Strength and stiffness properties of mixtures of granitic soil-cement

Resistance et déformabilité de mélanges de sol traité au ciment

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ABSTRACT

This paper will focus on the sensitivity of strength and stiffness properties of silty-sands, from granitic residual soil, which can be converted to a highly improved material if stabilized with cement. The study of soil stabilization with cement demands to quantify the influence of the cement percentage, porosity and water content adopted in the admixing process for different stresses and physical states. Firstly, this influence was quantified in terms of the unconfined strength and maximum deformability modulus executing unconfined compression tests as well as seismic wave velocities measurements in thoroughly controlled conditions in laboratory, varying the factors indicated above. Then, drained triaxial tests with very precise instrumentation were performed in some specimens with such a cement percentage and water content fixing the relationship between the void ratio and the volume of cement.

RÉSUMÉ

Les propriétés de résistance et de rigidité des mélanges de sol-ciment sont analysées dans cet article. En effet, les sables limoneux utilisés dans cette étude peuvent devenir un matériau très résistant si amélioré en ajoutant ciment. L'étude de la stabilisation par ciment nécessite la quantification de l'influence du pourcentage de ciment, porosité et teneur en eau adopté dans le mélange pour les différents états physiques et de contraintes. D'abord, l'influence est analysée par la résistance à la compression uniaxial et par la vélocités des ondes séismiques. Ensuite, quelques essais triaxiaux drainés ont été réalisés sur éprouvettes préparés avec un pourcentage de ciment et quantité d'eau suffisantes pour que les vides divisé par le volume de ciment soit fixé.

Keywords: soil-cement, unconfined compression tests, triaxial tests

1 INTRODUCTION

Soil stabilization with cement is a good solution for the construction of roadway and railway lines, especially in "noble" foundation layers, such as subgrades, under the platforms, and mostly in transition zones between embankments and rigid structures, where the mechanical properties of supporting soils are very much demand full. These solutions are especially attractive in infrastructures for transportation where other ground improvement techniques are too complex and time consuming. On the other hand, the economic and environmental costs of such works are very dependent on a good balance between excavation and embankment volumes. For this purpose, the improvement of in situ soil can bring great advantages, avoiding a great amount of borrow material as well as dump soil. These are the main reasons why this technique has been used extensively in many countries.

Consoli et al. (2007) have been studying several mixtures of soil with cement, focusing in the key parameters that control strength of artificially cemented soils. In this paper the same indexes and parameters that control both stiffness and strength were investigated for a mixture of silty sand with an early strength Portland cement. For that purpose, unconfined and triaxial compression tests, as well as seismic wave velocities measurements were performed. This experimental framework is the base of a good definition of the mechanical parameters used in design and in quality control of earthworks execution of line works especially for foundations and subgrades of the platforms.

2 MATERIALS

The soil involved in this research is a silty sand originated by weathering of Porto granite (Viana da Fonseca et al., 2006). It is classified as a SM (silty sand) in the Unified Classification System. The physical parameters of this soil are expressed in Table 1. As can be observed in Figure 1, it is a very well graded soil with about 30% of fines with no plasticity.

Table 1. Physical parameters of the soil.

γ_s (g/cm^3)	D_{50} (mm)	C_u	C_c	ω_L	ω_P
2.72	0.25	113	2.72	34%	31%

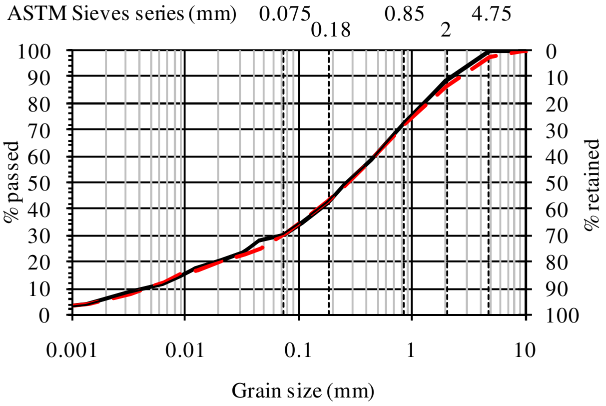

Figure 1. Grain size distribution curve.

