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POROSITY-TO-CEMENT INDEX CONTROLLING UNCONFINED COMPRESSIVE STRENGTH OF A CEMENTED SOIL

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ABSTRACT

The present work presents the development of equations that estimate the simple compressive strength (q_u) of silty soil in Curitiba, Brazil, stabilized with Portland cement type V (CP V). The equations were developed using the porosity/volumetric cement content ratio (η/C_{iv}) or voids/cement ratio. Soil-cement specimens were molded in four apparent dry specific weights (γ_d) using cement contents of 3%, 5%, 7%, and 9% (concerning the dry weight of the soil) and subsequently tested under saturated conditions after of 28 days of cure. The results show that the addition of cement increases the strength of soil-cement mixtures linearly. Increasing the dry mold density also increases the qu values. On the other hand, if the porosity of the mixtures decreases, q_u increases. It is shown that with the decrease of the η/C_{iv} ratio the values of q_u increase. The maximum q_u value obtained with Portland V cement was 3365.1 kPa. A general estimation equation for q was developed to estimate the strength of mixtures. The equations and mathematical adjustments demonstrate that it is possible to estimate the q_u value of the stabilized soil within the ranges of γ_d, amount of cement, η/C_{iv} ratio, and curing time used in the present work.

INTRODUCTION

One of the methodologies to improve the physical-mechanical properties of soils is the addition of cement. The methodology has been used to stabilize soils for use in pavement layers, reinforce soils used to support shallow foundations, protect slopes, and build deep foundations. The methodology has been used for 100 years (Firoozi et al. 2017).

Soil-cement is a mixture of soil and measured amounts of Portland cement and water compacted to the desired density. Cement is most commonly used to increase the strength of sandy soils. When water is added to the soil-cement mixture and then compacted, hydration takes place, which means that cementing compounds of calcium silicate hydrate and calcium aluminate hydrate are formed, and excess calcium hydroxide [CaOH] is released (Ronoh et al. 2014).

Lade and Trads (2014) reported the role of cementation in the behavior of artificially cemented soils based on experimental studies using elastoplastic models to establish the influence of cementation power on the development of strength of soil-cement material. On the other hand, Horpibulsuk et al. (2010) analyzed the strength development of mixtures of silty clay mixed with cement-based on microstructural considerations, studying the influence of moisture content, curing time, and the amount of cement. The addition of cement improves the soil structure by increasing the inter-cluster bonding and thus reducing the pore space. For Horpibulsuk et al. (2010), water influences both hydration products and pore sizes, with optimal water being 0.8 times the value of optimal compaction moisture.

Pakbaz and Alipour (2012) investigated the influence of Portland cement addition on geotechnical properties in clayey soil, with cement additions of 4, 6, 8 and 10% in reference to the dry weight of the soil, using three mixing humidities, 30 , 48 and 70% and using 7, 14 and 28 days of curing. The researchers reported a single compressive strength of 250 kPa for 4% cement to 2900 kPa for the addition of 10% cement, both at 28 days of curing. The actual grain mass (Gs) after curing slightly increased from 2.68 (for the unstabilized sample) to 2.73-2.76 (for the cement stabilized samples). The Gs values of the treated samples decreased with an increase in the cement content and curing time.

Recently, Jin et al. (2018) reported values of up to 5000 kPa with soil mixtures stabilized with 3% and 15% cement in reference to the dry weight of the soil and with a significant reduction in the plasticity of the mixture. Consoli et al. (2013) studied the influence of Portland cement types (I, III and IV) in sandy soil by adding 3% to 9% of cement to the soil with curing times of 2, 7, and 28 days. The authors showed an increase in qu strength of up to 1600 kPa, 2600 kPa, and 1600 kPa for cement I, III and IV, respectively. Other authors such as Por et al. (2017) presented results of simple compression with the addition of 5 and 10%, in relation to the dry weight of the soil, obtaining results of up to 1500 kPa at 14 days and 2900 kPa at 28 days of curing, these results are similar to those reported by Consoli et al. (2013). The authors also report a significant decrease in the plasticity index and soil expansion, decreasing from 8% (without cement addition) to 0% with cement addition.

