



HAL
open science

Chemo-mechanical modelling of lime treated soils

Vincent Robin, Olivier Cuisinier, Farimah Masrouri, A.A. Javadi

► **To cite this version:**

Vincent Robin, Olivier Cuisinier, Farimah Masrouri, A.A. Javadi. Chemo-mechanical modelling of lime treated soils. *Applied Clay Science*, 2014, 95, pp.211 - 219. 10.1016/j.clay.2014.04.015 . hal-01418282

HAL Id: hal-01418282

<https://hal.univ-lorraine.fr/hal-01418282>

Submitted on 5 Jul 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

CHEMO-MECHANICAL MODELLING OF LIME TREATED SOILS

V. Robin^{1,2}, O. Cuisinier¹, F. Masroui¹, A.A. Javadi²

¹LEMETA – UMR 7563 CNRS, Laboratoire d’Energétique et de Mécanique Théorique et Appliquée, Université de Lorraine, France

² Computational Geomechanics Group, Department of Engineering, University of Exeter, United-Kingdom

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

25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49

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

75 behaviour of the structured soils. The destructured state accounts for the intrinsic parameters
76 of the soil, and especially the geometry of the particles. Artificial cementation arising from
77 the treatment involves chemical reactions that could alter the soil particles. This aspect should
78 be considered to adapt the existing framework to the case of lime stabilised compacted soils.
79 A key aspect of lime stabilization is the fact that the structure, and thus the mechanical
80 behaviour, relies on physicochemical processes that need to be quantified. Based on the soil
81 water transfer method (Zhu et al., 2007), Chiu et al. (2009) used centrifuge method to
82 determine the variation of soil water composition in dredged materials with high water
83 content. A different approach was used in this study to assess the chemical composition of
84 lime treated compacted soils with lower water content. Chemical composition in hydrates and
85 portlandite in cement and concrete was successfully determined using thermogravimetric
86 analysis (TGA) and differential thermal analysis (DTA). Some studies (Horpibulsuk et al.,
87 2010b; Maubec, 2010) have shown the suitability of this method to determine the chemical
88 modifications following a lime treatment. The objective of the paper is to investigate the
89 couplings between mechanical behaviour and physicochemical processes, and then to
90 introduce these aspects in a constitutive relationship.

91 To account for the treatment in the structure design, a chemo-mechanical coupling is required
92 to predict the mechanical improvements resulting from the addition of a given amount of
93 lime. This implies a good understanding of the mechanical behaviour of lime treated soils and
94 of the chemical modifications arising from the treatment. To this end, the paper aims at
95 shedding light on three aspects:

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

100 c) How can a lime treated soil be modelled?

101 2. MATERIAL AND METHODS

102 2.1. Tested soil and specimens preparation

103 The material selected in this study is a silt from the East part of France. The mineral
104 composition is as follows: quartz (55%), kaolinite (12%), feldspar (11%), illite (10%),
105 montmorillonite (4%), chlorite (1%), goethite (6.4%), and carbonates (0.6%). The lime
106 fixation point is near 1% and was determined according to the ASTM Standard D6276
107 (2006). Before proceeding to the moulding of the specimen, the material was first heated at
108 60°C and then sieved to get particles smaller than 2 mm. The main characteristics of the soil
109 are listed in Table 1.

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

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

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

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

128 **2.2. Drained triaxial experiments**

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

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

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

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

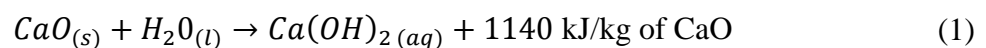
142 For isotropic consolidation, a rate of $3.47 \text{ Pa}\cdot\text{s}^{-1}$ was chosen and specimens were consolidated
143 up to a total effective stress of 3,320 kPa. Validation tests were performed to verify that there
144 was no excess pore pressure in the specimen under this rate.

