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THE EFFECT OF THE POROSITY/CEMENT RATIO ON THE COMPRESSION OF CEMENTED SOIL

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ABSTRACT

The compression behavior of an artificially cemented soil was analyzed by means of the adjusted porosity/cement ratio proposed using a correlation established in the recent literature. It was found that for each value of this parameter, defined as the ratio of porosity to the volumetric cement content, there is a unique Normal Compression Line (NCL). The NCLs of the cemented specimens for each adjusted porosity/cement ratio do not converge with the NCL of the uncemented silty sand at large stresses, but reach a line parallel to it, the lowest the adjusted porosity-cement index, the further the NCL of the cemented sand from the NCL of the uncemented sand.

INTRODUCTION

The improvement of soil characteristics by using cement is a generally economical and satisfying method that is used worldwide in pavement base layers, slope protection for earth dams, as a base layer to shallow foundations and to prevent liquefaction (Catton, 1962; Ingles and Metcalf, 1972; Dupas and Pecker, 1979; Porbaha et al., 1998; Thomé et al., 2005). The rules for designing cemented soil however are still predominantly empirical. In cement admixed clay, it is recognized that the strength is governed by the water and cement contents, and the ratio of clay-water content to cement content is generally used as a determining parameter (Miura et al., 2001; Horpibulsuk et al., 2005). In cemented sands however, there is no such recognized parameter. The porosity appears to be important, especially when specimens are molded in unsaturated conditions where most voids are not filled with water (Clough et al., 1981; Consoli et al., 2000; Rotta et al., 2003). Consoli et al. (2007) analyzed the effect of cement dosage, also an important parameter, on the behavior of unsaturated artificially cemented soils by using a porosity/cement ratio index. This index, which corresponds to the ratio of the soil porosity to the volumetric cement content (n/C_{iv}), was shown to govern the unconfined compression strength and to a certain extent the shear modulus of the improved soil (Consoli et al., 2007; Consoli et al., 2009). For example, a unique relationship between the unconfined compression strength and the porosity/cement ratio amplified by an exponent ξ specific to the soil could be found for a variety of soils, with ξ equal to 1.00 for a uniform sand from Brazil (Osorio sand; Consoli et al., 2009; Viana da Fonseca et al., 2009), ξ equal to 0.28 for a well graded residual soil from Brazil (Botucatu residual sandstone; Consoli et al., 2007), and ξ equal to 0.21 for the Portuguese Porto residual soil from granite - the soil used herein (Consoli et al., 2011 – in press). In the following, the value (n/C_{iv}^{ξ}) will be referred to as adjusted porosity-cement index. This note extends that work to the compression behavior of the improved Porto residual soil by examining the response to isotropic compression of specimens prepared at two given dosages, where a dosage corresponds to a fixed adjusted porosity-cement index but the cement content can vary.

TESTING MATERIAL AND PROCEDURES

Material

The host soil is a well graded non-plastic silty sand derived from weathered Porto granite that is abundant in Northern Portugal (Viana da Fonseca et al., 2006). The soil, kept consistent throughout the study, is classified as SM in the Unified Soil Classification System (ASTM, 1998). The density of the solids was determined as 2.72. The silty sand has an effective diameter D_{50} equal to 0.25 mm, and uniformity and curvature coefficients of 113 and 2.7 respectively (Table 1). Modified Proctor compaction tests were performed, and the maximum dry and optimum water content obtained were 18.5 kN/m^3 and 13%, as illustrated in Figure 1. A high strength Portland cement (CEM I 52,5R) was used as the cementing agent. The density of the cement grains is 3.15.

Specimen preparation

The particle size distribution of the specimens tested was kept constant throughout the study. Because the cement contributed to more fines in the soil, an equal quantity of soil fines to the amount of added cement was subtracted from the cemented specimens. 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 the density of the soil (G_s=2.72) and that of the cement (G_s=3.15), and thus it was different for different cement contents.

