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CHEMO-MECHANICAL MODELLING OF LIME TREATED SOILS

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Abstract. Lime treatment has been widely used to improve mechanical properties of soils. However, less has been done to account for the effect of the treatment on constitutive relationships. In this study, a comprehensive programme of isotropic consolidation tests and drained triaxial experiments were designed and carried out on saturated specimens of a silt treated with quicklime. The chemical composition in hydrates, portlandite, and carbonates was determined using thermogravimetric analysis and differential thermal analysis. The modifications to the mechanical parameters of the soil were evaluated in the framework of the Cam Clay elastoplastic model. The experimental results revealed that the addition of lime leads to the modification of the critical state. For concentrations in lime higher than 1%, the treated specimens displayed a different normal compression line compared to the untreated state. Chemical analysis revealed the production of cementitious compounds for every concentration tested. A constitutive model was proposed to describe the observed behaviour of lime treated soils in the framework of the Structured Cam Clay. The model accounts for the modifications on the mechanical parameters of the soil. A chemo-mechanical coupling was established between the yield stress and the mass concentration in cementitious compounds.

Keywords: quicklime; mechanical behaviour; chemo-mechanical coupling; constitutive modelling.

1. INTRODUCTION

For economic and environmental considerations, engineering companies are highly encouraged to use on site materials to construct earth structures like embankment, river levees, earth dams, etc. For soils with low mechanical characteristics, lime treatment (CaO) is an efficient method to improve their properties and allow their use in geotechnical structures (e.g. Little, 1995). It is of the greatest interest to account for artificial treatments in geotechnical design.

When added to the soil, quicklime reacts with the free water to produce hydrated lime, known as portlandite ($Ca(OH)_2$). Then, calcium cations Ca^{2+} and hydroxides anions HO^- are released in the soil, which increase the pH of the porous medium. Cation exchange process combined with the presence of large amounts of calcium ions adsorbed on the clay particles surface lead to a reduction of the size of the double diffuse layer of the clay particles. This results in the lowering of the repelling forces between clay particles and thereby gives rise to the flocculation of the clay particles. It is generally accepted that cation exchange and flocculation processes occur immediately after the addition of lime, and result in a decrease of the soil plasticity (e.g. Eades and Grim, 1966; Rogers and Glendinning, 1996). Moreover, the addition of lime leads to a high pH environment (near 12.4), which enables the dissolution of both silica and alumina present in the soil (e.g. North et al., 2008). These later react with the calcium. As a result of these chemical reactions, known as pozzolanic reactions, cementitious compounds such as calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH), and calcium aluminosilicate hydrates (CASH) can be formed (e.g. Metelková et al., 2012; Pomakhina et al., 2012). The formation of these compounds leads to a modification in the soil mechanical properties (e.g. Little, 1995).

Many authors have studied the mechanical behaviour of materials treated with lime or cement (e.g. Malandraki and Toll, 2001; Cuisinier et al., 2008; Consoli et al., 2011; Cuisinier et al.,

2011; Stoltz et al., 2012; Oliveira et al., 2013). In most of the cases, the addition of quicklime leads to a modification of the mechanical parameters such as the cohesion, the friction angle, and the yield stress. Improvements obtained with lime treatment regarding tensile strength and Young's modulus have been integrated in the design of pavement (Thompson, 1965). Nevertheless, less has been done to consider these improvements in the design of structures for global stability or settlement analysis. This last issue could be associated with the fact that there is no specific constitutive relationship accounting for the specific aspects of the mechanical behaviour of lime-treated soils, and for the coupling between physicochemical processes and mechanical behaviour. Such relationship is required to account for the treatment in the design of geotechnical structures, in the short term and also to foretell the long term behaviour of earthen structures built with lime-treated soils.

Lime treatment induces the formation of cementitious compounds that bind soil particles. Some studies (Leroueil and Vaughan, 1990; Liu and Carter, 2003) have shown that naturally structured soils and artificially treated materials have common mechanical features, treatment appearing to create a “structure” in the soil. In this paper, “structure” refers to the combination of the fabric and the bonding of the soil skeleton (Burland, 1990). Fabric accounts for the arrangement of particles, which depends on the state of compaction, and their geometry.

Several constitutive models have been proposed for structured materials (Gens and Nova, 1993; Cotecchia and Chandler, 2000; Vatsala et al., 2001; Nova et al., 2003; Baudet and Stallebrass, 2004; Lee et al., 2004). Liu and Carter (2002) proposed a Cam Clay based constitutive model for structured materials, adding only three extra parameters to the original Modified Cam Clay (Roscoe and Burland, 1968). Since then several enhancements (Horpibulsuk et al., 2010a; Suebsuk et al., 2011, 2010) have been proposed. Most of these constitutive models use the destructured state as reference to describe the mechanical

behaviour of the structured soils. The destructured state accounts for the intrinsic parameters of the soil, and especially the geometry of the particles. Artificial cementation arising from the treatment involves chemical reactions that could alter the soil particles. This aspect should be considered to adapt the existing framework to the case of lime stabilised compacted soils. A key aspect of lime stabilization is the fact that the structure, and thus the mechanical behaviour, relies on physicochemical processes that need to be quantified. Based on the soil water transfer method (Zhu et al., 2007), Chiu et al. (2009) used centrifuge method to determine the variation of soil water composition in dredged materials with high water content. A different approach was used in this study to assess the chemical composition of lime treated compacted soils with lower water content. Chemical composition in hydrates and portlandite in cement and concrete was successfully determined using thermogravimetric analysis (TGA) and differential thermal analysis (DTA). Some studies (Horpibulsuk et al., 2010b; Maubec, 2010) have shown the suitability of this method to determine the chemical modifications following a lime treatment. The objective of the paper is to investigate the couplings between mechanical behaviour and physicochemical processes, and then to introduce these aspects in a constitutive relationship. To account for the treatment in the structure design, a chemo-mechanical coupling is required to predict the mechanical improvements resulting from the addition of a given amount of lime. This implies a good understanding of the mechanical behaviour of lime treated soils and of the chemical modifications arising from the treatment. To this end, the paper aims at shedding light on three aspects:

- a) How can the effects of a lime treatment on a material and its consequences on the mechanical properties be described?
- b) How can a chemo-mechanical coupling be established between the mechanical improvements and the chemical modifications?

c) How can a lime treated soil be modelled?

