Weathering of a lime-treated clayey soil by drying and wetting cycles

Guillaume Stoltz, Olivier Cuisinier, Farimah Masroui

Summary

Lime treatment induces several time-dependent physico-chemical processes (cation exchange, pozzolanic reactions, etc.) that result in the bonding of soil particles. This treatment can reduce the swelling properties of clays and improve their strength. Nevertheless, these positive effects of lime-treatment could be altered by weathering in the very long term. In this paper, the effects of successive drying/wetting cycles on the hydro-mechanical properties of a lime-treated clayey soil are considered. Quicklime-treated samples were subjected to successive controlled-suction (osmotic technique) drying/wetting cycles; and also severe hydric cycles corresponding to an alternation of oven drying and saturation. The effect of quicklime dosage and curing time were considered. The results show a progressive increase of the swelling properties of the material and a progressive loss of strength with increasing number of drying/wetting cycles. The extent of the degradation is directly related to the amount of added quicklime and the amplitude of the suction cycles. Mercury intrusion porosimetry tests show that successive cycles lead to a progressive change of the micro-fabric, thus explaining partly the degradation of macroscopic properties. This study shows that weathering by successive drying/wetting cycles is likely to significantly alter the properties of a lime-treated soil, thus weathering effects should be accounted for the long term design of treated soil structure.

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1. Introduction

Swelling/shrinkage of expansive soils due to moisture content changes may cause damages to structures (e.g., Jones and Holtz, 1973; Chen, 1975). Many studies attempted to depict the couplings between variations in water content and the resulting modifications in volume, mechanical properties, or fabric of expansive soils, compacted or in a natural state (e.g., Push, 1982; Gens and Alonso, 1992; Simms and Yanful, 2002), with a special attention to the influence of drying/wetting cycles (Day, 1994; Al-Homoud et al., 1995; Alonso et al., 1999; Cuisinier and Masroui, 2005). Successive drying/wetting cycles may result in progressive accumulation of irreversible strains, (Chu and Mou, 1973; Alonso et al., 2005; Nowamooz and Masroui, 2009) leading to alteration of the mechanical behaviour. Among the potential mechanisms likely to reduce the impact of drying/wetting cycles on expansive soils, lime treatment would be of interest. Indeed, it induces several time-dependent physico-chemical processes (cation exchange, pozzolanic reactions, etc.) that result in the improvement of soil behaviour (Diamond and Kinter, 1965; Eades and Grim, 1966). In particular, it is known to reduce the swelling potential of expansive soils (Ashraf and Walker, 1963; Transportation Research Board, 1987; Basma and Tuncer, 1991; Nalbantoglu and Tuncer, 2001). Nevertheless, some authors have shown that the effects of lime treatment could be partially withdrawn by exposure to climatic conditions, like freezing and thawing (Thompson and Dempsey, 1969), or water circulation (De Bel et al., 2005; Le Runigo et al., 2009). In the case of lime treated expansive soils, a key question is the impact of successive drying and wetting periods. Gutschick (1978) and Kelley (1988), from field investigations of lime stabilised roads and earthfills, showed qualitatively that the alternation of dry/wet periods could be detrimental to the efficiency of lime treatment in the long term. Some experiments conducted on samples reconstituted in the laboratory were also reported in the literature. Khattab (2002) concluded that after a few number of wetting/drying cycles, the swelling potential of a lime-treated bentonite was of the same order of magnitude as the untreated bentonite. Guney et al. (2007) showed that the beneficial effect of lime stabilisation in controlling the swelling potential of lime-treated samples is partially lost, after having been exposed to several cycles of wetting and drying. These studies tend to indicate that such cycles can alter the effects of lime treatment on swelling potential of clays. However, in these laboratory studies, the samples were subjected to cycles between saturation (samples exposed to free water) and very low relative humidity associated to temperatures higher than 40 °C.
experimental conditions are severe compared to field conditions. Very few studies tested lime-treated samples subjected to successive wetting/drying cycles with more realistic water content variations. Cuisinier and Deneele (2008) performed suction-controlled oedometer tests on samples from an embankment three years after the construction. They concluded that the lime treatment efficiency could decrease with time due to successive wetting/drying cycles. Lastly, Tang et al. (2011) showed that successive wetting/drying cycles could lower the stiffness of a silty soil treated with 3% of quicklime.

