



HAL
open science

Physicochemical and Microstructural Evaluation in Lime-Treated Silty Soil Exposed to Successive Wetting-Drying Cycles Submitted to Different Testing Conditions

Geetanjali Das, Andry Razakamanantsoa, Gontran Herrier, Dimitri Deneele

► **To cite this version:**

Geetanjali Das, Andry Razakamanantsoa, Gontran Herrier, Dimitri Deneele. Physicochemical and Microstructural Evaluation in Lime-Treated Silty Soil Exposed to Successive Wetting-Drying Cycles Submitted to Different Testing Conditions. *Journal of Materials in Civil Engineering*, 2023, 35 (3), pp.4636. 10.1061/(ASCE)MT.1943-5533.0004636 . hal-04012053

HAL Id: hal-04012053

<https://hal.science/hal-04012053v1>

Submitted on 30 Jul 2024

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.

1 **Physicochemical and microstructure evaluation in lime-treated silty soil exposed to**
2 **successive wetting-drying cycles submitted to different testing conditions.**

3 Geetanjali Das¹; Andry Razakamanantsoa²; Gontran Herrier³; Dimitri Deneele⁴

4 ¹Ph.D student, Université Gustave Eiffel, Laboratoire GERS-GIE, F-44344 Bouguenais, France
5 (corresponding author). ORCID: <https://orcid.org/0000-0003-0573-9077>.

6 E-mail : geetanjavidas55@gmail.com

7 ²Researcher, Université Gustave Eiffel, Laboratoire GERS-GIE, F-44344 Bouguenais, France. E-mail :
8 andry.razakamanantsoa@univ-eiffel.fr

9 ³Formerly Senior Research Engineer, Lhoist Recherche et Développement, rue de l'Industrie 31, 1400
10 Nivelles, Belgium. Email : gontran.herrier@gmail.com

11 ⁴Researcher, Université Gustave Eiffel, Laboratoire GERS-GIE, F-44344 Bouguenais, France. Researcher,
12 Université de Nantes, CNRS, Institut des Matériaux Jean Rouxel, IMN, F-44000 Nantes, France. E-mail:
13 dimitri.deneele@univ-eiffel.fr

14

15 **Abstract**

16 Physicochemical-and microstructural-evolution in lime-treated soil subjected to successive wetting and
17 drying (W-D) cycles were investigated, and the relevancy of the laboratory-implemented testing condition
18 with in-situ conditions was discussed. Lime-treated soils were exposed to 17 W-D cycles using different
19 testing conditions. Two laboratory testing conditions were operated at laboratory temperature, consisting of
20 W-D duration representing the saturation level close to the one experienced in in-situ soil during rainy-and
21 drought-periods. The results obtained were interpreted with those obtained using the reference ASTM
22 procedure, which involves oven-drying of specimens at 71°C. Drying of lime-treated soil at 71°C reduced
23 the water content from about 20% to 0.85%. This has led to greater contact between soil particles, thus,
24 increasing the suction from about 143.5 MPa to 270 MPa. Such a phenomenon increased the Unconfined
25 Compressive Strength (UCS) of the oven-dried soil up to about 3 times compared to the air-dried specimen,
26 though the available cementitious bonding reflected by the presence of pores smaller than 3000 Å was
27 comparatively low in the former than the latter. Percentage leaching of calcium components with respect to
28 the initial calcium content of the soil was significantly low during W-D cycles due to greater exposure of
29 only the outer part of the compacted soil structure during wetting. However, the leaching was comparatively
30 higher in the oven-dried soil. The implemented wetting duration and drying temperature influence the

31 wetting front velocity of water, which significantly affects the duration taken by infiltrated water to invade
32 the core of an earthen structure, and hence its durability.

33 Keywords: Wetting and drying cycles; Unconfined compressive strength; physicochemical; microstructure;
34 Lime-treated soil.

35

36 **Introduction**

37 The sustainability of earth structures by lime treatment was shown to improve through several laboratories
38 (Cuisinier et al. 2011; Runigo et al. 2009; 2011; Shen et al. 2021) and a few field investigations. Some
39 recent in-situ evidence was provided in the study reported by Akula et al. (2020) and Das et al. (2020).
40 Akula et al. (2020) reported the behavior of the Friant-Kern Canal in California, United States, a hydraulic
41 earthen structure built with heavy plastic clay soil. The Friant-Kern Canal suffered severe erosion and slope
42 sliding in the early stages after construction due to the low engineering properties of the plastic soil. Several
43 sections of the Canal were renovated with 4% quicklime during the '70s. Study of up to more than 40 years
44 was conducted to inspect the long-term performance of the lime-treated material used for the repair and
45 reinforcement of the bottom and blankets of the canal. The study evidenced the increased long-term strength,
46 reduction in swelling and shrinkage potential, as well as significant resistance to erosion, thus showing the
47 improved geo-mechanical stability of the structure. Another study, reported by Das et al. (2020), was related
48 to the mechanical and physicochemical performance of a 2.5% quicklime-treated embankment built with
49 silty soil after 7 years of atmospheric exposure. The embankment was exposed to the climate of Rouen,
50 France, which experiences a mostly damp climate throughout the year due to heavy rainfall and frost.
51 However, despite this exposure, an average UCS of $3.29 \pm (0.45)$ MPa was reported in the core of the lime-
52 treated embankment. Additionally, the physicochemical and microstructural investigation evidences the
53 long-term impact of lime treatment towards such significant evolution in compressive strength.

54 Lime, when added to soil in the presence of water, brings physical improvement in the short-term
55 and chemical modifications in the long-term. The short-term improvement includes decreasing the plasticity
56 of the soil, thus resulting in increased workability of the soil (Diamond and Kinter 1965; Little 1995). In the

57 long-term, lime undergoes pozzolanic reactions, which form cementitious compounds such as Calcium
58 Silicate Hydrate (CSH), Calcium Aluminate Hydrate (CAH) (Ali and Mohamed 2019a; Mehenni et al.
59 2016). These compounds play a central role in improving the long-term hydromechanical performance of
60 lime-treated soil.

61 Although several studies report the improvement brought by lime treatment; however, the
62 performance of lime-treated soil upon its exposure to successive alterations of seasonal temperatures as well
63 as fluctuations in water level is still a concern. Such concern varies with the climate of the specific regions
64 in which the structure is located or constructed. Some field investigations conducted with lime-stabilized
65 roads evidenced that a significant alteration in climatic conditions can negatively impact the performance
66 of lime-treated soil (Cuisinier and Deneele 2008; Kelley 1977). Additionally, several laboratory studies are
67 available that delineated the severity of wetting and drying (W-D) cycles, as well as freeze/thaw cycles on
68 degrading the improved hydromechanical behavior of lime-treated soil (Chittoori et al. 2018; Cuisinier et
69 al. 2020; Nabil et al. 2020). For instant, Chittoori et al. (2018) reported that lime-treated expansive soil
70 containing higher montmorillonite content suffers premature failure during W-D cycles than the one
71 dominant in other clay minerals. Another study reported by Nabil et al. (2020) stated that the severity of W-
72 D cycles impact on lime-treated soil is resistible only for soil treated with greater lime content. The effect
73 of W-D cycles in the field is explained below.

74 In the field, the slope of the lime-treated hydraulic earthen structure built near water bodies often
75 suffers W-D cycles due to several fluctuations in water level (Chen et al. 2018; Jia et al. 2009; Johansson
76 and Edeskär 2014; Xiong et al. 2019). During heavy rainy periods, due to the rise in water level in water
77 bodies, the slope towards the base of the hydraulic structure may remain underwater for several weeks to
78 months. Such a situation can increase the available saturation level of the soil. On the other hand, during
79 severe drought periods, a drastic decrease in the water level might occur, thus exposing the same base level
80 to severe drying for several months to years, which in turn can decrease the saturation level. Such a
81 fluctuation in the saturation level can modify the mechanical resistivity of the lime-treated soil and might
82 impact the service life of the structure. Though assessment of the durability of lime-treated soil subjected to

83 W-D cycles was extensively studied, of which most of the studies were made following the testing condition
84 provided in ASTM D559 standard (ASTM 2015). According to the ASTM standard, the soil sample is
85 alternatively immersed in water for 5 hours at laboratory temperature and then placed in the oven for 42
86 hours of drying at 71°C. The benefit brought by lime treatment was then shown to be partially lost under
87 the impact of alterations of W-D Cycles either by showing the loss in mass or decrease in strength as a
88 function of the number of cycles. However, how well this technique represents the above in-situ W-D
89 situation is less investigated.

90 Recently, Cuisinier et al. (2020) demonstrated the importance of establishing a field-representative
91 laboratory testing protocol to evaluate the W-D cycles impact on stabilized soil. The study compared results
92 obtained from specimens subjected to W-D cycles as per ASTM standard and by drying at laboratory
93 temperature. It showed that oven-drying and full immersion of specimens during W-D cycles conducted as
94 per ASTM standard led to comparatively greater UCS degradation and increased the hydraulic conductivity
95 values up to two orders in magnitude. This demonstrates the essentiality of investigating the mechanism,
96 which has led to such differences in UCS, and hydraulic conductivity based on the implemented testing
97 conditions.

