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Volumetric strains due to changes in suction or stress of an expansive bentonite/silt mixture treated with lime

Déformations volumiques dues aux variations de succion ou de contrainte d'un mélange bentonite–limon traité à la chaux

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ABSTRACT

To further our knowledge of the coupling between the hydraulic cycles and mechanical behavior of treated swelling soils, this Note presents an experimental study on a bentonite/silt mixture treated with lime using a suction controlled osmotic oedometer. Successive wetting and drying cycles were applied at different suction ranges between 0 and 8 MPa, followed by a loading/unloading cycle at different suctions (2, 4 and 8 MPa). The compression curves of the aforementioned suctions provide the necessary information to analyze the influence of hydraulic cycles on the hydromechanical parameters of the treated swelling soils, such as the apparent preconsolidation stress $P_0(s)$, the virgin compression index $\lambda(s)$ and the unloading elastic index value κ. The suction ranges as well as the number of suction cycles influence the mechanical parameters of the treated swelling soil greatly.

RÉSUMÉ

Afin de mieux connaître le comportement couplé hydrique et mécanique des sols traités, cet article rapporte les études expérimentales effectuées à l'œdomètre avec imposition de succion par la méthode osmotique sur un mélange de bentonite/limon traité à la chaux. Plusieurs cycles de séchage/humidification compris entre 0 et 8 MPa ont été appliqués sur trois éprouvettes. A la fin des cycles de succion, les courbes de compressibilité pour le sol traité à différentes succions imposées (2, 4 et 8 MPa) permettent de déterminer les différents paramètres mécaniques de sol traité: la pression de préconsolidation $P_0(s)$, l'indice de compression vierge $\lambda(s)$ et l'indice de déchargement élastique κ. La gamme d'imposition de succion ainsi que le nombre de cycles hydriques influencent de manière importante le comportement mécanique des sols traités gonflants.

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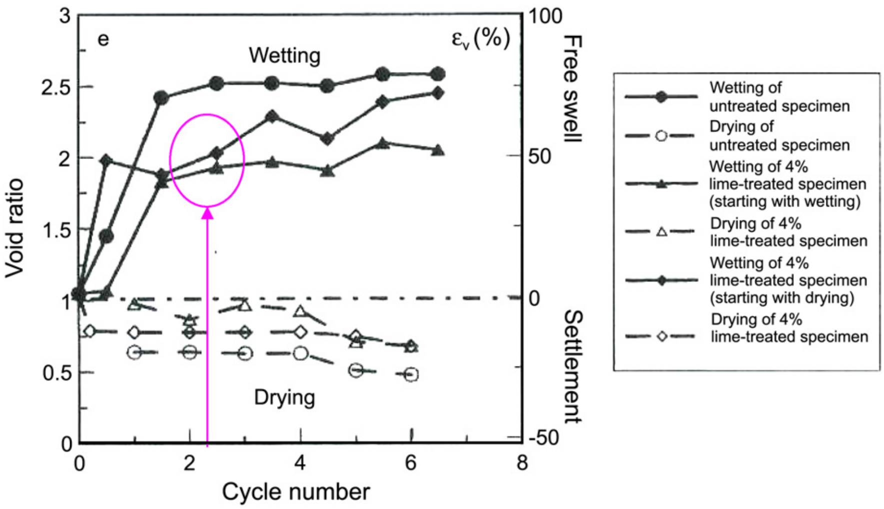

Fig. 1. Wetting and drying cycles for the lime-treated specimen (Khattab et al. [10]).

1. Introduction

Cyclic drying and wetting phenomena of expansive clayey soils cause progressive deformations, which may affect building foundations, drainage channels, buffers in radioactive waste disposals, etc. These fluctuations can also influence hydromechanical properties in a significant manner. Tests on expansive soils reported by Dif and Bluemel [1], Al-Homoud et al. [2], Alonso et al. [3] and Nowamooz and Masrouri [4] showed shrinkage accumulation of the expansive soils exposed to cyclic wetting and drying, which increases at higher vertical stresses. This behavior was explained by the continuous rearrangement of the soil particles, leading to a less active microstructure. In contrast, Chu and Mou [5], Pousada [6], Nowamooz [7] and Nowamooz et al. [8] observed the opposite effect, in which the amount of swelling strains increases with the number of successive cycles. All of these tests showed that the equilibrium elastic state could be reached at the end of several cycles.

The improvements of the physical properties of clay treated with lime are evident over short periods, but the durability of the performance obtained using these treatments has not been clearly established. It was shown that damage could result from the recommencement of swelling within a few months or years after the soil treatment, in certain cases. Guney et al. [9] showed that the beneficial effect of lime treatment (6%) is lost at the end of the first cycle of a drying–wetting procedure. They noted that a stabilization of the potential of swelling is reached at the end of the 4th cycle of drying–wetting. Khattab et al. [10] studied the influence of the hydraulic solicitations on a swelling soil treated with 4% lime during six successive wetting and drying cycles. Fig. 1 shows the variation of the void ratio with the cycle number. A recommencement of the swelling deformations at the beginning of the second cycle can be seen. Cuisinier and Deneele [11] also studied the behavior of the clays treated with 3% lime and of untreated clays reconstituted at the laboratory and compacted at the optimum (water content = 27%, dry density = 1.46 $\mathrm{Mg\,m^{-3}}$) using the osmotic method. They observed that the volume variations also depend on the range of imposed suction (tested once between 0 and 1 MPa and then between 0 and 8 MPa).

To study the mechanical properties of the lime-treated soils, it is necessary to take into account two points: (i) the effect of suction cycles on shrinkage and swell; and (ii) the effect of cycles on the durability of the lime treatment.

In this context, this Note presents an experimental study on a bentonite/silt mixture treated with lime using osmotic suction controlled oedometers. Successive wetting and drying cycles were applied at different suction ranges between 0 and 8 MPa, followed by a loading/unloading cycle at different suctions (2, 4 and 8 MPa). The compression curves of the aforementioned suctions provide the necessary information to analyze the influence of hydraulic cycles on the hydromechanical parameters of the treated swelling soil, such as the virgin compression index $\lambda(s)$, the apparent preconsolidation stress $P_0(s)$, and the elastic compression index value κ.