When the effects of hydric stresses on a lime-treated soil are investigated, one major issue is the reasons that could explain the alteration of the soil behaviour. This implies the analysis of the physico-mechanical processes at micro-scale. In the above referred studies, no authors have investigated such mechanisms even if it is crucial to know if some minerals from lime hydration were washed away due to water exchange. Regarding this question, Le Runigo et al. (2009) investigated the effect of long term leaching on the physical properties of a silty soil treated with two dosages of lime. After 150 days of leaching, they concluded that there was likely some dissolved portlandite and cementitious compounds but they supposed that there was simultaneously a competition between dissolution and precipitation processes. Finally, their study evidenced that the weathering processes of lime-treated materials at micro-scale are very complex.

In this context, a study was undertaken to assess the long term hydro-mechanical properties of a quicklime-treated expansive clayey soil subjected to cyclic suction variations. Osmotic suction-controlled oedometers were used to determine the shrinkage/swelling behaviour of soils subjected to drying/wetting cycles in the range of suction comprised between about 8 MPa–0 MPa (suction range discussed in Section 2.2.2). To evaluate the effect of the cycle amplitude, severe hydric cycles corresponding to an alternation of oven drying and saturation were performed. At the end of the cycles, the mechanical properties were measured and compared to those of the intact specimens. The effect of quicklime dosage (i.e. 2% and 5% quicklime) and curing time (i.e. 0, 28 and 180 days), corresponding to the time during which the lime-treated samples were stored before the imposition of the cycles, were considered. Moreover, to study the effect of drying/wetting cycles on the soil fabric, pore size distribution (PSD) was investigated by mercury intrusion (MIP) tests. To interpret the quicklime-treated soil fabric after hydric cycles, the study of Stoltz et al. (2012) that examines the effect on both wetting and drying paths on the quicklime-treated soil fabric will be considered. At last, by coupling macroscopic aspects with fabric changes, the weathering process of lime-treated clayey soil was discussed.

2. Materials and methods

2.1. Tested materials

The studied soil was an expansive clayey soil sampled in the eastern part of France (Table 1). This soil is an inorganic clay of high plasticity (CH group symbol) according to the Unified Soil Classification System. The clayey fraction (<2 μm) analysed by X-ray diffraction shows that it was mainly composed of smectite and muscovite minerals with a small quantity of chlorite. The lime used in this study contained 94% quicklime (CaO). The Atterberg limits of the lime-treated soil evidenced a significant increase of the liquid and plastic limits, which is typical with this kind of clayey soil.

For the sample preparation, the water content of the clayey soil was adjusted to reach the optimum water content of compaction which depended on the considered quicklime content (Table 2). After a storage period of 24 h to homogenise the moisture content, the soil and the quicklime were mixed thoroughly. The mixture was left 1 h in an airtight container before compaction to allow the development of immediate reactions between the quicklime and soil particles. Then, the mixture was statically compacted in a mould to the target dry density (Table 2). When a curing period prior to testing was required, the compacted samples were wrapped in plastic sheets to prevent any water loss and kept at 20 ± 1.5 °C.

2.2. Experimental techniques

Three types of oedometer tests were used: constant rate of strain (CRS) test to follow the kinetic of the increasing mechanical performances of lime-treated soils; standard oedometer test to assess the mechanical performances of lime-treated soils at high effective stresses and osmotic oedometer tests including wetting/drying cycles.

2.2.1. Mechanical tests

In this study the effect of quicklime treatment on the tested samples was evaluated through oedometer tests with the determination of swelling potential and yield stress. To monitor the variation of yield stress as a function of time, CRS oedometer tests were carried out in a modified Rowe cell on lime-treated samples for various quicklime dosages comprised between 0 and 5% and various curing times comprised between 1 h and 360 days. The initial height of the samples was \( h_0 = 1.9 \pm 0.10 \) cm and the diameter was equal to 7.6 cm. The CRS test consists in compressing at constant rate of vertical strain a fully saturated sample placed in an oedometric cell. The progressive loading applied to the sample results in an increase of total vertical stress \( \sigma \) and pore water pressure \( u_b \) at the base of the sample whilst drainage takes place at the top. Following Wissa et al., 1971, who suggested that the soil can be supposed to be a linear material provided that the rate of strain is slow enough to keep the ratio \( u_b/\sigma \) less than 0.05, it is possible to relate the void ratio to an average effective stress. In this case, the average effective stress is given by the following equation:

\[
\sigma_v = \sigma_v - 2/3u_b
\]

where \( \sigma_v \) is the total vertical applied stress and \( u_b \) is the pore pressure measured at the base of the specimen. To meet this ratio of 0.05, a rate of vertical strain of 0.07/\text{min} was suitable for the CRS tests on the studied quicklime-treated materials.