98 In this context, this study focuses on analyzing the physicochemical and microstructure mechanism
99 contributing to the evolution of UCS in compacted lime-treated cured specimens subjected to different
100 testing conditions. It is worth noting that the previous study by Das et al. (2020) demonstrates the long-term
101 effect of lime treatment on the physicochemical and microstructural properties of silty soil after 7 years of
102 atmospheric exposure. This study is aimed to highlight the importance of reproduction of laboratory testing
103 conditions close to the field's weather and soil condition, while evaluating the W-D effect on the long-term
104 performances of lime-treated soil by comparing the UCS, physicochemical and microstructural evolution.
105 Two laboratory testing conditions were proposed to represent the W-D cycles lime-treated soil may
106 experience in the field. The results obtained were compared with the respective results obtained using the
107 reference ASTM standard. The first part of the study focuses on comparing the UCS evolution and volume
108 variation of the specimens. Later, the physicochemical and microstructure characteristics are presented. In

109 the end, the mechanism correlating the physicochemical and microstructure properties with the UCS
110 evolution is explained.

111

112 **Properties of Soil and Lime**

113 The soil used was silty soil imported from Marche-Les-Dames (Belgium). The geotechnical properties of
114 the soil, which is obtained from the study reported by Nguyen et al. (2019) are presented in Table 1. The
115 mineralogy of the soil was obtained by X-ray diffraction, which showed the presence of Illite, Kaolinite,
116 and Chlorite as clay minerals, along with Quartz and Feldspars (Nguyen et al. 2019).

117 Quicklime (CaO) was used for the treatment. The lime consists of 90.9% of available CaO and a
118 reactivity (t_{60}) of 3.3 min. The Lime Modification Optimum (LMO) of the silt was determined by Eades and
119 Grim test as per ASTM standard D 6276-99a (ASTM 2006) and was found to be 1% by weight of lime. The
120 Lime Modification Optimum is defined as the minimum amount of lime that is essential to initiate the
121 hydration reaction between lime and soil (Cherian and Arnepalli, 2015; Little, 1987). However, in field
122 practice, to ensure a long-term pozzolanic reaction between lime and soil as well as the enhancement of its
123 hydromechanical performances, the quantity of lime to be added is recommended to be higher than LMO
124 (Runigo et a., 20011; Das et al., 2022). Thus, lime content, 1.5% higher than LMO, *i.e.*, equal to 2.5%, was
125 used herein. Also, this 2.5% of quicklime was shown to be sufficient to bring significant long-term
126 improvement in a full-scale experimental embankment built using the studied soil by Das et al. (2020).
127 Besides, this embankment was previously studied by Makki-Szymkiewicz et al. (2015), where the
128 permeability performance of the lime-treated soil is reported. Hence, 2.5% quicklime content is chosen in
129 the present study to keep the continuation of any necessary comparison required to be made with previous
130 studies.

131

132 **Sample preparations**

133 The maximum dry density, $\rho_{d(max)}$, and Optimum Moisture Content (OMC) of the untreated and the lime-
134 treated silty soil were obtained as per ASTM D698-12e2 (ASTM 2012) (Table. 2).

135
136 The silt was mixed with distilled water at a water content of $1.1 \times \text{OMC}$, *i.e.*, specimens were
137 prepared at the wet of optimum (WMC). This is because a compaction moisture content similar to the one
138 reported by Das et al. (2020) was maintained, which involved a study regarding the performance of an in-
139 situ embankment built with the present soil configuration. The soil mixture was then stored in sealed plastic
140 bags to allow moisture content homogenization for about 24 hours. The soil mixture was then mixed with
141 lime and rested for 1 hour before compaction. This process of soil preparation was as per the French GTS
142 Technical Guide for soil treatment (GTS - LCPC-Setra Technical Guide 2000).

143 Cylindrical specimens of dimensions 0.10 m in height and 0.05 m in diameter were prepared by the
144 static compaction method at WMC. The process of static compaction involves compression of the
145 specimens from top and bottom, as demonstrated by Holtz et al. (1981). A total of 2 untreated and 14 lime-
146 treated specimens were prepared, of which 4 lime-treated specimens were presented in Fig.1. After
147 compaction, specimens were wrapped in plastic film and then subjected to curing at a laboratory temperature
148 of 20 ± 1 °C. A 10 month curing time was implemented herein, considering it the longest laboratory
149 implemented curing time to have the most suitable results in a one-year time frame.

150

151 **Laboratory Experiments**

152 This section explains the testing conditions developed, followed by tests performed successively in the
153 study.

154

155 *Testing conditions for Wetting and drying cycles*

156 The W-D cycles were imposed as per the ASTM standard and using two laboratory-developed testing
157 conditions. The testing condition implemented as per the procedure demonstrated in ASTM D559, which
158 involves 5 hours of wetting at laboratory temperature followed by 42 hours of oven-drying at 71°C is
159 denoted as AP. Fig. 2 shows the wetting and drying of the AP subjected specimens. The second and third
160 testing conditions were proposed to represent the situation a soil might experience in the field during rainy
161 and drought seasons, respectively.

162 Alteration of W-D cycles brings an increase and then decrease of the soil-saturation level,
163 respectively. During rainy periods, when the slope towards the base of the hydraulic earthen structure
164 remains under water for a long time, the soil can be assumed to have attained a maximum saturation level
165 of 85-90%. Again, due to the greater frequency of precipitation during the rainy season, the soil can be
166 assumed to have reach a saturation level not less than 65-70% during the drying period, when the water
167 level in the water bodies decreases for a certain period. Similarly, the soil was assumed to dry up to a
168 saturation level of 25-30% during the drought season, and considering the slightest rainfall that can probably
169 happen during the drought period; the soil was supposed to reach a maximum saturation level of only 65-
170 70%. For the present lime-treated soil, the duration required to attain the above assumed saturation level
171 during rainy and drought periods was measured in the laboratory, during which the temperature and relative
172 humidity varied from 22.1-25.2°C and Relative Humidity (RH) of 34.3-52.8%, respectively. The present
173 study considers the laboratory temperature and RH as the reference condition to highlight the essentiality of
174 considering the field conditions. The obtained wetting and drying duration were then used to undergo
175 successive W-D and drying-wetting cycles to represent the rainy and drought situations, respectively. The
176 testing conditions and the duration required to attain the assumed levels of saturation are provided in Table
177 3. The second and the third testing conditions, which represent the rainy periods and drought periods,
178 respectively, are regarded as RP and DP, respectively, in the following study. It is worth noting that
179 specimens subjected to AP and RP experience alternate W-D cycles, whereas specimens subjected to DP
180 experience alternate drying and wetting (D-W) cycles.

181 The RP and DPs were conducted by a laboratory proposed device, which involves successive
182 wetting of the specimens by soaking in water for the proposed time and then drying the same by allowing
183 the water to move out after completion of the wetting duration. A part of the water after each wetting, *i.e.*,
184 the effluent, was stored for chemical analysis. A total of 17 wetting-drying and drying wetting (W-D/D-W)
185 cycles were operated using the three testing conditions. This is because, within the time frame of one year,
186 10 months were used for curing, and in the remaining 2 months, 17 was found to be the maximum number
187 of cycles that can be achieved for all the testing conditions. The mass and volume of the specimens subjected
188 to all three conditions were recorded at the end of each cycle. During these measurements, samples were
189 carefully handled, and the excess water around the specimens was wiped off to avoid any error in the
190 measurements. To establish the homogeneity of the specimens, they were periodically turned during the
191 alternate cycles.

192 Of the 14 lime-treated specimens prepared and cured, three sets of 4 specimens were subjected to
193 the three testing conditions, and the remaining 2 were used to evaluate the initial state of the specimen after
194 10 months of curing.

195

196 ***Unconfined Compressive Strength measurement***

197 10 months cured specimen, *i.e.*, the initial specimen, and the specimens subjected to 5th, 9th, 13th, and 17th
198 alternate W-D/D-W cycles in each of the three testing conditions were subjected to UCS test using a
199 mechanical press with a load sensor of 10 KN. The load was applied to the specimens at a constant axial
200 displacement rate of 1 mm/min.

201

202 ***Measurement of Physicochemical properties***

203 The water content of each UCS-subjected specimen was measured by oven drying at 105°C (ASTM D2216-
204 10) and was used to estimate the water content corresponding to the remaining cycles. The suction of the
205 UCS subjected specimen was determined using the WP4C Dewpoint Potentiometer. The pH of the UCS
206 subjected specimens was also measured. Specimens collected at the end of the UCS test were crushed and

207 then mixed with demineralized water in a 5:1 liquid: solid ratio for 1 hour, and then the pH of the solution
208 was recorded (ASTM D4972-19). To have more reliable results, at least an average of the three values of
209 preceding properties was reported.

210 The Electric Conductivity (EC) of the effluents collected after each wetting was determined by a
211 Water Quality Meter. A part of the collected effluent corresponding to a certain number of wetting cycles
212 was filtered using a 0.45 μm syringe and then subjected to Inductively Coupled Plasma Optical Emission
213 Spectrometry (ICP OES) analysis. This was done to determine the elementary concentrations of Calcium
214 (Ca) that have been leached from the lime-treated soil subjected to W-D/D-W cycles.

