Porosity/cement index to evaluate geomechanical properties of an artificial cemented soil

Le paramètre porosité/ciment pour l'évaluation des propriétés géomécaniques d'un sol cimenté artificiellement

Rios S., Viana da Fonseca A.
Faculty of Engineering of the University of Porto

ABSTRACT: This paper highlights the importance of the porosity/cement index on the evaluation of the geomechanical properties of soil-cement mixtures as a contribution to analyse these materials. This index is defined as the ratio between porosity and volumetric cement content combining the degree of compaction with the cement content. The relevance of these two parameters is defined by an exponent to the volumetric cement content which changes with the type of soil. This paper results from a broad experimental program with unconfined compression tests, indirect tensile tests, triaxial tests and oedometer tests, which were all analysed by this index adjusted by a specific exponent value. The (tensile and compression) strength, the (elastic and initial tangent) stiffness, as well as the compressional behaviour are conveniently represented by this index and a different behaviour is observed when this index is changed.

RÉSUMÉ : L'importance du paramètre porosité/ciment dans l'évaluation des propriétés géoméchaniques des mélanges sol-ciment est présentée dans cet article comme une contribution pour l'analyse de ces matériaux. Ce paramètre est défini comme le rapport entre la porosité et la teneur volumique en ciment. L'importance relative entre la porosité et la teneur en ciment est introduite en introduisant un exposant à la teneur volumique en ciment dépendant du type de sol. Les résultats d'un vaste programme expérimental incluant essais de compression simples, essais de traction indirect, essais triaxiaux et essais œdométriques sont présentés et analysés par ce paramètre ajusté par un exposant spécifique. La résistance à la compression et à la traction, la rigidité élastique et tangente initiale, ainsi que le comportement en compression sont bien représentés par l'intermédiaire de ce paramètre et un comportement différent est observé si le paramètre est modifié.

KEYWORDS:soil-cement, porosity/cement index, tensile strength, compression strength, compressional behaviour.

1 INTRODUCTION

Soil-cement mixtures are very interesting for the construction of road and railway platforms, especially in the noble layers of subgrade as well as in transition zones between embankment and concrete structures, where good mechanical properties are required. This solution, not only concurs to improve those characteristics, but also leads to a significant reduction in the economic and environmental costs of these works. Despite these advantages this method has not a generalized application in Portugal due to the lack of design methodologies based on mechanical parameters.

There are several factors affecting the behaviour of cemented soils, such as the type of cement and cement content, the curing time and stress, the water content and porosity. Seeking for a ratio that would reflect the influence of some of these parameters Consoli et al. (2007) presented an index property defined as the ratio of porosity to the volumetric cement content, called porosity/cement ratio (n/C_{iv}). Some previous attempts have been made, such as the degree of cementation proposed by Chang and Woods (1992) that concerns the percentage of voids filled with cement, being this parameter developed for sands. Lorenzo and Bergado (2004) have also presented the ratio of the after curing void ratio to the cement content (e_{ot}/A_w) proving to be quite interesting for clay mixtures with high values of water and cement content.

Another available parameter is the water/cement ratio used for concrete. However, soil-cement mixtures for road or railway platforms are usually cured in a non saturated condition, which makes the previous ratio inadequate in the analysis of these mixtures behaviour. The main difference between soil-cement mixtures and concrete (besides the cement content) is that during the curing of concrete all voids are completely full of water and therefore concrete stress-strain behaviour is not dependent on the void ratio but on the water content. In opposition, soil-cement mixtures currently executed in embankments and transport platforms have curing water content lower than the saturation water content and so their compressibility will be related to its porosity. Moreover, while concrete has an almost linear behaviour for a wide range of deformations, soil-cement mixtures have a clear non-linear behaviour since very small strains as a result of the progressive degradation of the cemented structure. Therefore, even if the soil-cement mixture is saturated after the maximum strength has been achieved (i.e. after curing) the curing void ratio still has a very important role on the mechanical behaviour of the mixture.

The influence of the porosity/cement ratio on strength and stiffness parameters is described in Consoli et al. (2012) providing the comparison between two different materials mixed with Portland cement: well graded Porto silty sand and uniform Osorio sand. An advance analysis on the compression and shearing behaviour of cemented Porto silty sand through this parameter is described in Rios et al. (2012).