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Taking the fact that non conventional cement was used, a series of unconfined compression tests with a mixture of 3% of cement was performed in order to evaluate the necessary curing period. It was concluded that after 7 days the final strength was reached. Taking that into account, all tests herein presented were tested after 7 days of curing.

3 EXPERIMENTAL PROGRAM

3.1 *Preparation of the samples*

The samples (70 mm diameter and 140 mm height) were prepared with the necessary quantities of soil, water and cement in order to achieve the required percentage of cement, water content and unit weight. For each sample, a quantity of fines equal to the weight of cement to be introduced was removed from the soil. The purpose of this procedure is to have the same grain size distribution in the mixture of soil-cement as in the soil itself. The correct weight of soil-cement mixture was then placed into a cylindrical stainless steel lubricated mould, and statically compacted in three layers so that each layer reached the specified dry density. The top of each layer was slightly scarified. The procedures of mixing and compaction of the samples took less than 30 min as advised in the Portuguese specification LNEC E-264 (1972). Some samples were extracted from the mould two hours after this process and some others, highly compacted, were only extracted 12 hours after in order to prevent swelling. The water content of the mixture, as well as the weight and dimensions of the samples, were carefully evaluated in order to control the quality of the samples to be tested. Then, the samples remained 6 days in the humid chamber and submerged into water in the 7th day in order to reach saturation and minimize suction effects.

3.2 *Proctor tests*

First, Standard and Modified Proctor compaction tests were performed over the soil and the mixture of 3% of cement, in order to obtain the optimum condition in each case. Figure 2 presents two curves for both types of tests performed over the soil sample, as well as one curve for the Modified Proctor over the 3% soil-cement mixture. This last curve showed, for a mixture of 3% of cement, that the optimum values are around 12% of water content of 18.8 kN/m^3 of unit weight.

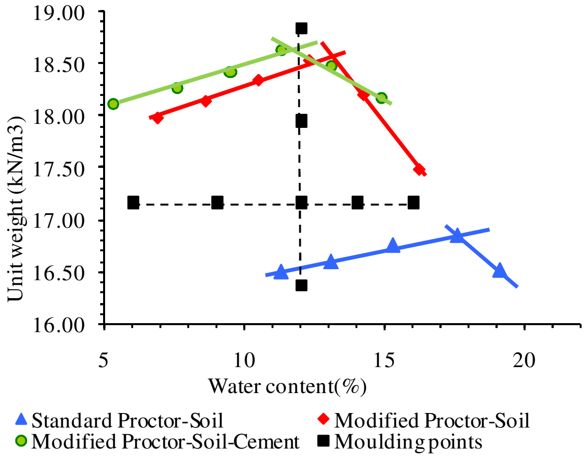

Figure 2. Proctor curves for soil and soil-cement samples of 3% of cement.

On this graph two lines were drawn in order to establish 8 moulding points for the next experimental programme. A vertical line (line A) with 12% of water content and a horizontal line (line B) with 17.2 kN/m^3 of unit weight were chosen, as can be seen in Figure 2.

3.3 *Unconfined compression testS*

The influence of the cement percentage, porosity and water content adopted in the admixing process, were first quantified in terms of the unconfined compression strength (UCS). For that purpose, an exhaustive experimental program of unconfined compression tests was defined on soil-cement samples moulded in the 8 conditions indicated in Figure 2, for 4 cement contents (2%, 4%, 5% and 7%), comprising 32 tests. Each test was repeated at least 4 times in order to confirm the results, and the values deviating more than 10% from the average value were rejected. The rate of displacement used in these tests was 0.1 mm/min, as these stiff samples fail at very small strains.

