Equation Controlling Split Tensile Strength of a Sedimentary Soil Depending on Curing Time

Jair de Jesus Arrieta Baldovino, Ronaldo Luis dos Santos Izzo, and Carlos Millan-Paramo

***Abstract*— Unconfined compression tests are usually used to assess strength in improved soils. However, split tensile strength is the most significant increase. Split tensile strength tests are important in rural, urban, and aviation pavement mechanics studies. Tensile stresses are produced by traffic movement, soil contraction, seasonal temperature variations, and, in some situations, by directly applying distributed loads on the soil. This study aims to analyze the influence of lime addition on the split tensile strength of clayey sedimentary soil at different curing times. Control parameters such as moisture, matric suction, lime content, porosity, volumetric lime content, and curing periods were evaluated. The sample results show that the split tensile strength increased as the lime content increased, and soil porosity decreased. Finally, the porosity/volumetric lime content ratio was chosen as a unique parameter to access split tensile strength.**

***Index Terms*— Lime-soil, split tensile strength; porosity/volumetric lime ratio; curing time.**

I. Introduction

THE split tensile test, also known as the indirect tensile test or Brazilian Test, was developed independently in Brazil and Japan in 1943. The test is performed by applying a compression load in a cylindrical specimen positioned between two rectangular pieces with dimensions determined as a function of the specimen diameter and positioned diametrically opposite from each other, as can be seen in Figure 1.

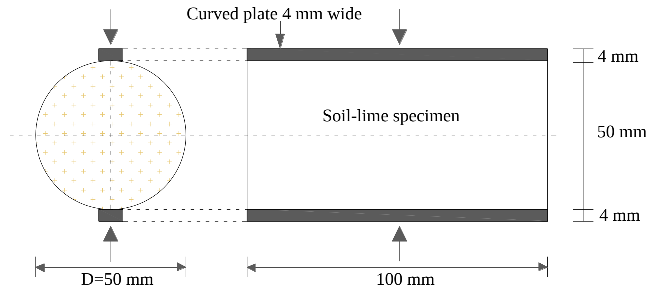

Fig. 1. Schematic sketch of specimen for split tensile test.

The test mechanism is carried out as follows: in addition to causing compression, the conditions imposed by the load in elastic materials also produce a practically uniform tensile stress over a significant area of the diametric plane containing the applied load [1]. Two types of test specimens are commonly used. One measuring 76.2 mm in height and 38.1 mm in diameter [2], and another measuring 100 mm in height and 50 mm in diameter [3], making sure to keep a 2 to 2.5 height/diameter ratio.

Soil stabilization or enhancement techniques were introduced years ago, with the main objective of improving soil geotechnical properties to the extent that they meet the required technical specifications such as in foundations, slopes and highway projects. Since then, several studies have focused on the influence of adding cementing agents, such as cement, lime, fly ash, polystyrene fibers, etc. in tensile strength improvement in sandy and clayey soils (e.g.: [2-7]). The effects of the cementing agent content, curing period, water/cementing agent ratio, size of geosynthetic fibers and especially the porosity/volumetric content of the cementing agent ratio are evaluated in split tensile tests. The volumetric content of the cementing agent is a dimensionless ratio defined by the volume of the cementing agent divided by the volume of the specimen in which it is included. In [3] and [5] studied the influence of the porosity/volumetric lime content ratio on the split tensile strength and unconfined compression of artificially cemented soils and concluded that the volumetric content of the cementing agent is a very important factor when making dosages to stabilize soils.

Lime is widely used in civil engineering applications such as road constructions, landfills and surface and deep foundations. When lime is added to clayey soils in the presence of water, several reactions occur that lead to enhanced soil properties. These reactions include cation exchange, flocculation, carbonation and pozzolanic reaction. The cation exchange occurs between the cations associated to the clay particle surfaces and the lime calcium cations. The term base change is attributed to this reaction, and the soil cation exchange with lime makes the soil more stable [8]. The cation exchange and attraction forms flakes by drawing the clay particles closer. This process is called flocculation and is the main reason for the geotechnical properties modification of clayey soils when treated with lime [9].

Soil stabilization techniques through the use of lime has been used in geotechnical engineering in cities such as Curitiba-Brazil, where the soils in the region are not adequate for some geotechnical works, such as pavement layers, since clays offer low CBR (California Bearing Ratio) and high physical and chemical expansibility. Therefore, the present study aims to analyze the effect of hydrated lime

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addition on the split tensile strength of clayey sedimentary soil from the metropolitan region of Curitiba-Brazil at different curing periods, as well as to create a split tensile strength estimation equation for any lime content applied and considering any desired curing period.

II. Materials and Methodology

A. Soil

The soil used in this research was collected in Fazenda Rio Grande, in the metropolitan region of Curitiba. According to the ASTM [10], the soil is composed of 7.5% of medium sand, 25.9% of fine sand, 66.5% of soil passing through the 0.075 mm sieve (# 200), in which 57.6% was composed of silt and 9.3% of clay as can be observed in Figure 2. Table 1 lists the soil's physical properties, highlighting the plasticity index of 21.3% and the 2.71 actual specific gravity of the grains. According to the Unified Soil Classification System (USCS), the soil is classified as an elastic sandy silt, and according to the Transportation Research Board (TRB) classification system, the soil is classified as clayey soil (A-7-6).

