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Nilo Cesar Consoli, A.V. Da Fonseca, Severiano Silva, Rodrigo Caberlon Cruz ...+1 more authors

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TECHNICAL NOTE

Parameters controlling stiffness and strength of artificially cemented soils

N. C. CONSOLI*, A. V. da FONSECA†, S. R. SILVA†, R. C. CRUZ* and A. FONINI*

The treatment of soils with cement is an attractive technique when a project requires improvement of the local soil for the construction of subgrades for rail tracks, for roads, as a support layer for shallow foundations, and to prevent sand liquefaction. This paper advances understanding of the key parameters for the control of strength and stiffness of cemented soils by testing two soils with different gradings and quantifying the influence of porosity/cement ratio on both initial shear modulus (G_0) and unconfined compressive strength (q_u). It is shown that the porosity/cement ratio is an appropriate parameter to assess both the initial stiffness and the unconfined compressive strength of the soil–cement mixtures studied. Each soil matrix has a unique relationship for G_0/q_u against adjusted porosity/cement ratio, linking initial stiffness and strength.

KEYWORDS: compaction; ground improvement; laboratory tests; sands; soil stabilisation; stiffness

Le traitement des sols au ciment est une technique attrayante pour les projets nécessitant un renforcement du sol pour la construction d'assiettes pour voies ferrées et chaussées, comme couche d'appui pour fondations peu profondes, et pour la prévention de la liquéfaction du sable. La présente communication renforce les connaissances sur les principaux paramètres pour la régulation de la résistance et de la rigidité des sols cimentés, en soumettant à des essais deux sols de différentes granulométries, et en quantifiant l'influence du ratio porosité / ciment à la fois sur le module de cisaillement initial (G_0) et sur la résistance à la compression simple (q_u). On y montre que le ratio porosité /ciment est un paramètre approprié pour évaluer à la fois la rigidité initiale et la résistance à la compression simple des mélanges sol – ciment étudiés. Chaque matrice de sol présente un G_0/q_u unique en fonction du ratio porosité /ciment, mettant en rapport la rigidité initiale et la résistance.

INTRODUCTION

In highway and other shallow constructions, cement is often used to improve local soils, for example to make them suitable as subgrades, formations and foundation backfill (e.g. Rattley *et al.*, 2008; Consoli *et al.*, 2009). Previous studies of soil–cement (Moore *et al.*, 1970; Clough *et al.*, 1981; Consoli *et al.*, 2010, 2011) have shown that its behaviour is complex, and affected by many factors, such as the physical-chemical properties of the soil, the amount of cement, and the porosity and moisture content at the time of compaction.

Consoli *et al.* (2007) were the first to establish a unique dosage methodology based on rational criteria where the porosity/cement ratio plays a fundamental role in assessment of the target unconfined compressive strength.

This study shows the influence of the amount of cement and the porosity on the initial shear modulus (G_0) and unconfined compressive strength (q_u) of two different soils: uniform Osorio sand and very well-graded Porto silty sand.

EXPERIMENTAL PROGRAMME

Materials

The results of characterisation tests on the two soils are shown in Table 1, and their grain size curves are shown in Fig. 1.

The first soil used in the testing was silty sand, derived from weathered granite obtained from the region of Porto, in Northern Portugal. According to ASTM D 2487-93 (ASTM, 1993), the soil is a very well-graded silty sand (SM). Mineralogical analysis showed that the predominant mineral for the soil fraction smaller than 2 μm was kaolinite, and that the larger grains were mainly quartz. The second soil used in the testing was a sand obtained from the region of Osorio, near Porto Alegre, in southern Brazil, classified (ASTM, 1993) as a non-plastic uniform fine sand (SP). Mineralogical analysis showed that the sand particles are predominantly quartz.

Portland cement of high initial strength (Type III, ASTM C 150-09; ASTM, 2009)] was used as the cementing agent. Its fast gain of strength allowed the adoption of 7 days as the curing time.

Specimen preparation and test methods

Moulding and curing of specimens. For all testing, cylindrical specimens 70 mm in diameter and 140 mm high were used. After the soil, cement and water had been weighed, the soil and cement were mixed to achieve a uniform consistency. The water was then added while 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 target moisture content was derived from the mass of dry soil and cement. Cement content is defined as the mass of cement divided by the mass of dry soil. The moisture content is defined as the mass of water divided by the mass of solids (sand particles and cement powder).

