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1 **Effect of freeze-thaw cycles on mechanical strength of lime-treated**
2 **fine-grained soils**

3

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27

28 **Abstract**

29
30 Lime treatment is a widely-used technique for the stabilization and improvement of fine-
31 grained soils in earthworks for transportation. In cold regions, lime treatment can be
32 considered as an appropriate method to improve freeze-thaw resistance of fine-grained
33 soils. The effectiveness of treatment can depend on soil nature, lime dosage and curing
34 time. In the present work, three soils (silt of low plasticity, clay of low plasticity, and silt
35 of high plasticity) were treated at three lime contents (lower, equal and higher than the
36 lime fixation point) at four curing periods (7, 28, 90 and 365 days). The mechanical
37 strength was determined from unconfined compression test performed on specimens
38 having a diameter of 100 mm and a height of 100 mm. Freeze-thaw cycles were applied
39 by varying the specimen temperature between -20°C and 20°C , the specimens being
40 beforehand saturated. The mechanical strength of specimen subjected to ten freeze-thaw
41 cycles was compared to those maintained in laboratory temperature (20°C). Results
42 showed that freeze-thaw cycles significantly decrease the mechanical strength of sample.
43 This decrease can be explained by damage induced by ice lenses formation/thawing
44 during freeze-thaw cycles, as illustrated by the observation at X-ray computed
45 tomography. Interestingly, lime treatment mitigates this damage and increase the soil
46 freeze-thaw resistance. The treatment appears more efficient for lower plasticity soil, a
47 higher lime content, and a longer curing time. This conclusion seems depend on the
48 specimen preparation procedure.

49
50
51 **Key words:** freeze-thaw cycles, lime content, fine-grained soils, ice lenses, curing time.

52 1. Introduction

53
54 Freeze-thaw (F-T) cycles related to seasonal change of temperature in cold regions can
55 induce negative effects on the quality of road pavement. At the field scale, one of the main
56 mechanisms inducing the degradation of the subgrade is the movement of water related
57 to cryo-suction creating ice lenses in the frozen zone; thawing of these ice lenses
58 significantly decreases the mechanical performance of the subgrade (Johnson et al., 1979;
59 Benson & Othman, 1993; Shoop & Bigl, 1997; Zhang & Kushwaha, 1998; Zhang et al., 2014;
60 Tang et al., 2018). At the material scale (i.e. microstructure level), F-T cycles create cracks,
61 increase the hydraulic conductivity, and decrease the mechanical strength of fine-grained
62 soils (Chamberlain & Gow, 1979; Graham & Au, 1985; Konrad, 1989a; Eigendbrod, 1996;
63 Konrad & Samson, 2000; Qi et al., 2006). The creation of ice in soil pore, related to the
64 movement of water due to cryo-suction, is also the main reason that induce soil structure
65 modification and thus changes of soil properties (Konrad, 1989b). For a saturated
66 sand/bentonite mixture, because of its low hydraulic conductivity that prevented the
67 water movement, the effect of F-T cycles was not observed (Kraus et al., 1997; Podgorney
68 & Bennett, 2006). In the case of unsaturated compacted fine-grained soils, F-T cycles also
69 decrease the mechanical strength and stiffness (Lee et al., 1995; Wang et al., 2007; Qi et
70 al., 2008; Ghazavi & Roustaei, 2010). Laboratory tests show that the F-T process, even
71 without ice lenses formation, causes significant reduction in resilient modulus and
72 unconfined compressive strength.

73
74 Lime treatment is usually used to improve the mechanical properties of fine-grained soils
75 (Little, 1995; Prusinski & Bhattacharja, 1999; Parsons & Milburn, 2003; Al-Mukhtar et al.,
76 2010; Tang et al., 2011; Wang et al., 2019). Actually, lime treatment of fine-grained soil
77 creates cementitious compounds from pozzolanic reaction, coating the soil particles and

78 bonding them together (Al-Mukhtar et al., 2012; Tran et al., 2014; Wang et al., 2015; Ural,
79 2016; Wang et al., 2016; Wang et al., 2017). In addition, the improvement depends on both
80 lime content and curing time (Bell, 1996).

81
82 There have been a few studies dealing with the F-T resistance of lime treated fine-grained
83 soils. Liu et al. (2010) investigated the dynamic properties of a lime-treated clay soil
84 subjected to F-T cycles and found that lime treatment increased the durability of
85 stabilized soil under F-T cycles as compared to the unmodified samples. Hotineanu et al.
86 (2015) investigated the effect of F-T cycles on the mechanical properties of two types of
87 clayey soils, a high-plasticity bentonite and low-plasticity kaolinite. The results showed
88 that F-T cycles induced crack formation by the formation of ice lenses in the soil pores.
89 However, lime addition improved the strength of soil, either subject to F-T cycles or not.
90 Tebaldi et al. (2016) found that mechanical performances of a lime-stabilized clay soil was
91 less affected by F-T cycles compared to untreated soil. Bozbey et al. (2018) studied a lime
92 stabilized clay and found the importance of using higher lime contents and extended
93 curing time for increasing F-T resistance. In spite of the abovementioned works,
94 knowledge on the combined effects of curing time, lime content and soil's plasticity on the
95 F-T resistance of fine-grained soils is still limited and deserves to be further developed.

96
97 In this study, three soils, taken from three sites in France and in Belgium, having various
98 plasticity indexes were tested. For each soil, three lime contents (lower, slightly above,
99 and higher than the lime fixation point) were considered. Soil strength was determined
100 for various curing periods (7, 28, 90, and 365 days) with and without F-T cycles. The
101 results were finally discussed in the context of lime treatment for earthworks.

102

103 2. Materials

104
105 The properties of the soils used in this study are shown in Table 1 and the grain size
106 distributions curves are shown in Figure 1. The clay fraction (< 2 micron) varies from 24%
107 to 70% and the plasticity index varies from 7 to 34. Note that A1, A2 and A3 are the
108 classification terms following the French standard (Afnor 1992). According to the Unified
109 Soil Classification System (ASTM 2006), these soils are classified as silt of low plasticity,
110 clay of low plasticity, and silt of high plasticity, respectively. In addition, these three types
111 of soils are fine-grained soils that are usually used for earthworks. Soil A1 was taken from
112 the excavation of a deposit of dolomite limestone in Marche-les-Dames (in Belgium); soil
113 A2 was used for the construction project of the high-speed railway Tours-Bordeaux,
114 France, and soil A3 was taken from a construction site in Charleville-Mézières, France.

115
116 Following X-ray diffraction results, soil A1 contains illite, kaolinite, chlorite, quartz,
117 feldspath; soil A2 contains illite, kaolinite, chlorite, quartz, montmorillonite; and soil A3
118 contains illite, kaolinite, chlorite, montmorillonite, and quartz. X-ray fluorescence
119 spectroscopy shows that the organic content of these soils is negligible.

120
121 The lime used is Proviacal ® ST, provided by the Lhoist company, which is a calcic
122 quicklime (CaO) CL 90-Q (building lime), according to European Standard (CEN 2010),
123 with an available CaO content of 90.1 %, and a t_{60} (reactivity) of 6.8 min.