215
216 ***Pore structure determination***

217 Pore Size Distribution (PSD) was analyzed by Mercury Intrusion Porosimetry (MIP) test and Barrett-Joiner-
218 Halenda pore (BJH) method (Barrett et al. 1951). Since MIP was known to investigate macropores and BJH,
219 the mesopores more elaboratively, as shown by Das et al. (2020); hence both the methods are used herein.
220 The analysis was made on the freeze-dried samples gathered from the core of the 10 months cured specimen
221 and the specimens subjected to the UCS test.

222 During the MIP test, mercury (Hg) was progressively intruded into freeze-dried specimens
223 contained inside a sealed penetrometer after the evacuation of the specimen via heating. The intruded Hg
224 volume and the corresponding applied pressure, p (MPa), were registered, using which pore sizes were
225 obtained from the Washburn equation (Romero and Simms 2008). Similar, to the MIP test, freeze-dried
226 samples were degassed at 50°C, and then nitrogen gas was injected during the Brunauer-Emmett-Teller
227 (BET) test (Brunauer et al. 1938). From the isotherms obtained in the freeze-dried specimens, the BJH
228 method analyzes the PSD using the Kelvin equation. The discussion of pore structure is presented as per the
229 International Union of Pure and Applied Chemistry (IUPAC) (Rouquerol et al. 1994), which classifies pores
230 based on their pore-width as macropores ($> 500 \text{ \AA}$), mesopores (20-500 \AA), and micropores ($< 20 \text{ \AA}$).

231

232 **Results**

233 This section is focused on presenting the observation made with the results, and then the mechanism behind
234 such observations is followed up in the discussion section.

235

236 *W-D/D-W cycle influence on UCS evolution*

237 The untreated compacted silty soil was destroyed when submitted to the first wetting cycle, as shown in Fig.
238 3; hence, no UCS test and any further tests could be conducted with the untreated specimens.

239 The UCS evolution of the lime-treated soil subjected to 17 W-D/D-W cycles as per the 3 testing
240 conditions is presented in Fig. 4. The UCS of the initial specimen after 10 months of curing was measured
241 to be 1.26 MPa. This UCS increased to 3.40 MPa after the lime-treated soil underwent 5 cycles of W-D
242 cycles as per the AP (Fig. 4). Further increase in the W-D cycles brought a slight decrease in the UCS to
243 about 3.26 MPa after the 9th W-D cycle compared to the UCS attained after the 5th cycle. This UCS decreased
244 significantly to 2.28 MPa, and 1.57 MPa after the 13th, and 17th W-D cycles, respectively. Thus, the UCS of
245 the AP-subjected soil increased significantly after the 5th and 9th W-D cycles and then decreased. However,
246 the overall evolution of UCS throughout the 17 W-D cycles remained higher than the UCS obtained with
247 the initial specimen.

248 For the RP-subjected soil, the UCS decreased slightly to 1.04 MPa after the 5th W-D cycle and then
249 reached a value that was about 0.40 MPa higher than the initial UCS after the 9th W-D cycle. After 13th W-
250 D cycle, the UCS again decreased to a level similar to the one attained after the 5th W-D cycle and then
251 remained the same as the initial UCS after the 17th W-D cycle. However, compared to the initial UCS, the
252 overall fluctuations observed in the evolution of UCS with the RP-subjected specimens were significantly
253 less than the one attained with the corresponding AP-subjected specimens throughout the 17 W-D cycles.

254 The UCS of the DP-subjected soil showed a gradual decrease up to the 13th D-W cycle, and then
255 after the 13th and 17th D-W cycles, the obtained UCS was almost similar.

256

257 *W-D/D-W cycle influence on volume variations*

258 The change in volume of the specimens during W-D/D-W cycles is presented as a percentage increase or
259 decrease in the volume of respective specimens compared to the volume of the initial specimen in Fig. 5 (a-
260 c). The presented percentage change in volume is the average of the volume change obtained during the 17
261 W-D cycles of the 4 specimens subjected to each RP, AP, and DP.

262 The amplitude of average volume changes between the wetting and drying phase and between 2
263 successive cycles during the W-D cycles remained less significant in the specimens submitted to the RP
264 testing condition (Fig. 5a). A maximum increase and decrease of about 0.8% in the average volume occurred
265 compared to the initial volume.

266 Compared to the initial volume of the specimen, the AP submitted specimens showed a slight
267 increase in average volume during the 1st wetting, and then the volume decreased by about 2% after the 1st
268 oven-drying (Fig. 5b). In the successive W-D cycles from 1st to about 8th cycles, the amplitude in average
269 volume variations between the wetting and drying phase remained almost similar, where the increase and
270 decrease in the average volume was less than 1% and 2%, respectively than the initial volume. The
271 fluctuation in the average volume variation was then lowered in the following W-D cycles. However, the
272 maximum increase in average volume during wetting remained lower by about 0.4% compared to the initial
273 volume throughout the 17 W-D cycles.

274 DP-subjected soil underwent a maximum decrease in average volume during drying of about 1.5%,
275 and the maximum increase in average volume corresponds to the initial volume from the 1st to about 7th D-
276 W cycles. For the remaining cycles, the loss in the average volume was almost insignificant (Fig. 5c). The
277 overall trend observed in the average volume variation between the AP, and the DP submitted specimens
278 were almost the same. However, the percentage of average volume loss after each drying was comparatively
279 higher in the AP compared to the DP-subjected soil. On the other hand, the percentage increase in average
280 volume after each wetting was relatively higher in the DP than the AP-subjected soil.

281

282 *W-D/D-W cycle influence on water content variations in the specimens*

283 The water content was measured for the 10 months cured soil and for the specimen subjected to UCS test
284 after 5th, 9th, 13th, and 17th cycles. The water content corresponding to the remaining cycles was then
285 estimated by using the bulk mass of the soil measured after each cycle and the dry mass of the soil measured
286 at the end of the 17th cycle. This method of back estimation was approved in ASTM D559. The evolution
287 of average water contents is presented in Fig. 5 (d-f).

288 According to Fig. 5d, a maximum of 2% increase and decrease in the average water content occurred
289 during the wetting and drying phases, respectively, at laboratory temperature in the RP-subjected soil
290 throughout the 17 W-D cycles. This increase and decrease in the average water content were found to almost
291 correspond with the average maximum and minimum saturation level set earlier for the RP testing condition.
292 The global trend of average water content evolution between 2 successive wetting and drying cycles
293 remained almost constant.

294 Similar to the RP-subjected soil, the overall trend in the variation of the average water content
295 between the wetting and drying phases and between 2 successive cycles remained almost constant in the
296 AP-subjected soil (Fig. 5e). About 1% increase in the average water content compared to the initial water
297 content occurred during every 5 hours of wetting at laboratory temperature; however, almost a complete
298 loss in water content occurred during each 71°C oven-drying of the AP submitted soil.

299 In the DP submitted soil, the increase in average water content level during each wetting remained
300 almost at a similar level, which was equivalent to the initial water content (Fig. 5f). However, a mean loss
301 in average water content of about 13% occurred during the D-W cycle compared to the initial water content.
302 The increase in average water content attained during almost each wetting, though corresponds with the
303 average saturation level set for the DP testing condition, the average saturation level has fluctuated during
304 the drying in certain number of cycles.

305

306 *W-D/D-W cycle influence on soil suction and soil pH evolution*

307 At the end of the UCS test, the soil suction and pH of the soil were measured and presented in Fig. 6 for
308 each testing condition, with the soil suction and soil pH recorded from the initial soil.

309 As expected, the soil suction of the AP submitted soil increased significantly in comparison to the
310 initial suction of the soil due to almost total loss in water content (as seen in Fig. 5). The soil suction
311 increased to 143.5 MPa after 5th cycle, then it increased to 270.0 MPa after 9th cycle and then remained
312 approximately unchanged for the 13th and 17th cycles. The difference in the soil suction measured for the
313 corresponding RP submitted soils remained less significant compared to the initial soil suction (Fig. 6a).
314 The soil suction decreased for the DP-subjected soil up to 9th cycle, and then this decrease was slightly
315 lowered after the 13th and 17th D-W cycles.

316 The pH measured for the initial specimen was 11.86. For the RP-subjected soil, this pH remained
317 approximately unchanged up to 17th cycle (Fig. 6b). The pH of the AP-subjected soil decreased to 10 from
318 the initial soil pH after the 5th cycle. The pH then further decreased; however, the decrease was relatively
319 lower and remained above 9.3. Similar to the AP submitted soil, the pH of the DP submitted soil also
320 decreased compared to the initial pH of the soil (Fig. 6b).

321

322 *W-D/D-W cycle influence on Ca concentration and EC evolution in the effluents*

323 Fig. 7 presents the concentration of *Ca* and EC measured in the effluents collected during the W-D/D-W
324 cycles conducted as per the testing conditions. The initial CaO in the untreated silty soil was estimated as
325 0.5%, and 2.5% of CaO was added during specimen preparation. Thus, the lime-treated soil consists of 3%
326 CaO before curing. The *Ca* content in the 3% of the CaO, *i.e.*, $Ca_{initial}$ was estimated, and the release of *Ca*
327 measured in the effluent, *i.e.*, $Ca_{leached}$ was then expressed as a percentage of the former in Fig. 7a.

