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29 **Keywords**

30 Stabilized soil - Lime/Cement - Resonant column test – Shear Modulus degradation curves – Curing
31 stress

32 **1. Introduction**

33 Economic and environmental imperatives are now prompting project owners to optimize the volumes
34 of excavation/backfill by using *in situ* materials for earthworks. When these soils don't have the required
35 mechanical performance, chemical and mechanical improvement solutions are used. In current linear
36 projects (railway lines, roads and canals), soils are first stabilized with lime to improve their workability,
37 then stabilized with hydraulic binder and compacted, which will give them greater rigidity, cohesion
38 and strength. In order to reduce the carbon impact of these projects, the binders used are increasingly
39 composed of Portland cement, combined with a low-carbon substitute (blast furnace slag, fly ash, etc.).
40 Typical dosages for these projects are 1% lime and 4 or 5% hydraulic binder. Growing knowledge of
41 these materials and their durability has encouraged their use in innovative solutions for geotechnical
42 structures such as high embankments (> 10m).

43 To ensure that stabilized soils achieve the expected mechanical properties after chemical treatment and
44 compaction, laboratory tests are carried out after different curing periods on reconstituted specimens or
45 on specimens cored on experimental embankment (Bell, 1996; Makki-Szymkiewicz et al., 2015;
46 Sariosseiri & Muhunthan, 2009; Wild et al., 1998). Curing period corresponds to the time required for
47 the anhydrous phases contained in the lime and the cement to react with moist soil and form hydrated
48 phases. Soils mechanical properties (strength, modulus) and intrinsic characteristics (permeability, void
49 index) over time are controlled by laboratory tests on these specimens. These tests are executed to be as
50 close as possible to the conditions in which the soil was in the field (state of stress, saturation and
51 draining condition).

52 Previous authors have noticed a difference in mechanical properties between cemented materials
53 collected on site and the same materials prepared in the laboratory (Consoli et al., 2000; Dalla Rosa et
54 al., 2008). By applying, during curing time, stresses to the laboratory-cemented soils similar to those

55 present *in situ*, these authors noted that they approximate the mechanical properties of the cored
56 materials. They define "curing stress" (CS) as the stresses applied to the specimen during its curing time.
57 These initial observations were made on naturally or artificially-cemented sands by using an oedometric
58 ring to study K_0 (the coefficient of earth pressure at rest) (Zhu et al., 1995), then triaxial tests (Consoli
59 et al., 2000; Filipe Veloso Marques et al., 2019; Taher et al., 2011) or UCS (Uniaxial Compressive
60 Strength) tests (Liu & Starcher, 2013; Suzuki et al., 2014). These phenomena have also been observed
61 on cement paste backfill (CPB) since the 1980s and on Deep Soil Mixing columns. The CPB method
62 consists of forming tailings fills with 4%-10% cement addition in layers that are progressively buried
63 (Chen et al., 2021; Cui & Fall, 2016; Fahey et al., 2011; Zhao et al., 2021). Soil mixing consists of
64 creating rigid columns up to 50m depth by mixing soil with hydraulic binders (up to 30%) (Åhnberg,
65 2007; He et al., 2020; Yaghoubi et al., 2020; Zhang et al., 2017). The common point of these methods
66 is that the mechanical properties measured on specimens reconstituted in the laboratory tend to be
67 underestimated compared to those cored at great depth.

68 Hence, to reduce the disparity between the cemented materials properties measured in the laboratory
69 and *in situ* cored specimens, it is necessary to recouple the hydration period and the confinement of the
70 specimens undergoing long curing times. This means keeping the soil, during hydration, under confining
71 pressure until its mechanical behavior is assessed by a geotechnical test.

72 A resonant column apparatus (RCA) in torsion mode was used to investigate the impact of the curing
73 stress on the hydration kinetic of lime and binder- stabilized silty soil from a mechanical point of view
74 (Chae et al., 1981; Chepkoit & Aggour, 1996; Chiang & Chae, 1972; Lang et al., 2020; Tsai & Ni,
75 2011). This apparatus had a double utility in our study. On one hand, the RCA test is considered as a
76 nondestructive test (ASTM, 2021) that can be used on intact or reshaped specimens. This allows the soil
77 specimen to be maintained in the confining cell, measurements to be taken at regular intervals, and
78 provides the evolution of the shear modulus as a function of time on the same specimen. Consequently,
79 the hydration evolution can be followed without modified curing conditions (temperature or pressure).
80 On the other hand, it allowed us to capture soil behavior in small deformations (10^{-7} - 10^{-4}), the dynamic

81 properties of stabilized soils required to anticipate their response under dynamic loading linked to
82 earthquakes, traffic loads, and construction loads.

83 The materials used in the study are a silty soil to which 1% lime and 5% hydraulic binder by weight of
84 material were added. This is a standard mix for linear infrastructure in France. The objective was to
85 highlight the difference in shear modulus degradation curves for this stabilized soil with two curing
86 conditions: one curing at atmospheric pressure (up to 270 days) and the other with isotropic curing
87 stresses (300 kPa or 500 kPa) applied throughout the curing process (up to 28 and 70 days). These
88 stresses correspond to backfill depths of around 15 and 26 m. After defined cure times, tests were
89 performed on normalized specimens at two different isotropic testing pressures: 300 kPa or 500 kPa. At
90 each testing pressure, tests were also carried out on compacted and untreated silt specimens. Finally, a
91 law for predicting the shear modulus at very low strain (G_{max}) as a function of curing time was
92 proposed. It predicts G_{max} for both curing conditions up to 270 days.

93 **2. Materials and specimen preparation**

94 **2.1 Silty soil**

95 The soil used in the study was a silt that comes from the North of France. It was extracted with an
96 excavator and stored in bags. In the laboratory, it was sieved to 0.2 mm and passed through a riffle box
97 for dividing soil aggregates into representative specimen increment for testing. The particle size analysis
98 performed by laser diffraction showed that for the sieved soil, 80% of the grains were smaller than 0.008
99 mm and that the maximum grain diameter D_{max} was equal to 0.1346 mm (ISO, 2020). The particle size
100 curve (Figure 1) indicates a composition equivalent to 81% silt, 11% clay and 8% sand. The
101 mineralogical composition was analyzed by X-ray diffraction (XRD): the silt was mostly composed of
102 quartz, carbonate phases (calcite and dolomite), silicates (muscovite, microcline and clinocllore)
103 feldspars (albite), clay minerals (kaolinite) and hematite. As summarized in Table 1, the soil was low
104 clayey and had a low Plasticity Index (PI). This allows it to be classified according to the Unified Soil
105 Classification System (USCS) as ML (silt with a low liquid limit) (ASTM, 2020). These characteristics

106 were similar to several silty soils from northern France (Das et al., 2022; Lemaire et al., 2013; Makki-
 107 Szymkiewicz et al., 2015).