2. Osmotic controlled-suction technique

The study of the hydromechanical behavior of the bentonite/silt mixture used in this paper required experimental devices to impose a suction range between zero and several MPa. To achieve this goal, the osmotic method was selected. In this method, the soil sample and a solution of macromolecules are placed in contact, with a semi-permeable membrane between them (Zur [12]). This membrane prevents the PEG (*polyethylene glycol*) macromolecules from moving towards the sample, but it allows for water exchange. Water movements, and thus matrix suction variations, are controlled by the osmotic phenomenon. The higher the concentration of the solution, the higher the imposed suction. The relationship proposed by Delage et al. [13] is

$$s = 11c^2 \tag{1}$$

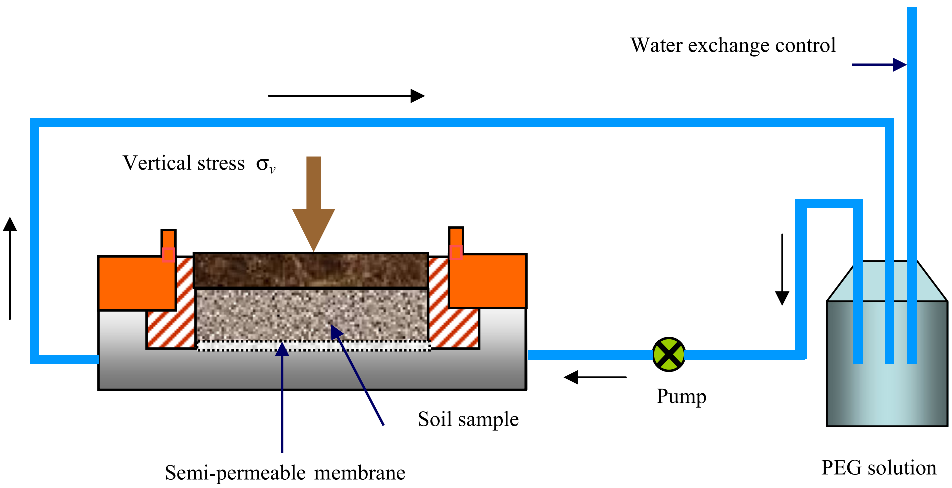

Fig. 2. Schematic of the suction-controlled oedometer device using osmotic solutions (Nowamooz and Masrouri [19]).

Table 1
Soil properties used in this study.

Soil	Liquid limit (%)	Plasticity index (%)	Specific gravity (G_s)
Silt	52	15	2.71
Bentonite	111	30	2.63
Mixture	87	22	2.67

Table 2
Mechanical parameters at different applied suctions.

Test	P_0 (kPa)	$\lambda(s)$	κ
Untreated sample M1	50	0.12	0.015
Treated sample with 1% lime M2	230	0.09	0.015

where c is the concentration expressed in grams of PEG per gram of water, and s is the imposed suction expressed in MPa, as justified by the data of various authors (Williams and Shaykewich [14], Cuisinier and Masrouri [15]). The molecular weight of PEG chosen for these tests was 6000 Da (1 Dalton, Da $= 1.6605 \times 10^{-24}$ g), which made it possible to impose a maximum suction of 8.5 MPa. A schematic representation of an osmotic oedometer proposed by Kassif and Ben Shalom [16] and modified by Delage et al. [17] is presented in Fig. 2.

3. Tested material

The study was performed on an artificially prepared mixture of 40% silt and 60% bentonite (percentage by weight). The mineralogical composition of the materials was determined by X-ray diffraction. The silt contained 60% quartz, 20% calcium montmorillonite and 11% feldspar, and the remaining component was composed of kaolinite and mica. The bentonite, also called bentonil FVO (commercialized by S.F.B.D. – *Société française de bentonites et dérivés*), was composed of more than 90% calcium montmorillonite, with a cation exchange capacity (CEC) of 85 meq/100 g. Liquid limit, plasticity index and specific gravity of the materials and the mixture are shown in Table 1. The particle size used to prepare the samples was less than 400 μm (obtained by sieving).

Since the lime treatment will dry the soil at the preparation phase, the mixture of bentonite–silt was prepared at a higher water content of 27%. During the experimental tests, it was verified that the initial water content of the treated mixture returned back to its desired water content of 26%. The treated mixture was then statically compacted at a water content of 26% under a vertical pressure of 1000 kPa, corresponding to an initial dry density of 1.52 ± 0.03 Mg m^{-3}.

The swelling potential ($\varepsilon_s = \Delta h/h_0$) for the samples treated with different quantities of lime between 0 and 5% were measured using the free swelling test (ASTM, 1995 [18]). The samples were all compacted at the same water content of 26% and the same initial dry density of 1.52 Mg m^{-3}. Fig. 3 shows that only 1% lime is enough to decrease the swelling potential significantly; this quantity of lime was selected for the entire experimental program. Otherwise, 1.5 to 6% lime is generally added in practical projects involving treated soils.

The compression tests after two days of the saturation phase of the free swelling tests (Fig. 4) were compared for an untreated sample (M1 test) and a sample treated with 1% lime (M2 test), to analyze the influence of the treatment on the hydromechanical behavior of the compacted bentonite/silt mixture. The compression curves made it possible to