As seen before, soil stabilization with cement has been extensively researched, especially in places where soils, due to their physical and mechanical characteristics, cannot be used in geotechnical engineering or civil construction. Thus, the present work presents the effects of the addition of CP V (Portland Cement Type V, In Brazil) on the simple compressive strength of silty soil in the metropolitan region of Curitiba/PR. The article presents the factors that influence the increase or decrease in mechanical strength.

EXPERIMENTAL PROGRAM

The experimental program was divided into two stages: the first was to carry out soil and cement characterization tests: soil granulometry according to the American standard ASTM D2487 (ASTM, 2000), Atterberg limits of the soil according to Brazilian standards NBR 7180 (ABNT, 1984) and NBR 6459-84 (ABNT, 1984), the actual specific gravity of the soil grains according to ASTM D854 (ASTM, 2014), the actual specific gravity of the grains of the types of cement according to the Brazilian standard NBR 6474 (ABNT, 1984) and soil compaction properties in the three energies (standard, intermediate and modified) according to the Brazilian standard NBR 7182 (ABNT, 2016); and the second stage consisted of molding, curing and breaking the soil-cement specimens submitted to simple compression tests.

Materials

In the present work, three materials were used: soil, Portland cement CP V and distilled water. The soil sample was collected in the southern area of Curitiba (Brazil) manually in a deformed state, avoiding possible contamination and in sufficient quantity to carry out all the tests. Soil has already been used in previous studios by Baldovino et al. (2018a; 2018b) for stabilization with lime. A local producer supplied cement. Table 1 presents the physicochemical properties of cement. The producer provided chemical properties, and physical properties were calculated in the laboratory. According to Table 1 the CP V cement has a specific gravity of 3.11.

Table 1. Physic chemical properties of cement

Property	Value
% MgO	4.11
% SO3	2.99
% CaO	60.73
% Insoluble residue	0.77
Strength at 28 days	53 MPa
% Fineness	0.04
Gs_C	3.11

To perform all soil characterization tests, soil-cement 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 in the study.

According to the Unified Soil Classification System, the soil is classified as sandy elastic silt (MH). The soil granulometric distribution curve is shown in Figure 1. The results of the soil physical characterization tests are shown in Table 2. The soil has an average sand percentage of 7.5%; fine sand of 25.9%; 57.6% silt and 9.3% clay, with the percentage of silt (0.002 mm < ϕ < 0.075 mm) making up the most significant portion of the soil.

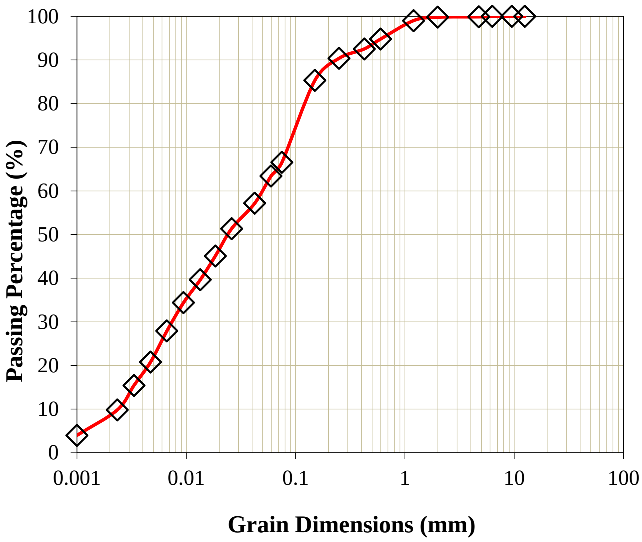

Figure 1. Grain size distribution of soil.

Table 2. Physical properties of the soil sample

Property	**Value**
Liquid limit	53.1%
Plastic index	21.3%
Specific gravity	2.71
Gravel (4.75 mm < ϕ< 19 mm)	0%
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
SUCS classification	MH

Molding Points and Curing Conditions

The molding points were established after conducting the soil compaction tests in the three energies: normal, intermediate and modified, according to the Brazilian standard NBR 7182 (ABNT, 1986). Figure 2 shows the soil compaction curves, the saturation curves of 100, 80 and 60% and the proposed molding points (A1, A2, A3 and A4)