328 The percentage of *Ca* leached from the lime treated soil was observed to be extremely low in all the
329 specimens, regardless of the testing conditions (Fig. 7a). However, the loss of *Ca* and the magnitude of EC
330 obtained were relatively higher in AP-subjected soil compared to the corresponding RP-subjected soil
331 throughout the W-D cycles. The trend of the loss in *Ca* concentration and the measured EC decreased during
332 the W-D cycles for the AP-subjected soil. On the other hand, this trend remained almost constant for the
333 corresponding RP-subjected soil.

334 For the specimens subjected to DP testing conditions, the leaching of Ca and EC measured remained
335 relatively lower than both RP and AP-subjected specimens, and the overall evolution was almost similar
336 throughout the D-W cycles (Fig. 7b).

337
338 ***W-D/D-W cycle influence on pore structure modifications***
339 The PSD and cumulative pore volume evolution in the lime-treated W-D/D-W cycles subjected specimens
340 were compared with the one obtained from the untreated and the 10 months cured soil by MIP and BJH,
341 respectively, in Fig. 8.

342
343 ***Determination of PSD by MIP***
344 Fig. 8 showed that the untreated soil exhibits greater intensities of macropores of diameter in the range of
345 10^4 and 10^5 Å. After lime treatment and 10 months of curing, macropores of diameter 10^5 Å evolved, a
346 significant decrease of macropores of diameter 10^4 and 10^5 Å and an increase in pores smaller than 3000 Å
347 occurred (Fig. 8(a-c)). Pores of diameter 10^5 Å were due to agglomeration of lime-treated soil, while pores
348 smaller than 3000 Å evolved because of cementitious bonding as reported in previous studies (Das et al.
349 2021; 2022; Cuisinier et al. 2011).

350 On subjecting the 10 months cured lime-treated soil to the W-D cycles as per the AP testing
351 condition, macropores of diameter 10^4 Å increased, and the broad pore peak developed in the 10 months
352 cured soil over pores smaller than 3000 Å was narrowed down during the W-D cycles (Fig. 8a). These
353 features remained almost similar irrespective of the number of W-D cycles the specimens were subjected.
354 On the other hand, 10 months cured lime-treated soil, despite being subjected to over 17 cycles of W-D as
355 per the RP, showed no significant change in the broad pore peak developed over a pore range smaller than
356 3000 Å (Fig. 8b). A slight insignificant rise in intensities of pores of diameter 10^4 Å occurred during the
357 W-D cycles.

358 For specimens subjected to DP, pores smaller than 3000 Å were gradually decreased, and pores of
359 diameter 10^4 Å increased with an increased number of D-W cycles (Fig. 8c).

360

361 ***Determination of cumulative pore volume evolution by BJH***

362 Using the BJH method, the evolution of cumulative pore volume in the pore range 24-250 Å, which comes
363 under the mesopores range, was analyzed and presented in Fig. 8(d-f).

364 According to Fig. 8(d-f), lime-treated 10 months cured soil showed a significant development of
365 pore volume in the mesopore range 24-250 Å compared to the untreated soil.

366 For the AP-subjected specimens, after the 5th W-D cycles, the cumulative pore volume in the
367 mesopore range 24-250 Å remained at a similar level to the initial 10 month cured specimen (Fig. 8d).
368 However, after the 9th W-D, these cumulative pore volumes increased by about 1.3 times compared to the
369 initial specimen. Further increase in W-D cycles, *i.e.*, after the 13th and 17th W-D cycles, has resulted in a
370 decrease in the cumulative pore volume by about 1.5 to 1.6 times compared to the initial specimen.

371 Specimens that underwent W-D cycles as per the RP testing condition showed a minimal difference
372 in the cumulative pore volume in the mesopore range 24-250 Å over the entire 17 W-D cycles compared to
373 the initial specimen (Fig. 8e).

374 For the DP-subjected soil, the cumulative pore volume in the mesopore range 24-250 Å after the 5th
375 D-W cycles remained at a similar level to the initial specimen (Fig. 8f). This feature then gradually decreased
376 by about 1.1 times in the specimen that has suffered the 9th D-W cycles and by about 2 times in the specimen
377 subjected to the 13th D-W cycles. The cumulative pore volume then remained almost similar for the 17th D-
378 W subjected specimen with the 13th D-W subjected soil.

379

380 **Discussions**

381 The UCS of a lime-treated soil is the resistance to deformation of the compacted soil structure under
382 unconfined compression. This resistance is a resultant of the inter-and intra-aggregates modifications, which
383 are influenced by the water content (Yin et al. 2018) and cementitious compounds (Little 1995). Thus,
384 during these W-D/D-W cycles, a significant loss or gain in water can modify the inter-aggregate structure
385 of the compacted soil. In the present study, subjecting the lime-treated soil to high drying temperature (71°C

386 in oven) as per AP testing condition resulted in accelerated pozzolanic reactions between soil minerals and
387 lime (Little 1995; Wang et al. 2017). Concurrently, a total loss of moisture content occurred as measured at
388 the end of each AP's W-D cycle (Fig. 5e). Again, the development of pozzolanic reactions is dependent on
389 water availability (Diamond and Kinter 1965; Little 1995). Hence, the loss in water content and the necessity
390 of water for pozzolanic reactions possibly have created a competition between the pozzolanic reaction and
391 soil suction evolution during the cycles. However, Fig. 6(a) presents a significant increase in total suction
392 of the AP-subjected soil compared to the initial soil suction, and the AP-subjected soil did not show
393 significant evolution of cementitious compounds during the W-D cycle as reflected by the difference in the
394 generation of pores smaller than 3000 Å in Fig. 8a & d. Thus, it can be derived that the high UCS developed
395 in the AP-subjected soil was mostly contributed by the high soil suction generated due to induced contact
396 between soil particles because of water loss. The preceding statement is supported by the less significant
397 evolution of soil suction (Fig. 6a) and UCS (Fig. 4) in the specimens with similar configurations but was
398 subjected to air-drying as per RP and DP testing conditions. Thus, the soil suction developed in the lime-
399 treated soil during successive W-D/D-W cycles possibly contributes to the evolution of UCS.

400 The insignificant soil suction generated in the RP-subjected soil (Fig. 6a) during the W-D cycle
401 compared to the initial suction is attributed to only 2% average water content loss during every 17 hours of
402 air-drying at 22.1-25.2°C (Fig. 5d). However, though the average water content loss after each air-drying
403 was higher in the DP-subjected soil compared to the RP-subjected soil, due to the longer air-drying of the
404 DP-subjected soil (Figs. 5d & f), the suction evolution was comparatively lower in the former than the latter
405 (Fig. 6a). This was due to the presence of higher water content in the DP-subjected soil, as the soil suction
406 was measured after the wetting phase of the D-W cycles, while suction measurement was conducted after
407 the drying phase of the W-D cycles in the AP-and RP-subjected soil.

408 The amplitude of the average volume variations between wetting and drying phases and the overall
409 trend of average volume changes in the specimens over the 17 W-D cycles evolved based on the
410 temperatures and durations of wetting and drying applied as per the three different testing conditions (Fig.
411 5 (a-c)). However, the overall trend of average volume variations was insignificant. Such an observation

412 can be due to the absence of smectite as a clay mineral in the present silty soil, which is mainly responsible
413 for the volume change behavior of soil (Das and Bharat 2016; Gopak et al. 2017). Also 2.5% quicklime
414 treatment might have subsided the possible ability of the soil to show considerable volume change (Chittoori
415 et al. 2013, 2018). For the RP-subjected soil, owing to the air-drying at 22.1-25.2°C, which caused a
416 minimum loss in average water content, the amplitude of average volume change in each cycle remained
417 almost insignificant compared to the initial volume of the specimen (Fig. 5a). Though DP-subjected soil
418 was also air-dried at 22.1-25.2°C, however, due to 70 hours of drying, which was 53 hours higher than the
419 RP-subjected soil, the amplitude of average volume change was comparatively higher (Fig. 5c). However,
420 the complete evaporation of water in the AP-subjected soil caused the maximum average volume loss of the
421 specimen during each oven-drying (Fig. 5b).

422 Durability of a hydraulic earth structure is interlinked with the ability of water to flow into the
423 structure. Water flow level can be quantified by the rate at which the wetting front developed during the
424 infiltration of water into the soil (Johnson 1963; Kirkham 2014). This velocity of the wetting front can be
425 said to vary based on W-D cycles created by the in-situ water fluctuations. Thus, a greater wetting front
426 velocity can increase the dampness of the structure and causes the structure to collapse due to loss in
427 mechanical strength (Jia et al. 2009; Johansson and Edeskär 2014). Besides, lime-treated soil is prone to
428 leach more lime if subjected to a greater wetting front velocity (Chittoori et al. 2013; Hara et al. 2008).
429 Thus, considering the wetting front velocity of water as an important parameter, the same was estimated
430 herein for the specimens subjected to W-D/D-W cycles as per the different testing conditions. Using the
431 average increase in the volume of the specimens during each wetting of the W-D/D-W cycles, the average
432 volume flow rate of water (Q) was calculated. From the Q , the average velocity of wetting front (W_f) into
433 the specimens was estimated as per Eq. 1.