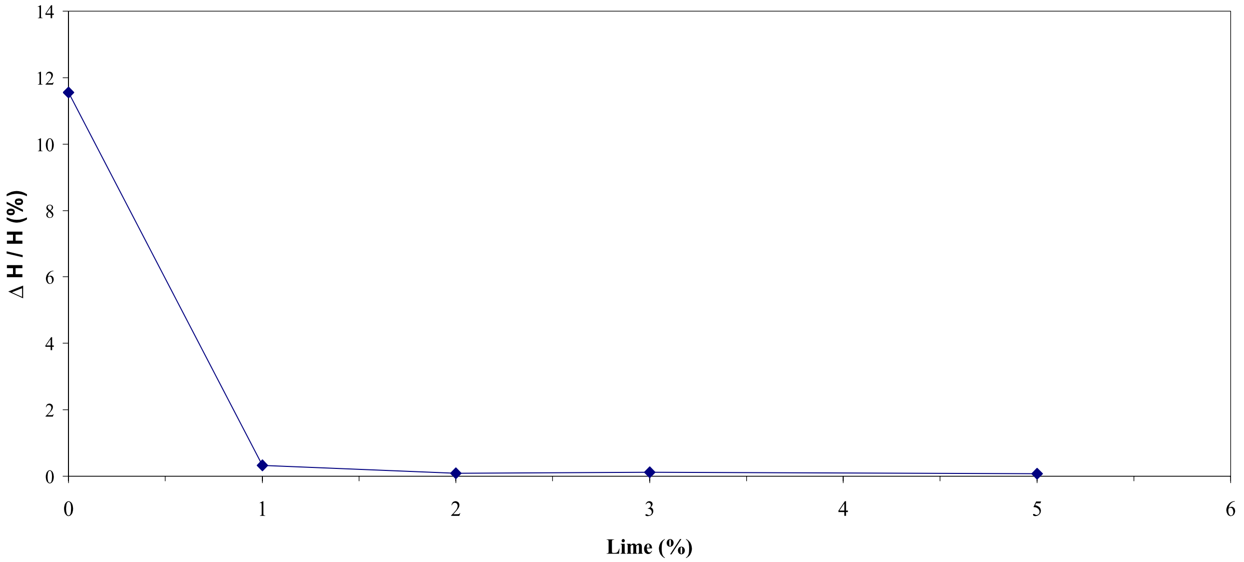

Fig. 3. Variation of the swelling potential with the lime quantity.

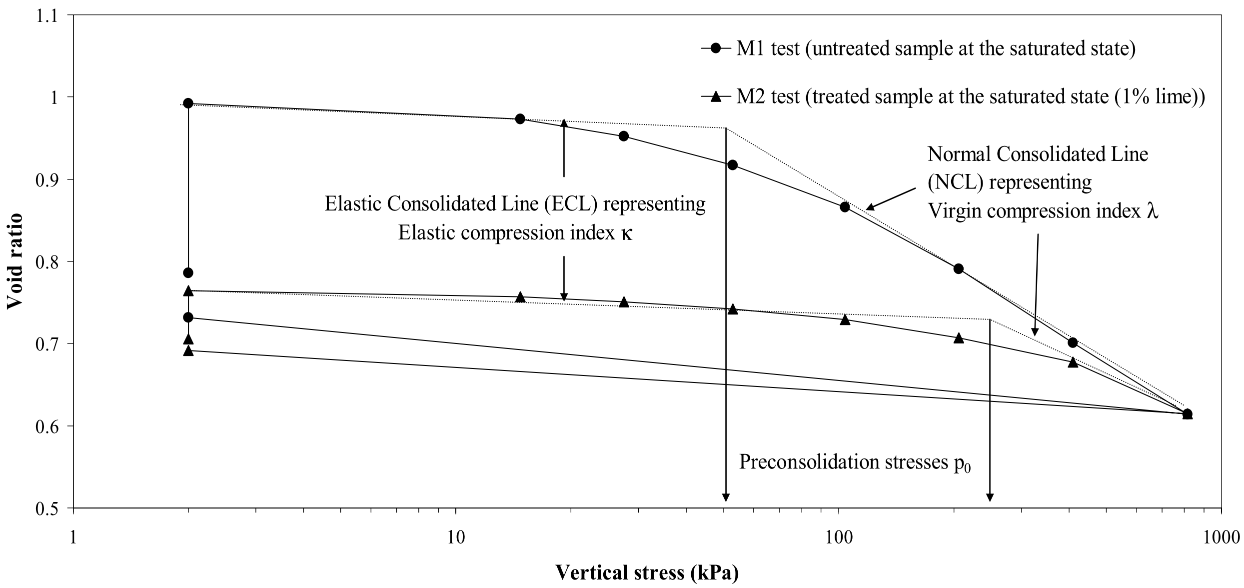

Fig. 4. Compression curves at 0 MPa suction for treated and untreated samples.

obtain the mechanical parameters at the saturated state: the preconsolidation stress (P_0), the virgin compression index λ, and the compression or loading elastic index (κ) (Table 2). The preconsolidation stress P_0, as presented in Fig. 4, is the intersection between the elastic consolidated line (ECL) and the normal consolidated line (NCL). We can observe that the treated sample presents a higher preconsolidation stress. The virgin compression index λ decreased from 0.12 ($=\frac{0.7-0.615}{\ln(817/410)}$) for the untreated sample to 0.09 ($=\frac{0.67-0.61}{\ln(817/410)}$) for the treated sample. However, for the treated sample, vertical stresses higher than 1000 kPa may be helpful to obtain a more precise λ value. The loading or compression elastic index κ was considered to be the same for both samples.

Fig. 5 shows the water retention curves of the 1% lime-treated and untreated samples compacted at the same water content of 26% and the same initial dry density of 1.52 $Mg\,m^{-3}$. To obtain these curves, two suction imposition techniques were used: the osmotic technique for the matrix suction less than 8.5 MPa and the vapor equilibrium (or salt solution) technique for the total suction higher than 8.5 MPa. The results obtained by the free swelling test for the saturated state were also added to the water retention curves. These curves show that the lime treatment changes the initial (matrix) suction of the sample at a water content of 26% slightly from 2.1 to 1.5 MPa.