The specimens were statically compacted to the target density in three layers inside a cylindrical stainless steel mould, which was lubricated. The top of each layer was slightly scarified. After the moulding process, the specimen was immediately extracted from the mould, and its weight, diameter and height were measured. The specimens were then placed within plastic bags to avoid loss of moisture.

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* Department of Civil Engineering, Federal University of Rio Grande do Sul, Brazil.
† Faculty of Engineering, University of Porto, Portugal.

Table 1. Physical properties of soil samples

Property	Porto silty sand	Osorio sand
Liquid limit: %	34	–
Plastic limit: %	31	–
Plasticity index: %	3	Non-plastic
Specific gravity	2·72	2·63
Fine gravel (2·0 mm < diameter < 6·0 mm):* %	11·5	0
Coarse sand (0·6 mm < diameter < 2·0 mm):* %	27·0	0
Medium sand (0·2 mm < diameter < 0·6 mm):* %	16·5	10·0
Fine sand (0·06 mm < diameter < 0·2 mm):* %	16·0	90·0
Silt (0·002 mm < diameter < 0·06 mm):* %	22·5	0
Clay (diameter < 0·002 mm):* %	6·5	0
Mean effective diameter, D_{50}: mm	0·25	0·16
Uniformity coefficient	113	1·9
Curvature coefficient	2·7	1·2
Maximum dry unit weight for modified Proctor compaction effort: kN/m^3	18·9	–
Optimum moisture content for modified Proctor compaction effort: %	13	–
Minimum void ratio	–	0·60
Maximum void ratio	–	0·90
Soil classification, ASTM D 2487-93 (ASTM, 1993)	SM	SP

* Soil size range based on British Standard BS 1377 (BSI, 1990).

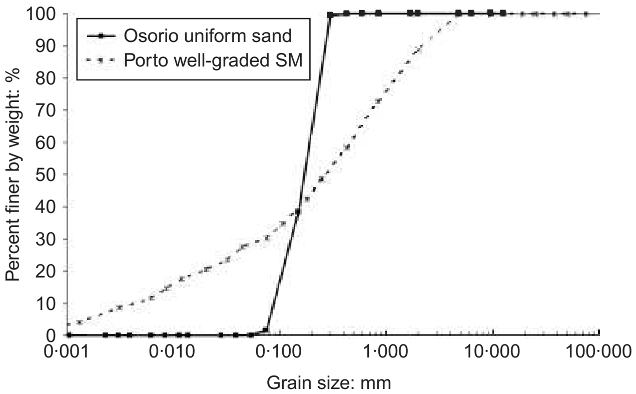

Fig. 1. Grain size distribution for both soils (uniform Osorio sand and very well-graded Porto silty sand)

They were cured in a humid room at 23° ± 2°C and relative humidity above 95% for 6 days.

Unconfined compression tests. Unconfined compression tests have been used in most of the experimental programmes reported in the literature in order to verify the effectiveness of the stabilisation with cement, or to access the importance of influencing factors on the strength of cemented soils. For this study the procedure described in ASTM D 2166-06 (ASTM, 2006) was adopted. After curing in a humid room for 6 days, the specimens were submerged in a water tank for 24 h for saturation and to minimise suction. The water temperature was controlled and maintained at 23°C ± 2°C. Then the unconfined compression test was carried out and the maximum load reached by the specimen was recorded.

Bender element tests. Bender elements were installed on the top and bottom specimen platens, and their movement was therefore horizontal, so that the shear wave propagated vertically and was polarised horizontally (V_s^{vh}). Two types of transducer were used. Bender elements (BE), manufactured at ISMES/Enel-Hydro (Brignoli *et al.*, 1996), were used in the tests over the Porto silty sand, whereas in the Osorio sand tests T-shaped pairs of bender/extender elements (B/EE), manufactured at the University of Western Australia (UWA) in Perth were used (Fig. 2). The bender elements penetrated the specimen by 3 mm at each end.

The principle of BE testing is simple (e.g. Viggiani & Atkinson, 1995), but a clear identification of travel time is not always possible. Clayton (2011) summarises the wide range of issues that have been identified in the manufacture and use of bender elements. For our sand–cement mixtures there was great difficulty in interpreting the results, even when combining simultaneous and automated analysis of the coherence between the input and output signals with a graph of time against frequency deduced from frequency sweep data. This led to the adoption of the simpler time domain method of identification of first arrivals.

