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► **To cite this version:**

Lucile Pigeot, Nathalie Dufour, Anthony Soive, Fabienne Dermenonville, Ahmed Loukili, et al.. Influence of curing under stress on the geotechnical behavior of a treated silty soil. XVIII ECSMGE 2024, Aug 2024, Lisboa, Portugal. 10.1201/9781003431749-490 . hal-04706115

HAL Id: hal-04706115

<https://hal.science/hal-04706115v1>

Submitted on 13 Jan 2025

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Influence of curing under stress on the geotechnical behavior of a treated silty soil

Influence sur le comportement mécanique d'une pression appliquée pendant la cure d'un limon traité

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ABSTRACT: Improving the soil in place by adding lime, hydraulic binder and increasing compaction is widely used to carry out geotechnical works. Laboratory test campaigns are conducted to validate the treatment and its consistency with the expected mechanical properties. They allow on the one hand to follow the mechanical evolution due to hydration of the cement phases and on the other hand to observe the soil response under various stresses. The standards for treated soils recommend carrying out tests on specimens which have undergone curing conditions in airtight packaging, at a temperature of 20°C and atmospheric pressure. However, if these normalized conditions represent the conditions of a low height embankment, when the structure is of great height it is interesting to take into account the pressure to which the material is subjected during its curing. The study focused on comparing the evolution of the mechanical properties of silt treated with lime and hydraulic binder then compacted, when it was subjected to a normalized cure or a confined cure of 500 kPa. In order to monitor the mechanical gain of the confined specimen regularly and without modifying its curing conditions, a resonant column apparatus (RCA) in torsion mode was used. With this device carrying out measurements of the shear modulus in very small deformations, the curing and testing phases could be coupled, the tests not being destructive. The curing stress brings the expected properties more quickly and confers superior properties of around 15% in the long term.

RÉSUMÉ: L'amélioration des sols en place par ajout de chaux, liant hydraulique et compactage est largement employée pour réaliser des ouvrages géotechniques. Des campagnes d'essais en laboratoire sont conduites afin de valider le traitement et sa cohérence avec les propriétés mécaniques attendues. Elles permettent de suivre l'évolution mécanique liée à l'hydratation des phases cimentaires et d'observer la réponse du sol sous diverses sollicitations. Les normes sur les sols traités préconisent de conduire les essais sur des éprouvettes ayant subi des conditions de cure dans un emballage hermétique, à température constante de 20°C et à pression atmosphérique. Cependant, si ces conditions normalisées représentent bien les conditions d'un remblai de faible hauteur, pour un ouvrage de grande hauteur, il est intéressant de prendre en compte la pression à laquelle le matériau est soumis. L'étude s'est portée sur la comparaison de l'évolution des propriétés mécaniques d'un limon traité à la chaux et au liant hydraulique puis compacté, soumis à une cure normalisée ou une cure confinée de 500 kPa. Afin de suivre le gain mécanique de l'éprouvette confinée de manière régulière et sans modifier ses conditions de cure, une colonne résonnante en mode torsion a été utilisée. Avec cet appareil réalisant des mesures du module de cisaillement en très petites déformations, les phases de cure et d'essais ont pu être couplées, les essais n'étant pas destructifs. La pression pendant la cure apporte plus rapidement les propriétés attendues et confère sur le long terme des propriétés supérieures d'environ 15%.

Keywords: Stabilized soil; lime and binder treatment; resonant column apparatus; curing stress conditions; shear modulus.

1 INTRODUCTION

The use of stabilized soils in geotechnical infrastructure works is widespread today because it

provides ecological and economic gain. This reduces CO² emissions linked to the transport of excavated and backfilled material, and minimises the use of non-renewable materials from quarries. In order to predict