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

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

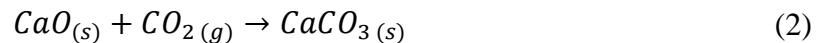
150 **2.3. Monitoring of the physicochemical reactions**

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



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

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



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

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

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

187 **3. RESULTS**

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

192 **3.1. Mechanical behaviour**

193 *3.1.1. Isotropic consolidation*

194 To assess the effects of the treatment on the yield stress, isotropic consolidation tests were
195 performed on 0, 0.5, 1, 2, and 5% lime-treated specimens. For concentrations greater than
196 1%, three isotropic tests were carried out to ensure the highest representativeness. Only one
197 result is reported in Figure 2. The yield stress was determined using Casagrande's method.

198 Yield occurred for an effective mean stress of 177 kPa for the untreated specimen (Figure 2).

199 When lime was added to the soil, the yield stress was increased even for low lime content of
200 0.5%. The evolution of the yield stress as a function of the lime content is given in Figure 3.

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

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

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

219 *3.1.2. Shear behaviour*

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

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

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

232 **3.2. Yield loci for lime-treated soils**

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

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

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

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

244 **3.3. Chemical analysis**

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

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

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

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

262 **4. DISCUSSION**

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

270 **4.1. Influence of lime on mechanical parameters**

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

278 In the case of a treated soil with quicklime, this assumption was only valid for a soil treated
279 with 0.5% of quicklime. Isotropic consolidation results revealed a full loss of the structure for
280 0.5% lime treated specimens, which displayed the same virgin consolidation line as the non-
281 treated specimens at a mean stress value of 1,340 kPa. However, for concentrations greater or
282 equal than 1% it could be assumed that the position of the virgin consolidation line following
283 the destructuration is shifted. This feature is usually controlled by the fabric, and especially
284 by the geometry of the particles. Therefore, one may assume that the geometry of the
285 particles is modified by the treatment and is lime content-dependant. This observation is
286 corroborated by the drained triaxial test results, which revealed a modification of the critical
287 state line. The increase of the y-intercept is a result of the cementation (Figure 5). The slope

288 of the critical state line, M , is a direct function of the angle of friction (Schofield and Wroth,
289 1968) and describes the relationship between the particles and their geometry. A modification
290 of M (Table 6) implies a modification of the angle of friction, and therefore of the geometry
291 of the particles (Stocker, 1974; Wissa, 1965). Therefore, in the framework of the lime-treated
292 soils, our results show that these mechanical parameters are modified.

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

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

307 **4.2. Correlation between physicochemical processes and yield stress**

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

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

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

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

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

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

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

340 (b) Above a critical lime content, yield stress does not increase anymore (Rotta et al.,
341 2003). To account for this feature in the coupling, the interpolation function must
342 converge to a finite value for high concentrations in hydrates.

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

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

345 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 $\frac{df^2}{d^2\Delta m_h} = 0$

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

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

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

356 **4.3. Modification of the Structured Cam Clay model for application on lime treated soils**

357 Several studies (Leroueil and Vaughan, 1990; Liu and Carter, 2003) have shown that
358 naturally structured soils exhibit similar behaviour to artificially treated materials. Under
359 isotropic consolidation, structured and treated soils display at yield a higher void ratio
360 compared to the remoulded/untreated state (Callisto and Rampello, 2004; Coop and
361 Atkinson, 1993). This additional void ratio tends to disappear as the mean effective stress is
362 increased to finally match the behaviour of the remoulded/untreated state (Burland et al.,
363 1996). For drained experiments, Leroueil and Vaughan (1990) noted that a structured
364 material exhibits a rate of maximum dilatation after the peak while this occurs before the
365 peak for a non-structured material. Based on these considerations and the results of this study,
366 one can assume that naturally structured soils and lime treated materials have a similar
367 mechanical behaviour for both isotropic and shear stresses.

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

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

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

375 where:

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

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

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

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

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

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

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

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

395
 396
 397

398

5. CONCLUSION

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

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

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

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

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

434

435

REFERENCES

436 Alarcon-Ruiz, L., Platret, G., Massieu, E., Ehrlacher, A., 2005. The use of thermal analysis in
437 assessing the effect of temperature on a cement paste. *Cem. Concr. Res.* 35, 609–613.
438 doi:10.1016/j.cemconres.2004.06.015

439 ASTM Standard D6276, 2006. Standard Test Method for Using pH to Estimate the Soil-Lime
440 Proportion Requirement for Soil Stabilization. pp. 1–4.

