The Influence of Moisture Content on Tensile and Compressive Strength of Artificially Cemented Sand

Fernanda Stracke, Jonatan Garrido Jung, Eduardo Pavan Korf, Nilo Cesar Consoli

Abstract. Applying Portland cement to soils is an excellent technique when it is necessary to improve local soil for the construction of stabilized pavement bases and to have a support layer for shallow foundations. Consoli *et al.* (2007, 2009, 2010) developed a rational dosage methodology for artificially cemented soils based on porosity/cement index, which can be applied to unconfined compressive strength, as well as to splitting tensile strength. Furthermore, a unique q_t/q_u relationship was found, independent of the cement content and voids ratio. Following the assessment of the main factors that influence the strength of artificially cemented soils, the present research aims to quantify the influence of the moisture content in the tensile and compressive strength of an artificially cemented sand. A program of splitting tensile tests and unconfined compression tests was carried out. There were tested three voids ratio (0.65, 0.73 and 0.81), four cement contents (3%, 5%, 7% and 9%) and five moisture contents (6%, 8%, 10%, 12% and 14%). The results show that the reduction in moisture content of the compacted mixture increases both the tensile and compressive strengths. Furthermore, it has been shown that q_t/q_u relationship was kept constant, being independent of the porosity/cement ratio and the moisture content.

Keywords: tensile strength, compressive strength, soil-cement, compacted soils, moisture content.

1. Introduction

Portland cement is worldwide used in the improvement of local soils. Several studies have shown that soil-cement blends have a complex behavior that is affected by many factors, such as the amount of cement, the porosity and moisture content at the time of compaction (Clough *et al.*, 1981, Tatsuoka and Shibuya 1992, Huang and Airey 1998; Horpibulsuk *et al.*, 2003, Consoli *et al.*, 2003, 2006, 2007, 2009, 2010, Thomé *et al.*, 2005, Dalla Rosa *et al.*, 2008).

Consoli *et al.* (2007) developed the first rational dosage methodology for artificially cemented soils considering the porosity/cement ratio (η/C_{iv}), defined as the porosity of the compacted soil-cement mixture divided by the volumetric cement content, as an appropriate index to evaluate the unconfined compressive strength of soil-cement mixtures. Further studies (Consoli *et al.*, 2009, 2012) quantified the influence of the amount of cement and porosity on the initial shear modulus (G_0) and effective strength parameters (c', ϕ') of artificially cemented sandy soils.

Additionally, Consoli *et al.* (2010) showed that the porosity/cement ratio (η/C_{iv}) was an appropriate index to evaluate not only unconfined compressive strength (q_u) of soil-cement mixtures, but splitting tensile strength (q_t) as well. The q_t/q_u relationship was shown to be unique for a given soil-cement mixture studied, being independent of the porosity/cement ratio.

All these previous studies covered a wide range of voids ratio (corresponding to high, medium, and reduced relative densities) and of cement percentages. The only variable that was not assessed was the moisture content, which was the same in all the studies (w = 10%). Based on this fact, there is still a variable (moisture content) that has to be better evaluated in soil-cement mixtures. Therefore, this study aims to quantify the influence of moisture content in the tensile strength (q_t) and compressive strength (q_u) of artificially cemented sand. Moreover, the variation of the q_t/q_u relationship with moisture content and porosity/cement ratio is evaluated.

2. Experimental Program

The experimental program has been carried out in two parts. First, the geotechnical properties of the soil and cement were characterized. Then, a number of splitting tensile and unconfined compression tests were carried out.

2.1. Materials

The soil used in the testing was a sand obtained from the region of Osório, near Porto Alegre, in Southern Brazil, classified (ASTM 1993) as non-plastic uniform fine sand (SP). The mean effective diameter (D_{50}) of the studied sand is 0.16 mm, being the uniformity and curvature coefficients of 1.9 and 1.2, respectively. Sand particles have a rounded shape and specific gravity of the solids is 2.65. Mineralogical analysis showed that sand particles are predominantly

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quartz. The minimum and maximum void ratios are 0.6 and 0.9, respectively. The angle of shearing resistance at constant volume is about 30°.

