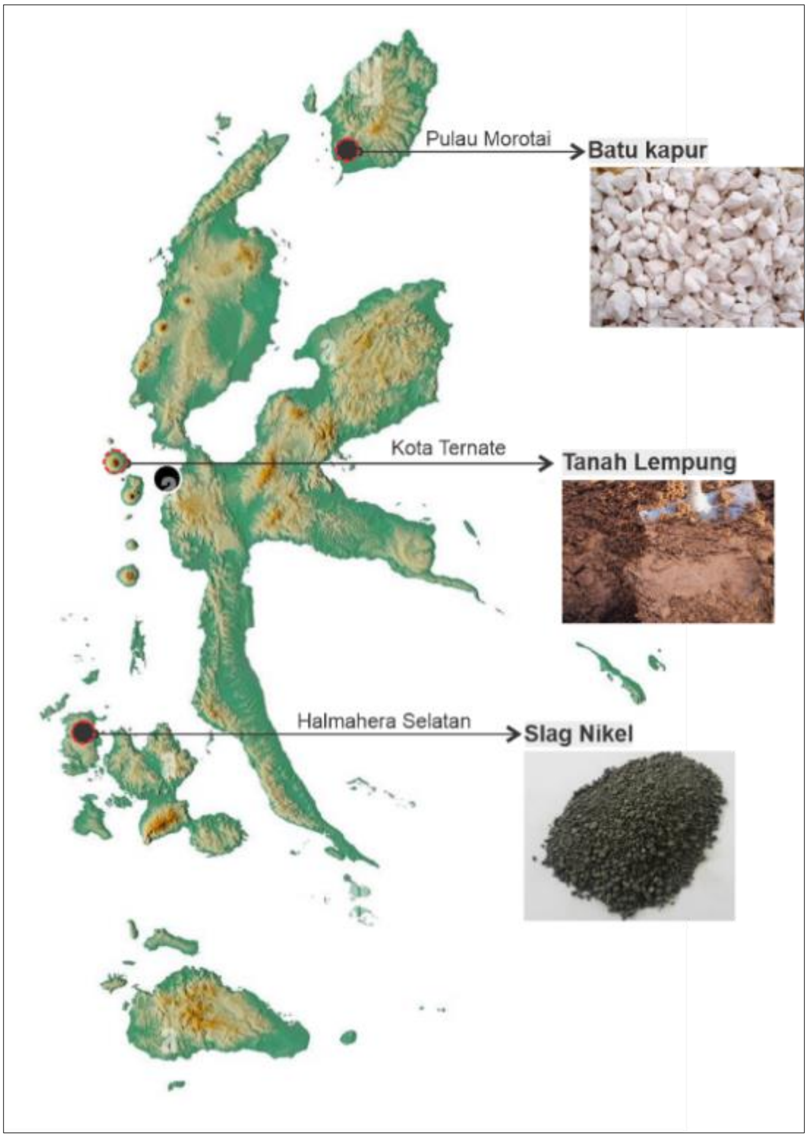

Figure 1: Materials Quarry

Preparation Process for Test Specimens

Sample Preparation: The material preparation and test specimen fabrication stages were carried out with careful procedures to ensure the samples met the specifications and testing standards. The preparation process involved the following steps: Initial Soil Treatment: The collected soil sample was air-dried for 48 hours to remove excess moisture. Afterward, the soil was sieved using a sieve with a maximum particle size of 2 mm to ensure uniformity in particle size. Nickel Slag and Limestone Processing: The nickel slag and limestone were crushed to finer sizes using a crusher and then sieved using a 0.075 mm sieve to achieve the desired particle size.

Material Mixing: The mixture of soil, nickel slag, aluminum hydroxide, and limestone was prepared in specific proportions based on weight ratios. The limestone concentration was varied at 2%, 4%, and 6% of the total weight of the mixture. Nickel slag and aluminum hydroxide were added in fixed amounts, determined based on preliminary study results, where the optimal weight ratio of nickel slag to aluminum hydroxide was 1,5. The materials were mechanically mixed using a laboratory mixer to ensure even distribution of each component at the optimum moisture content.

