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Behavior Of Stabilized Soil With Cellulose Ash And Hydrated Lime

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ABSTRACT

The simple compressive strength and the tensile strength by diametral compression were systematically investigated to analyze the performance of a silty soil from the metropolitan region of Curitiba (Brazil) stabilized with ash from the paper production industry and with hydrated dolomitic lime, using cure of 14, 28 and 90 days. A series of compaction tests at normal Proctor energy were performed to calculate the optimal compaction parameters of soil-ash-lime mixtures: maximum dry specific weight ($\gamma_{d\text{-}max}$) and optimal moisture content (ω_o). Four cellulose ash contents were added and used (5%, 10%, 15% and 20% in relation to the dry mass of the soil) and a fixed lime content (L) of 5% based on the initial consumption of modified lime and established from the interpretation of pH measurements performed on various soil-ash-lime mixtures. The results demonstrate that there is an increase in the optimal moisture content and a decrease in the maximum dry specific weight of the compaction curves with increasing cellulose ash content. On the other hand, the tests of simple compression and tension by diametral compression reveal that there is an increase in the values of mechanical strength of the mixtures up to an ash content of 15%. Finally, dosage equations that allow estimating the strength values of mixtures were developed based on a semi-empirical model taking into account the specific mass and volume of the materials in addition to the compaction energy.

Keywords: Soil-gray-lime, simple compression, tension by diametral compression, porosity/lime index, cellulose ash.

1. INTRODUCTION

Recent studies demonstrate the improvement of the Guabirotuba Formation (FG) soils using different stabilizers. Baldovino et al. (2018a) studied the improvement of a silty soil from FG stabilized with hydrated lime using 180 curing, showing an improvement in both compression and tension. Then, Baldovino et al. (2018b) analyzed the effects of adding lime from another FG silty soil using normal Proctor energy and 90 days of curing, the results showed an increase in simple compression and indirect tension of up to 75%. Recently Moreira et al. (2019) improved a silty-sandy soil of the FG with cement and ground tile residue, obtaining an increase in simple compression, directly influenced by the voids and volume of cement added. However, soil stabilization studies of FG using cellulose ash and lime nor in other soils have not yet been carried out.

Therefore, this study proposes to study the mechanical properties of a soil characteristic of the third layer of the Formation (yellow layer) using hydrated lime and cellulose ash, with this a new geomaterial is introduced in the literature and an alternative procedure is used in soil stabilization of FG using a residue that can be used in civil construction.

2. EXPERIMENTAL PROGRAM

The experimental program was divided into two stages: the first was the characterization tests of the soil, cellulose ash and hydrated dolomitic lime: soil granulometry according to the American standard ASTM D2487 (ASTM 2011), Atterberg limits of the soil according to Brazilian standards NBR 7180 (ABNT 2016) and NBR 6459 (ABNT 2016), the actual specific gravity of the soil grains according to the ASTM D854 (ASTM 2014) standard, the actual specific gravity of the cellulose ash and lime grains hydrated powder according to Brazilian standard NBR 16605 (ABNT 2017) and soil compaction properties with different ash and lime contents in normal Proctor energy according to Brazilian standard NBR 7182 (ABNT 2016); and the second stage consisted of molding, curing and breaking the soil-ash-lime specimens submitted to simple compression and tensile tests by diametrical compression at different curing times.

2.1 Materials

A yellow silty soil from the FG, cellulose ash from the paper industry, hydrated dolomitic lime and distilled water were the materials used in the research. The soil sample was collected on a road slope at 3 m from the ground level (third layer of the FG) in the municipality of São José dos Pinhais, near the city of Curitiba (Brazil), manually in a deformed state, avoiding a possible contamination and in sufficient quantity to carry out all the tests. A soil with similar characteristics of the red color FG has already been used in previous studies by Baldovino et al. (2018b, a) for stabilization with hydrated lime. Hydrated lime was supplied by a local producer, which has a grain density of 2.39 g/cm^3 and a percentage passing through the #0.075 mm sieve of 95%.

The cellulose ash was collected in a company (located in the city of Canoinhas - Santa Catarina / Brazil) that produces white paper for the production of toilet paper, in this manufacture recycled paper is used in which cellulose fibers are recovered from the scraps to use them in their products, thus discarding part of this material as liquid waste with high solids content, requiring the removal of large amounts of liquids from the material, forming what is called primary sludge, this sludge is formed by kaolin, cellulose, traces not significant amounts of chemicals and water. Thus, classified as non-inert class II A pulp and paper industry waste according to technical standard NBR 10004 (ABNT 2004). After removing the moisture from the sludge, the calcination process is carried out so that the unit is completely evaporated, reaching a temperature around 900° C, thus resulting in the final product, which is the ash used in this article. Finally, for all soil characterization tests, soil-ash-lime mixtures and for the molding of specimens, distilled water at 24±3°C was used to avoid unwanted reactions and limit the number of variables.

