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Original Research Article

Stress-Strain Behavior of Soft Soil Stabilized with Nickel Slag, Limestone, and Aluminum Hydroxide

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Abstract: Soil stabilization by combining several minerals is a form of material engineering aimed at increasing the bearing capacity of the soil to a higher level. The development of waste-based materials and the utilization of local potential are part of environmentally conscious construction. This study aims to analyses the mechanical behaviour of soil stabilized with several pozzolanic materials derived from nickel processing waste and limestone, which are local materials with very large deposits. ASTM standards were used in this study for both physical and mechanical testing. Unconfined compressive strength (UCS) tests were conducted to compare the mechanical behaviour of stabilized soil with that of natural soil. The test samples used were cylindrical with a diameter of 35 mm and a height of 70 mm. The binding materials consisted of nickel slag, aluminium hydroxide, and limestone, with the amount of each material based on the dry soil weight (γ_{dry}). The addition of lime in this study was varied at 2%, 4%, and 6%. The test results generally show that lime variations and curing time affect the increase in unconfined compressive strength (qu), with the highest value of 30.91 kg/cm² observed at 6% lime content after 28 days of curing.

Keywords: Nickel Slag, Aluminium Hydroxide, Limestone, Soil Stabilization.

INTRODUCTION

Chemical stabilization has become a method of soil improvement that is considered more effective and efficient. The fundamental principle of chemical stabilization is to alter the physical and chemical properties of a material to enhance its stability through the addition of specific chemicals. These chemicals will react with the soil, reducing the plasticity index of clay soils and their permeability, thereby increasing their bearing capacity and durability [1, 2], which helps meet the technical specifications in civil engineering design.

In the chemical stabilization development, the materials used for chemical soil improvement have shifted towards the utilization of natural materials and waste materials. This change is closely related to the increasing awareness of sustainable and environmentally friendly development. Conventional stabilization materials, such as cement and the calcination process of lime, have become significant contributors to environmental pollution [3]. A report released by the Intergovernmental Panel on Climate Change (IPCC) in 2005 stated that 7% of global CO2 emissions come from the cement industry [4].

The utilization of natural and waste materials as binding agents in soil improvement efforts is based on the pozzolanic properties of the chemical materials used in the formation of new compounds that exhibit cementitious properties [5], such as Calcium Silicate Hydrate (CSH), Calcium Aluminate Hydrate, and Calcium Silicate Aluminate Hydrate (CSAH). Several studies have shown that the use of natural pozzolans and waste materials has a positive impact on enhancing soil bearing capacity, such as the utilization of trass [6], waste from asphalt processing [7], zeolite [8], etc.

Chemical stabilization using a single chemical may have some drawbacks, such as slow reaction processes or solubility in wet environments [9]. This is because each waste material has a different effect on the soil. Therefore, combining several waste materials often yields more optimal results. Research conducted by Almajeed *et al*., (2023) [10], James and Pandian (2016) [11]. Bakr (2024) [12], has indicated that the bearing capacity of soft soils, in terms of both shear strength and unconfined compressive strength, can be improved by adding cementitious additives. Thus, the addition of lime enhances the reaction of the cementing material compared to without lime.

North Maluku is one of the provinces in Indonesia that has a nickel processing industry. The extraction process of nickel ore generates a significant amount of slag waste. A study conducted by Rauf *et al*., (2024) [13], shows that the chemical composition of this nickel waste is rich in silica minerals (48%) and is classified as pozzolan type F. Furthermore, this nickel slag has the potential to be developed into advanced materials [14]. Additionally, limestone deposits located on Morotai Island provide another mineral resource that can be processed into stabilization materials for soft soil improvement efforts. The significant potential of mineral resources in North Maluku poses a challenge for us in developing environmentally friendly cementitious materials.

RESEARCH METHODOLOGY

Material Research

The material samples in this study are local materials sourced from North Maluku Province, as shown in Figure 1. The clay soil was taken from Halmahera Island, specifically from Subaim village. Limestone was obtained from Gamlamo village located on Morotai Island, while nickel slag comes from the nickel extraction industry in Kawassi village on Obi Island. The manufactured material used as an additive in this study is aluminium hydroxide [$Al(OH)_3$].

