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STUDY OF THE MECHANICAL STRENGTH OF SILTY SOIL TREATED WITH LIME

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ABSTRACT

The Guabirotuba formation is located in the sedimentary basin of Curitiba, Brazil. Most of the formation's soils are fine-grained, and cannot be used to construct layers for pavements and slope protection or to support shallow foundations. The objective of the present research is to study the strength of a Guabirotuba formation soil treated with different lime contents after 90 days of curing, through unconfined compression, split tensile and direct shear tests, and to study the influence of the water/lime, and porosity/volumetric content (η/Lv) ratios on this strength. The control parameters evaluated were porosity, moisture content, lime content, curing time, and η/Lv ratio. The results demonstrated the effectiveness of the η/Lv ratio to evaluate the spit tensile/compression ratio of this type of soil. In the direct shear tests, increased cohesion and friction angle were also observed.

INTRODUCTION

In geotechnical engineering, soil can be used for two purposes: reinforcement and construction. In the former case, the soil can be used to support shallow foundations such as spread footings, or deep foundations such as piles. For the latter, for example, soil can be used for the construction of pavement bases and sub-bases, and as a landfill for retaining walls and gravity walls. To support foundations, the soil must meet two requirements: firstly, withstanding loads that are above it without entering the failure or rupture zone, and, secondly, reaching the permitted settlement without exceeding the values established in the codes (Das, 2021).

When used to construct pavement layers, the soil must be able to bear and distribute the pressure produced by the vehicle load, and not exceed the permissible deflections and expansions (Guymon et al., 1993).

Fine-grained clayey soil presents problems in these situations, which becomes a constraint in cities like Curitiba, in Brazil, where most of the soils of the local geological formation are fine-grained and expansive and have low load-bearing capacity. As a result, most of these soils cannot be used to develop the city's infrastructure. This poses a problem for building developers and the city’s economy since it is necessary to bring material from other places in the region, which burdens the civil works budget. Treating these soils with reinforcing agents, such as lime and cement, has been a widely used technique in geotechnical engineering because it improves the soil for the previously mentioned usages (Consoli et al., 2009).

Lime is widely used in civil engineering applications such as road construction, landfills, and shallow and deep foundations. When lime and water are added to clayey soils, several reactions occur that lead to improved soil properties. These reactions include cation exchange, flocculation, carbonation, and pozzolanic reaction. Cation exchange occurs between the cations associated with the surfaces of the clay particles and the calcium cations of the lime. The effect of the exchange and attraction of cations causes the clay particles to aggregate, and thereby, form flakes; this process is called flocculation. Flocculation is primarily responsible for the modification of the geotechnical properties of clayey soils treated with lime (Sherwood, 1993).

Research conducted by Consoli et al., (2009), Consoli et al., (2011a) and Consoli et al., (2011b) established a methodology for the determination of artificially lime-enhanced soil by using the porosity/volumetric lime content ratio (η/L_v), where the volumetric lime content is equal to the volume of lime divided by the total volume of a test specimen. This methodology suggests that, by using the η/L_v ratio, the amount of lime and the appropriate porosity to provide the desired strength for lime-soil mixtures at minimal cost can be chosen. Moreover, Consoli et al. (2007) studied the influence of the water/cement ratio on the strength of sand-cement mixtures and concluded that there is an increase in strength when this relationship decreases, which also applies to studies of lime-soil mixtures.

The objective of this research is to study the strength of an artificially lime-enhanced silty soil of the Guabirotuba formation of the city of Curitiba in Brazil, and the influence of water/lime (w/L) and η/L_v on this strength.

MATERIALS AND METHOD

Soil And Lime

The soil used in this research was collected in the municipality of Fazenda Rio Grande, in the metropolitan region of Curitiba. The lime used for this study was a dolomitic hydrated lime (CH-III). The CH-III type is one of the most commonly used types of hydrated lime in Brazil. The lime is composed mainly of calcium hydroxides –$Ca(OH)_2$- and magnesium –$Mg(OH)_2$- and is produced in the municipality of Almirante Tamandaré (Paraná, Brazil).

The physical-chemical properties of the soil and lime-soil mixture were: granulometry (ASTM D2487, 2000); liquid limit (ASTM D4318, 2010); plastic index (ASTM D4318, 2010); specific gravity (ASTM D854. 2014)).

Lime Dosage, Molding Points And Curing Time

Before treating the soil mixtures with lime, an investigation was undertaken to define the minimum lime content as a function of the pH value. The methodology proposed by Rogers et al., (1997), also called the ICL (Initial Consumption of Lime) method, was used.

The molding points were defined by soil compaction tests of the following three compaction energies: standard, intermediate, and modified.

