SHRINKAGE / SWELLING BEHAVIOR OF A LIME-TREATED CLAYEY SOIL

COMPORTEMENT D'UN SOL ARGILEUX TRAITE A LA CHAUX VIS-A-VIS DU RETRAIT / GONFLEMENT

Gontran HERRIER[1], Jaime ABAD[2], Bertrand FRANCOIS[3], Daniel PUIATTI[4]
1 Lhoist Recherche et Développement, Nivelles, Belgique
2 Rheinisch-Westfälische Technische Hochschule, Aachen, Allemagne
3 Université Libre de Bruxelles, Département BATir, Belgique
4 DPST Consulting, Villemomble, France

ABSTRACT – Clayey soils show changes in consistency, depending on their water content: hard and brittle when dried, it becomes plastic and workable from a given moisture content. These changes take place together with volume changes, whose magnitude can sometimes be spectacular. The means used so far to control the risk of shrinkage or swelling are often expensive and require great efforts and constructive energy. Moreover, they do not solve the problem fundamentally. In this context, this paper present data allowing setting out arguments in favour of the effectiveness of lime treatment to control the expansion and shrinkage of clay soils, either for construction of buildings or infrastructures.

RÉSUMÉ – Un matériau argileux voit sa consistance se modifier en fonction de sa teneur en eau : dur et cassant lorsqu'il est desséché, il devient plastique et malléable à partir d'un certain niveau d'humidité. Ces modifications de consistance s'accompagnent de variations de volume, dont l'amplitude peut être parfois spectaculaire. Les moyens employés jusqu'à présent pour maîtriser le risque de retrait ou gonflement sont souvent coûteuses et demandent des grands efforts constructifs et énergétiques ; en outre, elles ne solutionnent pas fondamentalement la nature du problème. Dans ce contexte, cet article présente des résultats permettant d'élaborer une argumentation par rapport à l'efficacité d'un traitement à la chaux pour maîtriser l'expansion et le retrait des sols argileux, que ce soit dans une application de construction de bâtiments ou d'infrastructures.

1. Introduction

The means used until now in order to control the shrinkage or swelling risks of soils, such as micropiles or substitution of clayey layers by aggregates or granular soils, are often expensive and requires a lot of building and energy expenditures. Moreover, applied methods don't solve the problem itself – the shrinkage/swelling behavior – but rather prefer an indirect solution.

However, the possibility exists to directly modify the shrinkage characteristics of clayey soils. In earthworks, the lime treatment is often used with success, to improve bearing capacity, mechanical performances and cohesion of soils (GTS, 2000). A lime treatment can also have a significant effect on the shrinkage and swelling potential of the treated soil.

The mechanisms associated with volume variations of fine soils are generally linked to three main phenomenon (Zerhouni, 2002 ; Verbrugge, 2001 ; Laloui, 2010 ; Cecconi, 2008 ; Cuisinier, 2010 ; Tedesco, 2008 ; Duc, 2008) :

- the mechanical effect : each modification of external stress leads to a soil deformation when reaching the new equilibrium state. This displacement results from the integration of elementary strains, created on every point of the soil mass. Lime treatment can influence the soil behavior vs deformation, thanks to the structure modification, e.g. flocculation and progressive cementation.

- hydric effect (Verbrugge, 2001 ; Laloui, 2010) : a change in the soil hydric conditions leads to a modification of interstitial pressures. Under the water table, interstitial pressures are positive and the water content corresponds to the saturation. Above the groundwater table, water is in depression (below atmospheric pressure), this is the suction case. In this case, water content is linked to suction through water retention curve. When water content decreases, suction increases and leads to an increase of effective stress and a soil volume reduction. In return, a water content rise leads to a loosening of this stress and provokes a swelling. In a given range of suction (which can go up to several MPa), clayey soils stay saturated during hydric conditions changes, so that volume variation corresponds to the expelled or adsorbed water volume by the soil. It is also identified that a lime treatment affects the water retention properties of a soil (Cecconi, 2008 ; Cuisinier, 2010 ; Tedesco, 2008).