Consoli et al. (2007) showed that for soil-cement mixtures in an unsaturated condition (common in compacted fills), the water/cement ratio is not a good parameter for the assessment of the unconfined compression strength as it is for concrete. On the other hand, the void/cement ratio was demonstrated to be the most appropriate parameter to evaluate the unconfined compression strength of these soil-cement mixtures.

Following these conclusions, the results herein presented were analysed in terms of that index property, that is the ratio of porosity (η) to the volumetric cement content (Civ), expressed as a percentage of cement volume regarding the total volume (η/Civ). For these mixtures it was found that for the relationship between unconfined compression strength (UCS or q_u) and void/cement ratio, the optimum fit could be obtained applying the power law on an exponent of 0.21 to the parameter Civ. This value was obtained for line A with a good adjustment of R^2=0.98, as can be seen in Figure 3. Figure 4 show the results obtained for lines A and B, where a greater dispersion is observed.

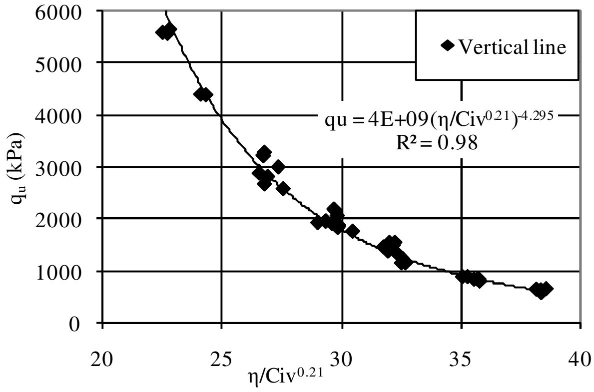

Figure 3. Unconfined compression strength (q_u) of samples moulded in line A with adjusted voids cement ratio (□/Civ$^{0.21}$).

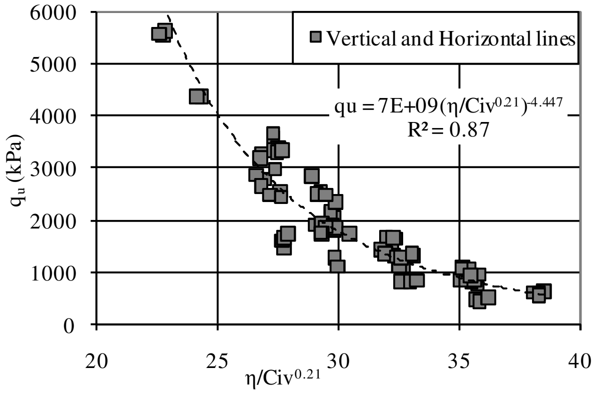

Figure 4. Unconfined compression strength (q_u) of samples moulded in lines A and B with adjusted voids cement ratio (□/Civ$^{0.21}$).

The unconfined compression tests were executed with local measurement of deformations with LDT's (Local Deformation Transducers), giving validity to the deformability modulus determined by this means. The results of the initial tangent modulus were plotted against the same index, as presenting in Figures 5 and 6, for samples moulded in line A and, lines A and B, respectively. Although with a lower R^2, the deformability modulus still showed a good trend when plotted against the same index defined for unconfined strength (□/$Civ^{0.21}$). It is very important to notice that void/cement ratio remains a very good parameter when stiffness properties are concerned.

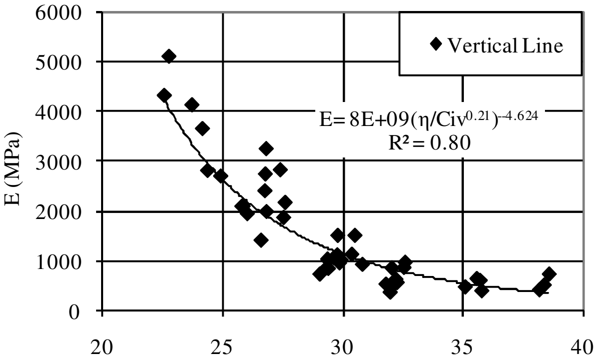

Figure 5. Deformability modulus (E) of samples moulded in line A with adjusted void cement ratio (□/$Civ^{0.21}$).

