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Shrinkage/swelling of compacted clayey loose and dense soils

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Abstract

This Note presents an experimental study performed on expansive compacted loose and dense samples using osmotic oedometers. Several successive wetting and drying cycles were applied in a suction range between 0 and 8 MPa under different values of constant net vertical stress (15, 30, and 60 kPa). During the suction cycles, the dense samples showed cumulative swelling strains, while the loose samples showed volumetric shrinkage accumulation. At the end of the suction cycles, the volumetric strains converged to an equilibrium stage that indicated elastic behavior of the swelling soil for any further hydraulic variations. At this stage, the compression curves for the studied soil at the different imposed suctions (0, 2, and 8 MPa) converged towards the saturated state curve for the high applied vertical stresses. We defined this pressure as the *saturation stress* (P_{sat}). The compression curves provided sufficient data to examine the soil mechanical behavior at the equilibrium stage. ***To cite this article: H. Nowamooz, F. Masrouri, C. R. Mecanique 337 (2009).***

Résumé

Retrait/gonflement des sols gonflants compactés et des sols denses. Cette Note rapporte les études expérimentales effectuées dans des œdomètres avec imposition de succion par la méthode osmotique sur des sols gonflants compactés denses et lâches. Plusieurs cycles de séchage/humidification compris entre 0 et 8 MPa ont été appliqués sur trois éprouvettes sous trois contraintes mécaniques constantes (15, 30 et 60 kPa). Les éprouvettes lâches/denses manifestent un retrait/gonflement cumulé lors des cycles de séchage/humidification. A la fin des cycles de succion, les déformations volumiques convergent vers un état d'équilibre qui correspond à un état élastique du sol gonflant pour toutes sollicitations hydriques supplémentaires. A cet état élastique, les courbes de compressibilité pour les deux sols étudiés à différentes succions imposées (0, 2 et 8 MPa) convergent vers l'état saturé à partir d'une contrainte élevée. Nous définissons cette pression comme la « contrainte de saturation (P_{sat}) ». Les courbes de compression obtenues produisent une base de données suffisante pour examiner le comportement mécanique des sols à l'état d'équilibre élastique. ***Pour citer cet article : H. Nowamooz, F. Masrouri, C. R. Mecanique 337 (2009).***

Keywords: Continuum mechanics; Expansive soil; Experimentation; Modeling; Suction cycles

Mots-clés : Milieux continus ; Sol gonflant ; Expérimentation ; Modélisation ; Cycles de succion

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1. Introduction

Cyclic drying and wetting of expansive clayey soils causes progressive settlements that can affect the foundations of buildings, drainage channels, and clay buffers in radioactive waste disposal sites. After their installation, these materials are subjected to natural environmental hydraulic fluctuations that can influence their hydromechanical properties. To study the hydromechanical properties of swelling soils, it is necessary to determine the behavior of these soils according to the applied suctions.

Cyclic shrinking and swelling tests on compacted expansive soils have been reported by several authors [1–5]. Their results have shown that the equilibrium elastic state can be reached at the end of several cycles, which indicates elastic behavior of the swelling soil for any additional hydraulic variations. Some experimental results [1,2,4] have reported plastic shrinkage accumulation of expansive soils exposed to cyclic wetting and drying that increases at higher vertical stresses. This behavior was explained by the continuous rearrangement of the soil particles, which leads to a less active microstructure. On the other hand, an opposite effect was observed in which the swelling strains increase with the number of successive cycles [3,5].

Different authors have highlighted the appearance of reversible deformations at the end of the shrink–swell cycles, but the coupling between these hydraulic cycles and the mechanical behavior has rarely been studied. The influence of a suction cycle on the mechanical behavior of a compacted bentonite–kaolin mixture at a constant suction of 200 kPa [6] showed a yield stress reduction as the result of a wetting–drying cycle. However, the compression curve gradually converged towards the reference curve that corresponds to the sample at the same suction that had not been subjected to a wetting–drying cycle. This phenomenon occurs during the cyclic wetting–drying because of hydraulic hysteresis.

This article presents an experimental study performed on an expansive compacted clayey soil using osmotic oedometers. Four successive wetting and drying cycles were applied in a suction range between 0 and 8 MPa with different constant vertical net stress values (15, 30, and 60 kPa). At the end of the suction cycles, a loading/unloading cycle at different imposed suctions (0, 2, and 8 MPa) was applied. The experimental results allow us to examine the mechanical soil behavior at the end of the wetting and drying cycles.

2. Studied material

The studied soil comes from a depth between 5.20 and 5.70 m of a core sample collected near Le Deffend, which is located approximately 4 km southeast of Poitiers (France). X-ray diffractometry tests showed the presence of smectite as the dominant mineral. This clayey soil had a liquid limit of 65%, a plastic index of 25%, a specific gravity (Gs) of 2.62, and a clay content of 52%. The samples were remolded with an initial water content of 10% at different initial dry densities: 1.28 Mg/m^3 for the loose samples and 1.75 Mg/m^3 for the dense samples. The compaction pressures were 80 kPa for the loose samples and 1500 kPa for the dense samples. To complete the compression test results at the saturated state, an additional sample was compacted with the same water content at an initial dry density of 1.20 Mg/m^3 under a compaction pressure of 50 kPa. The initial height of the samples was 10 ± 0.5 mm, and their diameter was 70 mm in the odometers. The total suction measured by filter paper [7] gave the same value of 20 MPa for both samples because the suction value is not influenced by the initial soil state on the dry side of the optimum point [8].