Figure 1: Research Materials Quarry

Test Specimen Preparation Procedure

The sample preparation process begins with drying the natural materials obtained from each location. This drying is performed under sunlight to avoid chemical changes due to excessive heating that might occur if the drying process is conducted in an oven. Each material is then ground, either manually or using a machine. The soft soil used is material that passes through a No. 4 sieve, while the limestone and nickel slag used are materials that pass through a No. 400 sieve. This process is conducted because particle size significantly influences the internal interaction of the materials [15].

The composition of the mixture for the preparation of the test specimens is based on the dry weight of the soil and the optimum water content obtained from the soil density test. Previous research has shown that the mixture of nickel slag and aluminium hydroxide that yields the highest compressive strength is at a nickel slag/aluminium hydroxide weight ratio of 1.5. The addition of limestone is varied at 2%, 4%, and 6%.

The test specimens are in the form of cylinders with a diameter of 3.50 cm and a height of 7.00 cm. The process of preparing the test specimens involves mixing the soil with all the materials at the optimum water content and manually stirring for 10 to 15 minutes to ensure the mixture is homogeneous [16].

Unconfined Compressive Strength Test

The unconfined compressive strength test of the specimens is conducted after curing for 3 days, 7 days, 14 days, 21 days, and 28 days. This testing refers to the American Standard Test Methods (ASTM) D2166, which includes the determination of the unconfined compressive strength of cohesive soil in undisturbed, remoulded, or compacted conditions, as shown in Figure 2.