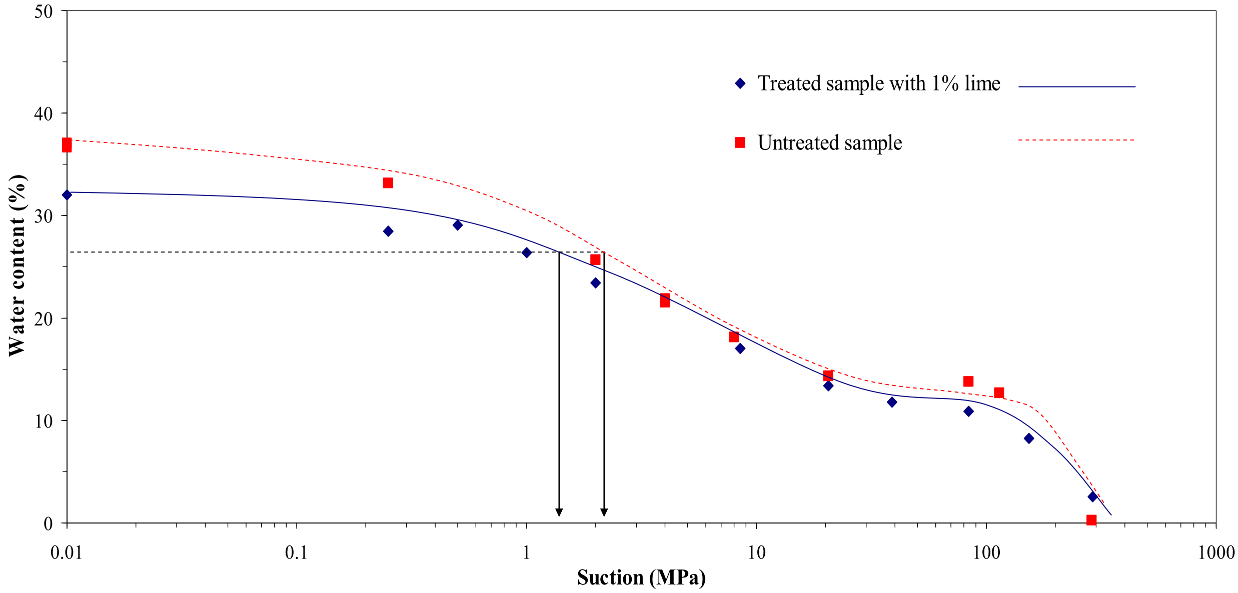

Fig. 5. Water retention curves for the treated and untreated samples.

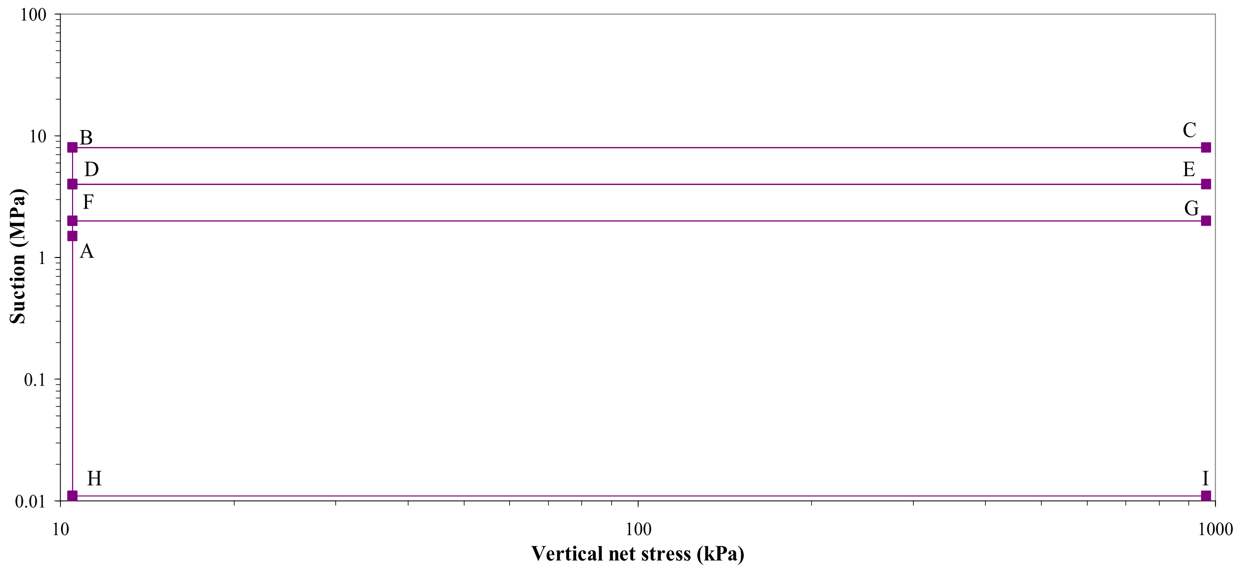

Fig. 6. Description of the $(\sigma_v - s)$ plane.

Fig. 5 also shows that the retention curves of the treated and untreated samples are completely separated from each other for a suction less than 8 MPa. However, for suctions higher than 8 MPa, both samples present the same hydric behavior.

4. Cyclic controlled-suction tests

This part concerns the wetting and drying cycles of the treated mixture. The compression curves were used to describe the influence of the range of applied suction on the mechanical behavior of the treated expansive soil.

It is essential to apply a minimum number of suction cycles to study the mechanical behavior of treated swelling soils. The applied suction cycles using the osmotic method took at least two or three months because of the technical limits of the experimental device. We could perform a maximum of two or three wetting and drying cycles over three months.

The stress paths of all tests with suction cycles (C1, C2, C3 and C4) and the free swelling tests (M1 and M2) are shown in Fig. 6 and in Table 3. In the logarithmic representation planes, zero suction is replaced by 0.01 MPa. The initial state is

Table 3
Description of the followed stress paths.

C1 (1 cycle)	A–F–H–F–G–F
C2 (2 cycles)	A–F–H–F–H–F–G–F
C3 (2 cycles)	A–D–H–D–H–D–E–D
C4 (2 cycles)	A–B–H–B–H–B–C–B
Free swelling tests (M1 and M2)	A–H–I–H