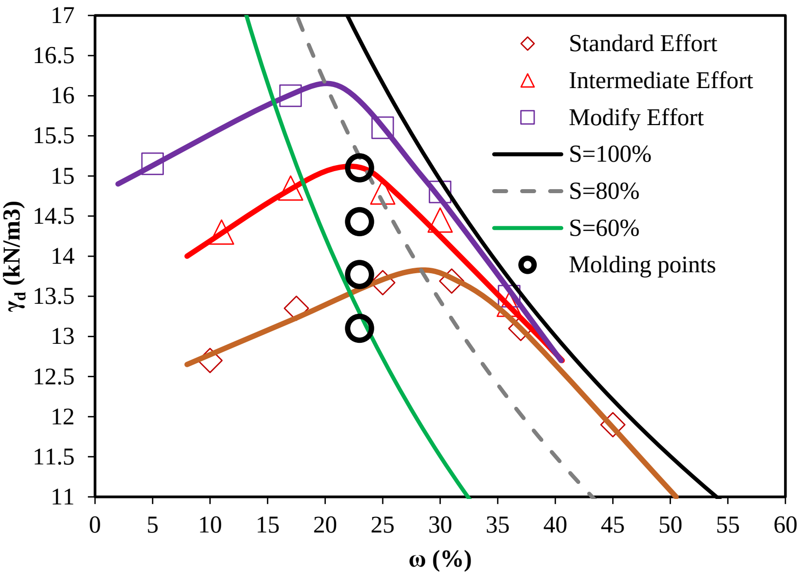

Figure 2. Compaction curves and molding points.

In order to study the influence of dry specific weight and voids on the mechanical strength of the soil artificially cemented with the mentioned cement, 4 molding points were defined: A1, A2, A3 and A4 (Table 3 and Figure 2).

Table 3. Molding points

Molding points	γ_d (kN/m^3)	ω (%)
A1	15.10	23
A2	14.43	23
A3	13.77	23
A4	13.10	23

These molding points were strategically defined considering possible field conditions, between 15.10 kN/m³ and 13.10 kN/m³, with a dry specific weight variation of 0.67 kN/m³ and a constant humidity of 23% . Strategic molding points to study improved soils have been used previously by Rios et al. (2012) and Consoli et al. (2017a; 2017b). All soil-cement specimens were tested after 28 days of curing under saturation conditions to nullify as much as possible the influence of suction on the strength of the mixtures.

Unconfined Compression Tests

For the simple compression tests, 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 the cement. According to previous studies, the amount of dry cement was added with reference to the dry weight of the soil sample at four different addition levels (3, 5, 7 and 9%) (Consoli et al. 2007; Rios et al. 2012). The soil was mixed with the cement to make the mixture 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 3. The soil-cement mixture with distilled water was carried out in a period not exceeding 5 minutes, trying to minimize the reactions of the cement with the water before the molding process of the specimens. The samples for molding the specimens were statically compacted in a single layer 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 3 and Figure 2. To ensure the maximum dry specific weight obtained during the compaction tests, the mold volume and wet mixture weight required for each specimen were calculated. After these calculations, each specimen's necessary amount of material was weighed. The molding was done with the help of a manual hydraulic press. After each molding process, three mixture samples were taken to measure the moisture content in an oven 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 extracted specimens 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 25°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 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 cement content, three specimens were molded. After 27 days of curing, 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 resistance. After immersion, they were superficially dried with a dry cloth. Thus, all samples were cured for 28 days.

To carry out the simple compression tests, an automatic press was used with rings calibrated for axial load with 4.5 kN and 10 kN. The tests were carried out with an automated system, measuring mainly the applied force, with a resolution of 2.5 N, the deformation with a sensitivity of 0.001 mm, and the test speed of 1 mm/min. The simple compression test procedures followed the Brazilian standard NBR 5739 (ABNT, 1980). 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. The unconfined or simple compressive strength (q_u) is adopted according to the following expression when, in the test, the axial stress-strain curve reaches a maximum peak:

$$q_u = \frac{P_R}{A_T} \quad (1)$$

where P_R is the rupture load at the peak of the axial stress-strain curve and A_T is the corrected cross-sectional area of the specimen

