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Cement And Lime Stabilized Sedimentary Silty Soil: Porosity/Cement Index Controlling The Split Tensile Strength

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ABSTRACT

This work evaluates the development of silty soil's split tensile strength (q_t) from the Guabirotuba Formation of Curitiba/BR artificially cemented over 28 days. For this, two binders were used: lime and cement. The lime used was hydrated dolomitic type, and the cement had high initial strength, added in percentages of 3, 5, 7 and 9% about the dry mass of the soil. Specimens of 50 mm in diameter and 100 mm in height were molded with different contents of lime (L), different contents of cement (C), different porosities (η), different apparent dry weights (γ_d), moisture of molding (ω) between 20 and 23% and subjected to indirect traction under saturation conditions. The voids/lime (η/L_{iv}) and voids/cement (η/C_{iv}) ratio represented by the porosity/volumetric binder content ratio (η/B_{iv}) was used to evaluate the development of qt in addition to variables such as L, C and η and its influence on qt. The results demonstrate an increase in strength with increasing lime and cement content and with decreasing voids (i.e., higher dry specific weight and lower η). In terms of addition, the soil-cement mixture developed greater tensile strength than the soil-lime mixture by 15%. Finally, a dosage equation for qt of the studied soil mixed with lime and cement was calculated using the η/B_{iv} ratio adjusted to an exponent of 0.20 for cement and lime, obtaining an acceptance of 95% and a mean error of 4%.

Keywords: Soil stabilization, porosity-binding, tensile strength.

1. INTRODUCTION

Fine-grained soils sometimes present problems when they are used for the construction of pavement layers, surface foundations and protection of slopes and slopes, which becomes a problem when, in cities such as Curitiba-south of Brazil, most soils of the local geological formation (Guabirotuba) are fine-grained, expansive, and of low load capacity. For this reason, most of the soils in this region cannot be used for the development of the physical infrastructure of the city, which is an imbroglio for builders and the city's economy since materials must be brought from other places in the region, increasing the civil works budget.

The treatment of these soils with cementing agents has been a technique widely used in geotechnical engineering because it improves the soil for the conditions mentioned above. Recently Baldovino et al. (2018b) studied the effects of adding hydrated lime to silty soil in the metropolitan region of Curitiba at different curing times, achieving a maximum simple compressive strength of 1,300 kPa with 9% lime addition after 90 days of curing at 1,300 kPa. normal compression energy. However, most of the time it is not possible to wait that long to allow the use of engineering works such as floors and therefore, it is essential to have additional luting agents such as cement that can provide high resistance in less time. Even though lime is more economically viable than cement, sometimes shortening the time to gain the desired strength can balance construction costs. Thus, this study compares the tensile strength developed by sedimentary soil stabilized with lime and cement. Furthermore, the influence of voids and porosity are evaluated in terms of the volumetric contents of lime and cement on q_t.

2. EXPERIMENTAL PROGRAM

The experimental program was divided into two stages: the first was to carry out soil, lime and cement characterization tests: soil granulometry according to the American standard ASTM D2487 (ASTM 2011), Atterberg limits of the soil according to the Brazilian standards NBR 7180 (ABNT 2016) and NBR 6459 (ABNT 2016), the actual specific gravity of the soil grains according to ASTM D854 (ASTM 2014) and the actual specific gravity of the grains of the types of cement and lime according to the Brazilian standard NBR 16605 (ABTN 2017); and the second consisted of molding, curing and breaking the soil-lime and soil-cement specimens submitted to tensile tests by diametrical compression.

2.1 Materials

A silty soil from the Guabirotuba Formation, dolomitic hydrated lime, high initial strength cement (ARI) CP V and distilled water were the materials used in the research. The soil sample was collected in the municipality of Fazenda Rio Grande, near the city of Curitiba (Brazil), manually in a deformed state, avoiding possible contamination and sufficient quantity to carry out all the tests. The dolomitic hydrated lime used is produced in the municipality of Almirante Tamandaré (Paraná) and was supplied by a local producer. Finally, CPV cement was supplied by the Materials Laboratory of UTFPR.