- physico-chemical effect : this effect is linked to clayey elementary particles hydration phenomenon. Hydration mechanisms are determined by numerous parameters such as clayey minerals nature and their physic-chemical properties, material structure and pore voids arrangement, total suction in the soil, ionic concentration of interstitial fluid – including adsorbed water – and his role on osmotic suction, material history, especially processes leading to cementitious bindings. Soil treatment with lime modifies the chemical composition and influences the hydration phenomenon of elementary soil particles.

In reality, those three effects are rarely separated and it is difficult to make a precise and quantitative separation between them. Geotechnical parameters of the soil, possibly associated with physic-chemical parameters, are insufficient in order to satisfactorily determine the clayey sol sensitivity to shrinkage and swelling (Duc, 2008).

The objectives of this contribution are to bring relevant informations, in order to put the light on the benefits of lime treatment of clayey soils, on their stability versus drying and wetting processes. After a short presentation of the studied soil, results and interpretation of several trials, combining hydric and mechanical paths will be shown and discussed. We successively will address drying tests with shrinkage recording and water retention properties, and after swelling tests through saturation followed by swelling pressure and oedometer compression determination.

2. Materials

The sampled clayey soil comes from the diversion road (RD438) construction site of Héricourt (Haute-Saône, France). Chemical composition of the soil, identification results and particle size distribution are listed in Tables 1 and 2. On the basis of the French classification and the clay activity, this soil can be considered as belonging to the A3 or even A4 category (NF P11-300 standard), that corresponds to a heavy plastic soil.
On the mineralogic point of view, X-ray diffraction analyses highlighted the presence of clay minerals : muscovite-type illite, chlorite and interstatified clay minerals of illite-smectite nature, susceptible to swell.
The used lime for treatment studies is a calcic quicklime CL 90-Q, with 90,9 % available CaO (calcim oxide) and a reactivity (t_{60}) of 3,3 minutes. This quicklime was provided by Lhoist.

Table 1. Chemical composition chimique of the clayey soil from the Héricourt (Haute-Saône, France) diversion road construction site.

Compound	Amount (%)
SiO_2	52.2
Al_2O_3	18.5
Fe_2O_3	7.0
MgO	7.1
K_2O	4.7
Na_2O	0.15
P_2O_5	0.13
CaO	1.1
SO_3	0.08

Table 2. Geotechnical identification of the clayey soil.

Passing through 80 µm sieve (%)	Below 2 µm particles (%)	w_L (%)	w_P (%)	PI (%)	MBV (g/100g)
94	75	72	35	37	18

3. Results

3.1. Behavior of the clayey soil vs lime treatment and compaction

Beforehand the trials aiming to examine the behaviour vs shrinkage and swelling phenomenon, compaction behavior of the natural (untreated) clayey soil and after lime addition were assessed. Following a lime fixation point determination (LFP, determined by Eades and Grim test, Eades, 1966), a 5 % lime dosage was applied. This dosage is slightly above LFP, and theoretically corresponds to an optimal improvement procedure fo this soil, also allowing to keep a small reserve of available lime for further puzzolanic reactions development and stabilization at a later stage.

Consequences of lime treatment on Standard Proctor Compaction are : shift of the Optimal Moisture Content (OMC) towards higher moisture contents (up to à 28.2 %) regarding lime content, and decrease of dry density values of treated soil up to 12.4 Mg/m³ (in place of 14.5 Mg/m³ in the case of untreated soil). Compaction parameters and immediate bearing capacity are listed in Table 3.

Table 3. Compaction parameters and immediate bearing capacity (IBI) of natural soil and same soil after 5 % lime addition.

