Strength properties of sandy soil-cement admixtures

Propriétés de résistance des mélanges de sol sableux et de ciment

António Viana da Fonseca
University of Porto, Portugal, viana@fe.up.pt

Rodrigo Caberlon Cruz
Federal University of Rio Grande do Sul, Brazil, rccaberlon@hotmail.com

Nilo Cesar Consoli
Federal University of Rio Grande do Sul, Brazil, consoli@ufrgs.br

ABSTRACT

Soil stabilization with cement is a good solution for the construction of subgrades for roadway and railway lines, especially in "noble" foundations layers, 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 line works where other ground improvement techniques are extensive and, therefore, very expensive. On the other hand, the economic and environmental costs of such works should be optimized with good balances between excavation and embankment volumes. For this purpose, the improvement of locally available soils can bring great advantages, avoiding a great amount in borrowing appropriate material, as well as the need of disposing huge volumes in deposits. This paper focus on the characteristics of two soils, Osorio sand and Botucatu residual sandstone (BRS), which can be converted to well accept materials to that purpose, if stabilized with cement. The study of soil stabilization with cement relies on the quantification of the influence percentage of cement and porosity that is adopted in the admixing process for different state and stress conditions. This influence will be evaluated from the analysis of unconfined compression strength (UCS) test results. This experimental framework will enable a good definition of mechanical parameters used in design of foundations and subgrades of railways platforms and for their execution quality control.

RÉSUMÉ

La stabilisation de sols avec du ciment est une bonne solution pour la construction de fondations des routes et des lignes de chemin de fer, surtout dans les couches de fondations « nobles », sous les plates-formes ainsi que dans les zones de transition entre les terrassements et les structures rigides, là où l'on exige beaucoup des propriétés mécaniques des sols de soutènement. Ces solutions sont surtout attrayantes dans les travaux de ligne où d'autres techniques d'amélioration des sols sont beaucoup plus extensives et donc beaucoup plus coûteuses. D'autre part, les coûts tant économiques qu'environnementaux de tels travaux devraient être optimisés par de corrects équilibres entre l'excavation et les volumes de terrassement compactés. Dans ce but, l'amélioration de sols disponibles localement peut apporter de grands avantages, en évitant de prendre ailleurs une grande quantité de sols adéquats, ainsi que le besoin de disposer d'énormes volumes de sols inadéquats en dépôt. Cet article se concentre sur les caractéristiques de deux sols, le sable d'Osorio et le grès résiduel de Botucatu (BRS), qui peuvent être converti en un matériau bien accepté dans ce but, s'il est stabilisé avec du ciment. L'étude de stabilisation de sol avec du ciment se base sur la quantification de l'effet du pourcentage de ciment, de la porosité et de l'eau contenue adopté dans le processus de mélange pour différents états et conditions de tension. Cette influence sera évaluée à partir de l'analyse des résultats de la résistance uniaxial de compression, obtenus avec des échantillons préparés avec différentes quantités de facteurs relevants. Ce cadre expérimental permettra une bonne définition des paramètres mécaniques utilisés dans le projet de fondations et pour le contrôle de qualité d'exécution de plates-formes de routes et de chemins de fer.

Keywords: stabilization, soil-cement, dosage, UCS.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-52