108 *Table 1: Geotechnical properties of silt used in the study.*

| Properties | Values |
|---|--------|
| Methylene blue value VBS [g/100 g] | 2,2 |
| Liquidity limit LL [%] (NF P 94-051) | 28 |
| Plastic limit PL [%] (NF P 94-051) | 21 |
| Plasticity Index PI [%] (NF P 94-051) | 7 |
| Unified Soil Classification System (USCS) | ML |

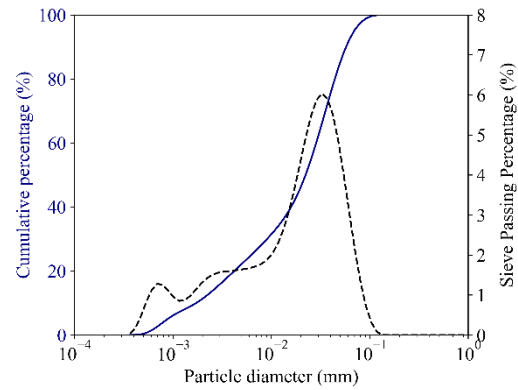


Figure 1: Particle size distribution.

110 **2.2 Lime**

111 The wet silt was stabilized with 1% lime. The quicklime content corresponds to free lime (or unbound),
 112 which is able to react chemically with the available water. The X-ray diffraction analysis conducted on
 113 lime highlights the purity of the product used with a majority of quicklime (89.6% of CaO) which was
 114 low in carbonate (0.4% of CaCO₃) and hydrate (7.1% of Ca(OH)₂). Its specific surface was measured at
 115 6550 cm²/g.

116 **2.3 Cement**

117 The 5% cement dosage is classic in linear projects. The low-carbon hydraulic binder chosen is based on
 118 a blast furnace slag with a composition similar to CEM III/A. It has a claimed composition of
 119 approximately 35% Portland cement clinker and 65% blast furnace slag (from spectrometry analysis:
 120 48.2% CaO, 30.8 of SiO₂, 7.1 of Al₂O₃, 1.06 of Fe₂O₃, 4.56 of MgO, 1.34 of K₂O, 0.57 of Na₂O and
 121 2.76 of SO₃ and RDX and TGA analysis: Quartz, Alite – C₃S, Belite - C₂S, Aluminate - C₃A,
 122 Brownmillerite – C₄AF, Calcite, Portlandite, Gypsum and Anhydrite). It is usually used to treat soils in
 123 place and in mixing stations. Its specific surface measured is 5120 cm²/g.

124 **2.4 Specimen preparation**

125 Standard Proctor test (NF P94-093, 2014) was conducted to determine the Optimum Moisture Content
 126 (OMC) [%] corresponding to the maximum dry density [Mg/m³] for a mixture of silt with 1% lime and

127 5% cement. The results of the test are presented in Figure 2 with the dry density as a function of the
 128 water content [%]. The Proctor curve is displayed with the saturation ratio (S_r [%]) curves which
 129 correspond to 100%, 90% and 80% pore water saturation. The maximum dry density measured
 130 ($\rho_d = 1.75 \text{ Mg/m}^3$) corresponds to an OMC $w = 17.5\%$.

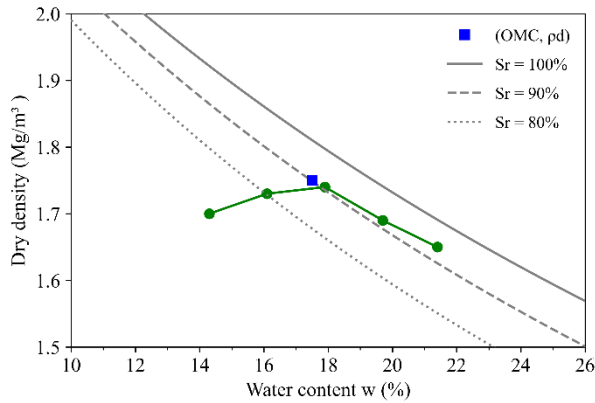


Figure 2: Proctors curve and saturation curves
 ($S_r = 80\%, 90\%, 100\%$)

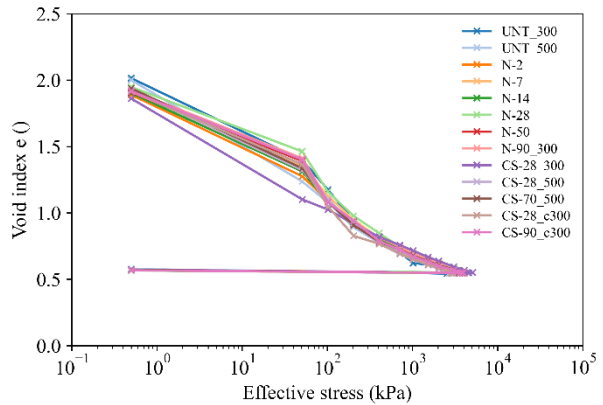


Figure 3: Compaction curves

131 In order to reproduce the treatment process used on site, the same sequencing was reproduced in the
 132 laboratory. First, the addition of lime caused the soil to flocculate. Then the cement was added, and the
 133 soil was mixed until it was homogeneous. The mixture was statically compacted (Serratrice, 2018): it
 134 was placed in a single layer in a greased steel tube with an internal diameter of 50 mm and a height of
 135 100mm. The force was applied on both sides of the cylinder until 96% of optimal density was reached.
 136 Filter paper was placed at the top and bottom of the tube extremities.

137 Figure 3 presents compactions curves for each specimen with e , the void index, as a function of σ ,
 138 the axial stress [kPa]. The curves provided an estimate of the homogeneity of the specimens produced.
 139 The average void index of the 16 specimens was $e = 0.577$. The initial void index of the specimens must
 140 be the same in order to be able to compare results tests (Fahey et al., 2011).

141 2.5 Curing and testing conditions

142 The characteristics of the 16 tested specimens are listed in Table 2. The two untreated silt specimens are
 143 UNT_300 and UNT_500. They were respectively tested at isotropic stresses of 300 kPa and 500 kPa.

144 Following the standards, to ensure hydration reactions in the soil, stabilized soil specimens must be
 145 stored hermetically at a temperature of 20°C (Das et al., 2022; Lemaire et al., 2013). These conditions
 146 were respected in both types of curing compared in the study:

- 147 - Some specimens (N-2, N-7, N-14, N-28, N-50 and N-90) were hermetically protected and
 148 placed in an air-conditioned room at 20°C and atmospheric pressure (Patm). Those were
 149 maintained in this condition for a defined curing time (2, 7, 14, 28, 50 and 90 days) and a
 150 different specimen was used for each curing time test.
- 151 - Specimens subjected to curing stress (CS-28_300, CS-28_500 and CS-70_500), were directly
 152 placed in the RCA cell, in a neoprene membrane with damp filter paper at the extremities. Two
 153 specimens were placed in the RCA from 0 to 28 days under an isotropic curing stress of CS =
 154 300 or 500 kPa (respectively CS-28_300 and CS-28_500) and one from 0 to 70 days at CS =
 155 500 kPa (CS-70_500). For the CS-28_300 specimen, tests were carried out at 0, 1, 2, 3, 4, 7, 8,
 156 9, 11, 14, 16, 18, 21, 23, 25 and 28 days. For CS-70_500, they were carried out at 0, 1, 2, 3, 6,
 157 7, 8, 12, 14, 17, 20, 21, 23, 24, 28, 34, 35, 37, 42, 45, 49, 52, 56, 59, 63, 66 and 69 days.
- 158 - A third type of curing condition was tested out to approximate the test protocols of previous
 159 authors working on curing stress. For this, the specimens were compacted and placed in a cell
 160 at CS = 300 kPa for 28 and 90 days (CS-28_c300 and CS-90_c300). The specimens were then
 161 removed from the cell and placed in the RCA cell (unloading and reloading) for testing at 300
 162 kPa.