2. MATERIAL AND METHODS

2.1. Tested soil and specimens preparation

The material selected in this study is a silt from the East part of France. The mineral composition is as follows: quartz (55%), kaolinite (12%), feldspar (11%), illite (10%), montmorillonite (4%), chlorite (1%), goethite (6.4%), and carbonates (0.6%). The lime fixation point is near 1% and was determined according to the ASTM Standard D6276 (2006). Before proceeding to the moulding of the specimen, the material was first heated at 60°C and then sieved to get particles smaller than 2 mm. The main characteristics of the soil are listed in Table 1.

Five concentrations in quicklime were considered in this study: 0, 0.5, 1, 2, and 5% expressed on a soil dry weight basis. The non-treated specimen (0%) was used as reference to assess the mechanical and the chemical modifications arising from the treatment.

All the specimens used for the mechanical characterisation of the soil, with or without treatment, were prepared at the same moisture content and dry density. Indeed, the optimal moisture content and maximum dry density of the silt used in this study were not significantly modified by the lime-treatment (Table 2). Therefore, all the specimens have been prepared at the same mean initial water content of 20% and a dry density of 1.68 Mg.m⁻³. Thus, any modification of the mechanical behaviour of the soil after treatment can be attributed mostly to structure modification, i.e. fabric and bonding, but not to density.

The soil was first prepared at the target water content. After an equilibration period of several days, quicklime was added to the soil, both being mixed thoroughly until a homogenous mixture was obtained. Before the specimens were compacted, the quicklime-soil mixture was sealed in hermetic plastic bags for one hour before compaction. Then, 35mm x 70mm triaxial specimens were statically compacted up to target the dry density. After these steps, the actual

water content of the specimens was determined. It varied between 19.6% and 20.2%. The specimens were then wrapped in plastic bags to prevent any exchange with the atmosphere, and a curing time of 28 days was respected.

2.2. Drained triaxial experiments

To determine the shape of the yield function, three kinds of stress path were performed in this study: isotropic consolidation, drained paths (σ'_3 constant), and same stress ratio paths ($\eta = p'/q = 0.39$).

Saturation was achieved by first creating an upward water flow through the specimen. This was achieved by applying a pressure gradient between the bottom and the top of the specimen. Deaerated water was used to maximize the dissolution of air. Pore pressure was then increased in three stages (Table 3) while maintaining a constant effective mean stress.

After every triaxial experiment, saturation of the specimen was checked by determining the degree of saturation with paraffin according to the ASTM Standard D7263-09 (2009).

To ensure full drainage of the specimens during the experiments, filter paper strips were applied to the surface of the specimens. Low rates of consolidation and axial deformation were chosen in order to generate small excess of pore pressure. An external probe was used to measure accurately the pore pressure at the bottom of the specimen during shearing.

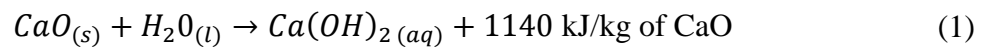
For isotropic consolidation, a rate of 3.47 Pa.s^{-1} was chosen and specimens were consolidated up to a total effective stress of 3,320 kPa. Validation tests were performed to verify that there was no excess pore pressure in the specimen under this rate.

Triaxial compression tests were carried out with an axial displacement rate of $2.46 \text{ }\mu\text{m.min}^{-1}$, leading to an axial deformation of about 5% per day. Validation tests have confirmed the suitability of this rate. All the experiments were performed following the procedure described

in the ASTM Standard D7181-11 (2011). The initial conditions of the specimens are given in Table 4.

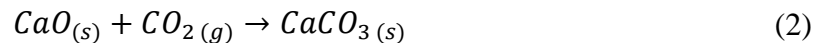
2.3. Monitoring of the physicochemical reactions

Lime can react with soil particles to produce only three different chemical compounds: portlandite, hydrates (cementitious compounds CAH, CSH, and CASH), and carbonates. Portlandite is produced by the hydration of quicklime introduced in the material, according to the following reaction:



Dissociation of portlandite induces release of hydroxide anions, thus increasing the pH. Once a suitable pH is reached in the porous medium, portlandite is consumed by pozzolanic reactions to produce hydrates.

Due to the high sensibility of lime with carbon dioxide, we also considered the evolution in carbonates in the specimens. Carbonates are produced by reaction of quicklime and carbon dioxide according to the following reaction:



Therefore, to monitor the progress of the physicochemical processes in the specimens, it is necessary to determine the amount of portlandite, hydrates, and carbonates.

Thermogravimetric analysis (TGA) consists of measuring the mass loss of a specimen as a function of the increasing temperature. This test is completed with a differential thermal analysis (DTA), which compares any temperature difference between the specimen and an inert reference (MacKenzie, 1970). Each peak on the curves is correlated to a chemical compound. Using the associated mass loss, the mass concentration of the species can be estimated (Mackenzie, 1972).

TGA/DTA analysis was first used successfully to determine the chemical composition of cements and concretes in hydrated products, portlandite, and carbonates. Some studies have shown that the decarboxylation processes of these three compounds were associated with three temperature domains (Das et al., 1996; Saikia et al., 2002; Alarcon-Ruiz et al., 2005). Recent studies have applied TGA/TDA analysis on artificially treated soils to assess the mass concentration in portlandite (unreacted lime), cementitious compounds, and calcium carbonates in artificially treated specimens (Horpibulsuk et al., 2010b; Maubec, 2010). The procedure for the determination of the chemical composition is illustrated on Figure 1. TGA/DTA analysis provides three different curves: the variation of the energy (TDA), the mass loss (TG), and the first derivative of the weight loss (DTG). First, TDA and DTG results were used to determine accurately the three temperature domains (Table 5). Each peak on the DTG curve (Figure 1) is associated to a variation of the weight loss and corresponds to the decarboxylation of a chemical compound. The two temperatures delimitating the peak correspond to the temperature domains, and the chemical compound is assumed to have completely disappeared when the upper temperature limit was reached. Therefore, the variation of weight (TG curve) between these two temperatures gives the mass of the chemical compound. Analyses were performed using a NETZSCH STA 409 PC/PG device. The accuracy of the TGA weighing scale was 0.01 mg.