Molding And Curing Of Specimens For Unconfined Compression And Split Tensile Strength Tests

For the unconfined compression and split tensile tests, test specimens of 100 mm in height and 50 mm in diameter were molded. The soil was dried completely in an oven at 100±5°C and then evenly distributed portions were mixed with the different lime contents. The amount of dry lime was added concerning the dry weight of the soil sample. The soil was then mixed with the lime so that the mixture would be as homogeneous as possible. Then, a percentage of water by weight was added, where the percentage was relative to the optimum water content of the molding points.

The samples for the molding of the specimens were statically compacted under optimum conditions in two layers with a stainless steel mold with an internal diameter of 50 mm, a height of 100 mm, and a thickness of 5 mm. To ensure the maximum dry unit weight obtained during the compaction tests, the mold volume and the wet mixing weight required for each specimen were calculated. After these calculations were done, the required quantity for each specimen was weighed.

The specimens were weighed on a precision scale of 0.01 g and the dimensions of the specimens were measured using a caliper with a 0.1 mm measurement error. The extracted specimens were wrapped with clear plastic to maintain the moisture content. Finally, the specimens were placed in a humidity chamber for a curing time of 90 days. The average temperature was 25°C to prevent significant changes in moisture control until the day of the test. Samples had to meet the following maximum measurement errors to be used for the unconfined compression and split tensile tests: sample sizes with a diameter of ±0,5 mm and a height of ±1 mm, dry unit weight (γ_d) of ±1% and moisture content (ω) of ±0,5 %. For each molding point and lime content, 3 specimens were molded.

Molding And Curing Of Specimens For Direct Shear Test

For the direct shear tests, specimens 100 mm wide, 100 mm long, and 20 mm thick were molded. The samples were compacted into the steel mold ensuring the maximum unit weight obtained during the compaction tests. The calculation of mold volume and wet mix weight required for each specimen was performed. Using a static method, each specimen was compacted in a single layer, ensuring the following maximum measurement errors after molding:

– Dimensions of the width and length of the specimen: ±1 mm
– Thickness dimension: ±0,5 mm
– Dry unit weight (γ_d): ±1 %
– Moisture content (ω): ±0,5 %.

The specimens were wrapped in plastic and placed in a humidity chamber. The average temperature was 25°C to maintain the moisture content during the 89 days of curing time. Before testing, the specimens were placed in distilled water for 1 day, having a total curing time of 90 days, so that at the moment of rupture they were as saturated as possible.

Matric Suction Tests

After rupturing, the specimens that were submitted to the unconfined compression test were used to measure matric suction. By definition, matric suction is the difference in pressure between the pore-air pressure and the pore-water pressure. Therefore, the value of matric suction is the soil water pressure deficit for air pressure or the soil water potential deficit concerning the soil water potential at the ambient air pressure (Lu, 2008). Matric suction comes from the capillary forces of the lime-soil test specimens and was therefore measured to determine its influence on the compressive strength and the tensile strength. Using the filter paper technique, samples between 25 and 35 mm thickness and 50 mm in diameter were used to measure matric suction (Marinho, 1995). The filter-paper calibration equations developed by Chandler et al. (1992) were used, where ω is the moisture content of the filter paper after being in equilibrium with the lime-soil samples:

$$\text{Suction (kPa)} = 10^{\,6{,}05-2{,}48\log\omega} \quad \text{to } \omega > 47\% \tag{1}$$

$$\text{Suction (kPa)} = 10^{\,6{,}05-2{,}48\log\omega} \quad \text{to } \omega > 47\% \tag{2}$$

Unconfined Compression And Split Tensile Tests

To perform the unconfined compression and split tensile tests, a Wille Geotechnik UL60 automatic press was used, as well as rings calibrated for axial load with a capacity of 4,5 kN and 10 kN. The tests were performed using an automated system, measuring the applied force with a resolution of 2,5 N, deformation with a sensitivity of 0,001 mm, and test speed (1mm/min). The test procedures adhered to the Brazilian standard NBR 12770 (NBR 12770, 1992). The strength of the unconfined compression is the value of the maximum rupture load of the material or the pressure value corresponding to the load in which a specific deformation of the cylinder of 20 % occurs, in the cases where the axial stress-strain curve does not have a maximum peak. According to the following expression, when the axial stress-strain curve reaches a maximum peak in the test, the unconfined compression strength (q_u) is:

$$q_u = \frac{P_R}{A_T} \tag{3}$$

Where P_R is the rupture load at the peak of the axial stress-strain curve and A_T is the corrected cross-sectional area of the specimen. The split tensile strength (q_t) according to the following expression is:

$$q_t = \frac{2P_R}{\pi DH} \tag{4}$$

Where P_R is the rupture load at the peak of the split tensile stress-strain curve, and D and H are the diameter and height of the specimen, respectively.