	Optimal Moisture Content (% - Standard Proctor compaction)	Dry density at OMC (Mg/m³)	IBI at OMC (%)
Natural soil	26.8	14.5	12
After 5% lime addition	28.2	12.4	26

3.2. Hydric behavior characterization

3.2.1. Shrinkage curve

The free shrinkage test is one trial used for the determination of the volume variation curve of a soil, submitted to natural drying. Tests on natural and lime-treated soil were performed according the German Standard DIN 18122-2 method. A homogeneous disc of the material, moisturized to water content around 110 % (mud state), is prepared and let to dry under ambient lab atmosphere. Shrinkage as a function of water loss is drawn on a graph, and the shrinkage limit of the soil (w_S) corresponds to the intersection point of 2 lines : the first one being the tangent to the drying points (often linear), and the second is a horizontal line corresponding to the zero water content level (oven-dried sample). Those water contents, corresponding to shrinkage limits, are 16.5 % (natural soil) and 55 % (lime-treated soil), respectively (Figure 1).

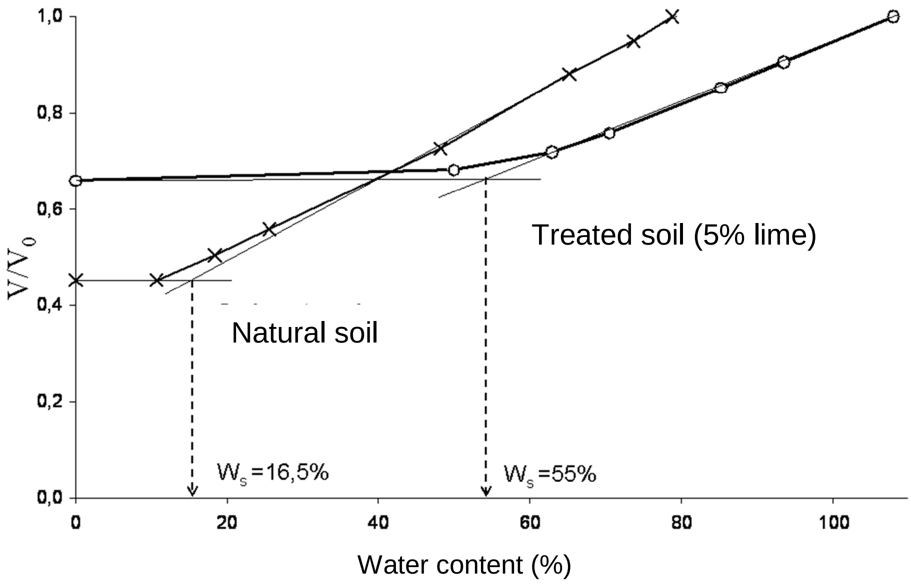

Figure 1. Free shrinkage curves of natural and 5% lime-treated soil.

Modifications induced by lime on the hydric behavior are quite evident. Natural soil is subjected to a volume decrease (shrinkage) of more than 50 %, through drying, until it becomes almost dry (water content of 16.5 %). On the contrary, once treated with lime, the soil shows a limited shrinkage amplitude (around 30 %), which ends at a high humidity level (55 % moisture content), well above water content at compaction.

3.2.2. Suction curve

Suction curves allow to study the hydric behavior, by characterizing the water retention potential of the soil, this means the relationship between the water content remaining in the soil and applied suction (Verbrugge, 2001 ; Laloui, 2010 ; Nowamooz, 2010). Those trials are generally performed under zero mechanical stress. The retained water content can be expressed in terms of mass (water content, w) or volume (saturation level, S_r). The relationship between these values is :

$$S_r = \frac{\gamma_s}{\gamma_w}\frac{w}{e} \qquad (1)$$

where γ_s is the volume weight of solid particles (γ_s = 26.5 kN/m^3) ; γ_w, is the volume weight of water and e is the void index.

In the present study, suction curves were established on compacted samples close to OMC conditions and dry density. The initial state being different from conditions of Figure 1 (free shrinkage tests), it is therefore not possible to quantitatively compare the obtained results from the two tests. Suction is controlled by axis translation, which consists to submit the sample to an air high pressure, whereas the water pressure remains equal to atmosphere pressure. The water and air pressure difference is ensured by a ceramic stone, water permeable but air impermeable until a given suction range (1,5 MPa in this case).

