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Research Article

Chemical and Mechanical Soil Stabilization Techniques for Foundations

Estabilización de suelos para cimentaciones: métodos químicos y mecánicos

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Abstract:
Introduction: The geotechnical study is crucial for foundation design and herein the feasibility of stabilizing soil from Quillollaco Formation in Loja, Ecuador with quicklime. **Methodology:** Laboratory tests followed ASTM standards. Unaltered soil samples were extracted at depths ranging from 2,00 to 3.00 m and fed quicklime at varying percentages (13,00 to 21,00% and 3,00% for quicklime) during curing periods of 7 to 28 days. Before obtaining results, the soil was classified by primary classification. Laboratory tests included Atterberg limits, Standard Proctor, unconfined compressive strength and permeability. **Results:** Consequently, the results indicated that the soil is primarily clay with low plasticity. Although the addition of quicklime increases plasticity and compressive strength, the improvement is minimal and varies with dosage and cure time. Greater compaction and workability are observed with lower quicklime contents. Regarding permeability, moderate to high improvement is recorded with quicklime addition, suggesting enhanced drainage capacity. **Disscusion:** Stabilization of

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quicklime soil may improve some geomechanical properties, but its effectiveness and profitability could be limited, especially in clay soils of low plasticity. Emphasis is placed on the need to consider soil stabilization alternatives that are efficient and sustainable from economic and environmental points of view.

Keywords: geotechnical; quicklime; stabilization; compressive strength; permeability; clay; dosage; plasticity.

Resumen:
Introducción: El estudio geotécnico es esencial para el diseño de cimentaciones, evaluó la viabilidad de estabilizar el suelo con cal viva de muestras extraídas en la Formación Quillollaco, Loja, Ecuador. **Metodología**: Se realizaron ensayos de laboratorio según las normativas ASTM para dosificar la cal viva y evaluar su resistencia a la compresión y permeabilidad. Las muestras inalteradas se extrajeron a una profundidad de 2,00 a 3,00 m y se dosificaron con cal viva en porcentajes del 13,00% al 21,00% y 3,00% de Cal durante períodos de curado de 7 a 28 días. **Resultados:** Previamente a la obtención de resultados, se evaluó el suelo mediante clasificación primaria, lo ensayos de laboratorio fueron: Límites de Atterberg, Proctor Estándar, Compresión simple y Permeabilidad. **Discusión:** Por consiguiente, los resultados indicaron que el suelo de la zona es principalmente arcilla de baja plasticidad. Aunque la adición de cal viva aumenta la plasticidad y la resistencia a la compresión, esta mejora es mínima y varía según la dosificación y el tiempo de curado. Se observa una mayor compactación y trabajabilidad con menores contenidos de cal viva. Respecto a la permeabilidad, se registra una mejora moderada-alta con la adición de cal viva, lo que sugiere una mejor capacidad de drenaje.

Palabras clave: geotecnia; cal viva; estabilización; resistencia; permeabilidad; arcilla; dosificación; plasticidad.

1. Introduction

In recent years, the significance of slope instability and its multifaceted causes have attracted increasing attention, emphasizing the pressing need to find an effective solution. The design of the foundations is based on the characteristics of the subsoil to understand its behavior and make fundamental design and construction decisions (Makusa, 2013). This involves the transportation of material for improvement from quarries or other sites to increase soil strength and optimize its mechanical properties (Jiang et al., 2022). Therefore, it is pertinent to explore alternative perspectives for soil stabilization based on chemical and mechanical properties (Enrique, & Montes, 2020). Many instability problems in expansive soils affect structures due to mechanical and hydraulic stresses. These distortions can be caused by natural or human activities (Romero-Ruiz et al., 2018). In this way, it is convenient to provide other alternatives to soil stabilization based on the modification of chemical and mechanical properties through stabilizing agents (Moale, & Rivera, 2019). Stabilizing materials have been classified into five groups, including nanomaterials, fibers, polymers, biological materials for soil improvement, and industrial waste materials (Khodabandeh et al., 2023). Each material must provide improvement, so the question arises as follows. How can their influence and effectiveness be verified? Based on the results of laboratory tests, the behavior of the soil and the improvement material must demonstrate and ensure a performance that confirms that the soil has experienced improvements in its geomechanical properties related to load-bearing capacity and resistance (Espinosa et al., 2023).

The study area where the samples were collected is Loja, Ecuador, which belongs to the Quillollaco Formation. The material present is known to be conglomerates containing layers of claystone. Loja City contains a high clay content in several sectors. Lime, when used, improves soil behavior mechanically and chemically, increasing strength and durability. Clay behavior depends on moisture content, plasticity, volumetric instability, permeability, and load bearing capacity for housing design (Hamid, & Alnuaim, 2023). It can cause erosion and degradation, visible as cracks, affecting strength and durability, and affecting the workability of the construction process's workability (Bauzá, 2015). The use of quicklime in small doses is one of the techniques considered to evaluate soil resistance in the area. Its structure derives from a calcination process in which, upon release of carbon dioxide, it transforms into calcium oxide (CaO) and then, upon contact with water, it allows the production of lime mortars used to carry out stabilization tasks (Parra, 2018). It is considered efficient, depending on the behavior of the elastoplastic soil, to improve compressive strength without altering adhesion. This research addresses the critical need for effective soil stabilization methods, particularly in regions such as Loja, with limited information on lime stabilization. The study aims to provide an economical and efficient alternative to stabilize soils for conventional foundation designs. Unlike similar literature, this paper proposes lime stabilization because quicklime in clays exhibits a behavior such that it increases bearing capacity, enhances cohesion, durability, reduces compressibility, and all of this occurs due to the effective chemical reaction between clays and quicklime (Jara, 2014). Focusing on the formation of Quillollaco, it explores the potential of lime as a stabilizing agent, offering insights into its effectiveness in improving soil properties and addressing construction challenges.

