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Effect of wet-dry cycles on the durability, strength and stiffness of granite residual soil stabilised with Portland cement

Effet des cycles sec-humide sur la durabilité, la résistance et la rigidité d'un sol granitique stabilisé avec du ciment Portland

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ABSTRACT: This study aims to assess the influence of the initial dry density on the durability and mechanical performance of a common northern Portugal granite residual soil stabilised with a Portland cement. This information is deemed necessary for general soil improvement applications, especially for surface soil stabilisation (e.g. roads and railways). The durability test followed the contents of ASTM standards, while the stiffness and strength evolution were monitored using seismic waves and indirect tensile strength tests, respectively. The loss of mass of the stabilised material, after each wet-dry cycle, was also registered. The results allowed the estimation of the “accumulated loss of mass” (ALM), the shear modulus and the tensile strength as a function of the porosity-cement index (η/C_{iv}). A relation connecting ALM, indirect tensile strength and shear stiffness respectively to porosity cement index is determined to cover both the tolerance and the strength aspects of compacted soil – Portland cement mixes.

RÉSUMÉ: Cette étude vise à évaluer l’influence de la densité sèche initiale sur la durabilité et les performances mécaniques d’un sol résiduel de granite du nord du Portugal, stabilisé avec un ciment Portland. Ces informations sont jugées nécessaires pour les applications générales d’amélioration des sols, en particulier pour la stabilisation des sols de surface (par exemple, les routes et les voies ferrées). L'essai de durabilité a suivi le contenu des normes ASTM, tandis que l'évolution de la rigidité et de la résistance ont été contrôlées à l'aide d'essais d'ondes S sismiques et de résistance à la traction indirecte, respectivement. La perte de masse du matériau stabilisé, après chaque cycle de séchage à l'état humide, a également été enregistrée. Les résultats ont permis d'estimer la “perte de masse accumulée” (ALM), le module de cisaillement et la résistance à la traction en fonction de l'indice porosité-ciment (η/C_{iv}). Une relation entre l'ALM, la résistance à la traction indirecte et la rigidité au cisaillement, respectivement, à l'indice porosité-ciment est déterminée pour couvrir à la fois les aspects de tolérance et de résistance des mélanges compacté sol – ciment Portland.

Keywords: Soil stabilisation; wet-dry cycles; durability; stiffness; strength.

1 INTRODUCTION

Soil stabilisation through the addition of Portland cement is a well-known technique that is used worldwide in order to improve the mechanical characteristics of local soils for the construction of shallow foundations and road and railway embankments, among other geotechnical issues (Ingles and Metcalf 1972; Mitchell 1981). In this context, Consoli et al. (2007) was piooner in the development of a rational dosage methodology for artificially cemented soils, based on the porosity/cement ratio (η/C_{iv}), defined as the porosity of the compacted cemented soil specimen divided by its volumetric cement content. Subsequent studies have demonstrated that, in addition to the strength, the η/C_{iv} index is also appropriate to evaluate the effects of the stabilisation on both stiffness and durability (Consoli et al. 2017; Consoli and Tomasi 2018; Consoli et al. 2018). In short, it is possible to assess the overall performance of artifitially cemented soils by using such parameter.

The evaluation of the long term performance is an essential aspect concerning the practical applications of any stabilisation technique, especially when cementing agents (chemical stabilisation) are used. In the laboratory, this can be conducted by means of wet-dry cycles, where the treated specimens are submited to extreme conditions (wet and excessive heat) and then tested for strength, stiffness and/or durability, using a standardized brushing procedure.

The present study aims to evaluate the effect of the initial dry unit weigth and cement content on the tensile strength of a granitic residual soil, using the split strength test, after 0, 3, 6, 9 and 12 wet-dry cycles. Three distinct dry unit weights were defined – 16.38, 17.36 and 18.34 kN/m³ – for a single moisture content of 10.40 %. In additon, durability and ultrassonic pulse velocity tests were carried out to evaluate the cement content effect on the intermediate dry unit weight specimens.

2 EXPERIMENTAL PROGRAMME

The experimental programme was carried out in four parts. First, the physical properties of the original materials were determined. Based on this information, three controllable factors were defined – dry unit weight (γ_d), moulding moisture content (*w*) and cement content (C). The strength, durability and stiffness (seismic waves velocity measurement) tests were then performed, and the results were analysed and correlated to the η/C_{iv} index. Table 1 summarizes the controllable factors employed in the present study.

