CEC

Civil Engineering Collaboration

https://jcivil-upiyptk.org/ojs

2026 Vol. 11 No. 1 Page: 1 - 7 e-ISSN: 2615-5915

The Effect of Lime Addition on Consistency and Maximum Stress in Silt-Clay Soil

Risayanti[1] ✉, Indra Farni [2], Zufrimar[3]

[1,2,3] Bung Hatta University

risayanti@bunghatta.ac.id

Abstract

Silty–clayey soils with moderate to high plasticity often present geotechnical problems due to high compressibility, low bearing capacity, and sensitivity to moisture variations. This study aims to evaluate the effect of lime addition on soil consistency characteristics and maximum stress and to investigate the quantitative relationship between the plasticity index (PI) and maximum stress (qu) as an integrated approach for assessing soil stabilization. Laboratory tests were conducted using lime contents of 0%, 3%, 5%, 7%, and 9% by dry weight of soil. The evaluated parameters included liquid limit (LL), plastic limit (PL), plasticity index (PI), and unconfined compressive strength (UCS). The results indicate that lime addition significantly reduced the plasticity index from 23.13% to 8.89%, accompanied by an increase in maximum stress from 0.119 kg/cm² to 0.291 kg/cm². Regression analysis revealed a strong negative linear relationship between PI and qu, with a coefficient of determination (R^2) of 0.98. The optimum lime content was found to be in the range of 5–7%, providing the most efficient combination of plasticity reduction and strength improvement. These findings suggest that the plasticity index has strong potential to be used as a preliminary parameter for estimating strength improvement in lime-stabilized silty–clayey soils during the early stage of ground improvement planning.

Keywords: soil stabilization, lime, plasticity index, unconfined compressive strength, silty–clayey soil.

1. Introduction

1.1 Background

Fine-grained soils, particularly silt-clay soils with moderate to high plasticity, often present geotechnical problems due to their high compressibility, low bearing capacity, and high sensitivity to changes in water content. These conditions cause the soil to easily experience plastic deformation and reduced strength, making it less suitable for direct use as a construction base soil [1] .

Cohesive soil behavior is generally evaluated through consistency properties including liquid limit (LL), plastic limit (PL), and plasticity index (PI). A high PI value indicates a wide range of plastic conditions and the soil's tendency to undergo permanent deformation under loading. Various studies have reported that soils with a high PI generally have low unconfined compressive strength, so consistency parameters are often used as an initial indicator of soil stability [2,3] .

One widely used soil improvement method is chemical stabilization using lime. The addition of lime is known to reduce LL and PI values through cation exchange and flocculation-agglomeration mechanisms, as well as increase soil strength due to the formation of cementation bonds from pozzolanic reactions. Several studies have shown that lime stabilization is effective in increasing the unconfined compressive strength of clay soils [4,5, 6,7] .

However, most previous studies still evaluate changes in consistency properties and increases in soil strength separately. The relationship between the decrease in plasticity index and the increase in maximum stress is generally presented descriptively, without a clear quantitative approach. As a result, consistency parameters have not been optimally utilized as predictive indicators of soil strength resulting from stabilization [8,9,10] . Based on these conditions, this study focuses on an integrated study of changes in plasticity index and maximum stress response of silt-clay soil due to lime stabilization.

1.2 Research Objectives

This study aims to analyze the effect of varying lime content on changes in the consistency values of silt–clay soil (LL, PL, and PI) and the increase in maximum soil stress based on the results of the unconfined compressive strength (UCS) test. In addition, this study aims to identify the quantitative relationship between the plasticity index and maximum stress (PI–qu) as an integrated evaluation approach in assessing the effectiveness of soil stabilization, as well as determining the optimum lime content that provides the most efficient improvement in soil properties.