1 INTRODUCTION

The use of geotechnical engineering traditional techniques for infrastructures, such as the replacement of unsuitable soils for stiff and resistant embankment, is often problematic for their high costs, but mostly due to environmental reasons. In roads, for instance, the use of granular bases become unsuitable when the borrow site is distanced from the construction site. Another example is the construction of foundations in soils with low bearing capacities, but where deep foundation solutions' costs may be incompatible with the overall costs of low-budget building projects. In these cases, the alternative of improving the local soil with the addition of Portland cement may be an excellent solution. The soil-cement technique has been used successfully in pavement base layers, slope protection for earth dams, as a base layer to shallow foundations and to prevent sand liquefaction [Ingles & Metcalf (1972), Dupas & Pecker (1979), Porbaha et al. (1998), Thomé et al. (2005)]. In spite of the numerous applications, there are no dosage methodologies based on rational criteria as in the case of the concrete technology, where the water/cement ratio plays a fundamental role in the assessment of the target strength. In recent works the soil-cement ratio has been assessed by numerous laboratory tests that aim to find the minimum amount of cement to achieve target properties in terms of stiffness, strength and durability. This approach probably results from the fact that soil-cement shows a complex behaviour that is affected by many factors, such as the soil physical-chemical properties, the amount of cement, and the porosity and moisture content at the time of compaction [Felt (1955), Moore et al. (1970), Clough et al. (1981), Porbaha et al., 2000, Consoli et al. (2000, 2001, 2003, 2006)].

This study therefore aims to quantify the influence of the amount of cement and porosity on the strength of two artificially cemented sandy soils, as well as to evaluate the use of voids/cement ratio to assess its unconfined compression strength.

2 EXPERIMENTAL PROGRAM

The experimental program was carried out in two parts. First, the characterization of geotechnical properties of the soil and cement was carried out, and then, the analysis of the admixtures strength's sensitivity to different compositions by performing extensive unconfined compression tests, which results will be discussed in what follows.

2.1 *Materials*

The soils used in this study were a fine sand, designated by "Osorio Sand", and a residual sandy soil, the Botucatu residual sandstone ("BRS"), well known in Brazil's South region. The samples were collected disturbed, but integral, by manual excavation, in sufficient quantity to complete all the planned tests. The results of the characterization tests of Osorio sand and BRS are shown in Table 1 and the grain size curves are plotted in Figure 1. These soils are classified as uniform fine sand (SP) and silty sand (SM) respectively according to the Unified Soil Classification System. For the cementing agent, Portland cement with high rate of strengthening (Type III) was used, allowing the adoption of seven days as the curing time. The specific gravity of the cement grains is 3.15.

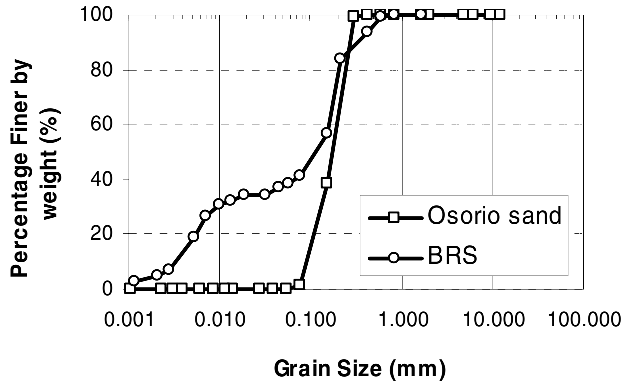

Figure 1. Grain size distribution.

2.2 *Methods*

Moulding and Curing of Specimens

For the unconfined compression tests, cylindrical specimens (5.0 x 10.0cm) were used. For each materials dosage, mixing has assured a homogeneous paste, taking care of limiting the time to set up of the specimens (mix and compact) to less than 1 hour, which is shorter than the initial setting time of the Portland cement used. After curing time of 6 days in wet chamber, the specimens were submerged in a water reservoir for 24 hours, to assure almost complete saturation and to minimize suction; in the seventh day compression test were carried out.

3 UNCONFINED COMPRESSIVE STRENGTH (UCS)

Unconfined compression tests have been used in most of the experimental programs reported in the literature in order to evaluate the effectiveness of the stabilization with cement or to access the relevance of specific factors in influencing the strength of soil-cement admixtures. One of the reasons for this is the accumulated experience with this kind of test for concrete.

The test is as simple and fast, as reliable and cheap. The unconfined compression tests were carried out up to failure, with the maximum load reached (UCS) of each the specimen being carefully registered. The acceptance criterion for UCS was fixed in the maximum of 10% for standard deviation.