3. RESULTS

The experiments performed in this paper aimed: 1) to determine the effects of the quicklime on the intrinsic parameters of soils, 2) to assess the shape of the yield function in order to choose the most suitable model for lime-treated soils, and 3) to measure the concentrations in portlandite, hydrates, and carbonates of a lime-treated specimens.

3.1. Mechanical behaviour

3.1.1. Isotropic consolidation

To assess the effects of the treatment on the yield stress, isotropic consolidation tests were performed on 0, 0.5, 1, 2, and 5% lime-treated specimens. For concentrations greater than 1%, three isotropic tests were carried out to ensure the highest representativeness. Only one result is reported in Figure 2. The yield stress was determined using Casagrande's method.

Yield occurred for an effective mean stress of 177 kPa for the untreated specimen (Figure 2). When lime was added to the soil, the yield stress was increased even for low lime content of 0.5%. The evolution of the yield stress as a function of the lime content is given in Figure 3.

For concentrations between 0.5% and 2%, the gradient of the curve was significantly increased. Above 2% the slope decreased, and as concentration increased, yield stress value seemed to approach 2,000 kPa. One can note that there exists a one-to-one correspondence between the lime content and the resulting yield stress after 28 days of curing.

At yield the treated soil displayed higher specific volume compared to the reference state (Figure 2). This could be due to the structure. When the effective mean stress reached the yield stress, the additional specific volume began to decrease as the effective mean stress was increased until a new normal compression line was reached, parallel to the one of the non-treated state. This decrease of the additional specific volume corresponds to the loss of the structure. Only 0.5% lime treated specimen has shown to completely lose the additional specific volume at high mean stresses. In this case, the normal compression line matched the one of the non-treated state. For lime contents greater than 1%, specimens did not appear to converge to the non-treated state for mean effective stresses lower than 3,320 kPa. At some point, a secondary normal compression line, different from the non-treated state but still parallel, seems to be reached. This feature is particularly noteworthy for the 1% treated specimen. The 2% and 5% lime-treated specimens have shown such significant

improvements in mechanical properties that this feature could not be seen because of the limits of the applied pressure in triaxial cell (3,500 kPa).

3.1.2. Shear behaviour

Drained triaxial experiments were performed to assess the shape of the yield function and the gradient of the critical state line. Different stress paths and pre-consolidation pressures were performed on 0, 1, 2, and 5% lime-treated specimens.

The shear behaviour of the non-treated specimens (Figure 4a) was significantly improved with 5% lime treatment (Figure 4b). For an isotropic pre-consolidation pressure of 245 kPa, the yield locus of the reference state was reached for a deviatoric stress of 400 kPa. With 5% of lime, this value was increased up to 1,250 kPa.

As the confining pressure was increased, one can see that contraction behaviour was gradually observed. This feature was particularly marked for the 5% lime-treated specimens (Figure 4b). For a confining pressure of 20 kPa, the specimens had significant dilation behaviour. As the confining pressure increased, the specimens started to exhibit a contraction behaviour.

3.2. Yield loci for lime-treated soils

Yield loci and critical states were determined from the previous results and plotted in the (p', q) plane (Figure 5). Results from the same stress ratio paths ($\eta = 0.39$) were also included.

To use these results in a constitutive model, yield loci and critical states were determined based on the critical state theory (Muir Wood, 1991). Yield was assumed to occur when plastic deformation appeared ($\varepsilon_q^p > 0$), and critical state was reached when:

$$\frac{\partial p'}{\partial \varepsilon_q} = \frac{\partial q}{\partial \varepsilon_q} = \frac{\partial v}{\partial \varepsilon_q} = 0 \quad (3)$$

The elastic domain showed to be significantly increased with increasing the lime content, without any significant anisotropic behaviour, and the critical state lines appeared to be modified with the treatment. The gradient and the y-intercept of the critical state lines both increased with increasing the amount in lime. The results appear to be well described by the Modified Cam Clay model.

3.3. Chemical analysis

The results of TGA/DTA tests to measure the chemical composition in portlandite, hydrates, and carbonates on 0, 0.5, 1, 2, and 5% lime treated specimens are plotted in Figure 6. The y-axis values correspond to the variation of mass compared to the untreated specimen.

The chemical composition of the soil appears to be modified after addition of lime and a curing time of 28 days. Concentration in portlandite is increased only for lime contents greater than 0.5%. The latter is used by pozzolanic reactions to produce cementitious compounds. For a concentration of 0.5%, all the portlandite produced by the hydration of the quicklime was used by pozzolanic reactions.

Concentration in hydrates was increased for all the lime contents. It is worth to note that there is a one-to-one correspondence between the lime content and the mass concentration in hydrates. The fact that neo-portlandite is measured for high lime contents means that pozzolanic reactions are unfinished and concentration in hydrates is likely to evolve if the curing time is extended.

Concentration in carbonates revealed to be increased only for high lime contents. Probability of carbonation is higher at high lime contents and this could explain the sudden formation of carbonates. It is more likely that these new carbonates are the result of the reaction of the unhydrated lime with the atmospheric carbon dioxide.

4. DISCUSSION

In the first part of the discussion section, the influence of lime on the mechanical properties of soil is discussed. Moreover, a quantification of the physicochemical processes induced by lime-treatment after 28 days of curing is provided. The main objective of the second part of the discussion section is to highlight the coupling between the mechanical behaviour and the amount of the different compounds formed during the curing period, and to propose an equation for the coupling. In the last part, a framework to account for the effects of the treatment on the intrinsic parameters is proposed.

4.1. Influence of lime on mechanical parameters

Lime has appeared to modify the mechanical behaviour of the soil, and parameters like the position of the virgin consolidation line and the slope of the critical state line, M . Following the definition proposed by Burland (1990), “structure” consists of the combination of the cementation and the fabric. In the case of structured soils, Leroueil and Vaughan (1990) showed that isotropic consolidation induced a progressive loss of structure at yield. After total loss of structure, the normal compression line of the structured soil converges to that of the same soil prepared in a remoulded state before compression.