163 *Table 2: Specimens curing and testing conditions.*

| Specimen | Test | Curing stress (kPa) | Curing time (days) | Testing pressure (kPa) | Tests per specimen |
|----------|---------------|---------------------|--------------------|------------------------|--------------------|
| UNT_300 | RCA untreated | Patm | - | 300 | 1 |
| UNT_500 | RCA untreated | Patm | - | 500 | 1 |
| N-2 | RCA 2 days | Patm | 2 | 300 - 500 | 2 |
| N-7 | RCA 7 days | Patm | 7 | 300 - 500 | 2 |
| N-14 | RCA 14 days | Patm | 14 | 300 - 500 | 2 |
| N-28 | RCA 28 days | Patm | 28 | 300 - 500 | 2 |
| N-50 | RCA 50 days | Patm | 50 | 300 - 500 | 2 |
| N-90 | RCA 90 days | Patm | 90 | 300 - 500 | 2 |
| N-270 | RCA 270 days | Patm | 270 | 300 - 500 | 2 |

| | | | | | |
|-------------------|------------------------|-----|----|-----|----|
| CS-28_300 | RCA 28 days CS | 300 | 28 | 300 | 16 |
| CS-28_500 | RCA 28 days CS | 500 | 28 | 500 | 13 |
| CS-70_500 | RCA 70 days CS | 500 | 70 | 500 | 29 |
| CS-28_c300 | RCA 28 days CS in cell | 300 | 28 | 300 | 1 |
| CS-90_c300 | RCA 90 days CS in cell | 300 | 90 | 300 | 1 |

164 *RCA: Resonant column apparatus use in torsional mode - UNT: Untreated - N: Normalized - CS: Curing stress - c: cell -
165 Patm : Atmospheric pressure.

166 3. Resonant column apparatus (RCA)

167 In torsion mode, the RCA test consists of exciting the top of the specimen by performing a torsional
168 movement of a predetermined amplitude over a given frequency interval until the maximum amplitude
169 of the response is reached. This maximum amplitude A_{max} [V] corresponds to the resonance frequency
170 f_n [Hz] of the material under test. Shear wave velocity V_s [m.s⁻¹] (1) permits to calculate the shear
171 modulus G [MPa] (2):

$$V_s = \frac{\omega_n L}{\beta} \quad (1)$$

$$G = \rho V_s^2 \quad (2)$$

172 Where ω_n is the angular frequency [rad·s⁻¹] corresponding to $\omega_n = 2\pi f_n$. The resonance frequency is the
173 lowest frequency at which the torsion is 90° out of phase with the rotational displacement. L [m] is the
174 length of the specimen and D its diameter [m]. The parameter β depends on the apparatus specificities.
175 ρ is the specimen density [g.cm³]. This test allows shear modulus measurements at strains between 3×10^{-7}
176 (rigid materials) and 2×10^{-3} (softer materials). The distortion (γ) [] associated to the frequency peak is
177 calculated with the following formula:

$$\gamma = \frac{4,596 \cdot A_{max} \cdot D}{f_n \cdot L} \quad (3)$$

179 A total of 74 tests were executed for this study. A test corresponded to a series of about 25 points
180 performed in the range of amplitude between 0.005 V and 1 V. The tests were performed starting at the
181 lowest amplitudes (0.005 V) up to the highest (1 V). All the present tests were conducted on unsaturated

182 specimens with drain open to the air, at testing pressure of 300 kPa or 500 kPa. The G modulus measured
183 at the smaller amplitudes (0.005 V) with an RCA was designated G_{max}.

184 **4. Results and discussions**

185 **4.1 Degradations curves**

186 As mentioned previously, the aim of the tests was to highlight the effect of curing stress on the kinetic
187 mechanical properties' evolution. The RCA device provides resonance peaks at each amplitude step
188 imposed. The previous equations give shear modulus G [MPa] degradation curves as a function of the
189 distortion for the different specimens and each curing condition (Figures 4 to 7, graphs (a)). The
190 normalized decreased curves (G/G_{max}) as a function of the shear strain are also presented (Figure 4 to
191 7, graphs (b)).

192 Before improving the soil, tests were carried out on untreated compacted soil specimens (blue crosses
193 in Figures 4 to 7) with the same test conditions (unsaturated specimens, open drainage to air). The testing
194 pressures used were 300 and 500 kPa (specimens UNT_300 and UNT_500, respectively). At 300 kPa,
195 the untreated silt specimen has a G_{max} of 135 MPa which corresponds to a shear deformation of 5×10^{-6} .
196 At 500 kPa, the untreated silt specimen has a G_{max} of 175 MPa, which corresponds to a shear
197 deformation of 5×10^{-6} . By comparison, the specimens of stabilized soil are located on much smaller
198 deformations which decelerate according to the curing time as the specimen stiffens. As summarized in
199 Table 2, a different specimen was used for each curing time to study the mechanical properties after
200 curing at atmospheric pressure. The results are illustrated in Figures 4 and 5.

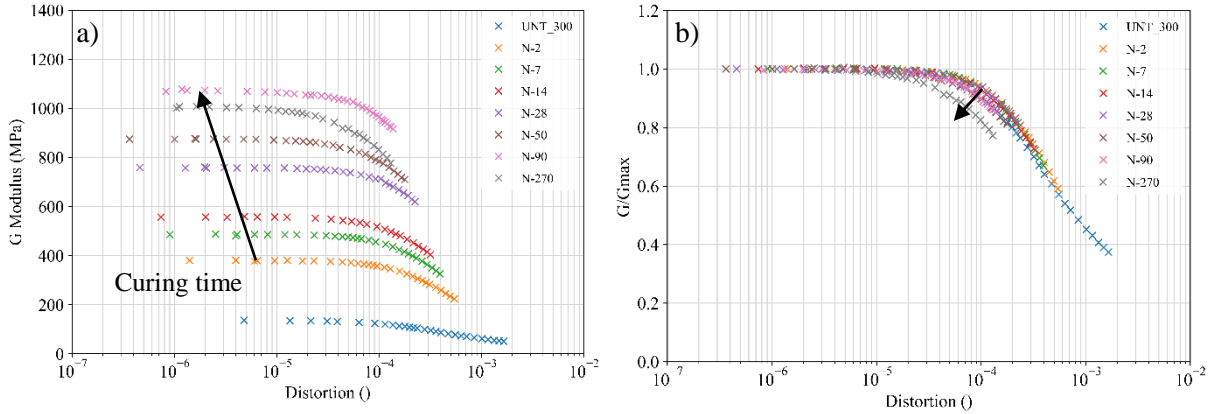


Figure 4 : RCA tests results for atmospheric pressure curing condition (testing pressure of 300 kPa). (a) Degradation curves: G modulus as a function of shear strain (b) G/Gmax curves as a function of shear strain