This paper summarizes some geomechanical properties of cemented Porto silty sand through this index in terms of strength (unconfined, tensile and triaxial), stiffness (initial tangent and unload-reload) and one-dimensional compression.

2 MATERIALS AND SPECIMEN PREPARATION

A well graded soil, classified as silty sand (SM) in the unified classification system (ASTM, 1998) was used in this study. The soil is derived from weathered Porto granite which is abundant in Northern Portugal (Viana da Fonseca et al., 2006). Its particle specific gravity is 2.72, and it contains around 30% fines, although a low plasticity index was obtained ($I_P=w_L-w_P=34\%-31\%=3\%$). From the particle size distribution curve presented in Figure 1 an average diameter D_{50} equal to 0.25 mm was obtained, as well as uniformity and curvature coefficients of 113 and 2.7 respectively.A high strength Portland cement (CEM I 52,5R) of grain density equal to 3.15 was used as the cementing agent in order to speed up the laboratory tests.

The experimental program is performed with specimens made by the mixture of silty sand, Portland cement and tap water that is compacted statically in three layers in a stainless steel mould. For each specimen, a quantity of fines equal to the weight of cement to be introduced was removed from the soil, in order to have the same grain size distribution curve in the mixture of soil-cement as in the soil itself. Following this procedure the dry density of the soil was also constant throughout the study even though the cement content changed. The specific gravity of the cement-soil mixture was calculated as a weighted average of those of the soil (Gs=2.72) and of the cement (Gs=3.15), and thus it was different for different cement contents.

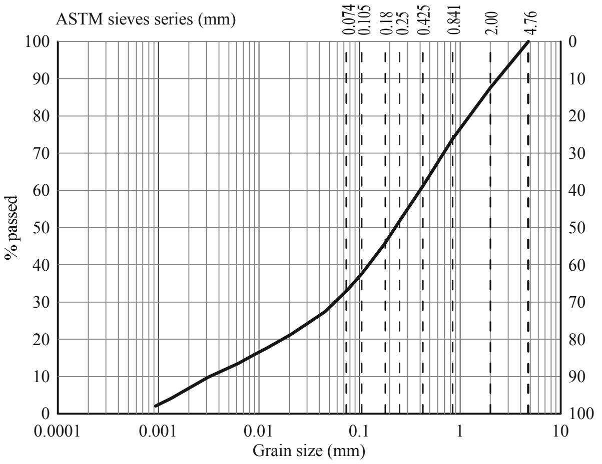

Figure 1. Grain size distribution curve

3 STRENGTH PARAMETERS

3.1 Unconfined compression strength

Strength properties of the cemented sand were evaluated in different ways by means of unconfined compression tests, indirect tensile tests, as well as triaxial tests. First, several specimens moulded to have different cement contents (2%, 3%, 5% and 7%) and dry unit weights (16.4, 17.2, 18.0 and 18.8 kN/m^3) were tested in unconfined compression in a total of 16 tests. In these tests, the water content was kept equal to 12%. The representation of the unconfined compression strength (UCS) and the ratio of porosity to the volumetric cement content (n/C_{iv}) revealed that some adjustment was needed and therefore, an exponent was added to C_{iv}. This exponent was defined as the value that provides the best correlation coefficient with the data, which, for this material, was found to be 0.21 – Eq. (1).

$$\text{UCS (kPa)} = 4\text{E}{+}09\ (n/C_{iv}^{0.21})^{-4.296} \qquad (1)$$

This exponent seems to depend on the type of soil as other authors have found different coefficients when working with different soils (Consoli et al., 2007, 2011): an exponent of 0.28 was found in a residual soil from sandstone (Botucatu soil), while a value of 1.0 was found in an uniform sand (Osorio sand). Based on this parameter, named adjusted porosity/cement ratio ($n/C_{iv}^{0.21}$), the results of different tests were analysed.