Direct Shear Tests

To perform the direct shear tests, an ELE International press (Direct Shear Apparatus 220-240V 50/60Hz 1Ph) was used, with a maximum capacity of 5 kN, and axial load calibrated rings with capacities of 4,5 kN. The tests were conducted using an automated data collection system, that measures, in particular, the force applied in Newtons, the deformation (with a sensitivity of 0,001 mm), and the test speed (1 mm/min). Normal stress values of 50, 100, 200, and 400 kPa were used.

RESULTS AND DISCUSSION

The soil is composed of 7,5% sand, 25,9% fine sand, 57.6% silt, and 9.3% clay (Fig. 1). Table 1 is a summary of the soil’s physical properties showing a plasticity index of 21,3% and a specific grain density of 2,71. According to the Unified Soil Classification System (USCS), the soil is classified as elastic sandy silt.

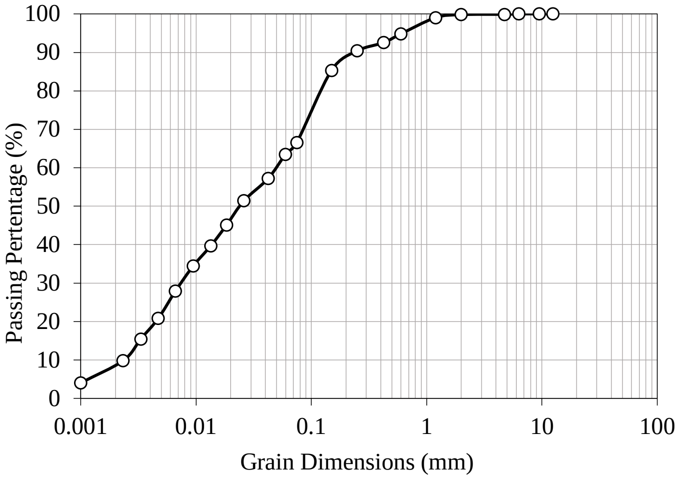

Figure 1. Grain size distribution of soil.

Table 1. Physical properties of the soil sample

Property	**Value**
Liquid limit	53.1%
Plasticity limit	31.8%
Plastic index	21.3%
Specific gravity	2.71
Coarse sand (2.0 mm < ϕ< 4.75 mm)	0%
Medium sand (0.42 mm< ϕ <2.0 mm)	7.5%
Fine sand (0.075 mm < ϕ < 0.42 mm)	25.9%
Silt (0.002 mm < ϕ < 0.075 mm)	57.6%
Clay (ϕ < 0.002 mm)	9.3%
Mean particle diameter (D_{50})	0.025 mm

Regarding the lime, the retained percentage accumulated in the #200 sieve was 9%, which is following the Brazilian standard NBR 7175 (NBR 7175, 2003) which specifies that there must be ≤15% of lime retained in the #200 sieve. The unit weight of the lime is 2,39 g/cm³. The ideal pH value is one in which the pH reaches a maximum constant value as shown in Fig. 2. It was verified that at a pH of 12,5 with 3% lime, the pH remained constant and was independent of the increase in lime content. Therefore, the initial lime content used in this study was 3%. The following lime contents were selected: 3%, 5%, 7% and 9%.

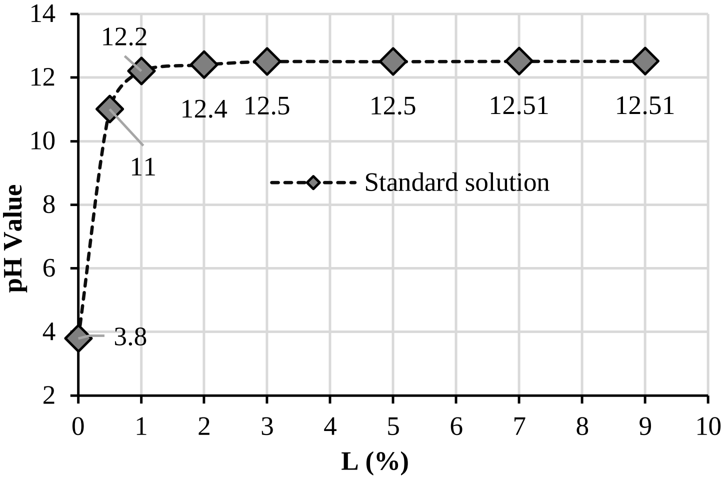

Figure 2. Results of ICL tests for the soil-lime mixtures.