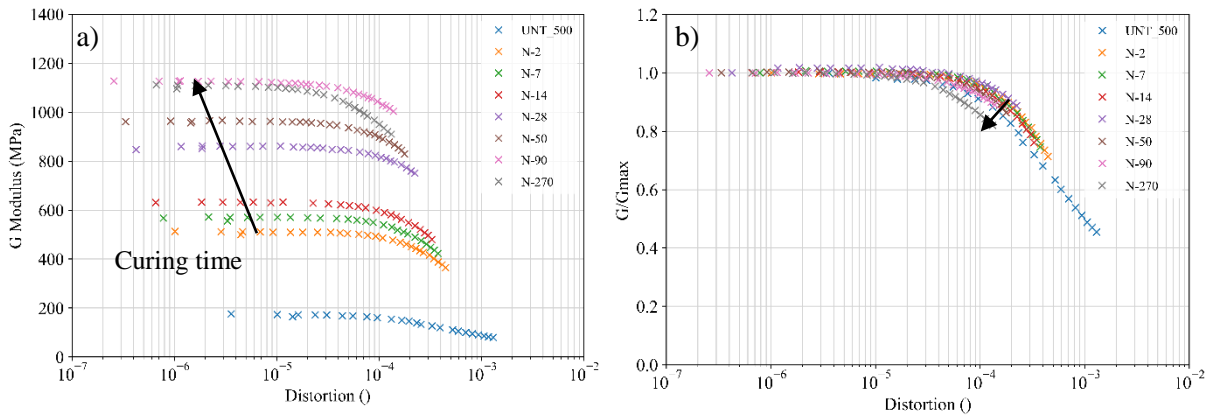


Figure 5: RCA tests results for atmospheric pressure curing condition (testing pressure of 500 kPa). (a) Degradation curves: G modulus as a function of shear strain (b) G/Gmax curves as a function of shear strain.

201 To investigate the influence of curing stress, 3 specimens were realized (testing pressure of 300 kPa:
 202 CS-28_300, testing pressure of 500 kPa: CS-28_500, CS-70_500, see Table 2). However, since the
 203 results of the CS-28_500 test were identical to the first 28 days of the CS-70_500 test, they are not
 204 presented. The evolution of the shear moduli from 0 to 28 days at 300 kPa curing stress is reported in
 205 Figure 6. At 500 kPa, the G modulus evolution was measured up to 70 days (see Figure 7). In the legends
 206 to Figure 6 and Figure 7, the day of the cure on which the test was carried out is indicated by "1d" (for
 207 the first day of curing, for example). In these figures, the arrows show the evolution of the degradation
 208 curves from the first day to the last day curing.

209 For each curing condition, the lowest G moduli are observed for the specimens with the youngest age
 210 (see Figures 4 to 7). At higher cure times, the curves have minimal G moduli at lower displacements
 211 because the RCA can only measure resonance peaks up to an amplitude of 1 V.

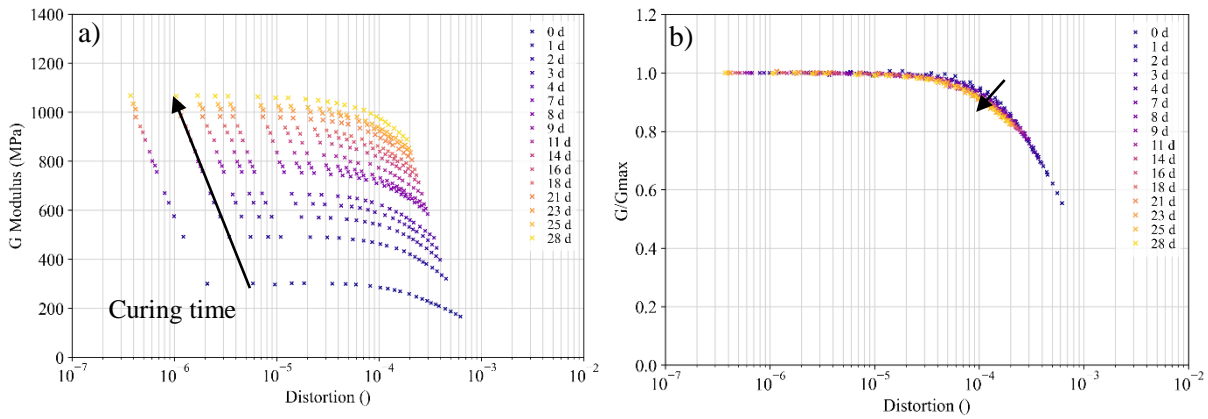


Figure 6: Specimen CS-28_300 cured with a curing stress of 300 kPa for 28 days (testing pressure of 300 kPa).
 (a) Degradation curves: G modulus as a function of shear strain
 (b) G/Gmax curves as a function of shear strain.

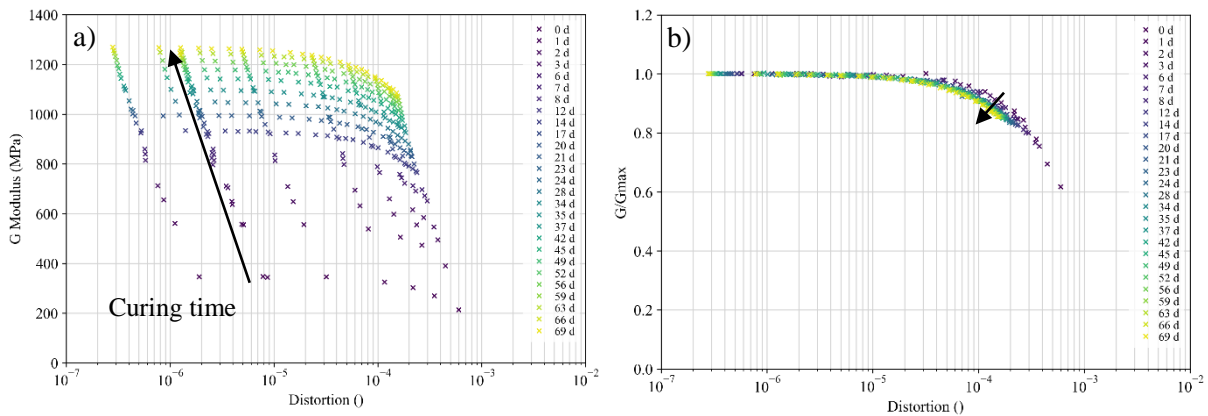


Figure 7: Specimen CS-70_500 cured with an isotropic stress of 500 kPa for 70 days (testing pressure of 500 kPa).
 (a) Degradation curves: G modulus as a function of shear strain,
 (b) G/Gmax curves as a function of shear strain.

212 Globally, the mechanical evolution within the specimen as a function of curing time is visible at several
 213 levels: the evolution of the shape of the curves, the increase in Gmax as a function of time, and the shift
 214 of the curve towards smaller deformations.