1.1 *Tensile strength*

Taking into account the possibility of shrinkage in cemented materials, the evaluation of the tensile strength is of utmost importance. In that sense, indirect tensile tests following the standard EN 13286-42 (CEN, 2003) were performed on similar specimens whose results were plotted against $n/C_{iv}^{0.21}$ for which Eq. (2) was obtained,

$$R_{tb}\ \text{(kPa)} = 2\text{E}{+}09\ (n/C_{iv}^{0.21})^{-4.719} \qquad (2)$$

The results showed that the indirect tensile strength (R_{tb}) was about 11% of the UCS. In Figure 2 both R_{tb} and UCS are plotted against $n/C_{iv}^{0.21}$ in different scales for comparison. It is clear that both trends are very similar (except for the absolute values) corroborating the convenience of the adjusted porosity/cement ratio.

In Consoli et al. (2011), where the data from these tests is plotted together with data from other two soils, it is shown that for the three soils a decrease in porosity promotes an increase in the tensile strength as a consequence of the higher number of contact points between particles which improves the cementation. Also for the other two soils, a unique correlation was found between the adjusted porosity/cement ratio and the indirect tensile strength, the exponent of the ratio depending on the soil.

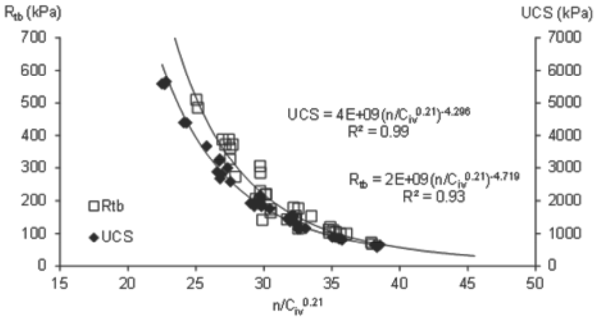

Figure 2. Indirect tensile strength and unconfined compression strength against the adjusted porosity/cement ratio

3.2 Triaxial tests

Drained triaxial compression tests were performed over soil-cement specimens, which were moulded to have two different adjusted porosity/cement ratios ($n/C_{iv}^{0.21}$=36 and 29) corresponding respectively to UCS of 800 kPa and 2000 kPa. For these ratios, two moulding conditions were defined characterized by cement content and dry unit weight while the water content remains constant and equal to 12%. For the first ratio ($n/C_{iv}^{0.21}$= 36), 2 and 4% cement contents were considered which lead to dry unit weights of 16.7 and 15.4 kN/m^3, respectively. For the second ratio ($n/C_{iv}^{0.21}$ = 29) higher strength was needed, so 5 and 7% of cement contents were assumed with 17.0 and 16.4 kN/m^3 of dry unit weight. The tests were performed at three different effective confining pressures (30, 80 and 250 kPa) over specimens moulded in four moulding points, comprising 12 tests (Table 1).

The stress-strain curves (see Figure 3 as an example) clearly evidence that the specimens with $n/C_{iv}^{0.21}$=29 have higher peak deviator stresses than the specimens with $n/C_{iv}^{0.21}$=36 independently of the cement content. Adding cement to the sand had the effect of increasing the shear strength by up to five times for the adjusted porosity/cement ratio of 36 and tenfold for the adjusted porosity/cement ratio of 29.All specimens initially compressed, followed by significant dilation, which was associated to a peak strength, before strain softening. This is typical of cemented soils, with the maximum rate of dilation taking place right after the peak strength (Viana da Fonseca 1998). The peak strength corresponds to the onset of significant breakage in the cement, while dilation involves particle rearrangement that is only possible after bonding breakage. Assuming only compressive volumetric deformations up to the point of zero dilation, beyond this point yielding exists, which indicates that the onset of cement breakage is progressive starting even before peak. However, being the peak strength not frictional but controlled by the cement yielding, then most destructuration may take place only at peak.