In preparing the specimens, the correct quantities of soil and cement were mixed until reaching uniform consistency, and then water was added while continuing mixing until a homogeneous paste was created. The amount of cement for each mixture was calculated from the mass of the dry soil in order to achieve the desired cement content. The static compaction of the specimens was carried out in three layers in a cylindrical stainless steel mold that had been lubricated. Each layer was slightly scratched for better bonding. At least 12 hours after molding (to prevent swelling) the specimen was extracted from the mold, and its weight and dimensions were measured with accuracies of 0.01g and 0.1mm. They were placed in plastic bags to avoid significant variations of moisture content, and then they were left to cure in a humid room for six days, at 23º±2ºC temperature and 95% relative humidity. The curing time was set at nine days for all specimens. Thanks to the rapid hardening property of the cement there was no significant gain in strength past the seven days curing, and thus the mechanical behavior of these latter specimens should not have been affected by it.

The cemented specimens were prepared at two different dosages, or molding points, taken from the relationship between unconfined compressive strength (q_u) and the adjusted porosity/cement ratio ($n/C_{iv}^{0.21}$) expressed in Figure 2, which is detailed in Rios et al. (2009) and Rios (2011). This relationship was obtained with specimens molded with a water content of 12%, determined from the Normal and Modified Proctor curves for cemented soil in Figure 1, but for different densities and cement contents. Adding cement has the effect of decreasing the optimum water content and increasing the maximum dry unit weight (because of the increase in fines content). In this study however, because the quantity of fines was kept constant by replacing soil fines with cement, the effect was minimized and thus specimens with different cement contents should have similar Proctor curves. The two molding points selected for the study were for cemented sand of strengths of 800kPa and 2,000kPa, of magnitude relevant to practice. As shown in Figure 2, they correspond to adjusted porosity-cement indices

$n/C_{iv}^{0.21}$=36 and $n/C_{iv}^{0.21}$=29 respectively. Considering the usual economical range of cement contents for soil treatment ranges between 2 and 7%, four molding conditions were defined, in terms of cement content (see Figure 3): for the higher strength (2,000 kPa), higher cement contents were used (5% and 7%) and for the lower strength (800 kPa) the lower bound of the previous range was adopted (2 and 4%). The corresponding porosities were calculated from the definition of the adjusted porosity/cement ratio. The molding water content was the same in all specimens, chosen as the optimum value obtained in Figure 1 for the soil-cement specimen.

The uncemented specimens were prepared by mixing soil and water at a target moisture content and compacting in layers in a similar way to the cemented specimens to achieve two different compaction degrees. Table 2 summarizes the molding conditions of all the specimens.

Testing procedures

Isotropic compression tests were performed in the soil mechanics laboratories of Imperial College London (UK). In pure sand, isotropic yield stresses are often reached at pressures well in excess of the pressures available in conventional triaxial apparatus. The same is generally true of cemented sand (Cuccovillo and Coop, 1999). The compression tests were therefore carried out in a 70MPa high pressure apparatus on specimens of 50 mm diameter and 100 mm height. Two axial non-submersible LVDTs with exposed contacts were used for local measurement of deformations (Cuccovillo and Coop, 1997). The cell and pore water pressure were measured using pressure transducers of 70MPa capacity and the variation of volume of the specimen was monitored using a 50cc Imperial College volume gauge.

The specimens were cured for nine days before being placed in water to facilitate saturation, generally for about fifteen hours overnight, then they were put for an additional forty minutes within water in the vacuum chamber. This procedure allowed a degree of saturation of 90% as measured by the weight of the specimen before and after being placed in water. Full saturation was achieved in the triaxial cell, where a B-value of 0.9 was reached for a back pressure of 700 kPa.

ISOTROPIC COMPRESSION TEST RESULTS

Results from the isotropic compression tests are plotted in Figure 4. The compression curves of the cemented sand specimens are initially flat, reflective of the stiffness of the cement but at a stress of about 2 MPa the slope of the curves increases markedly. This sharp yield is the result of damage to the cementitious bonds. The slope progressively reduces until a mean effective stress around 20 MPa, where for each adjusted porosity/cement ratio the compression curves for the two different cement contents eventually converge to a unique compression line. This line, which represents the locus of significant breakage of the cement due to isotropic compression, is the normal compression line of the cemented sand (NCL_{cement}). The NCL_{cement} are distinct for the two dosages and appear to be parallel.