1.3 Characteristics of Clay and Silt Soil

Plastic clays and silts are fine-grained soils whose mechanical behavior is strongly influenced by particle size, mineralogy, and water content. Soils with a dominant fine fraction have a large specific surface area,

Accepted: 02-03-2026 | Revised: 10-04-2026 | Published: 12-05-2026 | doi: 10.35134/jcivil.v7i2.1

allowing them to adsorb large amounts of water and exhibit significant plasticity. This condition makes soils with moderate to high plasticity susceptible to deformation and decreased strength when the water content increases [1, 11, 12].

The plasticity index (PI) is often used as the main parameter to describe the plasticity level of cohesive soil. A high PI value indicates a wide range of plastic conditions and the soil's tendency to undergo permanent deformation under loading. Several studies have reported that soils with a high PI generally have high compressibility and relatively low unconfined compressive strength, making them less favorable for use as subgrade without improvement treatment [9].

These characteristics make highly plastic silt-clay soils require stabilization efforts to reduce plasticity and increase mechanical strength. Therefore, understanding the relationship between index properties and soil mechanical response is a crucial aspect in evaluating and planning soil improvement.

1.4 Soil Consistency Value

Soil consistency values consisting of liquid limit (LL), plastic limit (PL), and plasticity index (PI) are basic parameters in the classification and evaluation of cohesive soil behavior. LL represents the water content at the transition state of the soil to liquid behavior, while PL indicates the lower limit of the plastic condition. The difference between the two, namely PI, reflects the range of water content in which the soil behaves plastically [2]. Empirically, PI can be written with the following equation [12,13]:

$$PI = LL - PL \qquad (1)$$

Soils with high LL and PI values generally exhibit high sensitivity to changes in water content, which directly impacts soil stability and strength. Increased water content in high PI soils is often accompanied by decreased strength and increased plastic deformation, thus increasing the potential for geotechnical failure [9].

Several previous studies have shown that changes in consistency values due to chemical stabilization correlate with improvements in soil mechanical properties. A decrease in PI is generally accompanied by an increase in unconfined compressive strength and soil structural stability [4,10]. However, most studies still report this relationship qualitatively, without a quantitative approach directly linking PI changes to increased soil strength.

1.5 Soil Stabilization with Lime

Soil stabilization using lime is a widely used method to improve the properties of cohesive soils. The primary mechanism of lime stabilization involves cation exchange reactions and flocculation–agglomeration processes in the initial stages, which cause clay particles to clump together into coarser, more stable structures. This process reduces the soil's specific surface area and reduces its water-binding capacity [11,14].

At adequate lime content and with a certain curing time, a pozzolanic reaction begins to develop. This reaction produces cementitious compounds such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), which act as binders between soil particles and increase the stiffness and strength of the stabilized soil [5, 6,15].

Several studies have reported that adding lime can significantly reduce LL and PI values and increase the unconfined compressive strength of soil [4,16]. However, the effectiveness of stabilization is greatly influenced by the lime content used. Too low a lime content does not produce optimal improvement, while too high a content can potentially result in strength increases disproportionate to the added material [15].

1.6 Maximum Soil Stress

The maximum soil stress, which in laboratory testing is generally represented by the unconfined compressive strength (UCS), is an important parameter for evaluating the soil's ability to withstand axial loads without failure. The UCS value reflects the combined effects of cohesion and the soil's internal structure [17]. The maximum stress value (qu) is determined based on the maximum axial load received by the specimen until failure occurs in the UCS test, in accordance with standard procedures for cohesive soil testing [12,13].

In cohesive soils, the UCS value is strongly influenced by the level of plasticity and microstructure of the soil. Soils with high PI tend to have lower UCS values due to the dominance of plastic deformation and weak interparticle bonds [18]. Lime stabilization has been shown to increase the UCS value by reducing plasticity and forming cementation bonds that strengthen the soil structure [5].

Although increases in UCS due to lime stabilization have been widely reported, studies directly linking increases in maximum stress to changes in the plasticity index are still relatively limited. The quantitative relationship between PI and UCS has the potential to provide a more integrative approach to evaluating the effectiveness of soil stabilization, particularly in the early planning stages of soil improvement [4,9].