124
125 In this study, each soil was treated with three different lime contents: (i) the minimum
126 lime content, slightly lower than the lime fixation point (*LFP*), which corresponds to the
127 short-term improvement objective; (ii) the intermediate lime content, slightly higher than
128 the *LFP*; (iii) and the maximum lime content, higher than *LFP*, which corresponds also to
129 the long-term stabilization objective. The *LFP* is the threshold lime content between the

130 improvement and stabilization objectives as lime added in excess of *LFP* can be mobilized
131 for pozzolanic reaction. *LFP* is determined by soil – lime pH test following the protocol
132 defined in ASTM (1999). *LFP* is the addition of lime needed for the maximum modification
133 of soil, which gives an indication of the minimum quantity of lime that must be added to
134 achieve a significant change in soil properties, mainly in terms of plasticity and
135 compaction. The excess lime reacts with silicate tetrahedra and aluminate octahedra of
136 the lattices of clay minerals (Al-Mukhtar et al. 2010). Thereby, the lime contents chosen
137 are for soil A1 1%, 2% and 4%; for soil A2 1.5%, 3% and 5 % and for soil A3 2%, 4% and
138 7%.

139

140 The natural soil was firstly dried or humidified with water to reach the desired water
141 content and then stored in a plastic box for 48 h for moisture homogenization. Then the
142 moist soil and required lime content were mixed in a mixer for one hour prior to
143 compaction.

144

145 Standard Proctor compaction and California Bearing Ratio (*CBR*) tests were first
146 performed on specimens compacted by dynamic compaction in *CBR* mold of 150 mm high
147 and 150 mm in diameter following ASTM (2005). The results on untreated and treated
148 soils are presented in Figure 2. The compaction curves show that in comparison with the
149 untreated soils, the treated soil has flatter compaction curves. In addition, at higher lime
150 content, the optimum moisture content is higher and the maximum dry density is lower.
151 The immediate bearing index (*IBI*) is generally improved with treatment. Note that for
152 the soils of low plasticity, A1 and A2, the optimum can be easily detected from the
153 compaction curves and the degree of saturation (S_r) at this state is close to 85%. By
154 contrast, for soil A3 (high plasticity silt), the compaction curves are very flat; therefore, it

155 is difficult to determine the optimum moisture content. The optimum was then
156 determined at the degree of saturation of 80 % following Afnor (1993a). The maximum
157 dry density (ρ_{dmax}) and the optimum moisture content (w_{opt}) of natural and treated soils
158 are shown in Table 2. Note that the water content of treated soils shown in this table was
159 measured after the treatment. It can be observed that for all the three soils, at higher lime
160 content the maximum dry density is lower and the optimum moisture content is higher.
161 After Bell (1996), the reduction in maximum dry density could be due to an immediate
162 formation of cementitious products which reduce compactibility and hence the density of
163 the treated soil.

164 3. Experimental method

165
166 To assess the frost susceptibility of lime-treated soil in terms of damage induced by F-T
167 cycles, tests were performed following the procedure suggested by CEN/TC 227/ WG4
168 (2010).

169
170 The soils were first treated with different lime contents and statically compacted (Afnor,
171 1993b) to obtain a dry density equal to 95% of the maximum Proctor dry density with a
172 water content on the wet side of the Standard Proctor curve. The initial conditions of the
173 tested specimens are shown in Table 2.

174
175 The dimensions of the compacted specimens are 100 mm in diameter and 100 mm in
176 height. After the compaction, the specimen was covered with plastic film and wax to avoid
177 moisture exchange during the curing period. Four curing periods were investigated: 7, 28,
178 90 and 365 days. For each lime content and each curing period, four identical specimens
179 were prepared. At the end of the curing period, all the specimens were immersed in a

180 water bath during two days for saturation. Afterwards, two specimens were removed
181 from the water bath, surface dried and tightly wrapped in plastic film (set A) while the
182 two other specimens remained in the water bath (set B). The specimens of set A were then
183 placed in a temperature-controlled climate chamber and subjected to ten F-T cycles, each
184 cycle lasting 24 h. The temperatures measured at the center of the specimen and in the
185 climate chamber during a preliminary test are plotted in Figure 3. The measures show
186 that the soil temperature varied from 20 °C to -20 °C during this cycle.

187
188 After the completion of the F-T cycles, all the four specimens (in a saturated and surface
189 dry condition) were subjected to unconfined compression test. The experimental device
190 is shown in Figure 4. The axial force applied to the specimen (via a mechanical press) was
191 increased by a constant rate of 150 N/s until failure. The strength of the sample was
192 calculated as the ratio of the maximal force to the cross-section area of the sample. The
193 retained strength factor (RFT), after F-T cycles, was then calculated as follows: $RFT =$
194 M_A/M_B , where M_A and M_B are the average strengths of the sets A and B, respectively. As
195 the set A was subjected to F-T cycles and the set B was not, RFT represents the frost
196 susceptibility of the material. It is close to 1 when the soil's strength is not affected by the
197 F-T cycles.

198
199 Besides, one sample subjected to F-T cycles was scanned with X-ray computed
200 tomography (XRCT) in order to observe the cracks developed inside the specimen. The
201 experimental setup of the XRCT scan is shown in Figure 5. The visualized parameter from
202 XRCT observations was the linear attenuation coefficient, which was represented as a
203 grey level. This parameter depended on density, the atomic number and the used X-ray
204 energy (Molinero Guerra et al. 2018).

205

206 4. Experimental results

207

208

209 The results obtained with soil A1 are shown in Figure 6. It appears that the strength of set
210 B (without F-T cycles) treated with a lime content of 1% (corresponding to the short-term
211 improvement objective) remained almost independent of the curing time (Figure 6a),
212 except the values at 90 days which were unusually high. Set A treated with a lime content
213 of 1% was heavily damaged by the F-T cycles and its strength is null for any curing time
214 (Figure 6b). As a result, the retained strength factor of soil A1 treated with a lime content
215 of 1% was null for any curing time (Figure 6c). Note that the results of all the specimens
216 (two specimens for each curing time) are shown in the Figures 6a and 6b (the lines show
217 the mean values) while only the mean values of retained strength factor are shown in the
218 Figure 6c.

219

220 In the case of soil A1 treated with a lime content of 2% and 4% (corresponding to the
221 long-term stabilization objective), the strength of set B (without F-T cycles) was higher at
222 a longer curing time (Figure 6a). RFT of the samples treated with 2% of lime content
223 remained negligible (lower than 20%) for short curing times (7 and 28 days); but it
224 reached 60-70 % for longer curing times (90 and 365 days) (Figure 6c). For sample
225 treated with 4% lime content, even at short curing times (7 and 28 days), the RFT already
226 reached 30%. At 365 days, it reached to 90%.