Two untreated samples and two series of 5% lime treated samples (of 2 samples each) were compacted according Standard Proctor conditions and tested. Treated samples had, at the beginning of the test, a few days age. However, suction trials carrying on several months, the properties of treated samples will evolve with time, which is difficult to take into account here. Samples are submitted to soaking in order to reach a succion of 1 kPa, then an air pressure to simulate growing suction values. Water retention curves are illustrated in Figure 2.

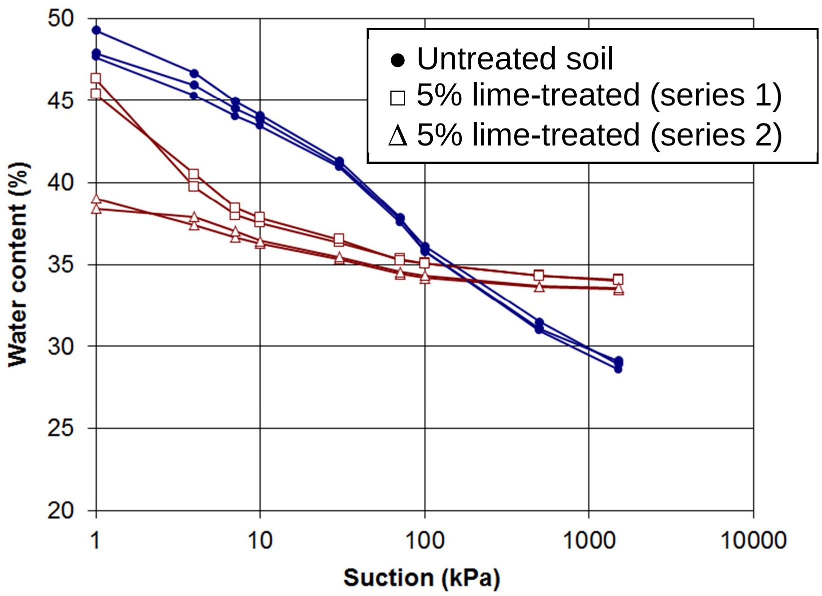

Figure 2. Water retention curves of natural soil and two series of 5% lime-treated soil.

During the soaking phase, natural soil passes from OMC compaction conditions (w= 26.8 % ; ρ_d=14.5 Mg/m^3 ; e=0.8 ; S_r = 87 %) to a saturated configuration, which has significantly swelled (w=48%, e=1.25 ; Sr=100%), the void index shifting from 0.8 to 1.25. During the imposition of successive suctions, suction curves of natural soil has a similar profile, with a strong water loss in the measured suction ranges (between 1 and 1500 kPa), and a slight inflexion in high suction ranges (around 100 kPa and at a water content of 35 %).

Assuming an initial state (after compaction) corresponding to OMC conditions (w = 28.2 % ; ρ_d=12.4 Mg/m^3 ; e=1.19 ; S_r = 63 %), series 1 shows a saturated configuration without significant swelling (w= 46 % ; e=1.21 ; S_r = 100 %), void index moving from 1.19 to 1.21. Results of second series of treated soil are more questionable, the materials being probably not well resaturated before suction curve acquisition. Initial suction could be different from 0. Saturation degree being unknown, the void index cannot be deduced from

Equation 1 anymore. This explains the water content differences at low suction ranges. However, above 10 kPa suction value, the two series converge.

In the case of untreated soil, a moisture content decrease of more than 20 % was recorded in the measured suction range, and this content stays permanently above the measured shrinkage limit (16.5 %). We didn't recover information about volume change during the drying step for those compacted samples. Nevertheless, for this kind of clayey materials of high plasticity, we can assume that the air entry suction is several MPa. For the submitted suction range, the material stays therefore saturated. According this hypothesis, one can deduce the final void index for a 1500 kPa suction, that is e = 0.76. In this case, the strong water loss of natural material is balanced by a dramatic decrease of its volume.