Single sine-wave input pulses were used at preset frequencies of 1, 3, 5, 7, 9, 11 and 13 kHz, which covered the range of resonant frequencies of the sample–BE(BE/E) system. The output signals were captured on an oscilloscope, transferred directly to the PC, and plotted to a common timebase using Wavestar software. 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. Fig. 3 illustrates this interpretation for one of the specimens.

Programme of unconfined compression and bender element tests. The programme was chosen in such a way as to evaluate, separately, the influences on the mechanical strength and initial shear modulus of the artificially cemented soils, regarding specifically the cement content, the porosity and the porosity/cement ratio.

The moulding points for testing the unconfined compressive strength and initial shear modulus of the well-graded Porto silty sand had a moisture content of about 12%, different dry unit weights (16·4 kN/m^3, $e = 0{\cdot}64$; 17·2 kN/m^3, $e = 0{\cdot}57$; 18·0 kN/m^3, $e = 0{\cdot}50$; and 18·8 kN/m^3, $e = 0{\cdot}43$), and four different cement percentages: 2%, 3%, 5% and 7%. For the Osorio sand, voids ratios of 0·62 ($\gamma_d = 16{\cdot}2$ kN/m^3), 0·70 ($\gamma_d = 15{\cdot}5$ kN/m^3) and 0·80 ($\gamma_d = 14{\cdot}6$ kN/m^3) were chosen, with a moisture content of about 10% and cement percentages of 2%, 3%, 5% and 7%. Because of the typical