434

435
$$W_f = Q/A = V_i/A \times t \quad (\text{Eq. 1})$$

436 where Q is the average volume flow rate of water into the specimens in m^3/s ; V_i is the increase in the average
437 volume of the specimens during each wetting in m^3 ; t is the duration of wetting during each cycle in s ; W_f
438 is the average wetting front velocity of water in m/s ; A is the total surface area of cylindrical specimen in
439 m^2 . Since the flow of water into the specimen occurred from all directions during wetting hence, the total
440 surface area of the cylindrical specimen was considered.

441 Table 4 presents the average of the estimated average W_f of water into the specimens subjected to
442 W-D/D-W cycles as per the different testing conditions. Using the estimated average velocity of W_f the
443 duration required by the infiltrated water to flow to the center of an in-situ structure of reference thickness
444 1m was obtained (see Table 4).

445 The average W_f caused during wetting of the W-D/D-W cycles was maximum for the DP- followed
446 by AP-, and then RP-subjected soil. Correspondingly, the duration estimated for the water to invade the
447 center of an in-situ structure was maximum for RP- followed by AP-, and then DP-subjected soil. Thus,
448 Table 4 evidence that lime-treated soil exhibiting similar configuration on being subjected to W-D/D-W
449 cycles conducted as per different testing conditions can show different W_f which can lead to a difference in
450 the durability of the structures. However, interestingly, the W_f was higher in the DP-subjected soil compared
451 to the AP-subjected soil, though the AP-subjected soil underwent complete evaporation of water during
452 each drying (Fig. 5e). Such an evolution was noticed due to greater amplitude of average volume increase,
453 *i.e.*, swelling during wetting in the DP-compared to the AP-subjected soil (Fig. 5b & c). Studies have
454 reported that oven-drying of soil cause soil aggregation and loss in plasticity, thus, resulting in a reduction
455 of the swelling potential of soil (Basma et al. 1994; Sunil and Deepa 2016). Thus, in the present case, it
456 might be probably due to the preceding statement the swelling was relatively lowered in the AP-subjected
457 soil due to oven-drying. Since the W_f was estimated based on the increase in volume during each wetting
458 thus, it occurred to be lower in the AP- than the DP-subjected soil. Thus, oven-drying of soil may cause an
459 underestimation of the W_f

460 Specimens subjected to W-D/D-W cycles showed Ca leaching, which was significantly lower than
461 the Ca content estimated to be present in the soil during sample preparation (Fig. 7a). This is attributed to

462 the consumption of *Ca* by the pozzolanic reactions during the 10 months curing, thus, probably leaving a
463 limited soluble *Ca* in the soil. Also, the limited contact of the soil structure with water during wetting, which
464 mostly exposes the outer layer of the compacted soil to leach a comparatively higher amount of minerals
465 than the internal soil structure, has led to the presence of such lower *Ca* concentration in the effluent.
466 However, despite the fact that the RP-subjected soil was exposed to longer wetting hours than the
467 corresponding AP-subjected soil, the leaching of *Ca* and EC measured was comparatively higher in the
468 latter than the former (Figs. 7a & b). Such an evolution was due to the complete drying of the AP-subjected
469 soil because of oven-drying, thus, making the soil more vulnerable to loss of minerals during wetting.
470 However, due to only 2 hours of contact of the specimens with water during each wetting as per the DP
471 testing condition, the loss in *Ca* and the measured EC remained relatively lower (Figs. 7a & b).

472 Additionally, according to Figs. 7a & b, the trend observed in the evolution of *Ca* and EC was
473 almost equivalent. Fig. 9 presents the obtained linear trend for the *Ca* and EC evolution in the W-D/D-W
474 subjected specimens. Such an observation demonstrates the important role of *Ca* component on controlling
475 the EC evolution of the lime-treated soil. Thus, EC can be used as an important parameter to assess the
476 leaching process of *Ca* occurring during the W-D/D-W cycles.

477 The above discussion shows that specimens subjected to RP testing condition exhibited an
478 insignificant change in soil suction (Fig. 6a), minimum volume and water content variations (Figs. 5a & d),
479 minimum *Ca* loss, and EC evolution (Fig. 7). Thus, the soil pH remained almost unchanged compared to
480 the initial soil pH (Fig. 6b), despite being subjected to 17 W-D cycles. The preceding
481 feature favored the conservation of cementitious bonding formed in the 10 months cured soil as evidenced
482 by the almost similar presence of smaller pores lower than 3000 Å (Fig. 8b) and mesopores volume (Fig.
483 8e) in the RP-subjected soil. On the other hand, a gradual loss in soil pH up to less than 10 from the initial
484 soil pH 11.86 (Fig. 6b) occurred in the AP-and DP-subjected specimens. Fig. 8a & c showed that the
485 significant evolution of pores smaller than 3000 Å in the initial specimen decreased, and macropores at 10⁴
486 Å increased. The former feature evidenced the possible loss in cementitious bonding, which contributed to
487 the decrease in soil pH, and the latter was probably due to soil shrinkage, thus, inducing crack and increasing

488 the macropores. In addition to the loss in cementitious bonding, the observed loss in soil pH in the AP and
489 DP submitted soil could also be a consequence of possible carbonation, as reported in previous studies
490 (Deneele et al. 2021; Xu et al. 2020).

491 However, the observed decrease in pores smaller than 3000 Å compared to the one available in the
492 10 months cured soil was more significant in the DP-compared to the AP-subjected soil during the D-W
493 and W-D cycles, respectively. Owing to the subjection of specimens to high temperature during each drying,
494 accelerated-pozzolanic reactions were induced (Little 1995; Wang et al. 2017), which probably have
495 resulted in the presence of more pores smaller than 3000 Å in the AP-subjected soils. The preceding
496 statement was evidenced by the pore structure analyzed by both MIP and BJH in Fig. 8a & d, where the
497 pores smaller than 3000 Å increased after the 9th cycle in the AP-subjected soil. Such a feature was missing
498 in the specimens subjected to other testing conditions. Thus, such a phenomenon explains that 5 hours of
499 wetting duration followed by oven-drying at 71 °C provides sufficient water to reactivate the generation of
500 cementitious compounds in the AP-subjected soil. Thus, such evolution can overestimate the actual
501 cementitious compounds that can be expected from an in-situ lime-treated soil subjected to W-D cycle.

502 Additionally, the gradual decrease in pores smaller than 3000 Å with increased D-W cycles in the
503 DP-subjected soil can be attributed to only 2 hours of contact of the lime-treated soil with water during each
504 wetting (Fig. 8c & f). This is evident from the maintenance of cementitious compounds in the RP-subjected
505 soil (Fig. 8b & e), which was subjected to 5 hours of wetting under the same testing environment
506 (temperature and RH), as the DP-subjected soil. Thus, the duration of wetting hours implemented during
507 the W-D/D-W cycles significantly influence the maintenance of cementitious compounds.

508

509 **Conclusions**

510 The physicochemical properties and microstructure modification that underlines the mechanism governing
511 the UCS evolution in lime-treated soil subjected to W-D/D-W cycles as per different testing conditions were
512 evaluated. Following conclusions were derived based on the evaluations:

513 1) The soil suction generated in the lime-treated soil during successive W-D/D-W cycles contributes towards
514 the UCS evolution. Lime-treated soil subjected to W-D/D-W cycles did not show any significant generation
515 of cementitious compounds compared to the one that evolved during curing time. However, the total loss in
516 water content during the oven-drying of the AP-subjected soil induced a greater soil-particles contact, which
517 increased the soil suction and resulted in up to about 3 times greater UCS in the AP-subjected soil. At the
518 same time, the corresponding UCS and suction evolution remained insignificant in the soil subjected to
519 testing conditions that represent a situation close to the field condition.

520 2) Wetting front velocity of water in specimens during W-D/D-W cycles is an important index to estimate
521 the duration taken by infiltrated water to invade an in-situ hydraulic structure, which is interlinked with the
522 durability of such structure. Soil subjected to W-D/D-W cycles as per different testing conditions exhibited
523 different wetting front velocities. DP-subjected soil showed 3 times greater wetting front velocity than the
524 AP-subjected soil. At the same time, RP-subjected soil showed 3 times lower wetting front velocity than
525 the AP-subjected soil.

526 3) The leaching of calcium from specimens exposed to W-D/D-W cycles is mainly regulated by the exposure
527 of the soil structure to the water during wetting. Since such exposure was mainly limited to the external
528 surface of the specimens thus, the overall leaching of calcium remained significantly low, regardless of the
529 testing conditions they are subjected to.

530 4) Oven-drying of AP-subjected soil at 71 °C makes the soil comparatively more prone to leach minerals
531 during the wetting phase. Thus, the leaching of calcium and the electric conductivity measured in the
532 effluent obtained from the AP-subjected specimens was comparatively higher than the specimens subjected
533 to the RP testing condition.

534 5) A similar trend of *Ca* and EC evolution occurred in the lime-treated soil submitted to the W-D/D-W
535 cycles, thus, demonstrating *Ca* as a controlling component on the EC evolution of the lime-treated soil.
536 Thus, EC can be used as an important parameter to assess the leaching process of *Ca* occurring during the
537 W-D/D-W cycles.