3. Mechanical behavior at the saturated state

The swelling parameters, swelling potential ($\varepsilon_s = \Delta h/h_0$) and swelling pressure (P_s) for the compacted samples were measured using the free swelling test (ASTM) [9]. The samples with higher initial dry density presented higher swelling potential as well as higher swelling pressure (Table 1).

The free swelling method also made it possible to obtain the compression curves at the saturated state (Fig. 1) and the mechanical parameters: the preconsolidation stress (p_0), the virgin compression index (λ), and the unloading elastic index (κ) (Table 1). The preconsolidation stress $p_0(s)$ is the intersection between the Elastic Consolidated Line (ECL) and the Normal Consolidated Line (NCL).

Generally, there are two methods to saturate the soil samples: the imposition of 0 MPa suction or the application of high vertical stresses. As these swelling soil samples did not reach their saturation state even after applying a suction

Table 1
Mechanical parameters of the loose and dense samples in the saturated state.

Parameters	Values		
Initial dry density (Mg/m^3)	1.20	1.28	1.75
Swelling potential ε_g (%)	12	13	28
Swelling pressure σ_g (kPa)	60	110	2200
Preconsolidation stress (kPa)	25	40	800
Unloading elastic index (κ)	0.045	0.045	0.045
Virgin compression index (λ)	0.18	0.18	0.11
Saturation stress (kPa)	200	200	800

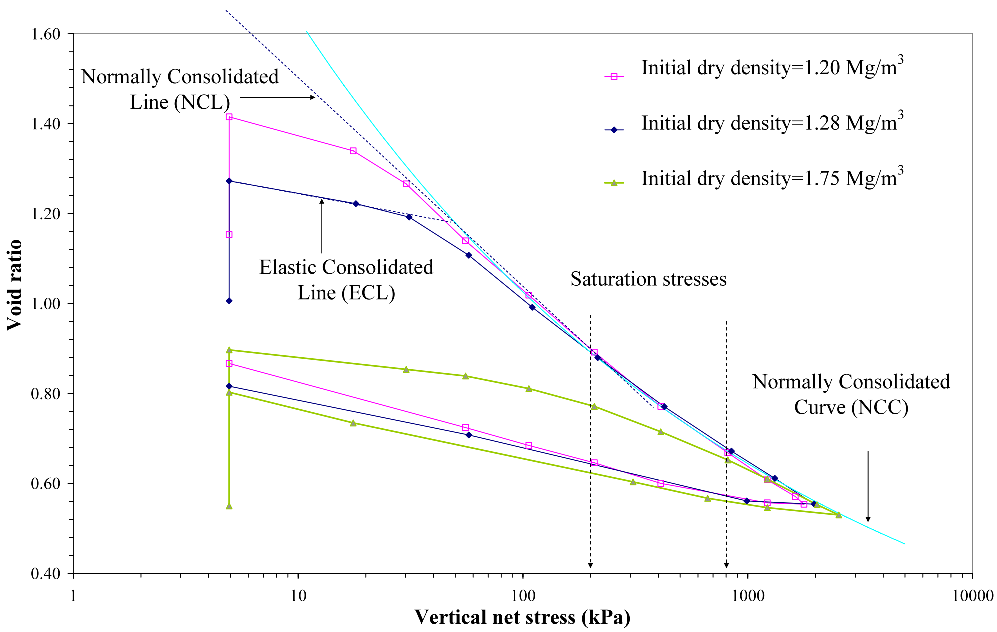

Fig. 1. Compressibility curves at the saturated state (initial water content = 10%).

of 0 MPa for 4 days, we used applied stress to reach the true saturated state the "saturation stress (P_{sat})". This stress was estimated to equal 200 kPa for both loose samples with initial dry densities of 1.20 and 1.28 Mg/m^3, where both compression curves present the same shape for the higher applied stresses. These loose samples showed a Normally Consolidated Line (NCL) for the applied stresses less than 200 kPa, which was used to estimate the preconsolidation stress for these samples (intersection between ECL and NCL). The preconsolidation stresses (20 and 40 kPa) are much lower than the saturation stress of 200 kPa.

Accordingly, the compression curve lost its initial linear shape for stresses higher than 200 kPa. For the whole range of applied stresses, a Normally Consolidated Curve (NCC) was then defined to control the plastic strain variations in the saturated state.

The dense sample with an initial dry density of 1.75 Mg/m^3 converged to the NCC at a stress equal to its preconsolidation stress. As the dense samples, even in their unsaturated state, converged to the NCC and presented the same mechanical behavior as their saturated state [10], the preconsolidation stress and the saturation stress could be considered to be the same for this dense soil. The virgin compression index λ decreased drastically for this dense sample, while the unloading elastic index κ maintained the same value as that of the loose samples.