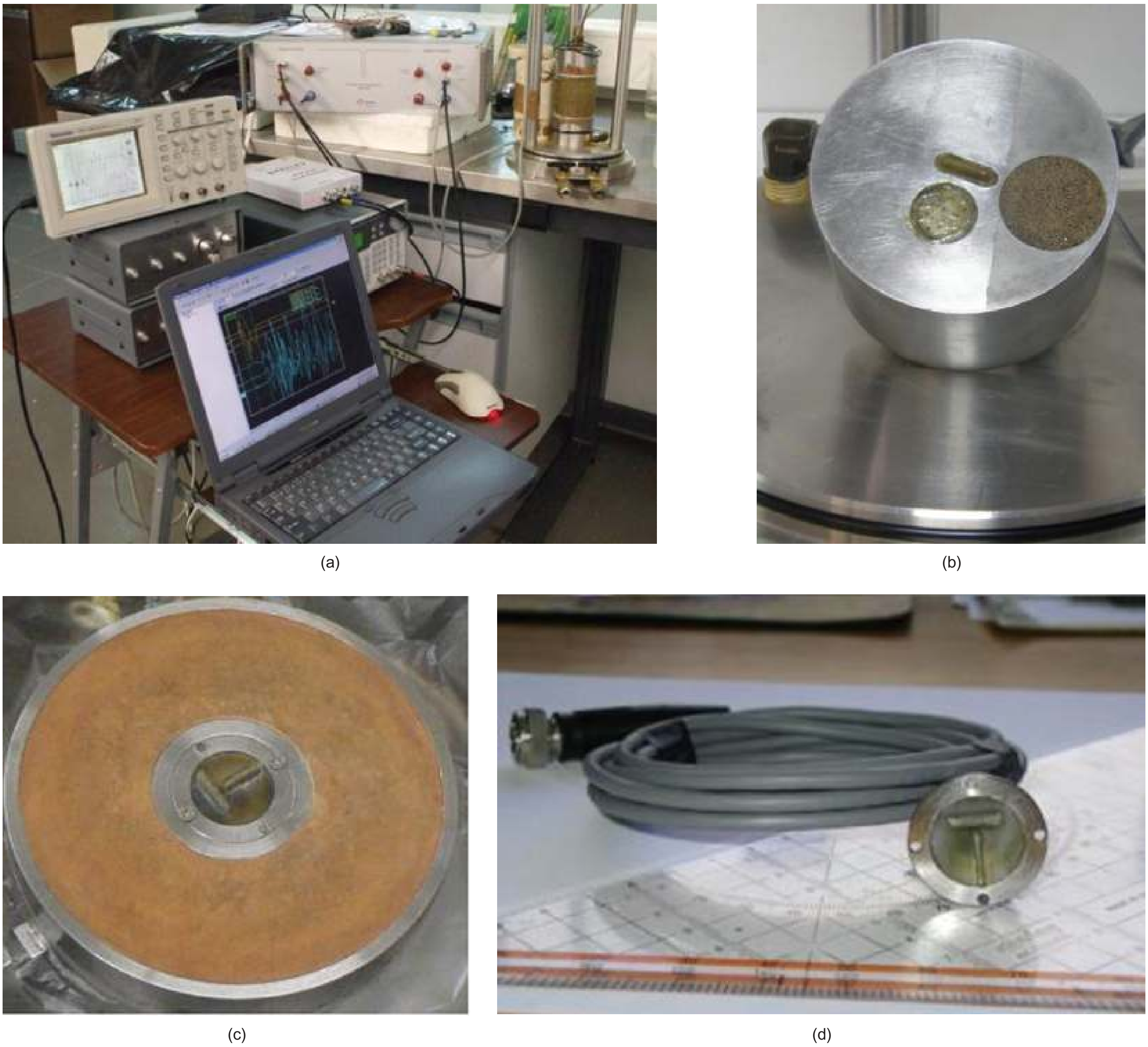

Fig. 2. Laboratory equipment used for seismic wave measurements: (a) testing set-up; (b) ISMES-Geo bender element and compression transducer; (c) UWA T-shaped pairs of bender/extender elements (B/EE)

scatter of data for unconfined compression tests, for each point, three to five specimens were tested.

RESULTS

Effect of cement content and porosity on unconfined compressive strength and initial shear modulus

Figure 4 presents the raw data and trend lines for unconfined compressive strength (q_u) as a function of the cement content (C) for both the Osorio sand and Porto silty sand, considering separately all the dry unit weights tested. It can be seen that the cement content had a great effect on the strength of both soils, and the unconfined compressive strength increased approximately linearly with increase in cement content. Fig. 5 illustrates how the porosity affects the unconfined compressive strength of both soils studied. The unconfined compressive strength increased with reduction in porosity of the compacted mixture. The mechanism by which the reduction in porosity increases the soil–cement strength is presumably related to the existence of a larger number of contacts. Comparing results of both soils at the same porosity, the influence of grain size distribution is considerable, given that the mean effective diameters of the soils are comparable.

Figure 6 shows the relation between the initial shear modulus G_0 and the cement content C for both the Osorio sand and Porto silty sand, considering each dry unit weight tested. Similarly to q_u, G_0 increases approximately linearly with increase in cement content. Fig. 7 illustrates the influence of porosity on the initial shear modulus of both soil–cements studied. G_0 decreases with increasing porosity, as observed with the q_u results.

Effect of porosity/cement ratio on unconfined compressive strength and initial shear modulus

As seen in the results presented above (Figs 4–7), both G_0 and q_u are dependent on both the porosity and the cement content. For both the soil–cement blends, rising values of porosity cause a reduction of G_0 and q_u, while increasing values of cement content produce larger values of

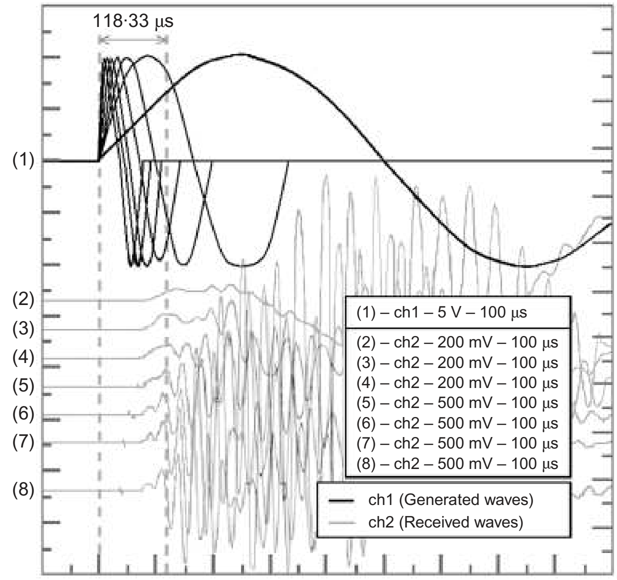

Fig. 3. BE S-waves' time domain interpretation for the specimen with 7% cement and 16·4 kN/m^3 of volume weight: $t_S = 118{\cdot}3$ μs; $V_S = 581$ m/s (preset frequencies: 1, 3, 5, 7, 9, 11, 13 kHz; outputs in reversed polarity)

q_u and G_0. Below empirical relationships are developed for G_0 and q_u as a function of porosity/cement ratio (η/C_{iv}).

