Experimental analysis of the mechanical properties of artificially cemented soils and their evolution in time

Analyse expérimentale des propriétés mécaniques des sols cimentés artificiellement et leur évolution dans les temps

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ABSTRACT: In view of the new challenges in the field of foundation design induced by the necessity to resorting to reinforced soils, the evaluation of behavior parameters of soils and soil-binder mixes by means of laboratory tests has become an important task. In this context, experimental characterization of soil-cement mixtures in terms of elastic stiffness and its evolution in time has been carried out. Both shear and oedometric moduli at infinitesimal strains have been measured through the technique of wave propagation along cylindrical specimens of 70 mm and 140 mm in diameter. The analyzed specimens were molded with quartzitic sand and fast curing cement using four relative densities of sand and five cement contents. Several loading times (i.e., times when the specimens are subjected to wave propagation), ranging between the first and seventh curing day, were considered. The results have given evidence of a significant increase in the magnitude of the stiffness properties as the curing process continues. When compared to uncemented sand specimens with similar porosities, increases of about 360% to 6300% due to cement insertion are observed for the shear modulus, and of 900% to 6700% for the oedometric modulus. In addition, the analysis showed that the higher is the amount of added cement used in the mixture, the higher the ratio of initial modulus to final one.

RÉSUMÉ : Compte tenus des nouveaux défis induits, dans le domaine du dimensionnement de fondations, par la nécessité de recourir à des sols renforcés, l'évaluation des paramètres définissent le comportement des sols ainsi que des mélanges sol-liant au moyen de tests de laboratoire est devenue une tâche importante. Dans ce contexte, la caractérisation expérimentale des sols cimentés en termes de rigidité élastique et son évolution dans le temps a été réalisée. Les deux modules de cisaillement et oedométrique sous déformations infinitésimales ont été mesurées par la technique de propagation d'ondes le long d'échantillons cylindriques de 70 mm et 140 mmde diamètre. Les échantillons analysés ont été moulés utilisant du sable et du ciment à prise rapide en considérant quatre densités relatives de sable et cinq pourcentages de teneur en ciment. Plusieurs temps de chargement (c'est à dire, les instants où les échantillons sont soumis à la propagation d'ondes), compris entre le premier jour et le septième jours en termes de temps de prise, ont été considérés. Les résultats ont montré une augmentation significative de la rigidité au fur et à mesure que le processus de prise continue. Selon la teneur en ciment, des augmentations allant de 360% à 6300% sont observées pour le module de cisaillement, et de 900% à 6700% pour le module oedométrique. En outre, l'analyse a montré que le rapport entre module initial et le module final est d'autant plus élevé que la teneur en ciment du mélange est élevée.

KEYWORDS: ground improvement, artificially cemented soils, shear moduli, curing time period.

1 INTRODUCTION

Soil-cement is a geo-composite formed by highly compacted mixture of soil, Portland cement, and water. As the cement hydrates, the mixture gains strength, stiffness and improves the engineering properties of the raw soil. The major variables that control the properties and characteristics of soil-cement mixtures are the type of soil, the proportion of cement in the mix, the degree of compaction and curing time period. It is possible, simply by varying the cement content and/or porosity of mixture, to produce soil-cement that ranges from a basic modification of the compacted soil to fully hardened soil-cement that is strong, stiff and durable. 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 (Consoli *et al.* 2012a).

The unconfined compression test has been used as the most convenient means to investigate the effect of different variables on the soil-cement strength and to carry out dosage methodologies. The first rational dosage methodology for sand-cement was developed by Consoli *et al.* (2009) considering the porosity/cement ratio (η/C_{iv}), defined by the porosity of the compacted mixture divided by the volumetric cement content (volume of cement divided by total specimen volume), as an appropriate parameter to evaluate the unconfined compressive strength (q_u) of the sand-cement mixture. Consoli *et al.* (2011), has shown that compressive strength increases with curing time period in artificially cemented soils and that there is a unique function controlling strength with curing time period and that such relation is a function of porosity and cement content. However, nothing is known regarding stiffness behavior with time. So, present study aims at fulfilling a breach of knowledge at quantifying the influence of the curing time period, the amount of cement and the porosity on the initial shear and oedometric moduli of an artificially cemented sand, as well as searching for a unique relationship linking both moduli (G_o and M_o) with porosity/cement ratio (η/C_{iv}) and curing period (t). The main contribution of present work is showing the existence of a direct relationship between G_o, M_o and η/C_{iv} for all studied curing time periods and only scalars differ regarding the effect of curing time. So, for the sand-cement studied, unique relationships were reached linking G_o and M_o with η, C_{iv} and curing time (t).

2 EXPERIMENTAL PROGRAM

The experimental program has been carried out in two parts. First, the soil was characterized. Then a number of bender/extender elements tests were carried out considering four porosities and five cement contents at four distinct curing time periods (1, 3, 5 and 7 days).