In this study, CRS tests lasted less than 5 h. It was therefore possible to monitor accurately the variation with time of yield stress of the tested lime-treated materials even with very short curing time (i.e. 1 h, 1 day).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Main geotechnical properties of the clayey soil in this study.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Properties</td>
<td>Natural soil</td>
</tr>
<tr>
<td>Geotechnical</td>
<td></td>
</tr>
<tr>
<td>Passing sieve</td>
<td>90</td>
</tr>
<tr>
<td>80 μm (%)</td>
<td>–</td>
</tr>
<tr>
<td>Clay size content</td>
<td>70</td>
</tr>
<tr>
<td>(&lt;2 μm) (%)</td>
<td>–</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.675</td>
</tr>
<tr>
<td>Gs (–)</td>
<td></td>
</tr>
<tr>
<td>Liquid limit (%)</td>
<td>71</td>
</tr>
<tr>
<td>Plastic limit (%)</td>
<td>29</td>
</tr>
<tr>
<td>Plasticity index (%)</td>
<td>42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Compaction characteristics under normal Proctor energy of the quicklime-treated samples.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quicklime content (% CaO dry weight)</td>
<td>0.0</td>
</tr>
<tr>
<td>Maximum dry density ( \rho_d ) (Mg·m(^{-3}))</td>
<td>1.45</td>
</tr>
<tr>
<td>Optimum water content ( w_0 ) (%)</td>
<td>26.5</td>
</tr>
</tbody>
</table>
Because the maximum stress of the CRS devices (i.e., 2 MPa) was exceeded after 60 days of curing, standard oedometer tests were performed for extended curing time from 60 to 360 days.

2.2.2. Drying/wetting cycle imposition procedures

Suction controlled oedometers were used to perform most of the cyclic drying/wetting experiments. In this technique, a semi-permeable membrane is introduced between the solution of macromolecules (i.e., Polyethylene glycol, PEG) and the unsaturated soil sample. This membrane prevents the macromolecules from moving towards the sample but allows water exchange. Water movements and thus suction variations are controlled by the osmosis phenomenon: the higher the solution concentration, the higher the imposed suction (Williams and Shaykewich, 1969). A similar device of the osmotic oedometer proposed by Kassiff and Ben Shalom (1971) and used by several authors (e.g., Delage et al., 1992; Cuisinier and Masrouri, 2005) was used. In the device, a normal stress of 7 kPa was imposed on the top of the sample to ensure a good contact between the bottom of the sample and the semi-permeable membrane. In the experiments, cycles were performed between 8 MPa and null suction. It is worth noting that the suction range of 0 to 8 MPa represents realistic variations of suction in areas with Mediterranean climate. Soil water retention curves of the treated-materials showed that the range of suction variation corresponds to a moisture variation comprised between 10 and 15%. As the soil matrix suction before the application of hydric cycles are inferior or equal to 2 MPa and the air entry value of the quicklime-treated materials is below than the suction of 8 MPa, the first suction imposition, i.e., 8 MPa, conducted to soil drying, i.e., decrease of water content (Stoltz et al., 2012).

A second procedure was also retained to impose cyclic drying and wetting. It is derived from those proposed by Khattab (2002) and Guney et al. (2007), both being very close to the ASTM D559-03 standard. The quicklime treated samples in standard oedometer cells were alternatively immersed in tap water and placed in an oven at 60 °C to impose rather severe cycles to the samples. A normal stress of 4.6 kPa was applied to the samples due to the self-weight of the steel jack set on the top of the sample during the experiments.

For both types of procedures, sample height variation was monitored as a function of the number of cycles. After the imposition of the desired number of cycles, the samples were loaded under null suction to determine the yield stress. In both cases, thin specimens (initial height of the samples was H0 = 10 ± 1 mm) were employed to decrease the time to reach water pressure equilibrium. The typical duration of the wetting stage was one week to reach the imposed water content equilibrium, and the deformation stabilization obtained by the monitoring of the sample height variation and generally obtained after 3 days for both types of cycles. The duration of the drying stage was one week for the controlled suction cycles, whereas it was only 3 days for the severe cycles. First a drying stage cycle was applied to the samples followed by a wetting stage to complete the cycles.

2.2.3. Fabric determination

The mercury intrusion porosimetry (MIP) was selected to investigate the fabric of the samples. In the MIP method, the mercury pressure is increased by steps, and the intruded volume of mercury is monitored for each pressure increment. Assuming that the soil pores are cylindrical flow channels, Washburn’s equation is used to determine the pore radius associated with each mercury pressure increment:

$$r = \frac{2T_s \cos \alpha}{P}$$

where r is the entrance pore radius, T_s is the surface tension of the liquid (0.485 N m⁻¹ for mercury and 0.07275 N m⁻¹ for water), α is the contact angle of the fluid-to-solid interface (0° for air–water whilst 140° is average for mercury–air interface in soils) and P is the pressure difference between the two interfaces (Pa). To further interpret the MIP data, Juang and Holtz (1986) have proposed the determination of the pore-size density (PSD) function of the sample as follows:

$$f(\log r) = \frac{\Delta V_i}{\Delta(\log r)}$$

where ΔV_i is the injected mercury volume at a given pressure increment corresponding to pores that have an entrance pore radius of \(r_i \pm (\Delta(\log r_i)) / 2\).