In the case of a treated soil with quicklime, this assumption was only valid for a soil treated with 0.5% of quicklime. Isotropic consolidation results revealed a full loss of the structure for 0.5% lime treated specimens, which displayed the same virgin consolidation line as the non-treated specimens at a mean stress value of 1,340 kPa. However, for concentrations greater or equal than 1% it could be assumed that the position of the virgin consolidation line following the destructuration is shifted. This feature is usually controlled by the fabric, and especially by the geometry of the particles. Therefore, one may assume that the geometry of the particles is modified by the treatment and is lime content-dependant. This observation is corroborated by the drained triaxial test results, which revealed a modification of the critical state line. The increase of the y-intercept is a result of the cementation (Figure 5). The slope

of the critical state line, M , is a direct function of the angle of friction (Schofield and Wroth, 1968) and describes the relationship between the particles and their geometry. A modification of M (Table 6) implies a modification of the angle of friction, and therefore of the geometry of the particles (Stocker, 1974; Wissa, 1965). Therefore, in the framework of the lime-treated soils, our results show that these mechanical parameters are modified.

Parameters like M and the normal compression line are considered as intrinsic and invariable in the framework of naturally structured soils (Liu and Carter, 2002). For these materials, reconstituted state is used as reference to assess the mechanical improvements due to the structure. In this case, the soil particles have already experienced cementation processes. The soils particles of the untreated state have not been in contact with lime and hence no modification of their geometry has occurred. From this point of view, the use of the mechanical parameters of the non-treated state as reference appears to be inappropriate to assess the effects of the treatment. This is important to describe the improvements, but not enough to fully describe the mechanical behaviour of treated soils. To do this, an intermediate state appears to be required, the destructured state of the lime treated soil. This state would account for the effects of the treatment on the mechanical parameters.

These results have showed that mechanical parameters of a soil are modified with the addition of quicklime. Therefore, it appears of the greatest interest to compare those with the chemical modifications arising from the treatment.

4.2. Correlation between physicochemical processes and yield stress

It has appeared that lime treatment modified the nature of the soil by altering parameters classically considered as intrinsic. In the light of these results and using the approach proposed by Chiu et al. (2009), the yield stress was chosen as the mechanical coupling parameter. Apart from controlling the size of the initial yield function in most of the constitutive models, there is a one-to-one correspondence between the lime content and the

resulting yield stress. The mechanical results and the chemical compositions are plotted in a scatterplot matrix (Figure 7) to assess the trends between the yield stress and the mass concentration in cementitious compounds, portlandite, and carbonates.

The trends between the yield stress and the portlandite, and carbonates and hydrates are given in Figure 7. The results show a linear correlation between the yield stress and the portlandite. Hydrates also appear to be linearly correlated to the yield stress. The production of hydrates was noted for every lime content and a one-to-one correspondence with the lime content. A second trend can be noticed between the yield stress and the portlandite. Chemical analysis revealed that all the portlandite has been consumed by pozzolanic reactions for low lime-contents ($< 0.5\%$). However, mechanical results showed that this lime-content is enough to increase the yield stress. Therefore, portlandite cannot be considered as a relevant parameter for a chemo-mechanical coupling.

Production of carbonates was only observed for concentrations greater than 2%, but mechanical improvements can be measured for small lime contents. Maubec (2010) has shown that the contribution of the carbonates in the mechanical behaviour can be neglected. For the same reasons as the portlandite, carbonates are not suitable for a chemo-mechanical coupling. Lime can be easily carbonated in contact with CO_2 (Equation 2).

In the light of these observations, mass concentration in hydrates is the only parameter systematically modified by the addition of lime and presenting a one-to-one correspondence with the lime content. Since yield stress has also a one-to-one correspondence with the lime content, a coupling between these two parameters appears to be the most relevant choice.

In order to establish a coupling, a relationship was established between yield stress and the mass concentration in hydrates. To model accurately a lime-treated soil, the regression function must fulfil the following criteria:

(a) The point of lime fixation describes the minimum lime-content required to measure mechanical improvements. Thus, for low concentrations in hydrates (<0.05%), regression function must show a low gradient.

(b) Above a critical lime content, yield stress does not increase anymore (Rotta et al., 2003). To account for this feature in the coupling, the interpolation function must converge to a finite value for high concentrations in hydrates.

To account for these two conditions, we chose a generalised logistic function (also known as Richards's curve) of the form:

$$\forall \Delta m_h \in \mathbb{R}^+ \quad f(\Delta m_h) = p_{y,min} + (p_{y,max} - p_{y,min}) \cdot \frac{1}{1 + e^{-\beta(\Delta m_h - \Delta x)}} \quad (4)$$

with:

- $p_{y,min}$ The lower asymptote
- $p_{y,max}$ The upper asymptote
- β The growth rate
- Δx Δm_h value for which the first derivative is maximum and $\frac{df^2}{d^2\Delta m_h} = 0$

Using a non-linear least square method, the 4 variables $p_{y,min}$, $p_{y,max}$, β , and Δx were calculated to determine the optimal set of parameters (Table 7) based on the results of the isotropic tests. For lime concentrations greater than 1%, three isotropic tests were performed to reduce the error. The interpolation appears to satisfactorily describe the results (Figure 8) and fulfil the conditions (a) and (b).

The same procedure can be applied to link the mass concentration in hydrates with the lime content. If introduced in the equation 7, this will result in a direct coupling between the amount in lime introduced in the soil and the resulting yield stress. This correlation is allowed

since there is a systematic one-to-one correspondence between all the variables, which proves that a robust coupling between the mechanical behaviour and chemical composition exists.