2. Research methodology

2.1 Research Design and Approach

This study used a laboratory experimental approach to evaluate the effect of lime addition on changes in the consistency and maximum stress properties of silt–clay soil. The experimental approach was chosen because it allows for systematic control of variables, allowing for quantitative analysis of the causal relationship between variations in lime content and the mechanical response of the soil.

This research design is specifically designed to integrate consistency parameters (LL, PL, and PI) with soil strength parameters, namely the maximum stress represented by the unconfined compressive strength (UCS). In addition to analyzing changes in each parameter, this study was designed from the outset to identify the quantitative relationship between the plasticity index and maximum stress (PI–qu) as part of the empirical contribution of the study.

2.2 Research Materials

The soil used in this study was silt-clay soil taken from the Padang-Sicincin Toll Road Project site. Disturbed soil samples were collected, then air-dried, manually crushed, and sieved to achieve a homogeneous soil mixture before laboratory testing.

Table 1. Chalk Test Results

Description	Test Results
SiO2%	6.06
Al2O3%	2.76
Fe2O3%	1.64
CaO%	78.61
MgO%	9.64
SO3%	0.75
Na2O%	ND
K2O%	0.32
TiO2%	0.16
P2O5%	0.004

The stabilization material used was natural lime from Bukit Tui, Padang Panjang City, as shown in Table 1. Chemical analysis results showed that the lime contained 78.61% CaO, indicating the characteristics of active lime with high reactivity potential towards cohesive soil minerals. Other oxides such as MgO, SiO_2, and Al_2O_3 acted as supporting components in the stabilization process.

2.3 Research Variables

The independent variable in this study was the lime content, which was varied by 0%, 3%, 5%, 7%, and 9% of the dry weight of the soil. The dependent variables included the soil consistency value, which consisted of the liquid limit (LL), plastic limit (PL), and plasticity index (PI), as well as the maximum soil stress (qu) obtained from the unconfined compressive strength test.

Other variables such as mixing method, test conditions, and sample preparation procedures are controlled so that the observed effects directly represent the effects of variations in lime content.

2.4 Testing Procedures

The research phase began with testing the physical properties of the original soil as a reference condition. Atterberg limit testing was conducted to determine the soil's LL, PL, and PI values before treatment.

Next, the soil is mixed with lime at predetermined concentrations. The mixing process is carried out manually until a homogeneous mixture is obtained. After mixing, Atterberg limit tests are performed on each lime concentration to evaluate changes in soil consistency.

Maximum stress testing was conducted using the unconfined compressive strength (UCS) method on stabilized soil samples. The UCS method was chosen because it represents the capacity of cohesive soil to withstand axial loads without lateral pressure, making it suitable for evaluating changes in soil strength due to lime stabilization under static conditions.

2.5 Data Analysis Methods

Data analysis was conducted in several stages. First, a comparative analysis was conducted to evaluate changes in LL, PL, PI, and qu values for each lime content variation. These change patterns were used to assess the effectiveness of lime stabilization on soil consistency and strength.

Second, a correlation analysis was conducted between the plasticity index (PI) and maximum stress (qu) to identify the quantitative relationship between changes in index properties and the mechanical response of the soil. The PI–qu relationship was analyzed using an empirical regression approach to obtain a model that represents the trend of the test data.

Third, the determination of the optimum lime content is carried out based on the combination of the most technically significant reduction in the plasticity index and increase in maximum stress, taking into account the efficiency of material use.

3. Results and Discussion

3.1 Characteristics of Native Soil

The results of the physical properties test shown in Table 2 indicate that the test soil has the typical characteristics of fine-grained soil with a dominant clay fraction and high plasticity. The grain specific gravity (Gs) value of 2.59 is within the general range of inorganic mineral soils and reflects the dominance of silicate minerals commonly found in silt-clay soils. The Gs value within this range indicates that the soil does not contain significant organic material and has relatively good mineral stability, although mineral stability is not always directly proportional to the mechanical performance of the soil in the field [2].