Globally, the soil behavior is modified by a lime addition. After lime treatment, one have to maintain a "big effort" in terms of negative pressure in order to obtain water content below 35 %. On the other hand, the amplitude of this decrease doesn't exceed 10 % for the treated soil. The water loss is quite large for low suction values (< 10 kPa), but on the contrary, for higher suctions (> 100 kPa), treated soil shows large water retention capacities. This phenomenon was already observed in the past (Tedesco ,2008), and is attributed to the double structure of the material. On one hand, macropores (between soil aggregates) induce a lowering of the air entry suction value. On the other hand, the large amount of small pores inside soil aggregates gives a good retention capacity for high suction ranges.

It is also of interest to note that this water content stays permanently lower than tha shrinkage limit (55 %). In the case of lime treated soil, the material stays extremely rigid, tha water loss is not balanced by a volume variation. Consequently, the material de-saturates. The final degree of saturation, for a suction of 1500 kPa, is S_r = 75% (assuming voix index stays e=1.2). This de-saturation is explained by the very open porosity of treated soil compared with natural clayey soil. The macropores of treated material allow a better water drainage and therefore an easier de-saturation. This difference in the structure can be observed as on the Figure 3.

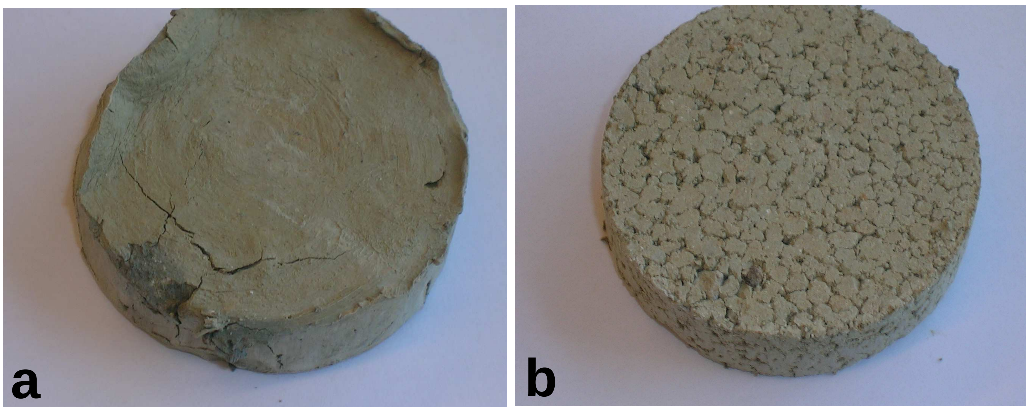

Figure 3. Visual observation of the structure of natural clayey soil (a) and 5% lime-treated (b) after compaction and drying.

3.3. Mechanical behavior characterization

3.3.1. Free swelling and oedometer compression test

The characterization of mechanical behavior, separated from hydric effect, is made by applying a zero effective suction ; in other words, by saturating a sample before an oedometer compression test, and by measuring the corresponding volume strain.

The test begins with a soaking under very little stress, and a swelling step until volume stabilization. This first measurement establishes the swelling potential, before the loading by steps, which allows to assess the swelling pressure ; this last value corresponds to the return of tha sample to its initial volume. The so-performed oedometer test (according ASTM D 4546-03) allows to draw a volume variation curve in function of the meachanical stress, when succion stays zero.

To avoid leaching of lime particles out of the samples during soaking period, it was decided to apply a curing time of 7 days to lime-treated samples. During the positioning of the samples in oedometer cell, a 12.5 kPa load was applied for 2 hours before 72 hours soaking. Afterwards, loading and unloading steps were applied (24 hours). Corresponding graphs are reported in Figure 4.

Swelling strains of the untreated soil during soaking period are 3.56 % in average ; this value could be a little bit larger considering the applied vertical stress of 12.5 kPa. Swelling pressures show an average value of 88.2 kPa. In the case of lime-treated soil, swelling strains are very low : 0.15 % in average. However, swelling pressure is rather large, about 200 kPa. This is explained by the high stiffness level of treated soil. Indeed, in order to balance the low swelling pressure, one have to apply a quite high pressure because the stiffness of the sample puts up this recompression. Note that the TR_3 test didn't shwo any initial swelling, and therefore the swelling pressiure is almost zero. This TR_3 test presents a different behavior compared with the two others and the plastic compressiion is probably not completely reached. The Cc value is thus to be cautiously considered.