It can be concluded that, at the same initial water content of 10%, there is an intermediate initial dry density of 1.50 Mg/m^3 (or initial void ratio of 1.00) where the preconsolidation and saturation stresses of 200 kPa could be superimposed. For initial dry densities higher than 1.50 Mg/m^3, both preconsolidation and saturation stresses increase together. For the looser samples, the preconsolidation stress is always less than the saturation stress of 200 kPa.

Table 2
Description of the followed stress paths.

L1	A–B–C_1–M_1–F_1–M_2–C_2–M_3–F_2–M_4–C_3–F_3–C_4–F_4–L–P
L2	A–B–D_1-I_1–G_1–I_2–D_2–I_3–G_2–I_4–D_3–G_3–D_4–I_5–K–N
L3	A–B–E_1–O_1–H_1–O_2–E_2–O_3–H_2–O_4–E_3–H_3–E_4–J–B
D1	A–B–C_1–M'_1–F_1–M'_2–C_2–F_2–C_3–F_3–C_4–F_4–L–P
D2	A–B–D_1–I'_1–G_1–I'_2–D_2–G_2–D_3–G_3–D_4–I–K–N
D3	A–B–E_1–O'_1–H_1–O'_2–E_2–H_2–E_3–H_3–E_4–J–B

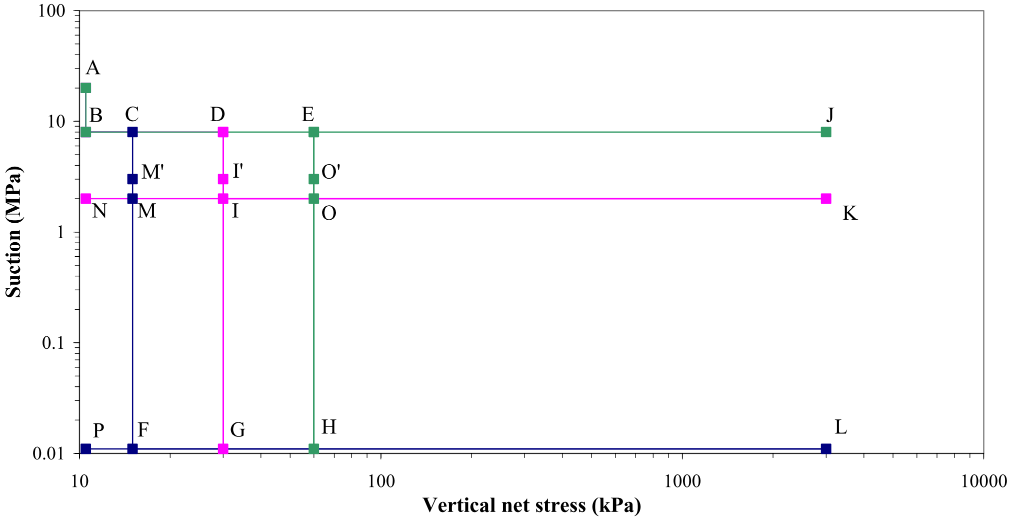

Fig. 2. Stress path in (σ_v–s) plane.

4. Suction cycles and hydromechanical behavior

The influence of the wetting and drying cycles on the mechanical behavior of the clayey materials was studied. Two series of tests with the same stress path were performed on the loose samples (L1, L2, L3) with an initial dry density of 1.28 Mg/m^3, and the dense samples (D1, D2, D3) had an initial dry density of 1.75 Mg/m^3. The stress paths of these tests are shown in Fig. 2 and in Table 2. The initial states are represented for both samples by point A in Fig. 2. Because the maximum imposed suction by the osmotic method is limited to 8 MPa [11,12], the starting point of the suction cycles was fixed at this suction value. Point B represents suction of 8 MPa at an initial vertical pressure of 10 kPa for all the tests. Thereafter, three different vertical stresses were applied: 15 kPa (point C_1) for tests D1 and L1, 30 kPa (point D_1) for tests D2 and L2, and 60 kPa (point E_1) for tests D3 and L3. Three successive wetting and drying cycles were then applied between 0 and 8 MPa. At the end of the successive suction cycles, a loading/unloading cycle was applied to these samples under three suctions: 0 MPa for tests D1 and L1, 2 MPa for tests D2 and L2, and 8 MPa for tests D3 and L3. The maximum vertical applied stress was about 3000 kPa.

4.1. Suction cycles

The void ratio variation versus suction of the loose and dense samples is presented in Fig. 3 for the different applied stresses: 15, 30, and 60 kPa.

For both series, the first wetting cycle (AB) produced the swelling strains. During the following suction cycles, the dense samples showed a cumulative swelling strain, while the loose samples had the opposite behavior: shrinkage accumulation. The volumetric strains converged to an equilibrium stage at the end of three successive cycles. The existence of this equilibrium stage is the principal hypothesis of the Barcelona Expansive Model (BExM) [13].