227

228 The results obtained on soil A2 are shown in Figure 7. As in the case of soil A1, Set B
229 treated with a small lime content corresponding to the short-term improvement objective
230 had a strength independent of the curing time, while the strength of set A (subjected to F-

231 T cycles) was almost null. In the case of soil specimens treated with a high lime content
232 corresponding to the long-term improvement objective, the strength was higher at a
233 higher curing time (Figure 7a). It is interesting to note that the strength of set B treated
234 with 3% of lime content was equal to that with 5% of lime content up to 90 days. Only
235 with 365 days of curing the strength of the specimens treated with 5% of lime content
236 was twice higher than those treated with 3% of lime content. The influence of lime content
237 on the strength of set A (subjected to F-T cycles) could be detected earlier (Figure 7b); the
238 strength of the specimens treated with 5% lime content was similar to those of 3% in
239 short curing times (7 and 28 days), but became 3-4 times higher at longer curing times
240 (90 and 365 days). Finally, when analyzing RFT versus curing time (Figure 7c) for the
241 specimens treated with 3% and 5% lime contents, the higher lime content had slightly
242 higher RFT at 7 days but significantly higher RFT at longer curing times. In addition, RFT
243 of soil A2 remained significantly lower (60%) than that of soil A1 (90%), even at long
244 curing time.

245

246 The results obtained on soil A3 are presented in Figure 8. Again, the strength of set B
247 treated with a lime content of 2% (corresponding to the short-term improvement
248 objective) was found to be independent of curing time (Figure 8a). At higher lime content,
249 higher strength could be observed only after 90 days of curing. It should be noted that
250 lime treated with a lime content of 4% had a strength slightly higher than that at 7%. This
251 could be explained by the fact that the dry density of specimens treated with a lime
252 content of 7% (1.25 Mg/m^3) is significantly lower than that at 4% (1.31 Mg/m^3), see Table
253 2. After applying the F-T cycles, all the samples of set A were severely damaged and the
254 strength are almost negligible (Figure 8b); M_A was null for soil with 2% and 4% of lime

255 content. Results on RFT show that even with higher lime content (7%) and long curing
256 time (90 and 365 days), RFT reached only 20%. For the other cases, RFT was null.

257

258 In order to better understand the mechanisms related to the effect of F-T cycles on the
259 strength of lime-treated soils, an X-ray computed tomography scan was performed on the
260 sample within soil A1, treated with 2% of lime content, cured at 28 days, and subjected to
261 10 F-T cycles. The voxel size was 77 microns. The vertical slide (Figure 9a) shows that the
262 soil was quite homogenous in the central zone. However, at the zones close to the borders,
263 several cracks can be observed. In these zones, some soil aggregates could be also
264 identified. In addition, close the side borders, vertical cracks were dominated while
265 horizontal cracks could be clearly observed close to the top of the specimen. Figure 9b
266 (horizontal slide in the middle of the specimen's height) and Figure 9c (horizontal slide at
267 the bottom of the specimen) also show several cracks close to the border. In addition, the
268 cracks created several concentric arcs.

269 Figure 10 shows images equally taken from soil A1, treated with 2% of lime content, cured
270 at 28 days. It can be observed that the F-T cycles clearly created concentric arcs on the set
271 A (Figure 10b) visible from the surface of the specimen while the surface of the set B
272 remains intact (Figure 10a).

273 In order to assess the effect of number of F-T cycles on the results, RFT was determined
274 at various F-T cycles for a series of soil specimens (soil A1, treated with 2% of lime
275 content, cured at 28 days). The results are shown in Figure 11. It can be seen that RFT_N
276 (retained strength factor at N cycles) reduced quickly from 100% to 55% only after the
277 first cycle. It remained constant at 40% after 5 cycles. These results hence confirm that
278 the choice of 10 cycles (mentioned in procedure suggested by CEN/TC 227/ WG4 (2010))
279 is appropriate to investigate the frost susceptibility of these soils.

280 5. Discussion

281
282 The results show that the kinetics of the variations of strength of lime-treated soils can be
283 divided into two phases: the first one corresponds to a low increase of strength (up to 28
284 days of curing), and the second one corresponds to a significant increase of this parameter
285 when the lime content is high. Actually, the first phase is usually explained by the
286 immediate reactions of cation exchange and flocculation-agglomeration. After Little
287 (1995), the soil improvement during this phase is reflected by the improved workability
288 and immediate bearing capacity, as well as the increase of cohesion. In this study, the
289 improvement of workability can be observed through the compaction curves (Figure 2)
290 where immediate strength increase is identified from the results of IBI. Another evidence
291 of this first phase is the fact that the soil strength measured at 7 and 28 days was
292 independent of the lime content (Figures 6a, 7a, 8a). The second phase corresponds to the
293 pozzolanic reactions that take longer time. After Al-Mukhtar et al. (2010), the excess of
294 lime added promotes pozzolanic reactions and produces new minerals. Little (1999)
295 stated that this phase can last 10 years under constant water content and temperature.
296 Furthermore, the starting time of the second phase is different from one soil to another,
297 varying from several hours to several days even weeks: 10 days after Locat et al. (1990),
298 14 days after Rogers et al. (2006), and 21 days after Wild et al. (1993). In the case of low
299 lime content (slightly lower than the lime fixation point, corresponding to the short-term
300 improvement objective), lime would be no longer available for the second phase. For this
301 reason, the second was not observed.

302

303 Application of F-T cycles decreased the strength of all the samples - *RFT* is lower than
304 100% (Figures 6c, 7c, 8c). This decrease can be explained by the damage induced by F-T
305 cycles. At the specimen scale, damages are represented by cracks observed in Figure 9

306 and Figure 10. The following mechanism can be suggested: while freezing is applied, the
307 temperature in the climate chamber is decreased progressively from 20 °C to -20 °C. That
308 induces a progressive decrease of temperature inside the specimen. When the
309 temperature at one point inside the specimen reaches a critical value (slightly lower than
310 0 °C) where pore water starts to be converted into ice, ice lenses will be formed because
311 of cryo-suction absorbing water from the surrounding zone having higher temperature.
312 These ice lenses, generally parallel to the soil surface, would then create cracks inside the
313 specimen. This mechanism would explain the concentric shape of the cracks observed in
314 Figure 9b and Figure 10b. Konrad (1989a,b) suggested similar physical processes to
315 explain the creation of ice lenses during F-T cycles in clayey silts.

316

317 The application of F-T cycles equally induces modification of soil microstructure at the
318 aggregates scale. Hohmann-Porebska (2002) observed aggregates of fabric created by ice
319 lensing and the aggregates remained generally stable even after thawing. After Svensson
320 & Hansen (2010), ice lensing absorbed water from the surrounding zone and induced
321 dehydration of clay particle in the unfrozen zone. Cracks and larger voids induced by F-T
322 cycles at the aggregates scale were observed by Liu et al. (2019) and Olgun (2013)
323 through scanning electron microscopy.

324

325 When comparing the *RFT* of different soils treated with lime content corresponding to the
326 long-term stabilization objective, the results show that the lime-treatment was more
327 efficient to improve the F-T resistance in long-term of lower plasticity soil (A1) than the
328 higher plasticity soil (A3). Hotineanu et al. (2015) found similar phenomenon when
329 testing lime-stabilized kaolinite and bentonite. Actually, the effect of F-T cycles at the
330 aggregates scale is similar to the wetting-drying process (Svensson & Hansen 2010).

331 Higher plasticity soils would be more sensitive to F-T cycles than lower plasticity soils
332 because of damages induced at the aggregates scale (Khattab et al., 2007; Tang et al.,
333 2011).