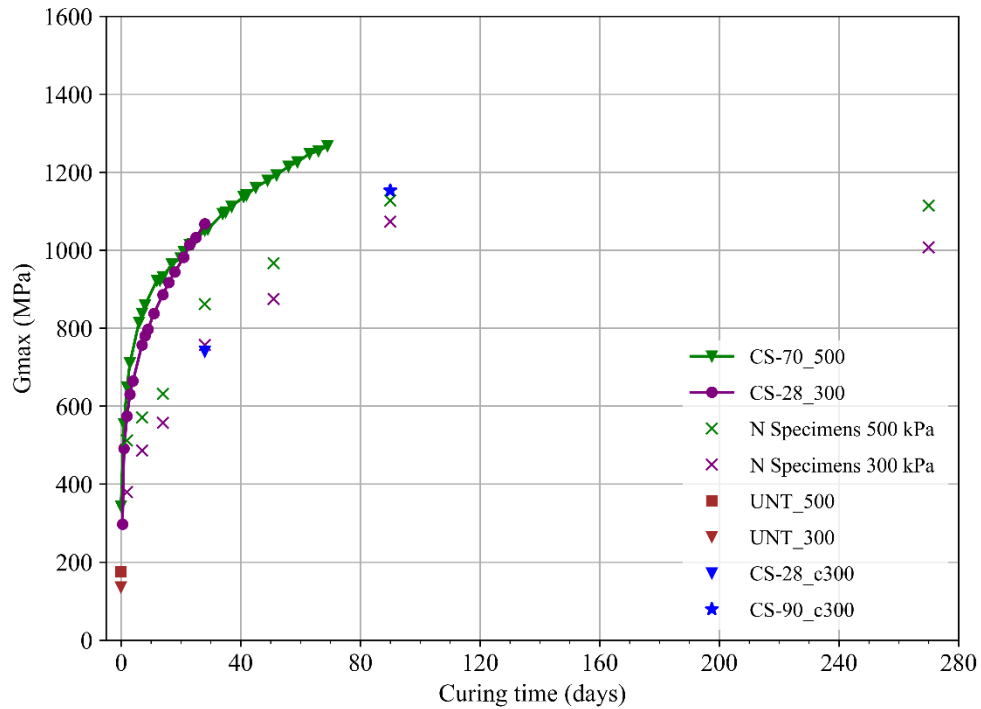
215 After a curing period of 90 days without any curing stress, tests performed at testing pressure of 300
 216 kPa provide a G modulus value of 1073 MPa for the specimen. In contrast, with curing stresses, the G
 217 modulus value reaches 1067 MPa after only 28 days. Therefore, the specimen CS-70_500, after 41 days

218 with a curing stress of 500 kPa, reaches the same modulus as the specimen N-90 after 90 days of curing
219 without stress (CS-70_500, $G_{max} = 1137$ MPa ; N-90, $G_{max} = 1127$ MPa). The influence of the testing
220 pressure seems to be more important for the tests carried out after a cure without curing stress. For
221 example, after a curing time of 90 days without curing stress, there is a difference of 55 MPa between
222 the test performed at 300 kPa and 500 kPa. By contrast, for the tests on specimens subjected to curing
223 stress, the difference in testing pressure between 300 and 500 kPa does not generate any difference
224 between the moduli obtained.

225 Concerning the G/G_{max} evolution versus distortion, one notices that the shape of the curves for the
226 same curing conditions is similar but shifts according to the black arrow added to the graphs (Figures 6
227 (b) and 7 (b)).

228 **4.2 Effect of curing stress on the evolution of G_{max} as a function of time**

229 Previous results can provide the evolution of G_{max} [MPa] as a function of curing time [days] as
230 illustrated by Figure 8 (see Appendix for all G_{max} values for each specimen). The results show two
231 different hydration kinetics. The first one corresponds to specimens cured with a curing stress of 300
232 kPa (CS-28_300, purple dots) and a curing stress of 500 kPa (CS-70_500, green dots). The second one
233 corresponds to specimens cured without stress and tested at different curing times with the RCA at a
234 testing pressure of 300 kPa (purple cross) or 500 kPa (green cross). For this last curing condition, each
235 cross represents a unique specimen, in contrast to CS-28_300 and CS-70_500 curves, for which each
236 point corresponds to the same specimen. The triangle and the blue star represent the G_{max} of a specimen
237 that has been cured in confining cell and subjected to a cycle of loading/unloading/reloading (for the
238 test in the RCA) at 300 kPa after a curing time of 28 days (CS-28_c300) and 90 days (CS-90_c300).



239

240

Figure 8 : Evolution of shear modulus G_{max} as a function of time for each curing condition.

241

Table 3: Percentage increase in G_{max} modulus as a function of time and curing conditions.

| Specimen | G_{max} after 0* day (MPa) | G_{max} after 2 days (MPa) | G_{max} after 28 days (MPa) | Gain from 0 to 2 days (%) | Gain from 2 to 28 days (%) | Gain from 0 to 28 days (%) |
|-----------|------------------------------|------------------------------|-------------------------------|---------------------------|----------------------------|----------------------------|
| N- (300) | - | 380 | 757 | - | 99 | - |
| CS-28_300 | 302 | 575 | 1068 | 90 | 86 | 254 |
| N- (500) | - | 512 | 861 | - | 68 | - |
| CS-70_500 | 352 | 655 | 1053 | 89 | 61 | 203 |

242

*Around 5 hours after compaction.

243

Table 3 presents the analysis of the percentage increase in G modulus for different curing conditions

244

shown in Figure 8. For specimens without curing stress, from 2 to 28 days, G_{max} increases by 99% for

245

300 kPa testing pressure and by 68% for 500 kPa. When the curing stress is 300 kPa (CS-28_300), from

246

0 to 28 days, G_{max} increases by 254% (from 302 MPa at 0 days of curing to up to 1070 after 28 days).

247

When the curing stress is 500 kPa, G_{max} increases by 203% from 0 to 28 days.

248

The percentage increase between 2 and 28 days for the two types of curing is almost identical (for tests

249

at 300 kPa: 99% and 86%, and for tests at 500 kPa: 68%, and 161%). On the whole, the kinetics of the

250

modulus increase is very high during the first 2 days and then grows more slowly until it reaches a

251 threshold. Indeed the Table 3 show that the shear modulus G increases more between 0 and 2 days of
252 curing than between 2 and 28 days of curing.

253 Previous studies have focused on the increase of the G_{max} G and its link with the chemical reactions of
254 hydration caused by the addition of hydraulic binders (Di Sante et al., 2022). The kinetics observed in
255 Figure 8 can be explained by isothermal calorimetry tests carried out on soil mixtures with lime and
256 cement (Bouras, 2020). These show two peaks in heat release after mixing: a peak associated with lime
257 in the first two hours and over the following 12 hours, heat associated with cement. Pozzolanic reactions
258 continue to develop over the long term, after which the quantity of non-hydrated anhydrous decreases
259 and reactions slow down (Bell, 1996). This is illustrated by Figure 8, which show an increase in G_{max}
260 up to 90 days, followed by stabilization of the modulus up to 270 days. These results reinforce the idea
261 that after 90 days most of the hydration reactions had been achieved (LCPC/SETRA, 2000). For
262 specimens subjected to curing stress, the study does not go beyond 70 days, but one cannot rule out the
263 hypothesis that a plateau is reached after 90 days as well.

264 As noted earlier, between specimens with the same curing condition, the influence of confining pressure
265 is not noticeable for specimens in curing stress. Indeed, at 28 days the measured modulus G_{max} of the
266 soil is the same under a pressure of 300 kPa and 500 kPa. It would be interesting to carry out these tests
267 with greater number of curing stresses values. This could eventually lead to determine the minimum
268 curing stress necessary to impact the kinetics of the material mechanical properties improvement or the
269 presence of a pressure threshold beyond which the G_{max} remains stable.

270 During the time that specimens are held under confining pressure, axial displacement shows a slight
271 settlement that occurs on the first day of curing but after no consolidation-related settlement is measured.
272 These measurements reveal that the increase in G modulus as a function of time is not a function of a
273 mechanical change in the soil but rather the result of chemical reactions with the lime and cement.
274 Indeed, the kinetics of module growth with confining pressure seem to be explained by faster and better
275 hydration of the anhydrous phases of cement and lime in the soil. Some authors explain this kinetic by
276 a macroscopically unmeasurable rapprochement of the soil aggregates induced by the curing stress that
277 increases the contact area between them without causing a significant densification of the material (Cui

278 & Fall, 2016). Enhancing contact between soil grains via curing stress would increase the contact
 279 between the cement shells, resulting in stronger cementitious bonds and thus solidifying the structure as
 280 a whole.