Figure 1 shows the granulometric distribution curve of soil and cellulose ash. The diameters of the soil particles corresponding to 10%, 30%, 50%, 60% and 90% of passing material were calculated as d_{10}=0.003 mm, d_{30}=0.01 mm, d_{50}=0.025 mm, d_{60}=0.038 mm and d_{90}=0.3 mm (see Figure 1). Additionally, the coefficient of uniformity (i.e., $C_u=d_{60}/d_{10}$) and the coefficient of curvature [i.e., $C_c=(d_{30})^2/(d_{10}\cdot d_{60})$] were calculated as C_u=8.33 mm and C_c=1.33. For cellulose ash, the diameters of the solid particles corresponding to 10%, 30%, 50%, 60% and 90% of passing material were calculated as

d_{10}=0.013 mm, d_{30}=0.03 mm, d_{50}=0.2 mm, d_{60}=0.35 mm and d_{90}=1 mm, consequently C_u and C_c were determined to be 26.92 and 0.35, respectively.

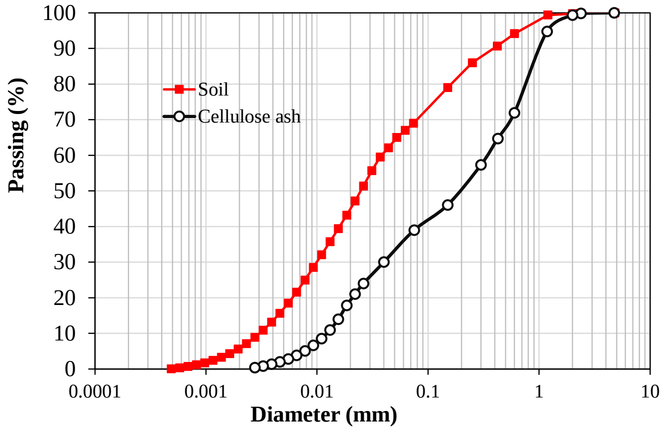


Figure 1. Grain size distribution curve of silty soil and cellulose ash

Table 1 presents the physical properties of soil and cellulose ash. According to the Unified Soil Classification System (SUCS), the soil is classified as sandy elastic silt (MH). The soil, of yellow color, presents a percentage of coarse sand of 5%; average sand of 12%; 18% fine sand; 60% silt and 5% clay, with the percentage of silt (0.002 mm < ϕ < 0.075 mm) making up the largest portion of the soil. During the Atterberg limit tests, it was noticed that the cellulose ash does not show plasticity while the soil has a plasticity of 14.86% and a real density of the grains of 2.62 g/cm^3.

Table 1. Physical properties of soil and cellulose ash

Properties	Soil	Cellulose ash
Liquid Limit, %.	50.82	–
Plasticity Limit, %.	35.96	–
Plasticity index, %	14.86	No plastic
Actual grain density	2.62	2.31
Coarse sand (0.6 mm< diameter<2 mm), %.	5	30
Medium sand (0.2 mm< diameter <0.6 mm), %.	12	20
Fine sand (0.06 mm< diameter <0.2 mm), %.	18	15
Silt (0.002 mm < diameter <0.06 mm), %.	60	35
Clay (diameter < 0.002 mm), %.	5	–
Effective diameter (D_{10}), mm	0.003	0.013
Average diameter (D_{50}), mm	0.038	0.20
Coefficient of uniformity (C_u)	8.33	26.92
Coefficient of curvature (C_c)	1.33	0.35
Classification (SUCS)	MH	–
UCS–Virgin soil, kPa	104,58	NC (No calculated)
STS–Virgin soil, kPa	16.62	NC

STS/UCS–Virgin soil ratio	0.16	–
ϕ–Virgin soil, (°)	26	NC
Cohesion– Virgin soil, kPa	23	NC
Color	Yellow	White

Table 2 displays the chemical composition of soil and ash determined with X-Ray Fluorescence. The chemical properties of lime also shown in Table 2 were provided by the producer and the physical properties were calculated in the laboratory. Note that the soil is mainly composed of silica and alumina with a small amount of sulfuric oxide. Table 3 presents the soil compaction properties in the three energies according to the Brazilian standard NBR 7182 (ABNT 2016). As typical of fine soils, an increase in the maximum sex specific gravity ($\gamma_{d\text{-}max}$) and a decrease in the optimal moisture content (ω_o) were found due to the increase in energy. The maximum point reached in the modified energy, according to Table 3, is found at $\gamma_{d\text{-}max}$=16.75 kN/m3 and ω_o=14.5%.