334

335 The low efficiency of lime treatment on soil A3 was observed on both mechanical
336 properties and F-T resistance. That can be partly explained by the heterogeneity of lime
337 distribution after the compaction of specimen. In addition, the preparation/mixing
338 method used for this plastic soil induces large macro-pores between aggregates. The large
339 size of aggregate can also limit the diffusion of lime inside the aggregates. To avoid such
340 problems, lime treatment of plastic soil would be done in two steps: (i) a small quantity
341 of lime is first added to the wet soil prior to first mixing to reduce the water content and
342 the aggregates size; (ii) once the soil aggregates size get smaller and the water content is
343 lower, the remaining part of lime is added prior to the second mixing in order to allow a
344 better distribution (and diffusion) of lime.

345

346 Application of the results observed in the present work to the earthwork for
347 transportation should consider various aspects. First, the conditions tested in the
348 laboratory are generally more severe than the field conditions: (i) saturation of soil
349 specimen enhances the effect of F-T cycles; (ii) the amplitude of temperature (from 20°C
350 to -20°C) is also higher than the annual temperature cycles observed in various cold
351 regions; (iii) in the laboratory, F-T cycles were applied to the specimen under free-
352 swelling conditions (specimen can expand during freezing), while in the field F-T cycles
353 are applied under in situ stress state (which would reduce expansion induced by
354 freezing). Second, as the damage was observed in the zone close to the soil specimen

355 surface (Figure 9), the results on mechanical properties of the soil specimen would
356 strongly depend on the specimen's dimensions.

357

358 6. Conclusion

359

360 The effect of ten F-T cycles on the mechanical strength of lime-treated fine-grained soils
361 was investigated in the laboratory. For this purpose, three soils (low plasticity silt A1, low
362 plasticity clay A2, and high plasticity silt A3) were treated with three lime contents (lower,
363 equal, and higher than the lime fixation point *LFP*) and for four curing periods (7, 28, 90,
364 and 365 days). The following conclusions can be drawn:

- 365 - The treatment with lime content equal to or higher than *LFP* increased
366 significantly the mechanical properties of low plasticity fine-grained soils (A1 and
367 A2), while the increase was less obvious for high plasticity silt (A3). For instance,
368 the mechanical strength of soil A1 treated with 5% of lime content increased from
369 0.53 MPa (after 7 days of curing) to 3.10 MPa (after one year of curing), i.e. six
370 times. However, for soil A3 treated with 7% of lime content, it increased from 0.36
371 MPa (after 7 days of curing) to 1.31 MPa (after one year of curing), i.e. four times.
- 372 - The increase of mechanical properties is more obvious at curing period longer
373 than 28 days. Significant change can still be observed between 90 days and 365
374 days. This confirms the two phases usually mentioned in lime treatment of fine-
375 grained soil: the short-term one corresponds to the immediate flocculation and
376 workability improvement, whereas the long-term one corresponds to the
377 initiation and development of pozzolanic reactions.
- 378 - The treatment with lime content equal to or higher than *LFP* increased
379 significantly the F-T resistance of low plasticity fine-grained soils (A1 and A2), but

380 it is inefficient for high plasticity silt (A3). For instance, for soils A1 and A2 treated
381 with lime content higher than LFP, RFT remained higher than 60% after 90 days
382 and 365 days of curing. However, for soil A3, RFT was equal to 20% in the best
383 cases.

384

385 The results obtained in the present work would be helpful for the design of earthwork for
386 transportation using lime-treated fine-grained soils in cold regions.

387

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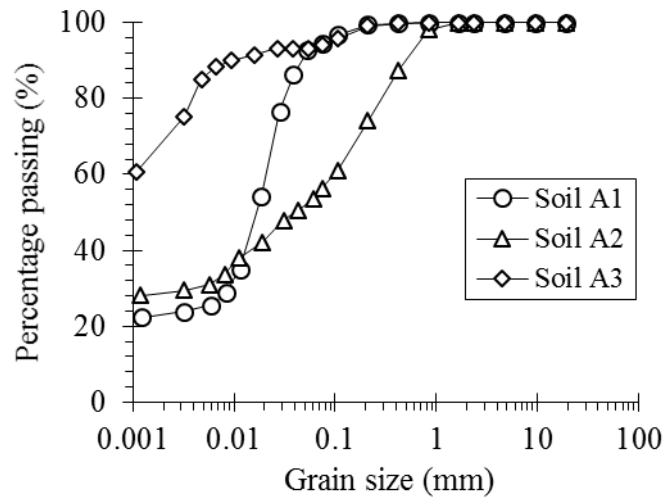
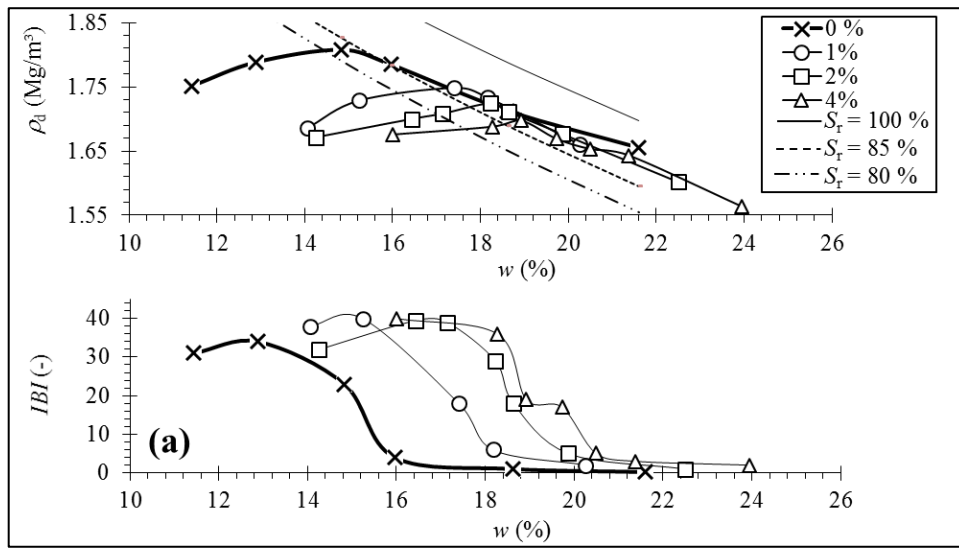


Figure 1. Grain size distribution of the studied soils.