2. Methodology

2.1. Materials

The study area from which the sample was extracted is located within the urban area south of Loja, Ecuador, in the Punzara sector, near the tourist spot known as Punzara Lake. Within the geomorphology of the study area, distinct characteristics have been identified. The geological formation present is Quillollaco, which is characterized by various materials such as conglomerates with thick layers of clayey siltstones. In other words, the formation originated during the late Miocene and is composed of metamorphic rocks such as conglomerates and sandstones. Its components provide soils with high compression resistance and low permeability. Furthermore, the thickness of the conglomerate layers is approximately up to 4 meters, consisting of phyllites, schists, quartzites, quartz veins, and rounded clasts about 30 cm in diameter (Bustamante, & Cabrera, 2010). Specifically, the area is close to a geological fault and an erosion scarp. Similarly, it is important to recognize nearby flood-prone areas and the magnitude or occurrence of flood events. It has been observed that the area is prone to flooding, forming bodies of water. However, there are no records of flooding events due to heavy rainfall.

The research was evaluated through tests applying ASTM standards for the dosage of the stabilizing material and its respective behavior under compression resistance tests, defining different dosages for each sample and test. Therefore, soil samples were extracted through a 50,00 x 50,00 x 50,00 cm trench at depths ranging from 2,00 m to 3,00 m. Water at 19,00°C-20,00°C was also used.

2.2. Quicklime

A study on key parameters regarding the addition of lime in stabilized soils demonstrated that the compressive strength increases with respect to soil compaction with increased lime dosage and longer curing periods (Consoli et al., 2009). What actually happens when lime is added is that flocculation occurs in the particles, promoting cation exchange by enhancing the bonding between the particles, acting as a coagulant, and transforming the soil into coarser and less plastic material (Thyagaraj, & Zodinsanga, 2015). The improvement material for chemical stabilization was approximately 25,00 kg of Quicklime/$CaCO_3$, characterized by the following:

- Grain size: fine (mesh #200)
- Calcination process: between 900,00 and 1.200,00 ° C.
- Appearance: Off-White Powder
- Molecular weight: 74,10 g/mol
- Calcium oxide content: Minimum 45,00%
- Heavy metals: Not detectable
- Moisture: maximum 7,00%
- pH (Hydrogen Potential): 12,50

2.3. Laboratory test

Essentially, all tests are based primarily on the analysis of the geomechanical characteristics of the soil to examine the potential causes or factors that govern the behavior of unstable or stable soil. Together with laboratory results, the objective is to find a mitigation measure. Therefore, ***Table 1.*** represents a synthesis of all laboratory tests conducted.

Table 1.

Laboratory tests conducted for soil

Laboratory tests	
Atterberg Limits	ASTM D4318
Standard Test Method for Unconfined Compressive Strength of Cohesive Soil	ASTM D2166-16
Standard Test Methods for Laboratory Composition Characteristics of Soil Using Standard Effort	ASTM D698-12
Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter	ASTM D5084-90

Source: Original analysis and formulation by the authors.

2.4. Primary classification

According to the characteristics of the project and the need to determine soil stability parameters, sampling points and open-air excavations of 2,00 to 3,00 m depth must be established. The primary classification of the stratum obtained at the excavation depth for the test pit was carried out, following standards such as ASTM D2488(ASTM D 2488, 2018) and Instituto Nacional de Vías (INVIAS, 2012), establishing three parameters: dry strength, toughness, and dilatancy.

When collecting undisturbed samples to carry out tests that allow classification according to their physical characteristics, it is necessary to obtain a sample that, in this case, must be undisturbed because its physical characteristics do not change. However, it is essential to preserve its moisture. Therefore, it is advisable to use airtight bags to contain moisture.

2.5. Atterberg limits

According to ASTM D438 Standard (ASTM D438, 2017), the fine material that passes through sieve No. 40 was utilized in the test. The objective of the test is to determine the type of soil and its plasticity conditions as indicated by the Unified Soil Classification System (USCS) for foundation design. Additionally, limit tests were conducted with dosages of 3,00% and 19,00% of QL due to the criterion of achieving the best results in terms of strength obtained, and without this content, aiming to observe the variation of IP and LL of the samples. The Plasticity Index (PI) is determined by the difference between the Liquid Limit (LL) and Plastic Limit (PL). This represents the variation in surface flexibility (Enrique, & Montes, 2020). The plasticity index is determined by the difference between the liquid limit and the plastic limit.

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

2.6. Compaction Characteristics of soil using standard effort dosages

Using ASTM D698 (ASTM D698, 2014), the Standard Proctor test using Method A was conducted to determine the optimal moisture content and density, as well as the appropriate dosage of QL. Subsequently, samples with 8,00%, 10,00%, 12,00%, and 14,00% water content were prepared to generate the compaction curve. As a secondary test to determine the ideal moisture content, tests between 8,00% and 10,00% were conducted to ascertain the curve's trend, that is, whether the optimum point lies at percentages lower than or higher than 8,00% and 10%.