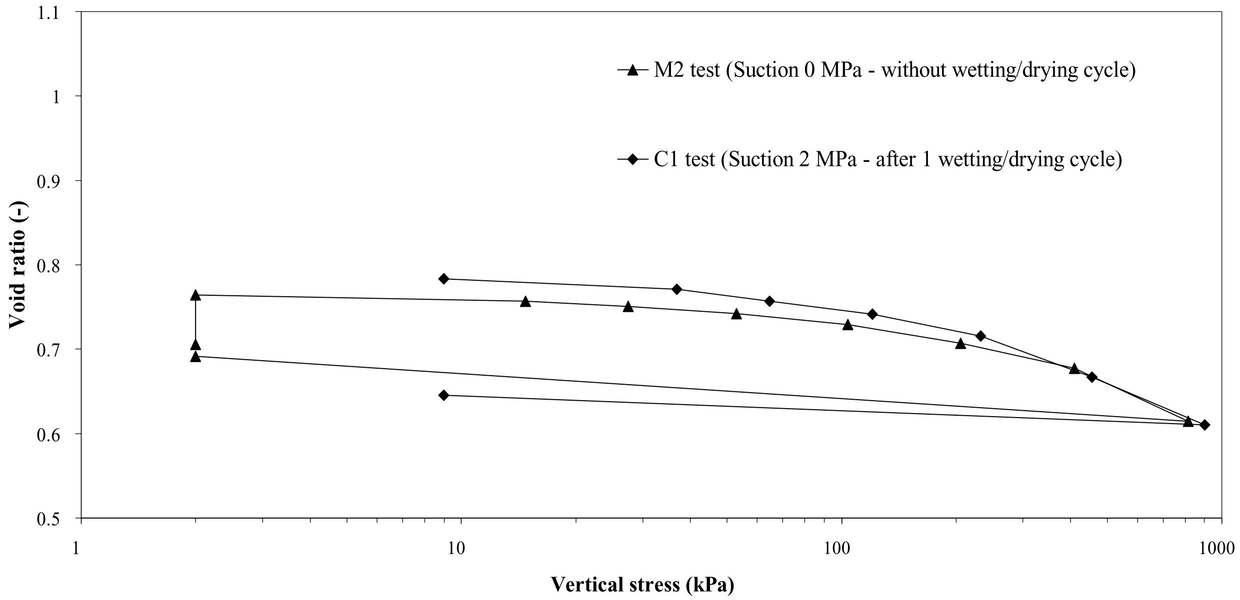

Fig. 7. Compression curve at suction of 2 MPa after 1 drying/wetting cycle (C1 test) compared with compression curve at saturated treated state (M2 test).

Table 4
Mechanical parameters for the performed tests (C1, C2, C3, C4 tests).

Test	Suction (MPa)	P_0 (kPa)	λ	κ
C1	2	200	0.085	0.015
C2	2	50	0.08	0.015
C3	4	70	0.06	0.015
C4	8	120	0.05	0.015

represented by point A, which corresponds to the sample treated with 1% lime once inserted in the oedometers. The initial height of the samples was 10 ± 0.5 mm, and their diameter was 70 mm.

4.1. Single wetting/drying cycle

For this series of tests (C1), the initial suction of the soil (1.5 MPa) was initially increased to 2 MPa and then decreased back to 0 (saturated state) under an initial vertical stress of 10 kPa (A–F–H). At the end of the suction cycle, a cycle of loading/unloading was applied at a suction of 2 MPa. The compression curves were compared with that of the untreated sample in the saturated state, obtained by the free swelling test (M2 test), in Fig. 7. The mechanical parameters (κ, $\lambda(s)$ and $P_0(s)$) of the C1 test are presented in Table 4.

It should be mentioned that the sample, at its initial suction of 1.5 MPa, was compacted under 1000 kPa of pressure. Therefore, the preconsolidation stress at a suction of 2 MPa can be assumed to be a little higher than 1000 kPa. Consequently, it can be concluded that the small void ratio increase due to the soil expansion during the single wetting and drying resulted in a significant softening in the compression curve although the compression curve at this suction presented the same shape of its saturated state without being submitted to suction cycles (Fig. 7). The preconsolidation stress decreased from a value of about 1000 to 200 kPa. The virgin compression index changed slightly for the different tests; however, it remained close to the value of its saturated state obtained with the M2 test. We believe that the unloading elastic index (0.015) does not depend on the stress path followed.

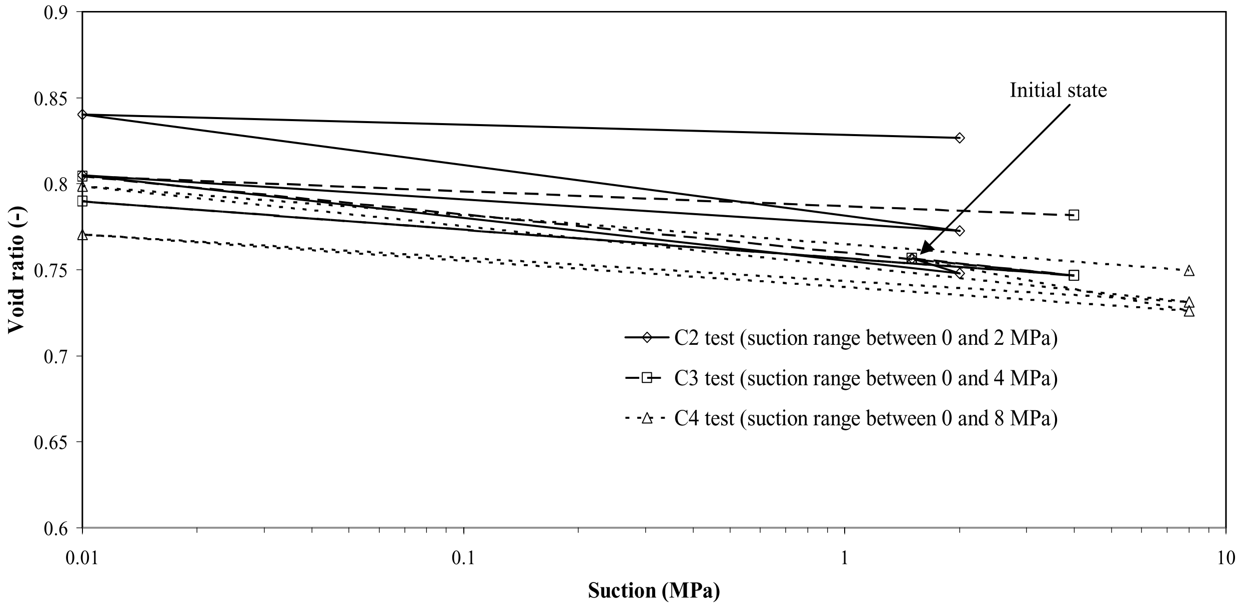

Fig. 8. Variation of the void ratio for the C2, C3 and C4 tests during two successive wetting and drying cycles.