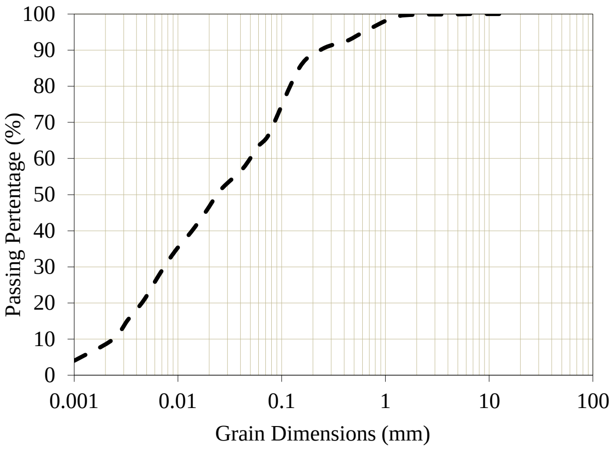

Fig. 2. Grain size distribution of soil.

TABLE I

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

B. Lime

This study used dolomitic hydrated lime (CH-III) which is one of the most used types of hydrated lime in Brazil. It is mainly composed of calcium hydroxides -Ca(OH)2- and Magnesium -Mg(OH)2-, and is produced in Almirante Tamandaré (Paraná, Brazil). The #200 sieve retained an accumulated percentage of 9%, which is in accordance with the Brazilian standard NBR 7175 [11] that specifies that this type of material should have less than 15% retained in the #200 sieve. The lime's actual specific gravity was calculated in 2.39.

C. Lime dosage, molding points and curing time

The methodology proposed by Rogers et al. [12], also called the ICL (Initial Consumption of Lime) method, in which a pH variation curve versus lime content is created, was used for the lime dosage. The ideal (minimum) lime percentage value is that in which the pH reaches a maximum constant value, as can be seen in Figure 3. Upon reaching the pH value of 12.5 with 3% lime, the pH remained constant, regardless of the increase in lime content. Therefore, the initial lime content used in this research was 3%. This study used 3%, 5%, 7% and 9% of lime content, considering international studies and for economy, due to its possible use in construction works.

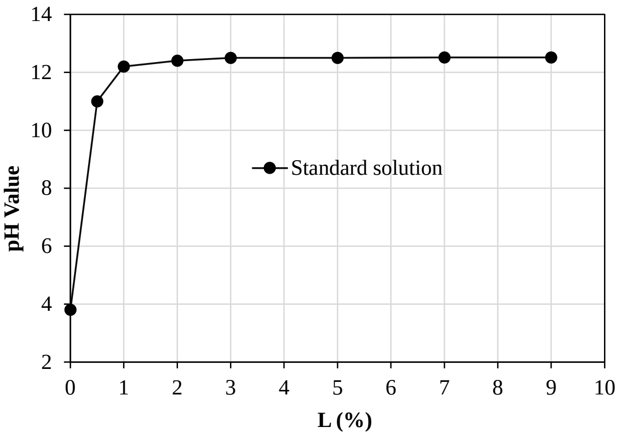

Fig. 3. Results of ICL tests for the soil-lime mixtures.

The molding points were defined by soil compaction tests at three compaction energies: standard (EN), intermediate (EI) and modified (EM) as can be seen in Figure 4. Each determined optimum point has a moisture content (ω) and an apparent maximum specific dry weight (γd). The molding points are: EN ω=28.5% and γd=13.80 kN/m3; EI ω=22.8% and γd=15.10 kN/m3; EM ω = 20% and γd=16.15 kN/m3. The 3 molding points are in the 82% saturation line. The soil-lime mixtures curing periods used for this study were defined in 15, 30, 90 and 180 days.

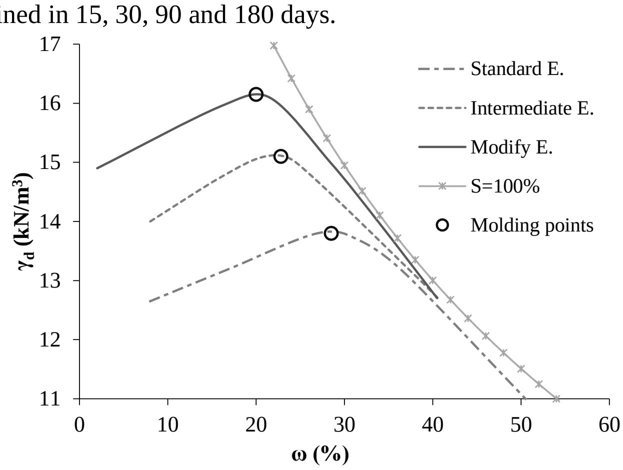

Fig. 4. Compaction curves and molding points.

D. Split Tensile Strength Tests

Specimens with 100 mm in height and 50 mm in diameter were molded for the split tensile tests. The soil was oven dried at 100±5°C and then placed in uniformly distributed portions to be mixed with the different lime contents. The amount of dry lime was added according to the dry weight of the soil sample. The soil was then mixed with the lime so that the mixture was as homogeneous as possible. Finally, a percentage of water by weight, relative to the optimum water content of the molding points shown in Figure 4, was added.