The molding points of the specimens can be seen in Fig. 3. Each point found has a moisture content (ω) and a dry unit weight (γ_d). The molding points are: standard effort (EN) ω = 28,5% and γ_d = 13,80 kN/m3; intermediate effort (EI) ω = 22,8% and γ_d = 15,10 kN/m3; modified effort (EM) ω = 20% and γ_d = 16,15 kN/m3. The 3 molding points are at the saturation line of 82%. The curing time of the soil-lime mixtures used for the present study was defined as 90 days.

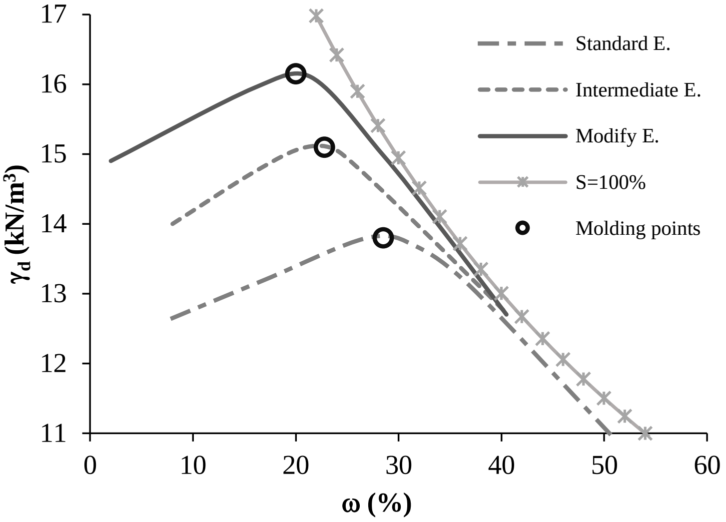

Figure 3. Compaction curves and molding points.

The results of the unconfined compressive strength and split tensile strength as a function of the lime content are shown in Figs. 4 and 5, respectively. An increase in strength is observed about the increase in lime content and the increase in the dry unit weight of the molding.

The maximum values of q_u and q_t were observed with 9% lime. The maximum value reached by q_u was 3400 kPa and 58 kPa for q_t, at point EM. The results of the strength of the 3 specimens for each lime content were plotted. The molding points did not show variations greater than 10% between them for q_u and q_t. The trend adjustment of the points was considered satisfactory, ranging as a linear trend from 0,92 to 0,99. With 0% of lime, the soil did not have a significant increase in strength after 90 days, even with the increase of the unit weight of the molding. For the other values of added lime, the strength gain for both spit tensile and compression was gradually increased, with the lowest gain being L=3% and the highest gain being L=9%.

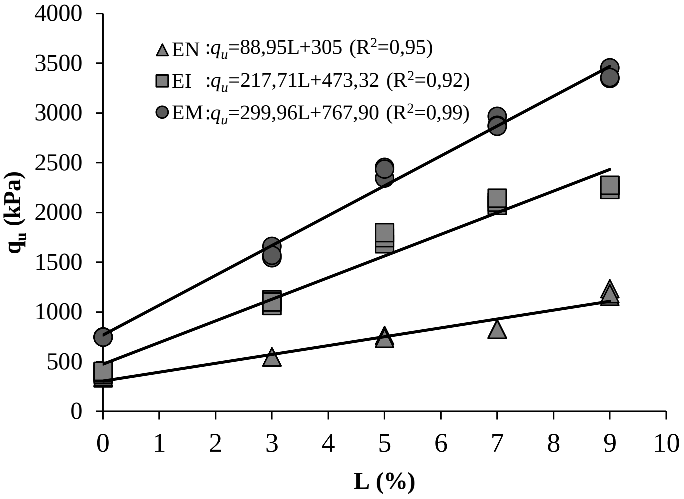

Figure 4. Variation of unconfined compression strength with lime content.

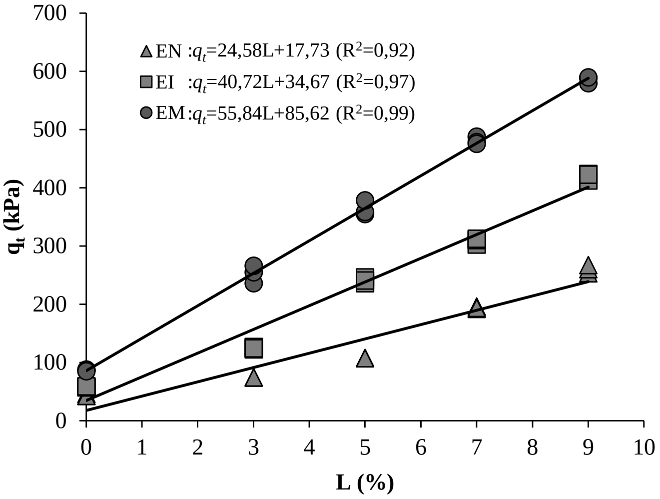

Figure 5. Variation of split tensile strength with lime content.