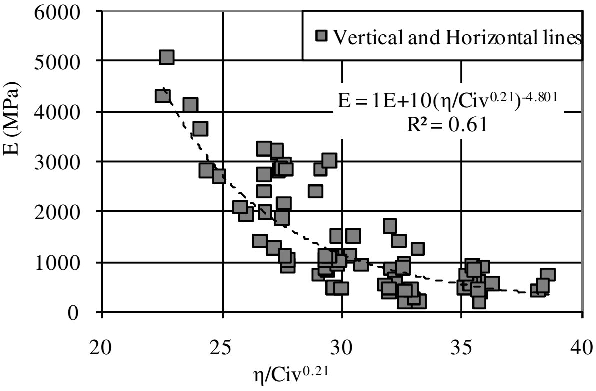

Figure 6. Deformability modulus (E) of samples moulded in lines A and B with adjusted void cement ratio (□/$Civ^{0.21}$).

3.4 *Seismic wave velocities measurements*

Having obtained the trend for the initial tangent modulus derived from LDT's measurements during unconfined compression tests, the same trend for the maximum deformability modulus was pursued. Seismic wave velocities measurements with bender elements and compression transducers (for S and P waves) were performed. Soil-cement samples were moulded for that purpose in the same conditions as described above for line A, except for the height of the samples which was equal to the diameter (70 mm). The P wave velocities measurements were much more reliable and easier to interpret than S wave velocities. The deformability modulus in very small strain levels (herein denoted as E_{el} or E_0), associated to these wave velocities taken as purely elastic, may be derived from the following equations based on the Theory of Elasticity:

$$M_0 = \rho V_P^2 \qquad (1)$$

$$E_0 = \frac{M_0\,(1-2\nu)(1+\nu)}{(1-\nu)} \qquad (2)$$

being M_0 the constrained modulus and ν the Poisson ratio, both in elastic conditions, and ρ the density of the material.

As it was still not possible to evaluate the Poisson ratio with confidence in these very stiff samples since the interpretation of S wave velocities is very difficult in such conditions (Viana da Fonseca et al., 2009), three values of this parameter were assumed for this sensitivity analysis (ν=0.3, 0.25 and 0.2). In Figure 7 the maximum deformability modulus results for the three values of Poisson ratio are plotted, as well as their fitting curves. All of these trends are very similar to the trend of the modulus from the LDT's presented in Figure 5 for line A, which confirms that the influence of void/cement ratio is also observed in stiffness in a similar way as that for strength. As expected, the absolute values of both moduli are completely different, as the strain level involved in each case is of different magnitude.

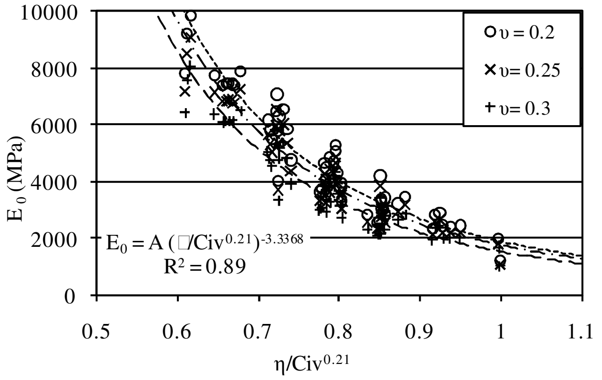

Figure 7. Maximum deformability modulus (E_0) obtained from Vp with adjusted void cement ratio (□/$Civ^{0.21}$). For simplification the equations of the three trendlines are condensed in one being the parameter A equal to 1883, 1744 and 1554 for υ = 0.2, 0.25 and 0.3.