Table 1. Controllable factors

Cement (% wt.)	**Dry Unit Weight (kN/m³)**	**Moisture Content (%)**	**Curing Period (days)**
3	16.38	10.4	7
5	17.36		
7	18.34		

2.1 Materials

The residual granitic soil used was collected in the northwest region of Portugal. Its chemical composition, obtained by X-ray fluorescence, showed high silica and alumina weight contents, of 65% and 22%, respectively. Its particle size distribution is presented in Figure 1. X-ray diffraction analysis showed the prevalence of quartz, kaolinite, muscovite and orthoclase minerals. Some additional geotechnical properties are presented in Table 2. According to the Unified Soil Classification System (ASTM D2487-11, 2011), it is classified as a SM – silty sand. Rapid hardening Portland cement type CEM I 42.5R was used. Distilled water was employed in all of the tests.

Table 2. Main geotechnical properties of the soil

Property	**Value**
Specific gravity (kN/m³)	26.2
D_{50} (mm)	0.42
Fines fraction (sieve Nº 200) (%)	22.8
Maximum dry unit weight (kN/m³)	18.5
Optimum water content (%)	12.3

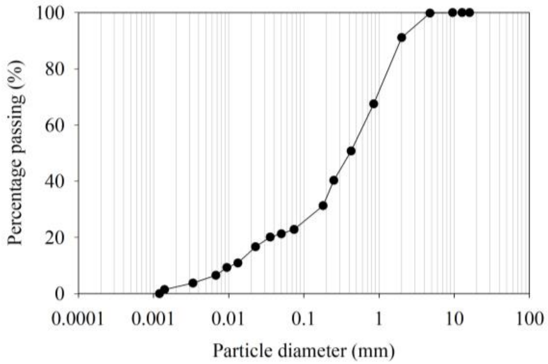

Figure 1. Particle size distribution of the soil

2.2 Methods

2.2.1 Moulding and curing of specimens

Cylindrical specimens were used for all types of tests performed. For the split tensile strength tests the specimens had 38 mm in diameter and 70 mm in heigth, while, for the durability and seismic waves tests, the specimens had 100 mm in diameter and 127 mm in height.

The dry materials (soil and cement) were weighed and dry blended by hand, until a visual uniformity was reached. Next, distilled water was added to the mixture that was blended until a homogeneous paste was achieved. Then, the mixtures were statically compacted into cylindrical split casts. After moulding, the specimens were weighed, measured and sealed in plastic bags, before being stored in a humid room with controlled moist (95% ± 2%) and temperature (23°C ± 2°C), for curing.

2.2.2 Split tensile strength tests

The split tensile strength tests were performed after 7 days curing, and after 3, 6, 9 and 12 wet-dry cycles. The cycles started as soon as the curing time was finished, and consisted of immersion in water for 5 hours, followed by drying for 42 hours, in an oven, at 71°C.

The tests were performed in accordance with the brazilian standard NBR 7222 (ABNT 1983), which is in conformity with the standard ASTM C496 (ASTM 2011). A servo-hydraulic testing machine, fitted with a 25 kN capacity load cell, with a resolution of 0.006 kN, was used for the strength tests, which were carried out under monotonic displacement control, at a rate of 0.1 mm/min (Figure 2).

Equation (1) states the relationship between the ultimate applied force and the split tensile strength.

$$q_t = \frac{2 \cdot F}{\pi \cdot D \cdot H} \qquad (1)$$

where qt (MPa) is the split tensile strength, F (MN) is the force applied, and D (m) and H (m) are the diameter and height (m), respectively, of the specimen.

Figure 2. Split tensile strength test

2.2.3 Durability tests

The durability tests were carried following the procedures established by the ASTM D559 (ASTM 2015), which defines the methodology to measure the mass, volume and moisture variations of the cemented soil specimens, throughout 12 wetting, drying and brushing cycles. Two specimens of each soil-cement combination were moulded, being one for the brushing procedure and the other for the volume and moisture variation assessment. After the curing period, these specimens were immersed in water for 5 hours, and then inserted back into the oven, to dry for 41 hours, at 71°C. Finally, one of the specimens was brushed, with a force of approximately 13.3 N. This cycle was repeated 12 times.