The dose typically varies between 2,00% and 10,00%. One of the methods used is known as the initial lime consumption method, which involves measuring the pH between lime and water and the soil. Lime is added following a certain pattern, such as every 1,00%, 2,00%, 3,00%, or according to the research conditions. The goal is to mix lime with potable water and soil samples, measure the pH at each dose, and plot the pH vs. lime content curve. The result will be a function whose curve reaches a constant value; at that point on the graph, the recommended dosage is determined (Baldovino et al., 2018). The other method is the use of the Proctor Compaction Test, which operates similarly to how the optimal soil moisture content is calculated. Depending on the percentage of moisture content considered by the author, it will be evaluated in the Proctor test to determine the appropriate dosage (Altamirano, & Díaz, 2015). In this case, the investigation included two scenarios, high and low dosages. In the first scenario, QL was dosed at 3,00% (mold: diameter equal to 50,00 mm and height 100,00 mm), while the second scenario was dosed at 13,00%, 16,00%, 19,00% and 21,00% relative to the weight of the soil. Two samples were prepared for each percentage for 7 to 28 days of curing periods. The same procedure was followed for QL dosing: the optimal water content and the lime percentage for each specimen were mixed with the soil sample. Samples were cured with a refrigerator while maintaining moisture and QL content. (See Figure 1.)

Figure 1.

Sample preparation with QL dosages

Source: Original analysis and formulation by the authors.

2.7. Unconfined Compressive strength

In Unconfined Compression ASTM D-2166 (ASTM D2166, 2016), a compressive strength value was obtained for cohesive soils under unconfined conditions using untreated and treated lime in dosages of 3,00%, 13,00%, 16,00%, 19,00% and 21,00%. For specimen preparation, the sample is reconstituted; once crushed, it is molded along with 10,00% moisture calculated from the Proctor test. Two specimens were prepared for each lime dosage, which was cured for 7 to 28 days. The load was applied to induce axial deformation at 0,25 $N/mm^2/s$. Finally, the load, deformation, and time values were recorded. Eventually, the sample is positioned on the compression apparatus so that it is centered on the lower platen. Subsequently, the loaded instrument is carefully adjusted so that the upper platen barely contacts the specimen. (see Figure 2.)

Figure 2.

Application of Compressive Strength Resistance

Source: Original analysis and formulation by the authors.

2.8. *Permeability*

Based on ASTM D5084-90 (ASTM D5084, 2016) Standard, the Permeability test follows the following requirements: Cylindrical samples with a minimum sample size in height and length of 25,00 mm, specimens are prepared with a diameter of 50,00 cm and a height of 10,00 cm. The same compaction procedure is followed, using two specimens: the first is under normal conditions and the next is prepared according to the optimum percentage of lime for the best curing.

Additionally, the coefficient of conductivity is expressed in terms of the volume of water (Q) collected over a period (t), represented by the formula on the right-hand side of the page. They should be referred to as Equation 1, etc., in the main text.

$$k = \frac{QL}{\mathrm{Aht}} \qquad (2)$$

Where:
Q = Total collected volume (m^3)
L = length of the sample (m)
A = area of the sample (m2)
h = variation in height between initial and final (m)
t = variation in time taken to collect the volume of water (s)

This parameter is important to consider in both granular and cohesive soils because the soil not only has to withstand the loads exerted by the weight of a structure, but it is also considered for the design of sanitary systems, surface drainage, and subsurface drainage (Alfaro, & Mora, 2014). (see Figure 3.)

Figure 3.

Permeability test

Source: Original analysis and formulation by the authors.
Note: Connection of the permeability cell to the specimen where the volume of filtered water was measured

Similarly, in order to compare values or numerical results and characterize a possible soil classification and its corresponding level of permeability, it is necessary to determine the hydraulic capacity. The mentioned parameter plays an important role in clays, as the result of this test can be affected by ionic concentration and the thickness of the water layers around the particles. Braja Das mentions in his book the general values of hydraulic conductivity in saturated soils (Das, 2015). (see Table 2.)

Table 2.

Typical values of hydraulic conductivity for saturated soils

Soil	K (cm/s)
Clean gravel	100 - 1
Coarse sand	1,0 - 0,01
Fine sand	0,01 - 0,001
Silty clay	0,001 -0,00001
Clay	<0,000001

Source: Adapted from Fundamentals of Geotechnical Engineering [Figure], by Das (2015, p. 122).

3. Resultados

3.1. Primary classification and Atterberg limits

Table 3 shows the behavior observed with quicklime (QL) at dosages of 3% and 19%, as well as without its addition. Overall, the primary classification in all three tests was characterized as low plasticity clay (CL). Upon laboratory testing, the results of Liquid Limit (LL) (17%) and Plastic Limit (PL) (11%), along with Plasticity Index (PI) (6%), classified the soil as low plasticity clay. However, with the addition of 19% QL, the results were modified notably, particularly LL (32%) and PI (18%), whereas PL (14%) remained relatively unchanged. Consequently, the Soil Unified Classification System (USCS) classification remained as CL. Finally, with the addition of 3% QL, the LL values were equal to 32, PL was 29, and PI resulted in 3.

Table 3.