RESULTS AND DISCUSSION

Figure 3 shows the qu results of the samples after 28 days of curing with varying CP V cement contents from 3 to 9%. It is noted that with the increase in the dry specific weight of the samples, the simple compressive strength increases, as well as with the increase of the cement content, there is also an increase in the simple compressive strength. At molding point A1, the specimens with 3% of cement reached an average value of q_u = 1191.6 kPa, for 5% of cement they reached an average strength of q_u = 2011.1 kPa, for 7% of cement they reached an average strength of q_u=2622.6 kPa and, finally, with 9% cement, the value of q_u reached by the specimens was 3365.1 kPa. At molding point A2, the specimens with 3% of cement reached a value of q_u = 1095.9 kPa, for 5% of cement they reached a strength of q_u = 1874.9 kPa, for 7% of cement they reached a strength of q_u = 2421.9 kPa and, finally, with 9% of cement, the value of q_u reached by the specimens was 2675.8 kPa. At molding point A3, the specimens reached a single compressive strength of 916.8; 1356.9; 1868.4 and 2201.6 kPa using 3, 5, 7 and 9% of cement, respectively. Finally, at point A4, the specimens reached a simple compressive strength of 801.8; 950.9; 1232.3 and 1985.9 kPa using 3, 5, 7 and 9% CP V cement, respectively.

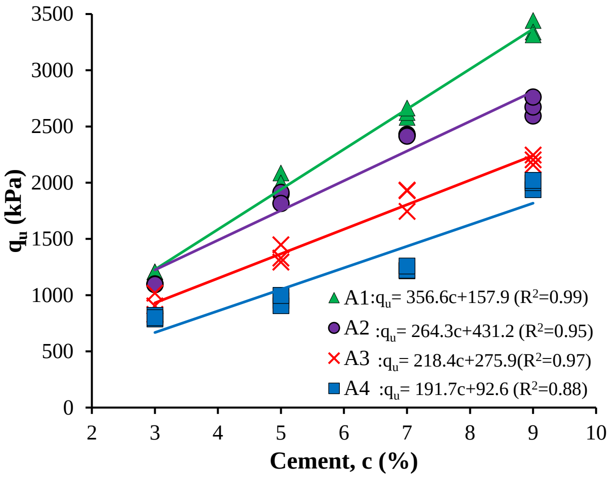

Figure 3. Influence of cement content on simple compressive strength

Thus, comparing the strengths qu at points A4 and A1 (lower and higher specific molding weight, respectively), it can be mentioned that there was an increase, in percentage values, of 49, 116, 112 and 70% in the strength q_u with the use of 3, 5, 7 and 9% CP V cement, respectively, that is, the greater the specific molding weight of the specimen, the greater the simple compressive strength of the material, and this gain in strength will be greater , the higher the percentage of lime added to the soil. Thus, it can be said that both the increase in the dry specific weight increases q_u, as well as the increase in the CP V cement content Figure 4 analyses the influence of initial porosity on the simple compressive strength of soil-cement mixtures. There is a variation in porosity from 44% to 52% for 3%, 5%, 7% and 9% of cement. There is also an inversely proportional relationship between porosity and q_u, because as porosity decreases, q_u increases.

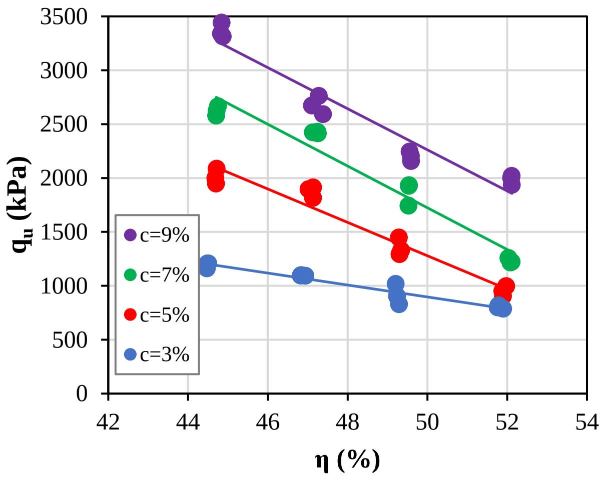

Figure 4. Influence of porosity on simple compressive strength

The best way to characterize the porosity variation and the observed simple compressive strength results were through the termination of a regression curve that could satisfactorily represent the results. The regression curve that best represented the points was linear. On average, the reduction of 8 percentage points in the porosity of the soil-cement specimens increased the simple compressive strength of the samples by 1050 kPa. Ingles and Metcalf (1972); Moore et al. (1970) and Consoli et al. (2013) also reported in their studies that the decrease in porosity with the increase of q_u.