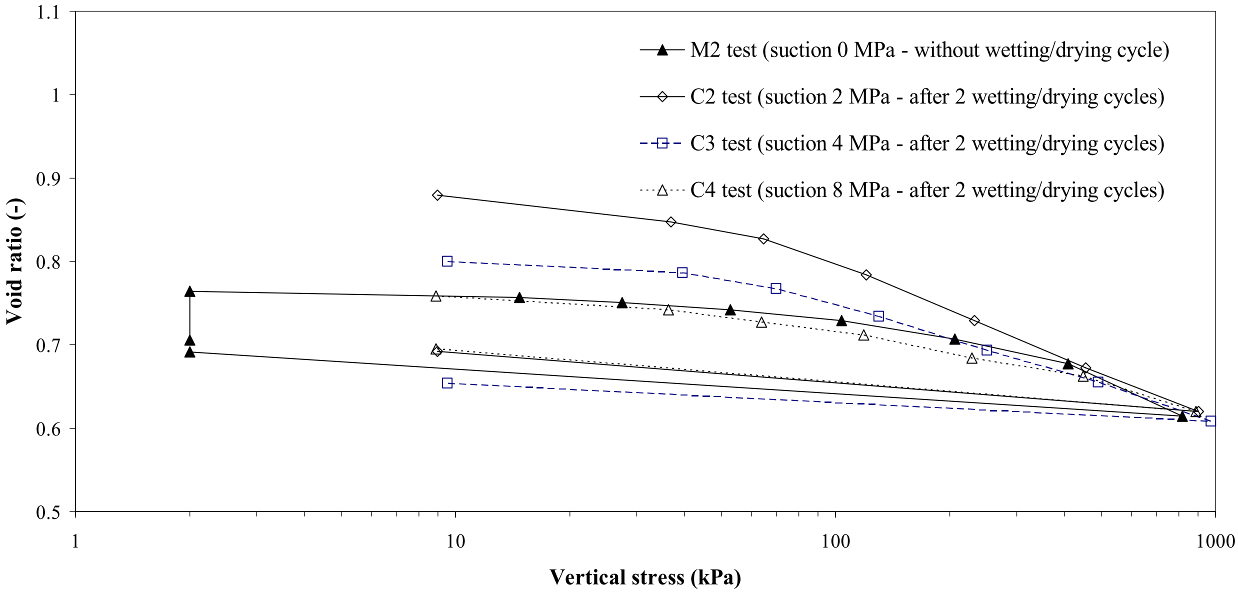

Fig. 9. Compression curves at different constant suctions after two wetting and drying cycles (C2, C3 and C4 tests) compared with the free swelling results (M2 test).

4.2. Two successive wetting/drying cycles

For the C2, C3 and C4 tests, the initial suction of 1.5 MPa was increased respectively to 2, 4 and 8 MPa and then returned to the saturated state under an initial vertical stress of 10 kPa. More wetting and drying cycles with the same suction range were then applied.

The variation of the void ratio for the cyclic tests is presented in Fig. 8. The first wetting/drying path produced a smaller expansion for all samples. However, the samples presented a higher swelling accumulation during the following cycle. This finding is completely in contrast to the usual behavior observed for the same untreated samples reported by Nowamooz [7] and Nowamooz and Masrouri [19] where the volumetric strains tended towards an equilibrium stage after three successive cycles in which the samples present a completely reversible behavior. In other words, the soil treatment lost its efficiency during subsequent cycles.

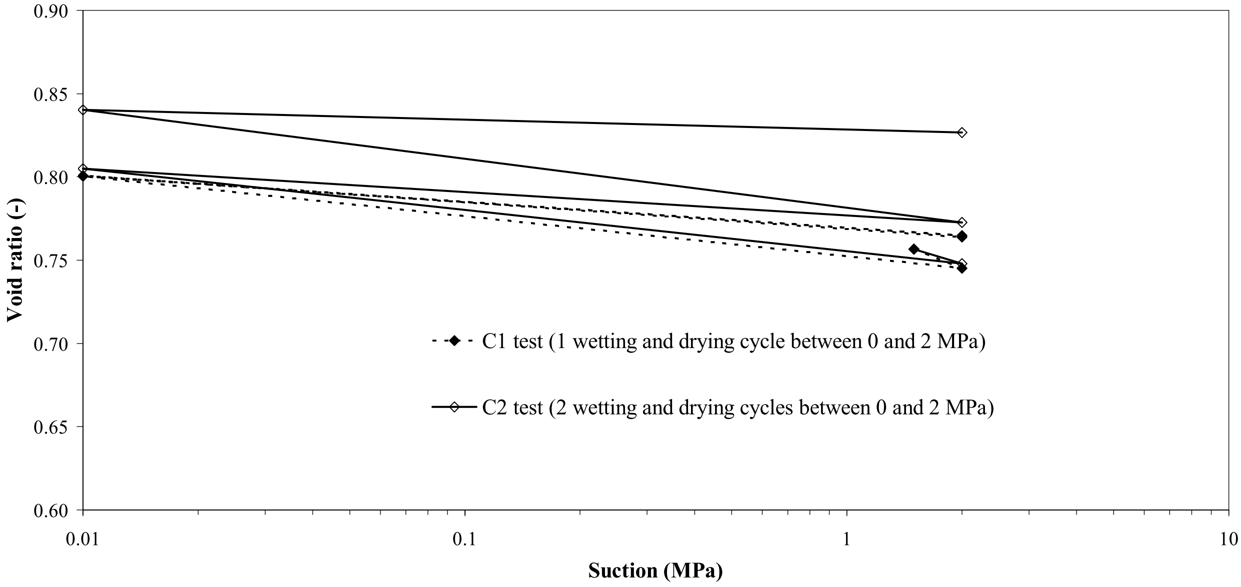

Fig. 10. Variation of the void ratio during the wetting and drying cycles for the C1 and C2 tests.