High early strength Portland cement was used as the cementing agent. Its fast gain of strength allowed the adoption of seven days as the curing time. The specific gravity of the cement grains is 3.15. Distilled water was used for these characterization tests and for molding specimens for the tensile and compression tests.

2.2. Methods

2.2.1. Molding and curing of specimens

For the splitting tensile and unconfined compression tests, cylindrical specimens 50 mm in diameter and 100-mm high were used. Once established a given voids ratio (e), the target dry unit weight (γ_d) was calculated according to Eq. 1

$$e = \frac{\gamma_s}{\gamma_d} - 1 \tag{1}$$

where γ_s = solids unit weight. A target dry unit weight for a given specimen was then established through the dry mass of soil-cement divided by the total volume of the specimen. In order to keep the dry unit weight of the specimens constant with increasing cement content, a small portion of the soil was replaced by cement. As the specific gravity of the cement grains (3.15) is greater than the specific gravity of the sand grains (2.65), for the calculation of void ratio and porosity, a composite specific gravity based on the sand and cement percentages in the specimens was used.

After the sand, cement, and water were weighed, the sand and cement were mixed until the mixture acquired a uniform consistency. The water was then added continuing the mixture process until a homogeneous paste was created. The amount of cement for each mixture was calculated based on the mass of dry sand and the moisture content. The specimen was then statically compacted in three layers inside a cylindrical split mold, which was lubricated, so that each layer reached the specified dry unit weight. The top of each layer was slightly scarified. After the molding process, the specimen was immediately extracted from the split mold and its weight, diameter, and height measured with accuracies of about 0.01 g and 0.1 mm, respectively. The specimens were then placed inside plastic bags to avoid significant variations of moisture content. They were cured for 6 days in a humid room at 23° ± 2 °C and relative humidity of above 95%.

The samples were considered suitable for testing if they met the following tolerances:

- *Dry unit weight* (γ_d): degree of compaction between 99 and 101% (the degree of compaction being defined as the value obtained in the molding process divided by the target value of γ_d);

and

- *Dimensions* : diameter to within ± 0.5 mm and height of ± 1 mm.

2.2.2. Splitting tensile tests

Splitting tensile tests followed Brazilian standard NBR 7222 (Brazilian Standard Association 1983). An automatic loading machine, with maximum capacity of 50 kN and proving rings with capacities of 10 and 50 kN and resolutions of 0.005 and 0.023 kN, respectively, were used for the unconfined compression tests.

After curing, the specimens were submerged in a water tank for 24 h for saturation to minimize suction. The water temperature was controlled and maintained at 23 ± 3 °C. Immediately before the test, the specimens were removed from the tank and dried superficially with an absorbent cloth. Then, the splitting tensile test was carried out and the maximum load recorded.

2.2.3. Unconfined compression tests

Unconfined compression tests have been systematically used in most experimental programs reported in the literature in order to verify the effectiveness of the stabilization with cement or to access the importance of influencing factors on the strength of cemented soils. One of the reasons for this is the accumulated experience with this kind of test for concrete. The tests usually followed Brazilian standard NBR 5739 (Brazilian Standard Association 1980), being simple and fast, while reliable and cheap.

The automatic loading machine and proving rings were the same used for the splitting tensile tests. Curing of specimens and acceptance criteria were exactly the same as for splitting tensile tests.

2.2.4. Program of splitting tensile and unconfined compression tests

The splitting tensile and unconfined compression tests constituted the main part of this research. The program was conceived in such a way as to evaluate, separately, the influences of the moisture content, cement content, porosity, and porosity/cement ratio on the mechanical strength of the artificially cemented sand.