We noted that one or two additional suction cycles were still necessary for the dense samples to reach this elastic stage, while the loose samples had already reached this stage after three wetting and drying cycles. The void ratio

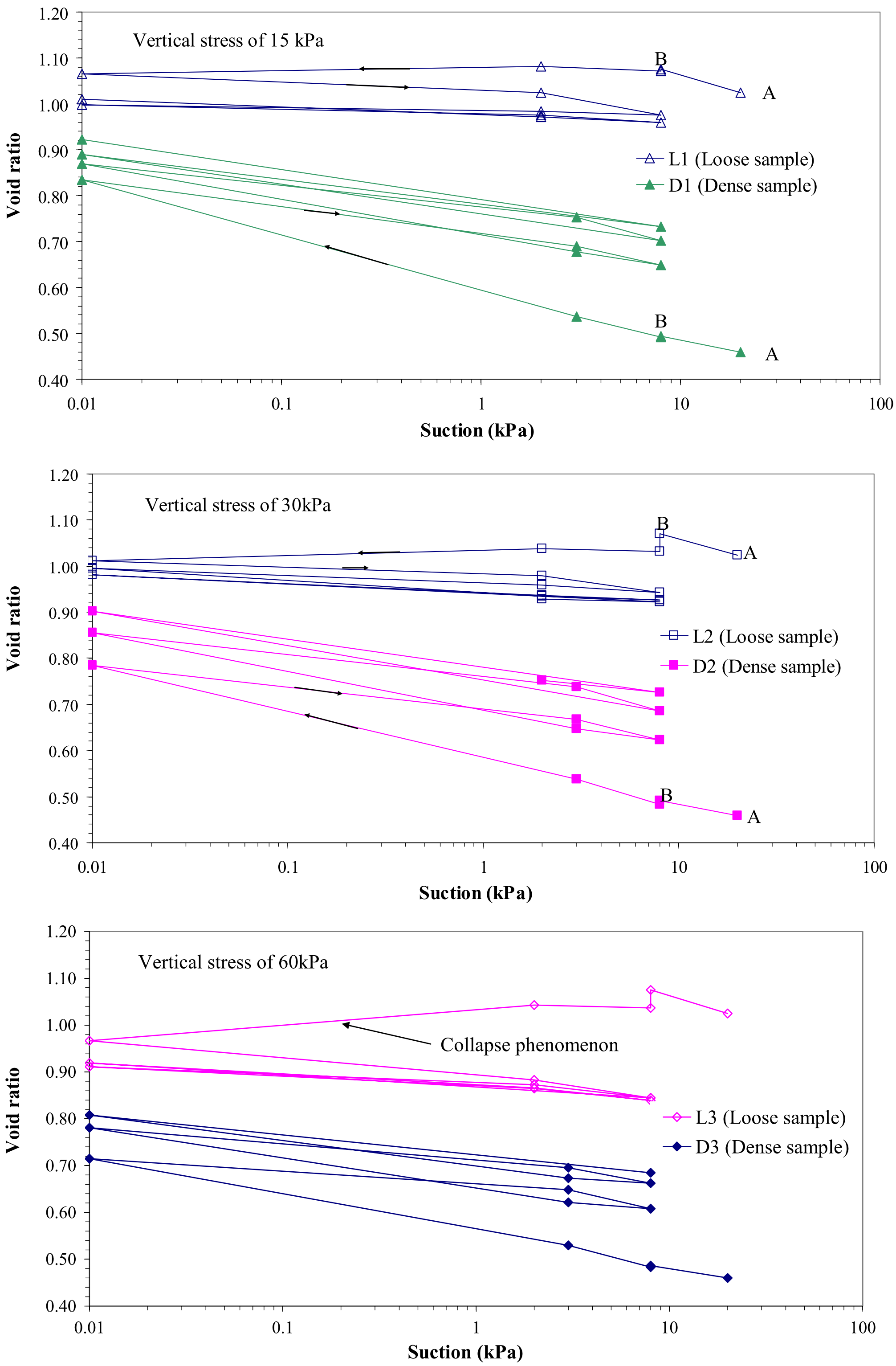

Fig. 3. Variation of the void ratio in cyclic controlled-suction paths at different vertical stresses for both loose and dense compacted clayey soils.