As a first conclusion, it seems that the lime treatment of a swelling soil can be beneficial for the reduction of free swell. It moves from 3.56 % in the case of untreated sample, to 0.15 % when lime is added. In contrast, on the point of view of swelling pressure, the positive effect is less clear. The low swelling being balanced by a high stiffness level, it induces a higher swelling pressure compared with untreated soil. The compression behavior can be resumed on the basis of data in Table 4.

Table 4. Values of oedometer compression parameters.

	Swelling index C_s	Compression index C_c	Preconsolidation pressure (kPa)
Untreated soil	0.048	0.306	100
	0.060	0.303	32
	0.056	0.286	61
5% lime-treated soil	0.010	0.451	660
	0.08	0.362	610
	0.005	0.139	490

Measured swelling and compression indexes of untreated soils are very homogeneous. The differences between curves is mainly located at the preconsolidation pressure values, which is very sensitive to compaction conditions of the samples. Indeed, the sample will acquire its overconsolided nature during this compaction step, and a slight water content difference (which will provoque a dry density condition difference) could explain differences in the acquired preconsolidation pressures.

Treated soils shows an increased rigidity (C_S 5 to 6 times lower in comparison with untreated soil) and a reinforced preconsolidation stress (5 to 10 times larger than untreated material). However, once the preconsolidation stress overtaken, the plastic compressibility is increased. This phenomenon is explained by a more severe damage to the microstructure. Indeed, under this range of stresses, bindings between soil aggregates created by lime treatment are broken and the soil progressively loses its initial very rigid structure, towards a more dispersed one. This phenomenon comes along with a strong volume reduction. Note that this behavior occurs at very high stress levels (MPa range), that is well above typical stresses met in embankment, capping layers of roads or other earthen structures applications.