Table 1.Moulding conditions of the specimens for the triaxial tests

Moulding Point	*%C (%)*	γ_d *(kN/m³)*	e_0	*w (%)*	$n/C_{iv}^{0.21}$	*UCS (kPa)*	σ'_c *(kPa)*
1	2	16.6	0.61	12	36	800	30
	2	16.5	0.62	12	36	800	80
	2	16.7	0.60	12	36	800	250
2	4	15.4	0.74	12	36	800	30
	4	15.7	0.71	12	36	800	80
	4	15.5	0.73	12	36	800	250
3	5	16.9	0.59	12	29	2000	30
	5	17.0	0.58	12	29	2000	80
	5	17.0	0.58	12	29	2000	250
4	7	16.3	0.66	12	29	2000	30
	7	16.5	0.63	12	29	2000	80
	7	16.7	0.61	12	29	2000	250

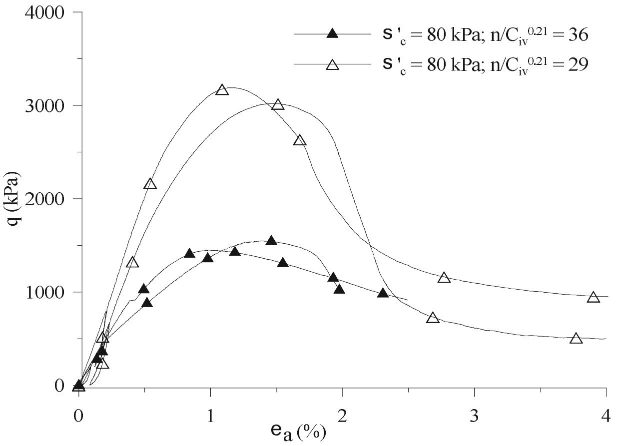

Figure 3. Stress-strain curves for the confining pressure of 80 kPa.

All the cemented specimens tested in triaxial tests suffered strain localisation. Therefore, it becomes difficult to rely on the local instrumentation at strain levels close and after the peak, but especially at ultimate conditions. In that sense, the stress invariants such as the deviator stress (q) and the mean effective stress (p') were not considered representative of the stress state and thus, the stresses acting on the shear plane were calculated by the procedure used by Gasparre (2005) based on the Mohr circles and taking into account the post rupture analysis described by Burland (1990).

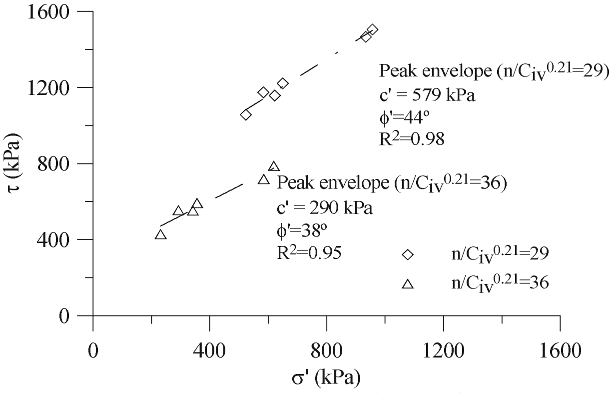

Figure 4.Peak strength envelopes by adjusted porosity/cement ratio.

In Figure 4 the stresses acting on the plane are plotted on a (σ', τ) graph for peak conditions from which the correspondent strength parameters were obtained. The points are assigned to each adjusted porosity/cement ratio ($n/C_{iv}^{0.21}$) expressed before. It is interesting to notice that for peak conditions two strength envelopes were obtained depending on the index ratio. The adjusted porosity/cement ratio influences the peak angle of friction and cohesion intercept, being the peak envelope for the index $n/C_{iv}^{0.21}=29$ higher than that for the index equal to 36. This could have been predicted from moulding characteristics as each ratio corresponds to different UCS.

4 STIFFNESS PARAMETERS

4.1 Initial tangent stiffness

The unconfined compression tests were performed with local measurement of deformation using LDT's and so the stiffness modulus could be evaluated. An initial tangent modulus (E_{ti}) was then calculated based on the linear part of the stress-strain curve. Plotting this modulus against the adjusted porosity/cement ratio for the 16 tests presented above, as Figure 5 shows, it can be concluded that the general adjustment of the data is quite reasonable.