Figure 1 shows the soil granulometric curve and Table 1 presents its physical properties. The soil is formed mainly by silt (57.6%) and fine sand (25.9%). According to the Unified Soil Classification System, the soil is classified as sandy silt (MH) with an average plasticity index of 21.3%.

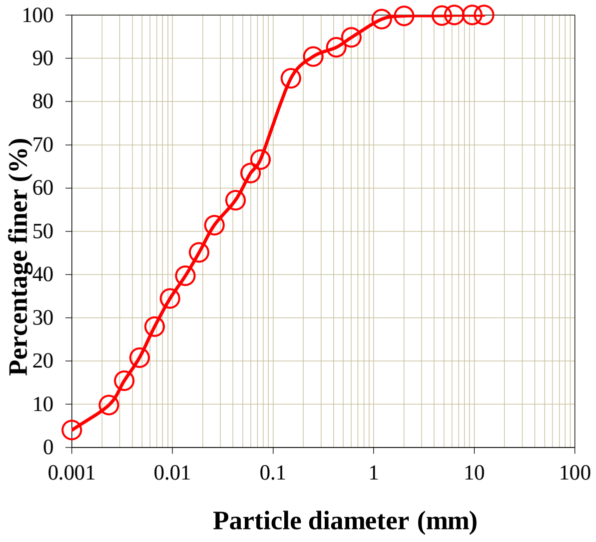


Figure 1. Particle size distribution curve

Table 1. Physical properties of soils and ground glass

Properties	Value
Liquid Limit, %.	53,1%
Plasticity index, %	21,3%
Actual grain density	2,71

Gravel (4,75 mm < ϕ < 19 mm)	0%
Coarse sand (2.0 mm< ϕ <4.75 mm), %.	0%
Medium sand (0.425 mm< ϕ <2.0 mm), %.	7.5%
Fine sand (0.75 mm< ϕ <0.425 mm), %.	25.9%
Silt (0.002 mm < ϕ <0.075 mm), %.	57.6%
Clay (ϕ < 0.002 mm), %.	9.3%
Average diameter (D_{50}), mm	0.025 mm
Classification (SUCS)	MH

Table 2 presents the chemical composition of the soil determined with X-Ray Fluorescence; the soil has a high presence of silica and alumina, essential components for chemical stabilization and geo-polymerization. Table 3 shows the physical and chemical properties of cement. The producer provided chemical properties and physical properties were calculated in the laboratory. According to Table 3 the CP V cement has a specific mass (Gsc) of 3.11. Table 4 presents the properties of lime. Lime has a specific gravity (GsL) of 2.39 and a percentage of fines of 91% passing through a diameter of 0.002 mm.

Table 2. Soil chemical composition

Compound	Concentration (%)
SiO_2	53.12
Al_2O_3	24.30
Fe_2O_3	10.46
CaO	0.03
MgO	0.28
K_2O	0.39
Na_2O	0.02
TiO_2	1.37
MnO	0.17
P_2O_5	0.22
Loss to fire	9.64

Table 3. Physicochemical properties of cement

Properties	Value
% MgO	4.11
% SO_3	2.99
% CaO	60.73
%Al_2O_3	4.38
%Fe_2O_3	2.83
%S_iO_2	19.9
% Insoluble residue	0.77
Compressive strength for 7 days (MPa)	42

Compressive strength for 28 days (MPa)	53
% Fineness	0.04
Gs_C	3.11

Table 4. Lime properties

Properties	Value
SiO_2, % by weight	0.70
Al_2O_3, % by weight	0.40
Fe_2O_3, % by weight	0.20
CaO, % by weight	63.2
MgO, % by weight	10.4
K_2O, % by weight	0.30
Na_2O, % by weight	0.1
TiO_2, % by weight	0.2
Loss to fire	24.5
Particles with diameter < 0.002 mm, %	91
Grain specific gravity – Gs_L	2.39

2.2 Molding points, cement contents and curing time

Table 5 presents the molding conditions of the soil-lime and soil-cement specimens. To study the effects of void volume on compressive strength, molding conditions close to field conditions were strategically established. Thus, for soil-cement mixtures, the molding moisture value was set at 23% and the molding density varied between 13.10 and 15.10 kN/m^3. For soil-lime mixtures, the moisture content varied between 20 and 28.5%, and the density between 13.80 and 16.15 kN/m^3. According to the Brazilian experience (Baldovino et al. 2018a; 2018b; Consoli et al. 2011), lime/cement contents were chosen as 3.5.7.9% in reference to the dry mass of the soil.