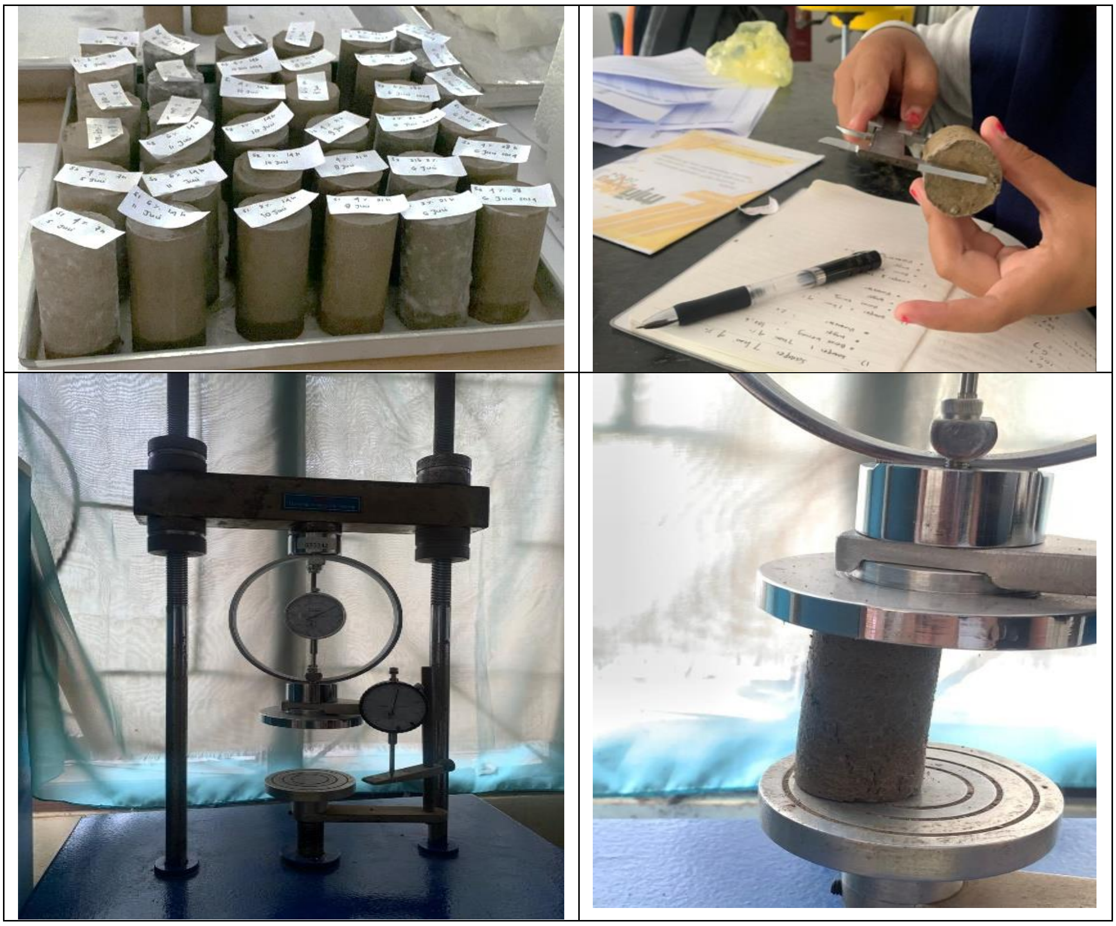

Figure 2: Unconfined Compressive Strength Testing Process

RESULTS AND DISCUSSIONS

Stress and Strain Behaviour

The mechanical characteristics of the material stabilized with nickel slag, aluminium hydroxide, and varying amounts of lime are shown in Figure 3. These results generally indicate that variations in lime addition and curing time significantly enhance the soil's bearing capacity. The relationship between stress and strain shows that the soil experiences an increase in stiffness as the amount of lime and the curing period increase. In soil with a lime percentage of 6%, there is a noticeable loss of plasticity more quickly, leading to a stiffer consistency compared to soil with 2% and 4% lime, which takes longer, especially after curing for 14 days.

This behaviour may be attributed to the stabilization process, where lime provides Ca^{2+} ions that bind to the surface of clay particles, replacing the previously attached cations. Due to the high charge of Ca^{2+} ions, the clay particles undergo coagulation and agglomeration [17]. The coagulation and agglomeration of soil particles determine the changes in the chemical structure of the soil, leading to a shift in the plasticity index toward a specific zone. Furthermore, this effect influences the particle size distribution, resulting in an intensive reduction of the stabilization particle surface. As the particles agglomerate, the angle of internal friction increases, and the cohesion value also rises. The addition of lime enhances the compressive strength of the soil, thereby increasing its load-bearing capacity [18].