Influence Of The Water/Lime Ratio (W/L) On The Unconfined Compression And Split Tensile Strength

The influence of the variable water/cement material (weight/weight or volume/volume ratio) is considered an important factor to obtain a good strength to unconfined compression. For example, in reinforced concrete, the water/cement ratio (w/C) is widely used for estimating axial strength. In soils reinforced with lime, the influence of the water/lime ratio (w/L) on the final strength of the mixtures can be studied. The influence of w/L on the unconfined compressive strength (q_u) and the split tensile strength (q_t) is shown in Figs. 6 and 7 respectively.

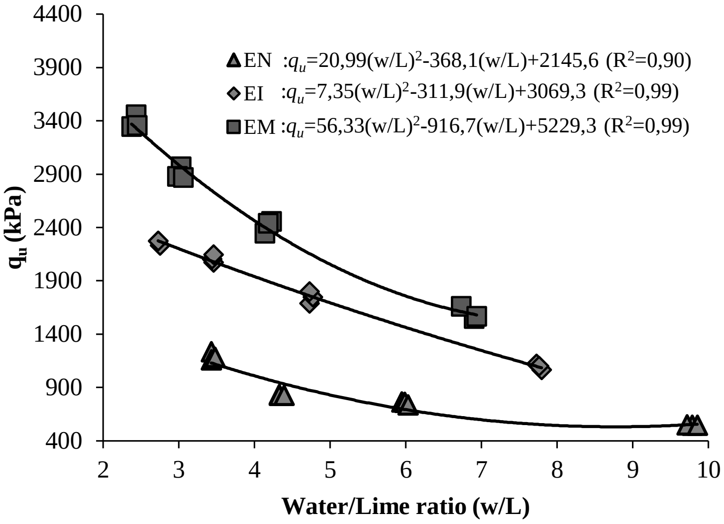

Figure 6. Variation of unconfined compression strength with water/lime ratio.

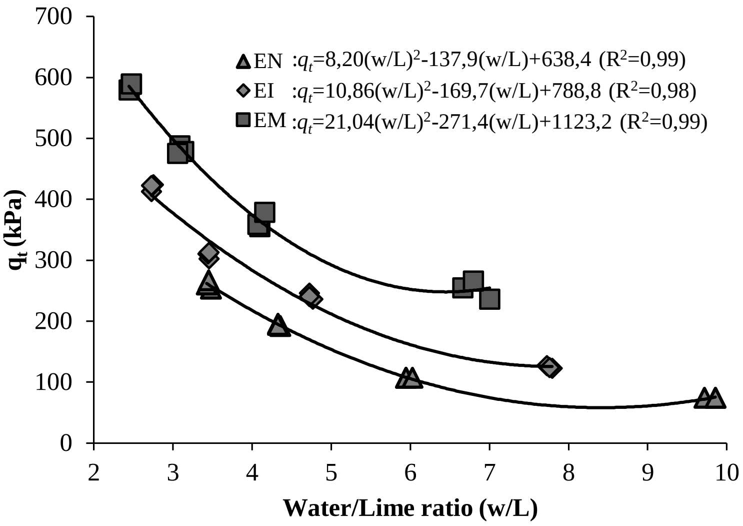

Figure 7. Variation of split tensile strength with water/lime ratio.

The w/L ratio varies between 2 and 10, obtaining the lime-soil mixtures' greater strength when w/L decreases and when γ_d increases. The compressive strength reaches a maximum value of 3500 kPa, while the split tensile strength reaches a maximum value of 580 kPa.

Influence Of Porosity (H) On The Unconfined Compression And Split Tensile Strength

Porosity influences the strength of the soils stabilized with lime, as the voids of the soil are reduced, and the mixture becomes more rigid. The porosity can be calculated as Consoli et al., (2014):

$$\eta = 100 - \frac{100\left(\left(\frac{V_s\gamma_d}{1+L/100}\left(\frac{S}{100}\right)\right)/G_{sS} + \left(\frac{V_s\gamma_d}{1+L/100}\left(\frac{L}{100}\right)\right)/G_{sL}\right)}{V_s} \quad (5)$$

Where V_S is the total volume of the specimen, γ_d is the dry unit weight, L is lime content, S is soil content, and G_{SS} and G_{SL} are unit weights of the soil and lime grains, respectively. Figs. 8 and 9 show the variation in unconfined compressive strength and split tensile strength, respectively, about the variation of porosity.