Samples for the specimen molding were statically compacted in two layers with a stainless-steel mold with a 50-mm internal diameter, 100-mm high and 5-mm thick, under optimum conditions. To confirm the maximum specific dry weight values obtained during the compaction tests, the mold volume and the wet mixing weight required for each specimen were calculated. The quantity required for each specimen was weighed in portions after the referred calculations.

The specimens were weighed on a scale with 0.01 g in precision and the dimensions were measured with a 0.1 mm error pachymeter. The extracted specimens were wrapped with transparent plastic to maintain the moisture content. Finally, to prevent significant changes in moisture control until the day of the test, the specimens were taken to a wet chamber for curing for 15, 30, 90 and 180 days at a mean temperature of 25°C. In order to be used in the indirect tensile test, the samples had to meet the following maximum errors: ±0.5 mm for the diameter and ±1 mm for the height of the sample sizes, ±1% for the specific apparent dry mass (γ_d) and ±0.5% for the moisture content (ω). A Wille Geotechnik UL60 automatic press and axial load calibrated rings with a capacity of 4.5 kN and 10 kN were used to perform the indirect tensile tests. The tests were performed with an automated data collection system, mainly measuring the test's applied force with 2.5 N in resolution, the deformation, with a sensitivity of 0.001 mm and the speed (1.00 mm/min). The split tensile strength (q_t) test procedures followed the American standard ASTM C496-96 [13]. When a maximum peak is reached in the axial stress-deformation test, the split tensile strength (q_t) is determined through the following expression:

$$q_t = \frac{2P_R}{\pi DH} \tag{1}$$

In which P_R is the rupture load at the peak of the diametral strain-deformation curve, D and H are respectively, the diameter and height of the specimen. Three specimens, one for each lime content used, were molded with their specific apparent dry mass and moisture and were tested again under the same conditions after the corresponding curing period, for the tensile strength analysis.

E. Matric suction tests

After the specimens subjected to the split tensile tests ruptured, they were used to measure the matric suction and thus evaluate its influence in the final resistance value. The matric suction is the pressure difference between the pore air pressure and the water pressure in the pores. Therefore, the matric suction value is the soil water pressure deficit in relation to the air pressure. In other words, it is the soil water potential deficit in relation to the soil water potential in the ambient air pressure [14]. The matric suction originates from the capillary forces of the soil-lime test specimens and was therefore measured to determine its influence on split tensile strength [15]. Samples between 20 and 30 mm thick and 50 mm in diameter were used to measure the suction with the filter paper technique following the procedure described by Marinho [16] and using a 0.0001 g precision scale. The equations developed by Chandler [17] were used for the paper calibration, in which ω is the filter paper's moisture content after its equilibrium state with the soil-lime samples:

$$\text{Suction (kPa)} = 10^{\,6.05-2.48\log\omega} \quad \text{to } \omega > 47\% \tag{2}$$

$$\text{Suction (kPa)} = 10^{\,4.84-0.0622\log\omega} \quad \text{to } \omega \leq 47\% \tag{3}$$

III. Results and Discussions

A. Split tensile strength variation per lime content

The influence of the cementing agent content is the first parameter to be evaluated in artificially cemented soil resistance, represented by lime in this study. Figure 5 and Figure 6 show the split tensile strength results for specimens with 15 and 30-day curing periods, respectively.

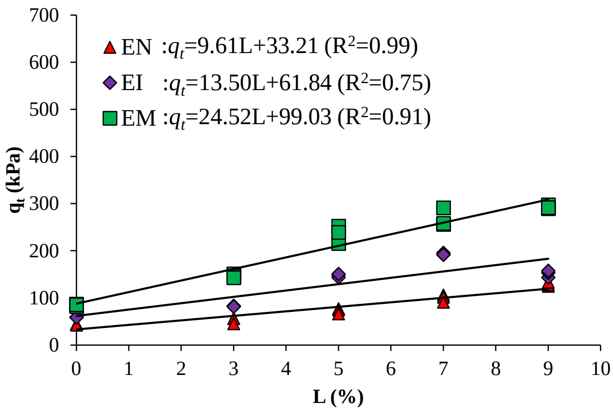

Fig. 5. Variation of split tensile strength with lime content for 15 days cure.

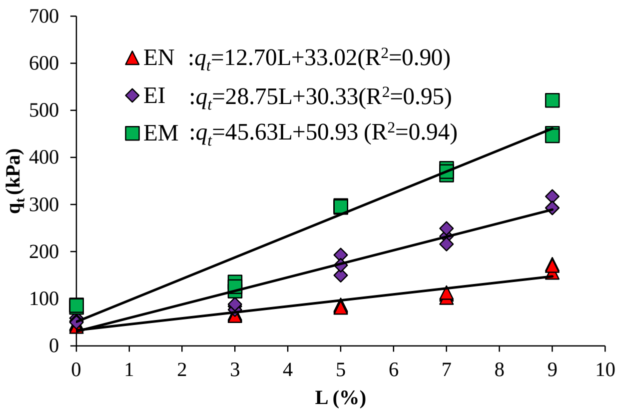

Fig. 6. Variation of split tensile strength with lime content for 30 days cure.