538 6) Re-wetting of lime-treated soil followed by oven-drying at 71°C during each cycle of the W-D cycles
539 induced pozzolanic reactions, which potentially overestimates the actual cementitious compounds that can
540 be expected from an in-situ lime-treated soil subjected to W-D cycle. As a result, though the loss of calcium
541 and soil pH in the AP-subjected soil was comparatively higher, pores smaller than 3000 Å, which evolved
542 due to lime treatment, seems to be less affected.

543 7) The maintenance of cementitious compounds in lime-treated soil subjected to W-D/D-W cycles is
544 significantly influenced by the wetting hours implemented under the same testing environment (temperature
545 and RH). RP-subjected soil being in contact with water for 7 hours, maintained the cementitious bonding
546 formed during the 10 months curing, while the same was gradually lost in the DP-subjected soil during the
547 successive D-W cycles, which remained only for 2 hours in contact with water.

548 The results emphasized the fact that based on the type of testing conditions implemented at a
549 laboratory for conducting W-D/D-W cycles, the physicochemical and microstructural modifications occur,
550 which brings a considerable change in the UCS evolution of lime-treated soils. Thus, consideration of the
551 temperature, RH, and wetting and drying durations based on soil saturation level is essential while
552 evaluating the impact of W-D/D-W cycles on the long-term performances of soil.

553 The present study is conducted under laboratory temperature, RH, and using an assumed saturation
554 level; however, in the field, based on the weather conditions of the in-situ project locations, these parameters
555 will vary. Also, the curing time implemented is 10 months, the difference in which can bring a variation in
556 the presently reported properties of the lime-treated soil. The selection of the convenient curing time is
557 fundamental as it ensures continuous contact between the soil, water, and the binder. Hence, further studies
558 should focus on reproducing a laboratory environment that resembles the actual temperature, RH, soil
559 saturation level of the targeted project sites, and intended curing time of the land infrastructure. This would
560 provide a more accurate representation of the expected long-term hydromechanical performance of the soil
561 structure under consideration.

562 Besides, additional studies should also be made (i) to evaluate the influence of the W-D/D-W cycle
563 on lime-treated soil that represents a situation similar to the one produced by wave effects on harbors, levees,

564 *etc.* during boat movements (ii) to investigate how such a difference in testing condition can affect the
565 carbonation of the lime-treated soil. However, based on the present results, it can be said that lime-treated
566 structures can maintain a longer durability in regions exhibiting longer rainy periods compared to the ones
567 with longer dry periods.

568

569 **Acknowledgement**

570 This work was financially supported by Association Nationale de la Recherche et de la Technologie with
571 grant N°2018/0219 and Lhoist Southern Europe with grant N°RP2-E18114. The authors are very thankful
572 to the research team of Université Gustave Eiffel and Lhoist R&D for their great support in performing
573 laboratory experiments and technical supports.

574 **Data Availability Statement**

575 Data generated or analyzed during the study is included in the submitted manuscript.

576 **References**

577 Akula, P., Hariharan, N., Little, D. N., Lesueur, D., and Herrier, G. 2020. “Evaluating the Long-Term
578 Durability of Lime Treatment in Hydraulic Structures: Case Study on the Friant-Kern Canal.”
579 *Transportation Research Record*, SAGE Publications Sage CA: Los Angeles, CA, 2674 (6): 431-443.
580 <https://doi.org/10.1177%2F0361198120919404>

581 Ali, H., and Mohamed, M. 2019. “Assessment of lime treatment of expansive clays with different
582 mineralogy at low and high temperatures.” *Construction and Building Materials*. Elsevier, 228:
583 116955. <https://doi.org/10.1016/j.conbuildmat.2019.116955>

584 ASTM. 2012. *Standard test methods for laboratory compaction characteristics of soil using standard effort*
585 *(12 400 ft-lbf/ft³ (600 kN-m/m³))*. ASTM D698-12e2. West Conshohocken, PA: ASTM.

586 ASTM. 2010. *Standard test methods for laboratory determination of water (moisture) content of soil and*
587 *rock by mass*. ASTM D2216-10. West Conshohocken, PA: ASTM.

588 ASTM. 2015. *Standard test methods for wetting and drying compacted soil-cement mixtures*. ASTM D559.
589 West Conshohocken, PA: ASTM.

590 ASTM. 2006. *Standard Test Method for Using pH to Estimate the Soil–Lime Proportion Requirement for*
591 *Soil Stabilization*. ASTM D 6276-99a. West Conshohocken, PA: ASTM.

592 ASTM. 2019. *Standard Test Methods for pH of Soils*. ASTM D4972-19. West Conshohocken, PA: ASTM.

593 Barrett, E. P., Joyner, L. G., and Halenda, P. P. 1951. “The determination of pore volume and area
594 distributions in porous substances. I. Computations from nitrogen isotherms.” *Journal of the American*
595 *Chemical society*. ACS Publications, 73(1): 373–380. <https://doi.org/10.1021/ja01145a126>

596 Basma, A.A., Al-Homoud, A.S., and Al-Tabari, E.Y. 1994. “Effects of methods of drying on the engineering
597 behavior of clays.” *Applied Clay Science*. 9(3): 151-164. [https://doi.org/10.1016/0169-](https://doi.org/10.1016/0169-1317(94)90017-5)
598 [1317\(94\)90017-5](https://doi.org/10.1016/0169-1317(94)90017-5)

599 Brunauer, S., Emmett, P. H., and Teller, E. 1938. “Adsorption of gases in multimolecular layers.” *Journal*
600 *of the American chemical society*. ACS Publications, 60(2): 309–319.
601 <https://doi.org/10.1021/ja01269a023>

602 Chen, M. L., Lv, P. F., Zhang, S. L., Chen, X. Z., and Zhou, J. W. 2018. “Time evolution and spatial
603 accumulation of progressive failure for Xinhua slope in the Dagangshan reservoir, Southwest
604 China.” *Landslides*. 15(3): 565-580. <https://doi.org/10.1007/s10346-018-0946-8>

605 Cherian, C., and Arnepalli, D.N. 2015. “A critical appraisal of the role of clay mineralogy in lime
606 stabilization.” *International Journal of Geosynthetics and Ground Engineering* 1: 8.
607 <https://doi.org/10.1007/s40891-015-0009-3>

608 Chittoori, B.C., Puppala, A.J., Wejrungsikul, T., and Hoyos, L.R. 2013. “Experimental studies on stabilized
609 clays at various leaching cycles.” *Journal of Geotechnical and Geoenvironmental*
610 *Engineering*. 139(10): 1665-1675. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000920](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000920)

611 Chittoori, B. C. S., Puppala, A. J., and Pedarla, A. 2018. “Addressing clay mineralogy effects on
612 performance of chemically stabilized expansive soils subjected to seasonal wetting and drying.”
613 *Journal of geotechnical and geoenvironmental engineering*. American Society of Civil Engineers,
614 144(1): 04017097. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001796](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001796)

615 Cuisinier, O., Auriol, J.-C., le Borgne, T., and Deneele, D. 2011. “Microstructure and hydraulic conductivity
616 of a compacted lime-treated soil.” *Engineering geology*. Elsevier, 123(3): 187–193.
617 <https://doi.org/10.1016/j.enggeo.2011.07.010>

618 Cuisinier, O., and Deneele, D. 2008. “Long-term behaviour of lime-treated expansive soil submitted to
619 cyclic wetting and drying.” *Unsaturated soils: advances in geoengineering: proceedings of the 1st*
620 *European Conference on Unsaturated Soils, EUNSAT*, 327.

621 Cuisinier, O., Masrouri, F., and Mehenni, A. 2020. “Alteration of the Hydromechanical Performances of a
622 Stabilized Compacted Soil Exposed to Successive Wetting–Drying Cycles.” *Journal of Materials in*
623 *Civil Engineering*. American Society of Civil Engineers, 32(11): 04020349.
624 [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003270](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003270)

625 Das, G., and Bharat, T.V. 2016. “Shrinkage behavior of clay soil: an experimental study.” *In: International*
626 *conference on soil and environment, ICSE*, Bangalore, 1-8.

627 Das, G., Razakamanantsoa, A., Herrier, G., Saussaye, L., Lesueur, D., and Deneele, D. 2020. “Evaluation
628 of the long-term effect of lime treatment on a silty soil embankment after seven years of atmospheric
629 exposure: Mechanical, physicochemical, and microstructural studies.” *Engineering Geology*. Elsevier,
630 281: 105986. <https://doi.org/10.1016/j.enggeo.2020.105986>

631 Das, G., Razakamanantsoa, A., Herrier, G., and Deneele, D. 2021. “Compressive strength and
632 microstructure evolution of lime-treated silty soil subjected to kneading action.” *Transportation*
633 *Geotechnics*, Elsevier, 100568. <https://doi.org/10.1016/j.trgeo.2021.100568>

634 Das, G., Razakamanantsoa, A., Herrier, G., and Deneele, D. 2022. “Influence of pore fluid-soil structure
635 interactions on compacted lime-treated silty soil.” *Engineering Geology*, 296, 106496.
636 <https://doi.org/10.1016/j.enggeo.2021.106496>

637 Deneele, D., Dony, A., Colin, J., Herrier, G., and Lesueur, D. 2021. “The carbonation of a lime-treated soil:
638 experimental approach.” *Materials and Structures*. Springer, 54(1): 1-12.
639 <https://doi.org/10.1617/s11527-021-01617-w>

640 Diamond, S., and Kinter, E. B. 1965. “Mechanisms of soil-lime stabilization.” *Highway Research Record*.
641 92 83–102.