Soil physical properties results

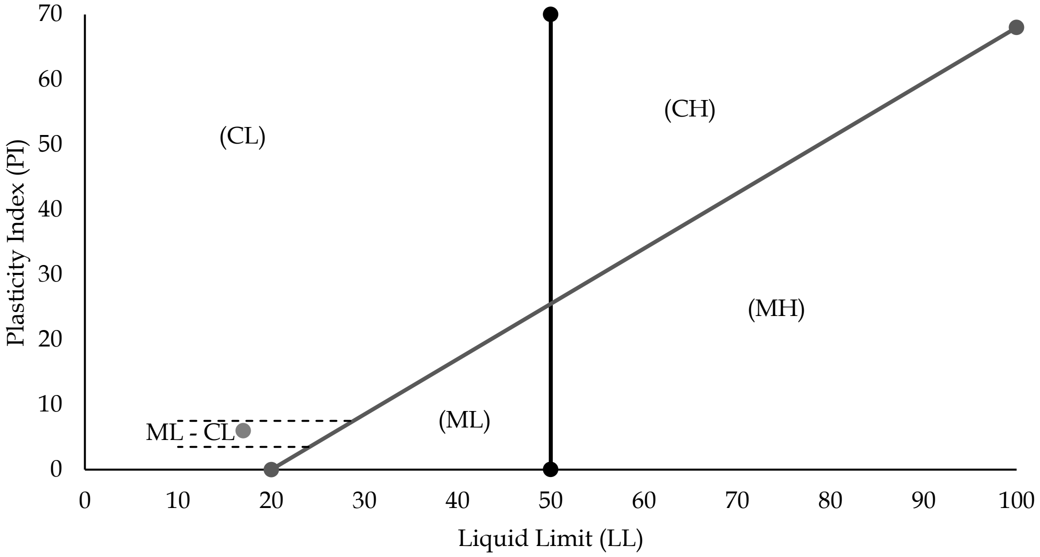
Results	With QL (3,00%)	With QL (19,00%)	Without QL
	Result 1	Result 2	Result 3
Liquid Limit (LL)	32,00 %	32,00%	17,00 %
Plastic Limit (PL)	29,00 %	14,00%	11,00 %
Plasticity Index (PI)	3,00 %	18,00%	6,00 %
Primary Classification			CL
USCS Classification	ML	CL	CL

Source: Original analysis and formulation by the authors.

In Figure 4. and
Figure 5., the graphical representation of the afore mentioned paragraph is depicted, considering that the graphs illustrate the soil behavior trend when adding quicklime (QL). As observed in the graphs, the results of LL and PI are close to values typical for low plasticity silts.

Figure 4.

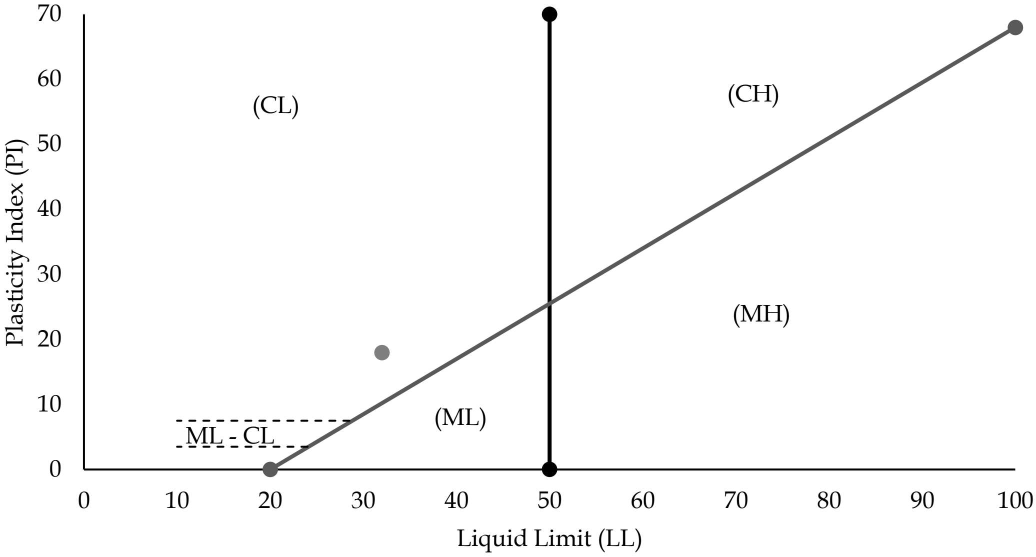
Soil classification without QL (USCS)



Source: Original analysis and formulation by the authors.
Note: The black dot indicates the soil classification (CL)

Figure 5.

Soil classification with 19,00% QL

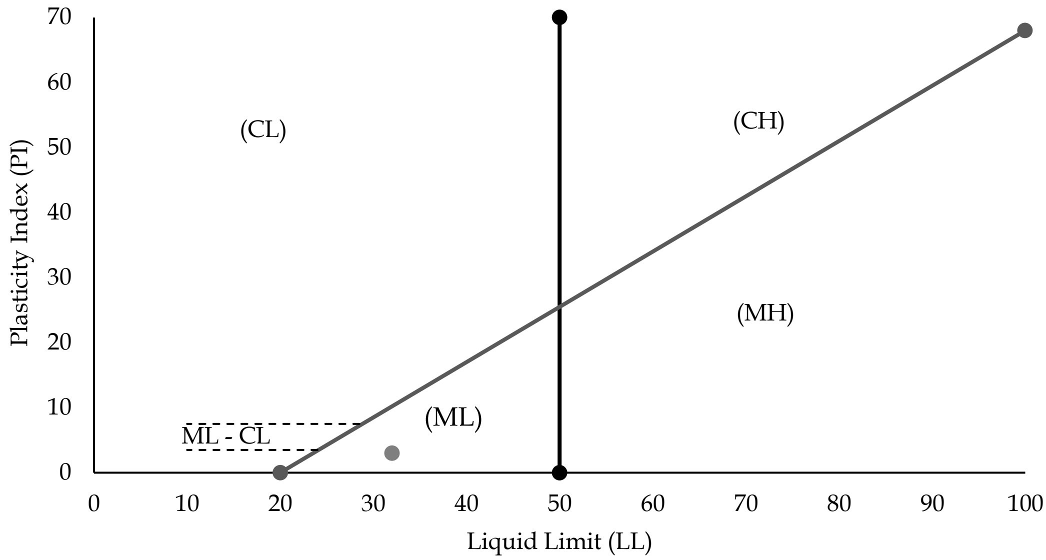


Source: Original analysis and formulation by the authors.
Note: The orange dot indicates the soil classification (CL)

In Figure 6., the soil classification with 3,00% quicklime (QL) content is depicted, reflecting the result presented in Table 14 as Low Plasticity Silt (ML).