Table 2. Results of physical properties tests of native soil

Types of Testing	Testing Standards	Parameter	Results
Specific Gravity	SNI 1964:2018	Gs	2.59
Sieve Analysis	SNI 3423:2008	Gravel	0.00%
		Sand	31.60%
		Clay	68.40%
Atterberg Limit	SNI 1967:2008	LL	57.65%
	SNI 1966:2008	PL	34.52%

IP	23.13%

The results of the grain gradation analysis showed that the soil was composed of 68.40% clay fraction, 31.60% sand fraction, and contained no gravel. This composition indicates that more than 50% of the soil particles passed the No. 200 sieve, so the soil is categorized as fine-grained soil. The dominance of the clay fraction causes the specific surface area of the soil to increase, which has implications for high water adsorption capacity and increased cohesion between soil particles [4,17]. This condition is generally correlated with low permeability and large deformation potential when the soil is in a saturated condition.

The results of the Atterberg limit test showed a LL value of 57.65%, PL of 34.52%, and PI of 23.13%. LL values exceeding 50% indicate that the soil has high plasticity and shows significant sensitivity to changes in water content. Soils with high LL values generally experience a drastic decrease in strength when the water content approaches or exceeds the liquid limit, thus potentially causing stability problems in geotechnical construction [5].

A PI value of 23.13% indicates a moderate to high level of plasticity, reflecting considerable cohesion but accompanied by a significant tendency for plastic deformation. The relatively wide plasticity range reflects that the soil has a dominant plastic phase, making it prone to permanent deformation under loading. This phenomenon is in line with the findings of several recent studies stating that highly plastic soils tend to exhibit high compressibility and mechanical behavior that is strongly influenced by water content [17,20].

Based on the USCS System, soil is classified by considering the percentage of fine fraction and plasticity parameters. With a fine fraction exceeding 50% and an LL value above 50%, the soil is included in the fine-grained soil group with high plasticity. Analysis of the LL–PI point position on the Casagrande plasticity diagram shows that the PI value of the soil is below the A-line, which indicates that silty characteristics are more dominant than clay, as seen in Figure 1.

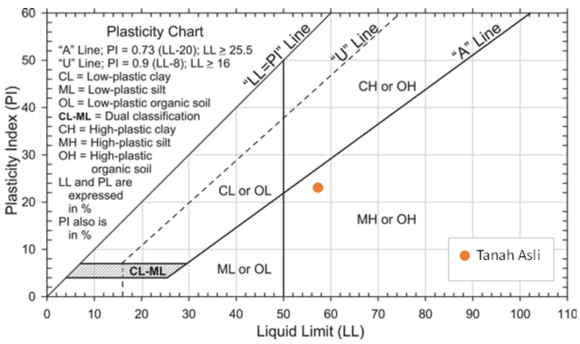

Figure 1. Casagrande Plasticity Diagram of Native Soil and USCS Classification

Thus, the test soil is classified as MH (inorganic silt with high plasticity). Although the clay fraction content is quite large quantitatively, the plasticity behavior of the soil is more like plastic silt than active clay. This indicates that the clay minerals contained tend to have low to moderate activity, so that the soil reactivity to water is not as high as active clay (CH) [20].

Soils classified as MH are generally characterized by high compressibility, low permeability, and relatively low bearing capacity, especially under saturated conditions. These characteristics make MH soils susceptible to consolidation settlement and differential settlement when subjected to structural loads. Several recent studies have shown that highly plastic silt soils often experience significant strength degradation due to wet-dry cycles and changes in stress conditions [17,19]. The sensitivity of the soil to changes in water content also makes MH soils less than ideal for direct use as subgrade without improvement treatment. Therefore, soil stabilization methods, such as the addition of lime or alternative binders, are needed to reduce plasticity and improve the soil microstructure. Recent studies have shown that chemical stabilization can significantly reduce LL and PI and increase the unconfined compressive strength and maximum stress of cohesive soils [2,4,18].