Due to technical requirements, the MIP test must be conducted on completely dried soil samples. For our study, freeze-drying technique was selected, an alternative to oven drying, to prevent the effects of shrinkage on drying. The soil specimen was quickly frozen with liquid nitrogen (−196 °C) and then placed in a freeze-drier for at least 72 h for the sublimation of the water before mercury injection.

3. Impact of quicklime treatment on swelling and yield stress

The goal of this part was to determine the quicklime dosages and the curing times to perform the second part of the program consisting in studying the impact of wetting/drying cycles. To do so, the minimum amount of quicklime required to prevent swelling and to initiate a significant increase in yield stress was determined. Then, a second amount of quicklime that induced pozzolanic reactions over a longer period was determined.

Compacted samples were prepared with quicklime content comprised between 0 and 5% by dry weight according to their compaction characteristics (Table 2), and cured at constant water content up to 28 days. After curing, the samples were inundated in oedometer cells to determine their swelling potential \(\Delta H/H_o\) measured with null lateral strains and with a normal pressure of 4.6 kPa applied to the sample due to the self-weight of the steel jack set above the sample top. The results show that 1% of quicklime permitted to reduce the swelling potential of the selected soil down to 0.1% (Table 3). This effect of quicklime treatment on swelling potential was effective before one day of curing (Table 4). It is worth noting that a too low amount of quicklime (e.g., 0.5%) reduced swelling but not prevented it. These results showing that quicklime addition to expansive soil enables to prevent swelling are coherent with those obtained by previous studies (Ashraf and Walker, 1963; Nabantoglu and Tuncer, 2001).

After the swelling potential determination, that takes approximately 3 days, the samples were loaded to determine their yield stresses. These results were compared to the intrinsic compression line (ICL) (Burland, 1990) of the untreated soil determined from an oedometer test conducted on an untreated sample prepared at 1.5 times the liquid limit and to the oedometric compression curve of the compacted untreated soil (Figure 1). Thus, it was possible to assess the impact of compaction and quicklime treatment on compression behaviour of the expansive soil selected in this study. The treatment induced an increase of the yield stress that increased with the amount of quicklime. This increase in yield stress results from the formation of cementitious compounds through pozzolanic reactions as demonstrated by several researchers (e.g., Diamond and Kinter, 1965; Eades and Grim, 1966).

To analyse these results, it was necessary to account for the influence of cementitious bonds and soil density on the behaviour of the quicklime-treated samples. In the case of structured soils, Leroueil and
Vaughan (1990) defined a “structure permitted space” in the plane e – log σ' corresponding to the compression curve of bonded materials that have their yield stress located on the right side of the ICL. In this case, the term “structure” is used to define the combination of “fabric” (the arrangement of the component particles), and “bonding”, the inter-particle forces that are not of a purely frictional nature (Lambe and Whitman, 1969). In this way, the behaviour of a lime-treated soil can be analysed similarly to the one of a structured soil, the main difference being the time dependency of the behaviour according to the pozzolanic reactions progress. Thus, the yield stress could be a mean of quantification of the “structure effect” (fabric and bonds) for lime-treated soils. Nevertheless, the samples treated with various quicklime contents could have different densities. From the studied clayey soil, it is observed that the higher the lime content, the higher the void ratio (Table 2), reflecting the macroscopic impact of lime treatment on soil fabric. This observation is well-known for lime-treated materials (Bell, 1996; Nalbantoglu and Tuncer, 2001). The yield stress does not quantify separately the “fabric effects” including “density effect” at macro-scale that is related to the stress history of the soil or the swelling/shrinkage phenomena and the “bonding effect” due to bonds between soil particles. To attempt the assessment of the amount of cementitious products, the stress sensitivity factor S_y (Burland et al., 1996; Cotecchia and Chandler, 2000; Gasparre and Coop, 2008), defined as the ratio between the yield stress σ_y of a “structured material” to the vertical stress σ_0 on the Intrinsic Characteristic Line (ICL) for the same void ratio, can be used. However, although this standardisation by the void ratio enables to remove some “fabric effects” at macro-scale (i.e. void ratio), it does not remove some “fabric effects” at micro-scale (e.g. soil particle arrangement may vary for the same void ratio) to only assess the amount of bonds. But, it can be supposed that, for lime-treated materials with the same void ratio, the “fabric effects” at micro-scale (e.g. pore size distribution) are negligible compared to the “bonding effects”. Therefore the stress sensitivity can be considered as a practical mean to compare the amount of cementitious products of lime-treated materials with various densities. Moreover, it can be observed that lime addition to soil changes its mineralogy due to reactions between clay particles and lime, which may change the ICL of the treated material. It is assumed that the studied lime dosages are not enough to profoundly change all the soil minerals and thus, if lime treatment effects on soil structure (fabric and bonds) can be fully removed, by wetting–drying cycles for example, the ICL of the lime-treated material will be almost superimposed with that of the untreated material. An example of the assessment of the stress sensitivity is shown on Fig. 2.