281 **4.3 A power law to predict Gmax as a function of time**

282 One of the aim of the study is to predict Gmax as a function of time up to 90 days. Indeed, as observed
 283 previously (Figure 8), this curing time seems to correspond to the time required to attract the stabilized
 284 properties of the stabilized silt. The experimental results showed that knowing the Gmax at 90 days gave
 285 an indication of the Gmax over the long term (at least up to 270 days). This applies in conditions where
 286 the material is not mechanically or chemically degraded. Some authors have tried to predict the time-
 287 dependent behavior of these soils using tests carried out in the first days after the addition of binders.
 288 For example, a power law that predicts the behavior of a lime-treated clay soil at 28 days of curing based
 289 on data from the first 2 days was proposed by (Toohey & Mooney, 2012). They suggested the following
 290 equation:

$$291 \quad G_{max}(t) = G_{max t1} \left(\frac{t}{t1} \right)^{\alpha} \quad (4)$$

292 Where Gmax(t) [MPa] represented the maximum shear modulus value at a specific time t [day]. The
 293 growth rate of the Gmax modulus compared to G_{max t1} (Gmax modulus at day 1) was represented by the
 294 parameter α . This model was based on the fact that most of the growth of the modulus takes place during
 295 the first two days of curing.

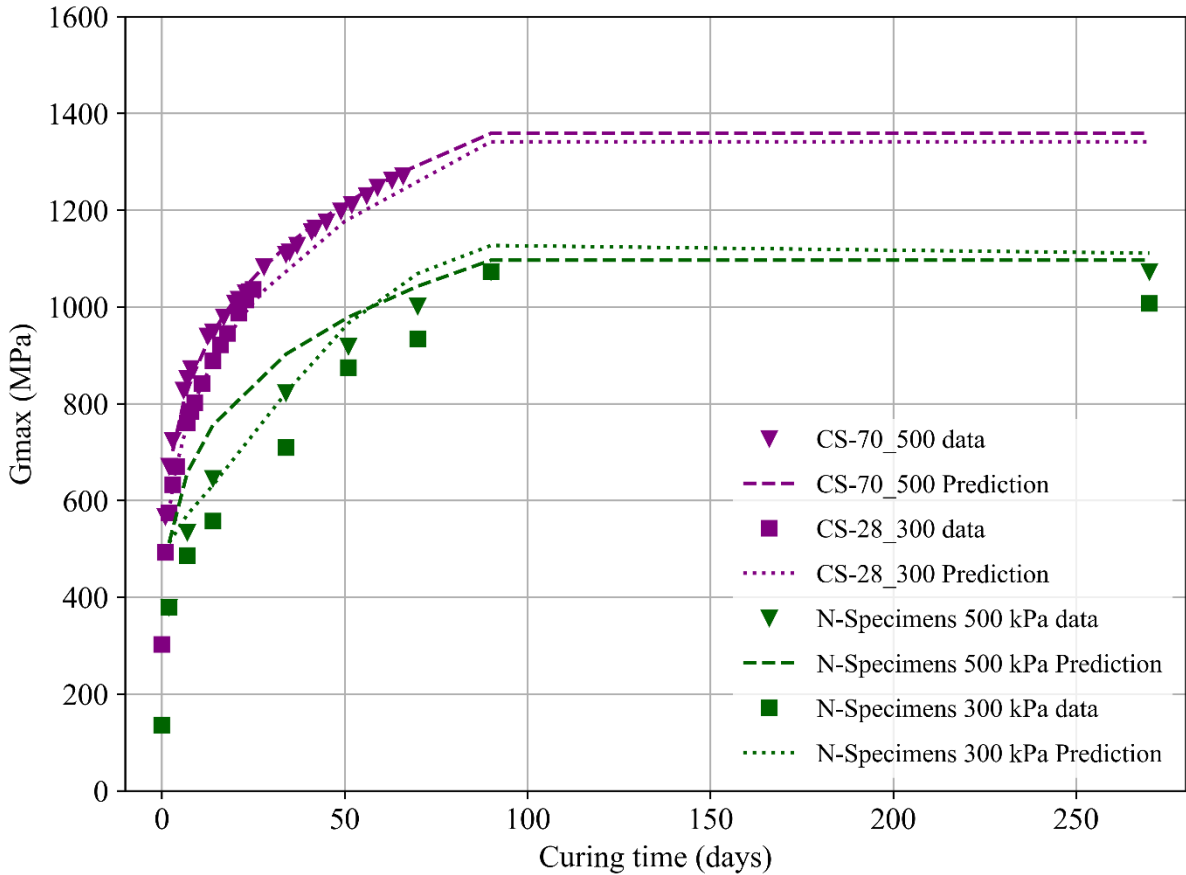
296 In accordance with the experimental results, it is possible to propose a law based on Equation (4) and
 297 beyond 28 days:

$$298 \quad 0 \leq t \leq 90 \text{ days} \quad G_{max}(t) = G_{max t1} \left(\frac{t}{t1} \right)^{\alpha(Cp,CS \text{ or } CN)} \quad (5)$$

$$299 \quad t \geq 90 \text{ days} \quad G_{max}(t) = G_{max}(t90)$$

300 Where the α parameter depends on the confining pressure to which the specimen is subjected during
 301 curing (CS or CN) and during the RCA test (C_p), and $G_{max}(t_{90})$ is the maximum shear modulus G_{max}
 302 after 90 days of curing.

303



304

305 *Figure 9: Prediction of G_{max} as a function of time using equation 5.*

306

Table 4: α parameters and R^2 obtained for the regression of G_{max} against time with equation 5.

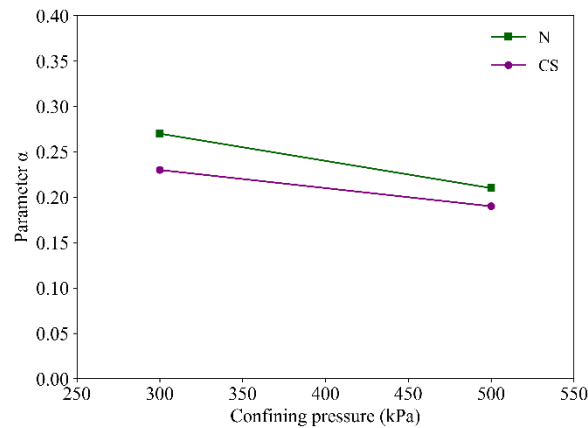
| | Specimens with curing stress (CS) | | | Specimens without curing stress (N-) | |
|----------|-----------------------------------|-----------|-----------|--------------------------------------|------------------|
| | CS-28_300 | CS-28_500 | CS-70_500 | Tests at 300 kPa | Tests at 500 kPa |
| α | 0.23 | 0.19 | 0.19 | 0.27 | 0.21 |
| R^2 | 0.999 | 0.997 | 0.997 | 0.981 | 0.943 |

307 The results of this power law are shown in Figure 9 where the dots correspond to the experimental
 308 measurements and the dashed curves to the law predictions (Equation 5). The curves of the tests on
 309 specimens without curing stress are plotted in green. The curves of the specimens subjected to curing
 310 stress (CS-28_300, CS-28_500 and CS-70_500) are shown in blue and purple.