3.2 Changes in Soil Consistency Values due to the Addition of Lime

The results of index property tests indicate that the addition of lime significantly influences changes in soil consistency characteristics. The parameters analyzed include the liquid limit (LL), plastic limit (PL), and plasticity index (PI), each of which represents the soil's response to changes in water content, as shown in Figure 2-4.

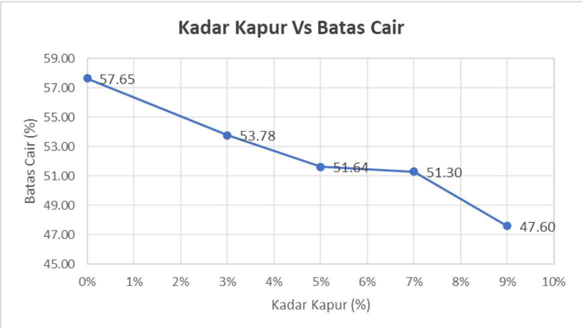

Figure 2. Graph of the Relationship between Lime Content and Liquid Limit

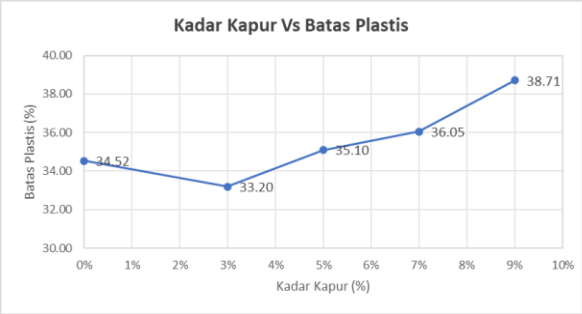

Figure 3. Graph of the Relationship between Lime Content and Plastic Limit

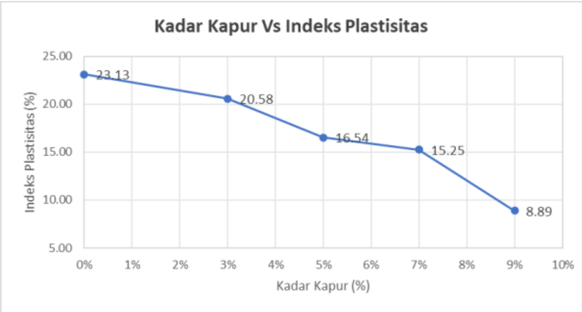

Figure 4. Graph of the Relationship between Lime Content and Plasticity Index

The liquid limit value decreased progressively with increasing lime content. Under untreated conditions (0%), the LL value was recorded at 57.65%, then decreased to 47.60% with the addition of 9% lime. This decrease indicates a reduced ability of the soil to retain water during the transition to the liquid phase. This phenomenon indicates that the soil structure becomes less sensitive to water after being stabilized with lime.

In contrast, the plastic limit showed an increasing trend from 34.52% in the original soil to 38.71% at 9% lime content. The increase in the PL value indicates that the soil requires a higher water content to enter a plastic state, reflecting increased stability of the soil structure against plastic deformation. The combination of a decrease in LL and an increase in PL causes the plastic range of the soil to narrow.

The plasticity index, the primary parameter of soil plasticity, showed a significant decrease, from 23.13% in the original soil to only 8.89% at 9% lime content. This more than 60% decrease in PI confirms that lime addition is effective in reducing the soil's plastic properties.

3.3 Mechanism of Changes in Soil Consistency Due to Lime

The process of exchanging Ca^{2+} cations with monovalent ions on the surface of clay particles reduces the thickness of the double diffusion layer and the electrostatic repulsion between particles, thus triggering flocculation–agglomeration and the formation of a coarser and more stable soil structure. These microstructural changes reduce the soil's specific surface area and water-binding capacity, which is reflected in a decrease in LL and PI values [2,18].