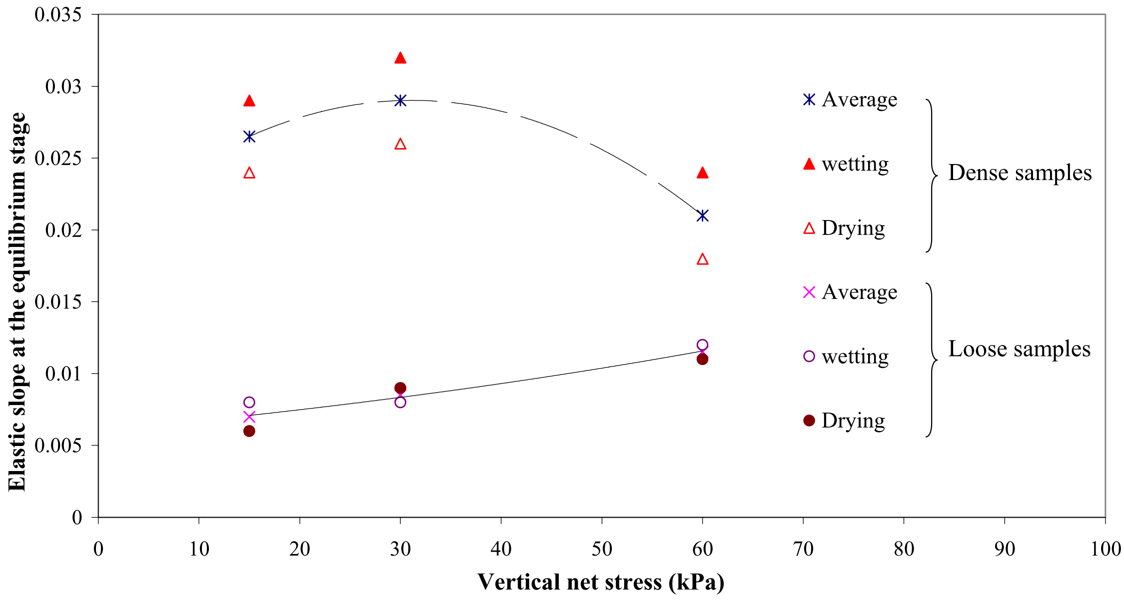

Fig. 4. Final elastic slopes (κ_m) at the equilibrium stage for both series.

difference between the L and D samples at a suction of 0 MPa was about 0.1 for all the applied stresses at the equilibrium stage. This difference became more significant for the higher suctions.

When the vertical stress applied to the dense samples increased, the cumulative swelling strains decreased. The most important swelling accumulation occurred during the first wetting and drying cycle. This accumulation decreased for the following cycles.

The loose samples demonstrated the collapse phenomenon during the first wetting cycle. With a stress of 60 kPa, which is higher than the preconsolidation stress of 40 kPa for the loose sample (Table 2), the collapse strains were more significant. However, this collapse can be considered negligible for applied stresses less than 40 kPa. This shrinkage accumulation disappeared during the successive wetting cycles and even transformed into a small swelling accumulation during the last wetting cycles for all the applied stresses.

Fig. 4 presents the final slope ($\kappa_m = \Delta e/\Delta \log s$) at the equilibrium stage versus the vertical net stress for both series. When equilibrium is reached, the final slopes of both series L and D for the same vertical stress are not the same. Moreover, the difference between the slopes decreases when the vertical stresses increase. Therefore, we can suppose that the slopes will approach the same value for higher vertical stresses.

4.2. Effect of suction cycles on the mechanical parameters

The loading/unloading tests at the end of the suction cycles at a constant suction of 0 MPa for the L1 and D1 tests, 2 MPa for the L2 and D2 tests, and 8 MPa for the L3 and D3 tests are plotted in Fig. 5. The loading/unloading tests without the application of the suction cycles are also plotted in Fig. 5a for the loose and dense samples in the saturated state ($s = 0$ MPa). Tables 3 and 4 present the mechanical parameters of both compacted samples.

For the loose soil in the saturated state (L1 and free swelling tests presented in Fig. 5a), the preconsolidation stress P_0 increases significantly after several hydraulic cycles, indicating that suction cycles tend to rigidify the soil, or in other words, the successive suction cycles drastically decrease the compression strains of the loading/unloading curves, especially for the lower applied stresses. For the higher stresses, even in the unsaturated state (Fig. 5), the compression curves converged toward the reference curves that correspond to a sample that had not been subjected to the wetting and drying cycles and toward the normally consolidated curve (NCC). This implies that P_0 becomes equal to the saturation stress P_{sat} after several wetting/drying cycles at the imposed suctions.

The saturated preconsolidation stress of the loose sample was estimated to be close to 200 kPa (L1 test in Table 3). This confirms that the initial dry density of 1.50 Mg/m^3 (or initial void ratio of 1.00) at the saturated state produced