Figure 6.

Soil classification with 3,00% QL



Source: Self-made.
Note: The orange dot indicates the soil classification (ML)

3.2. Compaction of Soil Using Standard Effort and Unconfined Compressive Strength

Before testing each specimen for unconfined compressive strength, the optimum moisture content for the tested soil type was determined. Considering a range of probable moisture percentages from 8,00% to 14,00%, following a pattern of every 2,00%, as shown in Table 4. Consequently, upon conducting the Proctor Compaction test, the optimum moisture content was found to be 10,16%, with a corresponding density of 1.887,00 kg/m^3.

Table 4.

Compaction curve without QL

Results without QL				
No.	**1**	**2**	**3**	**4**
Mold weight + sample [kg]	3.923,00	3.969,00	3.995,00	4.001,00
Mold weight [kg]	1.867,00	1.912,00	1.939,00	1.944,00
Wet density [Kg/m^3]	2.026,00	2.075,00	2.104,00	2.110,00
Moisture without QL				
Moisture Content [%]	8,00	10,00	12,00	14,00
Dry density [Kg/m^3]	1.876,00	1.887,00	1.879,00	1.851,00

Source: Self Self-made.

Similarly, in a second trial for moisture content determination, percentages of 8,00% and 10,00% were utilized. Consequently, the compaction curve trend indicated a need to increase the soil moisture content. To achieve this, percentages of 12,00% and 14,00% were employed. The resulting moisture content was determined to be 12,11%, with a maximum density of 1.629,45 kg/m^3. (see Table 5.)

Table 5.

Compaction curve without QL (second test)

Results without QL (Second test)				
No.	**1**	**2**	**3**	**4**
Mold weight + sample [kg]	4.621,00	4.413,00	4.416,00	4.422,00
Mold weight [kg]	408,00	344,00	347,00	353,00
Wet density [Kg/m³]	1.375,00	1.751,00	1.766,00	1.797,00
Moisture without QL				
Moisture Content [%]	8,00	10,00	12,00	14,00
Dry density [Kg/m³]	1.273,00	1.592,00	1.577,00	1.576,00

Source: Self-made.

Following the same procedure used in Proctor to find the optimum moisture content, an attempt was made to determine the quicklime (QL) dosage (see Table 6.). Percentages ranging from 13,00% to 21,00% were tested, following a pattern of every 3,00%, and two specimens were tested for each quicklime dosage. It was found that the compaction curve resulted in an optimum dosage of 13,00% QL, with a density of 1.755,00 kg/m³.

Table 6.

Compaction curve with different doses of QL

Results with QL				
No.	1	2	3	4
Mold weight + sample [kg]	3.884,00	3.808,00	3.811,00	3.818,00
Mold weight [kg]	1.828,00	1.752,00	1.755,00	1.762,00
Wet density [Kg/m³]	1.984,00	1.901,00	1.905,00	1.912,00
Moisture with QL				
Moisture Content [%]	13,00	16,00	19,00	21,00
Dry density [Kg/m³]	1.755,00	1.639,00	1.601,00	1.580,00

Source: Original analysis and formulation by the authors.

Finally, in Table 7., the same test was conducted with the focus on understanding the moisture behavior concerning the addition of 3,00% quicklime (QL). For this purpose, based on the obtained optimum moisture content, values between 11,00% and 13,00% moisture were applied. Subsequently, the trend of the initial results indicated a need to increase the moisture to 15,00% and 17,00%. Therefore, the optimum moisture content with 3,00% QL was found to be 11,69%, while the density was 1.561,58 kg/m³.

Table 7.

Compaction curve with 3.00% QL

Results with 3.00% QL				
No.	1	2	3	4

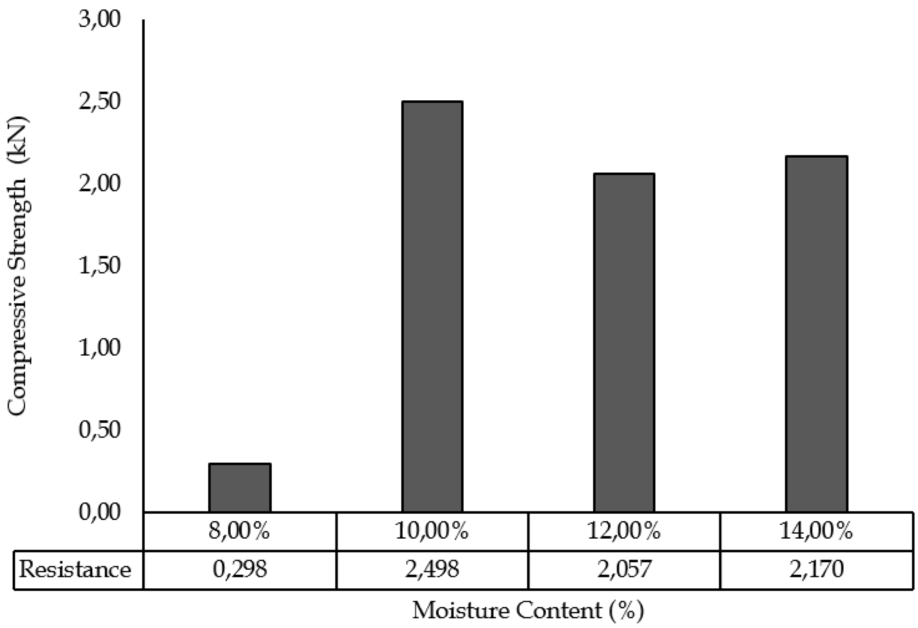
Mold weight + sample [kg]	4.410,00	4.416,00	4.422,00	4.426,00
Mold weight [kg]	340,00	346,00	352,00	356,00
Wet density [Kg/m³]	1.734,00	1.762,00	1.793,00	1.815,00
Moisture with 3.00% QL				
Moisture Content [%]	11,00	13,00	15,00	17,00
Dry density [Kg/m³]	1.562,00	1.559,00	1.560,00	1.551,00