642 Gapak, Y., Das, G., Yerramshetty, U., and Bharat, T. V. 2017. “Laboratory determination of volumetric
643 shrinkage behavior of bentonites: A critical appraisal.” *Applied Clay Science*. 135: 554-566.
644 <https://doi.org/10.1016/j.clay.2016.10.038>

645 GTS - LCPC-Setra Technical Guide. 2000. “Soil treatment with lime and/or hydraulic binders: Application
646 to the Construction of fills and capping layers.” LCPC Eds, Paris (France).

647 Hara, H., Suetsugu, D., Hayashi, S., and Du, Y.J. 2008. “Calcium leaching properties of lime-treated soil
648 by infiltration of tidal river water.” *In The Eighteenth International Offshore and Polar Engineering*
649 *Conference*. International Society of Offshore and Polar Engineers.

650 Holtz, R. D., Kovacs, W. D., and Sheahan, T. C. 1981. “An introduction to geotechnical engineering.”
651 Prentice-Hall Englewood Cliffs, NJ, 733.

652 Jia, G. W., Zhan, T. L., Chen, Y. M., and Fredlund, D. G. 2009. "Performance of a large-scale slope model
653 subjected to rising and lowering water levels." *Engineering Geology*. 106(1-2): 92-103.
654 <https://doi.org/10.1016/j.enggeo.2009.03.003>

655 Johnson, A.I. 1963. "A field method for measurement of infiltration". Washington: US
656 Government Printing Office. p. 49.

657 Kelley, C.M. 1977. "A long range durability study of lime stabilized bases at military posts in the
658 southwest." *National Lime Association*.

659 Kirkham, M.B. 2014. "Principles of soil and plant water relations." Academic Press.

660 Little, D.N. 1987. "Fundamentals of the Stabilization of Soil with Lime". *National Lime Association*.

661 Little, D. N. 1995. "Stabilization of pavement subgrades and base courses with lime." Kendall/Hunt
662 Publishing Company, Dubuque, Iowa.

663 Makki-Szymkiewicz, L., Hibouche, A., Taibi, S., Herrier, G., Lesueur, D., and Fleureau, J.-M. 2015.
664 "Evolution of the properties of lime-treated silty soil in a small experimental embankment."
665 *Engineering Geology*. 191:8–22. <https://doi.org/10.1016/j.enggeo.2015.03.008>.

666 Mehenni, A., Cuisinier, O., and Masrouri, F. 2016. "Impact of lime, cement, and clay treatments on the
667 internal erosion of compacted soils." *Journal of Materials in Civil Engineering*. American Society of
668 Civil Engineers, 28(9): 04016071. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001573](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001573)

669 Mitchell, J. K., and Soga, K. 2005. "Fundamentals of soil behavior (Vol. 3)." New York: John Wiley &
670 Sons.

671 Nabil, M., Mustapha, A., and Rios, S. 2020. "Impact of wetting—drying cycles on the mechanical properties
672 of lime-stabilized soils." *International Journal of Pavement Research and Technology*. Springer,
673 13(1): 83–92. <https://doi.org/10.1007/s42947-019-0088-y>

674 Nguyen, TTH., Cui, Y.-J., Ferber, V., Herrier, G., Ozturk, T., and Plier, F. 2019. “Effect of freeze-thaw
675 cycles on mechanical strength of lime-treated fine-grained soils.” *Transportation Geotechnics*. 21:
676 100281. <https://doi.org/10.1016/j.trgeo.2019.100281>

677 Romero, E., and Simms, P. H. 2008. “Microstructure investigation in unsaturated soils: a review with special
678 attention to contribution of mercury intrusion porosimetry and environmental scanning electron
679 microscopy.” *Geotechnical and Geological engineering*. Springer, 26(6): 705–727.

680 Rouquerol, J., Avnir, D., Fairbridge, C. W., Everett, D. H., Haynes, J. M., Pernicone, N., Ramsay, J. D. F.,
681 Sing, K. S. W., and Unger, K. K. 1994. “Recommendations for the characterization of porous solids
682 (Technical Report).” *Pure and Applied Chemistry*. De Gruyter, 66(8): 1739–1758.
683 <http://dx.doi.org/10.1351/pac199466081739>

684 Le Runigo, B., Cuisinier, O., Cui, Y.-J., Ferber, V., and Deneele, D. 2009. “Impact of initial state on the
685 fabric and permeability of a lime-treated silt under long-term leaching.” *Canadian Geotechnical*
686 *Journal*. 46: 1243–1257. <https://doi.org/10.1139/T09-061>

687 Le Runigo, B., Ferber, V., Cui, Y.-J., Cuisinier, O., and Deneele, D. 2011. “Performance of lime-treated
688 silty soil under long-term hydraulic conditions.” *Engineering geology*. Elsevier, 118(1–2): 20–28.
689 <https://doi.org/10.1016/j.enggeo.2010.12.002>

690 Shen, Y. S., Tang, Y., Yin, J., Li, M. P., and Wen, T. 2021. “An experimental investigation on strength
691 characteristics of fiber-reinforced clayey soil treated with lime or cement.” *Construction and Building*
692 *Materials*. Elsevier, 294: 123537. <https://doi.org/10.1016/j.conbuildmat.2021.123537>

693 Sunil, B.M., and Deepa, A.V. 2016. “Influence of drying temperature on three soils physical
694 properties.” *Geotechnical and Geological Engineering*. 34(3): 777-788.
695 <https://doi.org/10.1007/s10706-016-0001-2>

696 Wang, D., Zentar, R., and Abriak, N. E. 2017. “Temperature-accelerated strength development in
697 stabilized marine soils as road construction materials.” *Journal of Materials in Civil Engineering*.
698 American Society of Civil Engineers, 29(5): 04016281. [https://doi.org/10.1061/\(ASCE\)MT.1943-
699 5533.0001778](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001778)

700 Xiong, X., Zhenming, S., Yonglin, M. P., Xiaolong, M., and Feng Z. 2019 “Unsaturated slope stability
701 around the Three Gorges Reservoir under various combinations of rainfall and water level
702 fluctuation.” *Engineering Geology*. Elsevier, 261: 105231.
703 <https://doi.org/10.1016/j.enggeo.2019.105231>

704 Xu, L., Zha, F., Liu, C., Kang, B., Liu, J., and Yu, C. 2020. “Experimental Investigation on Carbonation
705 Behavior in Lime-Stabilized Expansive Soil.” *Advances in Civil Engineering*.
706 <https://doi.org/10.1155/2020/7865469>

707 Yin, C., Zhang, W., Jiang, X., and Huang, Z. 2018. “Effects of initial water content on microstructure and
708 mechanical properties of lean clay soil stabilized by compound calcium-based stabilizer.” *Materials*.
709 1, 1933. <https://doi.org/10.3390/ma11101933>

710

711 **Table 1.** Geotechnical properties of soil studied (Nguyen et al. 2019)

Clay fraction (< 0.002mm) (%)	Fraction (< 0.08 μm) (%)	Methylene Blue Value (g/100g)	Atterberg’s limit			USCS Classification
			PL (%)	LL (%)	PI (%)	
24	99	2.4	23.2	30.1	7	ML

712

713

714 **Table 2.** Maximum dry density and OMC of untreated and lime-treated silty soil

Soil	$\rho_{d(max)}$ (kN/m ³)	OMC (%)
Untreated silty soil	18.4	14.3
Silty soil treated with 2.5% lime	17.1	18.5

715
716
717
718
719
720
721
722
723
724

Table 3. Presentation of testing conditions

Designation	Testing conditions			Sequence of cycles	Number of specimens
	Wetting hours	Drying hours	Temperature (°C)		
AP (ASTM standard)	5	43	22.1-25.2 (wetting) 71 (drying)	Wetting then drying (W-D)	4
RP (to represent in-situ rainy situation)	7	17	22.1-25.2	Wetting then drying (W-D)	4
DP (to represent in-situ drought situation)	2	70	22.1-25.2	Drying then wetting (D-W)	4

725
726

727 **Table 4.** Estimated average velocity of wetting front and duration required by infiltrated water to flow to the center of a reference
728 in-situ structure

Testing conditions	Average W_f (m/s)	Duration to reach the center of a 1m reference thickness in-situ structure (years)
AP	3×10^{-09}	05
RP	1×10^{-09}	13
DP	9×10^{-09}	02

729

730

731

732

733

734

735

736 **Figure Captions List**

737 **Fig.1.** Statically compacted lime-treated specimens.

738 **Fig. 2.** Immersion of specimens during wetting (a) and oven-drying of specimens at 71 °C (b) as per ASTM
739 procedure.