441 ASTM Standard D7181-11, 2011. Method for Consolidated Drained Triaxial Compression
442 Test for Soils. ASTM International, pp. 1–11. doi:10.1520/D7181

443 ASTM Standard D7263-09, 2009. Standard Test Methods for Laboratory Determination of
444 Density (Unit Weight) of Soil Specimens. ASTM International, pp. 1–7.
445 doi:10.1520/D7263-09

446 Baudet, B., Stallebrass, S., 2004. A constitutive model for structured clays. *Géotechnique* 54,
447 269–278.

448 Burland, J.B., 1990. On the compressibility and shear strength of natural clays. *Géotechnique*
449 40, 329–378.

450 Burland, J.B., Rampello, S., Georgiannou, V.N., Calabresi, G., 1996. A laboratory study of
451 the strength of four stiff clays. *Géotechnique* 46, 491–514.
452 doi:10.1680/geot.1996.46.3.491

453 Callisto, L., Rampello, S., 2004. An interpretation of structural degradation for three natural
454 clays. *Can. Geotech. J.* 41, 392–407. doi:10.1139/T03-099

455 Chiu, C.F., Zhu, W., Zhang, C.L., 2009. Yielding and shear behaviour of cement-treated
456 dredged materials. *Eng. Geol.* 103, 1–12. doi:10.1016/j.enggeo.2008.07.007

457 Consoli, N.C., Lopes, L. da S., Prietto, P.D.M., Festugato, L., Cruz, R.C., 2011. Variables
458 Controlling Stiffness and Strength of Lime-Stabilized Soils. *J. Geotech.*
459 *Geoenvironmental Eng.* 137, 628–632. doi:10.1061/(ASCE)GT.1943-5606.0000470

460 Coop, M.R., Atkinson, J.H., 1993. The mechanics of cemented carbonate sands.
461 *Géotechnique* 43, 53–67.

462 Cotecchia, F., Chandler, R.J., 2000. A general framework for the mechanical behaviour of
463 clays. *Géotechnique* 50, 431–447.

464 Cuisinier, O., Auriol, J.-C., Le Borgne, T., Deneele, D., 2011. Microstructure and hydraulic
465 conductivity of a compacted lime-treated soil. *Eng. Geol.* 123, 187–193.
466 doi:10.1016/j.enggeo.2011.07.010

467 Cuisinier, O., Masrouri, F., Pelletier, M., Villieras, F., Mosser-Ruck, R., 2008. Microstructure
468 of a compacted soil submitted to an alkaline PLUME. *Appl. Clay Sci.* 40, 159–170.
469 doi:10.1016/j.clay.2007.07.005

470 Das, S.K., Mitra, A., Das Poddar, P.K., 1996. Thermal analysis of hydrated calcium
471 aluminates. *J. Therm. Anal. Calorim.* 47, 765–774.

472 Eades, J.L., Grim, R.E., 1966. A quick test to determine lime requirements for lime
473 stabilization. *Highw. Res. Rec.* 139, 61–72.

474 Gens, A., Nova, R., 1993. Conceptual bases for a constitutive model for bonded soils and
475 weak rocks. *Geotech. Eng. hard soils-soft rocks* 1, 485–494.

476 Horpibulsuk, S., Liu, M.D., Liyanapathirana, D.S., Suebsuk, J., 2010a. Behaviour of
477 cemented clay simulated via the theoretical framework of the Structured Cam Clay
478 model. *Comput. Geotech.* 37, 1–9. doi:10.1016/j.compgeo.2009.06.007

479 Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., Raksachon, Y., Suddeepong, A., 2010b.
480 Analysis of strength development in cement-stabilized silty clay from microstructural
481 considerations. *Constr. Build. Mater.* 24, 2011–2021.
482 doi:10.1016/j.conbuildmat.2010.03.011

483 Lee, K., Chan, D., Lam, K., 2004. Constitutive model for cement treated clay in a critical
484 state frame work. *Soils Found.* 44, 69–77.