The molding points were chosen considering moisture contents of 6, 8, 10, 12 e 14%, and voids ratio of 0.65, 0.73, and 0.81 (corresponding, respectively, to high, medium, and reduced relative densities). Each point was molded with four different cement percentages: 3, 5, 7, e 9%. These percentages were chosen following Brazilian and international experience with soil-cement (*e.g.*, Mitchell 1981; Consoli *et al.*, 2003, 2006, 2007, 2009, 2010, 2012; Thomé *et al.*, 2005). Two specimens were tested for each point for both splitting tensile and unconfined compression tests.

3. Results and Discussion

3.1. Effect of moisture content on tensile and compressive strengths

The splitting tensile strength is a function of the porosity/cement ratio (γ/C_{iv}) for the five moisture content used (6, 8, 10, 12 e 14%). The porosity/cement ratio is expressed as porosity (η) divided by the volumetric cement content (C_{iv}), the latter expressed as a percentage of cement volume regarding total volume, defined by Eq. 2.

$$\frac{\eta}{C_{iv}} = \frac{\left(\frac{V_v}{V_{total}}\right)}{\left(\frac{V_c}{V_{total}}\right)} = \frac{V_v}{V_c} \tag{2}$$

where V_v = volume of voids (water + air) of the specimen; V_c = volume of cement of the specimen; and V_{total} = total volume of the specimen.

Figure 1 presents the correlation between porosity/cement ratio (η/C_{iv}) and the splitting tensile strength (q_t) of the studied sand-cement mixes with moisture contents of 6, 8, 10, 12 and 14% [see Eq. 3 to Eq. 7, respectively].

$$q_t\ (\text{kPa}) = 17623 \cdot \left(\frac{\eta}{C_{iv}}\right)^{-1.70} \tag{3}$$

$$q_t\ (\text{kPa}) = 18\,947 \cdot \left(\frac{\eta}{C_{iv}}\right)^{-1.80} \tag{4}$$

$$q_t\ (\text{kPa}) = 11867 \cdot \left(\frac{\eta}{C_{iv}}\right)^{-1.75} \tag{5}$$

$$q_t\ (\text{kPa}) = 11370 \cdot \left(\frac{\eta}{C_{iv}}\right)^{-1.83} \tag{6}$$

$$q_t\ (\text{kPa}) = 11626 \cdot \left(\frac{\eta}{C_{iv}}\right)^{-1.90} \tag{7}$$

Figure 2 summarizes all results of splitting tensile strength, for all the moisture content tested (6, 8, 10, 12, 14%). In this figure, all the original exponents of the trend curves were kept. By examining this figure, it can be seen