Table 2. Physicochemical properties of soil and cellulose ash

Compound	**Concentration (%)**		
	Soil	**Cellulose ash**	**Dolomitic lime hydrated**
SiO_2	48.78	8.8	0.70
Al_2O_3	44.51	8.3	0.40
Fe_2O_3	0.61	0.7	0.20
CaO	–	55.6	63.2
MgO	–	0.9	10.4
K_2O	0.84	0.2	0.30
Na_2O	–	0.1	0.1
TiO_2	0.92	0.4	0.2
MnO	–	0.1	–
P_2O_5	–	0.2	–
SO_3	4.12	1	–
SrO	–	0.2	–
Cl	–	0.1	–
ZnO	–	0.1	–
CuO	–	0.1	–
Fire loss	0.22	23.9	24.5

Table 3. Soil compaction properties

Soil	**Maximum dry specific weight (kN/m^3)**			**Optimum moisture content (%)**		
	Normal Energy	Intermediate Energy	Modified Energy	Normal Energy	Intermediate Energy	Modified Energy
Yellow silt	13.72	15.43	16.75	26.5	20.5	14.5

2.2 Fixation of ash content, lime content, curing time and molding points

To determine a minimum lime content (L) the Eades and Grim (1960) method, also called "Optimum Lime Content" or OLC, was used. This method consists of adding lime to the mixture and measuring its pH. By the OCL method, the minimum lime content is one that leads to a maximum and constant pH value of approximately 12.4 which represents the lime content to satisfy the initial reactions and cation exchange. The method consists of: 20 g of stabilized gray soil sieved through a 425 µm sieve is mixed with 100 ml of distilled water and stirred for 30 seconds, then for a further 30 seconds every 10 min for a total of one hour. The pH of the resulting mixture is then tested with a pH meter calibrated to a pH=12 buffer solution. The OLC corresponds to the minimum lime content needed to produce a soil water pH of 12.4, namely a saturated lime solution. Although tests are conducted on the fine fraction of the stabilized material, that is, that fraction most reactive to lime stabilization, the results are assumed to apply to the entire material classification (Ciancio et al. 2014).

Lime contents between 3 and 7% were added in relation to various soil-ash mixtures (using ash contents between 5 and 20% and soil passing through the 425 µm sieve). Soil-ash mixtures reached a pH value close to 12.4 when added 5% lime powder to a percentage of 20% ash. Thus, the lime content chosen was 5% in reference to the dry mass of the soil and the ash contents were chosen as 5%, 10%, 15% and 20% also in reference to the dry mass of the soil. In this way, 4 soil-lime-ash mixtures were made: Soil+5%lime+5%ash, Soil+5%lime+10%ash, Soil+5%lime+15%ash and Soil+5%lime+20% Grey; and a virgin soil control mixture (i.e., without lime or ash addition). Because the soil-lime-ash pozzolanic reactions take place slowly, curing times up to 90-d (days) were chosen, thus 3 times were proposed to evaluate the mechanical strength of the studied mixtures: 14-d, 28-d and 90- d.

After fixing the ash and lime contents and the curing times, the compaction tests were carried out at the normal Proctor energy [Brazilian standard NBR 7182 (ABNT 2016)] of each mixture to establish the molding points (i.e., maximum dry specific gravity and optimum moisture content of each mixture). Figure 2 shows the soil compaction curve, the curve of each soil-ash-lime mixture and the saturation lines (i.e. 100%) of the soil and the mixture with the highest addition of ash and lime (5%L+20% Grey). In reference to these results, Table 4 establishes the molding criteria for each mixture taking into account the optimal point of each curve (γ_{d-max}, ω_o and degree of saturation%). These molding points are strategically defined considering possible field conditions, between 13.80 kN/m³ and 11.80 kN/m³, with a variation of the dry specific weight. Strategic molding points to study improved soils have been used previously by Rios et al. (2012), Festugato et al. (2017) and Consoli et al. (2014).