4.3. Modification of the Structured Cam Clay model for application on lime treated soils

Several studies (Leroueil and Vaughan, 1990; Liu and Carter, 2003) have shown that naturally structured soils exhibit similar behaviour to artificially treated materials. Under isotropic consolidation, structured and treated soils display at yield a higher void ratio compared to the remoulded/untreated state (Callisto and Rampello, 2004; Coop and Atkinson, 1993). This additional void ratio tends to disappear as the mean effective stress is increased to finally match the behaviour of the remoulded/untreated state (Burland et al., 1996). For drained experiments, Leroueil and Vaughan (1990) noted that a structured material exhibits a rate of maximum dilatation after the peak while this occurs before the peak for a non-structured material. Based on these considerations and the results of this study, one can assume that naturally structured soils and lime treated materials have a similar mechanical behaviour for both isotropic and shear stresses.

We propose in this paper a simple modification to the Structured Cam Clay model (SCCM) (Liu and Carter, 2002) to account for the effects of lime treatment on the intrinsic parameters. The SCCM was originally designed for naturally structured soils, but the results prove that it can be applied to lime treated specimen, provided that a modification is implemented to introduce the secondary normal compression line for lime treated materials.

The SCCM models structured soils by introducing an additional void ratio Δe to the Cam Clay equation of the void ratio as:

$$e = e^* + \Delta e = e^* + \Delta e_i \left(\frac{p'_{y,i}}{p'} \right)^b \xrightarrow{p' \rightarrow +\infty} e^* \quad (5)$$

where:

- e^* is the void ratio for the reconstituted soil,

- e_i is the additional void ratio at yield compared to the reconstituted soil at the same stress state,
- $p'_{y,i}$ is the yield stress of the structured soil, and
- b is the destructuring index.

The formulation of the additional void ratio is chosen to converge to zero for high levels of mean stress. In the case of a lime treatment, normal compression line appears to be vertically translated by a constant void ratio, called Δe_c . The modified equation of the additional void ratio can be written as follows:

$$\Delta e = \left[(\Delta e_i - e_c) \left(\frac{p'_{y,i}}{p'} \right)^b \right] + e_c \xrightarrow{p' \rightarrow +\infty} \Delta e_c \quad (6)$$

This formulation ensures the convergence toward the destructured state (intermediate state), rather than the untreated state. This additional parameter Δe_c can be measured from the same isotropic test used for the determination of e_i and $p'_{y,i}$. In the case where $\Delta e_c = 0$, equation (5) reverts back to the formulation of the MSCC. For use in constitutive modelling equation (5) can be written in an incremental form:

$$dv = -\lambda \frac{dp'}{p'} - (\Delta e_i - \Delta e_c) \cdot (p'_{y,i})^b \cdot b \cdot dp' \cdot (p')^{-b-1} \quad (7)$$

The first part is the classic incremental form of the normal compression line from the Cam Clay model and describes the untreated state. The second part adds the effects of the structure as an additional void ratio.

The suitability of this formulation for the 1% lime treated specimen of this study is given in Figure 9. Parameters used for the simulation are given Table 8.

5. CONCLUSION

This study has shown the potential of lime treatment to improve the mechanical properties of the materials initially unsuitable for geotechnical structures. Thus, a chemo-mechanical coupling to account for the treatment in the design is of the greatest interest.

This paper aimed first to describe in details the effects of lime on the mechanical behaviour of a soil and also on parameters usually considered as constant. The results have shown that there was an improvement of the mechanical parameters due to the chemical reactions occurring after the addition of the lime. For lime contents greater than 1%, the specimens converged toward a normal compression line different from the untreated state but parallel to it. Therefore, in the framework of the lime treated soils, the mechanical parameters of treated soils could be different from those of the untreated state.

The chemical composition of lime treated specimens has been successfully assessed using thermogravimetric and thermodifferential analyses. The results have shown that concentrations in cementitious compounds and portlandite increased with the lime content. They permitted to explain the mechanical results and especially the modification of some parameters such as the angle of friction. The production of the cementitious compounds involves several preliminary reactions where soil particles experience dissolution due to the high pH. From this point of view, the nature of soil is seriously altered, leading to an evolution of the mechanical parameters. Chemical results revealed that cementitious compounds were produced for every concentration tested. A chemo-mechanical coupling was established using a logistic function between the amount of cementitious compounds and the yield stress. The proposed equation appears to describe accurately the observations, and ensures a one-to-one correspondence between the mass concentration in cementitious compounds and the yield stress.

A modification of the formulation of the Structured Cam Clay model was proposed by introducing a new parameter Δe_c describing the position of the second normal compression line. Simulations proved the suitability of the new formulation for use in constitutive modelling.

The proposed coupling may be used to account for the treatment in the design of geotechnical structures. However, one must be aware of the durability of the treatment. The bonding structure resulting from chemical reactions occurring at high pH environment, and treated materials are often subjected to environmental conditions. For example, in the event of a continuous rainfall, water flow may occur changing the pH environment and altering the chemical equilibriums. This would result in the dissolution of the cementitious compounds and, therefore, in the extinction of the bonding structure. It is thus important to assess the durability for the treatment in the design of geotechnical structures.

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549

Table 1: Characteristics of the silt

Geotechnical properties	Value
Liquid Limit LL (%)	31.2
Plastic Limit PL (%)	7.8
Plasticity Index PI	23.4
Particle Density ρ_s (Mg.m ⁻³)	2.66
Methylene Blue Value (g/100 g of dry soil)	2.1
USCS ^a	ML
Physical chemistry properties	
pH (-)	5.7
Cation-Exchange Capacity (cmol+/100 g)	7.41
Carbonate Mass Concentration (%)	0.6
Initial conditions	
Dry density (Mg.m ⁻³)	1.68
Water content w (%)	20
Initial void ratio e_i (-)	0.6

^aUnified Soil Classification System

Table 2: Results of Proctor compression test for different concentrations in lime

Lime content (%)	Optimal moisture content (%)	Optimal dry density (Mg.m ⁻³)
0	17.9	1.76
1	18.8	1.72
2	20.3	1.68
3	20.9	1.64

Table 3: Saturation stages performed

	Stage 1	Stage 2	Stage 3
Duration (Days)	≈ 7	≈ 7	≈ 7
σ_3 (kPa)	50	100	200
P_{bottom} (kPa)	30	80	180
P_{top} (kPa)	20	70	170
$\overline{\sigma'_3}$ (kPa)	25	25	25