311 The alpha parameter (α) optimized for each curve according to the experimental data and the difference
 312 (R^2) between these curves and the measured data are shown in Table 4. In the Mooney and Toohey's
 313 study which sets out the previous empirical law (Equation 4), several types of soils with varying degrees
 314 of clay content were treated and the parameter α was characteristic of each soil type. The parameter α
 315 in Equation 5, which is a function of the confining pressure during curing and testing, decreases as these
 316 pressures decrease. The Figure 10 shows that the gradient is the same between the parameter α of
 317 specimens in normalized curing (N) as between the α of specimens in curing stress. An equation (6) is
 318 proposed to calculate α as a function of the confining pressure during curing (CS) and during the test
 319 (C_p):

320
$$\text{For } N \text{ specimens : } \alpha = 2,5 \cdot 10^{-4} C_p + 3,55 \cdot 10^{-1}$$

321
$$\text{For } CS \text{ specimens : } \alpha = 2,5 \cdot 10^{-4} C_p + 3,05 \cdot 10^{-1} \quad (6)$$



322

323 *Figure 10 : Evolution of parameter as function of the confining pressure.*

324 The high R^2 values (> 0.94) in Table 4 demonstrate that the power law effectively models the relationship
 325 between G_{max} and curing time. Particularly noteworthy is the remarkably high R^2 value of 0.997
 326 obtained for the CS-70 specimen, based on a robust dataset of 29 measurements. This result strongly
 327 supports the power law's ability to accurately model the G_{max} -curing time relationship. The consistency
 328 of parameter values across specimens indicates homogeneous material properties and repeatable test
 329 results. However, tests without curing stress exhibit slightly higher variation, likely due to the use of
 330 different specimens at each time point. The model's robustness was verified by using G_{max} at different
 331 reference times (7, 14, or 28 days). These variations in the starting G_{max} value (G_{max_t1}) did not

332 significantly impact prediction accuracy, as evidenced by consistent α values and R^2 . Therefore, this
333 model allows for long-term prediction of G_{max} at 90 days (and beyond) using just 2 days (or more) of
334 experimental data. For a given soil and treatment, the model can predict G_{max} at 28 days under curing
335 stress using the G_{max} at 90 days under normal curing conditions, and vice versa.

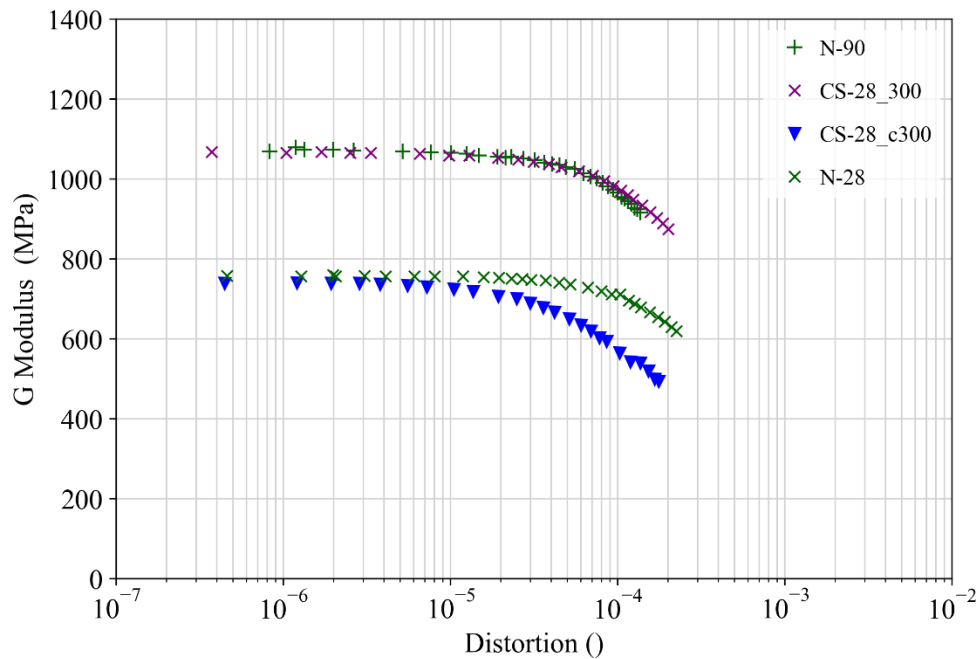
336 While the power law model demonstrates promising results, it is important to acknowledge its
337 limitations and explore potential avenues for further research. The model's performance might be
338 affected by specific curing conditions or variations in soil properties like initial moisture content or
339 binder dosage. Future studies could investigate the model's applicability under a wider range of
340 conditions to assess its robustness.

341 Additionally, the model's current focus is on predicting G_{max} at 90 days. Extending the prediction
342 capability beyond 270 days would be valuable for long-term assessments of stabilized soil behavior.
343 Furthermore, incorporating additional data points beyond the first two days could potentially refine the
344 model's accuracy. In terms of practical applications, predicting long-term G_{max} has significant
345 implications for geotechnical engineering. It could aid in optimizing construction schedules by
346 providing more accurate estimates of soil strength over time. Moreover, it could facilitate the assessment
347 of long-term stability for structures built on stabilized soils, enhancing safety and reducing the risk of
348 infrastructure failures.

349 **4.4 Proposal to simplify the experimental protocol**

350 In order to predict in the laboratory the mechanical properties of a stabilized soil when it is placed at a
351 certain depth of a backfill while it is being cured, but without having to place the specimen in a RCA
352 throughout the curing period, an experiment was carried out. The specimens were placed in a cell with
353 a curing stress, then unloaded and reloaded in the resonant column cell. Finally, a torsional test was
354 performed a few hours later. Two tests were conducted after 28 days and 90 days of curing time
355 (respectively on specimens CS-28_c300 and CS-90_c300). Indeed, a minimum of 28 days of curing
356 stress is recommended to stabilize the cementitious bonds between specimen particles. (Fahey et al.,
357 2011) has shown that 7 days with a curing stress of 800 kPa was not sufficient to provide a soil cement

358 mix with sufficiently strong cementitious bridges to withstand an unloading until 0 kPa. During the 7
 359 days of curing stress shear modulus raised and it decreased after unloading.



360

361 *Figure 11: Impact of an unloading cycle on the curing stress specimen after curing for 28 days in a cell and tested in the*
 362 *RCA (N-28, CS-28_300 and CS-28_c300).*

363 Figure 11 shows G modulus as a function of distortion and compares the results of a test with curing
 364 stress (CS-28_300, in yellow), without curing stress (N-28, in purple) and the unloading test (CS-
 365 28_c300, in green). Globally, the shape of the curves is identical for these three different curing
 366 conditions. However, after a curing time of 28 days (CS-28_c300), the Gmax value obtained is 862
 367 MPa. In comparison, the specimen that was cured in the resonant column cell without being moved (CS-
 368 28_300) has a Gmax of 1068 MPa for the same curing time. The specimen without curing stress (N-28)
 369 has a Gmax of 709 MPa after 28 days. This test confirms that 28 days of curing stress is not sufficient
 370 to produce cementitious bonds that are strong enough to resist unloading. However, the modulus is much
 371 higher than that of the specimen without curing stress, which shows an improvement of the hydration
 372 process with curing stress.