Table 5. Molding points for lime-soil and soil-cement compacted blends

Mix	Molding point	Dry unit weight (kN/m^3)	Moisture content
Soil-cement	A4	13.10	23
	A3	13.77	23
	A3	14.43	23
	A1	15.10	23
Lime-soil	A1	13.80	28.5
	A2	15.10	22.8
	A3	16.15	20.0

2.3 Preparation of specimens and mechanical strength tests

The battery of split tensile strength was divided into two groups. The first group consisted of specimens stabilized with hydrated lime and molded at the points listed in Table 5. The second group corresponded to specimens stabilized with cement.

For the split tensile tests, specimens 100 mm in height and 50 mm in diameter were molded. After field collection, the soil was completely dried in an oven at a temperature of 100±5°C and placed in evenly distributed portions to be mixed with lime and cement. The amount of lime or dry cement was added with reference to the dry weight of the soil sample at four different addition levels (3, 5, 7 and 9%). The soil was mixed with lime/cement so that the mixture was as homogeneous as possible. Then, a percentage of water by weight was added, referring to the moisture content of the molding points established in Table 5.

The mixture of soil-lime/soil-cement with distilled water was carried out in a period not exceeding 5 minutes, with this trying to minimize the reactions with water before the molding process of the specimens. The samples for molding the specimens were statically compacted in three layers with a stainless steel mold with an internal diameter of 50 mm, a height of 100 mm and a thickness of 5 mm, under the compaction conditions shown in Table 5. The first and second layers were scarified. To ensure the apparent dry density.

The mold volume and wet mixture weight (divided into three parts) required for each specimen were calculated. After these calculations, the necessary amount of material for each specimen was weighed. The molding was done with the help of a manual hydraulic press. After each molding process, three samples of the mixture were taken to measure the moisture content in an oven at 100±2°C for 24 hours.

The specimens were weighed on a 0.01 g precision scale and their dimensions were measured using a caliper with an error of 0.1 mm. The specimens extracted from their molds were wrapped with transparent plastic film to maintain the moisture content. Finally, the specimens were stored in a humid chamber for curing for 27 days (at an average temperature of 23±2°C) to prevent significant changes in humidity until the day of the test. The samples had to respect the following maximum errors to be used in the tensile tests: dimensions of the samples with a diameter of ±0.5 mm and a height of ±1 mm, specific dry weight (γ_d) of ± 1%, and moisture content (ω) of ±0.5%. For each molding point and lime/cement content, 3 specimens were molded.

The specimens were immersed in a tank with distilled water for 24 hours before the test to ensure their saturation and thus avoid the influence of suction on the strength as done in previous studies (Moreira et al. 2019). After immersion, they were superficially dried with a dry cloth. Thus, all samples were cured for a total of 28 days.

An automatic press with a capacity of 30 kN was used to carry out the tensile tests. The tests were carried out with an automated system, mainly measuring the applied force and the deformation with a sensitivity of 0.01 mm, with a test speed of 1.15 mm/min. The tensile strength (qt) is adopted according to the following expression when, in the axial stress-strain curve test, a maximum peak is reached:

$$q_t = \frac{2P_R}{\pi DH} \qquad (1)$$

Where P_R is the breaking load at the peak of the diametral stress-strain curve, D and H are the diameter and height of the specimen, respectively. The tensile strength test procedures (q_t) followed the Brazilian standard NRB 7222 (ABNT 2011).