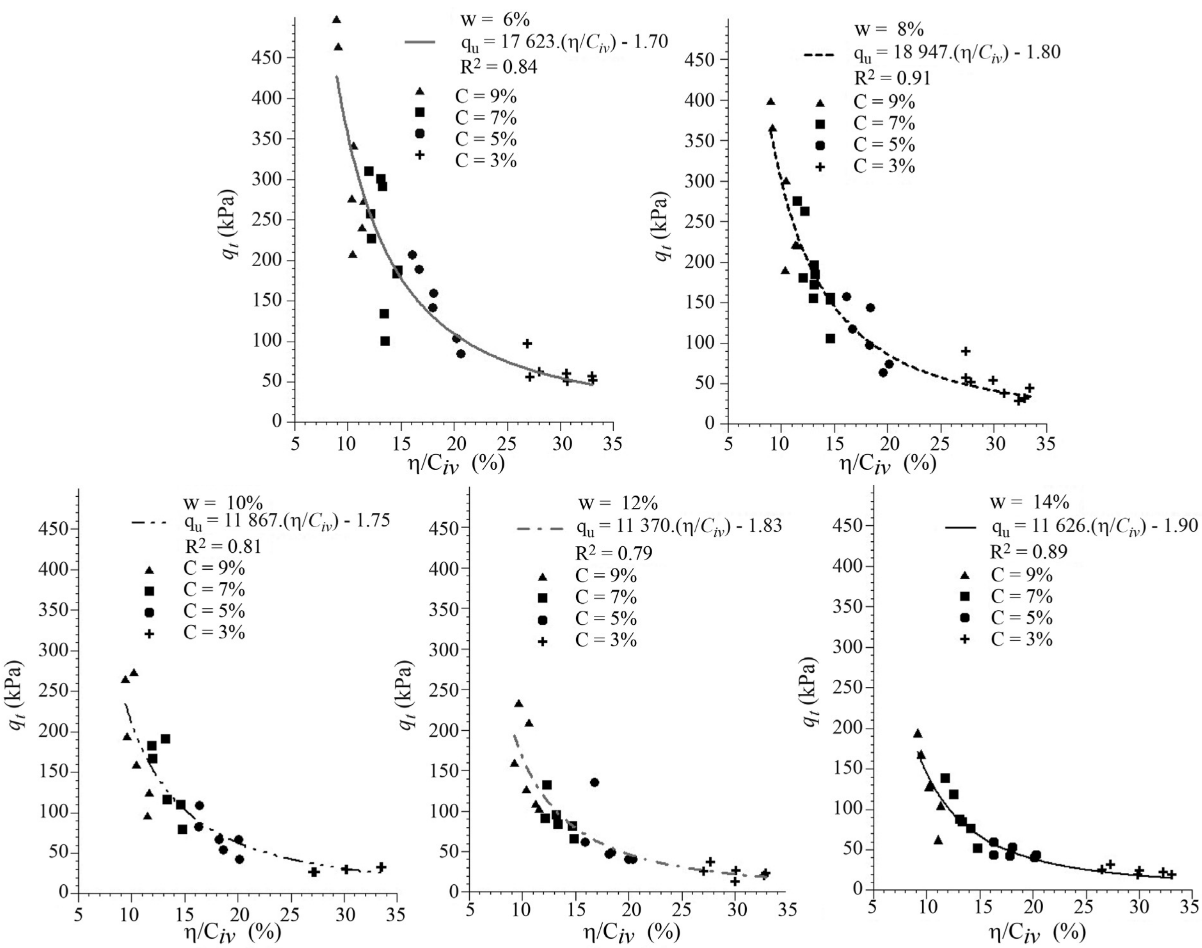

Figure 1 - Variation of splitting tensile strength (q_t) with porosity/cement ratio for moisture contents of 6, 8, 10, 12 and 14%.

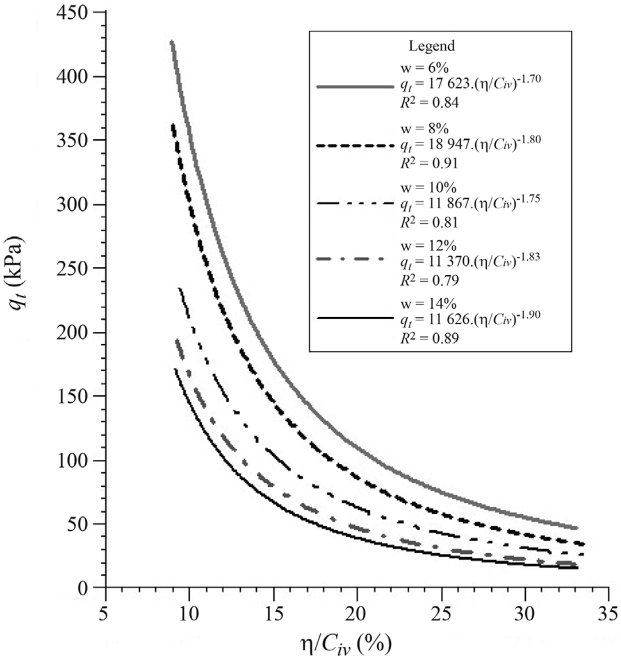

Figure 2 - Variation of splitting tensile strength for the distinct moisture contents of the compacted mixture.

the influence of moisture content in the splitting tensile strength. The reduction in moisture content of compacted mixture increases splitting tensile strength. The possible explanation for such results is that the cement containing less water during mixture will have fewer pores in the cement-water mixture, ending in stronger cementitious bonds.