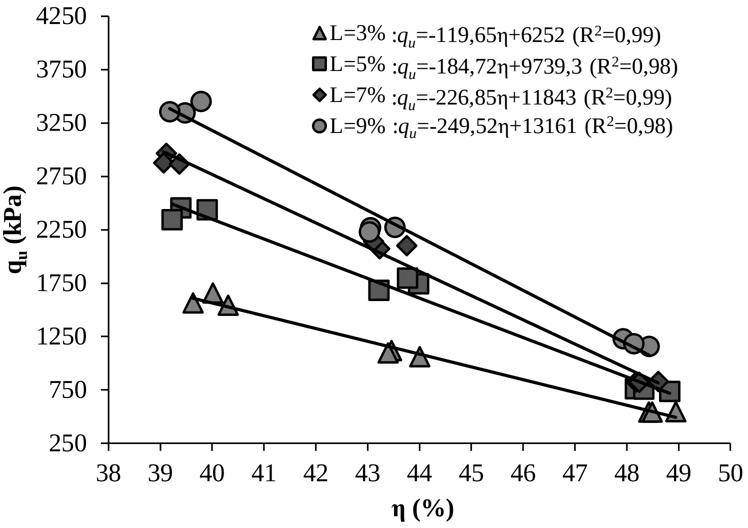

Figure 8. Variation of unconfined compression strength with porosity.

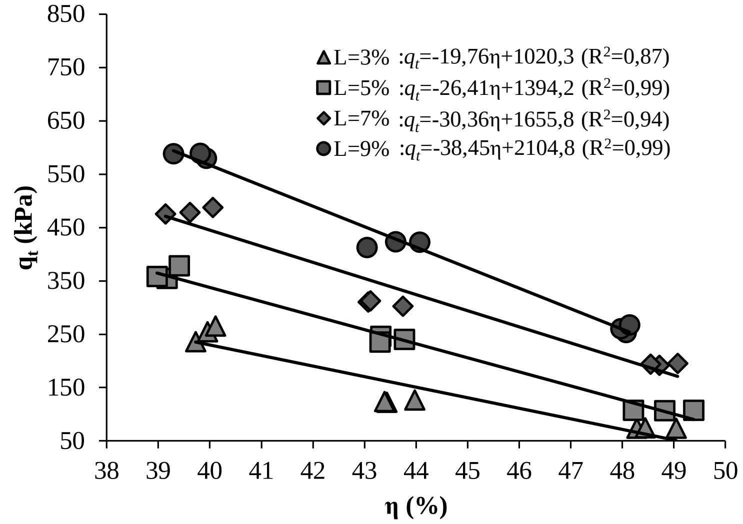

Figure 9. Variation of split tensile strength with porosity.

The porosity of the specimens ranged from 39% to 49%, increasing q_u and q_t while η decreased. When the lime content increased to 9%, the higher strengths increased both q_u and q_t.

Influence Of Porosity/Volumetric Content (Η/Lv) Of Lime On The Unconfined Compressive Strength And Split Tensile Strength

Figs. 10 and 11 show the variation in the compressive and tensile strengths with the η/Lv ratio, respectively. A trend can be observed where the points gather on the left when the lime content increases and η/Lv decreases.

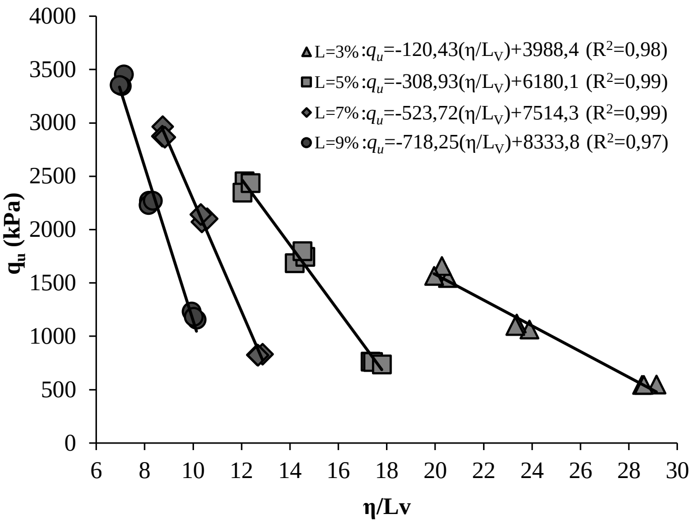

Figure 10. Variation of unconfined compression strength with porosity/volumetric lime content ratio.