2.2.4 *Ultrasonic pulse velocity tests*

The initial shear modulus (G_0) of an elastic and homogeneous medium can be correlated to the velocity of a shear wave propagating through it and its specific mass, as shown in the Equation (2).

$$G_0 = \rho \cdot V_s^{2} \tag{2}$$

where G_0 (Pa) is the initial shear modulus, ρ (kg/m³) is the specific mass and V_s (m/s) is the shear wave velocity.

The seismic wave measurements were carried out after each cycle of the durability tests, on the specimens specifically designated for the volumetric and moisture content assessments. The time of the shear wave propagation was measured with specific transducers, right after the drying period of each cycle, and only the results for cycles 0, 3, 6, 9 and 12 are presented.

3 RESULTS

The presentation of the results are divided in two separate sections: split tensile strength; and durability and stiffness.

3.1 *Split tensile strength*

The split tensile strength (R_t) results, after cycles 3 and 12, were correlated to the η/C_{iv} index, resulting in Equations (3) and (4), respectively:

$$R_{t,C3} = 6.18 \cdot \left[\frac{\eta}{C_{iv}}\right]^{-1.55}; R^2 = 0.84 \tag{3}$$

$$R_{t,C12} = 5.50 \cdot \left[\frac{\eta}{C_{iv}}\right]^{-1.55}; R^2 = 0.94 \tag{4}$$

where R_t (MPa) is the split tensile strength, η (%) is the porosity and C_{iv} (%) is the volumetric cement content.

The external exponent obtained was the same for every equation and is in accordance with the findings stated by Diambra et al. (2017). In addition, the scalar is of the same magnitude for each cycle, which is an indication of the similarity of the strength values along the cycles. An analysis of variance was performed, showing that the amount of cement (C) and the initial dry unit weight (γ_d) were the most influential factors on the strength response. The influence of the cycles was negligible, which can be concluded by the high significance value ($P > 0.005$), contrary to what was observed for the C and γ_d factors ($P < 0.001$). This is also corroborated by relative influence of each factor in the R-Squared value of the ANOVA model, presented in Figure 3.

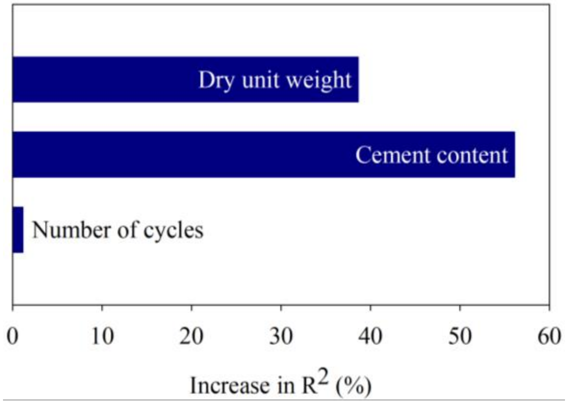

Figure 3. Contribution of each factor to the increase in the R-Squared value

The split tensile strength values are graphically presented in Figure 4, as a function of the η/Civ index. The smaller the η/Civ index, the higher the strength value. It means that qt increases with increasing amount of cement (C), and with increasing dry unit weight (γd).