- 485 Leroueil, S., Vaughan, P.R., 1990. The general and congruent effects of structure in natural
486 soils and weak rocks. *Géotechnique* 40, 467–488.
- 487 Little, D.N., 1995. Stabilization of pavement subgrades and base courses with lime, National
488 Lime Association. Arlington.
- 489 Liu, M.D., Carter, J.P., 2002. A structured Cam Clay model. *Can. Geotech. J.* 39, 1313–1332.
490 doi:10.1139/T02-069
- 491 Liu, M.D., Carter, J.P., 2003. Volumetric Deformation of Natural Clays. *Int. J. Geomech.* 3,
492 236–252. doi:10.1061/(ASCE)1532-3641(2003)3:2(236)
- 493 MacKenzie, R.C., 1970. Differential Thermal Analysis. Volume 1 □ : Fundamental Aspects.
494 Academic Press London, London-New York.
- 495 Mackenzie, R.C., 1972. Differential Thermal Analysis. Vol. 2. Applications., Academic P.
496 ed. Academic Press London, London-New York.
- 497 Malandraki, V., Toll, D.G., 2001. Triaxial Tests on Weakly Bonded Soil with Changes in
498 Stress Path. *J. Geotech. Geoenvironmental Eng.* 127, 282–291.
- 499 Maubec, N., 2010. Approche multi-echelle du traitement des sols a la chaux. Etudes des
500 interactions avec les argiles. Thèse de Doctorat, Université de Nantes, France.
- 501 Metelková, Z., Boháč, J., Přikryl, R., Sedlářová, I., 2012. Maturation of loess treated with
502 variable lime admixture: Pore space textural evolution and related phase changes. *Appl.*
503 *Clay Sci.* 61, 37–43. doi:10.1016/j.clay.2012.03.008
- 504 Muir Wood, D., 1991. Soil Behaviour and Critical State Soil Mechanics.

505 North, J.M., Becker, J.G., Seagren, E.A., Ramirez, M., Peot, C., 2008. Methods for
506 quantifying lime incorporation into dewatered sludge. I: Bench-scale evaluation. J.
507 Environ. Eng. 134, 750–761.

508 Nova, R., Castellanza, R., Tamagnini, C., 2003. A constitutive model for bonded
509 geomaterials subject to mechanical and/or chemical degradation. Int. J. Numer. Anal.
510 methods Geomech. 27, 705–732.

511 Oliveira, P.J.V., Correia, A.A.S., Garcia, M.R., 2013. Effect of Stress Level and Binder
512 Composition on Secondary Compression of an Artificially Stabilized Soil. J. Geotech.
513 Geoenvironmental Eng. 139, 810–820. doi:10.1061/(ASCE)GT.1943-5606.0000762.

514 Pomakhina, E., Deneele, D., Gaillot, A.-C., Paris, M., Ouvrard, G., 2012. ²⁹Si solid state
515 NMR investigation of pozzolanic reaction occurring in lime-treated Ca-bentonite. Cem.
516 Concr. Res. 42, 626–632. doi:10.1016/j.cemconres.2012.01.008

517 Rogers, C.D.F., Glendinning, S., 1996. The role of lime migration in lime pile stabilization of
518 slopes. Q. J. Eng. Geol. Hydrogeol. 29, 273–284.
519 doi:10.1144/GSL.QJEGH.1996.029.P4.02

520 Roscoe, K.H., Burland, J.B., 1968. On the generalized stress-strain behaviour of wet clay.
521 Eng. Plast. 535–609.

522 Rotta, G. V, Consoli, N.C., Prietto, P.D.M., Coop, M.R., Graham, J., 2003. Isotropic yielding
523 in an artificially cemented soil cured under stress. Géotechnique 53, 493–501.
524 doi:10.1680/geot.2003.53.5.493

525 Saikia, N.J., Sengupta, P., Gogoi, P.K., Borthakur, P.C., 2002. Hydration behaviour of lime–
526 co-calcined kaolin–petroleum effluent treatment plant sludge. *Cem. Concr. Res.* 32,
527 297–302. doi:10.1016/S0008-8846(01)00676-7

528 Schofield, A.N., Wroth, C.P., 1968. *Critical state soil mechanics*. McGraw-Hill.

529 Stocker, P.T., 1974. Diffusion and diffuse cementation in lime and cement stabilised clayey
530 soils - studies of plasticity and aggregation. *Aust. Road Res.* 5, 51–75.

