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Comparison Between Eggshell Lime and Commercial Lime as a Soil Stabilizing Agent

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ABSTRACT

Reducing the extraction of natural resources is a current demand in the construction industry. Studies show that eggshells are rich in calcium carbonate and have the potential to replace limestone in lime production. In this context, the objective of this article is to use an eggshell lime produced in the laboratory to stabilize a residual clayey soil and compare the unconfined strength of the admixtures with others using commercial dolomitic lime. Different lime contents and porosities were evaluated and the porosity/lime ratio was studied to understand the unconfined strength behavior of admixtures. In addition to the soil and limes characterization tests, X-ray diffraction tests were carried out to analyze the chemical and mineralogical composition of the materials. The results showed that increasing lime content and decreasing porosity increased unconfined strength. Also, the unconfined strength achieved with the eggshell lime was greater than that achieved with dolomitic lime for the same lime content. The X-ray diffraction tests showed that the eggshell lime is composed almost entirely of calcium hydroxide, and microscopic images demonstrated much stronger bonds in the final product obtained from eggshell lime. The porosity/lime ratio was a good parameter for evaluating unconfined strength. A unique relationship was achieved linking unconfined compressive strength with the porosity/lime ratio for both the eggshell and the dolomitic lime mixtures.

Keywords: soil improvement; eggshell lime; dolomitic lime; unconfined compressive strength.

1. Introduction

Reducing the extraction of natural resources is crucial for a more sustainable world, especially in construction and infrastructure projects that consume large amounts of materials. Eggshells are a waste product produced in enormous quantities around the world. De acordo com a Associação Brasileira de Proteína Animal (ABPA, 2023), somente em 2020 o consumo médio de ovos foi 251 unidades por pessoa, gerando 331.320 toneladas de casca, que poderiam ser transformadas em cerca de 150 mil toneladas de cal. Recycling or reusing this waste instead of disposing of it in landfills can be a valuable opportunity in the context of a circular economy. Eggshells are rich in calcium carbonate and can potentially replace limestone in lime production (Ferraz et al., 2018). Studies show that eggshell limes have less impact on aquatic ecotoxicity, terrestrial ecotoxicity, and land occupation compared to traditional limes because two processes (Quarrying of limestone and Limestone improvement) are eliminated (Saldanha et. Al., 2021).

Although it is a relatively recent line of research, studies indicate that eggshell lime can also be a good alternative for soil stabilization, since it has a similar chemical composition to limestone, standing out for its high degree of purity in relation to commercial mineral limes, especially when compared to dolomitic lime, which is the predominant lime in the southern region of Brazil (Guimarães, 2002), containing more than 98% calcium hydroxide (Araújo et al., 2021; Favretto, 2020; Ferraz et al., 2018).

The addition of lime to clay soils, specifically, causes their geotechnical properties to change immediately after treatment. These soils, when treated, lose their cohesive properties and behave like a granular material: the plasticity index and expansion pressure reduce, while the unconfined compressive stress and permeability increase (Ghobadi et al., 2014; Consoli et al., 2014a; Dash and Hussain, 2012). All these property changes originate from the modification induced by lime-clay reactions in the texture and structure of the treated clayey soil. These properties also change with curing time, as modification on the microscopic scale continues with the progression of the slow lime-clay pozzolanic reaction (Kumar et al., 2020; Al-Mukhtar et al., 2012).

Consoli et al. (2014a) conducted simple compressive strength tests on a low-plasticity sandy clay soil (CL according to the Unified Soil Classification System, SUCS) for 5 lime contents between 3% and 11% with a combination of different curing times (28, 90 and 360 days) and 3 porosities (dry unit weight of 16.0, 17.0 and 18.0 kN/m3). The results showed that the lime content has an important effect on the strength of lime-treated sandy clay. They also showed that the unconfined compressive strength increases non-linearly with increasing lime content for all curing periods studied. Furthermore, the soil's simple compressive strength can be increased almost five times by adding at least 7% lime after a curing time of 30 days. Several studies (Castro-Fresno et al., 2011; Amiralian et al., 2012, Manasseh and Olufemi, 2008; Harichane et al., 2011; Dash and Hussain, 2012) show that the unconfined compressive strength of treated soil increases with the addition of lime and curing time. However, these changes are insignificant in the samples tested with 1%. According to Al-Mukhtar et al. (2012), this amount of lime is fully used for the short-term reaction. In the clayey soil studied by Al-Mukhtar et al. (2012), RCS increased more than 4 times in samples treated with 4% and 10% lime after 7 days of curing and more than 6 times after 90 days compared to the untreated sample. Ghobadi et al. (2014) studied a clayey soil, using 5 lime contents (between 0% and 7%) and 4 curing times (7, 15, 30, and 45 days), the results of the simple compression test showed that the tension- deformation of untreated soils shows continuous deformation until a steady state is reached; no true failure points observed. This is in accordance with the behavior of normally consolidated soils, which do not present pronounced stress-strain peaks.