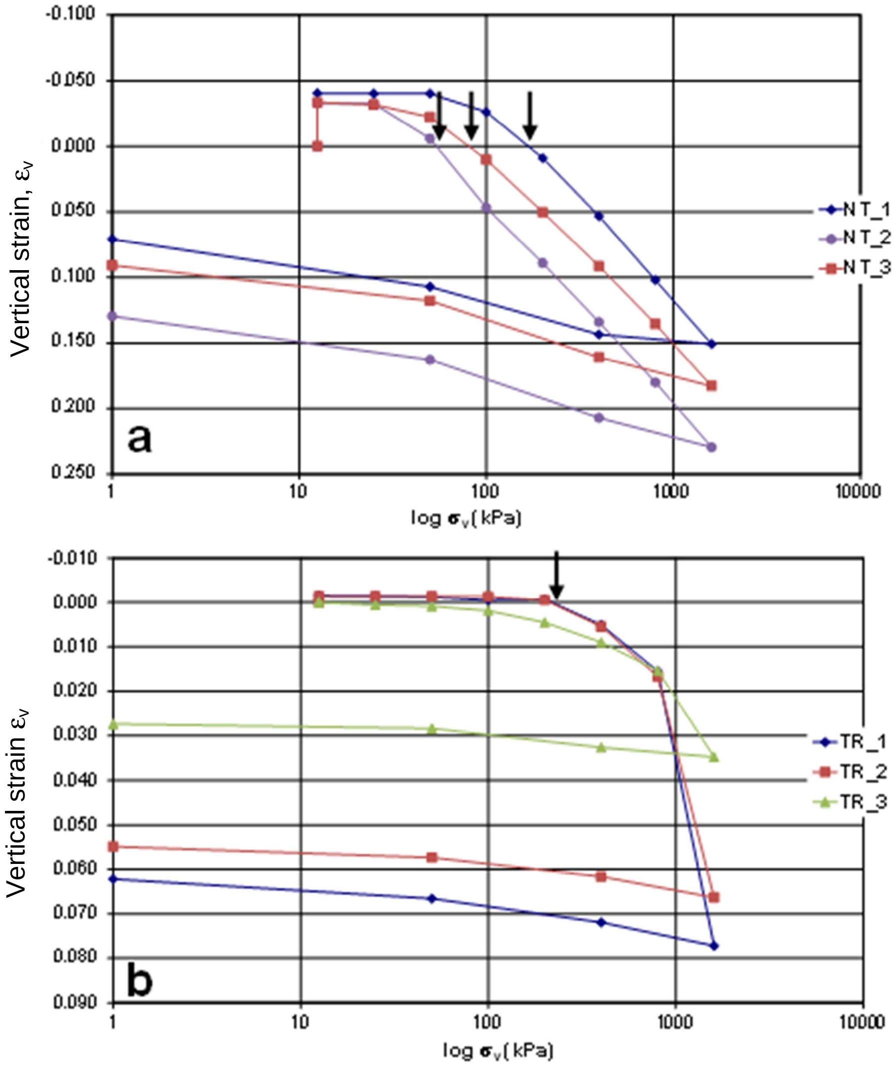

Figure 4. Initial swelling and evolution of vertical strain in function of vertical stress on untreated (a) and lime-treated (b) samples.
Arrows show location of measured swelling pressures.

3.3.2. Expression of the mechanical behavior in function of void index

In the same way as hydric behavior examination, it is possible to express the void index in relationship with mechanical stress. This behavior can be synthetized from Figure 5 : if the soil porosity (and thus its void index) is higher than that of natural soil, nevertheless it remains rigid until more severe stresses, and afterwards is subjected to plastic compression which tends to coincide to the porosity of natural soil, after the destruction of bindings induced by lime action. However, this convergence of void index curves is met when applied stress levels are very high, not representative of real earthen structures. This phenomenon was already related by some authors (Nowamooz, 2010 ; Rao, 2005).

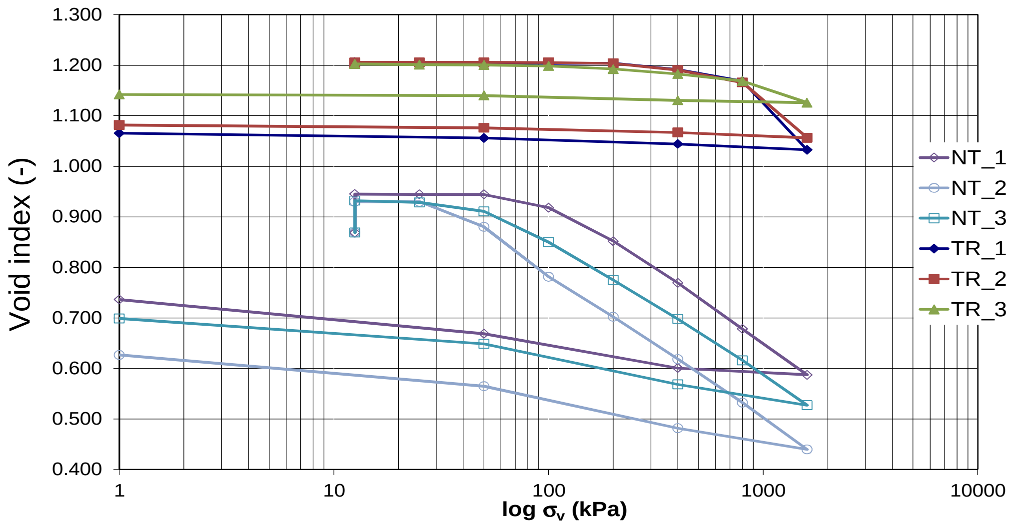

Figure 5. Synthesis of oedometric curves of the natural clayey soil (NT curves), and same soil after a 5 % lime treatment (TR curves).