Source: Original analysis and formulation by the authors.

Figure 7. highlights the results obtained from the unconfined compressive strength test with specimens without the addition of quicklime (QL). It is recognized that the optimum soil moisture content, equal to 10,16%, provided the highest capacity for unconfined compressive strength with a value of 2.498,00 kN. The remaining specimens exhibit similar strength trends, except for the specimen with a moisture content of 8,00%.

Figure 7.

Compressive Strength Results without QL



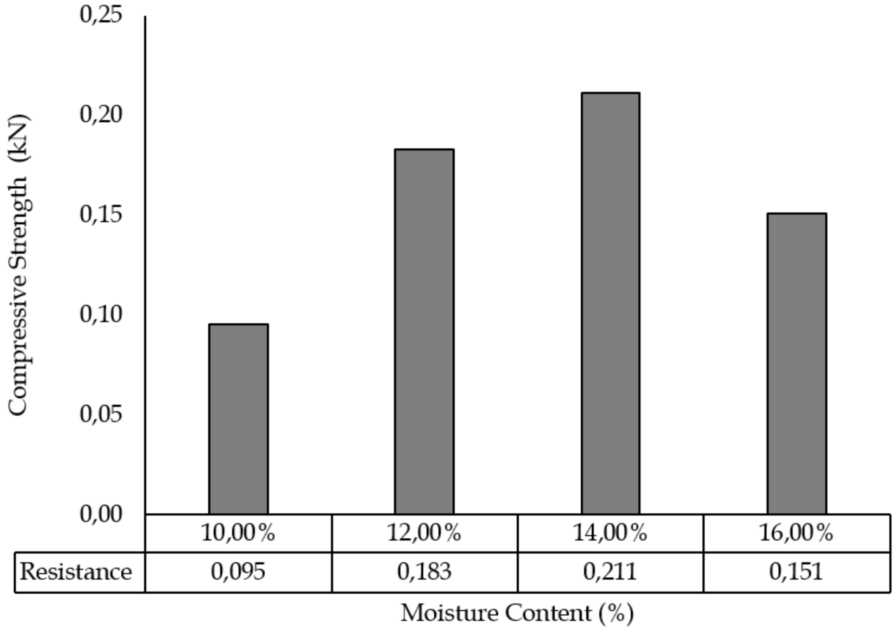
Source: Original analysis and formulation by the authors.
Note: First Compaction Curve Test Between 8,00% and 14,00% of Moisture Content

The specimens were assessed according to the unconfined compressive strength criteria, both with and without lime dosing, to validate the accuracy of the Proctor test dosage. The data is depicted in

Figure *8.*, which showcases the optimal moisture content determined through the second moisture content test.

Figure 8.

Compressive Strength Results Without QL (Second Test)

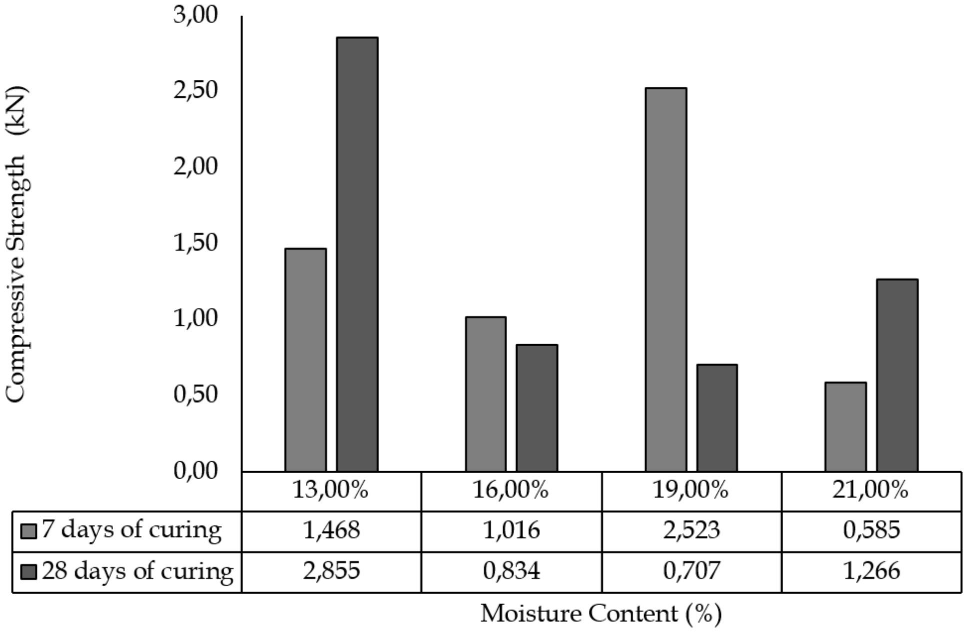


Source: Original analysis and formulation by the authors.