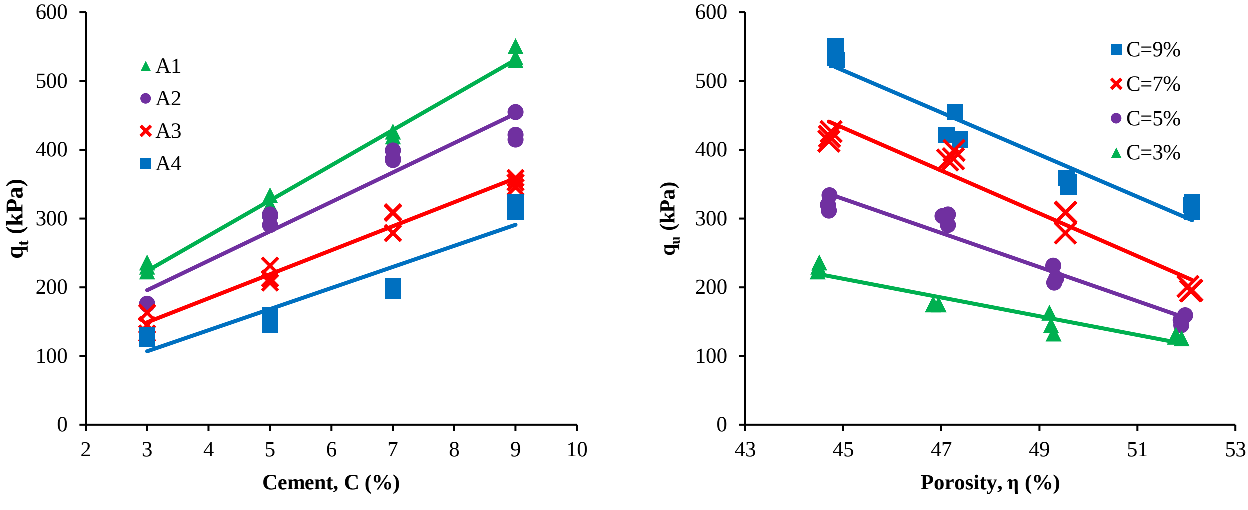
3. RESULTS AND DISCUSSIONS

3.1 Influence of cement/lime content and porosity on strength

Figure 2 shows the effects of cement addition and initial molding porosity (η) of soil-cement mixtures on tensile strength after 28 days of curing. First, there is an increase in tension value due to the increase in the amount of cement added. The tensile value increases when the mold density value also increases. Likewise, Figure 3 shows the results of indirect traction of soil-lime mixtures influenced by the amount of lime (Fig. 3a) and the initial molding porosity (Fig. 3b).

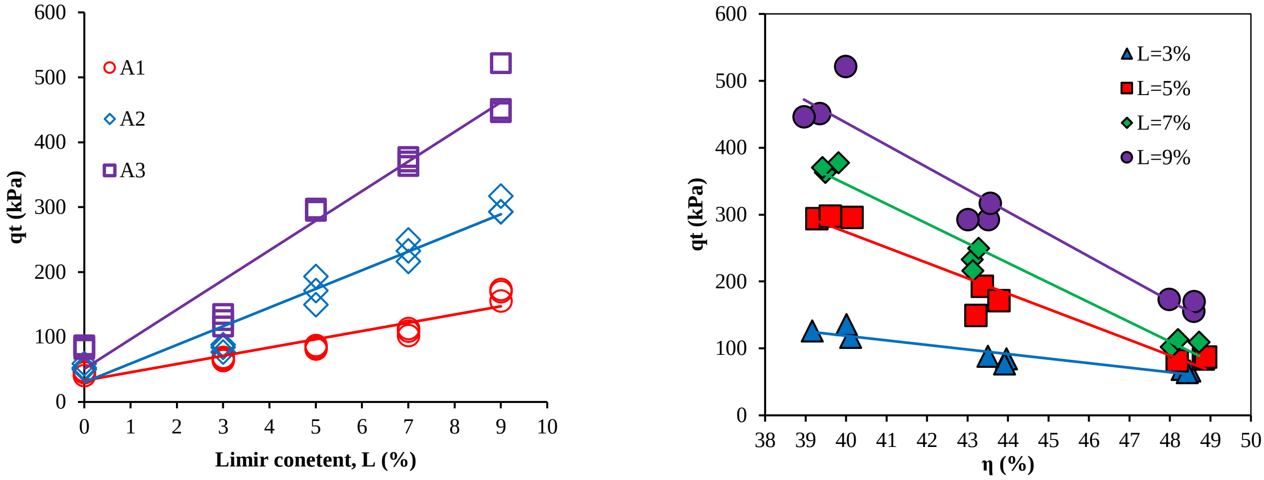
Comparing the effects of the addition of lime/cement content and molding density in q_t (Figs. 2a and 3a), it is noted that the soil-cement mixtures achieved higher strengths with the addition of a lower amount of binder. This result can be seen for the molding point of γ_d=15.10 kN/m^3 where the soil-lime mixture (A2) reaches q_t values of 300 kPa for L=9% while for the soil-cement mixture at these same molding conditions (A1) reaches resistance values of 550 kPa, with an increase of 83% in the q_t value.