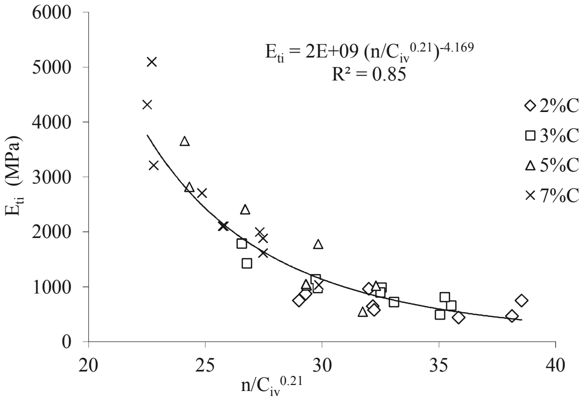

Figure 5. Indirect tensile strength and unconfined compression strength against the adjusted porosity/cement ratio

As expected, stiffness parameters are more scattered than strength parameters because strain measurements are always more sensitive to non-homogeneities of the specimen and anchors are introduced in the specimen in single reference points. On the contrary, strength measurements capture more easily an average value of the whole specimen.

4.2 Unload-reload moduli

In the triaxial compression tests reported above, a small static cycle was performed during shearing, between 30% and 15% of the expected peak deviatoric stress. These loads were selected to avoid soil yielding before the cycles so the modulus could be assumed elastic. Figure 6 summarizes the results of the unload-reload moduli (E_{ur}) obtained for the two adjusted porosity/cement ratio. The values of E_{ur} obtained from these triaxial tests are higher than the initial tangent modulus (E_{ti}) obtained in the unconfined compression tests presented in Figure 5. This can be considered expected because E_{ur} is usually assumed to follow an elastic pattern, if performed at low ranges of cyclic stress, while in the initial monotonic loading path some compliance errors of strain gauges may be presented. This graph also evidences a clear and almost discrete increase in the stiffness modulus values for the specimens with $n/C_{iv}^{0.21}=29$ (5% and 7% cement contents) in comparison with the specimens with distinct ratio $n/C_{iv}^{0.21}=36$ (2% and 4% cement contents). This could be even clearer if the instrumentation would perform in a completely satisfactory way for the highest cemented mixtures (for 5% and 7% of cement content).

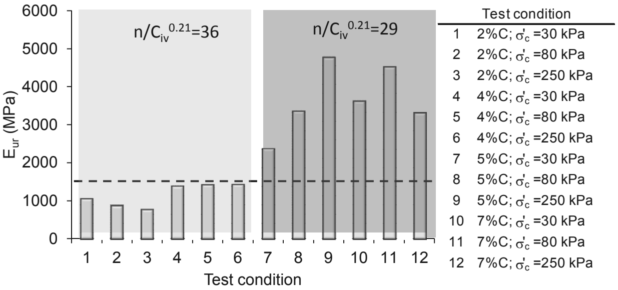

Figure 6. Stiffness modulus obtained in the unload-reload cycles.

5 COMPRESSIBILITY PARAMETERS

One-dimension compression tests in oedometer cells with constant rate of deformation (CRD) were performed over soil-cement specimens in the four moulding conditions presented in Table 1. The preparation of the different mixtures for these tests followed the same procedure of the other tests, as expressed briefly in section 2. Due to the size of the mould, the static compaction was performed in one layer, although the soil was placed in several stages followed by tapping. For the calculation of the mean effective stress (p') in each test the value of the coefficient of earth pressure at rest (k_0) was considered equal to 1 due to the high compaction degree that the specimens were subjected during moulding (>80% of the Modified Proctor test). Figure 7 shows two of those tests, corresponding to two different porosity cement ratios, indicating that these compressibility curves do not seem to converge.

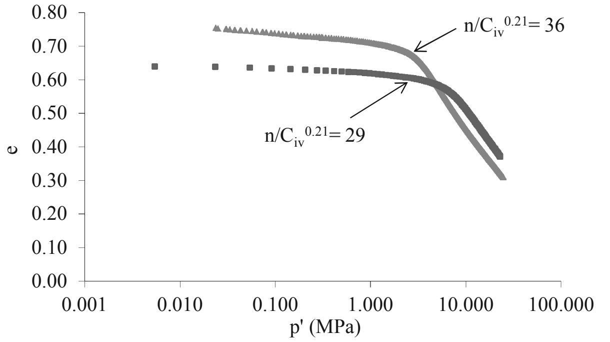

Figure 7.Void ratio against mean effective stress for two different porosity/cement ratios

However, plotting the tests performed over specimens with the same porosity cement ratio, a unique compressibility line was obtained. The same has happened for the other two tests with the other porosity cement ratio of 36. On the contrary, when specimens with the same cement content but different void ratio were represented no unique line was obtained. These results indicate that this ratio can better reproduce the behaviour in one-dimensional compression than the cement content or initial void ratio alone.