4. Conclusions

Consistancy modification of clayey swelling soils, regarding their water content, goes along with volume variations, whose amplitude can sometimes be very large. Lime treatment of a soil is a solution to control this issue in the field of earthen structures construction, embankments or capping layers.

Thank to this study of the hydric and mechanical behavior of a clayey soil sampled on the the diversion road construction site of Héricourt (Haute-Saône, France), reworked and compacted in laboratory according Standard Proctor conditions, following elements were highlighted :

- the lime treated soil shrinkage stops at a high moisture content (55 %), well above water content at compaction, ensuring its volume stability ;
- the water retention behavior of the soil is modified by lime treatment : after lime addition, negative pressures to be applied in order to decrease the water content are extremely high, the sol owing the tendency to maintain its humidity close to OMC ;
- lime treatment of a swelling soil seems to be beneficial for the free swell reduction, swelling is in this case divided by 20 in comparison with natural soil (oedometer test) ;
- treated soil shows an increased stiffness and a reinforced preconsolidation stress.

On the other hand, once this preconsolidation stress reached, the plastic compressibility is higher. However, this behavior occurs in the case of very high stress levels (MPa range), well above stress levels relevant in application such embankments, capping layers, earthen structures.

5. Acknowledgements

Authors wish to thank Aurore Degré et Daniel Baes, from Facultés Agronomiques de Gembloux (Belgium), for the acquisition of water retention curves ; Nicolas Canu and Simon Croegart (Université Libre de Bruxelles), for the achievement of oedometer tests, and Tamer Ozturk, for its contribution to this research.

6. References

BRGM, Bureau de Recherches Géologiques et Minières, site web dédié à l'aléa retrait-gonflement des argiles : *http://www.argiles.fr/presentation*

Cecconi M., Russo G. (2008). *Prediction of soil-water retention properties of a lime stabilised compacted silt. In:* Unsaturated Soils : Advances in Geo-Engineering – Toll et al. Eds (London), pp. 271-276.

Cuisinier O., Deneele D. (2010). *Effet de sollicitations hydriques cycliques sur le gonflement d'un sol argileux traité à la chaux.* Revue Française de Géotechnique, n°130, pp. 51-60

Duc M., Cui Y-J., Tang A-M., Makki L., Serratrice J-F., Calissano H., Bertaina G., Reiffsteck P., Ferber V., Khay M., Maloula A., Magnan J-P. (2008). *Caractérisation du comportement de retrait-gonflement de l'argile de Bavent.* Symposium international 'Sècheresse et Constructions 2008', Paris, pp. 265-272

Eades J.L., Grim R.E. (1966). *A quick test to determine lime requirements for lime stabilization.* Highway Research Board Bulletin 139, 61-72.

Laloui L., Nuth M., François B. (2010). *Mechanics of unsaturated soils.* In: Mechanics of unsaturated materials, Eds. L. Laloui, Wiley & Sons, Inc., pp. 29-54.

Nowamooz, H., & Masrouri, F. (2010). *Volumetric strains due to changes in suction or stress of an expansive bentonite/silt mixture treated with lime.* Comptes Rendus Mecanique, 338(4), 230-240.

Rao S.M., Shivananda, P. (2005). *Compressibility behaviour of lime-stabilized clay.* Geotechnical and Geological Engineering 23, pp 309-319.

Tedesco D.V., Russo G. (2008). *Time dependency of the water retention properties of a lime stabilised compacted soil. In:* Unsaturated Soils : Advances in Geo-Engineering – Toll et al. Eds (London), pp. 277-282.

Verbrugge J.C., Fleureau, J.M. (2001). *Bases expérimentales du comportement des sols non saturés, Chapitre 2,* In « Mécanique des sols non saturés », O. Coussy & J.M. Fleureau eds. Hermès.

Zerhouni M., Dhouib A., Hubert B. (2002). *Paramètres de gonflement et retrait des argiles – essais normalisés en France.* Symposium international Identification et Détermination des paramètres des sols et des roches pour les calculs géotechniques (PARAM 2002), Septembre 2002, Paris, pp. 167-171