3.5 *Suction measurements*

Even after 24h in water, the samples tested in unconfined compression, might not be totally saturated. The level of suction involved in each sample was, for that reason, evaluated with the aim of understanding the importance of suction in total strength and the differences between samples. The matrix suction was then measured by the Paper Filter Method following the standard ASTM D 5298 (1994). The filter paper used was Whatman Nº42, whose calibration curves are those presented by Chandler et al. (1992). It was observed that suction increases with the unit weight and with strength. However, the low values of suction obtained (in average 1.1% of the unconfined compression) revealed that submersion in water was a good procedure to assume almost no suction.

3.6 *Triaxial tests*

The triaxial testing program involved drained tests with local measurement of deformation using LDT's or submerged high resolution RDP LVDT's (Linear Variable Differential Transformers) in 4 moulding conditions chosen from the unconfined compression test results. Two points were selected from the curve presented in Figure 3 corresponding to (□/$Civ^{0.21}$; q_u) equal to (29; 800) and (36; 2000). For each point two moulding pairs of void ratio and cement content were defined and these 4 types of samples were repeated for 3 different confining pressures (30, 80 and 250 kPa), performing a total of 12 tests, as expressed in Table 2.

First the saturation of each sample was carried out at high back pressures (u =500 kPa) and then the consolidation took place. The load test was carried out under strain control at a rate of 0.01 mm/min. A static cycle was performed between 30% and 15% of the expected failure deviator stress, with the aim of evaluating the cyclic (unload-reload) modulus of deformation assumed to be the slope between the vertices of the hysteretic loop.

Table 2 – Moulding and test conditions of the samples.

Name	% C	γ_d (kN/m^3)	ω (%)	□/Civ$^{0.21}$	$q_u^{(*)}$ (kPa)	σ'$_c$ (MPa)
1	2	16.70	12	29	800	30
2	2	16.70	12	29	800	80
3	2	16.70	12	29	800	250
4	4	15.40	12	29	800	30
5	4	15.40	12	29	800	80
6	4	15.40	12	29	800	250
7	5	17.00	12	36	2000	30
8	5	17.00	12	36	2000	80
9	5	17.00	12	36	2000	250
10	7	16.40	12	36	2000	30
11	7	16.40	12	36	2000	80
12	7	16.40	12	36	2000	250

(*) q_u = uniaxial compression strength

The triaxial tests results concerning the failure parameters (deviator stress $q=\sigma_v-\sigma_h$ and mean effective stress $p' = (\sigma'_v+2\sigma'_h)/3$) as well as the deformability modulus from the cycles are presented in Table 3.

Table 3 – Triaxial test results

Name	q(*) (kPa)	p' (kPa)	E (MPa)
1	1121.69	405.06	1069
2	1566.42	601.58	880
3	2059.95	937.83	784
4	1451.44	517.05	1396
5	1447.64	565.69	1435
6	1880.47	875.27	1445
7	3067.83	1057.95	2383
8	3190.51	1143.36	3377
9	3830.93	1779.13	4778
10	2740.79	1125.22	3632
11	2900.83	1235.94	4536
12	3932.29	1565.19	3328

q = ultimate deviatoric stress, $(\sigma_1-\sigma_3)_{max}$

The deformability modulus seems to be decreasing with confining pressure for the 2% samples, while for the samples with higher cement content the stiffness increases with the stress level. Consoli et al. (2000) have found a similar behaviour in cemented soil cured under distinct conditions. The samples cured before confinement performed as the 2% samples with decreasing stiffness as the stress level increases. The samples cured under stress showed an increase in stiffness with higher confining pressure as it was observed in this experimental program for the highly cemented samples. This behaviour is a sign of some loss in structure of low cemented samples when the stress level increases.