the reaction of the soil to the treatment and the mechanical gain that could be provided over time, experimental campaigns in the laboratory are carried out. Overall, laboratory experimental conditions tend to represent *in situ* conditions as closely as possible (state of stress, saturation and draining condition, compaction etc.). In the case of improved soils, the mechanical properties of these materials vary according to the curing time, as they are a function of the hydration reactions of lime and binder's cementitious phases. This is because the hydrated phases form shells around the soil that has flocculated after the lime has been added (Cabane, 2004). To ensure these reactions, the standards recommend curing conditions in laboratory for treated specimens: stored hermetically at a temperature of 20°C and at atmospheric pressure (LCPC/SETRA, 2000). These test conditions generally make it possible to well simulate the *in situ* soil conditions in low-rise structures. However, previous authors have noted that notable differences in terms of mechanical properties were measured between specimens of materials cemented in the laboratory and specimens cored when the soil was taken at great depth (Consoli et al., 2000). This phenomenon is studied in the field of Cement Paste Backfill (CPB) (Zhao et al., 2021) or cemented sands (Basas et al., 2020) but currently little for treated fine soils (Åhnberg, 2006).

The objective of this article was to highlight the mechanical property differences for a stabilized silty soil with two curing conditions: one curing at atmospheric pressure and the other with isotropic curing stresses (500 kPa) applied throughout the curing time (up to 70 days). For this purpose, it was necessary to measure the evolution of the mechanical properties of the confined specimen without modifying its curing conditions. A resonant column apparatus (RCA) in torsion mode was therefore used in the study. It allowed the measurement of the shear modulus G as a function of the distortion in very small deformation (between $10e^{-7}$ and $10e^{-4}$) (Lang et al., 2020). Furthermore, this test being non-destructive, it was possible to carry out all measurements on the same sample kept confined throughout its treatment. The results of these tests were compared to tests carried out on specimens which had had a standardized cure and a specimen of untreated silty soil.

2 MATERIALS AND METHODS

2.1 Materials

The material used was a low plasticity silty soil that comes from northern France. In the 0.2 mm sieve, 80%

of the granulometry corresponds to silts. The X-ray diffraction (XRD) analysis indicated a composition of quartz, carbonate phases (calcite and dolomite), silicates (muscovite, microcline and clinocllore) feldspaths (albite), clay minerals (kaolinite) and hematite. To this soil with poor geotechnical properties was first added 1% lime. This lime is made up of approximately 90% quicklime (CaO). Then 5% of a hydraulic binder was added. This binder has a claimed composition of approximately 35% Portland cement clinker and 65% blast furnace slag (similar to a CEM III/A).

2.2 Specimen preparation

The freshly treated soil was then placed in a single layer in a mould for static compaction. The force was applied on both sides of the cylinder until 96% of optimal density and $w = OMC+1\%$ (Optimum Moisture Content). displayed by the proctor curve was reached (Figure 1). This curve indicates that the maximum dry density measured ($\rho_d = 1.75 \text{ Mg/m}^3$) corresponds to an $OMC = 17.5\%$. The saturation ratio (S_r [%]) lines on the figure correspond to 100%, 90% and 80% pore water saturation.

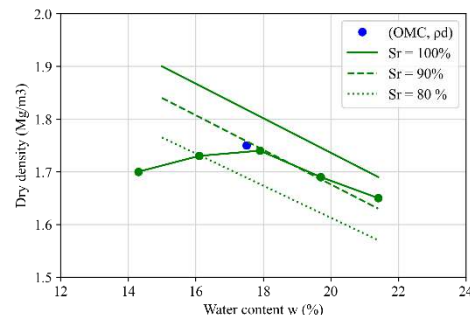


Figure 1. Proctors curve and saturation lines (S_r).

A compaction curve was plotted for each compacted specimen. The curves with e , the void index, as a function of σ , the axial stress [kPa] in Figure 2 illustrate the homogeneity of the specimens produced. The average void index of the 10 specimens was $e = 0.58$, the minimum 0.55 and maximum 0.59. The standard deviation of these measurements is 0.014. To be able to compare mechanical results tests, the initial void index of the specimens must be equal.

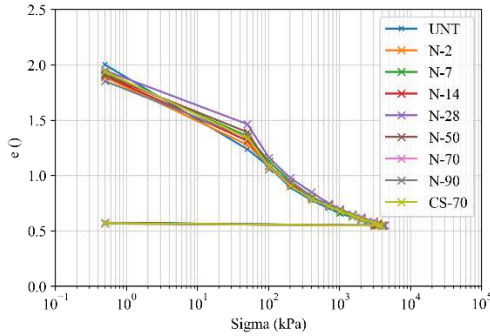


Figure 2. Compaction curves.