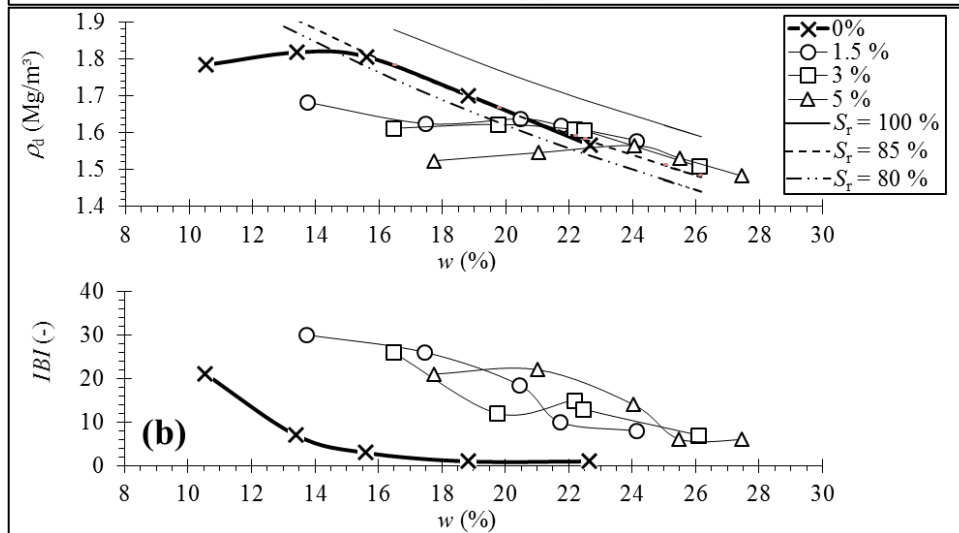
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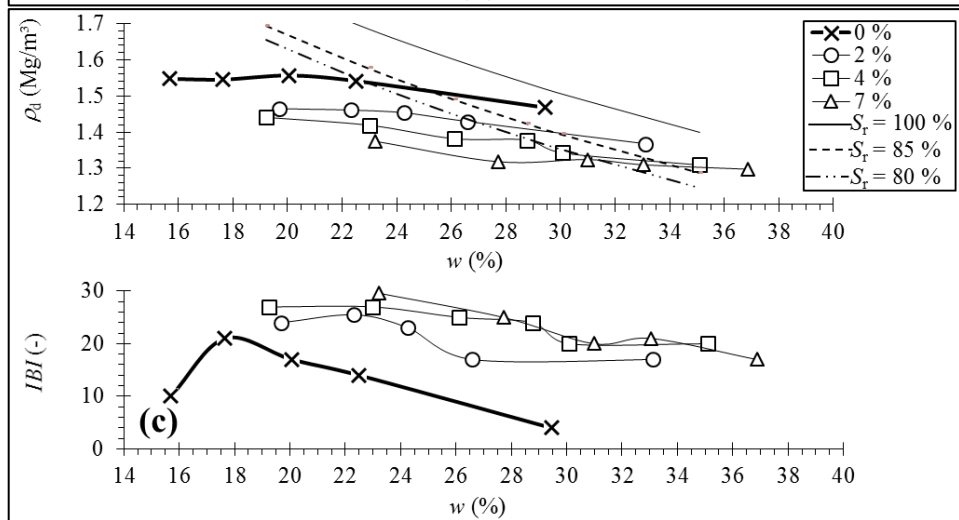
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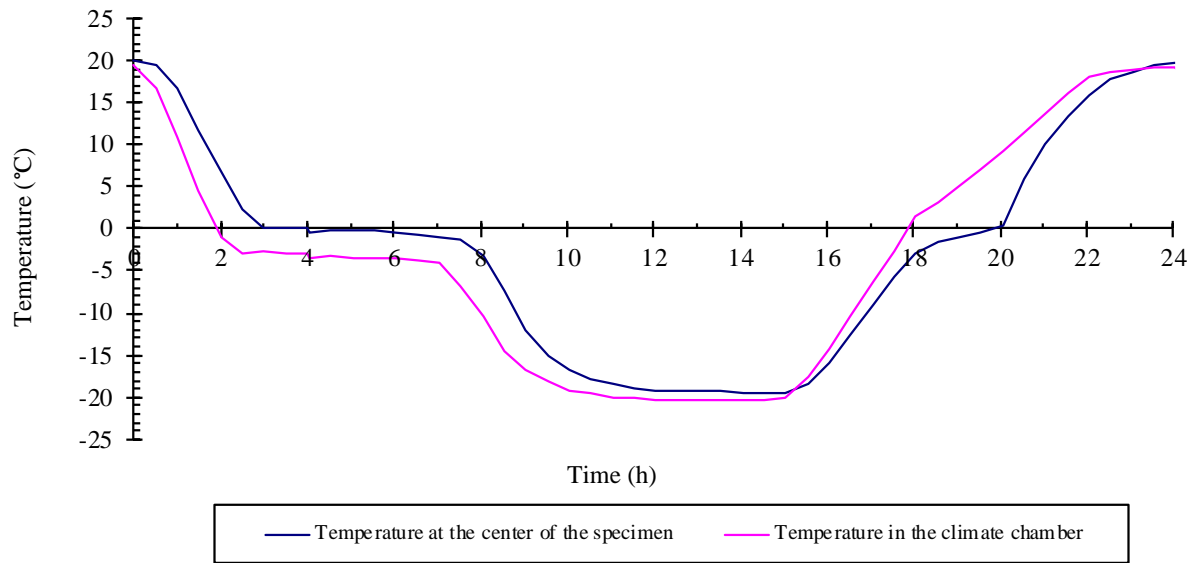


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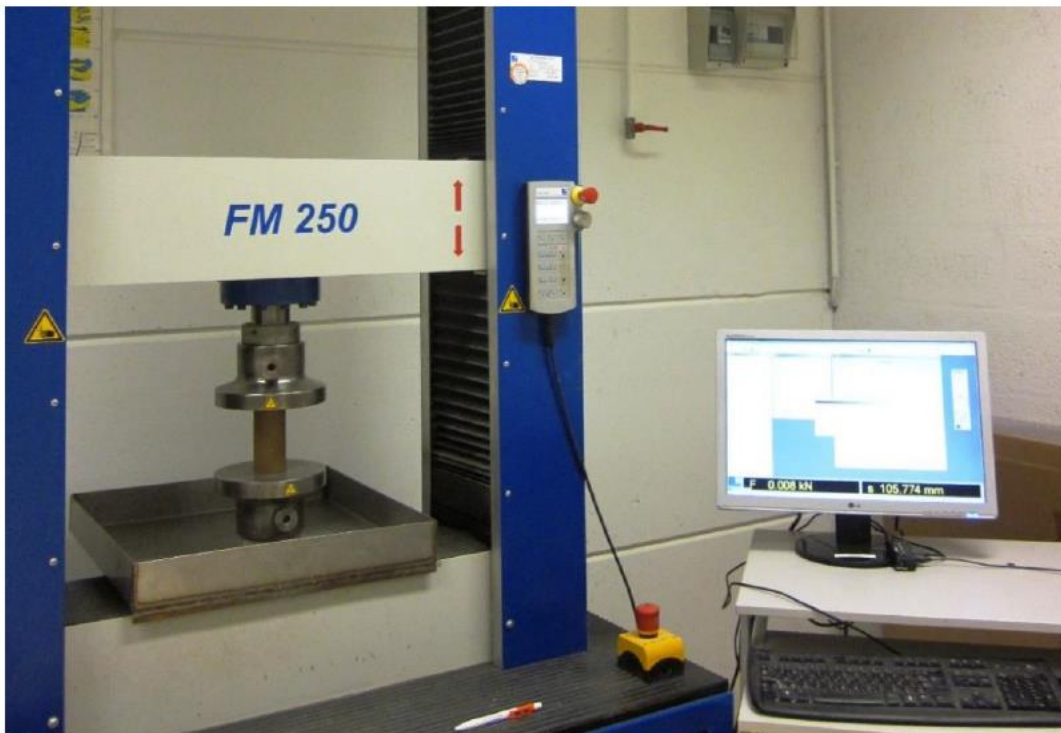
Figure 2. Results of Normal Proctor compaction and CBR tests: (a) soil A1; (b) soil A2; (c) soil A3.