Yield stresses (Figure 3a) and stress sensitivities (Figure 3b) were then assessed from oedometric curves. It is observed on Fig. 3a that an increase of the quicklime content from 0 to 2% induced an increase of the yield stress from 0.035 MPa to 0.95 MPa. When the quicklime content increased from 2% to 5%, the yield stress remained stable at about 1 MPa. Nevertheless, the stress sensitivity displayed on Fig. 3b increased from 3.7 to 9.8, which shows an increase in the amount of cementitious bonds in the case of the sample treated with 5% of quicklime. The initial density of the material with 5% of quicklime is lower than the one of the material with 2% of quicklime (Table 2), which may explain the equivalent yield stress for the two treated materials at 28 days of curing.

The evolution of the yield stress and stress sensitivity (Figure 4) for samples treated with 2 and 5% was characterised. Similar kinetic in the increase of yield stress as a function of curing time was observed for both quicklime dosages up to 28 days (Figure 4a). Nevertheless, after 28 days of curing, only the yield stress of the material treated with 5% quicklime content still increased. For the material treated with 2% quicklime content, it is shown on Fig. 4b that the stress sensitivity increased from 1 to 4 respectively between the curing times of 0 to 7 days and was nearly stabilised for higher curing times (i.e. 28 and 360 days). This may indicate that for the quicklime dosage of 2%, the available quicklime was almost totally consumed after 28 days of curing. In the case of a treatment with 5% quicklime content, the stress sensitivity increased from 2.5 to 18.4 respectively between the curing times of 0 day to 360 days. The increasing quicklime dosage from 2% to 5% induced physico-chemical reactions over a longer period. Unlike the yield stress that presented similar absolute values for the two quicklime-treated materials between 0 and 28 days of curing, the stress sensitivity was at least 5 times higher for the 5% quicklime dosage than for the 2% quicklime dosage, whatever the curing time.

These results show that 2% of quicklime is the minimum amount to cancel the swelling potential of the selected soil and to initiate pozzolanic reactions that could lead to a significant improvement of mechanical compressive characteristics. Regarding the yield stresses after 28 days of curing, i.e. in the short term, the dosages 2% and 5% of quicklime are equivalent. Deeper analysis shows that the lower compaction density of the sample treated with 5% quicklime content is counterbalanced by higher stress sensitivity mainly provided by cementitious compounds. In the long term, only the dosage of 5% of quicklime allows the yield stress to increase because of the pozzolanic reactions which take place at least until 360 days.

Table 4

<table>
<thead>
<tr>
<th>Curing time (days)</th>
<th>0</th>
<th>1</th>
<th>7</th>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔH/H₀ (%) (2% CaO)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(σ' = 4.6 kPa)</td>
<td>1.5</td>
<td>0.2</td>
<td>0.0</td>
<td>0.4</td>
</tr>
<tr>
<td>ΔH/H₀ (%) (5% CaO)</td>
<td>0.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Fig. 1. Compression curves of quicklime-treated materials for various quicklime contents (28 days of curing time) obtained from classical oedometric tests and compared to the intrinsic compression line (ICL) and the compacted soil at optimum moisture content (OMC).

Fig. 2. Determination of the stress sensitivity S_y from the ICL and an oedometric curve.
4. Effect of drying/wetting cycles on the hydro-mechanical behaviour

In the following, the irreversible shrinkage/swelling strains and the mechanical performances after hydric cycles of the selected soil treated with 2 and 5% of quicklime are compared.

Three curing times prior to the beginning of the imposition of drying and wetting cycles were selected. 0 day and more precisely 1 h were retained since only a few amount of cementitious compounds had been formed, thus it will permit to depict to what extent the cycles were likely to alter kinetic of performance improvement with time.