531 Stoltz, G., Cuisinier, O., Masrouri, F., 2012. Multi-scale analysis of the swelling and
532 shrinkage of a lime-treated expansive clayey soil. *Appl. Clay Sci.* 61, 44–51.
533 doi:10.1016/j.clay.2012.04.001

534 Suebsuk, J., Horpibulsuk, S., Liu, M.D., 2010. Modified Structured Cam Clay: A generalised
535 critical state model for destructured, naturally structured and artificially structured clays.
536 *Comput. Geotech.* 37, 956–968. doi:10.1016/j.compgeo.2010.08.002

537 Suebsuk, J., Horpibulsuk, S., Liu, M.D., 2011. A critical state model for overconsolidated
538 structured clays. *Comput. Geotech.* 38, 648–658. doi:10.1016/j.compgeo.2011.03.010

539 Thompson, M.R., 1965. *Shear strength and elastic properties of lime-soil mixtures*.
540 Washington.

541 Vatsala, A., Nova, R., Srinivasa Murthy, B.R., 2001. *Elastoplastic Model for Cemented Soils*.
542 *J. Geotech. Geoenvironmental Eng.* 127, 679–687.

543 Wissa, A.E.Z., 1965. *Effective stress-strength behavior of cemented soils*. Thesis (Sc. D.),
544 Massachusetts Institute of Technology.

545 Zhu, W., Zhang, C.L., Chiu, A.C.F., 2007. Soil–Water Transfer Mechanism for Solidified
546 Dredged Materials. J. Geotech. Geoenvironmental Eng. 133, 588–598.
547 doi:10.1061/(ASCE)1090-0241(2007)133:5(588)

548

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.

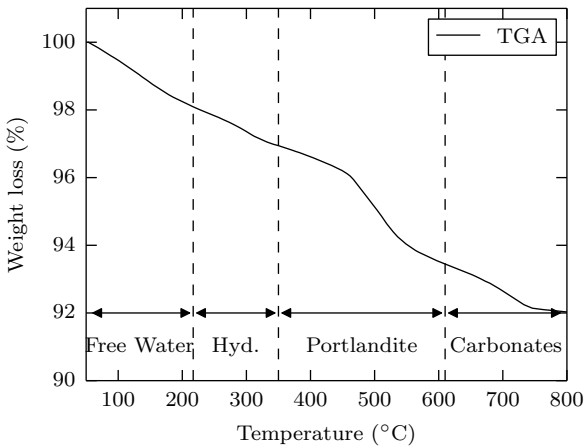
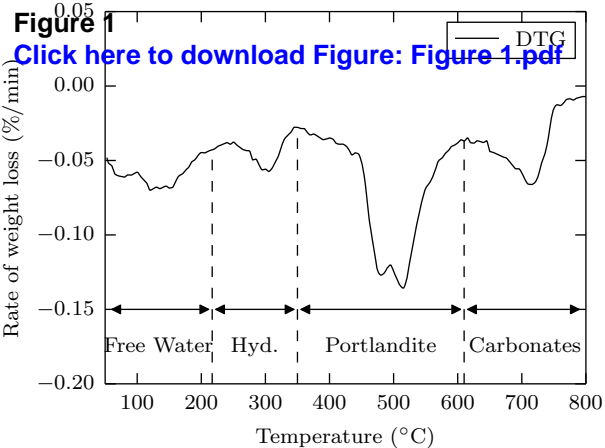


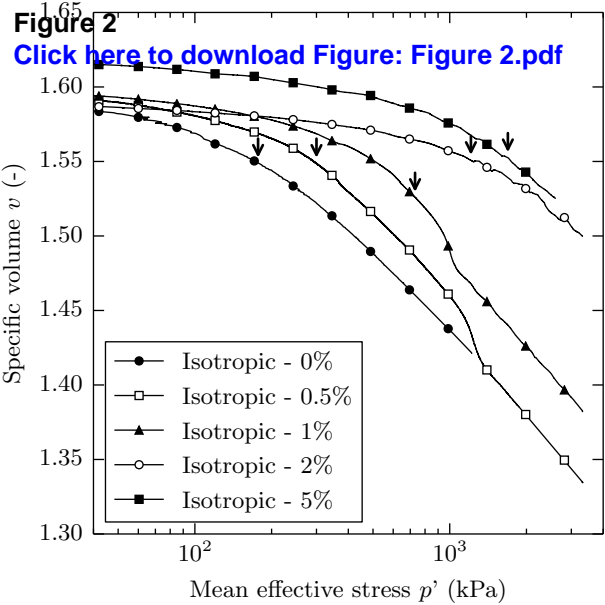
Figure 2[Click here to download Figure: Figure 2.pdf](#)