By trial and error it was found that for the relationship between unconfined compressive strength and porosity/cement ratio of the Porto silty sand, the optimum fit could be obtained by applying a power equal to 0·21 to the parameter C_{iv}, as shown in Fig. 8 (for the Osorio sand the power would be 1·0). Excellent correlations (coefficients of determination R^2 0·99 and 0·96 for Porto silty sand and Osorio sand respectively) can be observed in Fig. 8 between adjusted porosity/cement ratio ($\eta/(C_{iv})^{0{\cdot}21}$ for Porto silty sand and $\eta/(C_{iv})^{1{\cdot}0}$ for Osorio sand and the unconfined compressive strength q_u.

A similar analysis to the above was done for initial shear modulus as a function of the porosity/cement ratio. It was also found that for the relationship between initial shear modulus (G_0) and porosity/cement ratio of the Porto silty sand, the optimum fit could be obtained by applying a power equal to 0·21 to the parameter C_{iv}, as shown in Fig. 9 (for the Osorio sand the power would be 1·0). High coefficients of determination (0·89 and 0·92 respectively for Porto silty sand and Osorio sand) can be observed in Fig. 9 between the adjusted porosity/cement ratio and the initial shear modulus (G_0) for both soil–cement blends studied.

It is interesting to note that the influence of the adjusted porosity/cement ratio on the unconfined compressive strength q_u (Fig. 8) and on the initial shear modulus G_0 (Fig. 9) of artificially cemented uniform sand and artificially cemented well-graded silty sand is quite similar, since the shapes of the curves are almost the same. In the present research, it has been observed that the cement inclusion strengthens and stiffens the soil matrix, and that the amount of strengthening and stiffening is also a function of the soil matrix. The importance of soil grading, particle shape and D_{50} on very-small-strain stiffness of cemented sediments has been shown previously by Clayton *et al.* (2010).

For the Osorio sand–cement mixture, assembling the optimum fitting curves of the unconfined compressive strength (q_u) and initial shear modulus (G_0) with adjusted porosity/cement ratio allows a relationship for G_0/q_u to be determined as a function of $\eta/(C_{iv})^{1{\cdot}0}$ (see equation (1) and Fig. 10).

$$\frac{G_0}{q_u} \cong 127\left[\frac{\eta}{(C_{iv})^{1{\cdot}0}}\right]^{0{\cdot}97} \tag{1}$$

For the Porto silty sand–cement, assembling the optimum fitting curves of q_u and G_0 with adjusted porosity/cement ratio ($\eta/(C_{iv})^{0{\cdot}21}$) allows a unique relationship to be established for G_0/q_u (see equation (2) and Fig. 10).

$$\frac{G_0}{q_u} \cong 25\left[\frac{\eta}{(C_{iv})^{0{\cdot}21}}\right]^{0{\cdot}96} \tag{2}$$

So specific relationships for G_0/q_u are found for the two soils. The Osorio sand has a higher G_0/q_u relationship than the Porto silty sand.

The results presented in this note suggest that, by using the adjusted porosity/cement ratio, the engineer can choose the amount of cement and the minimum density appropriate to provide a mixture that meets the strength and stiffness required by the project at an optimum cost. The adjusted porosity/cement ratio can also be useful in the field control of soil–cement layers. Once poor compaction has been identified, it can be readily taken into account in the design,