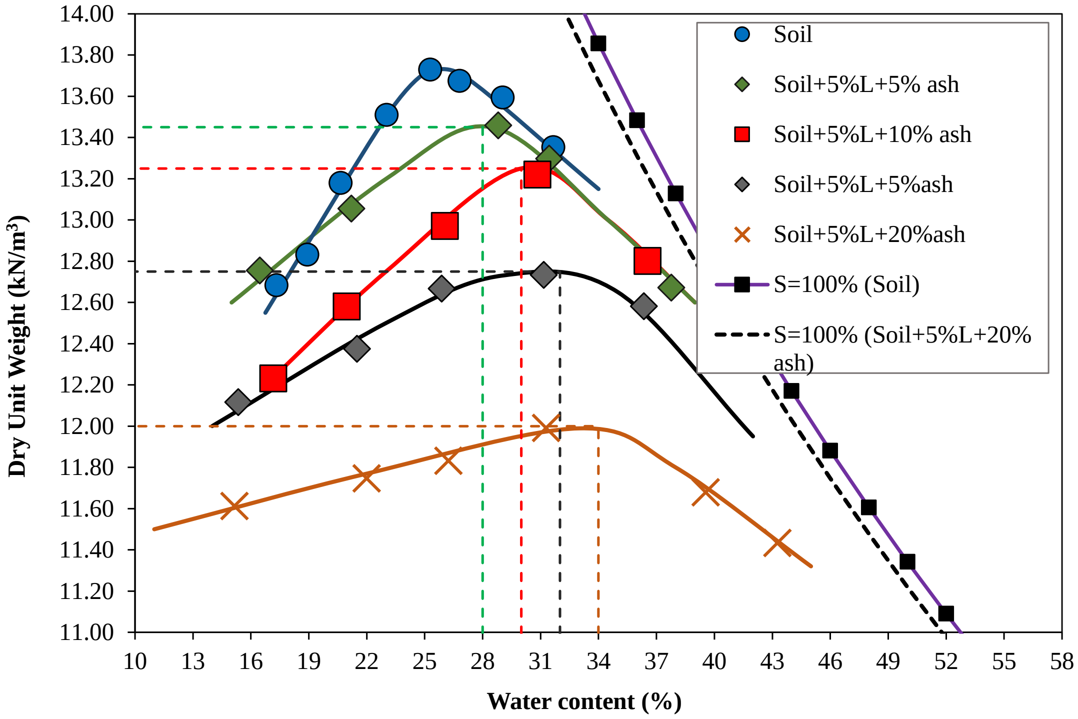


Figure 2. Soil compaction curve and mixtures of soil-cellulose ash-lime

Table 4. Defining the molding points

Mixture	$\gamma_{d\text{-}max}$ (kN/m³)	ω_o (%)	Degree of saturation %
Soil (Control)	13,72	26,5	0,75
Soil+5%L+5% ash	13,45	28	0,78
Soil+5%L+15% ash	13,25	30	0,82
Soil+5%L+20% ash	12,75	32	0,81
Soil+5%L+25% ash	12,00	34	0,77

2.3 Molding of specimens

For the tests of simple compression and tension by diametral compression, specimens of 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 ash and later with lime (in 5%). The amount of dry ash was added in reference to the dry weight of the soil sample at four different addition levels (5%, 10%, 15% and 20%) according to pH and OLC tests. Soon after, the amount of powdered lime was added in reference to the dry mass of the soil with a fixed content of 5%.

The mixture was mixed with ash and lime so that the mixtures were as homogeneous as possible. Then, a percentage of water by weight was added, this percentage referring to the optimal moisture content of the molding points established in Table 4 (ω_o). The mixture of soil-ash-lime with distilled water was carried out in a period not exceeding 5 minutes, with this trying to minimize the reactions of lime 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 4. To ensure the Apparent dry mold weight ($\gamma_{d\text{-}max}$) the mold volume and wet mixture weight 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 for 24 hours to ensure the value of ω_o.

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 the mold were wrapped with transparent plastic film to maintain the moisture content. Finally, the specimens were stored in a humid chamber for the curing process for 14, 28 and 90 days (at an average temperature of 24°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 simple compression and tensile tests by diametral compression: dimensions of the samples with a diameter of ±0.5 mm and a height of ±1 mm, dry apparent specific weight (γ_d) of ±1% and moisture content (ω) of ±0.5%. The values of q_u and q_t are expressed as a function of the initial molding porosity (η) for any lime content (L), celluse ash content (Ci) and apparent dry specific weight of molding, and is calculated with Equation (Consoli et al. 2014; Baldovino et al. 2018a):

$$\eta = 100 - 100\left[\left(\frac{\gamma_d}{1+L+Ci}\right)\left(\frac{1}{\gamma_{SS}}+\frac{L}{\gamma_{SL}}+\frac{Ci}{\gamma_{SCi}}\right)\right] \quad (1)$$

Where γ_{SS}, γ_{SL} and γ_{SCi} are the real density of soil, lime and ash grains, respectively. γ_d is the dry specific weight of the mold. For each molding or mixing point, 6 specimens were molded (3 for compression and 3 for traction). In total, 72 samples were compacted for these two tests.

2.4 Simple compression and tensile tests by diametral compression

The procedures of the simple compression and tensile tests by diametral compression followed the Brazilian standards NBR 5739 (ABNT 2018) and NBR 7222 (ABNT 2011), respectively. The simple compressive strength is the value of the maximum breaking load of the material or the value of the pressure corresponding to the load at which the specific deformation of the soil specimen of 20% occurs, in those cases in which the axial stress-strain curve does not present a maximum peak.

3. RESULTS AND DISCUSSIONS

Figure 3 presents the results of the influence of cellulose ash content on the maximum dry specific weight (PESM or $\gamma_{d\text{-}max}$) and on the optimal moisture content (TUO or ω_o) of the compaction curves of the mixtures shown in Figure 2 and detailed in Table 4 (obtained from compression at normal Proctor power). There is a decrease in the maximum dry specific weight as the dry amount of cellulose ash is added. In addition, an increase in the optimal moisture content is also found. A representative change in maximum dry weight and optimal moisture was observed for soil samples stabilized with cellulose material and lime up to 20% and 5%, respectively. The increase in cellulose ash from 5% to 20% caused large variations in the compaction characteristics of the soil-5% lime samples, decreasing the maximum dry specific weight by 14% and increasing the TOU by 30% in reference to the compaction curve. of the soil in a virgin state. This behavior is due to the addition of fine materials (ash and lime) and with lower density (2.39 g/cm^3 for lime and 2.31 g/cm^3 for ash) in reference to the soil (2.62 g/cm^3) that filled the voids between the largest silty-sandy soil particles and led to a decrease in the weight of solids per unit volume.