For the soil-cement mixture, a decrease of 7 percentage points (Fig.3b) meant an increase of 200 kPa in qt; for the soil-lime mixture, this same decrease in voids meant an increase of 190 kPa. Thus, the increase in the tensile strength of the mixtures was mainly determined by the type of binder used, while the decrease in porosity provided a greater capacity for stress distribution within the specimens, in the same way as the more remarkable ability to mobilize friction in the samples. Lower porosities also contribute to the material's gain in tensile strength. Thus, regardless of the amount of lime or cement used, the material's porosity reduction promotes considerable gains in split tensile strength (Consoli et al. 2009a). The best way to represent the tensile values influenced by the amount of lime/cement and porosity was through a linear regression curve, as seen in Figs. 2-3. This regression means that the strength gains due to an increase in a binder or a decrease in voids (independent of density) are always proportional.



(a) **(b)**

Figure 2. (a)Influence of cement content on split tensile strength (q_t); (b) Influence of the initial porosity of the soil-cement specimens on the split tensile strength (q_t) at 28 days of curing



(a) **(b)**

Figure 3. (a) Influence of lime content on split tensile strength (q_t); (b) Influence of the initial porosity of the soil-lime specimens on the split tensile strength (q_t) at 28 days of curing.

3.2 Influence of void/binder ratio on strength

Figure 4 shows the influence of the porosity/binder ratio (η/B_{iv}) on the tensile strength. The parameters η and B_{iv} influence the same magnitude, that is, proportional variations that keep the tensile strength value constant. Note a potential growth of qt for both mixtures, soil-lime, and soil-cement, dependent on η/B_{iv}. The additions are represented by equations 2-3 for soil-lime and soil-cement, respectively:

$$q_t = 5173{,}8\left[\frac{\eta}{(L_{iv})^1}\right]^{-1{,}32} \quad (R^2 = 0{,}80) \qquad (2)$$

$$q_t = 4620{,}8\left[\frac{\eta}{(C_{iv})^1}\right]^{-0{,}95} \quad (R^2 = 0{,}83) \qquad (3)$$

The η/B_{iv} ratio is defined in relation to the voids of the soil-binder mixture and the volume of binder used in the mixture in the initial molding conditions defined previously in Table 5. Porosity is calculated as an initial condition of the soil-cement/ soil-lime at a pre-set dry density γ_d and the desired moisture content. Thus, the mechanical strength of the soil-binder matrix can be a direct relation of the porosity of the specimens as well as a function of the inverse of the volumetric content of binder ($1/B_{iv}$), as demonstrated in previous studies. (Moreira et al. 2019; Baldovino et al. 2018b).