Considering that unconfined compressive strength constitutes an important parameter for evaluating the efficiency of a stabilizing agent, this study aimed to compare the strength enhancement of eggshell lime with a commercially available lime in a clayey soil for various lime percentages. It also examined the impact of porosity on the strength of the treated soil. The ICL (Initial Consumption of Lime) Method was used to determine the initial optimal lime content. The admixtures were evaluated with three lime percentages (3, 5, and 7%) for both limes being tested for Unconfined Compressive Strength (UCS) at three different densities and a curing time of 28 days. Additionally, a chemical and mineralogical characterization of both eggshell and commercial limes was carried out using laser granulometry and X-ray diffraction analysis (XRD). The study found that eggshell limes demonstrated better physical–chemical-mineralogical qualities for soil stabilization applications than commercial lime. Both limes were assessed for their strengths at different quantities and densities, and the study revealed that eggshell lime outperformed the commercial lime.

2. Experimental program

The experimental program was carried out in three parts. First, the soil was characterized, and X-ray diffraction tests were carried out for the soil and the limes. The modified Initial Consumption of Lime (ICL) (Rogers et al., 1997) was used to try to determine the minimum amount of lime required for stabilization. Then several unconfined compression tests were carried out as discussed below. In order to observe the interaction of the materials used on a nanometric scale, scanning electron microscopy (SEM) tests were carried out.

2.1. Materials

The soil used in the present study, derived from weathered granite, was obtained from Florianópolis, in southern Brazil. The results of the soil characterization tests are shown in Table 1.

Table 1. Physical properties of the soil sample.

Properties	**Values**
Liquid limit	61%
Plastic limit	35%
Plasticity index	26%
Specific gravity	2.65 g/cm^3
Fine gravel (0.2 < Diameter < 6.0 mm)	17
Coarse sand (0.6 < Diameter < 2.0 mm)	18
Medium sand (0.2 < Diameter < 0.6 mm)	8%
Fine sand (0.06 < Diameter < 0.2 mm)	12%
Silt (0.002 < Diameter < 0.06 mm)	20%
Clay (Diameter 6 0.002 mm)	25%
Mean diameter (D50)	0.07 mm

The soil is classified as inorganic clays of high plasticity, fat clays (CH) according to the Unified Soil Classification System (ASTM, 2006). X-ray diffraction showed that the fine portion is composed of 66% kaolinite, 12% quartz, and 22% amorphous phase.

Through the compaction test, it was established the maximum dry density of 1.72 gm/cm^3 and the optimal moisture content (ω) of 19.0%.

A commercially available hydrated dolomitic lime and hydrated eggshell lime were used as cementing agents. The eggshell was calcinated at a temperature of 900ºC for 4 hours. The specific gravity of both limes is 2.55 g/cm^3.

The results of the chemical composition of both limes obtained through X-ray diffraction tests are shown in Table 2.

Table 2. Chemical composition of the limes.

	dolomitic lime	**Eggshell lime**
$Ca(OH)_2$	39.5%	94.5%
$Ca(CO_3)$	35.5%	5.5%
$Mg(OH)_2$	15.5%	----
MgO	3.0%	----
SiO_2	6.6%	----

2.2. Modified initial consumption of lime

The minimum amount of lime required for soil stabilization, based on the modified Initial Consumption of Lime (ICL) (Rogers et al., 1997), was established from the interpretation of pH measurements performed on several soil–lime–water mixtures (solids–water proportion of 1:3). This method did not prove to be efficient for mixtures with eggshell lime, as shown in figure 1., so the values of 3%, 5%, and 7% were adopted based on the literature (Consoli et al., 2014)

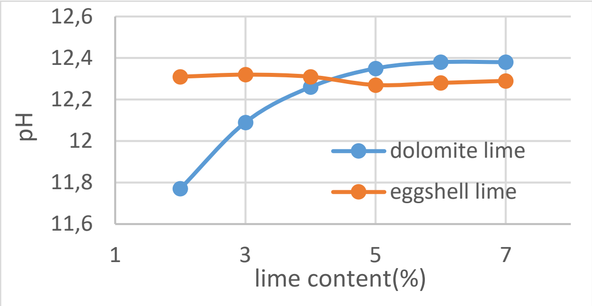

Figure 1. Figure 1. ICL modified method for both limes.