2.1. *Materials*

The Osorio sand used in the testing was obtained from the region of Porto Alegre, in Southern Brazil, being classified as non-plastic uniform fine sand. Specific gravity of the solids is 2.63. Mineralogical analysis showed that sand particles are predominantly quartz. The grain size is purely fine sand with a mean diameter of 0.16 mm, being the uniformity and curvature coefficients of 1.9 and 1.2, respectively. The minimum and maximum void ratios are 0.6 and 0.9, respectively.

Portland cement of high early strength (Type III) was used as the cementing agent. Its fast gain of strength and stiffness allowed the adoption of 1, 3, 5 and 7 days as the curing time periods. The specific gravity of the cement grains is 3.15.

Distilled water was used for these characterization tests and tap water for molding specimens for the compression tests.

2.2. *Methods*

Molding and curing of specimens, as well as bender element tests are detailed below.

2.2.1. *Molding and curing of specimens*

For the for the bender element tests, cylindrical specimens 70mm in diameter and 140mm high were used. 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 soil grains (2.63), for the calculation of porosity, a composite specific gravity based on the soil and cement percentages in the specimens was used.

After the soil, cement and water were weighed, the soil 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 soil 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 0.01g and 0.1mm, respectively. The samples were then placed inside plastic bags to avoid significant variations of moisture content. They were cured in a humid room at 23º±2ºC and relative humidity 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); Dimensions: diameter to within ±0.5mm and height ±1mm.

The molding points were chosen considering relative densities of 10%, 33%, 66% and 90%, with the same moisture content (about 10%). Each point was molded with five different cement percentages: 1%, 2%, 3%, 5% and 7%. These percentages were chosen considering the Brazilian and international experience with soil-cement [e.g., Mitchell (1981), Consoli *et al.* (2010, 2012b)], both in experimental and practical work.

2.2.2. *Bender/extender element tests*

T-shaped pairs of bender/extender (BE) elements, installed on the top and bottom specimen platens, were used in present study for emission and reception of shear “S” waves (2 to 20 kHz frequencies) and compression “P” waves (20 to 80 kHz frequencies), being directly related to shear and oedometric moduli measurement, respectively. The bender/extender elements penetrated the specimen by 3mm at each end. For present sand-cement mixtures, time domain method of identification of first arrivals was adopted.

Single sine-wave input pulses were used at pre-set frequencies of 1, 3, 5, 7, 9, 11, 13 kHz, which covered the range of resonant frequencies of the sample-BE system. The output signals were captured on an oscilloscope, directly transferred to the PC and plotted to a common time base. The first arrival of the shear wave was taken (on the basis of previous calibration) as the point at which the wave descended, with low noise higher frequency results being preferred in order to avoid near field effects.

3 RESULTS OF STIFFNESS MEASUREMENTS

Results of both initial shear (G_o) and initial oedometric (M_o) moduli versus relative density (DR) of Osorio sand are presented in Figure 1. Equations (1) and (2), fitted from experimental data, give the expressions of G_o and M_o with relative density of Osorio sand.

$$G_o^{sand}(MPa) = 17.60 + 0.076DR \tag{1}$$

$$M_o^{sand}(MPa) = 41.18 + 0.294DR \tag{2}$$

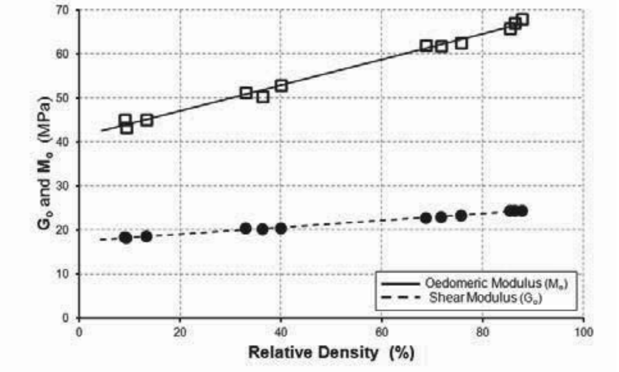

Figure 1. Shear (G_o) and oedometric (M_o) moduli versus relative density for Osorio sand.

Results of G_o and M_o on artificially cemented are also presented in Figures 2, 3, 4 and 5, respectively for, 1, 3, 5 and 7 curing days.

