Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-412

Degradation mechanisms of the hydro-mechanical behaviour of a lime-treated clay exposed to wetting and drying cycles

Mécanismes de dégradation relatifs à l'altération du comportement hydromécanique d'une argile traitée soumise à des cycles hydriques

N. Chabrat*
LEMTA (UMR 7563) CNRS, Université de Lorraine, Nancy, France

G. Russo, E. Vitale
DiSTAR, University of Naples Federico II, Naples, Italy

O. Cuisinier, F. Masrouri
**Nicolas.Chabrat@univ-lorraine.fr*

ABSTRACT: The present experimental study is focused on analysing the degradation processes of the mechanical performances of a lime-stabilised expansive clay exposed to wetting/drying cycles of various amplitude. Fully cured specimens were exposed to several wetting and drying cycles with suction-controlled techniques, and the maximum suction applied during the cycles ranged from 0.30 MPa to 95 MPa. This study highlighted that the main deterioration mechanism of lime-treated expansive soils exposed to cyclic wetting and drying is connected to micro-structural changes whose intensity were controlled by the amplitude of the cycles. The improved understanding of these mechanisms, as provided by this work, has the potential to more effectively forecast the conditions that could promote durability of lime-stabilised expansive soil.

RÉSUMÉ: L'objectif de cet article est d'évaluer les processus d'altérations relatifs à l'exposition d'une argile traitée à des cycles de séchage et d'humidification. Des éprouvettes traitées à la chaux ont été exposées à des cycles hydriques d'amplitudes allant de 0,30 MPa à 95 MPa. L'étude a permis de montrer que le mécanisme principal de dégradation du comportement mécanique des éprouvettes était la formation de fissure dont l'intensité était contrôlée par l'amplitude de succion appliquée. Ainsi, l'altération observée est principalement mécanique et résulte d'un endommagement des liaisons cimentaires, ce qui permet d'expliquer le rôle primordial de l'amplitude des cycles hydriques sur le comportement à long terme des sols argileux traités.

Keywords: Soil stabilization; durability; wetting and drying cycles; expansive soils; compressibility; microstructure.

1 INTRODUCTION

The alteration of mechanical performances over the service life of treated soils when exposed to seasonal wetting and drying cycles is one of the major concerns of the improvement technique. Indeed, several studies showed that wetting and drying cycles can alter the beneficial effects of treatments on soil performances (e.g., Khattab et al., 2007). Various methodologies have been employed to simulate the wetting and drying cycles during laboratory experiments. The major importance of the experimental protocol to impose the wetting and drying cycles has been highlighted by some authors. Stoltz et al. (2014) studied the impact of the amplitude of wetting and drying cycles on the mechanical behaviour of an expansive clay treated with lime, evidencing a progressive increase of swelling associated to strength reduction for increasing suction levels. They employed osmotic suction-controlled techniques to impose different wetting and drying amplitudes to the specimens. The results evidenced a progressive increase of the swelling properties associated to a loss of strength with higher suctions applied upon drying. Therefore, a key factor in the degradation of the mechanical performance of lime-stabilised soils exposed to wetting and drying cycles is the amplitude of the wetting and cycles. Nevertheless, only very few studies investigated the role of the amplitude of the cycles.

In addition, the degradation mechanisms associated to wetting and drying cycles are still poorly understood. Indeed, most of the available studies on the impact of wetting and drying cycles are based on results obtained at the macroscopic scale, without deciphering the different microstructural processes occurring during cycles. Thus, the mechanisms responsible for the degradation of lime-stabilised soils exposed to wetting and drying cycles still need to be identified. Tang et al. (2011) provided some evidences that the bonding induced by lime-treatment could be altered by successive wetting and drying, with a significant modification of the microstructure along the cycles. There is thus a limited knowledge on the mechanisms involved in the alteration processes triggered by the exposure to successive wetting and drying cycles, and the relative importance of each process.