Figure 3

[Click here to download Figure: Figure 3.pdf](#)

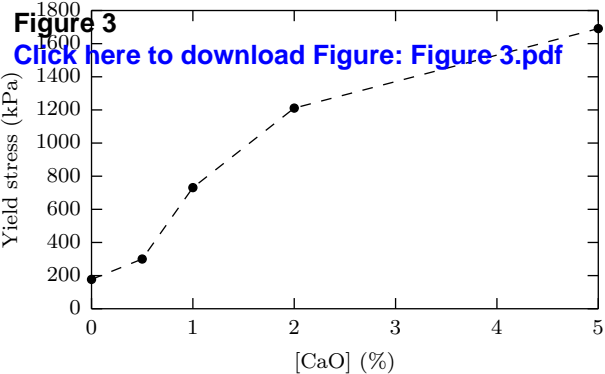


Figure 4a

[Click here to download Figure: Figure 4a.pdf](#)

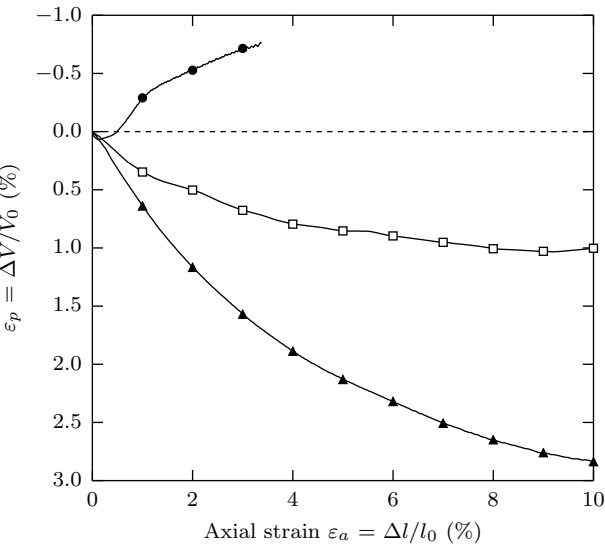
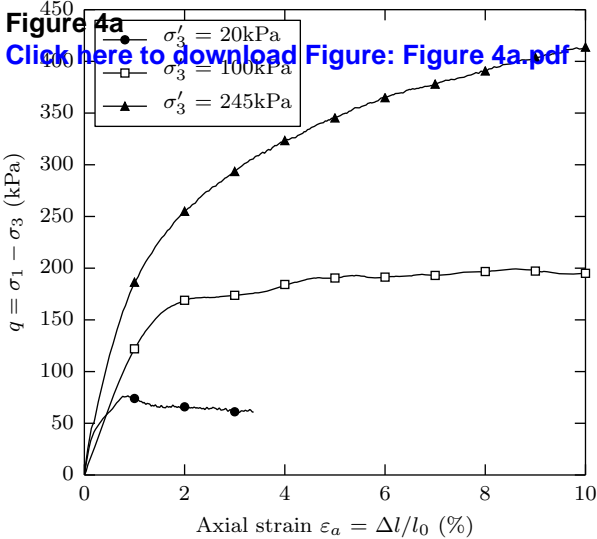