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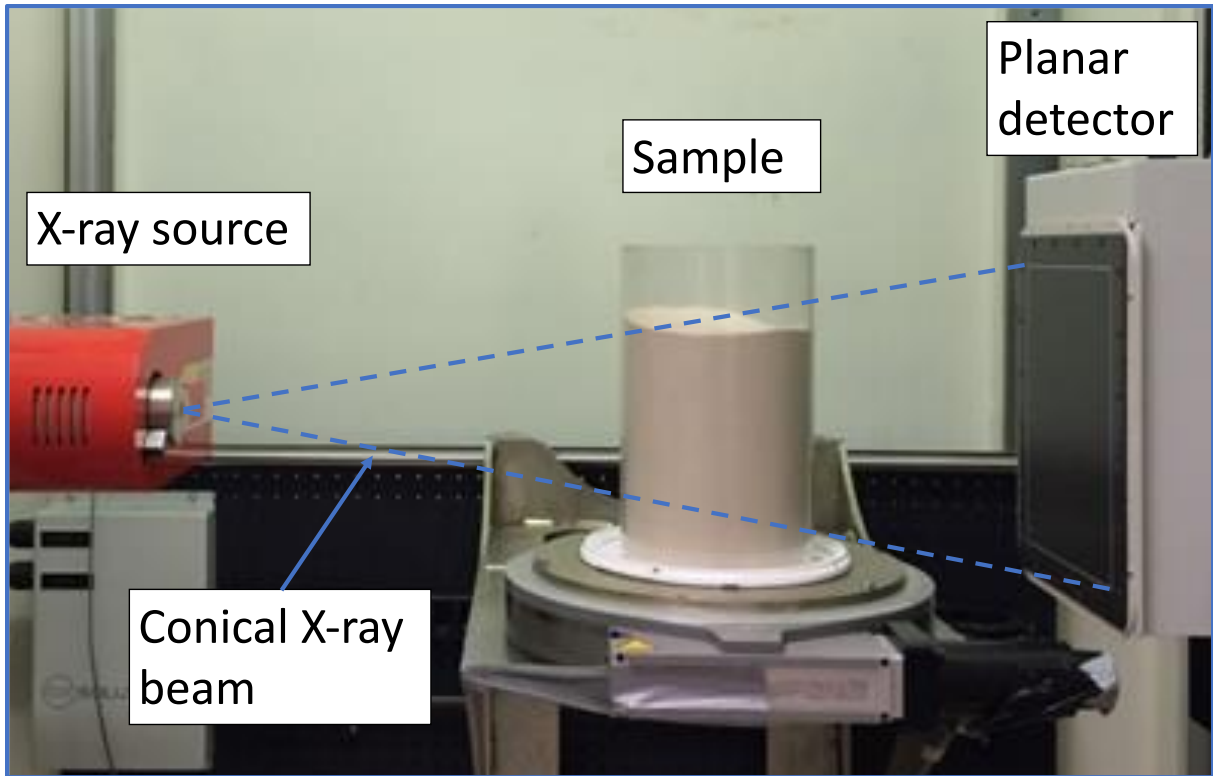
Figure 3. Temperatures measured at the center of the specimen and in the chamber during a typical freeze/thaw cycle.

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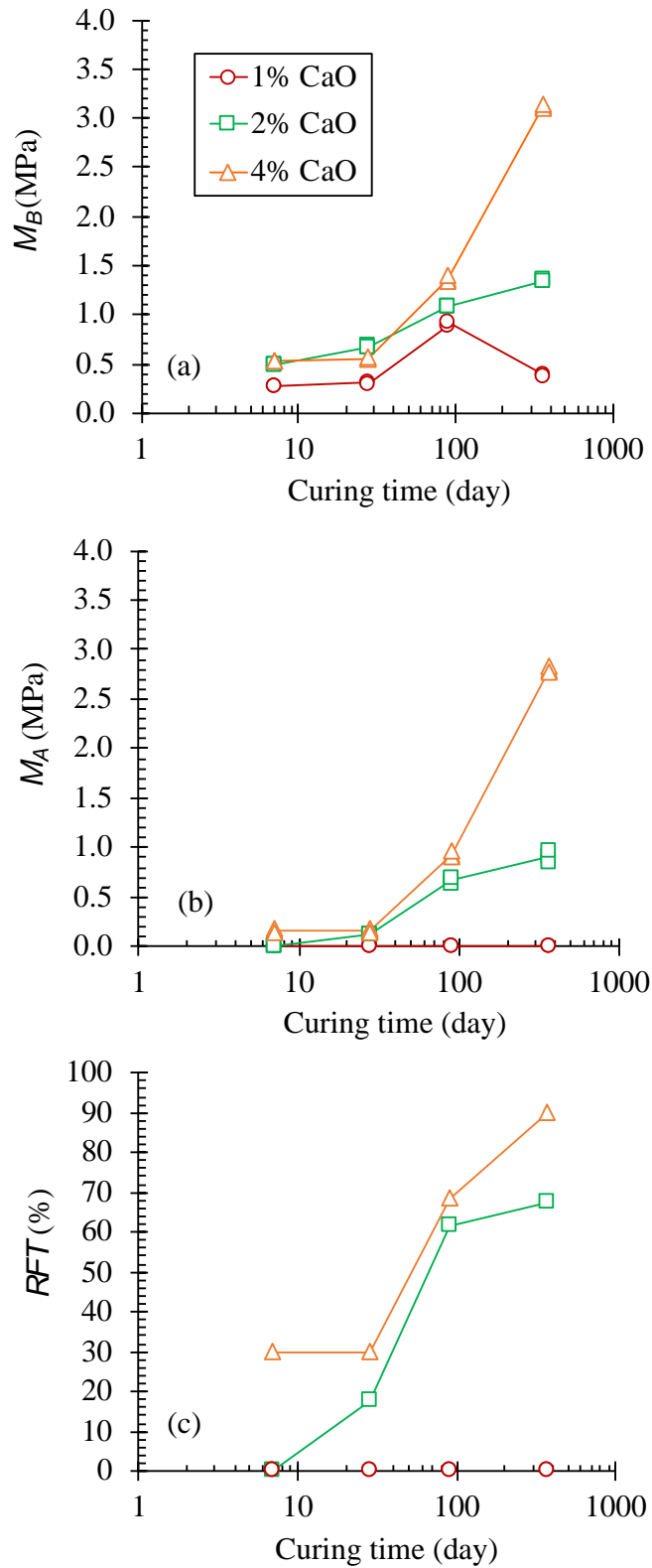
Figure 4. Device to determine the mechanical strength.



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Figure 5. Device X-ray computed tomography.