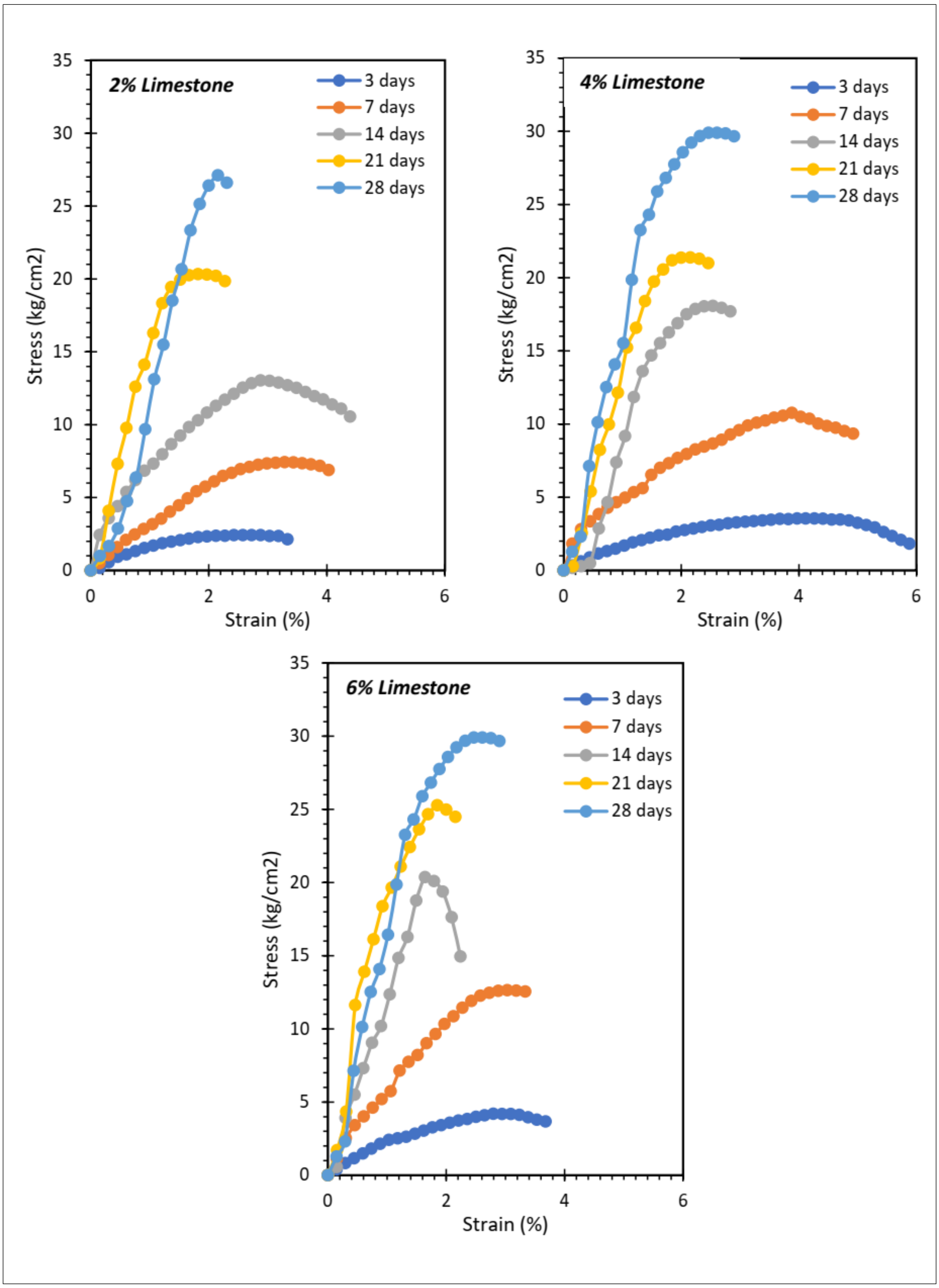

Figure 3: Stress and Strain behaviour with lime variation

Ratio of Maximum Compressive Strength Increase

The increase in the maximum mechanical values for each lime variation in soil stabilized with nickel slag and aluminium hydroxide is shown in Figure 4. The research results indicate that the addition of lime significantly increases the unconfined compressive strength of the soil compared to untreated soil and soil stabilized with nickel slag. Research conducted by Fahmi *et al*., [19], demonstrates that untreated soil exhibits a maximum stress of only 0.189 kg/cm². After stabilization with nickel slag, the stress increases to 0.462 kg/cm², representing an increase of approximately 2.44 times. However, when the soil is stabilized with the addition of aluminium hydroxide and lime at rates of 2%, 4%, and 6%, the increases in stress are much greater, at 158.73 times, 169.31 times, and 179.89 times, respectively, compared to untreated soil.