Figure 5 shows the influence of cement's porosity/volumetric content on the simple compressive strength.

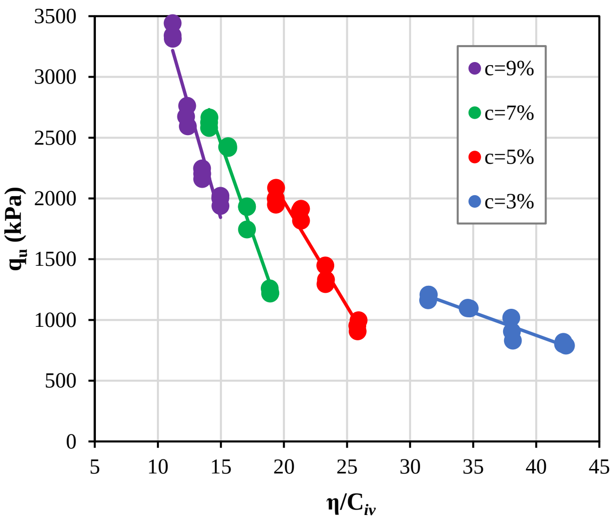

Figure 5. Influence of the porosity/volumetric content of cement on the simple compressive strength

The volumetric cement content (Equation 2) is defined as the ratio of cement volume to the volume of a specimen

$$C_{iv} = \frac{\left(\frac{\gamma_d}{1 + c/100}\left(\frac{c}{100}\right)\right)}{\gamma_{sc}} \qquad (2)$$

The volumetric content increases with increasing cement content, while the porosity/volumetric content ratio decreases. For mixtures, the η/Civ ratio varies from 10.1-13.6; 12.7-17.1; 17.5-23.5 and 28.5-38.2 for 9, 7, 5 and 3% cement, respectively (See Figure 5). On average, the range of η/C_{iv} for each cement content is 3.6; 4.5; 6.3 and 10.5 for 9, 7, 5 and 3%, respectively. The range increases with the decrease in the amount of cement in the specimen, and when the range decreases, it provides the highest values of mechanical strength.

It can be seen in Figure 5 that there is a linear trend of q_u dependent on η/Civ for each cement content. Although there is a linear trend of the points for each cement grade, the experimental points of all grades show a slight potential bias. Thus, seeking to establish the relationship η/C_{iv} for a single parameter that predicts the results of q_u, a potential trend was defined and is shown in Figure 6.

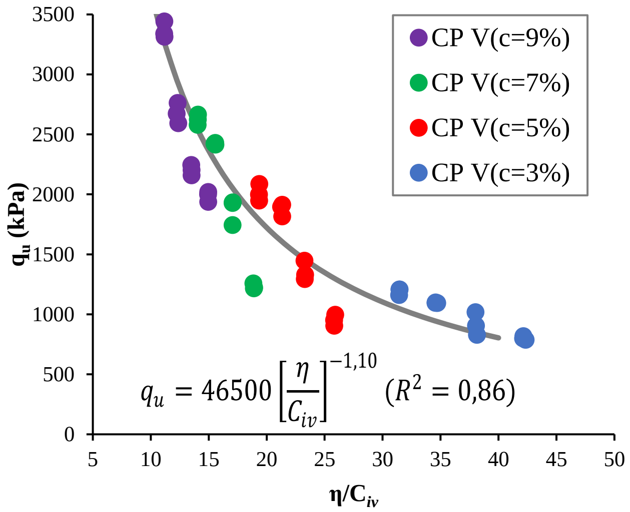

Figure 6. Influence of the porosity/volumetric content of cement on the simple compressive strength (potential regression)

Equation 3 defines the growth of that with the decrease of η/C_{iv} with the potential regression shown in Figure 6:

$$q_u = 46500\left[\frac{\eta}{C_{iv}}\right]^{-1,10} (R^2 = 0,86) \qquad (3)$$

Note that Equation 3 follows the form: $q_u = A\left[\frac{\eta}{C_{iv}}\right]^{-B}$; where A and B are constants. The value of A may depend on the curing time or the cementing element.