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554 **Figure 6. Tests on soil A1: (a) strength of set B (without F-T cycles) versus curing time; (b) strength of set A**
 555 **(with F-T cycles) versus curing time; (c) retained strength factor versus curing time.**

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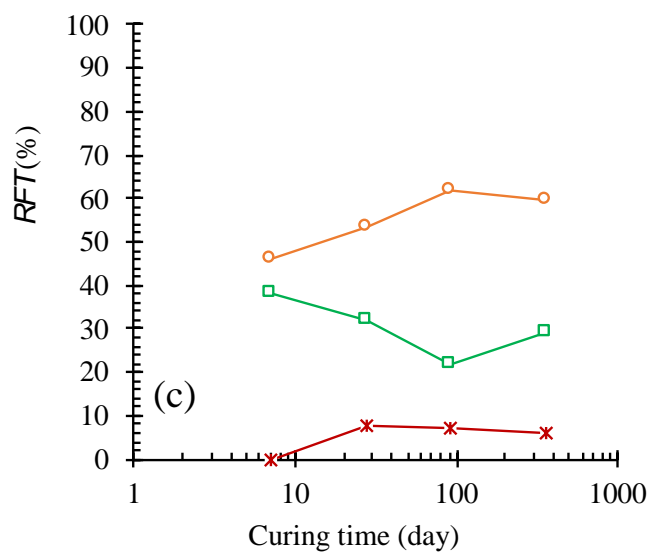
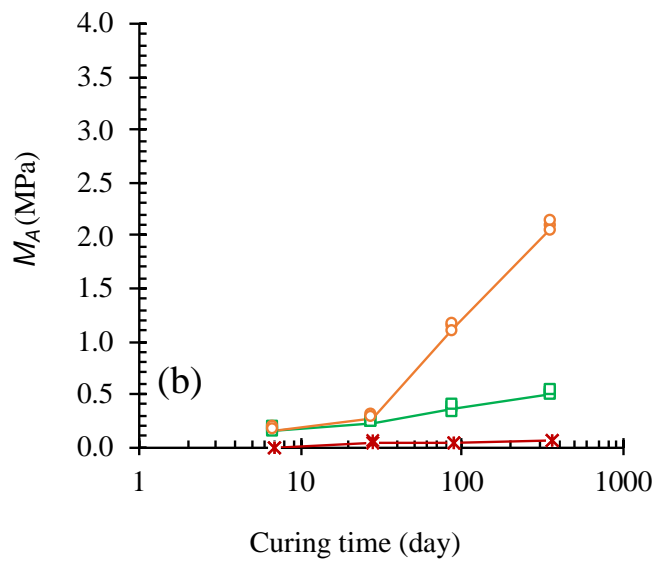
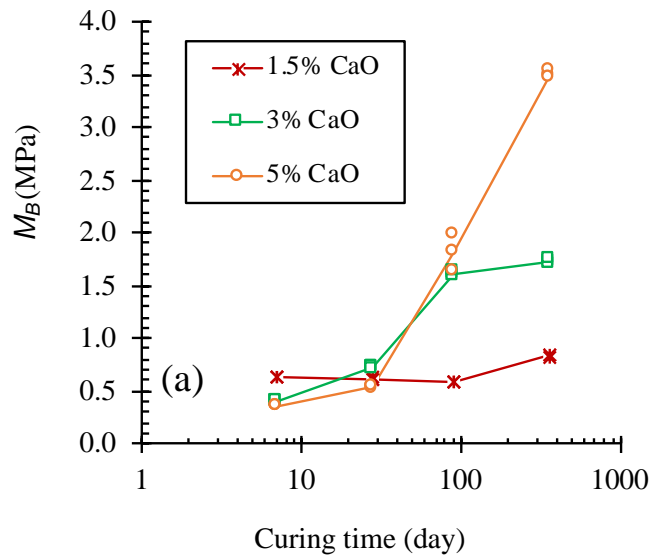
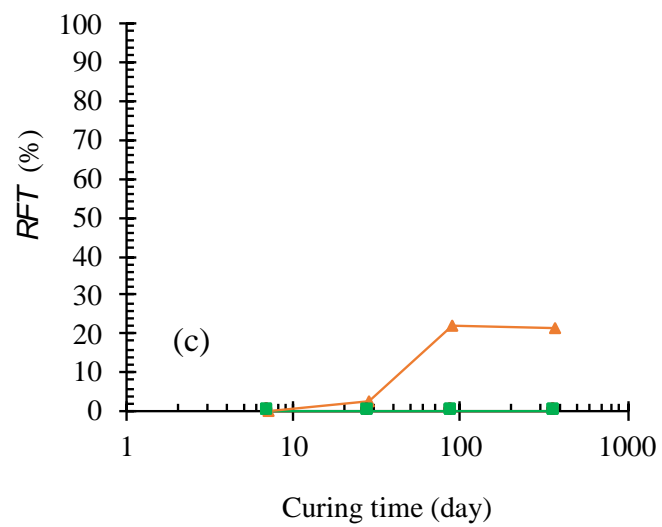
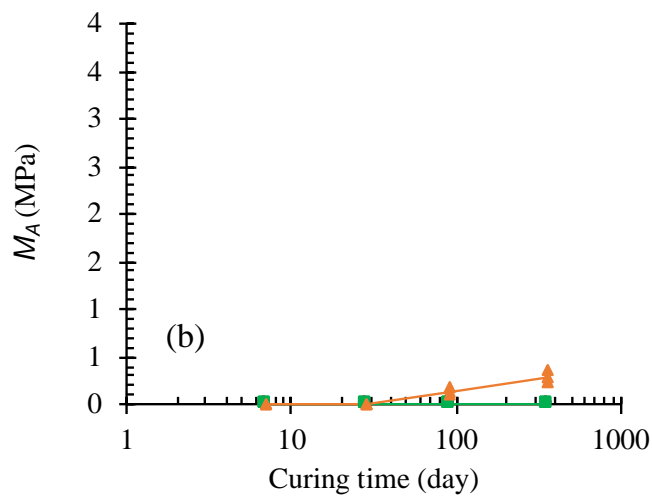
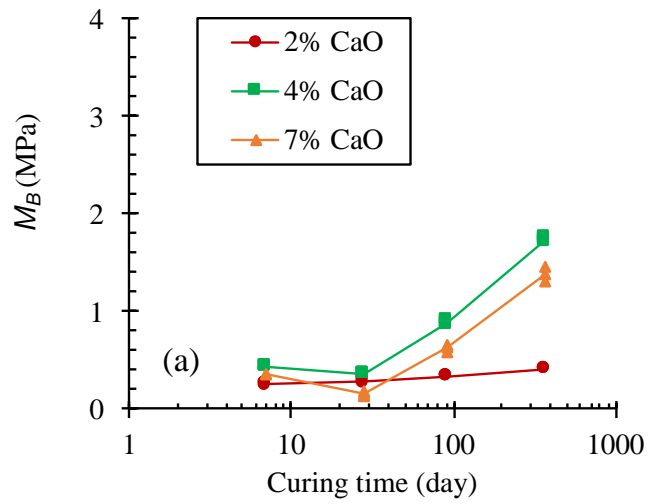


Figure 7. Tests on soil A2: (a) strength of set B (without F-T cycles) versus curing time; (b) strength of set A (with F-T cycles) versus curing time; (c) retained strength factor versus curing time.