P_{bottom} : Pressure at the bottom of the specimen - P_{top} : Pressure at the top of the specimen

Table 4: Characteristics of the specimens

Lime content (%)	Water content (%)	ρ_d (Mg.m ⁻³)	e_0 (-)	Hydraulic Permeability k (m/s)
0	20.0	1.67±0.01	0.60±0.02	10 ⁻⁹ - 10 ⁻⁸
0.5	19.6	1.67±0.01	0.60±0.01	10 ⁻⁹ - 10 ⁻⁸
1	20.2	1.67±0.01	0.60±0.01	10 ⁻⁹ - 10 ⁻⁸
2	19.6	1.67±0.01	0.60±0.01	10 ⁻⁸ - 10 ⁻⁷
5	20.2	1.66±0.01	0.60±0.02	10 ⁻⁸ - 10 ⁻⁷

Table 5: Ranges of temperatures used for the determination of the TGA/DTA

Range of temperature	Chemical compound
20°C – 217°C	Free and adsorbed water
217°C – 350°C	Cementitious compounds
350°C – 610°C	Portlandite ($\text{Ca}(\text{OH})_2$)
610°C – 800°C	Carbonates (CaCO_3)

Table 6: Influence of lime on the mechanical properties

Parameters	Values				
	0 %	0.5 %	1 %	2 %	5 %
p'_y (kPa)	177	300	731	1,211	1,691
ν_0	1.602	1.609	1.612	1.606	1.626
λ	0.075	0.088	0.085	N/A	N/A
κ	0.005	0.005	0.005	0.005	0.005
M	1.092	N/A	1.136	1.246	1.464
φ (°)	27.5	N/A	28.5	31.1	36.0
c (kPa)	11.4	N/A	47.9	152.9	207.6

c : Cohesion, φ : angle of friction

Table 7: Optimal set of parameters for a logistic interpolation

Parameter	$p_{y,min}$	$p_{y,max}$	β	Δx	R^2
Value	100	2,000	17.4	0.16	0.95

Table 8: Parameters for the Structured Cam Clay model adapted for lime treated soils

MSCC parameters	Lime content				
	0 %	0.5 %	1 %	2 %	5 %
b	0.0	1.8	7.2	-	-
Δe_i	0.0	0.027	0.066	0.129	0.159
Δe_c	0.0	0.0	0.046	-	-

MSCC: Modified Structured Cam Clay

Figure 1: TGA/DTA results for a lime treated specimen with the three temperatures domains
— Hyd.: Hydrates, DTG: Differential Thermo Gravimetric, TGA: Thermo Gravimetric Analysis

Figure 2: Isotropic consolidation curves for five concentrations in lime

Figure 3: Evolution of the yield stress after 28 days of curing with the lime

Figure 4: Drained triaxial results on 0 % and 5 % lime treated specimens - ε_p : volumetric deformations, ε_a : axial strain, q : deviatoric stress

Figure 4a: Shear behaviour for untreated specimens

Figure 4b: Shear behaviour for 5 % lime treated specimens

Figure 5: Yield loci and critical states of 0 %, 1 %, 2 %, and 5 % lime treated specimens –
YL: yield loci, CS : Critical State, M: Gradient of critical state line

Figure 6: Influence of a lime treatment on the variation of the mass concentration in hydrates (cementitious compounds), portlandite, and carbonates for a curing time of 28 days. – Δm_p : Mass concentration in portlandite, Δm_h : Mass concentration in hydrates , Δm_c : Mass concentration in carbonates.

Figure 7: Scatterplot matrix between the yield stress and the mass concentrations in cementitious compounds, portlandite, and carbonates.

Figure 8: Logistic interpolation for a chemo-mechanical coupling – Δm_h : Mass concentration in hydrates

Figure 9: Isotropic compression for 0 % and 1 % lime treated specimens — MSCC : Modified Structured Cam Clay ; Δe_i : Additional void ratio at yield ; Δe_c : Vertical translation of the virgin compression line.

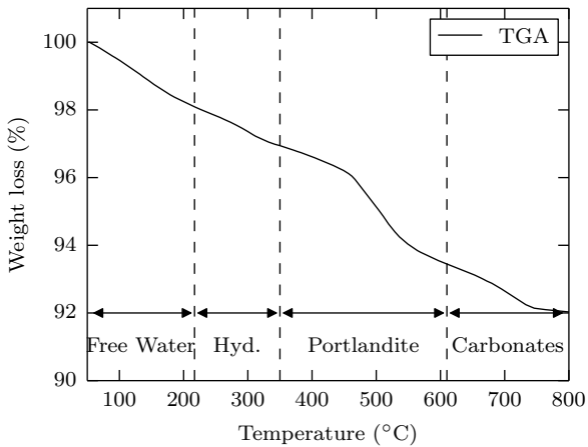
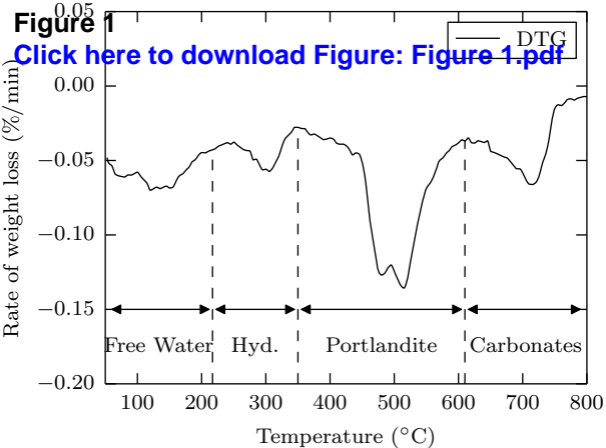