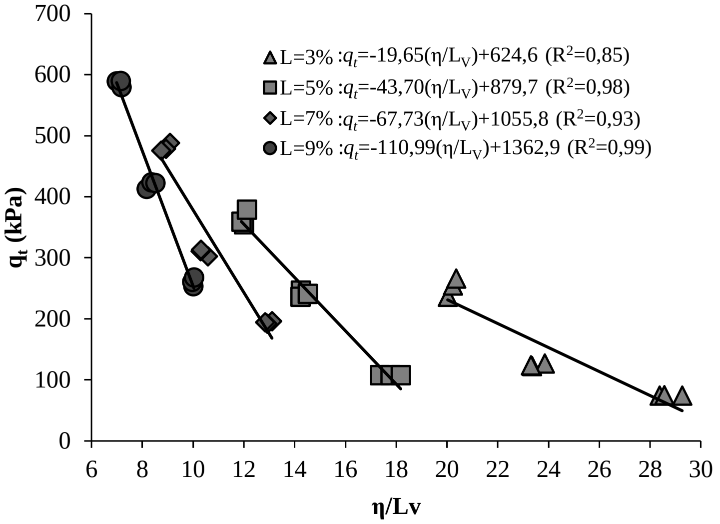

Figure 11. Variation of split tensile strength with porosity/volumetric lime content ratio.

For q_t and q_u, η/Lv ranges from 20 to 30 for test specimens of 3% lime, from 12 to 18 for 5% lime, from 9 to 13 for 7% lime, and from 7 to 10 for 9% lime; with variations of 10, 6, 4 and 3 to 3%, 5%, 7% and 9% of lime respectively. The variation of the η/Lv ratio decreases when the lime content is increased, whereas this decrease increases the strength of the lime mixtures.

Relation Between Unconfined Compression And Split Tensile Strength

The relationship between split tensile strength and unconfined compression strength is a very important variable in the mechanics of artificially improved soils since by knowing one of the two strengths it is possible to estimate the other. According to [17], a single trend of the points in Figs. 10 and 11 can be found if the volumetric lime content is raised to an exponent (Lv). In the present work, the exponent with which the points are organized, and with the best coefficient of determination (R^2) is 0,22, as can be seen in Fig. 12.

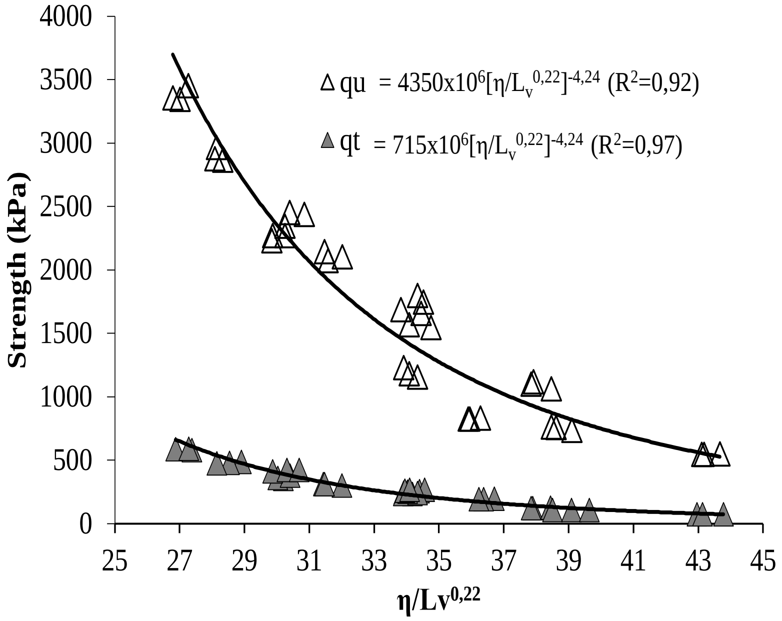

Figure 12. Variation of unconfined compression strength and split tensile strength with porosity/ volumetric lime content ratio with an exponent of 0,22.

From Figure 12, the split tensile/compression ratio q_t/q_u can be calculated in Equation (6). The value of q_t/q_u=0,16 means that the split tensile strength is 16% of the unconfined compressive strength.

$$\frac{q_t}{q_u} = \frac{715x10^6\left[\frac{\eta}{(L_v)^{0,22}}\right]^{-4,24}}{4350x10^6\left[\frac{\eta}{(L_v)^{0,22}}\right]^{-4,24}} = 0,16 \qquad (6)$$

An alternative way to find the relationship between split tensile and unconfined compression is to place the corresponding values of q_t and q_u of the samples in the same Cartesian plane. In this regard, a global tension and compression ratio for all lime contents, all curing times and all compaction energies can be analyzed in Fig. 13. It can be observed that the global relationship between q_t and q_u, without depending on the coefficient $\eta/Lv^{0,22}$, is 0,16.