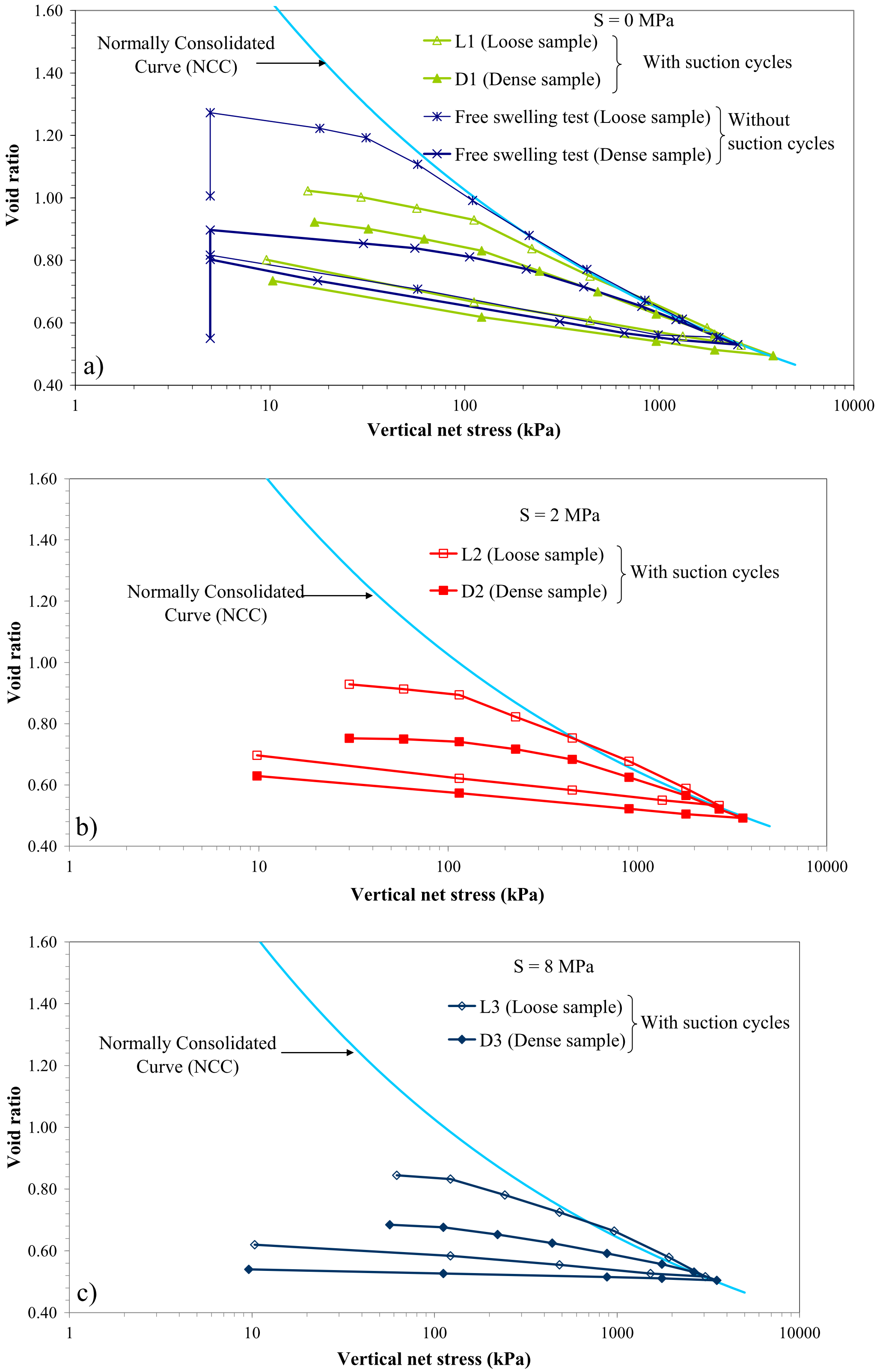

Fig. 5. Compressibility curves for both loose and dense samples at different suctions.

Table 3
Mechanical parameters at different applied suctions for loose soil.

Test	Suction (MPa)	P_0 (kPa)	$P_{sat}(s)$ (kPa)	λ_{sat}	κ
Free swelling	0	40	200	0.19	0.045
L1	0	200	∼200	0.14	0.045
L2	2	240	240	0.14	0.03
L3	8	300	300	0.13	0.02

Table 4
Mechanical parameters at different applied suctions for dense soil.

Test	Suction (MPa)	P_0 or $P_{sat}(s)$ (kPa)	λ_{sat}	κ
Free swelling	0	800	0.11	0.045
D1	0	380	0.10	0.045
D2	2	900	0.10	0.025
D3	8	1100	0.095	0.01

the unique preconsolidation and saturation stresses that correspond to the estimated initial critical dry density of $1.50\ \mathrm{Mg/m^3}$ at a suction of 20 MPa in the free swelling tests.

For the dense samples in the saturated state (D1 and free swelling tests presented in Fig. 5a), P_0 decreases significantly due to soil softening during the suction cycles. The dense samples showed a convergence towards the NCC before and after the application of the suction cycles (Fig. 5), which indicates that P_0 is equal to P_{sat} at the imposed suctions. For the imposed suctions, the smaller void ratio of the dense samples at the end of the wetting and drying cycles produces the higher saturation stress.

Generally, the virgin compression index λ values for the imposed suctions are considered to be the slope of the plastic part of the compression curve, which correspond to the tangent of the normally consolidated curve (NCC) at a saturation stress, λ_{sat}. The λ_{sat} values are almost the same for both samples at the end of the wetting and drying cycles. The unloading elastic index κ decreases with suction at the end of successive wetting and drying cycles for both samples.

5. Discussion

The compression curves in the saturated state obtained by the free swelling method demonstrated that the Normally Consolidated Line (NCL) [14] transforms to a nonlinear exponential form. We call this curve the normally consolidated curve (NCC), which is not influenced by the initial state of the soil [15,16]. This curve, presented in Fig. 1, gives the variation of the void ratio (e) as a function of the applied vertical stress (σ_v):

$$e = \alpha * (\sigma_v)^{\gamma} \tag{1}$$

where α and γ are two constants equal to 2.6 and −0.202, respectively, for this studied soil. The same equation was also proposed for a saturated compression curve where the compression curves at different imposed suctions converge to the saturated compression curve for heavily compacted soils that are associated with the absence of the macropores for dense materials [17,18].