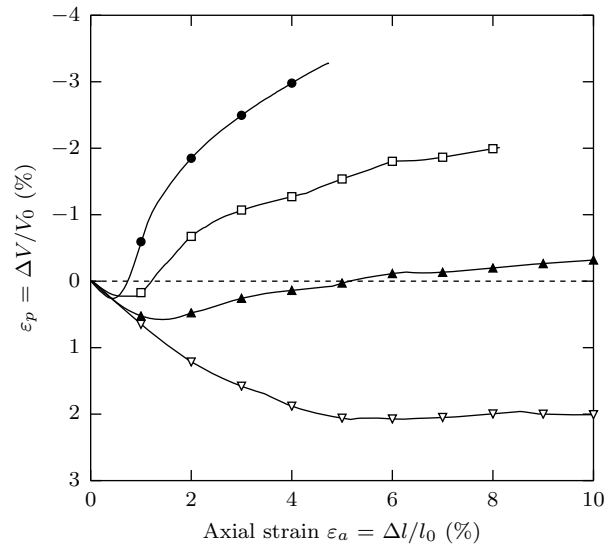
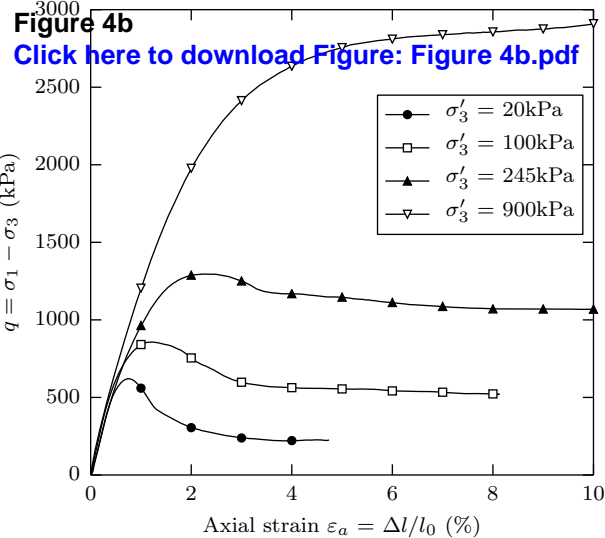
Figure 4b[Click here to download Figure: Figure 4b.pdf](#)

Figure 5. [Click here to download Figure 5.pdf](#)