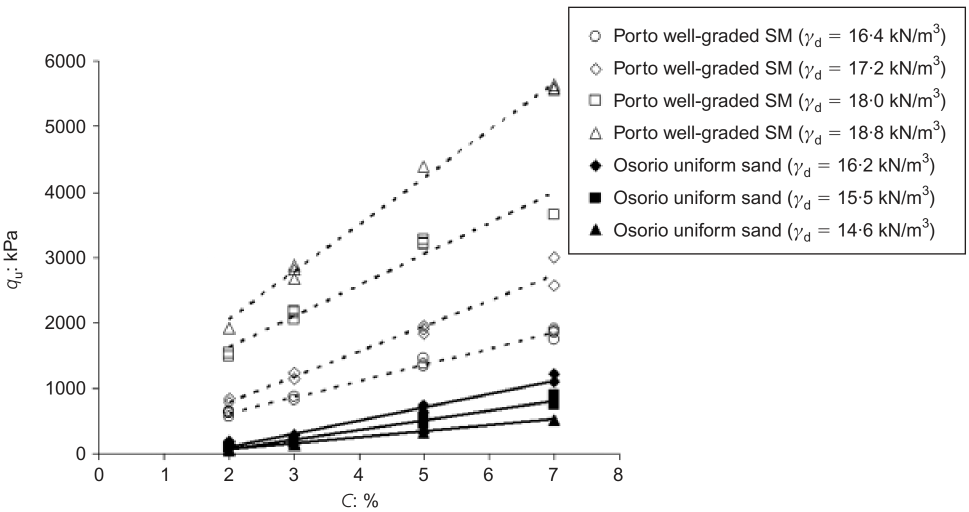

Fig. 4. Variation of unconfined compressive strength for both cemented soils (uniform sand and very well-graded silty sand) with cement content

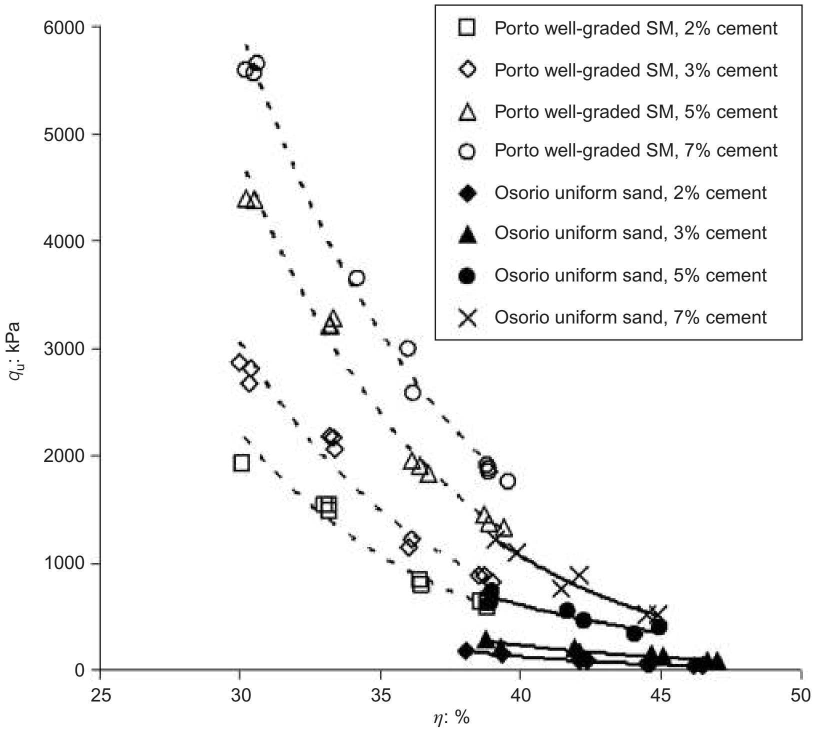

Fig. 5. Variation of unconfined compressive strength (q_u) for both cemented soils (uniform sand and very well-graded silty sand) with porosity

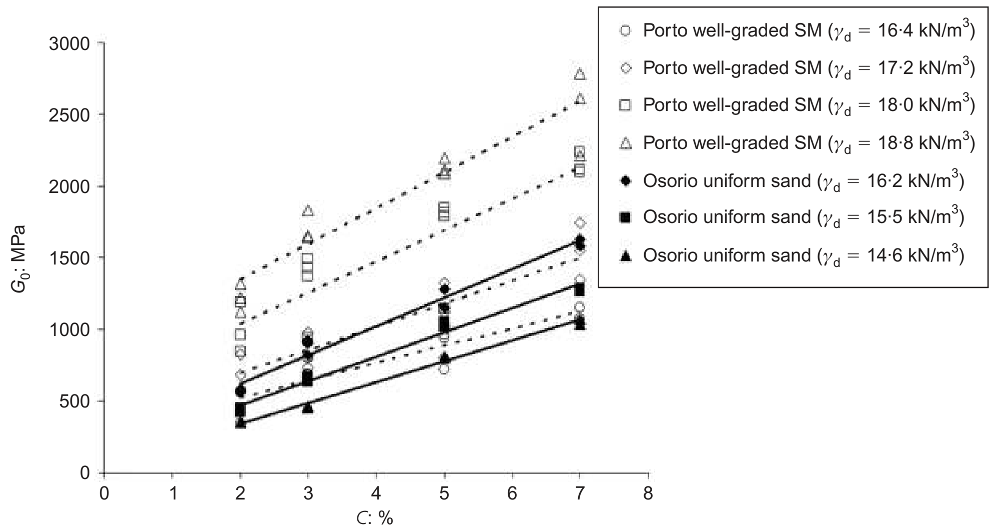

Fig. 6. Variation of initial shear modulus G_0 with cement content C for very well-graded Porto silty sand