In this context, a laboratory study has been performed to understand the link between wetting and drying amplitude, micro-scale changes in fabric and the modification of the mechanical behaviour of a lime-treated expansive soil exposed to wetting and drying cycles. Lime-stabilised specimens were exposed to successive wetting and drying cycles of different amplitudes. The hydromechanical behaviour of the expansive soil was then determined using oedometer tests. The microstructure was also evaluated to identify the alteration mechanisms involved. In this paper, the characteristics of the lime-stabilised expansive soil specimens employed in this study are first provided. The experimental techniques are then successively exposed. The effect of the number of cycles and their amplitudes on the mechanical behaviour of the lime-stabilised soil and on the microstructure are then discussed. This work provides new understandings of environmental-driven alteration of lime-stabilised expansive soils that is discussed in the last section.

2 MATERIAL AND METHODS

2.1 Tested soil

The soil employed in this study was a clayey soil classified as CH according to the Unified Soil Classification System, mainly composed of clay minerals such as illite, muscovite, and montmorillonite, along with the presence of quartz and feldspars. The geotechnical characteristics of this soil can be found in Table 1. The shrinkage potential of the untreated soil, initially prepared at optimum moisture content, equal to 14.1 %, while the addition of 1% quicklime reduced the shrinkage potential to 0.1% (Stoltz et al., 2012).

Treated specimens were retrieved from the internal part of an experimental embankment built in 2010 with this expansive soil treated with 4 % quicklime by vertical coring. The embankment was thoroughly studied by Chabrat et al. (2023), who showed that the internal part of the structure was not affected by significant alterations due to environmental-driven processes.

Table 1. Geotechnical properties of the studied soil.

Parameters	Values
Passing sieve 80 μm (%)	90
Clay size content (<2 μm) (%)	70
Specific gravity Gs (-)	2.675
Liquid limit (%)	71
Plastic limit (%)	29
Plasticity index (%)	42

2.2 Experimental techniques

To prepare the specimens from the cores, a dicing saw equipped with a diamond wire was employed. Water was used to avoid heating of the sample during the cutting process. The specimens were subsequently carefully trimmed to a diameter of 70±0.1 mm and a height of 12 ± 2 mm. Two specimens were exposed to the same combination of suction amplitude and number of cycles. One of the specimens was used to determine the compressibility of the material while the other was employed for the microstructural analysis. The different experimental techniques employed are successively introduced in this section.

2.2.1 Drying-wetting experimental procedures

One of the main goals of the study was to assess the impact of the range of suction applied during wetting and drying tests on the behaviour of the treated specimens. For this purpose, two different methods were chosen to apply different ranges of suctions. The first method employed osmotic suction-controlled oedometers. The cycles were applied between saturation (s = 0 MPa) and suction values ranging from 0.30 MPa to 8.00 MPa were applied to the specimens following the protocol developed by Stoltz et al. (2014). The second method employed climatic chamber to control the relative humidity of the soil. This method, also derived from the one developed by Stoltz et al. (2014), was chosen to simulate high-amplitude cycles, with $H_R = 50\%$ corresponding to s = 95 MPa and $H_R = 80\%$ corresponding to s = 30 MPa. During the cycles, the dimensions of the specimens were monitored to evaluate their swelling and shrinkage potential along the cycles.

2.2.2 Tests procedures

Following the drying and wetting cycles, some specimens were subjected to oedometer testing under saturated conditions. These tests involved saturating the specimens and loading them by increment. For microstructural analysis, cubes with approximate dimensions of 10±2 mm were cut from a sample after the cycles. The samples were dried using the freezing/drying method. The specimens were first immersed in liquid nitrogen at a temperature of -196°C. They were then placed in a vacuum chamber to undergo water sublimation. Observations with Scanning Electron Microscopy (SEM) were performed using the Hitachi SU5000 microscope. Prior to observations, a gold coating was applied to the sample on a fresh fracture surface. SEM images were taken at different magnifications of x1000 and x5000.

3 RESULTS

The axial deformation during the cycles was first analysed (Figure 1). After 2 wetting and drying cycles, the extent of variation in swelling and shrinkage behaviour appeared closely related to the maximum suction imposed during the cycles, ranging from less than 1% during drying at 0.30 MPa of suction up to 8 % when drying at a suction level of 95 MPa (Figure 1). The initial drying phase upon all the ranges of suction applied consistently led to irreversible shrinkage. Subsequently, during the wetting stage following the first drying, limited swelling occurred, resulting in irreversible shrinkage strains by the end of the first cycle.