Figure 2: Specimen fabrication process

Test Specimen Fabrication: Three test specimens were prepared for each variation in lime content and curing period. The specimens were cylindrical, with a diameter of 35 mm and a height of 70 mm, in accordance with the unconfined compressive strength testing standard (ASTM D2166) as presented in Figure 2. Each specimen was statically compacted using a mold and compaction tool to achieve optimal density. After molding, the specimens were stored under room conditions for 3, 7, 14, and 28 days before testing for compressive strength.

Testing Procedure

The mechanical characteristics were tested in a geotechnical laboratory using equipment and procedures that comply with the unconfined compressive strength testing standard (ASTM D2166). The test specimen was placed between two compression plates, and axial load was applied gradually until the specimen failed (ruptured) as presented in Figure 3. The applied load and the resulting vertical deformation were measured simultaneously. The results of this test provided the unconfined compressive strength (σ), which was calculated based on the ratio of the maximum load to the cross-sectional area of the specimen. After testing, the obtained data were analyzed to evaluate the impact of adding nickel slag, aluminum hydroxide, and limestone on the unconfined compressive strength of both natural soil and soil stabilized only with nickel slag. The test results were compared with the control (without any stabilizing additives) to observe the improvements achieved.

Figure 3: Unconfined Compression Strength Testing

RESULTS AND DISCUSSION

Soil Sample Characteristics

The results of the physical properties testing for the soil samples used in this study are shown in Table 1. Based on the analysis data, the soil used in this study is classified as CH (Inorganic Clay with High Plasticity) in the USCS system, as it has a Liquid Limit (LL) of 65.87% (LL > 50%) and a Plasticity Index (PI) of 24,76% (PI > 7%), with a clay content of 77,3%. In the AASHTO system, this soil falls under the A-7-6 category, which represents clay soil with high plasticity and low bearing capacity. The Group Index (GI) value of 7 further indicates that the soil is highly plastic and has poor characteristics for supporting structures without stabilization or improvement.

Table 1: Physical Characteristics of Soil

Soft soil properties		**Value**
Physical characteristics	Specific Gravity (Gs)	2,66
	Water Content ($w_{opt,}$ %)	33,08
	Sieve Analysis	
	Sand (%)	0
	Silt (%)	14,3
	Clay (%)	77,3
	Atterberg Limit	
	Liquid Limit (LL)	65,87
	Plastic Limit (PL)	41,11
	Plasticity Index (PI)	24,76
Mechanical characteristics	Density (kg/cm^3)	1,32
	Compression strength (kg/cm^2)	1,269

Based on the classification in both the USCS and AASHTO systems, it can be described that this soil has low bearing capacity, is highly sensitive to moisture content, and tends to experience significant shrinkage or expansion. Therefore, stabilization is essential, such as the addition of lime or cement to improve strength and reduce plasticity. Additionally, controlling drainage is crucial to prevent damage caused by changes in moisture content, and the addition of granular materials can help improve the soil structure to make it more stable.

Stress and Strain Behavior of the Material

The addition of active lime in varying concentrations of 2%, 4%, and 6% had a significant effect on the stress and strain behavior of the material stabilized with nickel slag and aluminum hydroxide as shown in Figure 4. At the early curing period (3 days), the material with 6% lime content exhibited the highest maximum stress compared to the 2% and 4% lime mixtures. This indicates that, at the initial stage, a higher lime concentration accelerates the strengthening reaction, leading to an increase in the unconfined compressive strength of the material. Meanwhile, strain showed a similar trend, ranging from 0.4% to 0.6%.