through the curves of q_u, G_0 and even G_0/q_u against adjusted porosity/cement ratio, and by adopting corrective measures accordingly, such as reinforcement of the treated layer, or a reduction in the transmitted load.

CONCLUSIONS

From the data presented in this note, the following conclusions can be drawn.

(*a*) $\eta/(C_{iv})^{exponent}$ is an appropriate parameter to assess the influence of both porosity and cement content on the initial stiffness and unconfined compressive strength of soil–cement mixtures.

(*b*) For a given soil matrix–cement blend, G_0/q_u varies almost linearly with $\eta/(C_{iv})^{exponent}$, revealing a consistent pattern of dependence between these geomechanical properties and that index.

(*c*) By using the $\eta/(C_{iv})^{exponent}$ index, practitioners may choose the amount of cement and the target density appropriate to provide a mixture that meets the strength and stiffness required by their project.

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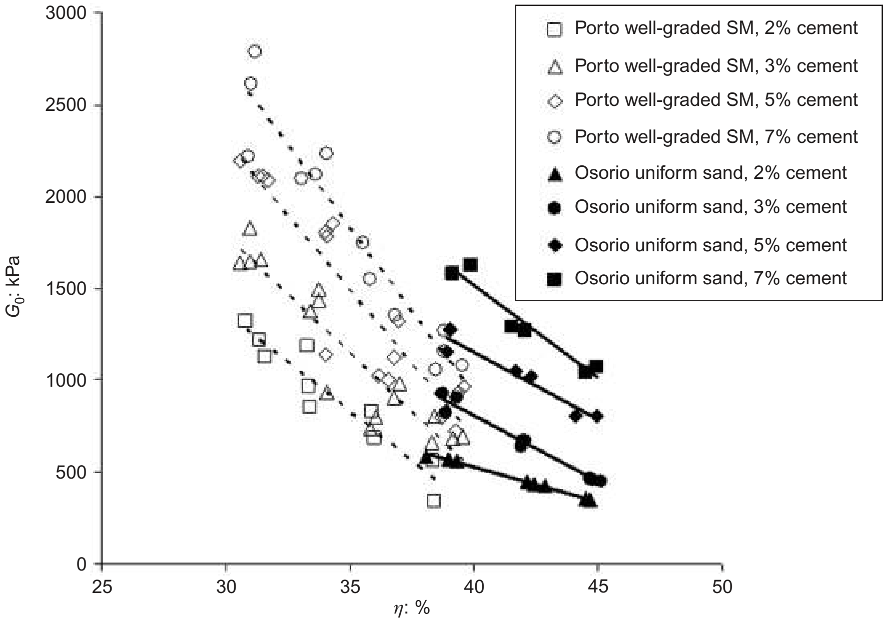

Fig. 7. Variation of initial shear modulus G_0 with porosity η for very well-graded Porto silty sand