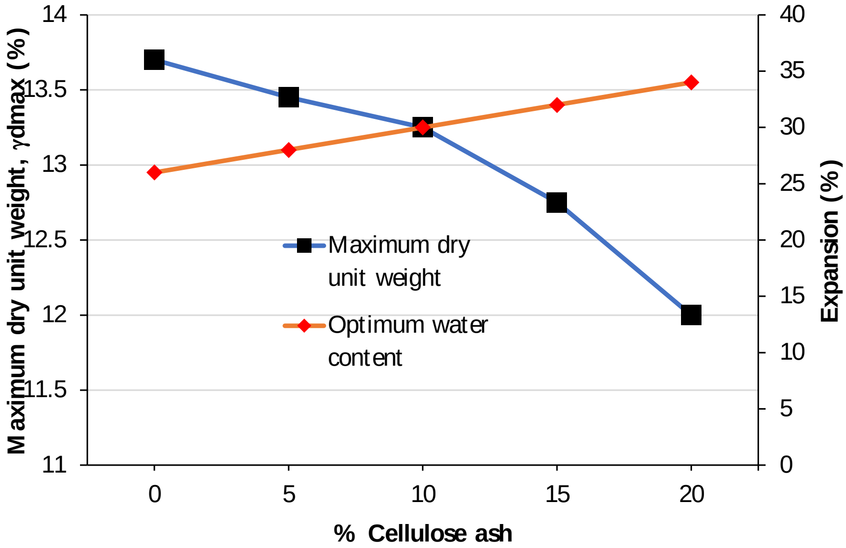


Figure 3. Influence of ash content on compaction properties (Maximum Dry Specific Weight-PESM and Optimal Moisture Content-TUO) of soil-ash-lime mixtures

Figure 4 shows the results of the influence of the addition of cellulose ash on the single compressive strength (q_u) for 14-d, 28-d and 90-d curing. For 14-d, 28-d and 90-d curing, the single compressive strength increased proportionately from 5 to 15% ash addition. After 15% gray (up to 20% gray), qu values decreased on average by 35%. At 14-d curing, qu increased by 25%, from 5% to 20% ash, for 28-d and 90-d curing the qu increment was 30% and 33%, respectively. In general, the maximum strengths were obtained when 15% ash was added to the soil+5%L mixture for all curing times.

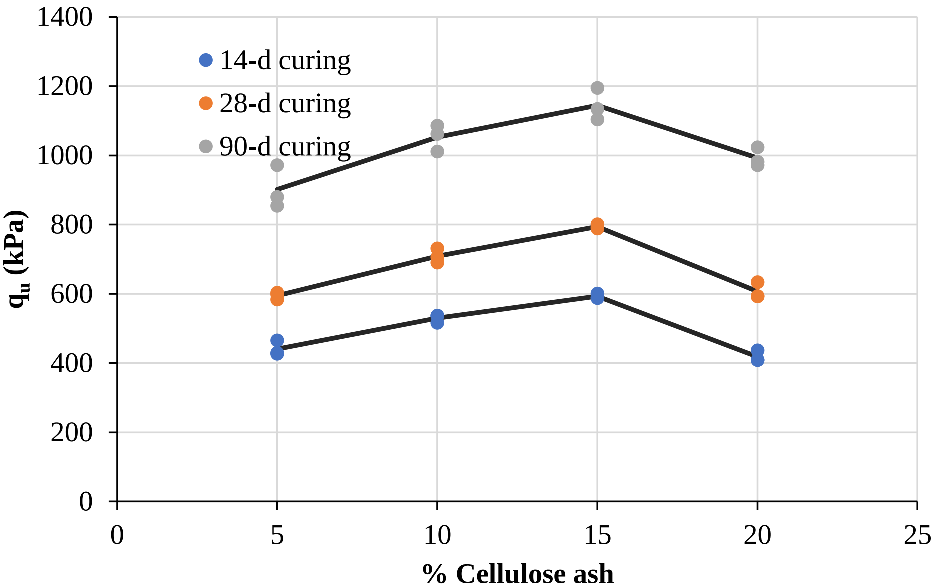


Figure 4. Influence of cellulose ash content on simple compressive strength in soil-5% lime mixture after 14, 28 and 90 days of curing.