2.3. Methods

Molding and curing of specimens

For the unconfined compression tests, cylindrical specimens, 50 mm in diameter and 100 mm high, were used. After weighing, the dry components (soil and lime)
2.3.1 were mixed until the mixture became uniform. The water was then added until a homogeneous paste was obtained. The amount of lime for each specimen was calculated based on the mass of dry soil.

After preparing the material, three small portions were taken for water content determination and the mixture was stored in a covered container to avoid moisture loss before subsequent compaction. The time it took to prepare (mix and compact) each specimen was less than 1 hour.

The specimens were then statically compacted in three layers (each layer had controlled its height – 1/3 of the specimen per layer) into a lubricated 50 mm diameter by 100 mm high split mold so that each layer reached the specified dry unit weight. After molding, the specimens were immediately extracted from the split mold, weighed, and measured with accuracies of 0.5 g and 0.5 mm, respectively. The tolerances adopted for accepting specimens were the following: dry unit weight (γ_d) within ±2% of the target value; water content (ω%) within ±1.0%; diameter within ±0.5 mm; and height within ±1 mm. The specimens were stored and cured, within plastic bags to avoid significant water content variations, in a humid room at 25 ± 2 °C. The authors have not observed any long-term volume changes during the curing period.

It is important to point out that the dry unit weight of the specimens was calculated as the dry weight of the soil and lime divided by the total volume of the specimen. To keep the dry unit weight of the specimens constant with increasing lime content, a small portion of the soil was
2.3.2 replaced by lime. As the specific gravity of lime (2.55) is smaller than the specific gravity of the soil (2.65), for the calculation of void ratio and porosity, a composite specific gravity based on the soil and lime proportions was used.

Unconfined compression tests

Unconfined compression tests have been used in most of the experimental programs reported in the literature to verify the effectiveness of lime stabilization and also to assess the absolute and relative importance of the several factors that control the strength of lime-treated soils. One of the reasons for this is the accumulated experience with this kind of test in concretes and mortars. The test is also simple and fast while being reliable and not expensive.

The unconfined compression tests constituted the main part of this research. The program was chosen in such a way as to evaluate the influences on the compressive strength of the lime-treated soil, of the following factors: lime type, lime content, and dry unit weight.

The variables used were:

- two types of lime: dolomitic and eggshell lime;
- three lime contents: 3, 5, and 7% and;
- three specific weights (1.5, 1.6, and 1.7 g/cm3) with a water content of 20.0%.

An automatic loading machine, with a maximum capacity of 50 kN and proving rings with capacities of 5 kN and 50 kN and resolutions of 0.005 kN and 0.023 kN, respectively, were used in the unconfined compression tests. The rate of displacement adopted was 1.14 mm per minute.

After curing in a humid room for 27, days, the specimens were submerged in a water tank for 24 hours to minimize suction effects, with a total curing time of 28 days. Immediately before testing, the specimens were drawn from the tank and dried superficially with an absorbent paper. Then, the unconfined compression test was carried out and the maximum load was recorded. For each mixture, it was tested three specimens and the average strength of the three was used in the results, with a deviation of each specimen being less than 10% from the average strength.

3. Results

3.1. Effects of lime type, lime content and porosity

Table 3 shows the UCS for each mixture and the difference between the dolomitic and the eggshell lime for the same lime content (L) and specific weight (γd).

Table 3. UCS for each mixture

γ_d (g/cm³)	*L* (%)	UCS (kPa)		Difference of UCS between the limes (%)
		Dolomitic Lime	Eggshell lime	
1.5	3	90.8	546.7	601%
1.5	5	205.9	1036.0	503%
1.5	7	390.0	1204.5	309%
1.6	3	196.0	1158.5	591%
1.6	5	372.2	2027.1	545%
1.6	7	723.2	2278.4	315%
1.7	3	392.1	2153.0	549%
1.7	5	662.6	2795.4	422%
1.7	7	1108.1	3090.3	279%

The eggshell lime outperformed the dolomitic lime for every mixture tested, although the difference in strength gain decreased with the increase of lime content.