Also shown in Figure 4 are two isotropic compression curves for the uncemented Porto silty sand, which were obtained from specimens molded at two different void ratios and tested in identical conditions as the cemented sand. The soil specimens initially have a stiff response with little volumetric deformation, then the compression curve changes progressively to a steeper slope. At higher stresses the specimens prepared at different initial void ratios converge to a unique normal compression line (NCL_{silty_sand}). The NCLs of the cemented specimens for each adjusted porosity/cement ratio do not coincide with the NCL_{silty_sand} but are parallel to it, with the curve obtained for the lowest adjusted porosity-cement index plotting to the right of the curve obtained for the higher index. The location of the NCL_{cement} to the right of the NCL_{silty_sand} suggests that there are still some elements of bonding in the cemented sand even at high stresses. Examination of the specimens of cemented sand after compression to

40MPa only showed that the cemented soil had broken into aggregates and clusters of smaller size.

Figure 2 indicates that there is a unique value of unconfined compressive strength for each adjusted porosity cement ratio, independently of the cement content. The relationship between unconfined compressive strength and yield stress in cemented clay has been established by previous researchers e.g. Horpibulsuk et al. (2004). Thus, it should be expected that the isotropic yield stress for a given porosity-cement index is also unique. Given the results obtained here, it is proposed that for the sand examined here, there is a family of parallel NCLs for the cemented sand parallel to the $NCL_{silty\ sand}$, each line representing a contour of dosage, and the lower the adjusted index, the further away the NCL_{cement} from the NCL_{silty_sand}. This is illustrated in Figure 5 which shows that the higher the cementation bond (corresponding to lower adjusted porosity/cement ratios) the higher is the additional void ratio in relation to the uncemented NCL.

Liu and Carter (2000) proposed a constitutive model to simulate the virgin compression line of naturally structured clays, which tend to be weakly cemented. This model was later used by Suebsuk et al. (2010) to simulate the compression behavior of artificially cemented clays up to high percentages of cement. While natural clays and some cement-treated clays with weaker bonding have comparatively high rates of destructuration and their NCLs converge to the NCL of the reconstituted or uncemented clay at large strains (e.g. Smith et al., 1992; Kasama et al., 2006), in soils with stronger bonding the structure tends to degrade less rapidly, and some elements of bonding can remain even at large stresses, which are sometimes assimilated to fabric. In this case, the NCL of the cemented soil never reaches the NCL of the uncemented soil but a line parallel to it, like the soil presented herein. This behavior can be simulated by constitutive models for structured soils that include effects of fabric and bonding, such as the Sensitivity 3-Surface Kinematic Hardening (S3-SKH) model developed by Baudet & Stallebrass (2004).

CONCLUSIONS

The most significant aspect of the results presented here is that for a given adjusted porosity-cement index, there is a unique NCL that is reached at large stresses. The existence of parallel NCLs for different adjusted porosity-cement indices suggests that even at large stresses there are some elements of the cementing that remain. The location of the NCL for a given dosage seems to be linked to the adjusted porosity-cement index, but further research is needed to verify it. The adjusted porosity-cement index was nevertheless demonstrated to be a powerful parameter to describe the behavior of cemented sand in pure compression.

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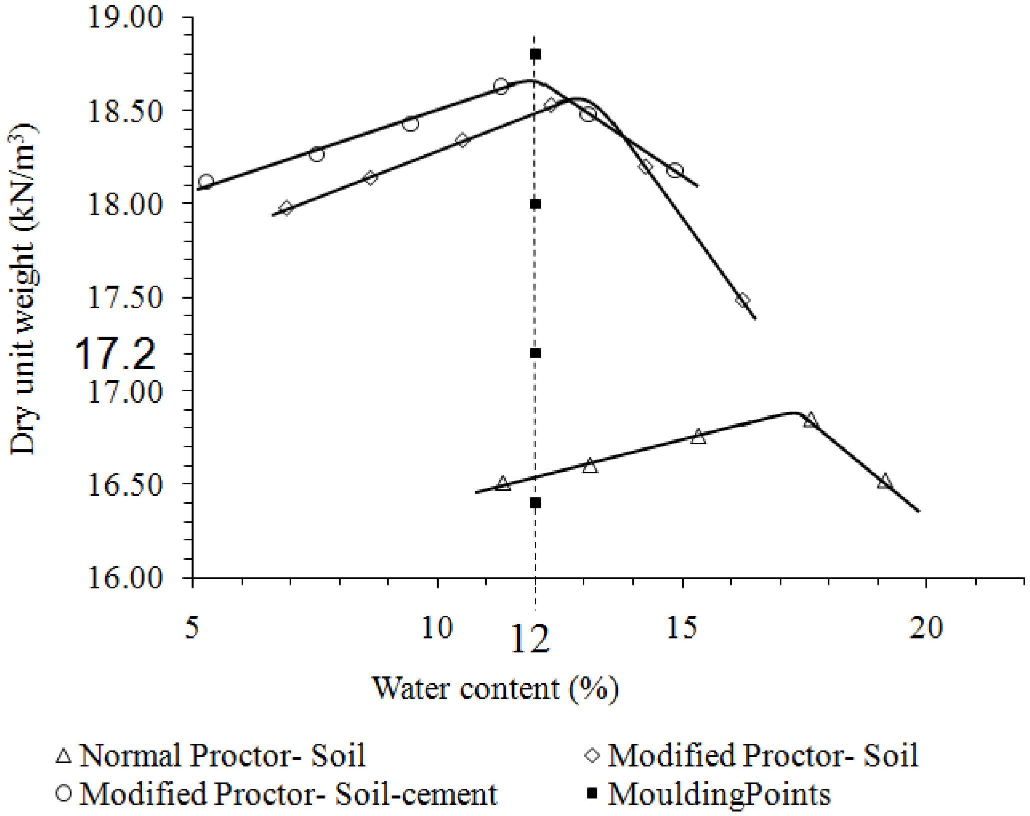