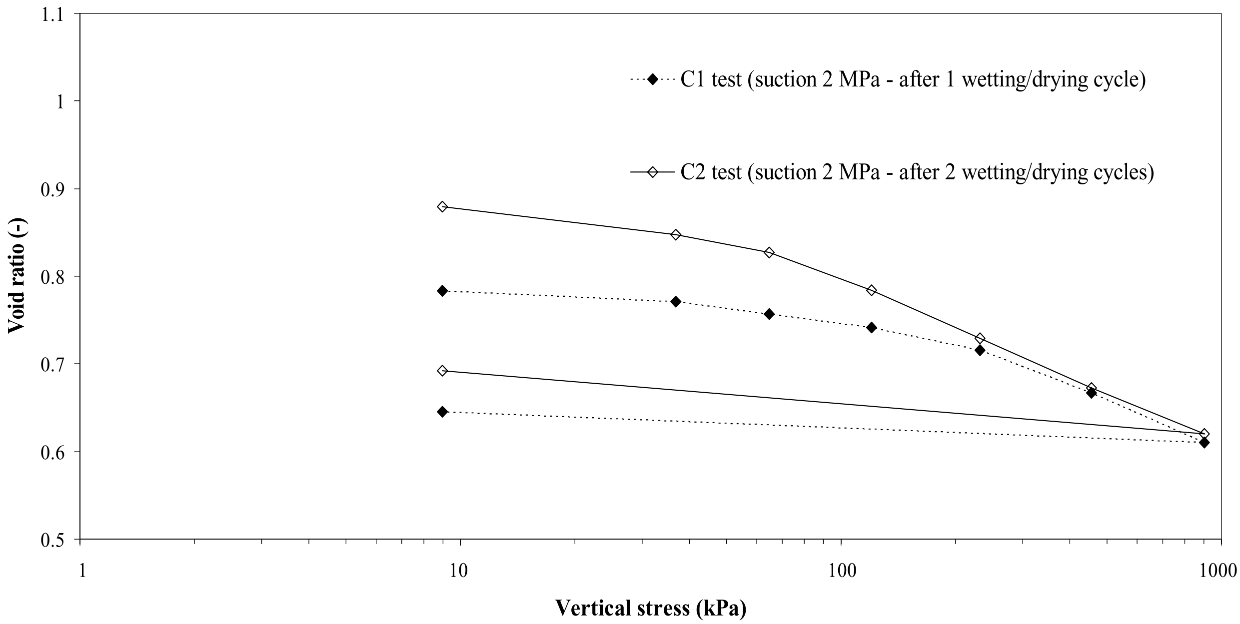

Fig. 11. Compression curves during the wetting and drying cycles at a suction of 2 MPa (C1 and C2 tests).

A loading/unloading cycle was then applied at three constant suctions at the end of the successive suction cycles. These applied suctions were 2 MPa for the C2 test, 4 MPa for the C3 test and 8 MPa for the C4 test. All of these compression curves as well as those obtained at the saturated state by the free swelling tests without application of suction cycles (M2 test) are plotted in Fig. 9.

The successive suction cycles increased the compression strains of the loading/unloading curves due to the swelling accumulation during the wetting/drying cycles.

The plastic swelling produced during a single wetting and drying cycle of the C1 test was less considerable compared to the amount of swelling accumulation during the two suction cycles of the C2 test (Fig. 10). The compression curves at the suction of 2 MPa after one wetting/drying cycle and after two wetting/drying cycles are also compared in Fig. 11.

Table 4 presents the mechanical parameters of the C2, C3 and C4 tests. The following comments can be made concerning the significant influence of the wetting and drying cycles on the mechanical behavior of swelling soils:

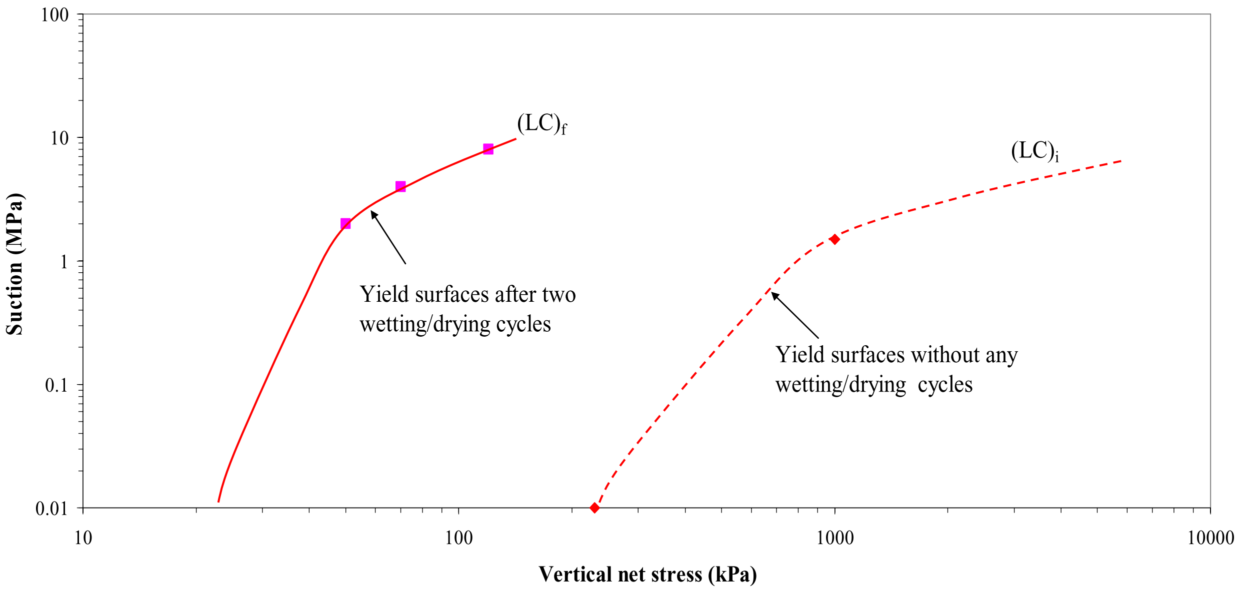

Fig. 12. Initial and final yield surfaces for all performed tests with and without suction cycles.

- P_0 decreased significantly after the hydric cycles for the imposed suctions, indicating that suction cycles tend to soften the soil. Because the equilibrium stage is not completely reached at the end of suction cycles for all tests, it was expected that the additional suction cycles could also decrease its value;
- λ was considered as the slope of the normally consolidated part of the compression curve and decreased as the suction increased. The successive wetting and drying cycles modified the λ value slightly with a suction of 2 MPa;
- κ, which was supposed to be constant with suction, was assumed to be equal to 0.015 at the end of successive wetting and drying cycles for all suctions imposed.