A curing period of 28 days was also selected since for both quicklime dosages, the yield stress was of the same order of magnitude whereas the stress sensitivity, i.e. an estimate of the amount of cementitious bonds, was two times greater for 5% of quicklime. The last selected curing time was 180 days to study the effect of an increase of the stress sensitivity, and thus an estimate of the amount of cementitious products, for the material with 5% of quicklime. The volumetric behaviour and the mechanical aspects are considered successively. In each case, the impact of both procedures of wetting and drying cycles was assessed.

4.1. Swelling and shrinkage behaviour

The variations in height (ΔH/H₀) of the quicklime-treated materials according to the number (nₖ) of controlled suction cycles are plotted on Fig. 5. The first drying conducted to a significant shrinkage whatever the quicklime content and the curing time (ΔH/H₀ comprised between −4% and −6%). So, although quicklime addition to the clayey soil prevented the swelling, it did not reduce significantly the amplitude of shrinkage upon drying from initial suction up to 8 MPa. After the first drying, the wetting stage induced a limited swelling, leading to irreversible shrinkage strains at the end of the first cycle. It can be noticed that the higher the quicklime content, the lower the shrinkage/swelling amplitude. With an increasing number of cycles, no significant alteration of the shrinkage/swelling amplitude was observed. The behaviour of the materials was almost elastic after the first cycle. No significant effect of the curing time prior the application of the cycles was evidenced. It is worth noting that the treated-materials with a very short curing time before the first drying presented a similar volumetric behaviour than those with longer curing times. So, it can be supposed that the first drying phase did not conduct to a loss of Ca²⁺ brought by quicklime even if this drying phase occurred rapidly after the treatment. Thus, these tests evidenced quicklime treatment positive effects on volumetric behaviour of the tested soil which remained stable even after the imposition of 5 cycles.

The vertical strains of the two quicklime-treated materials exposed to severe cycles (nₖ), corresponding to successive oven drying and saturation, are displayed on Fig. 6. The first drying stage conducted to shrinkage of the samples with similar amplitude than the one observed in the case of controlled suction drying/wetting cycles. The following wetting stage (nₖ = 1) led to a significant swelling of the material treated with 2% quicklime content whilst the material treated with 5%
quicklime exhibited a slight swelling. Nevertheless, Fig. 6 shows a progressive increase in the irreversible swelling strains as a function of the number of cycles. At the end of the severe cycles, irreversible swelling strains were obtained for both quicklime-treated materials. To conclude, the soil swelling stabilisation brought by quicklime addition was practically cancelled from the first severe hydric cycle, whatever the quicklime content and the curing time. However, the 5% high quicklime content permitted to reduce the amplitudes of swelling/shrinkage and limit the final value of the irreversible swelling strain.

These results show that the experimental procedure to evaluate the durability of quicklime treatment effects when treated materials are subjected to drying/wetting cycles is a key issue. Regarding the type of hydric cycles, irreversible shrinkage strains were obtained in the case of controlled suction amplitude whereas irreversible swelling strains were obtained at the end of the successive severe amplitude. Considering that one of the soil improvements by quicklime addition is to stabilise the soil swelling, it can be concluded that severe cycles led to a stronger weathering of the material.

4.2. Alteration of compression behaviour

After the imposition of the suction cycles, the samples were loaded, a key question being the potential alteration of their mechanical performances. The compression behaviour of samples subjected to cycles was compared to one of the samples cured at constant water content and not subjected to drying/wetting cycles (Figures 7 and 8). Results are analysed as a function of the method used to impose the drying/wetting cycles.

The imposition of five drying and wetting cycles between suctions of 8 and 0 MPa led to a significant alteration of the compression behaviour of the samples treated with 2% of quicklime (Figures 7a) even if the void ratios of materials subjected to hydric cycles were close to those of materials not subjected to hydric cycles. Regarding the influence of curing time, the increasing curing period from 28 to 180 days did not enable the treated-material to better resist versus cycles. This could be explained by the stress sensitivity that remained constant between 28 and 180 days of curing at constant water content (Figure 4). The compression curves determined after cycles show that, when the normal stress reached the yield stress (about 0.3 MPa), the curves merged the ICL line. This may indicate that the soil recovered its intrinsic mechanical behaviour (compression index, etc.) after the imposition of the wetting and drying cycles when the soil is treated with 2% of quicklime, which justifies the use of the ICL of the untreated material as a reference. Regarding the materials treated with 5% quicklime content, the imposition of 5 drying and wetting cycles between suctions of 8 and 0 MPa led to a significant modification of the compression behaviour (Figure 7b) even if the void ratio of the samples was of the same order of magnitude of their initial void ratio. At high normal stress, the curves merged those of the materials cured at constant water content. So, the loss of performance due to the cycles was limited and there were some remaining stiff cementitious compounds in the samples subjected to cycles. For both lime dosages 2% and 5%, it is worth noting that the materials with a very short curing time before the first drying presented a similar mechanical behaviour than those with longer curing times. So, if an amount of free lime was not hydrated after 1 h of curing, the first and the following drying phases did not prevent lime hydration and pozzolanic reactions during the following wetting phases.