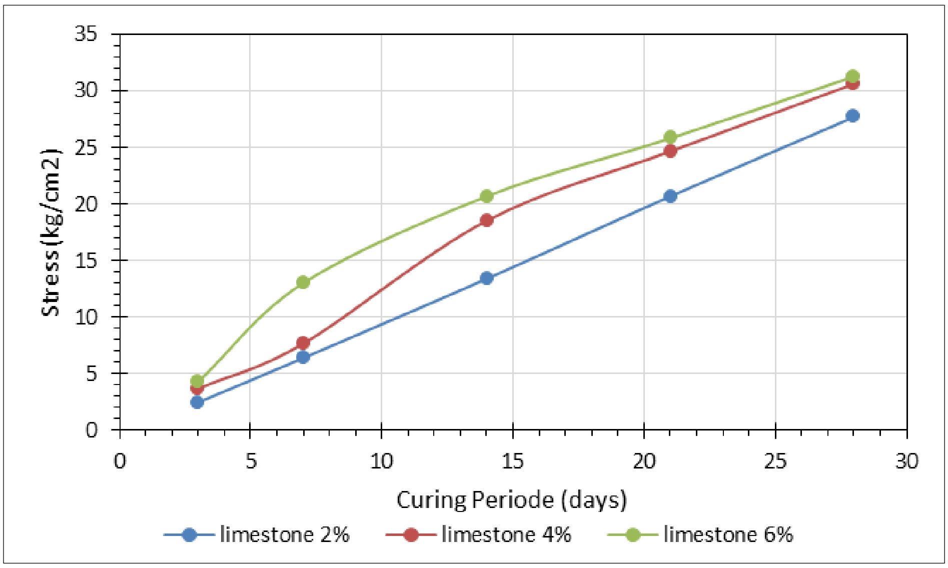

Figure 4: Increase in Unconfined Compressive Strength during Curing Period

Lime with a higher content (6%) results in the most significant increase in stress, reaching up to 34 kg/cm². In comparison, the stress values recorded for 4% and 2% lime content are 32 kg/cm² and 30 kg/cm², respectively. This clear trend indicates that the addition of lime not only accelerates the soil strengthening process but also enhances its effectiveness in improving the mechanical properties of the soil. The data suggests that higher lime content contributes to a more efficient stabilization process, allowing the soil to achieve greater load-bearing capacities in a shorter period.

The implications of this finding are critical for various civil engineering applications. For instance, in the construction of foundations, roads, and other infrastructure projects, the ability to quickly and effectively increase soil strength can significantly reduce project timelines and costs. Moreover, the use of lime as a stabilizing agent provides an environmentally friendly solution, as it is a natural material that can help minimize the ecological impact of construction activities.

In summary, the results of this research clearly demonstrate that lime serves as a highly effective stabilizing material. Its ability to markedly enhance the mechanical strength of soil underscores its potential for widespread application in engineering practices, particularly in areas where soil conditions may otherwise pose challenges to construction and infrastructure development. By incorporating lime into soil stabilization strategies, engineers can achieve better performance and durability in their projects, ultimately contributing to the sustainability and resilience of civil engineering practices.

CONCLUSIONS

From the findings of this research, a range of detailed conclusions can be formulated. The data collected throughout the study provide valuable insights into various aspects of soil stabilization, particularly concerning the impact of lime content on the mechanical properties and behavior of the soil. Here are some key points derived from the research that merit further elaboration:

- **Mechanical Strength:**

The findings indicate that higher lime content significantly accelerates the increase in soil strength. Specifically, soil mixed with 6% lime reached maximum stress levels more quickly than those with 2% and 4% lime. This trend was particularly evident after the 14th day of curing, suggesting that the chemical reactions initiated by the higher lime content contribute to a more rapid enhancement of the soil’s load-bearing capacity. The accelerated strength gain can be attributed to the effective pozzolanic reactions occurring between the lime and soil, which facilitate the formation of cementitious compounds that improve the overall mechanical properties.

- **Plasticity and Rigidity:**

The study further reveals that soil stabilized with 6% lime experiences a more rapid loss of plasticity, thereby becoming rigid in a shorter time frame. This change in plasticity is crucial for applications where soil stability is paramount, as excessive plasticity can lead to issues such as deformation under load. In contrast, the 4% lime content strikes a favourable balance, enhancing strength while maintaining an acceptable level of plasticity. On the other hand, the 2% lime content demonstrated a slower progression toward achieving optimal rigidity, indicating that lower lime levels may not be sufficient for applications requiring immediate strength and stability.

- **Effectiveness of Stabilization:**

The overall effectiveness of lime as a stabilizing agent is evident in the results, where higher lime content correlates with a quicker attainment of full stabilization. In the case of the 6% lime content, the soil not only reached optimal strength levels faster compared to lower lime concentrations but also exhibited certain drawbacks, such as increased brittleness under minor deformations. This brittleness can pose challenges in practical applications, as it may lead to cracks or failures when the stabilized soil is subjected to tensile stresses. Therefore, while higher lime content offers significant strength advantages, careful consideration must be given to its potential effects on the soil's behaviour under varying conditions.

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