FIGURE 1 - Normal and Modified Proctor curves for the uncemented and cemented soil with 3% of cement content.

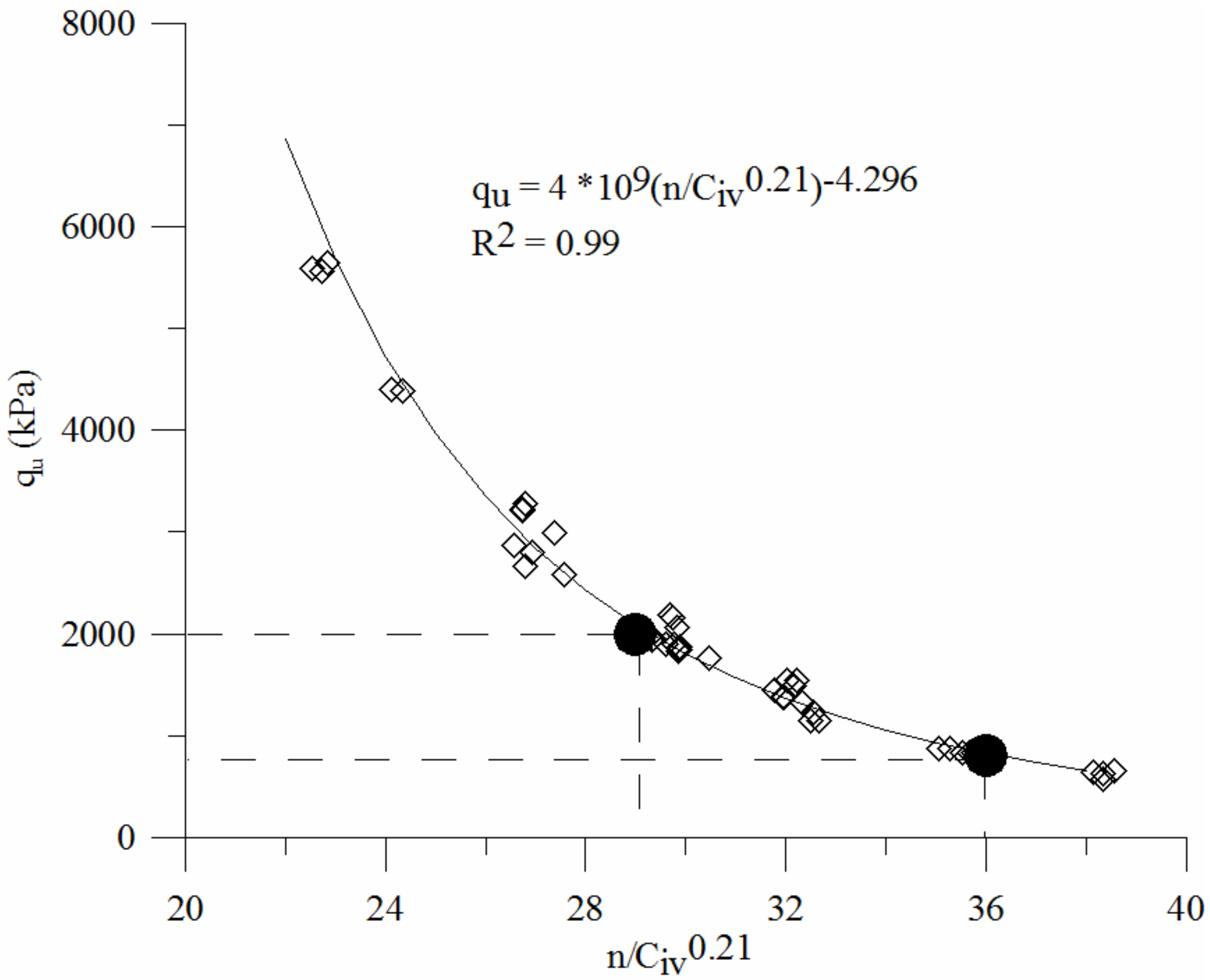

FIGURE 2 – Determination of molding conditions (data from Rios et al., 2009).

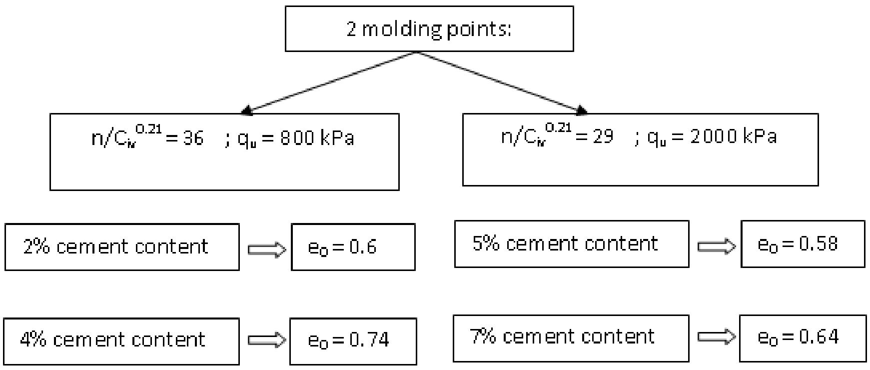

FIGURE 3 – Chart of the molding conditions.