Figures 2 and 3 show the unconfined compressive strength with lime content for the dolomitic lime and the eggshell lime, respectively. It can be observed that the UCS increases linearly with the increase of lime content, except for the eggshell lime between 5% to 7% content. This may be because the eggshell lime is close to its optimal content for the soil studied (Dash e Hussain, 2012).

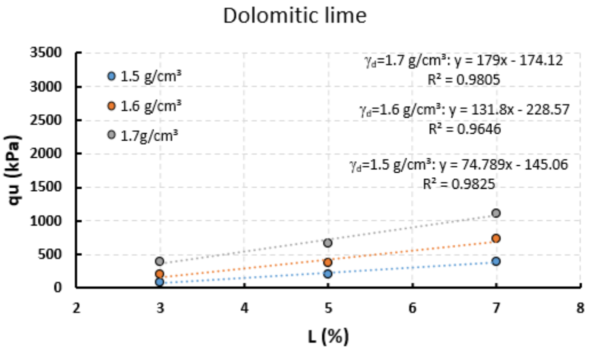

Figure 2. Variation of unconfined compressive strength with dolomitic lime content

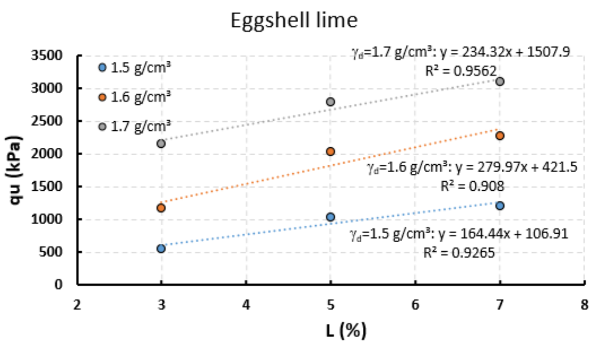

Figure 3. Variation of unconfined compressive strength with eggshell lime content

Figures 4 and 5 show how the porosity affects the unconfined compressive strength of the lime-treated soil studied the dolomitic lime and the eggshell lime, respectively. The unconfined compressive strength increases exponentially with the reduction in porosity of the compacted mixture. This beneficial effect of a decrease in porosity has been previously reported by several studies (Consoli et al., 2016; Consoli et al., 2011, Consoli et al., 2014), this is due to the existence of a larger number of contacts between particles.

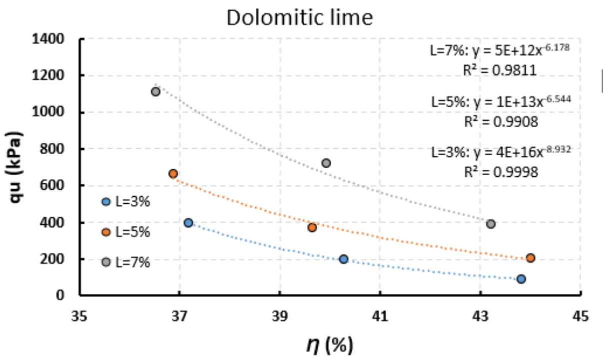

Figure 4. Variation of unconfined compressive strength with porosity for dolomitic lime mixtures

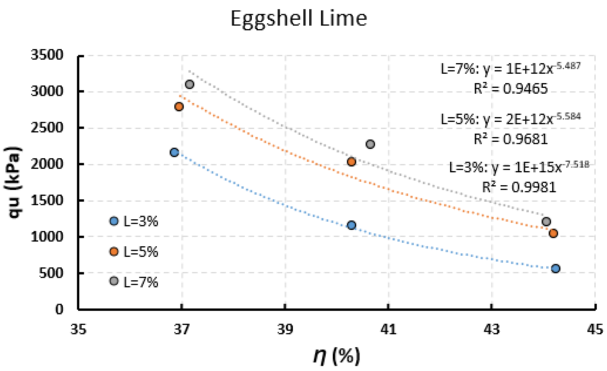

Figure 5. Variation of unconfined compressive strength with porosity for eggshell lime mixtures

3.2. Effect of porosity/lime ratio

Figures 6 and 7 show the UCS as a function of porosity/volumetric lime content (η/Lv) of soil and lime mixtures, for dolomitic and eggshell limes, respectively, for the γ_d values studied. Each curve has the same lime content (3%, 5% and 7%).