The soil obtained a maximum split tensile strength of 290 kPa with 9% lime at the EM point with a 15-day curing period. This means a 360% gain compared to the soil resistance with no lime addition. For a 30-day curing period, 450 kPa in maximum resistance was achieved at the EM point with the use of 9% lime, meaning an increase of 450% compared to L=0%. It is important to mention, observing Figure 5 and Figure 6, that there is a linear tendency of the split tensile strength depending on the molding point used. The resistance gain is proportional to the apparent dry specific mass increase of the specimens. Figure 7 and Figure. 8 show the split tensile strength variation per lime content used at the EN, EI and EM molding points for 90 and 180 days of curing periods, respectively.

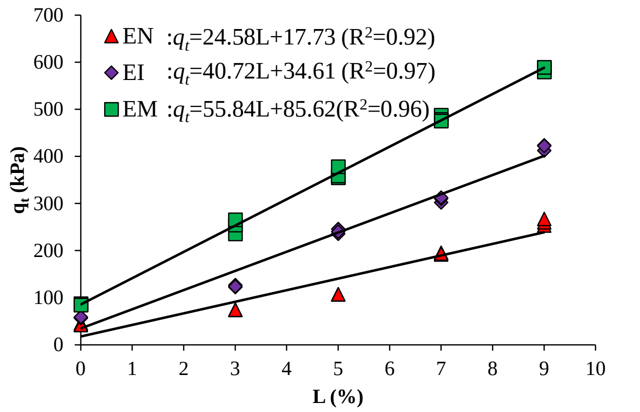

Fig. 7. Variation of split tensile strength with lime content for 90 days cure.

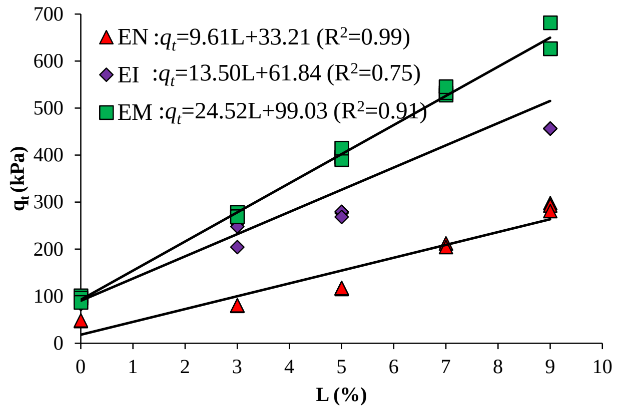

Fig. 8. Variation of split tensile strength with lime content for 180 days cure.

For a 90-day curing period, maximum resistance was achieved with L=9% in the EN, EI and EM points. The maximum results were 600 kPa for EN, 410 kPa for EI and 250 kPa for EM, respectively representing increases of 700%, 710% and 600% for L=0%. For a 180-day curing period, the q_t addition behavior was the same as the samples with 15 to 90 days of curing periods: resistance increase proportional to the lime content and apparent dry specific mass and the maximum q_t value was 680 kPa with L=9%. There was no constant resistance gain for the 4 curing periods with L=0%; the split tensile strength gains increased with the lime content. The lowest resistance gain was achieved by a 3% lime content and the highest gain with a l9% lime content. Therefore, the maximum resistance values were obtained with L=9% resulting in 390 kPa, 450 kPa, 600 kPa and 680 kPa for 15, 30, 90 and 180 days, respectively.

B. Split tensile strength variation per lime content

The influence of the water/cementing agent variable in a weight/weight or volume/volume relation is considered an important factor to obtain good resistance in enhanced soils. For example, the water/cement ratio (W/C) in concrete is widely used for estimating axial strength. In lime-enhanced soils, the water/lime ratio (W/L) influence on the final q_t resistance of the mixtures can be studied.

Figure 9, Figure 10, Figure 11, and Figure 12 illustrate the split tensile strength variation influenced by the W/L ratio at their respective 15, 30, 90, and 180-day curing periods.

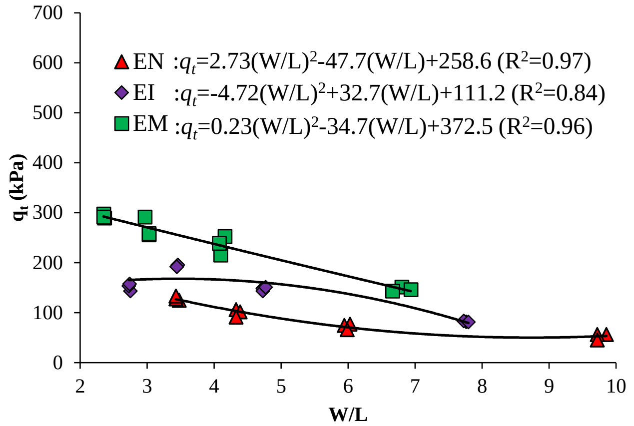

Fig. 9. Variation of split tensile strength with water/lime content ratio for 15 days cure.