The specimens were cured for 7 and 28 days to compare the strength when adding quicklime (QL). Figure 9. illustrates the results depending on the curing days. For the initial 7 days, the maximum strength was achieved at 19,00% QL, equal to 2,523,00 kN, whereas after 28 days of curing, the strength reached 2,855 kN for 13,00% QL.

Figure 9.

Compressive strength resistance, different cured period time

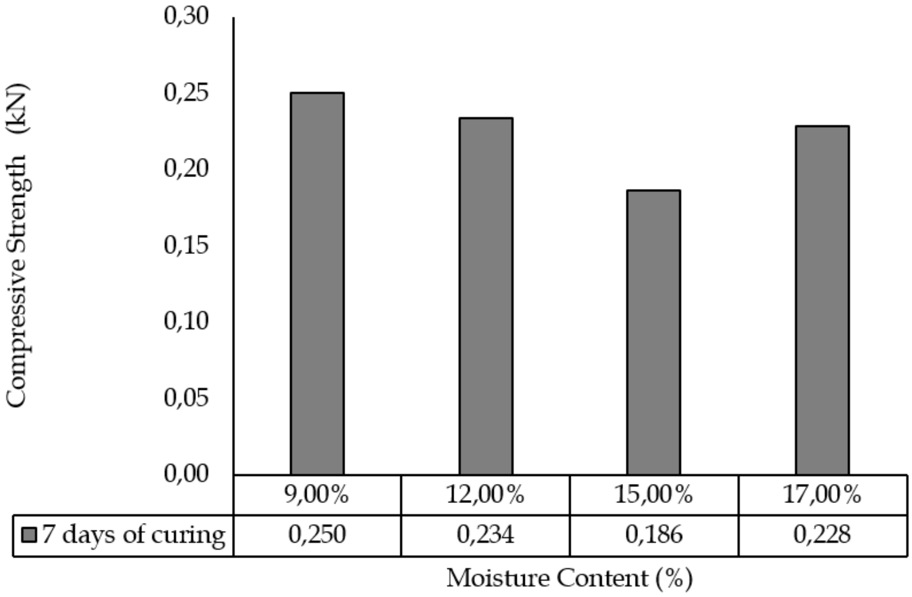


Source: Original analysis and formulation by the authors.
Note: Samples were cured for seven days (blue) and 28 days (orange). In this scenario, the optimum moisture content remains at 10,16%, while the lime dosages vary.

The specimens tested for 3,00% quicklime (QL) was subjected to this test, with dimensions of 50 mm in diameter and 100 mm in height. It is important to note that the QL content remained constant; it was the moisture content that varied, and the strength was evaluated accordingly. These results can be observed in Figure 10.

Figure 10.

Simple Strength Resistance added 3,00% of QL.



Source: Original analysis and formulation by the authors.
Note: The samples are cured for seven days (blue) and 28 days (red). In this second scenario, the optimal QL content remains at 3,00%, while the moisture content varies.

3.3. Permeability

During the permeability test, a curing period of 7 days was considered for each sample. Additionally, the lime (CaO) addition was set at 19,00%, considering the strength obtained in the Unconfined Compressive Strength test. Therefore, the following data is detailed for specimens without lime addition: specimens of 5,00 cm in diameter and 10,00 cm in height, moisture content of 10,16%, the water supply tank for the sample was 152,00 cm, while at the end of the test, the final height was 149,00 cm. Thus, in 16 hours and 35 minutes (62460 s), 145,00 ml of water drained, classifying this sample as moderately slow permeable clay with a hydraulic conductivity of 3,94E-06 m/s.

On the other hand, the sample with lime improvement at 19,00% had the same dimensions as the previous one. The initial height of the tank was 147,00 cm, and the final height was 145,00 cm. When tested, the sample drained 420,00 ml of water over a period of 22 hours and 8 minutes or 79.200 s. This resulted in moderately rapid permeable sandy clay with a hydraulic conductivity of 1.35E-05 m/s.

4. Discussion

4.1. Primary classification and Atterberg limits

According to the three parameters evaluated in the clay of the study area, it was found that the dry strength was medium to high, the dilatancy was found to be nil to slow, while the toughness was slow. Therefore, it can be observed that the soil contains low plasticity clays, indicating that the study area is characterized by a low capacity to retain water, likely leading to greater stability.

In contrast, during the laboratory Atterberg Limits test, 200,00 g of soil were sampled, and water was gradually added until the minimum number of blows required to conduct the test without lime addition could be achieved. When conducting the tests with different water contents and blows, it was considered to take the sample in the second range of blows due to the fragile manipulation required to form 3,00 mm cylinders. The results are shown in Table 3.

In Figure 8, the results are presented based on the Soil Unified Classification System (USCS). The soil is classified as low plasticity clay (CL) with a tendency towards low plasticity silts (ML) without lime addition. However, upon adding lime at 19,00 % in the mix, the results double in each property. Consequently, the clay increases in plasticity as well as the Plasticity Index (PI), exceeding 15,00. However, when conducting the test at 3,00% QL, it is observed that the PI (3,00) is even lower than the result without QL addition, thereby reducing the plasticity and classifying the soil as ML. It is likely that the soil may tend to be considered non-plastic (NP) both with the addition of QL and under natural conditions. The result cannot be fully verified as expansive clays without additional geophysical studies. Therefore, the improvement technique used would be more efficient in expansive clays because the plasticity exceeds 6,00% and would not alter the particle adhesion as it does in clays and silts with a plasticity less than 6,00%. The results represent the chemical variation among particles favoring flocculation, transforming the material size, and its plasticity.