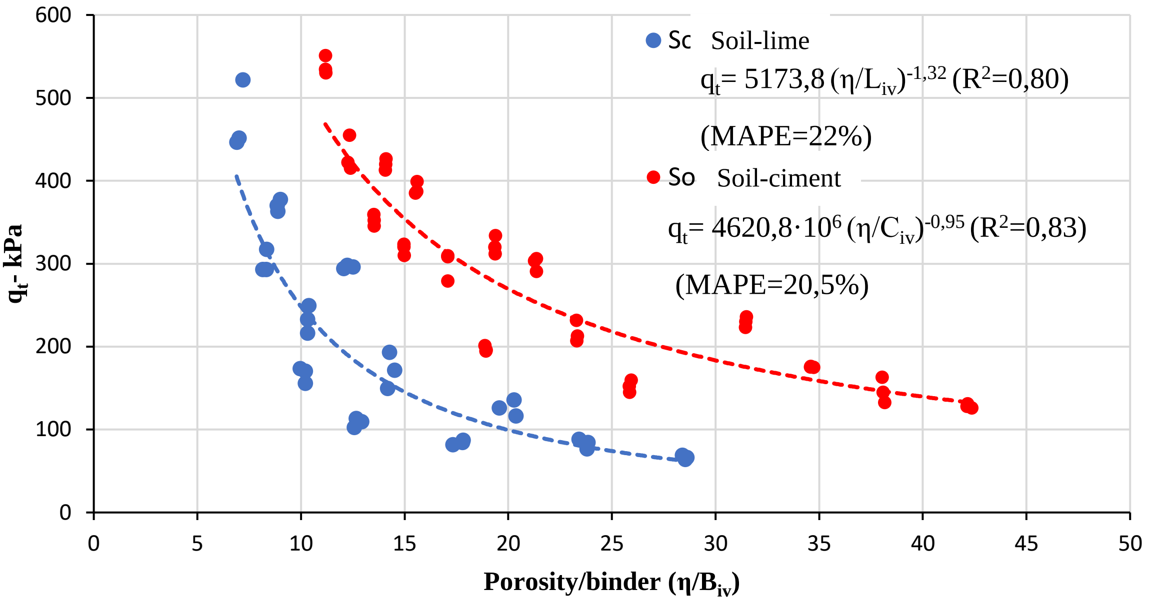


Figure 4. Influence of the porosity/binder ratio on the split tensile strength of soil-lime/soil-cement mixtures at 28 days of curing

The volumetric content of the binder may be called the volumetric content of cement (C_{iv}) and lime (L_{iv}), when relevant. Eqs. 2-3 obtained adjustments of 0.80 and 0.83, respectively. Thus, the relationship η/B_{iv} was not fully compatible and did not have a direct relationship. To find a direct and compatible relationship between η and B_{iv} as a mathematical ratio and to convert the two variables into dependence on qt, the value of B_{iv} must adjust to an exponent between 0.01 and 1.00 with variations of 0.01 as is done in the current literature (Baldovino et al. 2018a; Consoli et al. 2009b). Thus, the value of B that best fitted the qt values for the current experimental program was 0.20. The value of 0.20 means that the influence of porosity (η) and voids in the soil-binder mixture exerts a more significant influence on the indirect tensile strength qt than the volumetric content of the binder, in such a way that an increase in porosity requires a proportionally greater increment in the content of binder, in order to compensate for the increase in voids due to lack of compaction and maintain constant resistance (Leon 2018). Thus, Figure 5 shows the influence of the porosity/volumetric content of binder (set at 0.20) on the strength qt for both soil-lime and soil-cement mixtures.