The physical characteristics of the soils used in this study are included in Table 1.

Table 1. Physical properties of the soil samples

PROPERTIES	Osorio Sand	BRS
Specific Gravity (G)	2.65	2.64
Effective Diameter (D_{10}) (mm)	0.09	0.0032
Mean Diameter (D_{50}) (mm)	0.17	0.12
Uniformity Coefficient (C_u)	2.11	50
Maximum voids ratio (e_{max})	0.85	-
Minimum voids ratio (e_{min})	0.60	-
Maximum density ($\gamma_{d\,(max)}$) (kN/m^3)	-	19.7

Soil-cement admixtures were moulded/compacted in the terms presented in Tables 2 and 3

Table 2. Characteristics of Moulding Points (Osorio sand)

POINT	Voids ratio (e)	Water Content (%)
A_1	0.68	10.0
A_2	0.73	10.0
A_3	0.80	10.0

Table 3. Characteristics of Moulding Points (BRS)

POINT	Dry Density – γ_d (kN/m^3)	Water Content (%)
A_1	17.0	10.0
A_2	17.7	10.0
A_3	18.6	10.0
A_4	19.3	10.0

3.1 *Program of Unconfined Compression Tests*

The experimental program comprised enough unconfined compression tests in order to evaluate the influence of the two main factors in the behaviour of these admixtures: voids ratio (or dry density) and the amount of cement. Each point was moulded with different cement percentages: 1, 3, 5, 7, 9 and 12% for sand (Table 2), and 1, 2, 3, 5 and 7% for BRS (Table 3). These amounts were selected considering practice of the Portuguese and Brazilian, and most countries, with soil-cement admixtures [e.g., Mitchell (1981), Schnaid et al. (2001), Consoli et al. (2003, 2006, and 2007)]. Because of the typical scatter of data for unconfined compression tests, for each point three specimens were tested.

4 EFFECT OF VOIDS/CEMENT RATIO

Fig. 2 presents the unconfined compressive strength (UCS) as a function of the voids/cement ratio [expressed as volume of voids (V_v) divided by the volume of cement (V_{ce}), — V_v/V_{ce}], for both studied soils, defined by Eq. 1:

$$\frac{V_v}{V_{ce}} = \frac{\text{Absolute Volume of Voids (water + air)}}{\text{Absolute Volume of Cement}} \qquad (1)$$

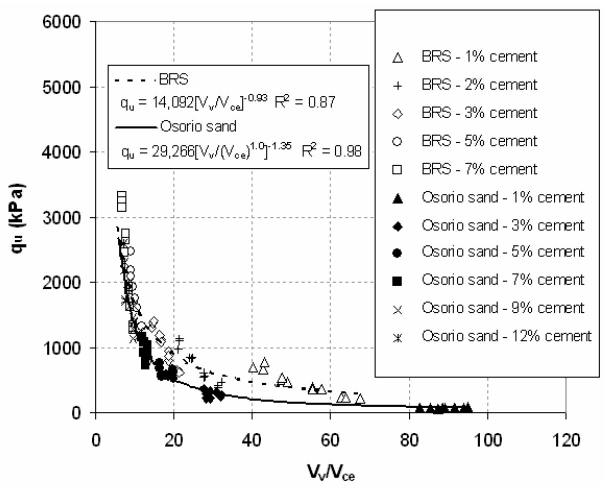

Figure 2. Unconfined compression strength (q_u) versus voids/cement ratio (V_v/V_{ce}).