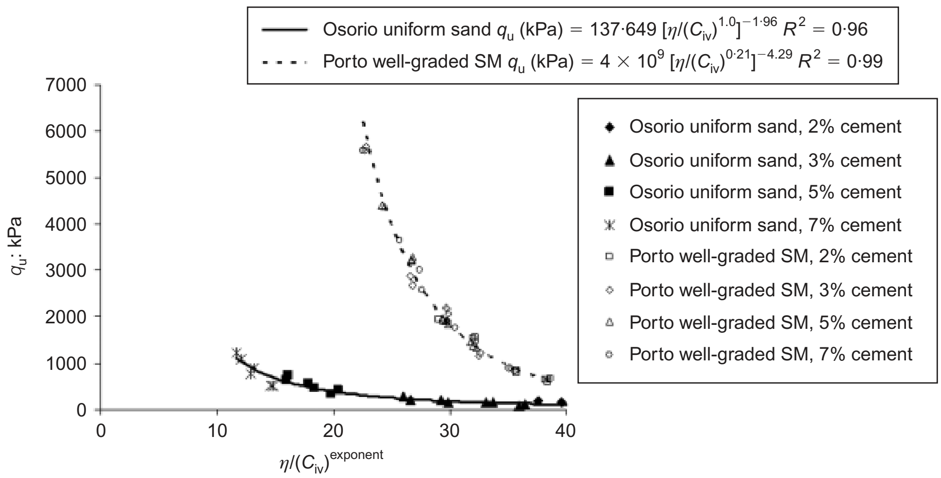

Fig. 8. Variation of unconfined compressive strength for both cemented soils (uniform sand and very well-graded silty sand) with adjusted porosity/cement ratio

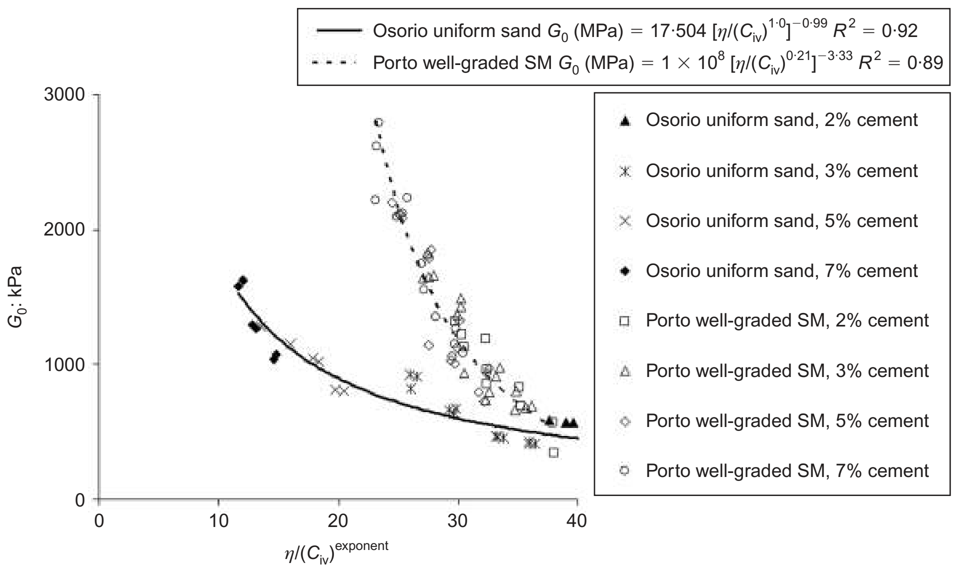

Fig. 9. Variation of initial shear modulus G_0 for both cemented soils (uniform sand and very well-graded silty sand) with adjusted porosity/cement ratio

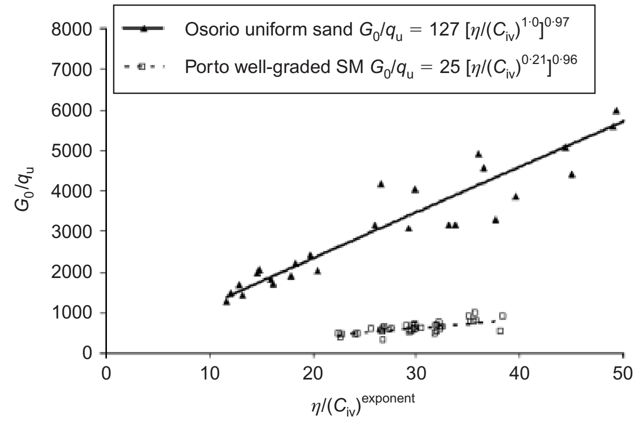

Fig. 10. Relations between G_0 and q_u for both cemented soils (uniform sand and very well-graded silty sand) with adjusted porosity/cement ratio

NOTATION

C	cement content
C_{iv}	volumetric cement content
D_{50}	mean effective diameter
e	void ratio
G_0	initial shear modulus
q_u	unconfined compressive strength
R^2	coefficient of determination
t	travel time of shear wave through sample
V_s	velocity of shear wave
V_s^{vh}	shear wave velocity propagated vertically and polarised horizontally
γ_d	dry unit weight
η	porosity
η/C_{iv}	porosity/cement ratio
$\eta/(C_{iv})^{exponent}$	adjusted porosity/cement ratio

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