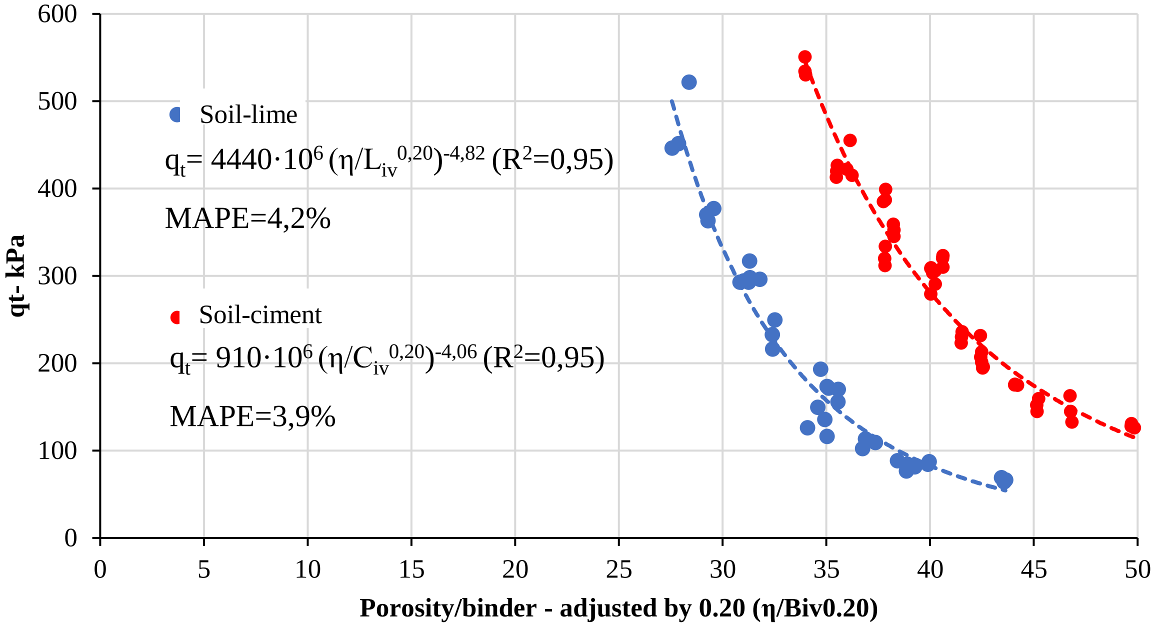


Figure 5. Influence of the porosity/binder ratio adjusted to an exponent of 0.20 on the split tensile strength of soil-lime/soil-cement mixtures at 28 days of curing

Using the exponent of 0.20 Eqs. 2-3 now have adjustments of R^2=0.95 and mean absolute percentage error (MAPE) as seen in Eqs. 4-5:

$$q_t = 4440 \bullet 10^6 \left[\frac{\eta}{(L_{iv})^{0,20}}\right]^{-4,82} \quad (R^2 = 0,95) \tag{4}$$

$$q_t = 910 \bullet 10^6 \left[\frac{\eta}{(C_{iv})^{0,20}}\right]^{-4,06} \quad (R^2 = 0,95) \tag{5}$$

Eqs. 4-5 represent the potential strength growth of soil-lime and soil-cement mixtures, respectively. These equations can be taken as functions to dose any stabilized mixture within the molding limits established in Table 5

3.3 Normalization of strength

The normalization (division) of the resistances is used to find an equation capable of estimating qt as a function of η/B_{iv} normalized to a single potential trend using the Eqs. 4-5. Second (Consoli et al. 2016), in order to find an estimation equation of silt/clay soils stabilized with cement and lime using the η/B_{iv} ratio, it is first necessary to determine all the normalization resistances using a particular value of $\eta/B_{iv}{}^{B}=\Delta$ for each variable depending on the resistance (in this case, or type of binder used). The particular value Δ to normalize can be chosen from the range reported in this research between 27 and 50 (Figure 5). Thus, the value of $\eta/C_{iv}{}^{0.20}=\Delta=35$ was chosen for the present work. The number Δ=35 is substituted in the Equations that control qt (Eqs.4-5) to calculate the normalizing strengths for each type of binder. The normalizing strengths for $q_{t\text{-normalized at 35}}$ are 160 and 490 kPa for soil-lime and soil-cement, respectively. After calculating the normalizing strengths, the strengths must be normalized over the reported values of indirect tensile, dividing each specimen's tensile strength value by the corresponding normalizing strength value. This division provides a relationship between experimental q_t and $q_{t\text{-normalized at 35}}$, as shown in Figure 6.