4.2. Compaction of Soil Using Standard Effort and Unconfined Compressive Strength

This test was the result of sample preparation using the Proctor Compaction test. In the Proctor test, the moisture content was established from 8,00% to 14,00%, with a difference of 2,00% in moisture content for each specimen. The specimens, with a height of 11,50 cm and a diameter of 10,10 cm, were compacted in 3 layers with 25 blows each. The compaction curve suggests that the optimum moisture content is 10,16%, with a maximum density of 1.887,00 kg/m^3 (see Table 4.)

In contrast, using 10,16% moisture content, lime dosages ranging from 13,00% to 21,00% were added for each additional 3,00% quicklime (QL) specimen, resulting in an optimal QL dosage of 13,00% and a maximum density of 1.755,00 kg/m^3 (see Table 6.)

To confirm the reliability of the Proctor test dosage, the specimens were evaluated based on criteria for Unconfined Compressive Strength for both specimens with and without dosages. It is worth noting that curing periods of 7 and 28 days were also considered when adding QL. The data is presented in

Figure *8.*

Thus, during the test for optimum moisture content determination, it was found that the highest resistance was for the 14,00% moisture specimen with values of 0,211 kN. Furthermore, when comparing with the addition of 3,00% QL, it was found that the highest resistance was for the 9,00% moisture specimen with values of 0,25 kN for 7 days of curing. The results indicate that the improvement in resistance remains minimal, approximately a 0,039 kN difference. Additionally, despite the 9,00% moisture specimen achieving better resistance, the workability is not optimal as it requires higher moisture due to the properties of QL. Therefore, the second-best resistance when adding the improvement material and with optimal workability is at 15,00% moisture content. The results derived from the addition of QL resulted in greater compaction and workability at lower QL content, which can be visualized in Figure 9. and Figure 10.

Thus, the soil's capacity achieved without stabilizing material belongs to the selected optimum moisture content determined by the compaction curve, equal to 10,16%. Consequently, the maximum resistance achieved is 2,50 kN. Now, if QL is added to all 4 specimens for each dosage, and the results are compared for 7 and 28 days of curing, in Figure 10., the result varies according to the dosage and curing days. The highest resistance (2,86 kN) is obtained at 28 days of curing with 13,00% QL, however, at 7 days, it is not the best (1,47 kN). In contrast, at 7 days, the best option is for 19,00% QL, equal to 2,52 kN, while at 28 days, it has poor resistance (0,71 kN). In all specimens with QL, the soil's behavior resembled that of sandy soil. Additionally, the increase in resistance is due to the pozzolanic reaction, leading to the formation of hydrated calcium aluminates and silicates. Therefore, the hypothesis proposed is confirmed since the soil's capacity does result in improvements in resistance, but not significantly as expected. Hence, the use of QL in CL clays does not appear to be optimal for use in construction or investment.

4.3. Permeability

Similarly, the specimens tested were for a 19,00% QL dosage and without QL. This dosage was selected based on the number of curing days during which the lime acted for foundation design. Therefore, CL clays are characterized by their lower water retention capacity. In this test, hydraulic conductivity, soil type, and the material's permeability will be determined. Consequently, the specimen was compacted with 3 layers of 25 blows each, with a diameter of 5,00 cm and a height of 10 cm. The first test without QL dosage lasted 16 hours and 35 minutes (6.2460 s) to reach a volume of 145,00 cm^3 of filtered water. The height difference in the tank was 3,00 cm, resulting in a hydraulic conductivity value of 3,94108 x 10-6 m/s. The soil type belongs to clay. Furthermore, the permeability is moderate to low. On the other hand, when adding QL, the sample took 22 hours and 8 minutes to filter 420,00 cm^3 of water, with a 2,00 cm difference in water height in the tank. Therefore, the hydraulic conductivity increased to 1,35041 x 10-5 m/s, interpreted as moderate to high permeability and the soil type as fine clay, silty, a mixture of sand, and silt.

5. Conclusion

This study analyzed the effectiveness of using Quicklime (QL) as a stabilizing material for soils classified as low-plasticity clays (CL) according to the USCS classification. Based on tests of simple compression strength, limits, and permeability in samples compacted and dosed with Quicklime according to the Proctor test, its application was determined for stabilizing foundations for housing. The following conclusions are:

- The variables of strength and cure time depend on the dose of Quicklime. There is an inversely proportional relationship between strength and quicklime content, higher content leads to lower strength.
- One reason is that lime as a stabilizing material is used in dosages ranging from 2,00% to 10,00% depending on how expansive the clay can be. Therefore, a test was conducted at 3,00% quicklime to assess strength, resulting in slight variation and inefficiency. The cohesion between particles decreased in the soil due to using Quicklime, altering its strength.
- The Atterberg limits for soil classification established a relationship in which, with a higher lime dosage, clay (CL) is prone to increase plasticity and become expansive clay due to activation caused by chemical reactions between calcium oxide (Quicklime) and montmorillonite, forming new minerals such as illite and kaolinite. It should be noted that adding 3,00% quicklime decreased the plasticity index, and the soil was considered ML. However, when observing the results of the liquid limit, the soil likely tends to be an NP.
- Regarding soil permeability, it increases with lime dosage. On the contrary, having soils with low permeability would prevent groundwater filtration, thereby preventing permanent damage to the foundation.
- The difference in moisture when adding Quicklime is related to its content; The added percentage of lime will approximate the increase in soil moisture.
- An excess of stone can trigger an exothermic reaction, potentially causing a temperature increase and changes in the soil's mineral composition. This could lead to a loss of cohesion and strength and increased soil hardness.

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