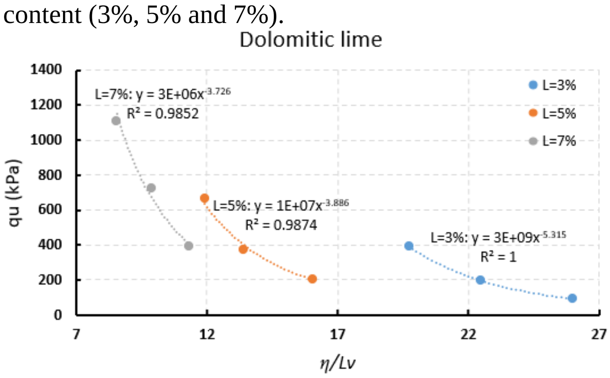

Figure 6. Variation of unconfined compressive strength with porosity/lime ratio for dolomitic lime mixtures

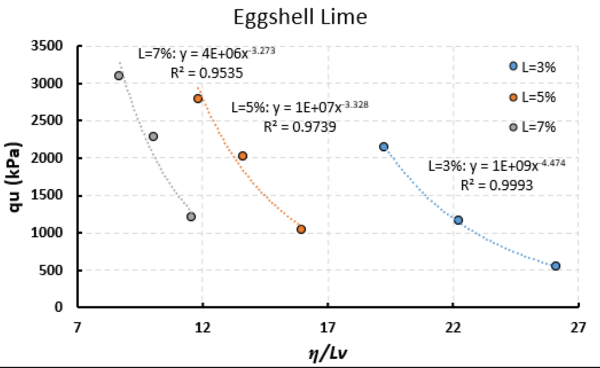

Figure 7. Variation of unconfined compressive strength with porosity/lime ratio for eggshell lime mixtures

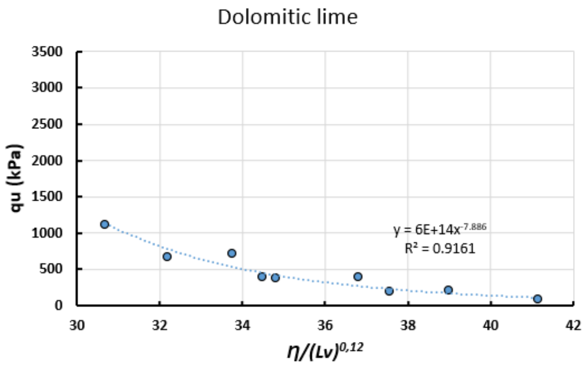

Figure 8. Adjusted porosity/lime ratio for dolomitic lime mixtures

It's possible to observe in Figures 6 and 7 a dispersion of the mixture points, if we consider the effects of the amount of lime and porosity, around an exponential trend.

It is seen that points with the same voids/lime ratio obtained in different ways (one by densification and the other by increasing the lime content) present different resistances, with the points with lower porosity and greater quantity of lime achieving higher resistances.

Assuming that a variation in the volume of voids would require a proportional variation in the volume of lime to counterbalance the loss or gain in resistance, in mathematical terms, we have that:

$$\frac{\eta}{L_V} = K \text{ e } \frac{\eta+\Delta\eta}{L_V+\Delta L_V} = K \text{, então } \Delta L_V = \frac{L_V}{\eta} \times \Delta\eta$$

Where:
$\Delta\eta$ = variation in porosity.
ΔL_v = variation in volumetric lime content.
K = constant.

This trend was verified for soil samples improved with cement and lime in studies by Consoli et al. (2016) and Consoli et al. (2014).

One way to make the rates of variation of the aforementioned quantities compatible is by applying a power to one of them. Therefore, a power equal to 0.12 was applied to the *Lv* parameter, as proposed by Consoli et al. (2016) for clayey soils improved with lime, which would provide better compatibility between variation rates, resulting in a better adjustment for the η/Lv factor. Figures 8 and 9 show the variation in UCS in relation to the factor $\eta/(Lv)^{0.12}$, for soil mixtures with 3%, 5%, and 7% lime contents, for dolomitic and eggshell limes, respectively, and with 28 days of curing.