Figure 2

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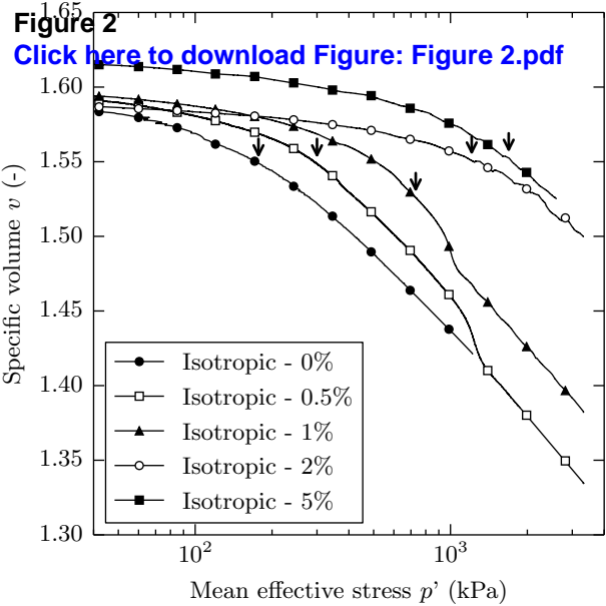


Figure 3

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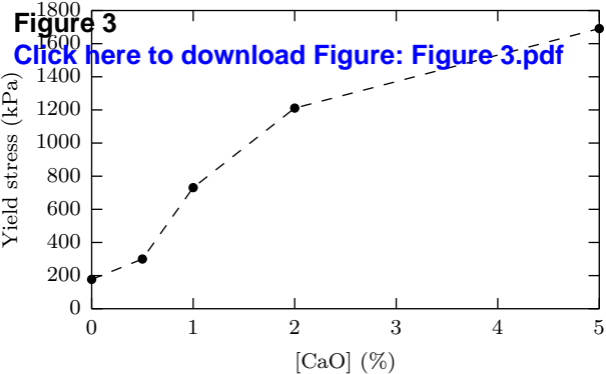
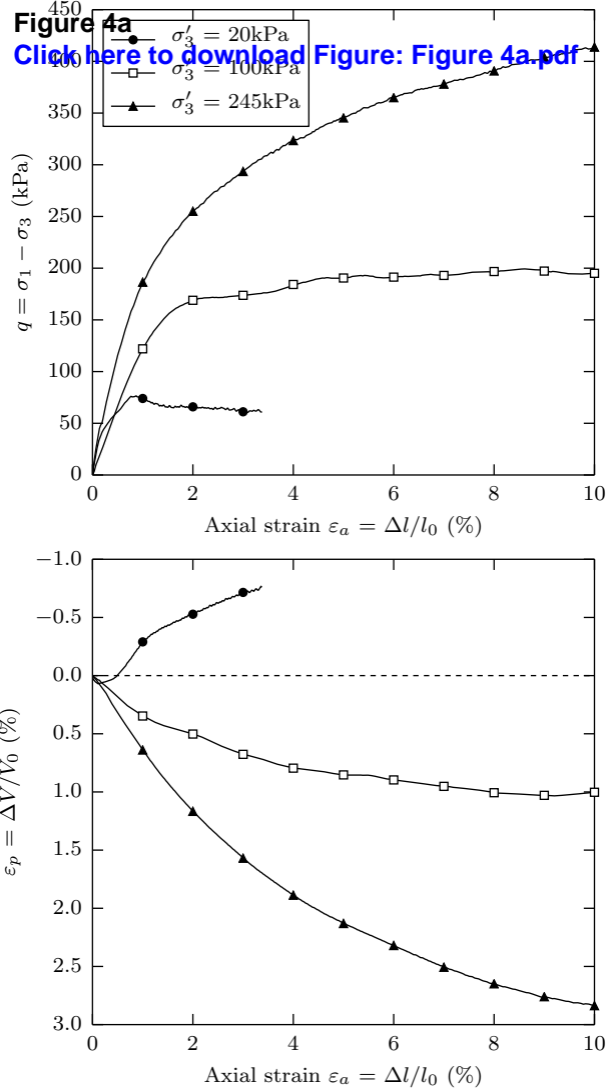


Figure 4a

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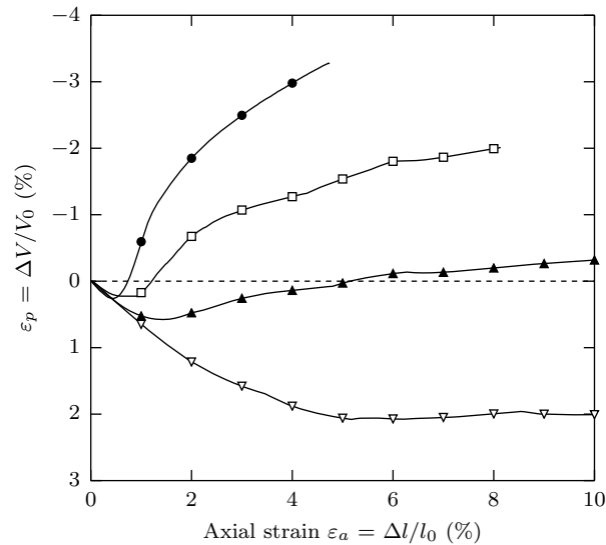
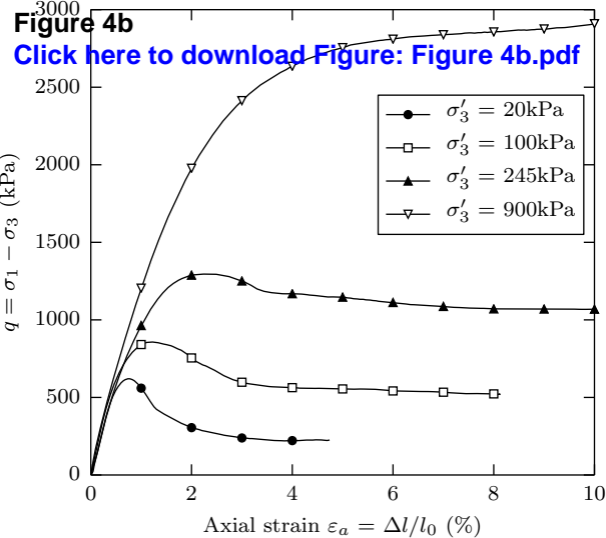
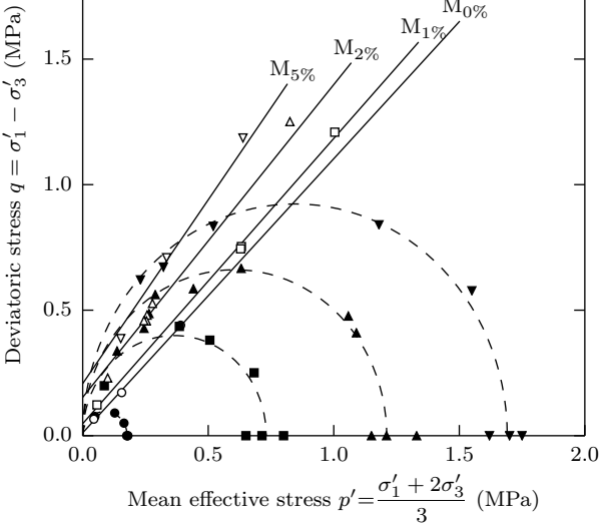