Figure 3 presents the correlation between porosity/cement ratio (η/C_{iv}) and the unconfined compressive strength (q_u) of the studied sand-cement mixtures with moisture contents of 6, 8, 10, 12 and 14% [see Eq. 8 to Eq. 12, respectively].

$$q_u\ (\text{kPa}) = 86160 \cdot \left(\frac{\eta}{C_{iv}}\right)^{-1.58} \tag{8}$$

$$q_u\ (\text{kPa}) = 95\,513 \cdot \left(\frac{\eta}{C_{iv}}\right)^{-1.65} \tag{9}$$

$$q_u\ (\text{kPa}) = 49\,875 \cdot \left(\frac{\eta}{C_{iv}}\right)^{-1.54} \tag{10}$$

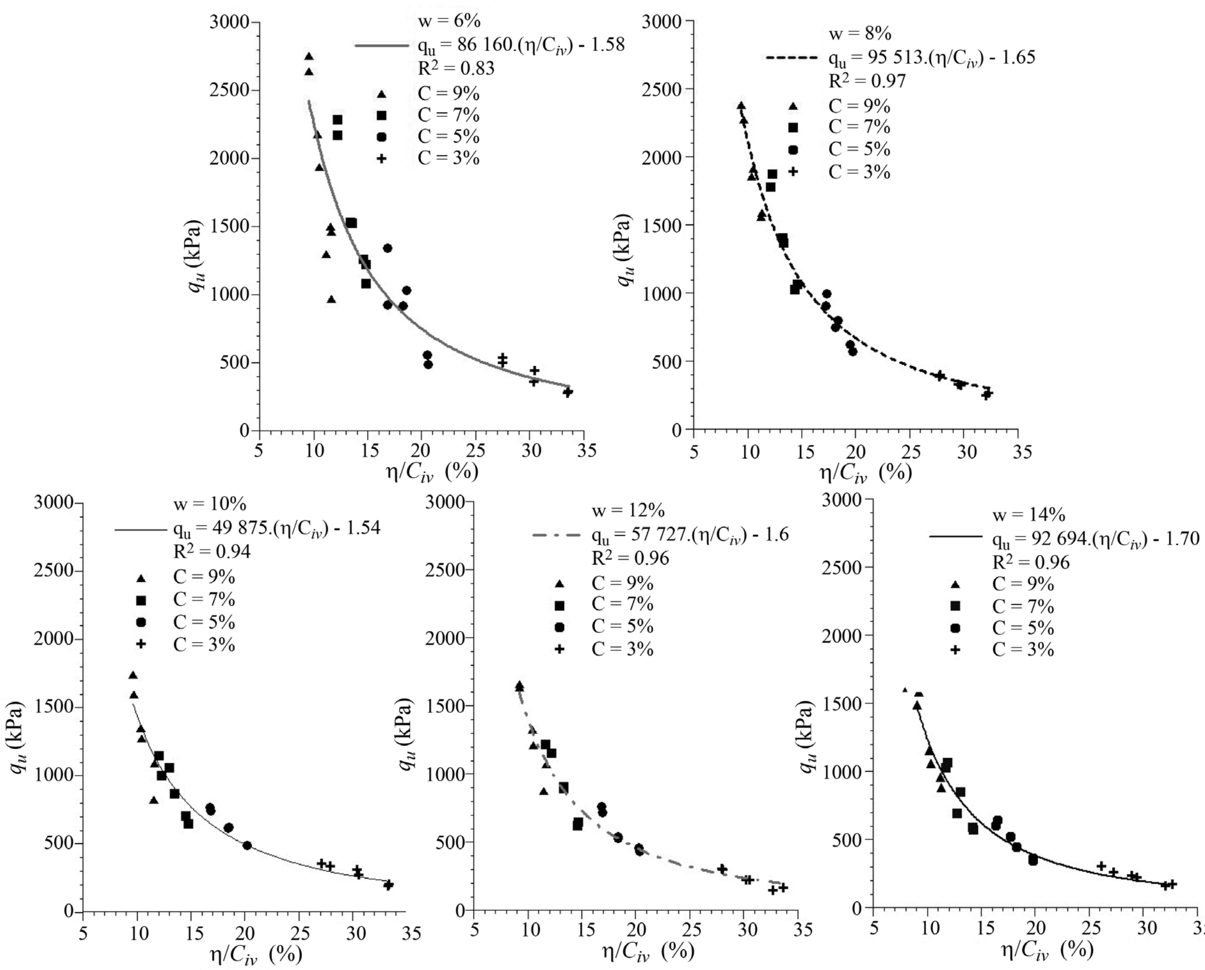

Figure 3 - Variation of unconfined compressive strength (q_u) with porosity/cement ratio for moisture contents of 6, 8, 10, 12 and 14%.

$$q_u\ (\text{kPa}) = 57\,727 \cdot \left(\frac{\eta}{C_{iv}}\right)^{-1.61} \tag{11}$$

$$q_u\ (\text{kPa}) = 92\,694 \cdot \left(\frac{\eta}{C_{iv}}\right)^{-1.70} \tag{12}$$

Figure 4 summarizes all the results of unconfined compressive strength tests, for all the moisture contents tested (6, 8, 10, 12, 14%). Also in this figure, all the original exponents of the trend curves were kept. By examining this figure, and equations