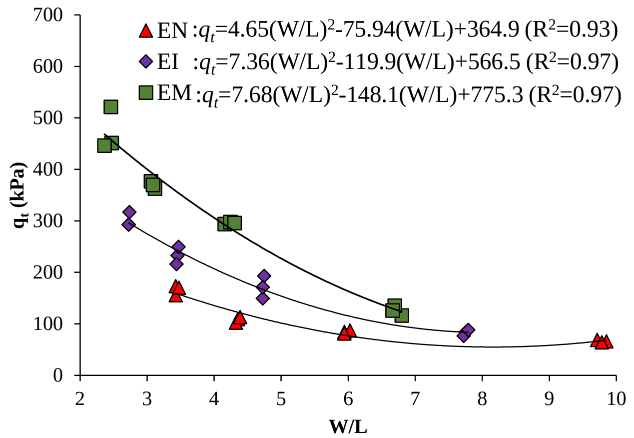

Fig. 10. Variation of split tensile strength with water/lime content ratio for 30 days cure.

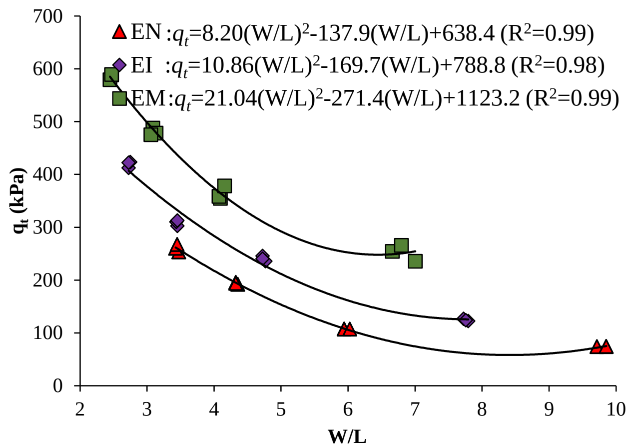

Fig. 11. Variation of split tensile strength with water/lime content ratio for 90 days cure.

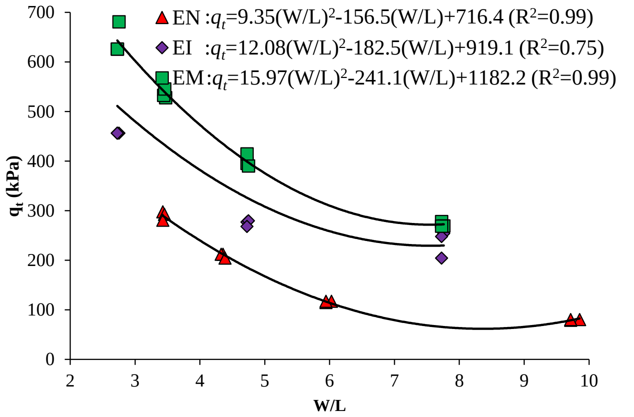

Fig. 12. Variation of split tensile strength with water/lime content ratio for 180 days cure.

The W/L ratio varies from 2 to 10 in all samples, with q_t increasing when W/L decreases and when the apparent dry specific mass increases. As can be observed in Figure 9-12, the q_t experimental points trend has a larger γ_d as the W/L ratio decreases, that is, the closer it gets to zero.

C. Split tensile strength variation with the specimen's porosity

Consoli et al. [18] state that porosity has an influence on the resistance in lime stabilized soils because when the voids in the soil are reduced, the mixture becomes more rigid. The split tensile variation together with the porosity reduction was evaluated in this study. The soil-lime specimen porosity can be calculated by the following equation:

$$\eta = 100 - \frac{100\left(\left(\frac{V_S\gamma_d}{1+L/100}\left(\frac{S}{100}\right)\right)/G_{SS}+\left(\frac{V_S\gamma_d}{1+L/100}\left(\frac{L}{100}\right)\right)/G_{SL}\right)}{V_S} \quad (4)$$

In which V_S is the specimen's total volume, γ_d is the apparent specific dry weight, L is the lime content, S is the soil content, and G_{SS} and G_{SL} are respectively the actual specific gravity of the soil and lime grains. The porosity decreases as the specimen's specific mass increases, so the higher the compaction energy, the smaller the porosity and the greater the resistance. Figure 13, Figure 14, Figure 15 and Figure 16 illustrate the porosity influence on tensile strength for samples cured for 15, 30, 90 and 180 days, respectively.

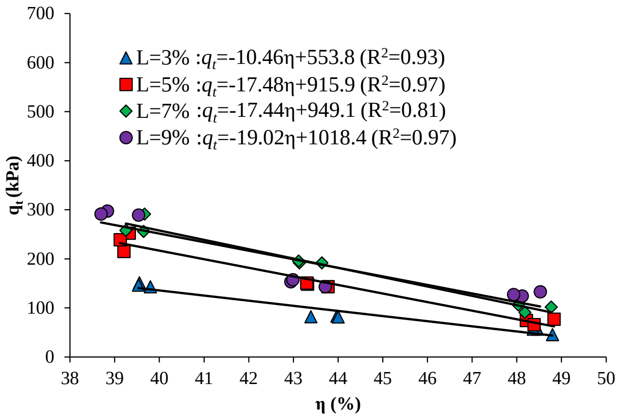

Fig. 13. Variation of split tensile strength with porosity for 15 days cure.