6 CONCLUSIONS

This paper presented a great number of data from different tests. Together, they allowed a better understanding of the artificially cemented soil used in this work. Compressive and tensile strength, strength envelopes, stiffness parameters and one–dimensional behaviour were some of the most important issues studied. The adjusted porosity/cement ratio revealed to be very consistent and useful for the analysis of the unconfined compression strength since a unique trend was obtained between this variable and $n/C_{iv}^{0.21}$. A similar trend was obtained for the indirect tensile strength performing tests over specimens moulded in the same conditions. The comparison of the two curves provided a relationship between indirect and compressive strength of about 11%.

The strength envelope values of the cemented specimens tested in triaxial compression were obtained through a procedure based on the Mohr's circles analysis to solve the lack of representativeness of principal stress analysis due to non correspondence of the real localised shear locus. In fact, strain localisation is unavoidable in these very stiff materials, and consequently, the global stress-strain measurements are no longer representative of the conditions throughout the shearing process. Two peak strength envelopes were obtained for each $n/C_{iv}^{0.21}$ ($n/C_{iv}^{0.21}$=36: ϕ'=30º and c'= 253 kPa; $n/C_{iv}^{0.21}$=29: ϕ'=39º and c'= 589 kPa), showing once again the convenience of this ratio for the analysis of these mixtures behaviour.

This ratio also seems to be very useful to reproduce the one dimensional compression behaviour of the mixture, since for each $n/C_{iv}^{0.21}$ a single line was obtained for higher stresses.

7 ACKNOWLEDGEMENTS

This research was developed under the activities of FCT (Portuguese Foundation for Science and Technology) research unit CEC, in FEUP [PTDC/ECM/ 099475/2008], and financed by the European Community (QREN/UE/FEDER), Operational Program for Competitive Factors "COMPETE".

8 REFERENCES

ASTM 1998. D 2487-98 Standard practice for classification of soils for engineering purposes (Unified Classification System)

Burland J. B. 1990. On the compressibility and shear strength of natural clays. *Géotechnique* 40(3), 329-378.

CEN 2003.EN 13286-42 - Unbound and hydraulic bound mixtures. Test method for the determination of the indirect tensile strength of hydraulically bound mixtures, ComitéEuropéen de Normalisation

Chang T. S. and Woods R.D. 1992. Effect of particle contact bond on shear modulus.*Journal of Geotechnical and Geoenvironment Engineering*118(GT8), 1216-1233.

Consoli N.C., Viana da Fonseca A., Cruz R., Rios S. 2011. Voids/Cement ratio controlling tensile strength of cement treated soils. *Journal of Geotechnical and Environmental Engineering*, 137(11), 1126-1131 (doi:10.1061/(ASCE)GT.1943-5606.0000524)

Consoli N.C., Viana da Fonseca A., Rios S., Cruz R. and Fonini A. 2012.Parameters controlling stiffness and strength of artificially cemented soils.*Géotechnique* 62(2), 177-183 (doi: 10.1680/geot.8.P.084)

Consoli N.C., Foppa D., Festugato L. and Heineck K. 2007.Key Parameters for Strength Control of Artificially Cemented Soils, *Journal of Geotechnical and Geoenvironmental Engineering* 133(2), 197-205.

Gasparre A. 2005. Advanced laboratory characterisation of London Clay. PhD dissertation presented to the University of London

Lorenzo G. and Bergado D. 2004.Fundamental parameters of cement-admixed clay - New Approach.*Journal of Geotechnical and Geoenvironmental Engineering* 130(10), 1042-1050.

Rios S., Viana da Fonseca A. andBaudet B. 2012. The effect of the porosity/cement ratio on the shearing behaviour of cemented soil.*ActaGeotechnica* (accepted)

Viana da Fonseca, A. 1998. Identifying the reserve of strength and stiffness characteristics due to cemented structure of a saprolitic soil from granite. The Geotechnics of Hard Soils - Soft Rocks, Evagelista and Picarelli (eds), Balkema, Roterdam

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