Figure 2 presents the variation of the shear (G_o) and oedometric (M_o) modulus with porosity/cement ratio (η/C_{iv}) considering all four studied relative densities (10, 33, 66 and 90%), five cement contents (1%, 2%, 3%, 5% and 7%) and 1 (one) day of curing. Equations (3) and (4) present the variation of G_o and M_o with η/C_{iv}, both with high coefficient of determination (R^2=0.95 and 0.93, respectively for shear and oedometric modulus).

$$G_o^{1day}(MPa) = 6{,}694\left[\frac{\eta}{C_{iv}}\right]^{-0.95} \quad (3)$$

$$M_o^{1day}(MPa) = 14{,}350\left[\frac{\eta}{C_{iv}}\right]^{-0.81} \quad (4)$$

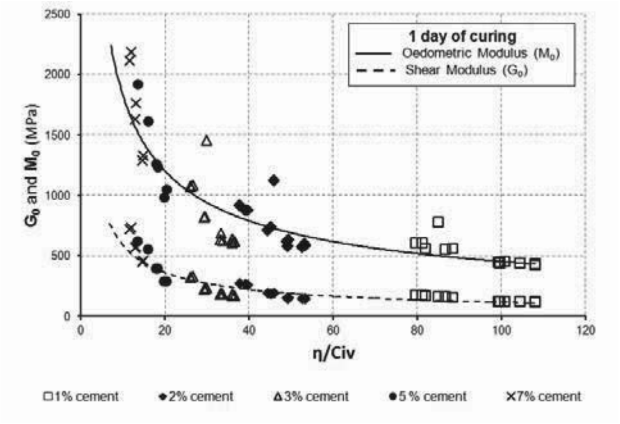

Figure 2. Shear (G_o) and oedometric (M_o) moduli at one day of curing.

Figure 3 presents the variation of the shear (G_o) and oedometric (M_o) modulus with porosity/cement ratio (η/C_{iv}) considering all four studied relative densities (10, 33, 66 and 90%), five cement contents (1%, 2%, 3%, 5% and 7%) and 3 (three) days of curing. Equations (5) and (6) present the variation of G_o and M_o with η/C_{iv}, both with high coefficient of determination ($R^2=0.95$).

$$G_o^{3days}(MPa) = 11{,}500\left[\frac{\eta}{C_{iv}}\right]^{-0.95} \quad (5)$$

$$M_o^{3days}(MPa) = 23{,}257\left[\frac{\eta}{C_{iv}}\right]^{-0.81} \quad (6)$$

Figure 4 presents the variation of the shear (G_o) and oedometric (M_o) modulus with porosity/cement ratio (η/C_{iv}) considering all four studied relative densities (10, 33, 66 and 90%), the five cement contents (1%, 2%, 3%, 5% and 7%) and 5 (five) days of curing. Equations (7) and (8) present the variation of G_o and M_o with η/C_{iv}, both with high coefficient of determination ($R^2=0.95$).

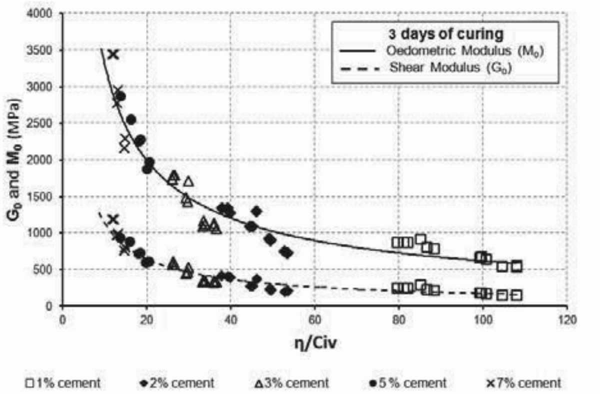

Figure 3. Shear (G_o) and oedometric (M_o) moduli at three days of curing.

$$G_o^{5days}(MPa) = 13{,}304\left[\frac{\eta}{C_{iv}}\right]^{-0.95} \quad (7)$$

$$M_o^{5days}(MPa) = 26{,}377\left[\frac{\eta}{C_{iv}}\right]^{-0.81} \quad (8)$$

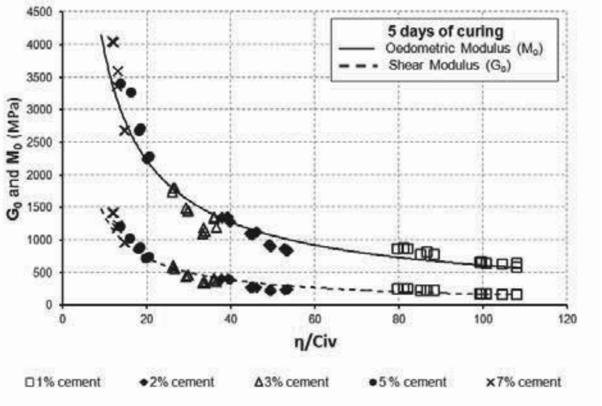

Figure 4. Shear (G_o) and oedometric (M_o) moduli at five days of curing.