Figure 5 shows the influence of 5%, 10%, 15% and 20% cellulose ash contents on the tensile strength by diametral compression (q_t) for curing times of 14-d, 28-d and 90-d. In the same way as for simple compression, the indirect tension increased proportionally up to 15% ash and fell from this content to 20% ash. Describing the decrease in qt from 15%-20% ash for each curing time, one has that for 14-d the q_t values decreased by 30%, for 28-d qt decreased by 40% and finally for 90-d the tensile strength dropped by 35%. The decrease in mechanical strength (both compression and tension) after 15% addition of cellulose ash is mainly due to two factors: first, the influence of porosity [Equation (1)] and voids of the soil-ash- lime did not exert a greater influence on the strength than the indirect tensile qt than the volumetric content of lime used (i.e. amount of lime inserted in the volume of soil for each specimen), in such a way that an increase in porosity requires an increment proportionately higher in lime content, in order to compensate for the increase in voids due to lack of compaction and keep the strength constant, and second, according to the chemical composition of the cellulose ash shown in Table 2, a portion of the material is inert and makes it unfeasible. pozzolanic reactions in the matrix of the mixtures in addition to being a material slightly less heavy than soil and lime, with a calculated density of 2.31 g/cm^3.

The above added to the fact that it is compacting at a lower dry specific weight compared to the other mixtures (i.e., soil-5%L-5%Gray, soil-5%L-10%Gray and soil-5%L-15%Gray) understands that the ash content of 20% is unfeasible as it reduces the strength of the mixture. Thus, an analysis of the possible application of soil-ash-lime mixtures in geotechnical engineering works must be formulated with the use of up to 15% of ash, being this percentage which potentiates the greatest resistances.

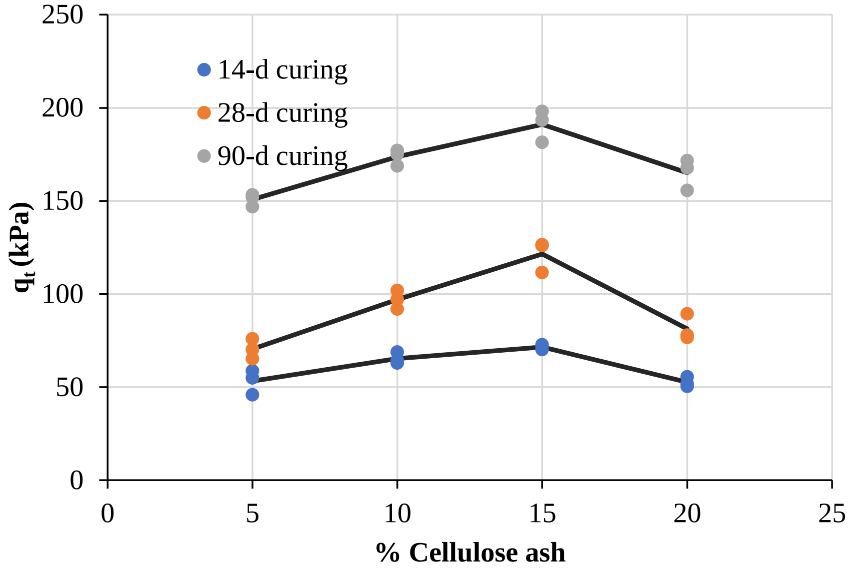


Figure 5. Influence of cellulose ash content on tensile strength by diametral compression in soil-5% lime mixture after 14, 28 and 90 days of curing.

The ratio of increase in strength to simple compression and tensile strength by diametrical compression is a very important variable in the mechanics of artificially cemented soils, since with the obtainment of a general dosage formula as a function of curing time and ash/ lime for the studied soil, it is possible to calculate the amount of ash, lime, degree of compaction and the curing time that must be used on the soil to obtain an experimentally desired compressive and tensile strength. In this case, a semi-empirical model based on the weight-volume phase relationships of the mixtures is applied up to a percentage of 15% ash, where the highest mechanical strengths are obtained. The model is based on the porosity/volumetric lime content index. The porosity of mixtures can be calculated using Equation (1) and the volumetric content of lime is defined as the ratio of volume of lime to volume of a specimen [Equation (2)]. The volumetric content increases with increasing lime content while the porosity/volumetric content ratio decreases.

$$L_{iv} = \frac{100\left(\left(\frac{\gamma_d V_s}{1 + L + Ci}(L)\right)/\gamma_{SL}\right)}{V_s} \quad (2)$$

Where V_s is the volume of the soil-ash-lime specimen (approximately 196 cm^3).

Figures 6a-6b show the influence of the porosity/volumetric content of lime on the simple compressive strength and tensile strength by diametrical compression for samples with 14-d, 28-d and 90-d curing. According to Consoli et al. (2014) it is possible to find a unique trend of the points of Figures 6a-6b raising the volumetric content of lime (Liv) to an exponent. In the case of the present research, the exponent with which the points are organized (and the best coefficient of determination is obtained) is 1.00.