Figure 8 presents the strength envelopes defined with triaxial and unconfined compression tests results for the two values of □/Civ$^{0.21}$. There seems to be a very good trend, especially for the mixtures of 2% and 4% of cement which corresponds to □/Civ$^{0.21}$=29.

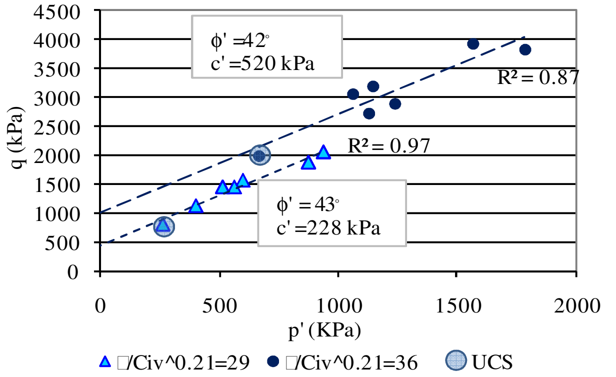

Figure 8. Strength envelopes for triaxial and unconfined compression tests results for each ratio □/Civ$^{0.21}$.

4 CONCLUSIONS

The study reported in the paper has been revealing very interesting results of soil-cement mixtures when tested in unconfined and triaxial compression.

The unconfined compression strength results support the conclusions taken by Consoli et al. (2007) that the index based on void/cement ratio seems to be adequate for the strength analysis of these mixtures. Moreover, stiffness values obtained in the unconfined compression tests showed the same trend obtained for strength indicating that there is a similar influence in both stiffness and strength. P wave velocities from which maximum shear modulus was derived for different values of Poisson ratio have also indicated the same trend.

Finally, triaxial tests showed two different stiffness patterns depending on the cement content. Highly cemented samples increase in stiffness with the stress level while in low cemented samples the stiffness decreases showing that the structure provided by cementation breaks as the confining pressure increases. Concerning failure evaluation, two main strength envelopes were identified for two different void/cement ratios. Nevertheless both envelopes have shown high angles of shearing strength and high cohesion intercept derived from the cementation.

REFERENCES

ASTM D 5298, 1994. Standard Test Method in Measurement of Soil Potencial (Suction) Using Filter Paper. Annual Book of ASTM Standards. Vol.04.08

Caberlon, R., 2008. Influency of the key parameters on the stiffness, strength and dilatancy of an artificially cemented sand. PhD thesis, Federal University of Rio Grande do Sul (In Portuguese)

Chandler, R., Crilly, M., Montgomery-Smith, G., 1992. A low-cost method of assessing clay desiccation for low-rise buildings. Proc. Institute of Civil Engineers, Vol.92, No.2, pp.82-89

Consoli, N., Foppa, D., Festugato, L., Heineck, K., 2007. Key parameters for strength control of artificially cemented soils. Journal of Geotechnical and Geoenvironmental Engineering, February, pp.197-205.

Consoli, N., Rotta, G., Prietto, P., 2000. Influence of curing under stress on the triaxial response of cemented soils. Géotechnique, Vol.50, No.1, pp.99-105

LNEC E 264, 1972. Soil-cement. Compression test. Specification of the National Laboratory of Civil Engineering, Lisbon (In Portuguese).

Viana da Fonseca, A., Carvalho, C., Ferreira, C., Santos, J.A., Almeida, F., Pereira, E., Feliciano, J., Grade, J. & Oliveira, A., 2006. Characterization of a profile of residual soil from granite combining geological, geophysical and mechanical testing techniques. Geotechnical and Geological Engineering, Vol.24, pp.1307-1348

Viana da Fonseca, A., Ferreira, C. & Fahey, M., 2009. A framework interpreting bender element tests, combining time-domain and frequency domain methods. Geotechnical Testing Journal, ASTM (Published on line Dec. 2008; and in the journal March de 2009 - Vol. 32, No. 2).