in the graphic, it can be seen the influence of moisture content in the unconfined compressive strength. In the same trend of the results of splitting tensile strength tests, the reduction in moisture content of compacted mixture increases unconfined compressive strength.

The results of present research show that moisture content of the sand-cement compacted mixtures influence the final tensile and compressive strengths. The reduction in moisture content of the compacted mixtures increases both the tensile and compressive strengths, as summarizes Figure 5.

Figure 5 shows all the exponential trend curves, with all the exponents adjusted to the average exponent (1.70). In this way, it is possible to compare different trend curves of different moisture contents.

Splitting tensile and unconfined compressive test results show that after 2% decrease in the moisture content there is an average increase of 17% in tensile and compressive strengths.

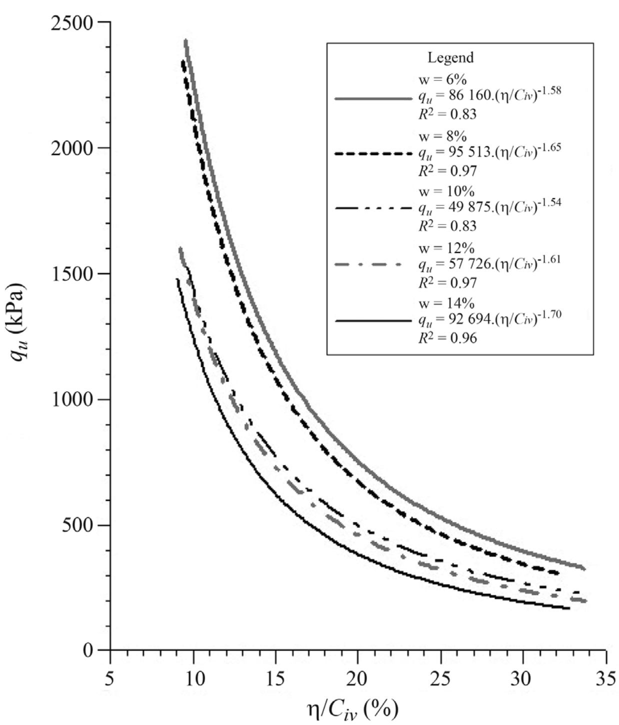

Figure 4 - Variation of unconfined compressive strength for the distinct moisture contents of the compacted mixture.