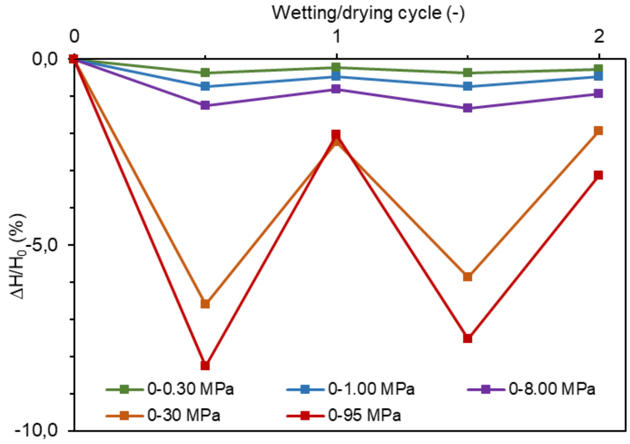

Figure 1. Volumetric variations obtained during 2 wetting and drying cycles.

Following the imposition of the suction cycles, the specimens were subjected to loading tests to determine their compressibility, and thus assess the impact of treatment (Figure 2). The compression curves obtained were compared to the one of the treated sample unexposed to wetting and drying periods (corresponding to N=0). The difference between the hydromechanical behaviour of the untreated and the treated soil suggests that the addition of lime effectively improved the mechanical performances of the soil. The compressibility of the specimens collected *in situ* was similar to the compressibility of specimens prepared in the laboratory. The impact of the cycles on the mechanical behaviour can be assessed by analysing the compressibility curves (Figure 2). After the first two cycles, it can be seen that the higher the suction applied during the drying phase, the larger the degradation of the mechanical behaviour. Up to an applied suction of 8.00 MPa, the compressibility is still significantly impacted by the lime treatment, as the yield stress of the soil was higher than 900 kPa. Beyond 8.00 MPa, the effect of lime stabilisation vanished, with values of yield stress lower than 100 kPa.

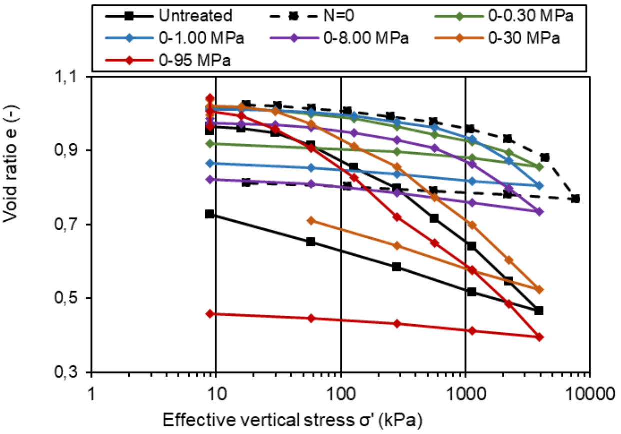

Figure 2. Compression curve of lime-treated specimens exposed to 2 wetting and drying cycles with different ranges of suctions.

Thus, for all amplitudes of wetting and drying periods, the first cycle induced plastic shrinkage deformation while only elastic deformation was generated during the subsequent cycles (Figure 1). The yield stress and the stress sensitivity were plotted as a function of the moisture content variation applied during the cycles (Figure 3). Extent of degradation was rather limited when the cycles were performed between 0.30 MPa and full saturation while the most significant mechanical degradation was observed when the applied suction during the cycles was larger than 8.00 MPa.

The microstructure was observed with SEM for the stabilized material unexposed to wetting and drying periods (Figure 4a), and then to specimens experimenting different ranges of suction applied (Figure 4b, c, d, e and f). The clayey particles observed on the unaltered specimen appear to be grouped together in aggregates bounded by macropores of about 1 µm wide, with a length higher than 10 µm. A coating on the surface of the particles was also observed that can be attributed to the precipitation of hydrated gel (i.e. C-S-H gel) as a result of the development of pozzolanic reactions (e.g., Vitale et al., 2020).