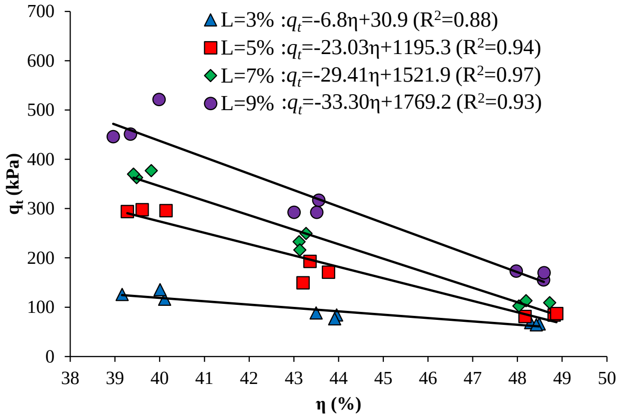

Fig. 14. Variation of split tensile strength with porosity for 30 days cure.

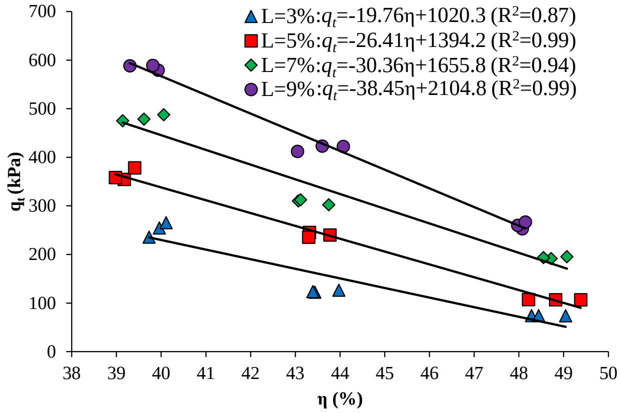

Fig. 15. Variation of split tensile strength with porosity for 90 days cure.

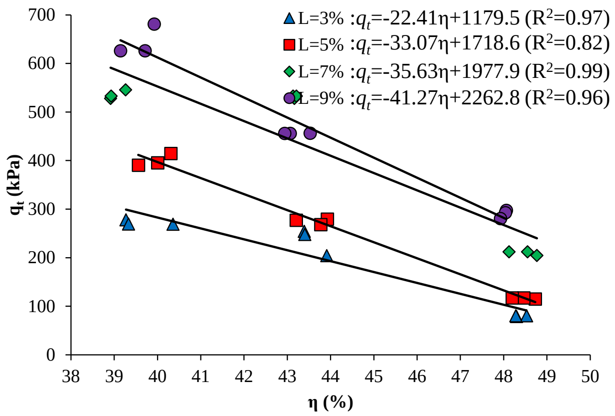

Fig. 16. Variation of split tensile strength with porosity for 180 days cure.

D. Split tensile strength variation with porosity/lime volumetric content ratio

The lime volumetric content is defined as the ratio between the lime volume and the specimen volume (Equation 5). The volumetric content increases proportionally to the increasing lime content while the porosity/volumetric content ratio decreases

$$L_V = \frac{100\left(\left(\frac{V_S\gamma_d}{1+L/100}\left(\frac{L}{100}\right)\right)/G_{SL}\right)}{V_S} \quad (5)$$

Figure 17, Figure 18, Figure 19 and Figure 20 illustrate the q_t variation concerning η/L_v for curing periods of 15, 30, 90 and 180 days, respectively.

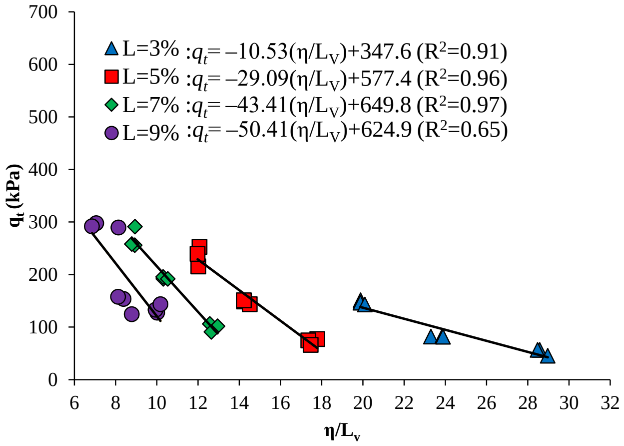

Fig. 17. Variation of split tensile strength with porosity/volumetric lime content ratio for 15 days cure.