At higher lime content, particularly above 5%, pozzolanic reactions begin to take effect. Silica and alumina from clay minerals react with calcium hydroxide to form cementitious compounds such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). These reaction products act as binders between soil particles, reinforcing the structural changes created by initial flocculation.

3.4 Effect of Lime Addition on Maximum Soil Stress

The maximum stress (qu) value from the unconfined compression test showed a consistent increase with increasing lime content. In untreated soil, the qu value was 0.119 kg/cm², then increased gradually to 0.291 kg/cm² with 9% lime addition. This increase indicates that lime stabilization effectively increases the soil's capacity to withstand axial loads. This can be seen in Figure 5.

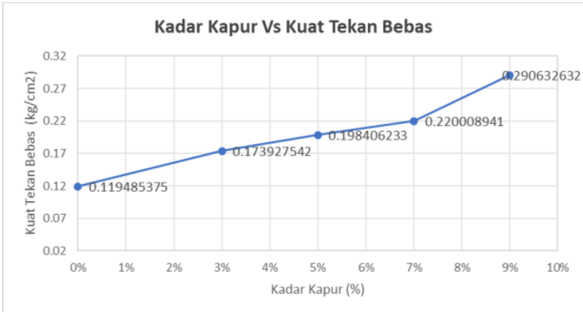

Figure 5. Graph of the Relationship between Lime Content and Unconfined Compressive Strength

A significant increase in maximum stress begins to appear at lime content of 5% to 7%, which indicates that in this range the soil improvement mechanism is not only dominated by modification of index properties, but also by the formation of more permanent cementation bonds as seen in Figure 6. Thus, the soil not only experiences improvements in plasticity properties, but also a transformation in mechanical behavior towards a stiffer and stronger material.

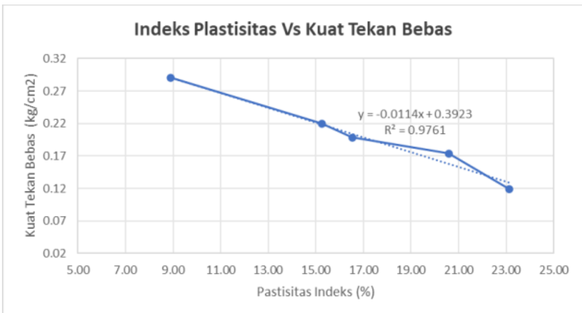

Figure 6. Graph of the Relationship between Plasticity Index and Unconfined Compressive Strength

Based on the test data, the relationship between the plasticity index (PI) and maximum stress (qu) can be approximated by the following negative linear equation:

$$q_u = 0{,}403 - 0{,}0123.PI \quad (2)$$

This equation shows that every 1% decrease in the plasticity index is followed by an increase in maximum stress of approximately 0.012 kg/cm². This correlation confirms the role of PI as a significant control parameter on the strength of lime-stabilized clay soils. The results of the regression analysis show that the linear relationship between PI–qu has a coefficient of determination (R^2) of 0.98, indicating a good level of model fit to the experimental data, so this model is suitable for empirical interpretation in similar soil conditions. The empirical relationship between PI–qu obtained in this study is specific to the type of silt–clay soil tested, variations in lime content, and the laboratory testing conditions used. Therefore, this model is not intended as a universal relationship, but rather as an initial approach to integrate soil consistency and strength parameters in the evaluation and initial planning stages of soil stabilization.

Although empirical and specific to the material being tested, this equation makes a significant contribution in bridging changes in index properties with the mechanical response of the soil. This approach has been relatively limited in previous research, and therefore could serve as a basis for developing more comprehensive predictive models in further studies.