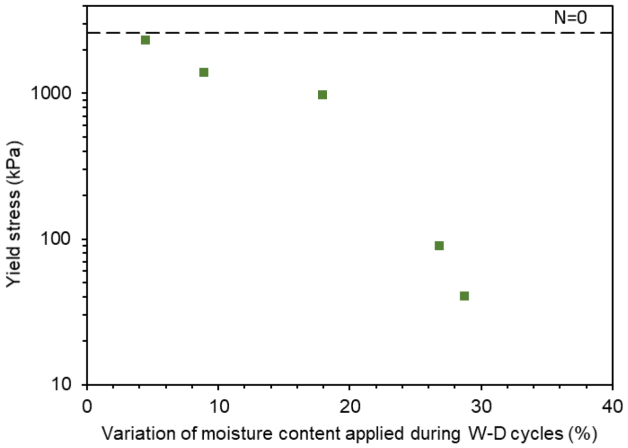

Figure 3. Effect of suction-controlled wetting and drying cycles on the yield stress of the quicklime-treated materials.

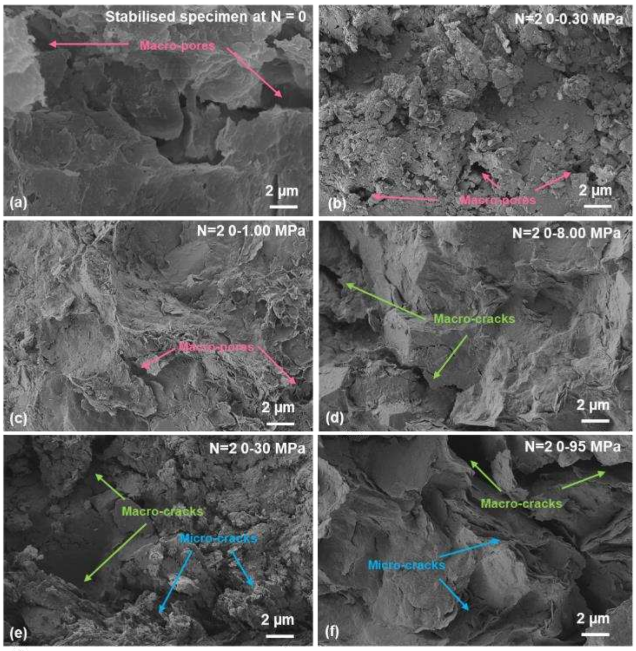

Figure 4. SEM pictures from specimens exposed to 2 wetting and drying cycles with different ranges of suctions.

Observations made on specimens exposed to a suction of 0.30 MPa (Figure 4b) showed low differences with the observations made on the unaltered treated soil (Figure 4a). The coating of the clayey particles is still visible and no significant evolution of the structure of the material could be observed. Specimens exposed to a suction of 1.00 MPa during the drying phase exhibited some longitudinal macro-cracks with a width of about 1 µm (Figure 4c). At the micro scale, the fabric of the specimens appeared to be massive and similar to the stabilised specimen unexposed to wetting and drying conditions. The newly formed macro-pores were even more present at an applied suction of 8.00 MPa, while the C-S-H gels were still visible on soil aggregates (Figure 4d). At 30 MPa and 95 MPa, macro-cracks could also be observed (Figure 4e and f). It was however possible to identify individual clay particles separated by pores smaller than 1 µm. Thus, a significant degradation of the microstructure was evidenced with the formation of macropores after the cycles when the maximum suction applied during the cycle was higher than 1 MPa. Beyond an applied suction of 8.00 MPa the cycles induced an additional alteration of the microstructure that led to the individualization of clay particles.

4 DISCUSSION

The purpose of this section is to explore the relationship between the modification of the microstructure, the amplitude of the wetting and drying cycles and the degradation of the compressibility. When the applied suction during wetting and drying periods was 0.30 MPa, the mechanical degradation of the material was very limited (Figure 2 and Figure 3), and the fabric of the soil seemed unaltered by the cycles. The height variation of the specimens occuring during wetting and drying cycles was also limited to 1% (Figure 1). When the maximum suction during the cycles was comprised between 1.00 and 8.00 MPa, newly formed macro-cracks were observed (Figure 4c and d). For suctions higher than 8.00 MPa, a complete change of the structure of the soil was evidenced, as both micro-cracks and macro-cracks were visible (Figure 4e and f). This rearrangement of the microstructure was associated to a complete degradation of the compressibility of the material.