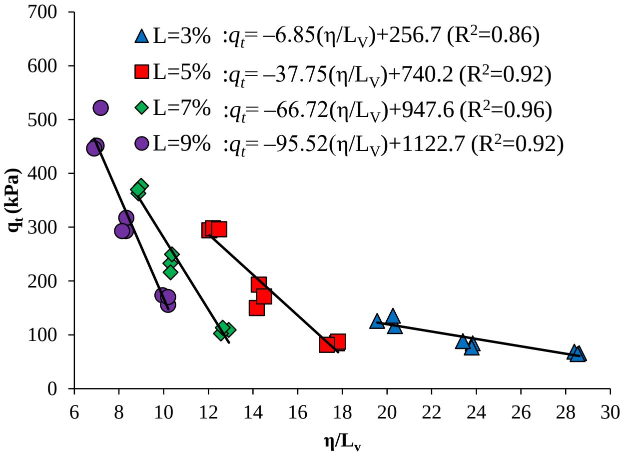

Fig. 18. Variation of split tensile strength with porosity/volumetric lime content ratio for 30 days cure.

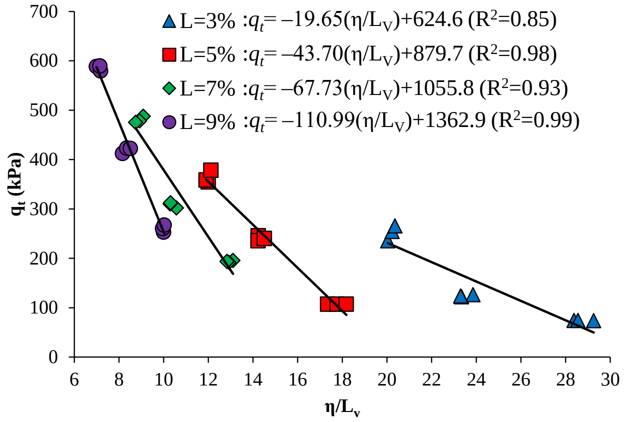

Fig. 19. Variation of split tensile strength with porosity/volumetric lime content ratio for 90 days cure.

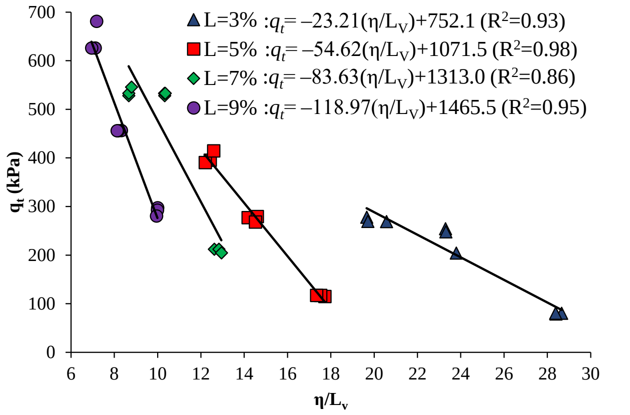

Fig. 20. Variation of split tensile strength with porosity/volumetric lime content ratio for 180 days cure.

For all curing periods, η/L_v ranges from 20 to 29 for L=3%, from 12 to 17.8 for L=5%, from 9 to 13 for L=7%, and finally from 6.9 to 10 for L=9%. The results show as the lime content increases, the η/L_v variation decreases. This is because lower lime contents at the molding points represent a greater η/L_v dispersion and low tensile strength gain as can be seen in Figs. 17-20. The η/L_v variation remained constant for all curing periods while q_t varied increasing proportionally to the lime content of the specimens. Although there is a linear point tendency for each lime content, the experimental points of all contents have a potential tendency.

E. Split tensile strength dosage of lime treated soil

The ratio of increase split tensile strength is a very important variable in artificially cemented soils mechanics. By obtaining a general dosage equation as a function of the curing period and lime content for the studied soil, one can calculate the amount of lime, the compaction degree and the necessary curing time to be employed on the soil to obtain a desired split tensile strength in the field.

Figures 17-20 illustrate the porosity/lime volumetric ratio influence on the split tensile strength for 15, 30, 90, and 180-day curing periods in all compaction energies. According to [18], it is possible to find a single point tendency in Figures 17-20 by raising the lime volumetric content (L_v) to an exponent. The exponent with which the points are organized and present the best determination coefficient in this study is 0.22. Therefore, the L_v variable was elevated to 0.22, and Figure 17-20 graphs were elaborated. Figure 21 illustrates the split tensile strength increase ratio for samples that were ruptured at 15, 30, 90, and 180-day curing periods. A direct influence of the $\eta/L_v^{0.22}$ factor on the q_t results is observed especially when the curing time increases (the R^2 values demonstrate this) [19]. As can be seen in Figure 21, the growth rate increased from 3.7 to 15 days, then increased to 5.05 for 30 days, then 7 to 90 days, and finally increased to 8.2 for 180 days. The equations describing the tensile behavior for 15, 30, 90, and 180-day curing periods are:

$$q_t=4.75\text{x}10^{8}\left[\frac{\eta}{L_v{}^{0.22}}\right]^{-4.30} \quad (R^2=0.92) \tag{6}$$

$$q_t=6.5x10^8\left[\frac{\eta}{L_v^{0.22}}\right]^{-4.30} \quad (R^2=0.96) \tag{7}$$

$$q_t=9x10^8\left[\frac{\eta}{L_v^{0.22}}\right]^{-4.30} \quad (R^2=0.97) \tag{8}$$

$$q_t=10.5x10^8\left[\frac{\eta}{L_v^{0.22}}\right]^{-4.30} \quad (R^2=0.90) \tag{9}$$