2.3 Curing and testing conditions

The characteristics of the 9 tested specimens are listed in. The untreated specimen (UNT) did not require any curing time and was tested immediately after being compacted with an isotropic confining pressure of 500 kPa. Normalized specimens (N-2, N-7, N-14, N-28, N-50, N-70 and N-90) were hermetically protected and placed in an air-conditioned room at 20°C without being subjected to curing stresses. Those were maintained in this condition for a define curing time and a different specimen was used for each curing time test. In contrast, to study the specimen subjected to curing stress, the soil specimen was not packed but directly placed in the RCA cell with an isotropic curing stress (CS) of 500 kPa for 70 days (CS-70). At the beginning of this curing time, one test per day was done, with one test per week conducted at its end. All the present tests were conducted on unsaturated specimens with drain open to the air, at testing pressure of 500 kPa.

Table 1. Curing and testing conditions.

Specimen	Curing time (days)	Curing stress (kPa)	Testing pressure (kPa)	Gmax modulus (MPa)
UNT	untreated		500	175
N-2	2	0	500	512
N-7	7	0	500	571
N-14	14	0	500	632
N-28	28	0	500	860
N-50	50	0	500	966
N-70	70	0	500	1069
N-90	90	0	500	1127
CS-70	70	500	500	1267

*UNT: untreated **N: normalized curing conditions ***CS: curing stress conditions

2.4 Resonant column apparatus tests

The evolution of the shear modulus as a function of distortion is obtained by torsion tests in the RCA. In this apparatus, the specimens are held fixed at the base and torsionally excited at the top. For each step of imposed amplitude, the resonance frequency

corresponding to the maximum measured amplitude is determined. The tests were performed starting at the lowest amplitudes (0.005 V) up to the highest (1 V) with about 25 measurement points. At each point, the resonance frequency f_n [Hz] of the material can be used to calculate an angular frequency ω_n [rad·s⁻¹] (1). The resonance frequency is the lowest frequency at which the torsion is 90° out of phase with the rotational displacement. From the angular frequency it is possible to calculate the shear wave velocity V_s , which is used to calculate the shear modulus G [MPa] (1).

$$\omega_n = 2\pi f_n \quad V_s = \frac{\omega_n L}{\beta} \quad G = \rho V_s^2 \quad (1)$$

Where L [m] is the length of the specimen and β depends on the apparatus specificities and the specimen geometry. ρ is the specimen density [g·cm³]. The maximum amplitude A_{max} [V] corresponding to the resonance frequency provides the distortion γ (2):

$$\gamma = \frac{4,596 \cdot A_{max} \cdot D}{f_n \cdot L} \quad (2)$$

The G modulus measured at the smaller amplitudes (0.005 V) and distortions is called G_{max} .

3 RESULTS

As detailed above, torsional RCA tests provide shear modulus decrease curves as a function of distortion. The test results are presented for each curing condition (standardised then confined) and compared with an untreated and compacted silty specimen. A total of 38 tests were carried out.

3.1 G modulus as function of distortion

The results of tests carried out on specimens under normalized curing conditions are shown in Figure 3 in which each curve corresponds to a specimen. The results of the tests on the curing stress specimen (CS-70) are shown in Figure 4. During 70 days of curing, each of the 30 tests was carried out at a curing time specified in the legend (e.g. CS-70-2 d; for a test at 2 days curing time). In these two figures, the blue curve (▼) corresponds to the untreated silty specimen which has a G_{max} of 175 MPa at a shear deformation of $5e^{-6}$. By comparison, the specimens of treated soil are located on much smaller deformations.

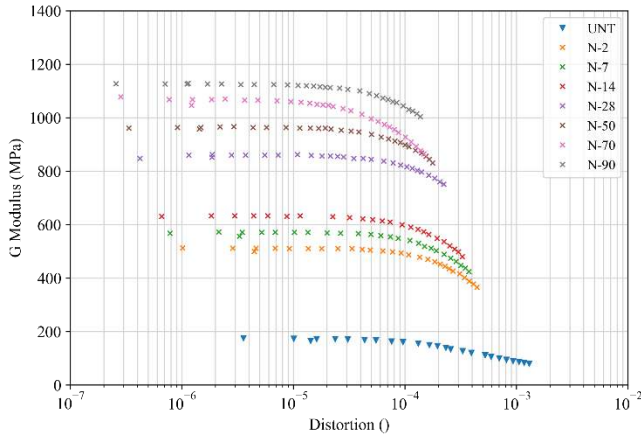


Figure 3. *G* modulus as function of distortion for normalized curing conditions.