The imposition of severe cycles was accompanied by a progressive increase of the void ratio of the samples treated with 2% of quicklime, with the increasing number of cycles (Figures 6 and 8a). The severe cycles induced a dramatic loss of yield stress. Extended curing time prior to the application of the wetting and drying cycles did not enable
the treated-material to better resist against severe cycles. The compression behaviour (Figure 8b) of the materials treated with 5% of quicklime subjected to severe cycles was also determined. It appeared that the severe cycles provoked a decrease of the yield stress compared to the samples cured at constant water content.

To assess the influence of the quicklime dosage and curing time on the compression behaviour, yield stress and the stress sensitivity factor of the samples were compared as a function of the time elapsed between the compaction of sample and the beginning of the compression (Figure 9). For example, let us consider the case of a quicklime-treated sample cured for 28 days. This sample was then subjected to 5 wetting and drying cycles which took 70 days. Thus, the oedometric compression started 98 days after its preparation.

In the case of the samples treated with 2% of quicklime, the strong decrease in yield stress, and stress sensitivity (Figure 9a and c), indicates that hydric cycles induced a dramatic loss in structure brought by quicklime addition. The compression behaviour (Figure 8a) of the quicklime-treated materials subjected to severe cycles was close to one of the materials subjected to controlled suction cycles (Figure 7a), thus indicating that the effect of quicklime treatment was cancelled by the wetting and drying cycles, regardless the method employed to impose those cycles. In practical application, even if this lime dosage increased the mechanical performances, it was not sufficient to let the treated soil to resist to environmental actions. For the samples treated with 5% of quicklime (Figure 9d), the stress sensitivity was divided by a factor of 3 to 4 depending on the curing time after suction controlled cycles, whilst it was divided by a factor of 8 to 10 for severe cycles. In this case, the degradation is a function of the type of wetting and drying cycles. For this quicklime dosage, regarding the curing time at constant water content, a long curing period did not permit the treated soil to better resist to hydric cycles. But, even if no curing period was respected before the first cycle, the treated material obtained however some mechanical performances practically in a same extent than those of the treated-material with longer curing periods. In practical application, this tends to show that a special care is necessary after lime-treated material compaction on site to protect it versus drying, because without a following wetting phase the pozzolanic reactions may not occur.

The results demonstrated that wetting and drying cycles could dramatically lower the yield stress of quicklime-treated expansive soil. The dosage and the type of cycle appeared to be key parameters. Even for the controlled suction hydraulic cycles, strong degradation of the yield stress and of the stress sensitivity factor characteristics could be observed whilst the efficiency of the treatment on volumetric behaviour remained unchanged. The process that could be put forward to explain such degradation was not related solely to the macroscopic swelling and shrinkage behaviour since the degradation was almost similar in both cases whilst suction controlled cycles were performed with limited volumetric modifications. It can be supposed that the loss of stress sensitivity is due to microscopic phenomena of physico-chemical processes. To attempt to answer this question, some microstructural investigations were carried out as presented in the last part of this paper.

4.3. Discussion about the alteration process

The major difference between the two types of cycles, that is to say controlled suction cycles and severe cycles was evidenced on the volumetric behaviour. For the two quicklime dosages, 2% and 5% of quicklime, the severe cycles led to a progressive accumulation of irreversible swelling of the samples whereas the controlled suction cycles conducted to a slight irreversible shrinkage after the first cycle, the behaviour remaining elastic after the first cycle. In the severe cycles, the dried samples, due to oven drying, are successively inundated by water unlike in the controlled suction cycles where the amount of water exchange was very low. So, it can be supposed that the great water exchange in the case of severe cycles conducted to a loss of the Ca$^{2+}$ brought by quicklime, which was not the case for the controlled cycles.
suction cycles. This loss of Ca\textsuperscript{2+} may explain the recovery of swelling potential of the treated soil and the observed irreversible swelling strains at the end of the cycles.