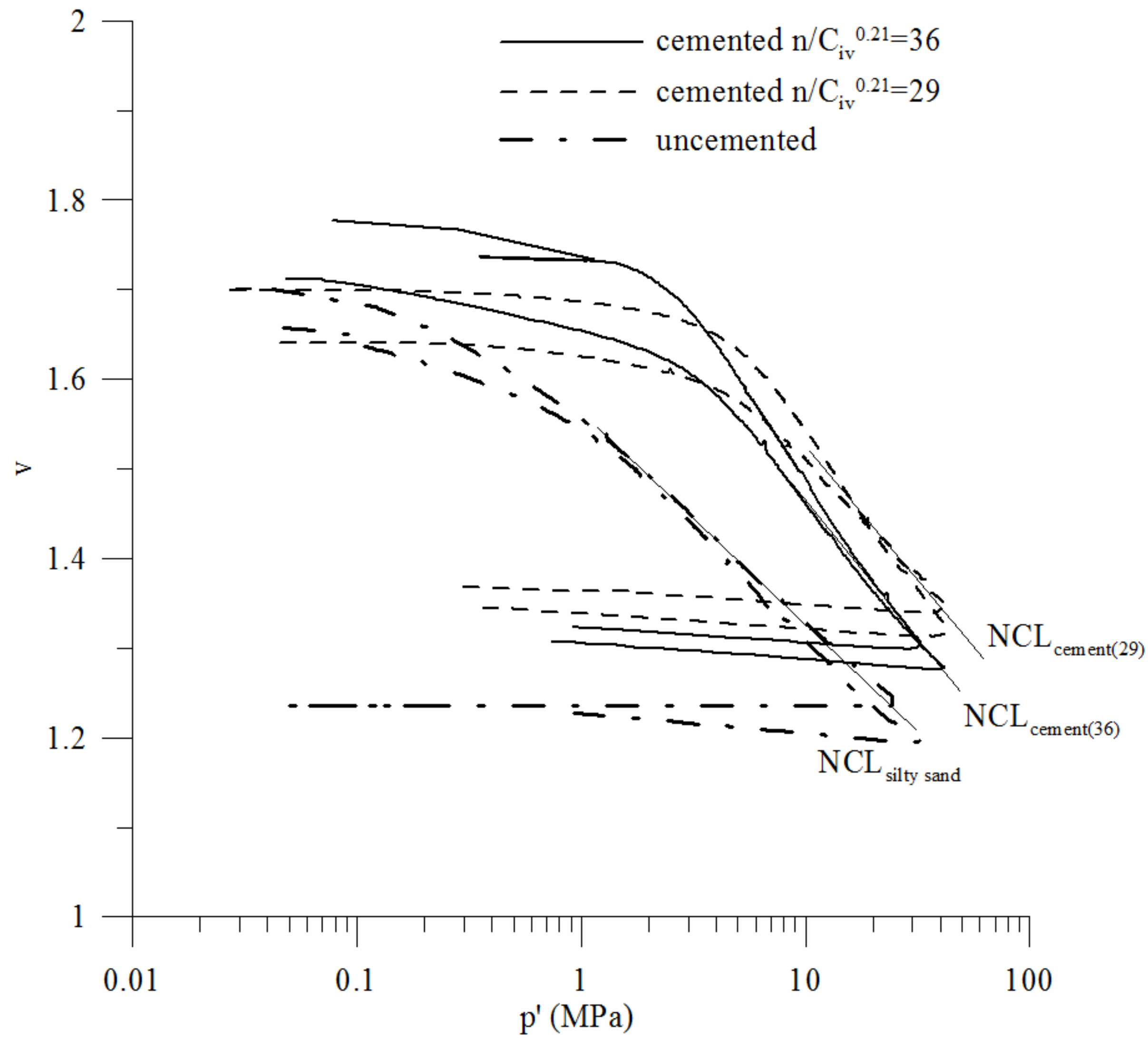

FIGURE 4 - Isotropic compression data and normal compression lines (NCL) for the clean silty sand and cemented silty sand.

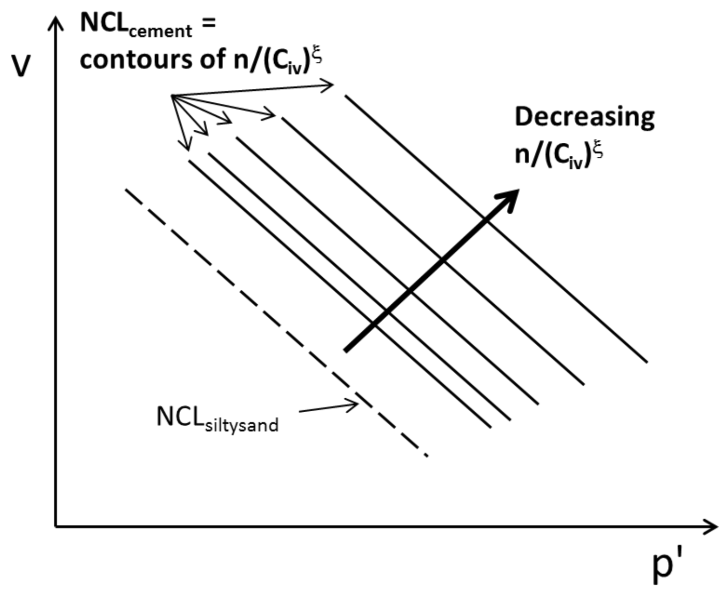

FIGURE 5 – Normal compression lines for cemented sand of given adjusted porosity-cement index.

TABLE 1 – Properties of Porto residual silty sand.

G_s	D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	D_{60} (mm)	C_u	C_c	ω_L	ω_P
2.72	0.003	0.055	0.25	0.4	113	2.72	34%	31%

TABLE 2 – Programme of isotropic compression tests.

Cement content %	Molding dry unit weight kN/m^3	Molding void ratio	Molding water content	Adjusted void cement ratio $n/C_{iv}^{0.21}$	UCS kPa
0	15.4	0.81	12	-	-
0	17	0.66	12	-	-
2	16.7	0.6	12	36	800
4	15.4	0.74	12	36	800
5	17	0.58	12	29	2000
7	16.4	0.64	12	29	2000