The experimental results permit us to obtain the mechanical yielding surfaces for both studied materials. The preconsolidation stresses at an initial suction of 20 MPa can be considered to be equal to the applied compaction pressures (80 kPa for the loose sample and 1500 kPa for the dense one). These compaction pressures, as well as the preconsolidation stresses at the saturation state of 40 and 800 kPa obtained by the free swelling test (Table 1), provide the necessary data to obtain the initial LC surfaces (before the application of the wetting and drying cycles) that represent the variations of preconsolidation stress (P_0) with suction in ($\log\sigma_v - \log s$) the plane (Fig. 6). We also defined the Saturation Curve (SC), which represents the saturation stress (P_{sat}) variations with suction in the same plane [15,16]. The initial LC and SC are considered to be the same for the dense soil, while these surfaces are completely different for the loose samples.

Fig. 6 also shows the yielding surfaces after the application of the wetting and drying cycles for both loose and dense soils. The swelling/shrinkage accumulation at the end of the wetting and drying cycles decreases/increases the

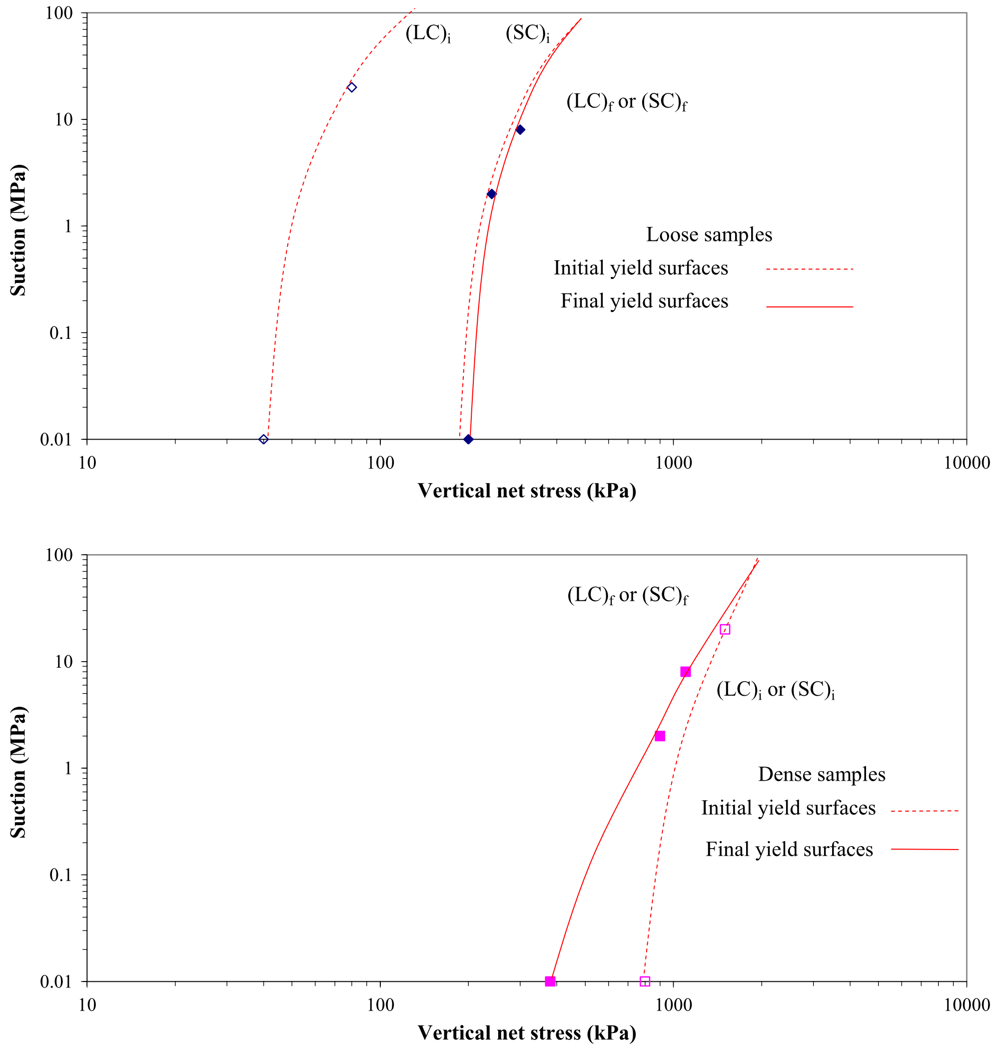

Fig. 6. Influence of the wetting and drying cycles on the yielding surfaces for the loose and dense samples.

preconsolidation stress for the dense/loose samples. At the equilibrium state, the compression curve for these imposed suctions follows the normally consolidated curve after its initial elastic phase, which suggests that the final LC and SC yield surfaces become unique.

It should be added that the equilibrium stage has not yet been achieved for the dense samples. This means that the additional wetting and drying cycles will further decrease the saturation stresses at different imposed suctions. It could be possible that the final Saturation Curve (SC) superimposes both loose and dense samples. In other words, both samples present the same mechanical behavior at their equilibrium stage after several wetting and drying cycles.