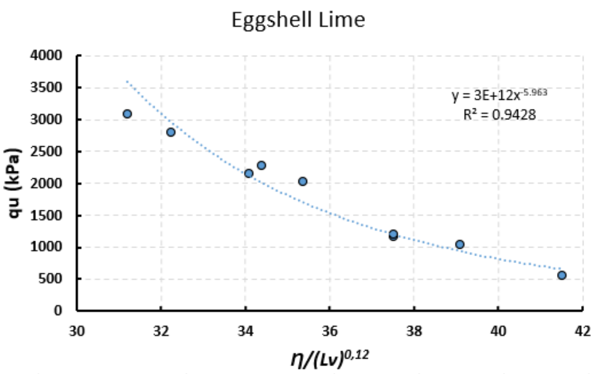

Figure 9. Adjusted porosity/lime ratio for eggshell lime mixtures

A good correlation can be observed between $\eta/(Lv)^{0.12}$ and the RCS of the soil-lime under study. It was used in the power curve adjustment, which presented better R^2 correlation coefficients.

3.3. Microscopy test

Figure 10 and 11 show samples of soil mixture with 7% dolomitic lime and soil mixture with 7% eggshell lime, respectively, magnified 5,000x.

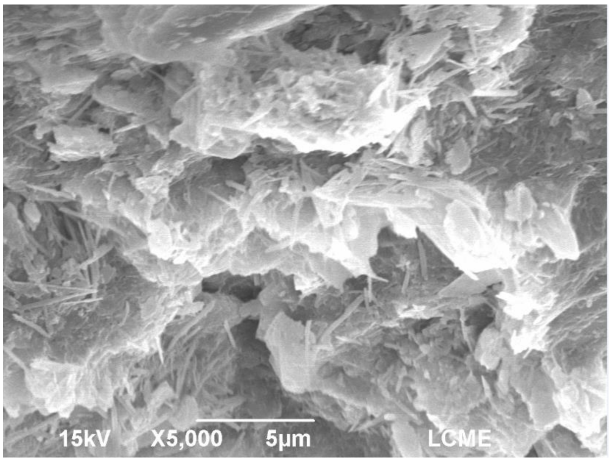

Figure 10. Soil samples with 7% dolomitic lime magnified 5,000x.

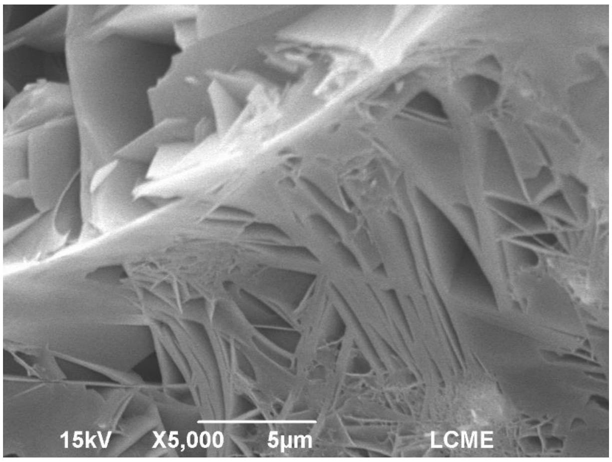

Figure 11. Soil samples with 7% eggshell lime magnified 5,000x.

In the soil treated with dolomitic lime (Figure 10), part of the clay minerals dissolve to form hydrated gels of calcium silicate (CSH), calcium aluminate (CAH) and calcium aluminate silicate (CASH) showing the occurrence of pozzolanic reactions between clay and lime particles, although it's still possible to see the original estructure of the clay particles in the needle like form. Similar images were obtained by Al-Mukhtar et al. (2012).

For the soil samples with 7% eggshell lime (Figures 4.24.c and 4.25.c), which obtained compressive strength 3 times higher than the samples with 7% dolomitic lime, the original structure of the soil was barely identified, having been practically entirely replaced by gels and a crystalline mesh formed by calcium silicate (CSH), calcium aluminate (CAH) and calcium aluminate silicate (CASH).

4. Conclusions

From the data presented in this paper the following conclusions can be drawn:

- The effectiveness of the eggshell lime for improvement of UCS of clay soils, being a better alternative from a technical standpoint than commercially available dolomitic lime.
- The porosity/lime ratio (n/Lv) adjusted by applying an exponent to the parameter Lv (0.12 for the soil and both limes used in the present work has been shown to be an appropriate index parameter to assess the UCS of the mixtures and curing time studied.

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