The formation of cracks has been recognized as a key factor to explain the degradation of naturally cemented soft rocks containing clay exposed to wetting and drying cycles. Indeed, wetting-drying cycles can cause cyclic expansion and contraction of the clay minerals, and this repeatedly act on soil microstructure, resulting in fatigue damage, leading to a mechanical degradation of the material (e.g., Liu et al., 2020). The amount of cracks is likely related to the shrinkage experienced by the specimens during the cycles. Therefore, these observations demonstrate that a key damage mechanism could be associated to the formation of cracks during the cycles, indicating a degradation of the bonds between the soil particles associated to the pozzolanic reactions induced by the lime addition.

5 CONCLUSION

The main objective of this study was to analyse the impact of the wetting and drying cycles amplitude on the behaviour of lime-stabilised samples, and to understand the associated degradation mechanisms. Fully cured specimens were exposed to several wetting and drying cycles. The amplitude of the cycles was controlled using suction-controlled techniques, and the maximum suction applied during the cycles ranged from 0.30 MPa to 95 MPa. The height variation was monitored during the cycles, and the compressibility of the soil was determined through oedometer tests. Structural modifications at the micro-scale were evaluated through scanning electron microscopy.

The study demonstrated that the compression behaviour of the treated material could be significantly altered by wetting and drying periods. The alteration of the material was mainly explained by the formation of cracks upon drying. The number and intensity of the newly formed cracks in the stabilised material were promoted by the increase of the maximum suction applied. The improved understanding of these mechanisms, as provided by this work, has the potential to more effectively forecast the conditions that could promote durability of lime-stabilised expansive soil.

ACKNOWLEDGEMENTS

The study presented in this paper is a part of the first author’s PhD thesis that has been funded by Ginger CEBTP. The authors gratefully thank Dr. Michel Khatib from Ginger CEBTP for their valuable support and fruitful discussions. Dr. Abner Colella, Dr. Claudia Di Benedetto and Dr. Roberto De Gennaro are gratefully acknowledged for their valuable support in conducting microstructural investigations.

The project has received funding from the European Union’s Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 778120.

REFERENCES

Chabrat, N., Cuisinier, O., Masrouri, F. (2023). In Situ Alteration of the Hydro-Mechanical Behaviour of a Compacted Stabilised Expansive Soil. Geotechnics 3, 921–936. https://doi.org/10.3390/geotechnics3030049.

Khattab, S.A., Al-Mukhtar, M., Fleureau, J.-M. (2007). Long-Term Stability Characteristics of a Lime-Treated Plastic Soil. Journal of Materials in Civil Engineering 19, 358–366. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:4(358).

Liu, S.-Y., Cai, G.-H., Cao, J.-J., Wang, F. (2020). Influence of soil type on strength and microstructure of carbonated reactive magnesia-treated soil. European Journal of Environmental and Civil Engineering 24, 248–266. https://doi.org/10.1080/19648189.2017.1378925.

Stoltz, G., Cuisinier, O., Masrouri, F. (2014). Weathering of a lime-treated clayey soil by drying and wetting cycles. Engineering Geology 181, 281–289. https://doi.org/10.1016/j.enggeo.2014.08.013.

Stoltz, G., Cuisinier, O., Masrouri, F. (2012). Multi-scale analysis of the swelling and shrinkage of a lime-treated expansive clayey soil. Applied Clay Science 61, 44–51. https://doi.org/10.1016/j.clay.2012.04.001.

Tang, A. m., Vu, M. n., Cui, Y.-J. (2011). Effects of the maximum soil aggregates size and cyclic wetting–drying on the stiffness of a lime-treated clayey soil. Géotechnique 61, 421–429. https://doi.org/10.1680/geot.SIP11.005.

Vitale, E., Deneele, D., Russo, G. (2020). Microstructural Investigations on Plasticity of Lime-Treated Soils. Minerals 10, 386. https://doi.org/10.3390/min10050386.