As the natural soil is submitted to several wetting and drying cycles, the mechanical soil behavior converges to its fully saturated state. Therefore, a loading/unloading test at three different suctions can lead us to determine the final Saturation Curve (SC) and define the hydromechanical soil parameter.

6. Conclusion

We observed that the compression curves of the expansive compacted loose and dense samples in the saturated state, obtained by the free swelling method demonstrated that the Normally Consolidated Line (NCL), is not a straight line and transforms to a nonlinear exponential form.

These curves also allow us to estimate an intermediate initial dry density of 1.50 Mg/m^3 for which the preconsolidation stress and the saturation stress equal 200 kPa. For the denser samples, both equal preconsolidation or saturation stresses increased together, while the preconsolidation stress was less than the saturation stress (200 kPa) for the looser samples.

The influence of several successive wetting and drying cycles under different values of constant vertical net stress on the expansive compacted loose and dense samples was also studied using osmotic oedometers. The dense samples showed cumulative swelling strains, while the loose samples showed an accumulation of volumetric shrinkage. At the end of several wetting and drying cycles, the volumetric strains converged to an equilibrium stage.

The wetting and drying cycles had a significant influence on the mechanical behavior of the swelling soils. The convergence of the compression curves to the normally consolidated curve (NCC) after the initial elastic phase at the end of suction cycles expressed the elimination of the virgin compression line, or, in other words, the preconsolidation stress was equal to the saturation stress at the imposed suctions for both samples.

For future study, it will be interesting to propose a simplified model to reasonably estimate the compression curves at different suctions at the elastic equilibrium stage for both studied soils.

References

[1] A. Al-homoud, A. Basma, A. Husein Malkawi, M. Al Bashabsheh, Cyclic swelling behavior of clays, Journal of Geotechnical Engineering 121 (1995) 562–565.
[2] E.E. Alonso, E. Romero, C. Hoffmann, E. Garcia-Escudero, Expansive bentonite/sand mixtures in cyclic controlled suction drying and wetting, Engineering Geology 81 (2005) 213–226.
[3] T.Y. Chu, C.H. Mou, Volume change characteristics of expansive soils determined by controlled suction tests, in: Proc. 3rd Int. Conf. Expansive Soils, Haïfa, vol. 2, 1973, pp. 177–185.
[4] A.E. Dif, W.F. Blumel, Expansive soils under cyclic drying and wetting, Geotechnical Testing Journal 14 (1991) 96–102.
[5] E. Pousada, Deformabilidad de arcillas expansivas bajo succión controlada, Doctoral Thesis, Universidad Politecnica de Madrid, Spain, 1984.
[6] S.J. Wheeler, R.S. Sharma, M.S.R. Buisson, Coupling of hydraulic hysteresis and stress–strain behaviour in unsaturated soils, Géotechnique 53 (1) (2003) 41–54.
[7] ASTM D 5298-94, Standard test method for measurement of soil potential (suction) using filter paper, 4.09, 1995, pp. 154–159.
[8] E. Romero, A. Lloret, A. Gens, Water permeability, water retention and microstructure of unsaturated Boom clay, Engineering Geology 54 (1999) 117–127.
[9] ASTM D 4546-90, One-dimensional swell or settlement potential of cohesive soils, 4.08, 1995, pp. 693–699.
[10] H. Nowamooz, F. Masrouri, Density-dependent hydromechanical behaviour of a compacted expansive soil: Experimental and analytical aspects, Engineering Geology 106 (3–4) (2009) 105–115.
[11] O. Cuisinier, F. Masrouri, Hydromechanical behavior of a compacted swelling soil over a wide suction range, Engineering Geology 81 (2005) 204–212.
[12] P. Delage, M.D. Howat, Y.J. Cui, The relationship between suction and the swelling properties in a heavily compacted swelling clay, Engineering Geology 50 (1998) 31–48.
[13] E.E. Alonso, J. Vaunat, A. Gens, Modelling the mechanical behaviour of expansive clays, Engineering Geology 54 (1999) 173–183.
[14] K.H. Roscoe, J.B. Burland, On the generalized stress–strain behaviour of the wet clay, in: J. Heyman, F.A. Leckie (Eds.), Engineering Plasticity, Cambridge University Press, Cambridge, 1968, pp. 535–609.
[15] H. Nowamooz, Retrait/gonflement des sols argileux naturels et compactés, Doctoral Thesis, Institut National Polytechnique de Lorraine, Nancy, France, 2007, 199 pp.
[16] H. Nowamooz, F. Masrouri, Hydromechanical behaviour of an expansive bentonite/silt mixture in cyclic suction-controlled drying and wetting tests, Engineering Geology 101 (3–4) (2008) 154–164.
[17] Y.J. Cui, M. Yahia-aissa, P. Delage, A model for the volume change behavior of heavily compacted swelling clays, Engineering Geology 64 (2002) 233–250.
[18] D.A. Sun, D.C. Sheng, H.B. Cui, S.W. Sloan, A density-dependent elastoplastic hydro-mechanical model for unsaturated compacted soils, International Journal for Numerical and Analytical Methods in Geomechanics 31 (11) (2007) 1257–1279.