A very good correlation (coefficient of determination – R^2=0.98) can be observed between this ratio and the unconfined compression strength (q_u) of the Osorio sand-cement studied (see Eq. 2).

$$q_u(kPa) = 29{,}266\left[\frac{V_v}{V_{ce}}\right]^{-1.35} \text{ (sand)} \qquad (2)$$

In Fig. 2, a poor correlation (coefficient of determination – R^2=0.87) is observed for the Botucatu residual soil (BRS), since there is some scatter of data around the best fit curve (see Eq. 3).

$$q_u(kPa) = 14{,}092\left[\frac{V_v}{V_{ce}}\right]^{-0.93} \text{ (BRS)} \qquad (3)$$

If the relationship defined by Equation 2 and 3 are correct, then for a given change in the volume of voids, a proportional variation in the cement volume would be enough to balance the strength gain or loss. Mathematically we may derive:

If: $\frac{V_v}{V_{ce}} = K$ (4) and: $\frac{V_v + \Delta V_v}{V_{ce} + \Delta V_{ce}} = K$ (5) so: $\Delta V_{ce} = \frac{V_{ce}}{V_v} \times \Delta V_v$ (6)

where: ΔV_v = change in the volume of voids.
ΔV_{ce} = change in the volume of cement.
K = Constant.

Fig. 2 distinguishes the plotted points by their cement contents. It can be readily seen that, for the BRS, points with the same voids/cement ratio, but obtained by different combinations of cement content and density show distinctly different strengths (such a difference is not observed for the Osorio sand).

It was found that for the relationship between unconfined compression strength and voids/cement ratio of the BRS, the optimum fit could be obtained applying a power equal to 0.28 to the parameter V_{ce} as shown in Fig. 3 (for the Osorio sand such power would be 1.0).

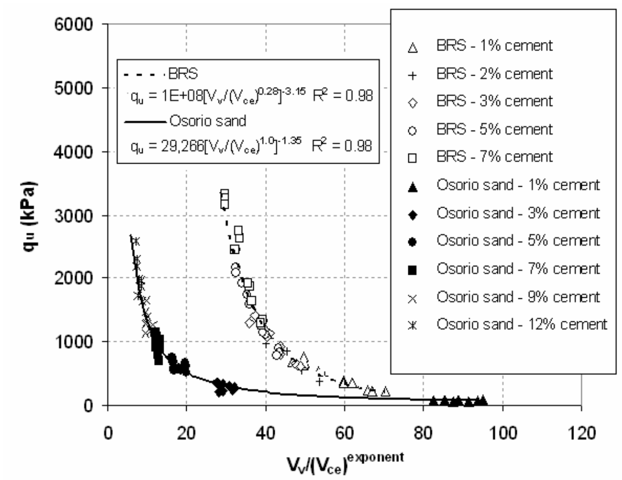

Figure 3. Unconfined compression strength versus void/cement factor with exponent.

A high-quality correlation (coefficient of determination — R^2=0.98) can be observed in Fig. 3 between $[Vv/(V_{ce})^{0.28}]$ and the unconfined compression strength (q_u) of the BRS-cement studied (see Eq. 4):

$$q_u(kPa) = 1 * 10^8 \left[\frac{V_v}{(V_{ce})^{0.28}} \right]^{-3.15} \text{(BRS)} \qquad (7)$$

Based on Figs. 2 and 3, it can be said that, for a given porosity and given cement content, the UCS of the BRS would give higher values that the UCS of the Osorio sand.

Therefore, the factor V_v/V_{ce} is an interesting and very coherent index for the assessment of strength of these soils.

5 CONCLUSIONS

From the data presented in this paper, and bearing in mind the limitations of this study (results are valid for the studied soils and cement), the following conclusions can be drawn.

The results allowed to assume that using the voids/cement ratio, as represented by absolute volume of voids divided by absolute volume of cement (V_v/V_{ce}), a very consistent framework can be obtained for the engineer to select the amount of cement and the compaction energy appropriate to provide a soil-cement admixture with the strength and stiffness required by the project at an optimum cost.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to PRODOC/CAPES/MEC and CNPq/MCT (Brazilian government) for their financial support to the research group. This work was also developed under the research activities of CEC from FEUP, supported by FCT (Portuguese Science and Technology Foundation).

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