If the equations (from Figures 6a-6b) controlling qu and qt are divided by the expression $102(\eta/L_{iv})^{-0.50}$, a constant that increases with curing time is obtained. Figure 7 shows the evolution of tensile strength and simple compression from 14 to 90 days of curing. Increasing the curing time produces an increase in qt and qu values showing a potential increase with coefficients of determination values of R^2=0.99 for both qt and qu. Thus, a dosage equation for qt and qu can be proposed with the ratio η/L_{iv} and the curing time (t). The dosage expressions for qt and qu are shown in Eq. (3) and Eq. (4), respectively. These dosage equations can be used within the limits of cellulose ash, lime and degree of compaction used in this research. If the equations controlling qt and qu shown in Figure 6a-6b for each curing time are divided (i.e., q_t/q_u) we obtain constants of 0.12-0.14 and 0.16 for 14, 28 and 90- healing days, respectively. That is, the tensile value of mixtures is always 12-16% of the simple compression value.

$$q_t = 41.88 \times t^{0,36} \left[\frac{\eta}{Liv}\right]^{-0,50} (R^2 = 0.99) \quad (3)$$

$$q_u = 531.21 \times t^{0,53} \left[\frac{\eta}{Liv}\right]^{-0,50} (R^2 = 0.99) \quad (4)$$

4. CONCLUSION

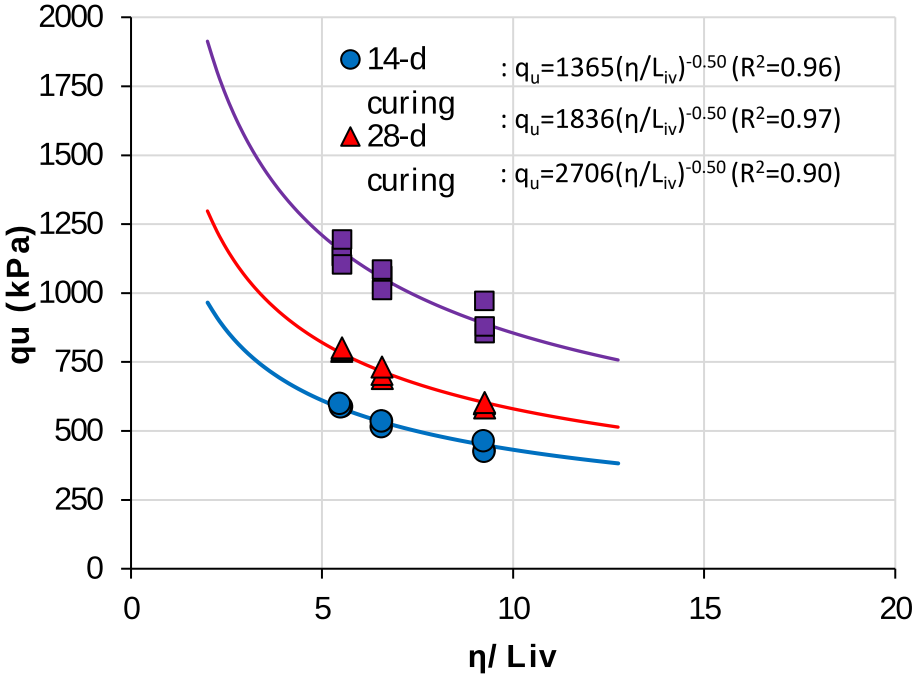
According to the experimental program and the analysis of the results, the following conclusions can be attached:

– The addition of cellulose ash and lime to the yellow silt of FG meant an increase in the simple compressive strength and tensile strength by diametric compression up to a percentage of 15% ash. The best way to represent this increase was through a linear trend.

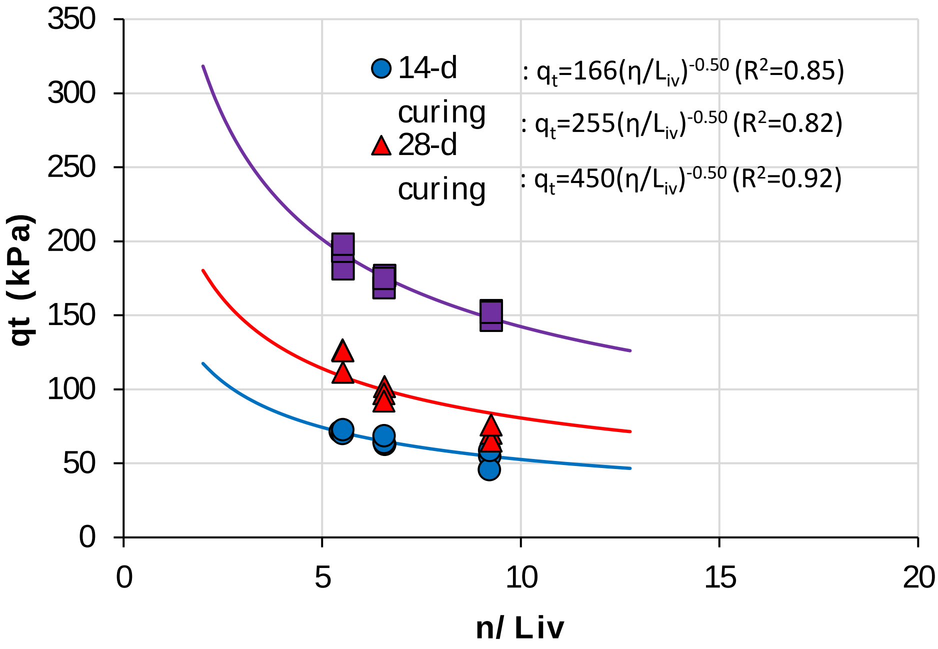
– The increase in the apparent dry specific weight of the mold, the increase in the curing time, the decrease in voids (porosity) and the increase in the volumetric content of lime in volume increased the strength of the mixtures.