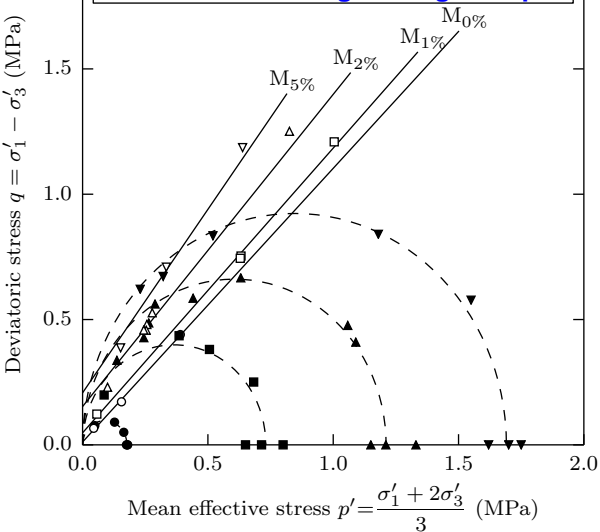


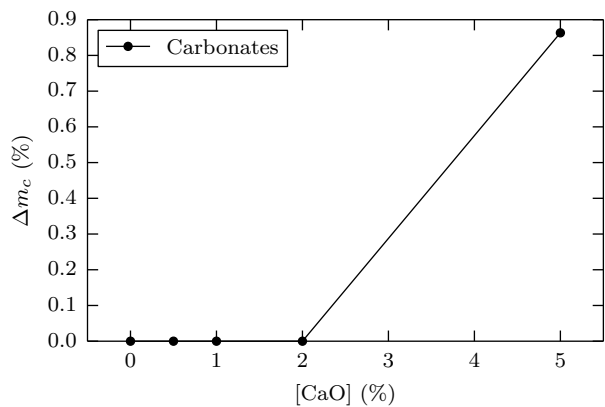
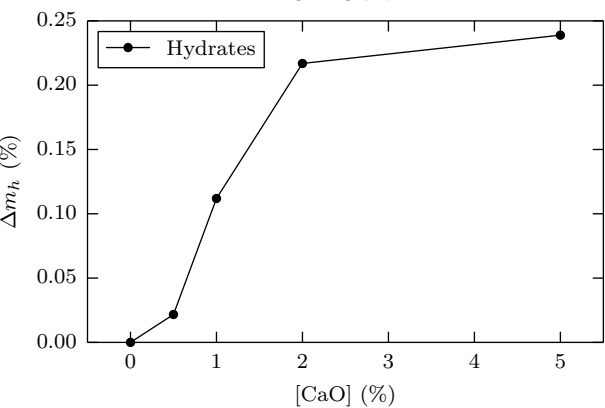
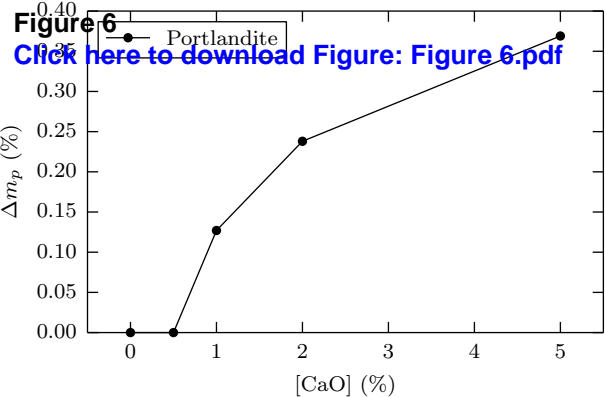
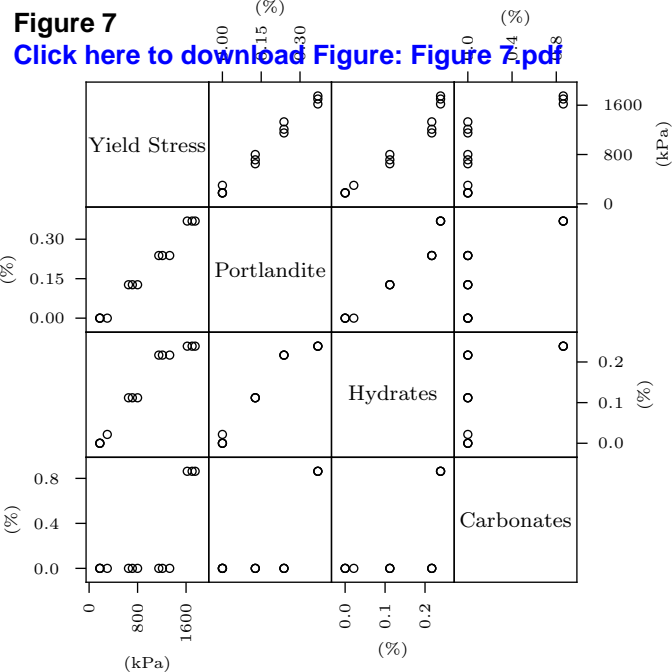
Figure 6[Click here to download Figure: Figure 6.pdf](#)

Figure 7

[Click here to download Figure: Figure 7.pdf](#)



2000
Figure 8

[Click here to download Figure: Figure 8.pdf](#)

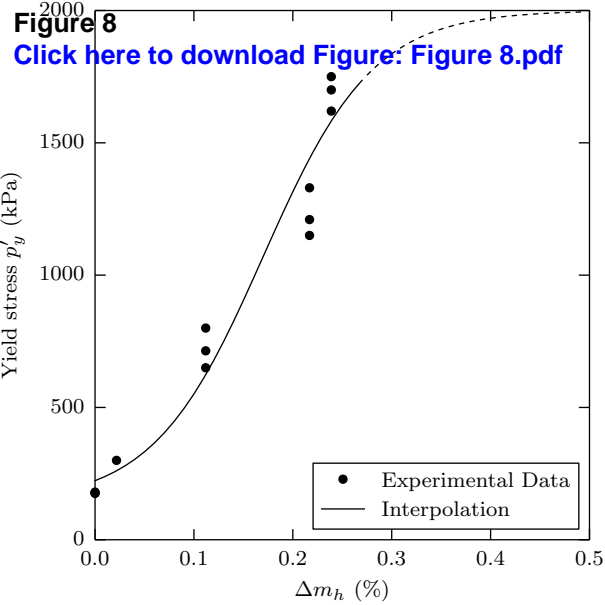


Figure 9

[Click here to download Figure: Figure 9.pdf](#)