3.5 Optimum Lime Content Analysis and Geotechnical Implications

Evaluation of the effectiveness of each lime content variation indicates that the 5–7% range is technically optimal. Within this range, the plasticity index decreases significantly, while the increase in maximum stress shows a stable and efficient trend. While adding up to 9% lime does produce the highest maximum strength, this increase has the potential for diminishing returns in terms of material efficiency and cost.

In the context of geotechnical planning, these results have important implications, particularly for subgrade and foundation soil improvement. Reducing plasticity reduces potential shrinkage and water sensitivity, while increasing maximum stress increases the soil's bearing capacity. Therefore, selecting the optimum lime content not only improves the soil's technical performance but also supports design efficiency and construction sustainability. Therefore, in geotechnical planning practice, these results demonstrate that the plasticity index can be used as a baseline parameter to estimate the strength increase of lime-stabilized soils. This approach allows for an initial evaluation of stabilization effectiveness without the need for further strength testing, thereby increasing time and cost efficiency during the subgrade improvement planning stage.

4. Conclusion

The addition of lime was proven to significantly reduce the plasticity of silt-clay soil as indicated by a decrease in the plasticity index from 23.13% to 8.89%, along with a decrease in the liquid limit and an increase in the plastic limit, which reflects the formation of a more stable and less water-sensitive soil structure. The improvement in consistency properties is directly proportional to the increase in the maximum soil stress, where the unconfined compressive strength value increased more than twofold from 0.119 kg/cm² to 0.291 kg/cm², indicating that the reduction in plasticity plays a direct role in increasing the soil's capacity to withstand axial loads. The quantitative relationship between the plasticity index and maximum stress (PI–qu) obtained in this study indicates that the plasticity index can be used as an initial empirical indicator to estimate the increase in strength of lime-stabilized silt-clay soil in the initial planning stage of soil improvement. However, the empirical relationship of PI–qu is still limited to the type of soil and the variation in lime content tested, so further research is needed to validate its application to different soil conditions and test methods.

Further research is recommended to examine the effect of curing time on the relationship between plasticity index and maximum stress to evaluate the development of lime pozzolanic reaction. Furthermore, the empirical PI–qu model needs to be validated on various types of fine-grained soils with different plasticity and mineralogical characteristics to determine its applicability. The development of nonlinear models or advanced statistical approaches is also recommended to improve the accuracy of PI–qu relationship predictions. In geotechnical design practice, the plasticity index can be used as an initial parameter for lime stabilization evaluation, but it still needs to be combined with advanced strength testing at the final design stage.

Reference List

[1] Qu, J., & Xiong, K. (2020). Influences of Curing Environment on Strength Performances of Shanghai Clayey Soil Reinforced with Palm Fiber. Advances in Civil Engineering, 2020, Article ID 9670806. https://doi.org/10.1155/2020/9670806

[2] Jalal, F., Mulk, S., Memon, S., Jamhiri, B., & Naseem, A. (2021). Strength, hydraulic, and microstructural characteristics of expansive soils incorporating marble dust and rice husk ash. Advances in Civil Engineering, 2021(1), Article 9918757. https://doi.org/10.1155/2021/9918757

[3] Zulnasari, A., Nugroho, SA, & Fatnanta, F. (2021). Changes in the Compressive Strength of Soft Clay Stabilized with Lime and Coal Combustion Waste. Civil Engineering Journal (JRS-UNAND), 17(1), 24–36. https://doi.org/10.25077/jrs.17.1.24-36.2021 .