– The porosity/lime volumetric content ratio η/L_{iv} proved to be an efficient parameter and index to study the qu and qt evolution of soil-ash-lime mixtures. To improve the bias of the experimental points, η/L_{iv} had to adjust to an exponent of 1.00 and -0.50. Thus, it was possible to calculate a dosage equation for q_u and q_t of the stabilized silt, obtaining adjustments of 99%.

– In terms of strength increases, yellow silt obtained higher tensile and single compressive strengths for percentages of 15% ash and 90-d cure. Thus, with the η/L_{iv} ratio, it was possible to establish a relationship between q_u and q_t (q_t/q_u) for the mixtures depending on the curing time, with this ratio of q_t/q_u= 0.12, 0.14 and 0.16 for 14-d, 28-d, and 90-d days, respectively.



(a)



(b)

Figure 6. Influence of the porosity/volumetric lime content ratio (η/L_{iv}) on the mechanical strength of mixtures up to 15% cellulose ash for curing times of 14-d, 28-d and 90-d. (a) η/L_{iv} vs. q_u (b) η/L_{iv} vs. q_t

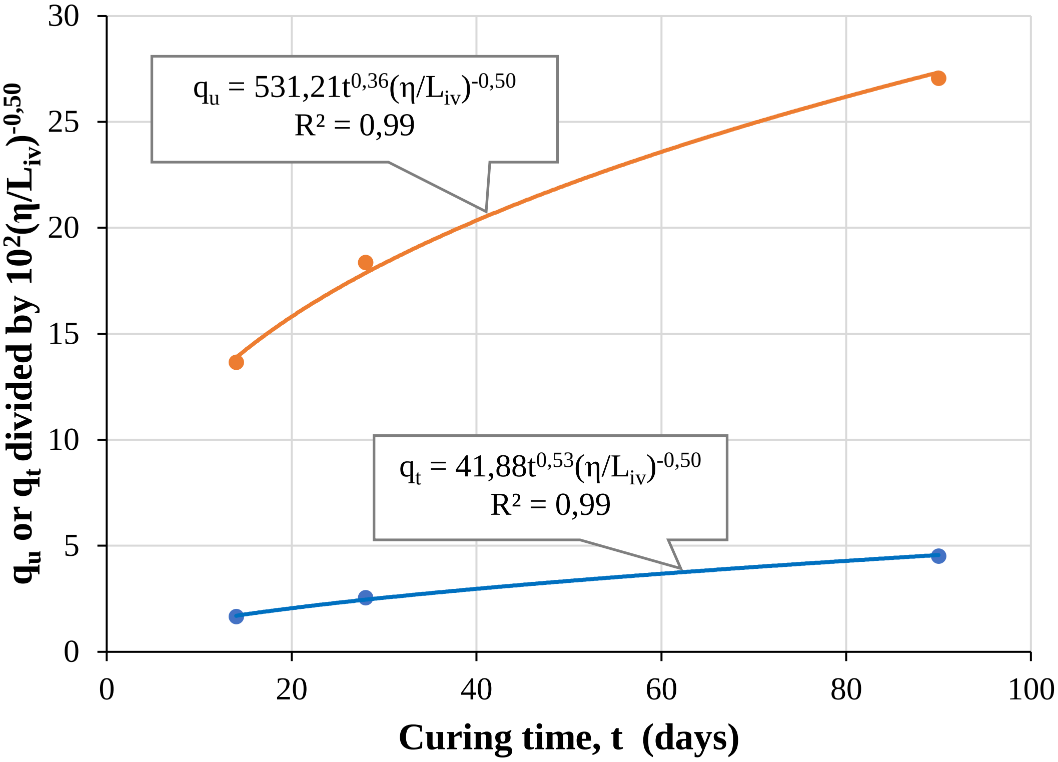


Figure 7. Dosing equations for simple compressive strength and tensile strength by diametrical compression using 14-d, 28-d and 90-d curing times and the ratio 102(η/L_{iv})$^{-0.50}$ divided by the values of the constants A_i corresponding to each time of cure.

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