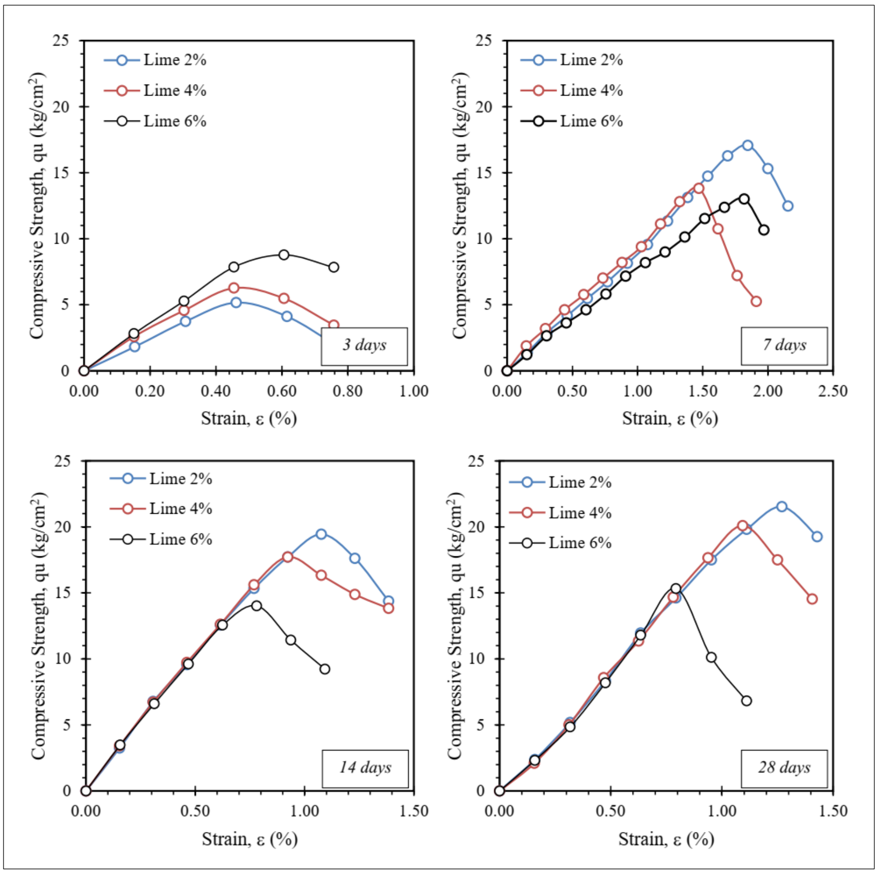

Figure 4. Stress-Strain Relation

At 7 days of curing, differences in the stress and strain patterns became evident for each lime concentration. The specimens with 2% and 4% lime concentrations started to show higher maximum stress values compared to the 6% lime specimens, even though they exhibited greater strain. The strain showed a linear trend with respect to the stress, indicating that the specimens were approaching a balance between strength and elasticity.

After 14 days of curing, the graphs showed that the specimens with 2% lime achieved the highest maximum stress, surpassing those with 4% and 6% lime. This suggests that the chemical reaction between lime, nickel slag, and aluminum hydroxide peaked at the 14-day curing period. The 4% and 6% lime specimens exhibited lower maximum stress, likely due to the formation of a material structure that was too rigid, reducing its ability to resist further strain.

At 28 days of curing, the 2% lime specimens continued to exhibit the highest maximum stress, demonstrating optimal performance in the long term. The specimens with 4% and 6% lime again displayed lower maximum stress and smaller strain, reflecting a material characteristic that was stiff but lacked elasticity. This suggests that 2% lime content provides the best balance of strength and stability over longer curing periods.

Overall, the lime concentration and curing time significantly influenced the material's mechanical properties. The 2% lime concentration resulted in a material that balanced strength and elasticity, with optimal performance at 14 to 28 days. While 6% lime was more effective in the early curing period (3 to 7 days), its rigid material properties limited its performance in the long term. Therefore, 2% lime is the optimal concentration for stabilizing materials for long-term applications.