Considering separately the quicklime dosages 2% and 5%, the effects of hydric cycles on the compression behaviour of the treated-materials were close for the two types of cycles. To further explain the weathering of cementitious bonds at micro-scale, MIP tests were performed on the two quicklime-treated materials cured during 28 days and not subjected to drying/wetting cycles. For these tests, the soil matric suctions, measured with filter paper method on another samples treated with 2% and 5% quicklime content, were equal to 1 MPa and 0.9 MPa respectively (Stoltz et al., 2012). Secondly, other MIP tests were performed on two similar samples but that were subjected to 1 controlled suction drying/wetting cycle. Lastly, two MIP tests were performed on samples subjected to 5 controlled suction drying/wetting cycles. At the end of the only one cycle or the 5 cycles, the samples were in a saturated state (suction $s = 0$ MPa).

Fig. 10 presents the results of MIP tests performed on the selected samples. The fabric of the two quicklime-treated materials presented a similar type of structure consisting of two classes of pores. This type of structure is usually observed on compacted clayey soils and is called “a double structure” (e.g. Diamond, 1971; Ahmed et al., 1974; Lloret et al., 2003; Delage et al., 2006). The smallest pores (micro-pores) correspond to the pores inside the aggregates, whilst the largest pores (macro-pores) are the spaces between these aggregates. For the quicklime-treated materials subjected to one controlled suction cycle, their fabrics presented few internal changes although it seems that, in both cases, the microporosity is slightly shifted towards the smallest pores. For quicklime-treated material with 2% quicklime content subjected to five controlled suction cycles, an increase of the amount of macropores was evidenced, possibly due to bond breakage, whilst the microporosity remained stable. This fabric alteration could explain the structure degradation observed by the mechanical tests. For quicklime-treated material with 5% quicklime content, the fabric did not present significant alteration compared to the two other fabrics. Thus, structure degradation of the tested materials could be a combination of several processes including physico-chemical processes (bond removal by washing, carbonation, etc.) that remain to be investigated.

5. Conclusion

This study intended to highlight the impact of successive drying/wetting cycles on the behaviour of a quicklime-treated compacted expansive clayey soil. The relevance is to quantify the quicklime-treated soil weathering by applying drying/wetting cycles with a realistic amplitude (i.e. 8 MPa–0 MPa) rather than a severe amplitude (i.e. oven drying – 0 MPa). The effect of quicklime content (i.e. 2% and 5% CaO) and curing time (i.e. 0, 28 and 180 days) were considered. Both the volumetric and the compression aspects were considered. To analyse the results in the framework of structured soils that defines “soil structure” as a combination of “fabric” and “bonds”, the stress sensitivity parameter (Burland et al., 1996) was used. The stress sensitivity is assumed to be an estimate of the amount of bonds resulting from cementitious products.

Regarding the effect of quicklime-treatment on the volumetric and the compression behaviour, it has been shown that:

- Quicklime treatment permitted to prevent the swelling potential of the expansive soil.
- The increasing quicklime dosage up to 5% conducted to an increase of the stress sensitivity, which shows that quicklime addition permitted to develop cementitious bonds by pozzolanic reactions. These pozzolanic reactions occur over a longer period when quicklime dosage increases.

Concerning the impact of drying/wetting cycles, the following conclusions can be drawn:

- The successive severe cycles led to irreversible swelling strains unlike the controlled suction cycles that led to irreversible shrinkage strains. Regarding that one of the soil improvement by quicklime addition is to stabilise volume change due to water content variation, it can be concluded that, in both cases, the hydric cycles do not permit to keep this improvement on the long term. The increasing quicklime content from 2% to 5% CaO reduced the amplitude of volumetric variations but no effect of curing time was evidenced.
- From a mechanical point of view, both type of cycles induced a strong decrease of the stress sensitivity. The role of the quicklime

![Fig. 10. Effect of controlled suction (0–8 MPa) drying/wetting cycles on the microstructure of the quicklime-treated materials 2% CaO (a and b) and 5% CaO (c and d).](image-url)
content was significantly evidenced. Indeed, high quicklime content (i.e. 5%) permitted to maintain some cementitious bonds whereas they were completely lost for the low quicklime content (i.e. 2%). For practical application, this conclusion shows that, for a given expansive soil, a minimum lime dosage is required to maintain its mechanical performances stable over time. However, no effect of curing time was evidenced whatever the quicklime dosage.

- The microstructural characterization after successive hydric cycles shows that the material with 2% CaO presented an increase of the amount of the largest pores, possibly due to bond breakage, which could explain the degradation of mechanical properties. For the material treated with 5% CaO, the few internal changes tended to show that the degradation of mechanical properties may be due to some other phenomena like physico-chemical processes (carbonation, etc.).

This study shows that volumetric and mechanical behaviour and microstructural effects should be considered together to assess the weathering of treated material subjected to hydric cycles. However, the bond loss may be due to other factors which require complementary physico-chemical analysis to better understand the weathering processes. These weathering processes should be taken into account in the design of structure including soil treatment.

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