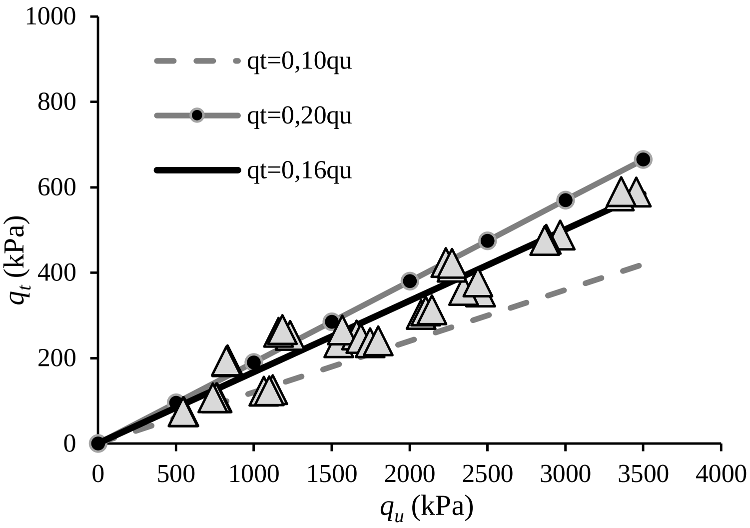

Figure 13. Variation of unconfined compression strength and split tensile strength with porosity/ volumetric lime content ratio with an exponent of 0,22.

Influence Of Matric Suction On The Unconfined Compressive Strength And Split Tensile Strength

After the unconfined compression and split tensile tests, the matric suction was measured employing the filter paper technique. The test specimens showed a variation of ±0,5% of the initial moisture content, with saturation being between 80% and 82,5%. The matric suction calculated with the filter paper presented results of 1% to 5,5% of the values of the compressive and split tensile strength. Therefore, it can be concluded that, for these values, suction is not a relevant variable for the analyses conducted in this study.

Direct Shear Tests

Four normal stresses (50, 100, 200, and 400 kPa) were used to trace the Mohr-Coulomb envelope. According to the results, cohesion increases with the increase of the lime content, which means that there is a greater development of cohesion between the grains when the lime reacts with the water in the voids. The direct shear tests were conducted in a saturated condition. After being tested, the saturation values of the samples varied from 90 to 96% in saturation. Thus, it can be concluded that matrix suction is not an analysis variable in the test.

The results of the direct shear tests of the lime-silt mixtures are shown in Table 2. The friction angle for the MS molding point decreases as the lime content increases to 7%; for 9%, on the other hand, it increases to 36º. For the EI molding point the friction angle does not have a significant variation; however, for the EM point, the angle increases when the lime content increases from 3 to 5% but decreases when lime is added to the soil.

Table 2. Results of direct shear tests of silt-lime mixtures

Molding point	Lime content (%)	Cohesion(kPa)	Friction Angle(º)
EN ω=28,5% and γ_d=13,80 kN/m^3	3	31,7	31,3
	5	51,5	30,2
	7	61,50	25,10
	9	39,4	36
EI ω=22,8% and γ_d=15,10 kN/m^3	3	22,12	36,50
	5	42,82	32,70
	7	49,45	35,80
	9	56,74	31,36
EM ω=20% and γ_d=16,15 kN/m^3	3	26,13	28,18
	5	74,20	35,15
	7	95,74	25,72
	9	190	14,6

Cohesion, and sometimes the angle of friction, can make it feasible to use this silt as a foundation material or for the protection of hillsides and slopes. Therefore, reinforces soil foundations increase the safety factor, decreases the dimensions of the spread footings, and due to increased cohesion, increases resistance to effective stresses.

CONCLUSION

According to the data presented, it can be concluded that:

– Unconfined compressive and split tensile strength of the studied silt increases with the increase of the added lime content and with the increase of the dry density of the molding points.
– There was an increase of cohesion in the direct shear strength tests and there was little variation in the angle friction with the increase of the lime content.
– There is a constant relationship of q_t/q_u=0,16 between the tensile strength and the compressive strength of the studied soils with 90 days of curing and the Equations (6) can be to mix design.
– The exponent of 0,22 with which the volumetric lime content was raised to find a better trend of q_t and q_u with the η/Lv ratio, was important in finding the constant q_t/q_u=0,16.
– It is possible to find an estimate of q_t and q_u with w/L and η/Lv. Thus, the silt of the studied Guabirotuba formation can be measured without testing by using a desired lime content and porosity.

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