5. Discussion

The variation of the preconsolidation stress with suction is given by the loading collapse (LC) yield surface (Alonso et al. [20], Gens and Alonso [21]). The dataset derived from the compression tests at the saturated state obtained by the free swelling (M2 test) as well as the applied compaction pressure of 1000 kPa at an initial suction of 1.5 MPa were used to define the initial LC yield surfaces in Fig. 12 in the $(\log s - \log \sigma_v)$ plane for the treated mixture.

The entire study demonstrates the strong dependence of the mechanical properties of the treated expansive soils on the range of applied suctions. Fig. 12 also shows the final yield surfaces in the $(\log s - \log \sigma_v)$ plane at the end of the suction cycles based on the C2, C3 and C4 tests. The applied suction cycles produced significant swelling accumulation (at the end of the suction cycles), softening the soil and significantly decreasing the preconsolidation stress.

We believe that the number of suction cycles plays an important role on the hydromechanical behavior of treated swelling soils. The soil treatment seems to be more efficient during the first drying/wetting cycle (C1 test). During the additional wetting and drying cycles, we can observe that the swelling accumulation increases (C2 test). A higher swelling accumulation indicates that the treated soil is losing its efficiency during the following wetting and drying cycles. This observation is completely in contrast to the untreated samples; the accumulation of the volumetric strains of the untreated soils decreased during successive suction cycles.

However, only a limited number of suction cycles were performed in this study, it can be assumed that with additional suction cycles, the treated samples may finally present the same behavior as the untreated samples. The results shown in Fig. 13 confirm this hypothesis, because the compression curve of the treated sample after two suction cycles at a suction of 2 MPa (C2 test) approaches that of the untreated sample in the saturated state (M1 test); however, the comparison is not made at the same suction values. In other words, the hydromechanical behavior of the treated soils may be considered the same as the behavior of the untreated ones after several suction cycles. Therefore, we expect that, similar to the behavior of untreated soils, an equilibrium state may appear during additional cycles. In this stage, the BExM model proposed for the swelling soils (Alonso et al. [22]) can be employed to explain the soil behavior. This point requires at least two or three supplementary wetting and drying cycles to be verified.

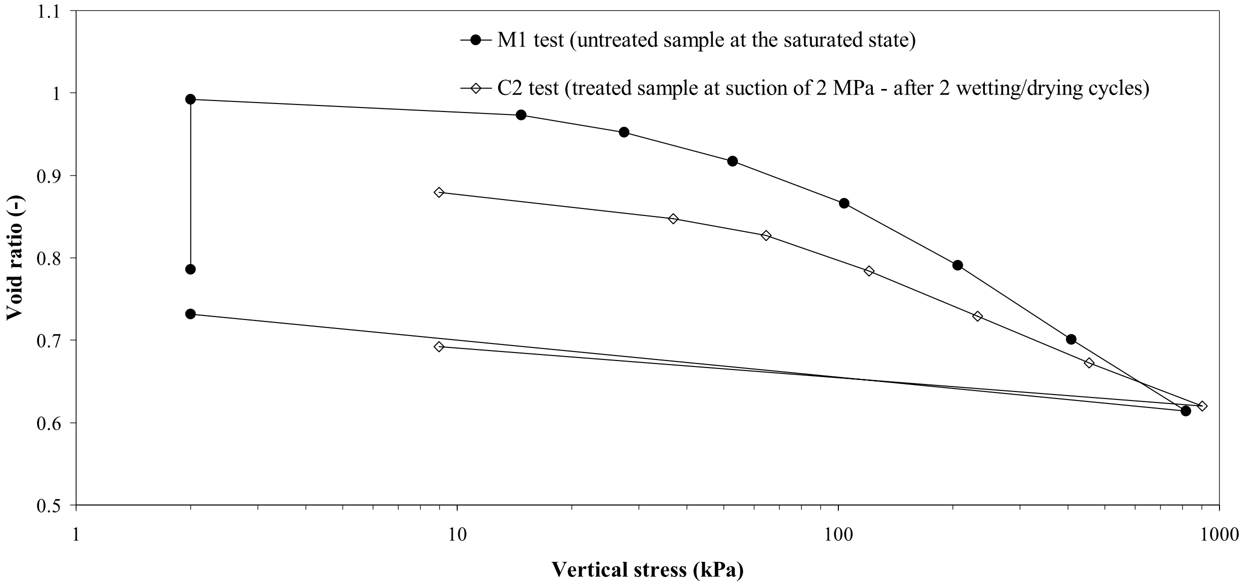

Fig. 13. Compression curves of the untreated sample in the saturated state (M1 test) and the treated sample at a suction of 2 MPa after several wetting cycles (C2 test).

6. Conclusion

The influence of suction cycles on the behavior of a compacted treated bentonite/silt mixture was studied. The samples treated with 1% lime were prepared by static compaction under a vertical stress of 1000 kPa with an initial dry density of 1.52 $Mg\,m^{-3}$ and an initial water content of 26%. The suction cycles were imposed at different suction ranges varying between 0 and 8 MPa by the osmotic method. A less important volume variation was observed for a single suction cycle between 0 and 2 MPa that was applied to the microstructure (C1 test). The samples presented a small swelling accumulation during the wetting and drying cycles (C1 test), indicating significant softening of the mechanical soil behavior. The swelling accumulation was highly significant during the following suction cycles (C2, C3 and C4 tests).

The study shows the extreme sensitivity of the hydromechanical properties of the treated expansive soils to any suction variations between 0 and 8 MPa. A mechanical loading/unloading cycle was applied at the end of the suction cycles. These results were compared with those obtained for the same samples that were not subjected to the wetting and drying cycles. The apparent preconsolidation stress $P_0(s)$ and the virgin compression index $\lambda(s)$ depend directly on the suction cycles followed. The elastic compression index κ was considered constant in this study. The hydraulic cycles changed the mechanical behavior of the soil due to the swelling accumulation during the wetting and drying cycles.

The hydromechanical behavior of the treated samples presents some differences from that of the untreated one during the wetting and drying cycles. The accumulation of volumetric strains of the treated soils during the second wetting and drying cycle was greater than that during the first one. The volumetric strains did not converge to an equilibrium elastic stage at the end of the second shrinking and swelling cycle.

However, during additional wetting and drying cycles, the treated samples may finally present the same behavior as the untreated samples. This point will be investigated in our future experimental studies.

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