The mechanical evolution within the specimen as a function of curing time is visible at several levels: the evolution of the shape of the curves, the increase in *G*_{max} as a function of time, and the shift of the curve towards smaller deformations. In these figures, it is remarkable that the greatest mechanical gain takes place in the first 2 days of curing time.

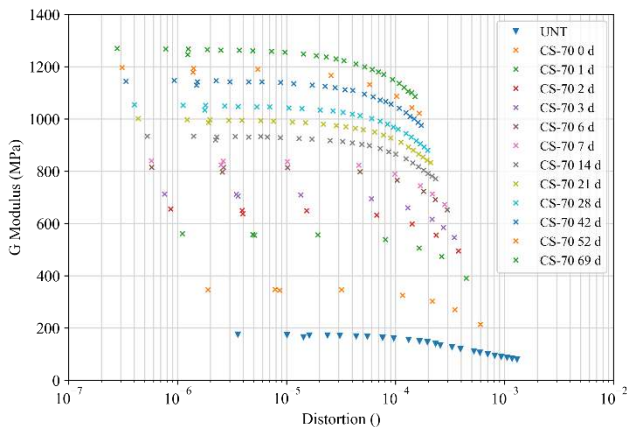


Figure 4. *G* modulus as function of distortion for curing stress conditions.

3.2 Kinetics comparison

The Figure 5 shows the *G*_{max} as a function of time for the 35 tests performed. It highlights two different hydration kinetics. The first one corresponds to the specimen cured with a curing stress (CS-70) and second one corresponds to specimens cured without stress and tested at different curing times with the RCA (N, green curve). Therefore, the specimen CS-70, after 42 days with a curing stress of 500 kPa (CS-70-42 d on Figure 4), reaches the *G*_{max} as the specimen N-90 curing without stress (CS-70-41 d, *G*_{max} = 1137 MPa; N-90, *G*_{max} = 1127 MPa).

A difference of approximately 200 MPa between the *G*_{max} of the two curing conditions is measured from 14 days and up to 90 days.

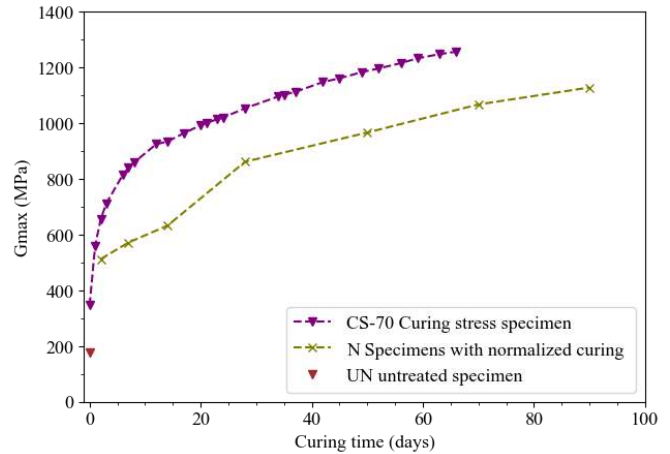


Figure 5. *G*_{max} as function of time.

4 CONCLUSIONS

This experimental campaign showed that there was indeed a difference between the evolution of the shear modulus measured for the confined and unconfined soil specimen during its curing time. It also highlighted the fact that the resonant column is a good tool for studying soils treated in the laboratory (allowing small deformation and non-destructive measurements). Further work is underway to investigate the microstructure and chemical composition inherent to these mechanical tests.

ACKNOWLEDGEMENTS

The PhD project is funded by EGIS STRUCTURES ET ENVIRONNEMENT and Centrale Nantes. We also wish to thank the Seine Nord Europe Canal Company.

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