Figure 6 shows that comparing the reduction of 20 percentage points of η/C_{iv} it is obtained that, for example, if reduce the voids/cement ratio of a mixture from η/C_{iv}=35 to η/C_{iv}=15, its strength increases at 1430 kPa.

Consoli et al. (2017c) suggest that a better trend of the experimental points of simple compressive strength of soil-cement and soil-lime mixtures can be obtained if the value of C_{iv} is adjusted to an exponent between 0.01 and 1.00 within the range of the specific η/C_{iv} ratio studied. In this way, the values reported in Figure 6 were adjusted to a decimal exponent between 0.01 and 1.00, the exponent being 0.40, which provided the best coefficient of determination for the cement used. Thus, the values of q_u depending on the $\eta/C_{iv}^{0.40}$ ratio for the cement are shown in Figure 7.

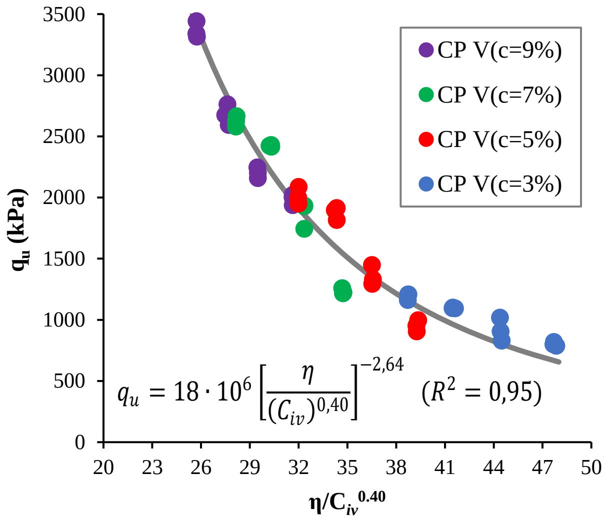

Figure 7. Influence of the porosity/volumetric content of cement (adjusted to an exponent of 0.40) on the simple compressive strength

It can be seen in Figure 7 that the values of coefficients of determination with the use of the adjustment exponent 0.40 increased from 0.86 to 0.95 for CP V cement. The reduction of 20 percentage points from $\eta/C_{iv}^{0.40}$=45 to $\eta / C_{iv}^{0.40}$=25 gives increase of 2893 kPa in the values of q_u. Equation 4 defines the growth of q_u with the decrease of $\eta/ C_{iv}^{0.40}$:

$$q_u = 18 \cdot 10^6 \left[\frac{\eta}{(C_{iv})^{0,40}}\right]^{-2,64} (R^2 = 0,95) \tag{4}$$

Equation 4 follows the form: $q_u = A\left[\frac{\eta}{C_{iv}}\right]^{-B}$. Based on studies carried out by Consoli et al. (2007; 2013; 2017c) the value of B and C depends on the soil type. The value of A with the 0.40 exponent grows depending on the type of cement used. Thus, it is possible to obtain the exact behavior of the simple compression results using the $\eta/C_{iv}^{0.40}$ ratio. The η/C_{iv}^{C} ratio can provide a unique trend in the strength of the silty soil experienced in the present work artificially cemented with a high initial strength cement. For Rios et al. (2012) and Mola-Abasi et al. (2016), the η/Civ ratio proves to be an excellent adjustment parameter to describe the unconfined compression behavior of cement-stabilized soils.

CONCLUSION

According to the type of soil used in the present research (silty soil), the type of cement used, the cement contents (3-9%) and the 28-day curing time to which the specimens were submitted in addition to the analyzes of the results, the following conclusions are addressed:

– The simple compressive strength of the specimens of soil-cement mixtures increased with the increase of the cement content and the increase of the molding dry specific weight. Furthermore, a linear trend was the best way to represent the growth of q_u with the variation of the cement content from 3 to 9%. On the other hand, the decrease in the porosity of the samples also increased q_u.

– The porosity/volume cement content ratio (η/C_{iv}) proved to be an efficient parameter for studying the mechanical behavior of mixtures as reported in previous studies. An exponent of 0.40 over the volumetric content of cement ($\eta/C_{iv}^{0.40}$) provided a better fit of the samples tested under simple compression.

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