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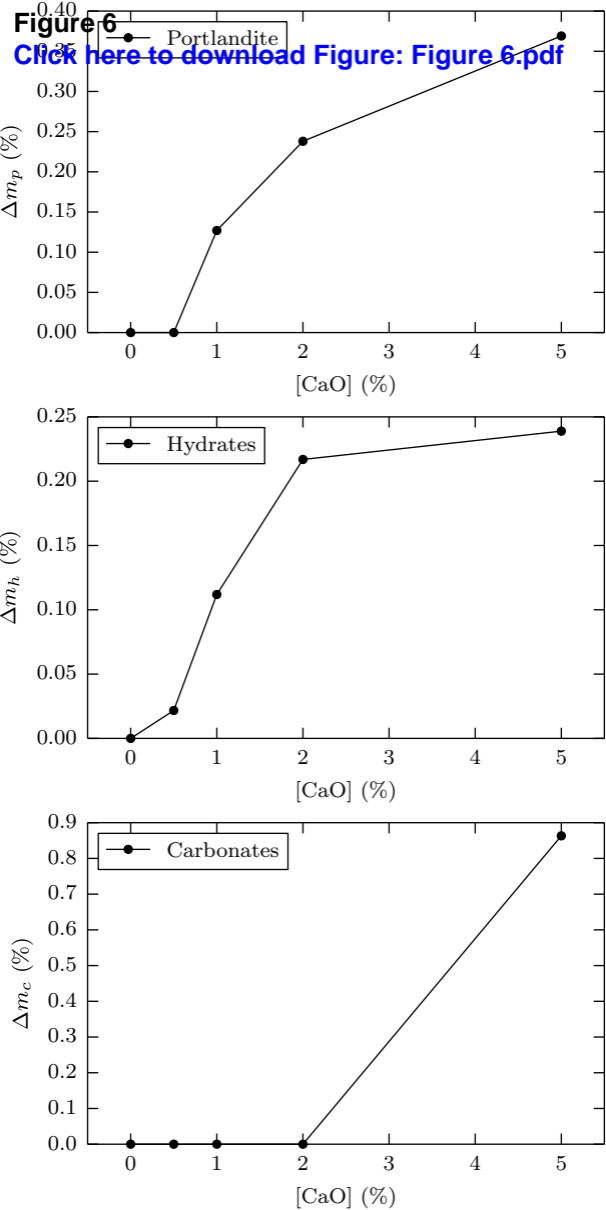


Figure 7

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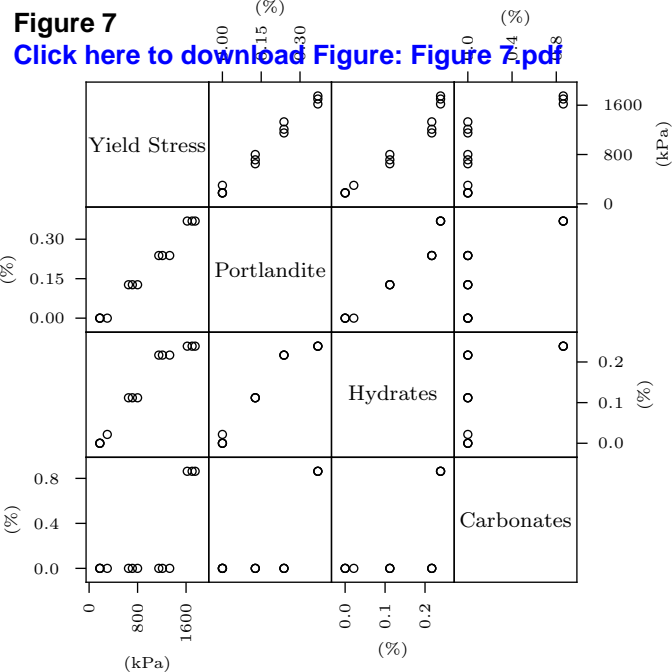


Figure 8

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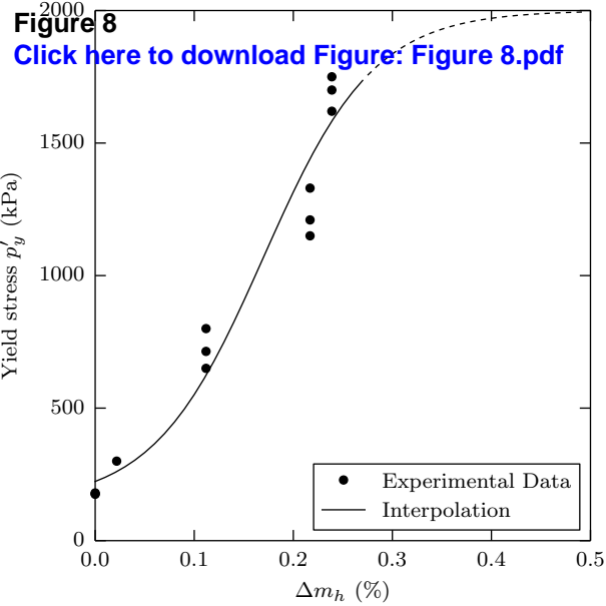


Figure 9
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