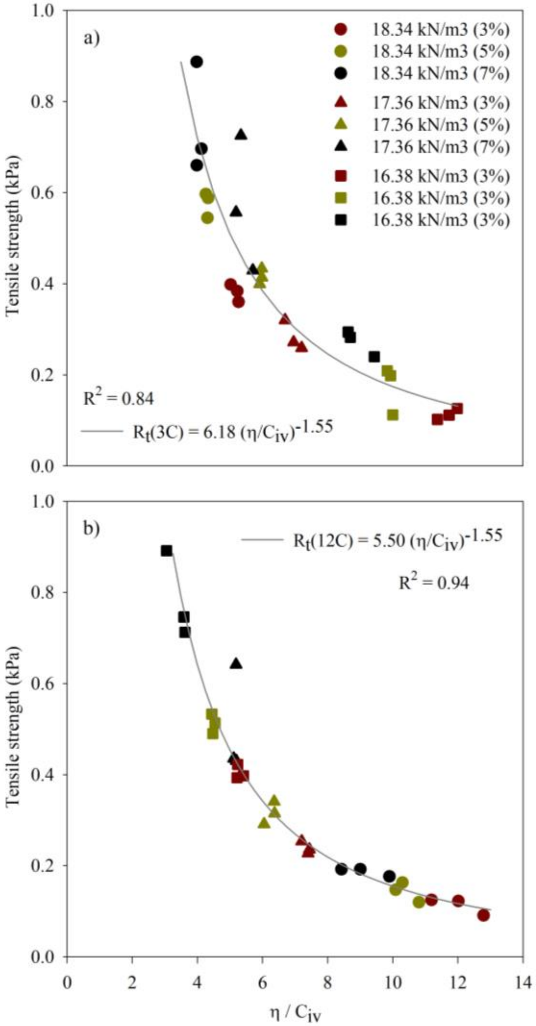

Figure 4. Relation between tensile strenght and the η/C_{iv} index after 3 cycles (a) 12 cycles (b).

3.2 Durability and stiffness

The results of the 17.36 kN/m^3 material, regarding the accumulated loss of mass (ALM) and the initial shear modulus (G_0), both measured after cycles 0, 3, 6 9 and 12, are shown in Figure 5. The general aspect of a 5% cement specimen, after 3 and 12 cycles, is presented in Figure 6.

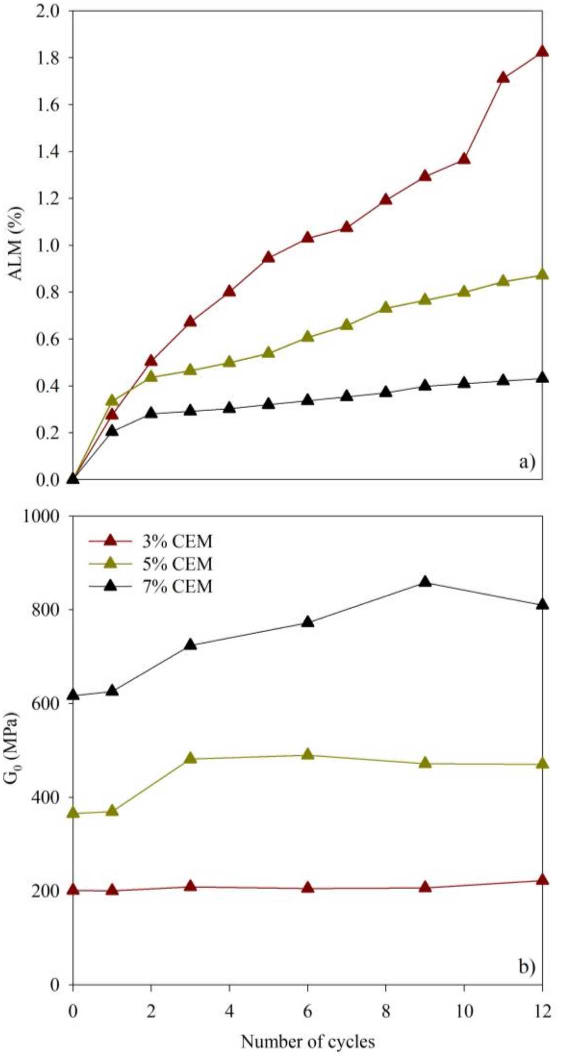

Figure 5. Evolution of the material with a dry unit weight of 17.36 kN/m^3 with the durability cycles: (a) ALM versus number of cycles (b) Initial shear modulus versus number of cycles.

Based on the images presented in Figure 6, confirmed by the measured mass variation, the stabilisation with cement allows the soil to withstand the aggressive conditions of each cycle. However, based on the initial shear modulus presented in Figure 5, it appears that most of the damage occurred during the first 3 cycles, with the exception of the 3% cement content.