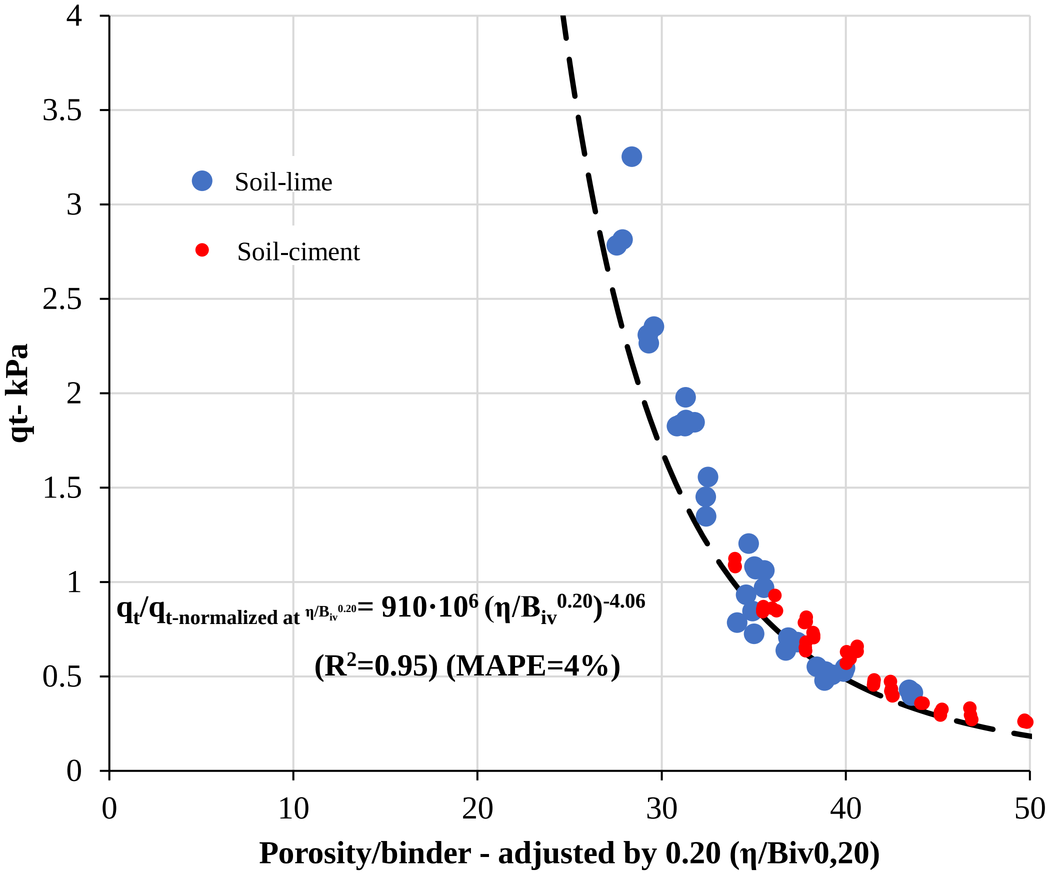


Figure 6. Normalization of split tensile strength (q_t) [for the entire range of $\eta/B_{iv}^{0.20}$] divided q_t into $\eta/B_{iv}^{0.20}=35$ considering the strength of silty soil treated with cement and lime, using 28 days of curing and molding moisture contents shown in Table 5.

Figure 6 also shows that under normalized conditions, the tensile strength also has an increasing potential behavior with an increase in the amount of lime/cement or with an increase in the compaction density of the samples, which follows the form of the following equation:

$$q_t/q_{t-\text{normalizaded at}\left(\frac{\eta}{Biv^{0,20}}=35\right)} = 4.5 \bullet 10^6 \left[\frac{\eta}{(B_{iv})^{0,20}}\right]^{-4,35} \qquad (6)$$

$$(R^2 = 0.95)$$

Eq. 6 has an error of 4% of the estimated values under the experimental values. This high acceptance of the results is due to the value of 0.20 which provides more significant adjustments to the tensile values dependent on the porosity index/binding content, as seen in Eqs. 4-5 went from having acceptance errors of 20% (See Eqs. 2-3 and Figure 4) to an average error of 4% (Figs. 5-6).

4. CONCLUSION

According to the methodology, presentation, and analysis of the results, the following conclusions can be presented:

– Both soil-cement and soil-lime mixtures increased indirect tensile strength with an increased binder added and mold density during sample compaction.

– In terms of voids, porosity had the same influence for both soil-lime and soil-cement, so the traction was mainly influenced by the type of binder (lime or cement), with the highest strengths being developed by the cement due to its high content of calcium oxide.

– The porosity/volumetric content of the binder ratio proved to be an effective index to estimate the tensile strength of all mixtures when adjusted to an exponent of 0.20.

– The porosity/volumetric content of the binder ratio adjusted to 0.20 allowed obtaining coefficients of determination greater than 0.90 and acceptance errors of 4% of the equations that controlled the strength of the soil-lime and soil-cement mixtures.

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