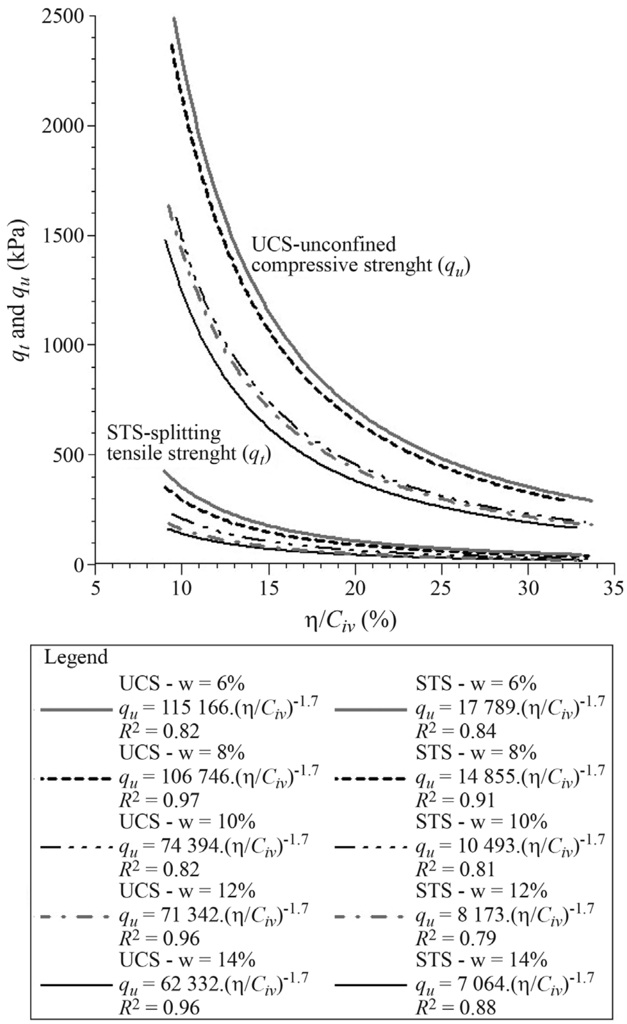

Figure 5 - Variation of unconfined compressive strength (q_u) and splitting tensile strength (q_t) for different moisture contents of the compacted sand-cement mixtures.

Furthermore, it can be concluded that splitting tensile strength - unconfined compressive strength ratio (q_t/q_u) is about 13% for all moisture contents tested. These results corroborate the results obtained by Consoli *et al.* (2010), where q_t/q_u ratio was a constant for the sand-cement mixtures studied. Present study and the one developed by Consoli *et al.* (2010) showed that the q_t/q_u ratio is independent of both porosity/cement ratio and moisture contents. This is very interesting, in the sense that dosage methodologies based on rational criteria can concentrate either on tensile or compression tests, once they are totally interdependent.

4. Conclusions

From the data presented in this technical note, the following conclusions can be drawn:

1. The reduction in moisture content of the compacted mixture increases both the tensile and compressive strengths.

2. A decrease of 2% in the moisture content increases both unconfined compressive strength and splitting tensile strength in about 17%, for the sand-cement mixtures evaluated in present research;
3. The q_t/q_u ratio is a scalar (0.13) for the sand-cement mixtures evaluated in the present study, being independent of moisture content and of porosity/cement ratio.

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Notation

C = cement content (expressed in relation to mass of dry soil)
C_{iv} = volumetric cement content (expressed in relation to the total specimen volume)
D_{50} = mean effective diameter
e = voids ratio
q_t = splitting tensile strength
q_u = unconfined compressive strength
R^2 = coefficient of determination
γ_d = dry unit weight
γ_s = solids unit weight
η = porosity
η/C_{iv} = porosity/cement ratio
ω = moisture content