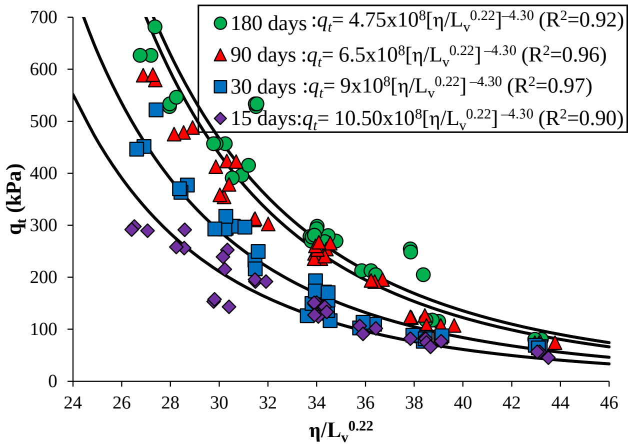

Fig. 21. Variation of Split tensile strength with porosity/volumetric lime content (using the exponent 0.22) ratio for 15, 30, 90, and 180 days cure.

Figure 22 illustrates the split tensile strength estimation of the soil-lime mixtures for any curing time and any η/L_v ratio. The q_t values for Equations 6-9 were divided by $108(\eta/L_v^{0.22)-4.30}$ obtaining a constant ranging from 4.75 and 10.5. A point tendency was determined to establish a general dosage equation for the studied soil. The equation for the soil-lime dosage is:

$$q_t= [2.3077\ln(t)-1.4291]x10^8(\eta/L_v^{0.22})^{-4.30} \quad (R^2=0.99) \tag{10}$$

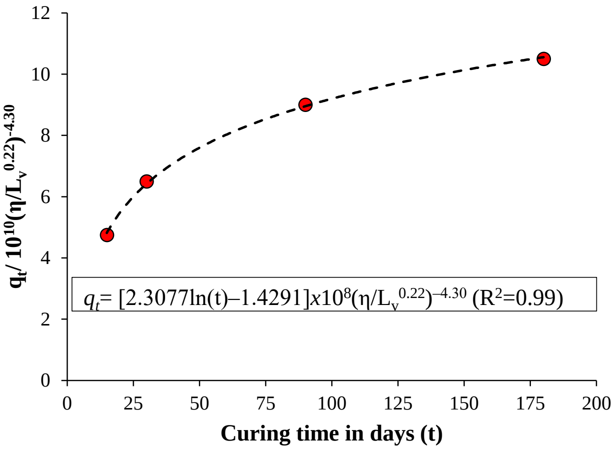

Fig. 22. Estimate q_t for any cure time using η/L_v ratio.

All the sample variables (porosity, lime content, curing time, moisture, etc.) in this study and their split tensile strength results were introduced into the dosage equation (Equation 10) to corroborate its efficiency. Figure 23 shows the split tensile strength experimental and theoretical (using the dosage equation) values. When the theoretical and experimental values were compared, Equation 10 presented a determination coefficient (R^2) of 0.95, concluding that it can be used for dosing the studied soil.

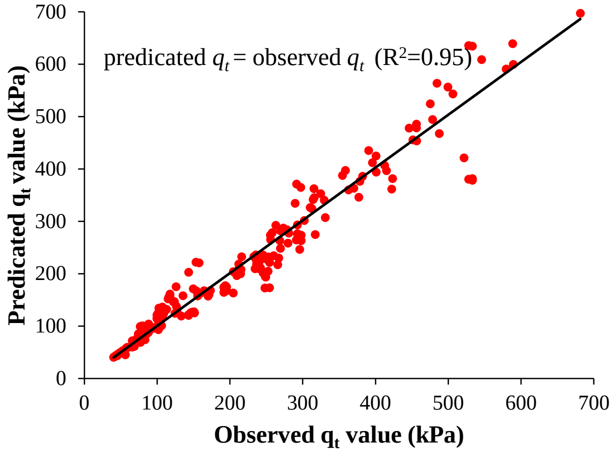

Fig. 23. Validation of estimate q_t for any cure time using η/L_v ratio.

F. *Matric suction influence*

Once the split tensile tests were carried out, the matric suction was measured using the filter paper technique described in item 2.5. The specimens showed a variation of ±0.5% from the initial moisture content of the split tensile tests. The matric suction calculated with the filter paper presented results ranging from 1% to 6% of the resistance values of the soil-lime mixtures. These are not significant figures and may be considered as an irrelevant variable in the analysis described in this study.

IV. Conclusion

According to the experimental and theoretical data presented on this research, the following conclusions can be considered:

– The η/L_v index influences the split tensile strength of the studied soil-lime mixtures. With the use of the n/Lv index was possible to develop a dosing equation to estimate qt for any curing period, dry unit weight, and lime content.

– The split tensile strength increase is directly proportional to the used lime content, the curing period, and the samples' porosity. The maximum q_t values obtained for the analyzed soil in this study was 680 kPa.

– The better tendency of the experimental points of the samples submitted to the tensile tests is established when the exponent on the volumetric content is 0.22. Therefore, it is possible to correlate all the curing periods by using the $\eta/L_v^{0.22}$ relation.

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