Figure 5 presents the variation of the shear (G_o) and oedometric (M_o) modulus with porosity/cement ratio (η/C_{iv}) considering all four studied relative densities (10, 33, 66 and 90%), the five cement contents (1%, 2%, 3%, 5% and 7%) and 7 (seven) days of curing. Equations (9) and (10) present the variation of G_o and M_o with η/C_{iv}, both with high coefficient of determination ($R^2=0.95$ and 0.93, respectively for shear and oedometric modulus).

$$G_o^{7days}(MPa) = 15{,}595\left[\frac{\eta}{C_{iv}}\right]^{-0.95} \quad (9)$$

$$M_o^{7days}(MPa) = 30,220\left[\frac{\eta}{C_{iv}}\right]^{-0.81} \tag{10}$$

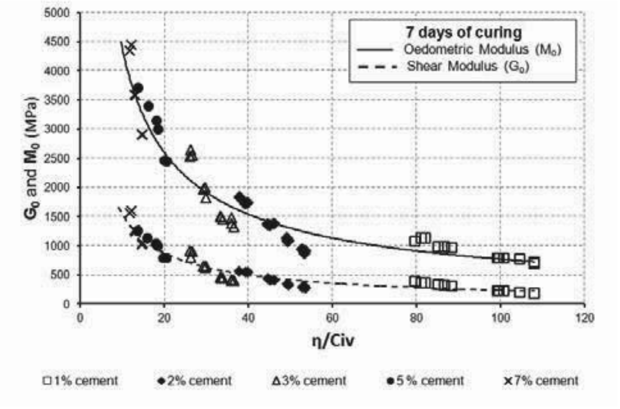

Figure 5. Shear (G_o) and oedometric (M_o) moduli at seven days of curing.

So, the use of the porosity of the compacted mixture divided by the volumetric cement content to assess both shear (G_o) and oedometric (M_o) moduli in the soil-cement mixtures studied herein is valid for all curing time periods studied. The results presented in this manuscript therefore suggest that using the porosity/cement ratio as represented by the porosity of the compacted mixture divided by the volumetric cement content, the engineer can choose the amount of cement and the porosity appropriate (within the studied range) to provide a mixture that meets the stiffness required by the project at the optimum cost. It can be seen from comparison of Eqs. (3), (5), (7) and (9) that G_o has a direct relationship with $(\eta/C_{iv})^{-0.95}$ for the all curing time periods and only a scalar differs regarding the effect of curing time. A similar situation is observed by comparing Eqs. (4), (6), (8) and (10), showing that M_o has a direct relationship with $(\eta/C_{iv})^{-0.81}$ for the all curing time periods and only a scalar differs regarding the effect of curing time. So, unique relationships can be achieved linking the G_o and M_o with η, C_{iv} and days of curing (t), as displayed in Fig. 6 and expressed mathematically by Eqs. (11) and (12), respectively for G_o and M_o. The coefficients of correlation are high [R^2=0.98 and 0.97, respectively for shear and oedometric modulus].

$$G_o^t(MPa) = \left[2,022 + 7,250.\ln(t)\right]\left[\frac{\eta}{C_{iv}}\right]^{-0.95} \tag{11}$$

$$M_o^t(MPa) = \left[7,631 + 12,038.\ln(t)\right]\left[\frac{\eta}{C_{iv}}\right]^{-0.81} \tag{12}$$

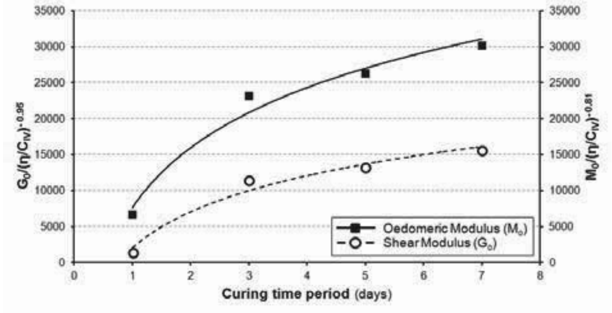

Figure 6. Increasing shear (G_o) and oedometric (M_o) moduli with curing time period.

4 CONCLUSIONS

From the data presented in this manuscript the following conclusions can be drawn:

- The porosity/cement ratio (η/C_{iv}) has been shown to be an appropriate index parameter to assess the shear (G_o) and oedometric (M_o) modulus in the sand-cement mixture studied herein for all curing time periods studied. Unique relationships were achieved linking the G_o and M_o with η, C_{iv} and time of curing (t);
- Based on the dosage equation established in present research for the studied sand-cement mixtures, there are several technical ways of reaching G_o or M_o target values for a given project and the best solution might change from situation to situation, depending on time period available, accessibility to equipment to reach a given porosity and cost of cement.

3. ACKNOWLEDGEMENTS

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