373 As can be seen in Figure 9, even after 90 days of curing time (CS-90_c300), the cementitious bridges
 374 formed between the shells surrounding the natural soil aggregates are not strong enough to resist
 375 unloading. Indeed, the G modulus obtained are practically identical to those observed for a curing time

376 without curing stress. In order to explain these differences, previous authors conducted a number of tests
377 to compare the amount of hydrates between a specimen with or without curing stress.
378 Thermogravimetric analysis (TGA) and X-ray diffraction (XRD) tests are performed to monitor the
379 evolution of hydrates and anhydrous phases within cementitious materials. Performed on CPB or soil
380 mixing specimens, these tests show a faster and greater amount of consumed cementitious phases and
381 hydrates in the specimens that had curing stress (Chen et al., 2021; Zhao et al., 2021). Very high-pressure
382 (100 MPa – 40 MPa) favors the dissolution of C3S (visible by the increase in conductivity) so that
383 Portlandite and CSH are formed earlier (Bresson et al., 2002). However, in stabilized soils, it is quite
384 difficult to distinguish hydrated phases because of the amount of treatment (<10%) and because the
385 hydrated phases formed are often not sufficiently crystallized (Lemaire et al., 2013). Another aspect that
386 can be studied using SEM (scanning electron microscope) observations is the difference in density of
387 hydrate matrices with or without curing stress. In the first configuration, hydrates have a denser matrix
388 and fewer visible macropores, and cracks are observed (Zhao et al., 2021).

389 To conclude, confining the specimen in a 28 or 90 day cell and placing it in the resonant column for a
390 torsion test leads to a degradation of the G_{max} , and therefore a poor representability of the G_{max} of the
391 specimen if it had not been unloaded. It is recommended to conduct a test after the specimen has been
392 cured for 1 or 2 days and then use equation (5) to predict its G_{max} over the long term.

393 **5. Conclusion**

394 In the context of a linear infrastructure project, the present study experimentally investigates the shear
395 modulus degradation curves of stabilized silt specimens with different curing conditions in laboratory
396 with a resonant column apparatus. The specimens of soil stabilized with 1% lime and 5% cement were
397 maintained under curing conditions of 20°C and atmospheric pressure or 20°C and isotropic confining
398 pressure around the specimen. The tests were conducted with curing and testing pressures of 300 and
399 500 kPa, which represent the presence of soil in a high embankment.

400 The main conclusions are as follows:

- 401 (1) The paper focuses on the shear modulus degradation curves as a function of curing time. These
402 curves show the stiffening of the natural soil by the addition of lime, a hydraulic binder, and by
403 compaction.
- 404 (2) The resonant column makes it possible to combine the curing and testing phases and thus to
405 represent the evolution of the treated soil within an embankment as a function of its curing time.
406 Indeed, this enables continuous monitoring from the first few hours up to durations not reached
407 in the literature (70 days).
- 408 (3) A power law has been proposed which allows G_{max} to be predicted over the long term (270
409 days) using the G_{max} after 1 or 2 days of curing (for both normalized and curing stress
410 conditions). The α parameter of the law depends on the cure and test pressure.
- 411 (4) Even after 90 days curing with stresses, the cementitious bridges formed between the shells
412 surrounding the natural soil aggregates are not strong enough to resist unloading.
- 413 (5) Further work is underway to investigate the microstructure and chemical composition inherent
414 to these mechanical tests. Indeed, an important question for future studies is to understand the
415 influence of curing stress on the mechanical properties of binder and lime-treated silt.

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511 Appendix

512 **Specimens with normalized curing period**

| Specimen | Test pressure (kPa) | Gmax Modulus (MPa) | Gmin Modulus (MPa) |
|----------|---------------------|--------------------|--------------------|
| UNT_300 | 300 | 136 | 51 |
| N-2 | 300 | 380 | 224 |
| N-7 | 300 | 487 | 326 |
| N-14 | 300 | 559 | 404 |
| N-28 | 300 | 761 | 620 |
| N-50 | 300 | 878 | 710 |
| N-90 | 300 | 1073 | 916 |
| N-270 | 300 | 1007 | 778 |
| UNT_500 | 500 | 175 | 80 |
| N-2 | 500 | 512 | 365 |
| N-7 | 500 | 571 | 423 |
| N-14 | 500 | 632 | 480 |
| N-28 | 500 | 861 | 751 |
| N-50 | 500 | 966 | 830 |
| N-90 | 500 | 1128 | 1003 |
| N-270 | 500 | 1112 | 909 |

513
 514 **CS-28_300**

| Curing time (days) | Gmax Modulus (MPa) | Gmin Modulus (MPa) |
|--------------------|--------------------|--------------------|
| 0 | 302 | 158 |

| | | |
|----|------|-----|
| 1 | 492 | 307 |
| 2 | 575 | 384 |
| 3 | 632 | 434 |
| 4 | 669 | 474 |
| 7 | 758 | 572 |
| 8 | 783 | 594 |
| 9 | 800 | 613 |
| 11 | 840 | 650 |
| 14 | 887 | 702 |
| 16 | 919 | 730 |
| 18 | 944 | 755 |
| 21 | 986 | 796 |
| 23 | 1016 | 823 |
| 25 | 1034 | 843 |
| 28 | 1068 | 875 |

515

516 **C-28_c300**

| Curing time (days) | Gmax Modulus (MPa) | Gmin Modulus (MPa) |
|--------------------|--------------------|--------------------|
| 28 | 740 | 493 |

517

518 **C-90_c300**

| Curing time (days) | Gmax Modulus (MPa) | Gmin Modulus (MPa) |
|--------------------|--------------------|--------------------|
| 0 | 1152 | 932 |

519

CS-28_500

| Curing time (days) | Gmax Modulus (MPa) | Gmin Modulus (MPa) |
|--------------------|--------------------|--------------------|
| 0 | 342 | 219 |
| 1 | 542 | 386 |
| 2 | 625 | 461 |
| 3 | 672 | 513 |
| 4 | 709 | 549 |
| 7 | 786 | 638 |
| 9 | 826 | 675 |

| | | |
|-----------|------|-----|
| 14 | 910 | 768 |
| 18 | 950 | 807 |
| 22 | 982 | 840 |
| 24 | 1011 | 858 |
| 25 | 1013 | 858 |
| 28 | 1042 | 881 |

520

521 **CS-70_500**

| Curing time (days) | Gmax Modulus (MPa) | Gmin Modulus (MPa) |
|---------------------------|---------------------------|---------------------------|
| 0 | 347 | - |
| 1 | 560 | 389 |
| 2 | 655 | 494 |
| 3 | 712 | 546 |
| 6 | 815 | 652 |
| 7 | 839 | 672 |
| 8 | 859 | 696 |
| 12 | 924 | 765 |
| 14 | 934 | 770 |
| 17 | 964 | 799 |
| 20 | 993 | 829 |
| 21 | 1000 | 833 |
| 23 | 1014 | 850 |
| 24 | 1020 | 856 |
| 28 | 1053 | 892 |
| 34 | 1096 | 925 |
| 35 | 1102 | 946 |
| 37 | 1112 | 953 |
| 42 | 1147 | 986 |
| 45 | 1161 | 988 |
| 49 | 1183 | 1031 |
| 52 | 1196 | 1021 |
| 56 | 1215 | 1059 |

| | | |
|-----------|-------------|-------------|
| 59 | 1232 | 1055 |
| 63 | 1248 | 1089 |
| 66 | 1256 | 1073 |
| 69 | 1269 | 1100 |

522

523