Compressive Strength vs. Curing Period

The graph 5 illustrates the relationship between compressive strength (qu) in kg/cm2 and curing period (days) for a mixture of nickel slag, Al(OH)3, and lime ($Ca(OH)_2$) at varying proportions of 2%, 4%, and 6%. The results indicate that compressive strength increases significantly within the first five days of curing for all lime proportions. However, after day 5, the increase in strength becomes more gradual and stabilizes around day 28. The mixture with 2% lime achieves the highest compressive strength compared to other proportions, indicating that this level of lime addition provides optimal efficiency in enhancing the material's structural properties. This indicates that the addition of lime increases the pH of the mixture, accelerating the pozzolanic reaction and producing more CSH and CAH. Moreover, lime strengthens the bonds between particles through ionic stabilization, where soil ions are replaced by Ca^{2+} cations, resulting in a denser and stronger soil structure [16].

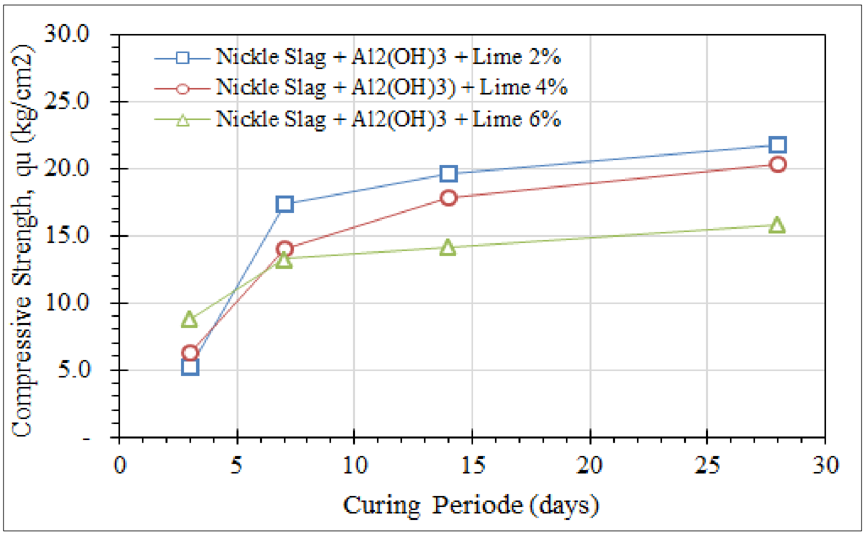

Figure 5: The Influence of Curing on Unconfined Compressive Strength

When compared to untretated soil, which has a qu value of 1,269 kg/cm^2, lime stabilization significantly improves compressive strength. The improvement ratios for 2%, 4%, and 6% lime are 17,2 times; 16 times, and 12,5 times, respectively. These findings highlight that the addition of 2% lime produces the most significant enhancement, while increasing lime content to 6% results in reduced performance. This reduction could be attributed to over-saturation effects, which diminish the efficiency of chemical reactions between the materials [17, 18].

From these results, it can be concluded that adding 2% lime is the optimal proportion for improving the compressive strength of materials based on nickel slag and $Al(OH)_3$. Higher lime proportions require further investigation to understand their impact on material microstructure and the chemical reactions occurring during the curing process. Additional studies could focus on the effect of lime content on pore distribution, hydration phases, and interactions among the components to optimize the performance of this material for civil engineering applications.

CONCLUSION

Soil stabilization with nickel slag, aluminum hydroxide ($Al_2(OH)_3$) and lime has shown a significant increase in compressive strength of the soil. The addition of lime ($Ca(OH)_2$) to this mixture results in an even more significant increase, especially at a lime concentration of 2%, which provides a compressive strength of over 21,83 kg/cm² at 28 days, or more than 17 times higher than the untreated soil. Lime at 2% shows optimal performance, with the chemical reacti ons occurring efficiently without negative effects such as base saturation, which inhibits ion diffusion in the pozzolanic reactions. In contrast, at higher lime concentrations (4% and 6%), compressive strength decreases due to reduced efficiency in the formation of calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) compounds, as well as issues related to material segregation and increased porosity. Based on these findings, the combination of nickel slag, $Al_2(OH)_3$, and 2% lime is recommended as the optimal stabilization method for enhancing compressive strength and soil stability in the long term.

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