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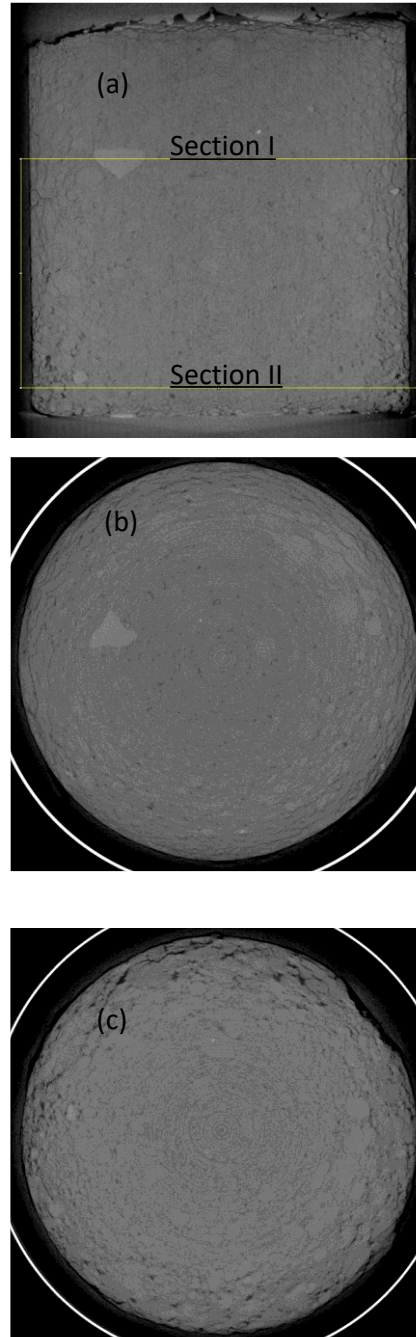


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Figure 8. Tests on soil A3: (a) strength of set B (without F-T cycles) versus curing time; (b) strength of set A (with F-T cycles) versus curing time; (c) retained strength factor versus curing time.

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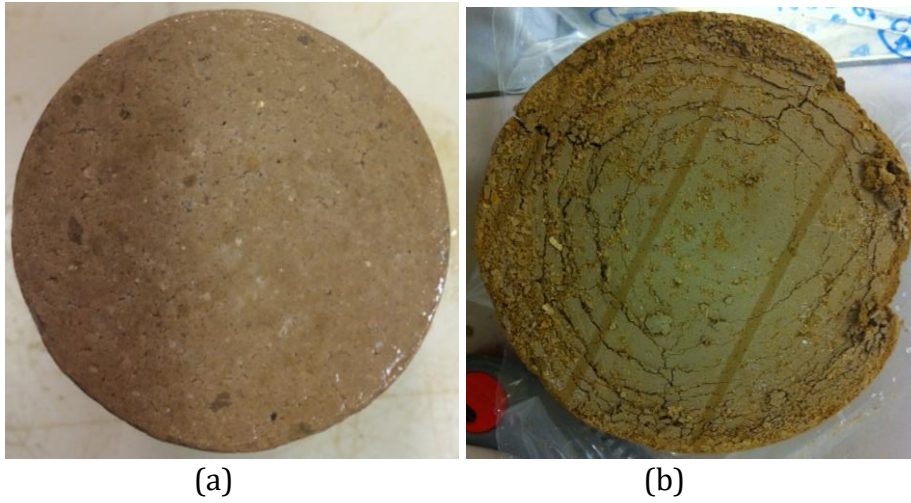
569 **Figure 9. Image obtained by X-ray computed tomography on soil A1 treated with 2% of lime, at 28 days of**
570 **curing under 10 F-T cycles: (a) vertical slide crossing the center of the sample; (b) horizontal slide in the**
571 **middle of the sample - Section I; (c) horizontal slide at the bottom of the sample - Section II.**

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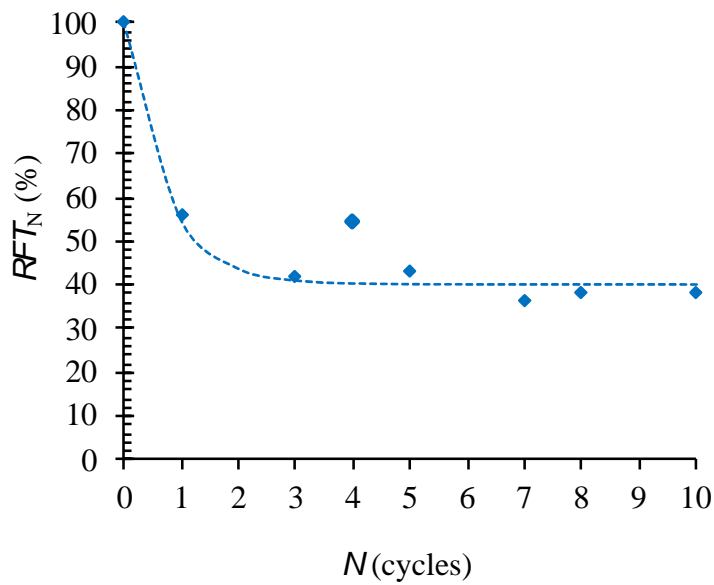
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Figure 10. Image obtained on soil A1 treated with 2% of lime, at 28 days of curing (a) Set B - without F-T cycles; (b) Set A - within F-T cycles.



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Figure 11. RFTN versus number of F-T cycles for soil A1 treated with 2% of lime, at 28 days of curing.

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Table 1. Properties of the soils studied

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Properties	Soil A1	Soil A2	Soil A3
Location	Marche-Les-Dames (Belgium)	Tours-Bordeaux (France)	Charleville-Mézières (France)
Fraction of size particle < 80 μm (%)	99	96	100
Fraction of size particle < 2 μm (%)	24	28	70
Methylene blue value, <i>MBV</i> (g/100g)	2.4	3.4	7.4
Plastic limit, w_P (%)	23.2	17.0	45.8
Liquid limit, w_L (%)	30.1	42.0	79.5
Plasticity index, <i>PI</i>	7	25	34
Classification (USCS)	ML	CL	MH

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603 **Table 2. Optimum and Initial conditions of the tested specimens.**

Soil	Lime content (%)	Optimum		Initial condition	
		Maximum dry density (Mg/m ³)	Optimum water content (%)	Dry density (Mg/m ³)	Water content (%)
A1	0	1.81	14.8	-	-
A1	1	1.75	17.4	1.66	20.2
A1	2	1.72	18.2	1.63	21.4
A1	4	1.70	18.9	1.62	22.4
A2	0	1.81	15.6	-	-
A2	1.5	1.65	20.4	1.56	24.5
A2	3	1.61	22.2	1.54	25.5
A2	5	1.56	24.0	1.48	27.0
A3	0	1.56	20.1	-	-
A3	2	1.43	26.6	1.36	31.5
A3	4	1.38	28.8	1.31	35.1
A3	7	1.32	31.0	1.25	42.0

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