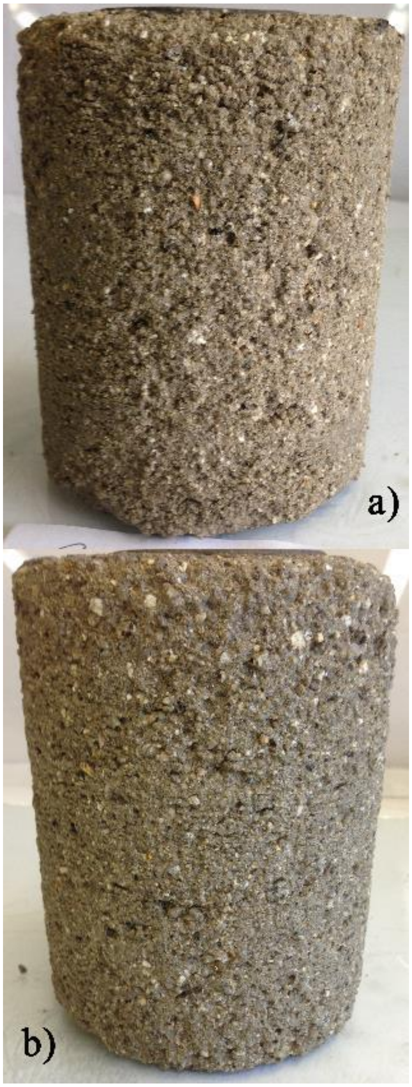

Figure 6. General aspect of a 17.36 kN/m³, stabilised with 5% cement, after 3 (a) and 12 (b) cycles.

The accumulated loss of mass for the 17.36 kN/m³ material, after cycles 3, 6, 9 and 12, is presented in Figure 7, and correlated with the η/C_{iv} index in equations (5), (6), (7) and (8), also represented in the same figure.

$$\mathrm{ALM}_{\mathrm{C3}} = 2.56 \cdot 10^{-2} \cdot \left[\frac{\eta}{\mathrm{C_{iv}}}\right]^{0.96}; R^2 = 0.97 \quad (5)$$

$$\mathrm{ALM}_{\mathrm{C6}} = 1.18 \cdot 10^{-2} \cdot \left[\frac{\eta}{\mathrm{C_{iv}}}\right]^{1.30}; R^2 = 0.97 \quad (6)$$

$$\mathrm{ALM}_{\mathrm{C9}} = 1.20 \cdot 10^{-2} \cdot \left[\frac{\eta}{\mathrm{C_{iv}}}\right]^{1.36}; R^2 = 0.96 \quad (7)$$

$$\mathrm{ALM}_{\mathrm{C12}} = 5.57 \cdot 10^{-3} \cdot \left[\frac{\eta}{\mathrm{C_{iv}}}\right]^{1.67}; R^2 = 0.99 \quad (8)$$

where ALM (%) is the accumulated loss of mass, η (%) is the porosity and C_{iv} (%) is the volumetric cement content.

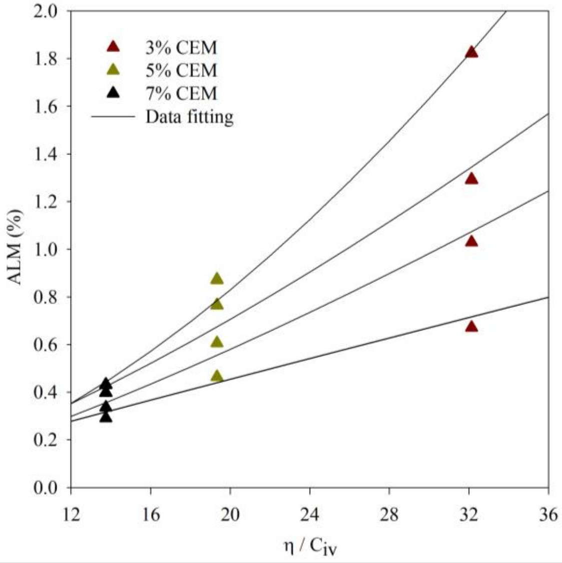

Figure 7. Relation between *ALM and the η/C_{iv} index, after 3, 6, 9 and 12 cycles, for the 17.36 kN/m³ material.*

Although minimal, the mass loss is clearly dependent on the cement content and dry unit weight. Such results corroborate those obtained regarding the split tensile strength,

4 CONCLUSIONS

Based on the data presented, the following conclusions can be drawn:

- The addition of Portland cement improved the soil performance, regarding strength, stiffness and durability; this improvement was proportional to the amount of cement added.
- For a given cement content, the decrease in porosity of the compacted mixtures resulted in significant strength gains.
- The wet-dry cycles appeared to have little influence in the mixtures' response, regarding their split tensile strength.
- The accumulated loss of mass observed after the durability tests was low and is in accordance to the limits established by international requirements to be used as road materials.

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