Parameters controlling stiffness and strength of artificially cemented soils

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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)1 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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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 \( (V_p) \). 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/extension 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/m³, \( e = 0.64 \); 17.2 kN/m³, \( e = 0.57 \); 18.0 kN/m³, \( e = 0.50 \); and 18.8 kN/m³, \( e = 0.43 \)), and four different cement percentages: 2%, 3%, 5% and 7%. For the Osorio sand, voids ratios of 0.62 (\( \gamma_d = 16.2 \) kN/m³), 0.70 (\( \gamma_d = 15.5 \) kN/m³) and 0.80 (\( \gamma_d = 14.6 \) kN/m³) were chosen, with a moisture content of about 10% and cement percentages of 2%, 3%, 5% and 7%. Because of the typical
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...
Below empirical relationships are developed for $G_0$ and $q_u$ as a function of porosity/cement ratio ($\gamma$/Civ). 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 Civ, 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 ($\eta/(C_{iv})^{0.21}$) for Porto silty sand and $\eta/(C_{iv})^{1.0}$ 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 Civ, 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 D50 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 $\eta/(C_{iv})^{0.21}$ (see equation (1) and Fig. 10).

$$\frac{G_0}{q_u} \cong 127 \left[ \frac{\eta}{(C_{iv})^{0.21}} \right]^{0.97}$$

(1)

For the Porto silty sand–cement, assembling the optimum fitting curves of $q_u$ and $G_0$ with adjusted porosity/cement ratio $(\eta/(C_{iv})^{0.21})$ allows a unique relationship to be established for $G_0/q_u$ (see equation (2) and Fig. 10).

$$\frac{G_0}{q_u} \cong 25 \left[ \frac{\eta}{(C_{iv})^{0.21}} \right]^{0.96}$$

(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,
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) $\eta/(C_v)^{\text{exponent}}$ 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 $\eta/(C_v)^{\text{exponent}}$, revealing a consistent pattern of dependence between these geomechanical properties and that index.

(c) By using the $\eta/(C_v)^{\text{exponent}}$ 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 $\eta$ for very well-graded Porto silty sand

$$G_0: \text{kPa}$$

Osorio uniform sand, 2% cement
Osorio uniform sand, 3% cement
Osorio uniform sand, 5% cement
Osorio uniform sand, 7% cement
Porto well-graded SM, 2% cement
Porto well-graded SM, 3% cement
Porto well-graded SM, 5% cement
Porto well-graded SM, 7% cement

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

Osorio uniform sand $q_u$ (kPa) = $137.649 \times \left(\eta/(Civ)^{0.96}\right) R^2 = 0.96$

Porto well-graded SM $q_u$ (kPa) = $4 \times 10^3 \times \left(\eta/(Civ)^{2.22}\right)^{0.9} R^2 = 0.99$

Osorio uniform sand, 2% cement
Osorio uniform sand, 3% cement
Osorio uniform sand, 5% cement
Osorio uniform sand, 7% cement
Porto well-graded SM, 2% cement
Porto well-graded SM, 3% cement
Porto well-graded SM, 5% cement
Porto well-graded SM, 7% cement

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

Osorio uniform sand $G_0$ (MPa) = $17.504 \times \left(\eta/(Civ)^{0.96}\right) R^2 = 0.92$

Porto well-graded SM $G_0$ (MPa) = $1 \times 10^3 \times \left(\eta/(Civ)^{2.33}\right)^{0.89} R^2 = 0.89$

Osorio uniform sand, 2% cement
Osorio uniform sand, 3% cement
Osorio uniform sand, 5% cement
Osorio uniform sand, 7% cement
Porto well-graded SM, 2% cement
Porto well-graded SM, 3% cement
Porto well-graded SM, 5% cement
Porto well-graded SM, 7% cement
PARAMETERS CONTROLLING STIFFNESS AND STRENGTH OF ARTIFICIALLY CEMENTED SOILS

NOTATION

- $C$: cement content
- $C_{\text{iv}}$: 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
- $V_{sh}$: shear wave velocity propagated vertically and polarised horizontally
- $\gamma_d$: dry unit weight
- $\eta$: porosity
- $\eta/C_{\text{iv}}$: porosity/cement ratio
- $\eta/(C_{\text{iv}})^{\text{exponent}}$: adjusted porosity/cement ratio

REFERENCES