[4] Lu, X., Luo, J., & Wan, M. (2021). Optimization of ionic soil stabilizer dilution and understanding the mechanism in red clay treatment. Advances in Civil Engineering, 2021(1), Article 5749863. https://doi.org/10.1155/2021/5749863

[5] Wassie, T. and Demir, G. (2024). Mechanical Strength and Microstructure of Soft Soil Stabilized with Cement, Lime, and

Metakaolin-Based Geopolymer Stabilizers. Advances in Civil Engineering, 2024(1). https://doi.org/10.1155/2024/6613742

[6] Biswas, N., Puppala, A., & Chakraborty, S. (2023). Experimental Studies and Sustainability Assessments of Quarry Dust for Chemical Treatment of Expansive Soils. Geotechnical Testing Journal, 47(1), 140-156. https://doi.org/10.1520/gtj20220243

[7] Vengala, J., Dharek, M., Kilabanur, P., Thejaswi, P., & Poudel, A. (2024). Effect of Sugarcane Bagasse Ash and Lime on Physico-Mechanical Properties of Clayey Soil. Advances in Civil Engineering, 2024(1). https://doi.org/10.1155/adce/3516016

[8] Onyelowe, K.C., et al. (2024). Estimating the strength of soil stabilized with cement and lime: dataset analysis and predictive modeling. Scientific Reports. https://doi.org/10.1038/s41598-024-66295-4

[9] Neguse, D., Assefa, E., & Assefa, S. M. (2023). Study on the performance of expansive subgrade soil stabilized with Enset ash. Advances in Civil Engineering, Volume 2023, Article ID 7851261. https://doi.org/10.1155/2023/7851261

[10] O'Kelly BC. (2024). Theory of liquid and plastic limits for fine soils, methods of determination and outlook. Geotechnical Research 11(1): 43–61, https://doi.org/10.1680/jgere.23.00038

[11] Zha, F., Liu, C., Kang, B., Xu, L., Yang, C., Chu, C., … & Liu, Z. (2021). Effect of Carbonation on the Leachability of Solidified/Stabilized Lead-Contaminated Expansive Soil. Advances in Civil Engineering, 2021(1). https://doi.org/10.1155/2021/8880818

[12] Bowles, J. E. (1979). Physical and geotechnical properties of soils. In Physical and geotechnical properties of soils

[13] Braja, M. Das. (1993). Soil Mechanics (Principles of Geotechnical Engineering). Jakarta: Erlangga.

[14] Tan, Y., Hu, Y., Chen, R., & Sun, W. (2020). Shrinkage Mechanism of Laterite Modified by Lime and Metakaolin. Advances in Civil Engineering, 2020(1). https://doi.org/10.1155/2020/6347597

[15] Ma, B., Cai, K., Zeng, X., Li, Z., Hu, Z., Chen, Q., … & Huang, X. (2021). Experimental Study on Physical-Mechanical Properties of Expansive Soil Improved by Multiple Admixtures. Advances in Civil Engineering, 2021(1). https://doi.org/10.1155/2021/5567753

[16] Cheng, X., Li, Q., Hai, R., Li, S., Hui, C., & Zhang, Z. (2023). Study on Mechanical Properties of Cement–Jute Fiber Modified Weak Expansive Soil. Advances in Civil Engineering, 2023, 1-13. https://doi.org/10.1155/2023/5955371

[17] Khan, K., Nasir, H., Alam, M., Khan, S., & Ahmad, I. (2020). Performance of Subgrade Soil Blended with Cement and Ethylene Vinyl Acetate. Advances in Civil Engineering, 2020(1). https://doi.org/10.1155/2020/9831615

[18] Wardani, M., Sari, P., & Refionasari, M. (2022). The Performance of $Ca(OH)_2$ to Reduce the Plasticity Index and Increase the Shear Strength Parameter for Expansive Soil. Journal of the Civil Engineering Forum, 237-244. https://doi.org/10.22146/jcef.3455

[19] Taylor, O., Hoyos, L., Likos, W., & McCartney, J. (2021). Editorial: Special issue on advances in laboratory experimentation for unsaturated soils. Geotechnical Testing Journal, 44(2), 235–236. https://doi.org/10.1520/GTJ20209998

[20] Gui, Y., Zhang, Q., Qin, X., & Wang, J. (2021). Influence of Organic Matter Content on Engineering Properties of Clays. Advances in Civil Engineering, Volume 2021, Article ID 6654121. https://doi.org/10.1155/2021/6654121