740 **Fig. 3.** Appearance of compacted untreated silty soil after the 1st wetting cycle

741 **Fig. 4.** UCS evolution in the lime-treated specimens subjected to W-D/D-W cycles as per AP, RP, and DP
742 testing conditions

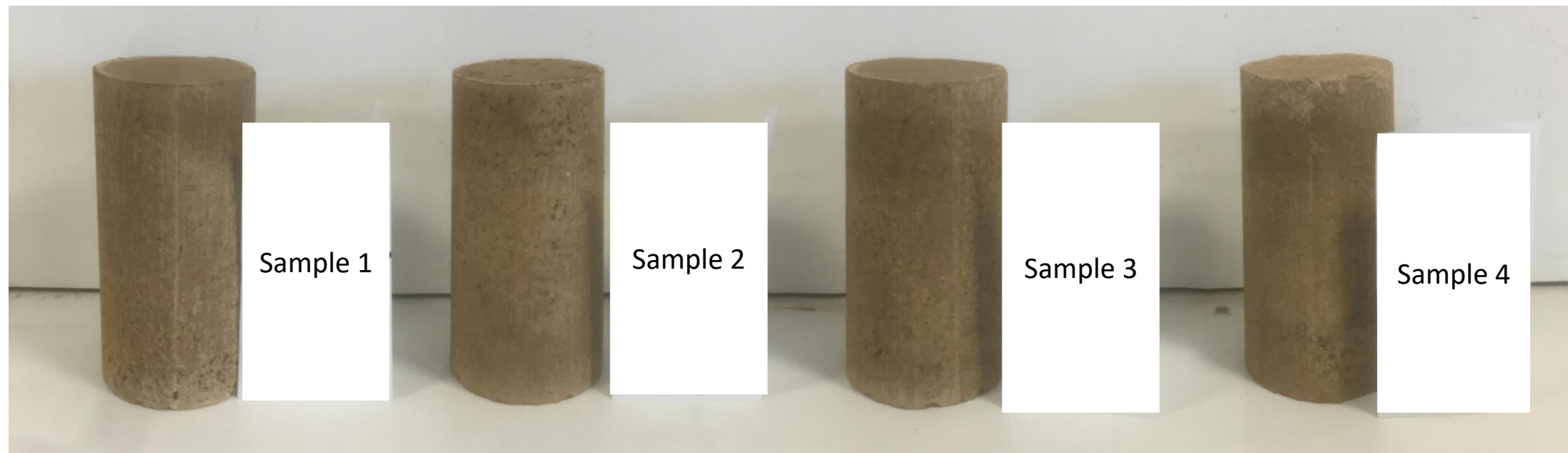
743 **Fig. 5.** Average volume variations (a-c), and water content variations (d-f) measured in the specimens
744 subjected to W-D/D-W cycles as per AP, RP, and DP testing conditions

745 **Fig. 6** Suction (a) and pH (b) measured in the initial and UCS subjected specimens during W-D/D-W cycles
746 as per AP, RP, and DP testing conditions.

747 **Fig. 7.** Calcium concentration (a) and Electric Conductivity (b) measured in the effluents collected from the
748 specimens subjected to W-D/D-W cycles as per AP, RP, and DP testing conditions

749 **Fig. 8.** Comparative PSD by MIP (a-c), and Cum. (cumulative) pore volume evolution by BJH (d-f) between
750 untreated and 10 months cured lime-treated specimen with the lime-treated specimens subjected to W-D/D-
751 W cycles as per AP, RP, and DP testing conditions

752 **Fig. 9.** Comparative evolution of calcium concentration and electric conductivity in the specimens subjected
753 to W-D/D-W cycles



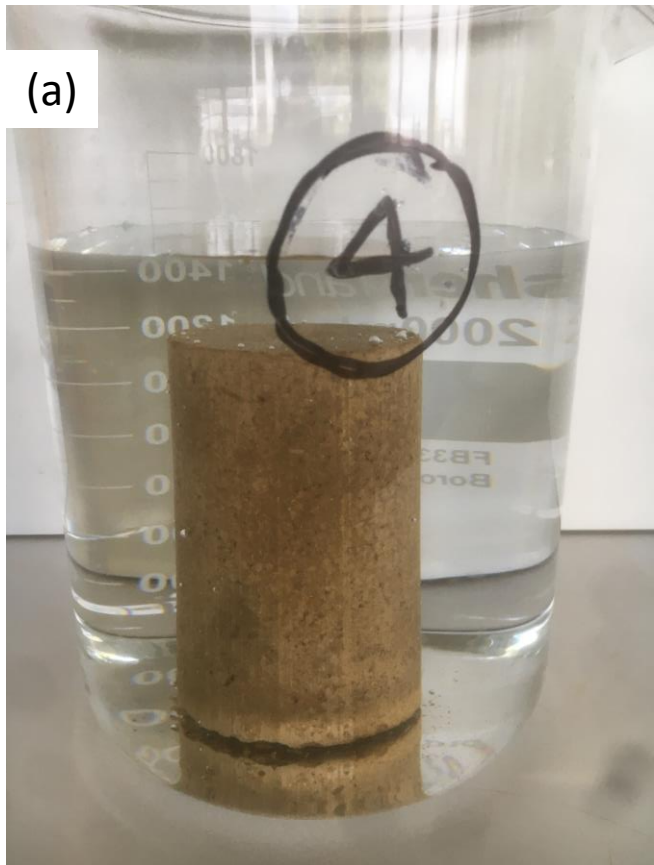




Fig. 4

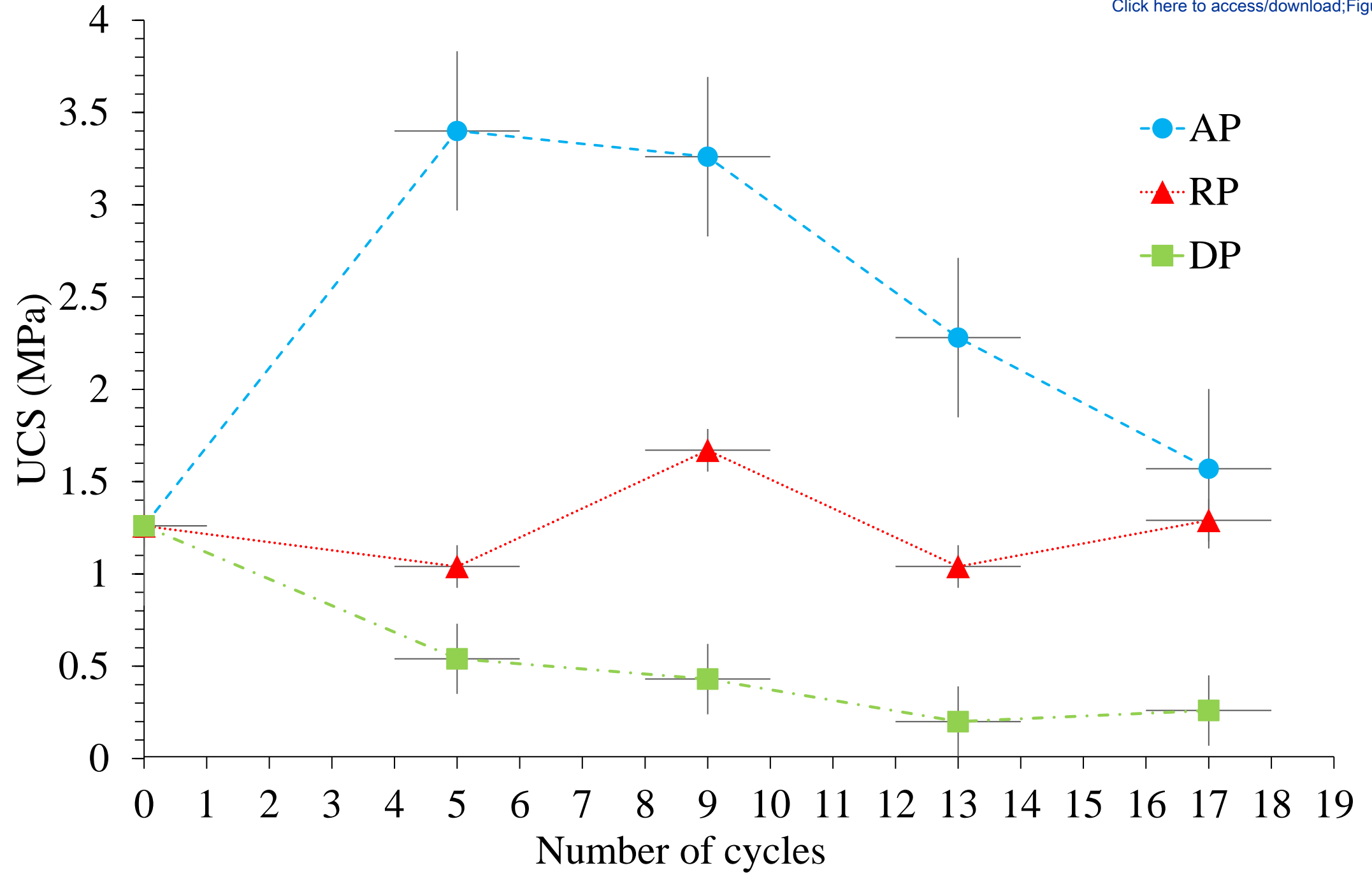
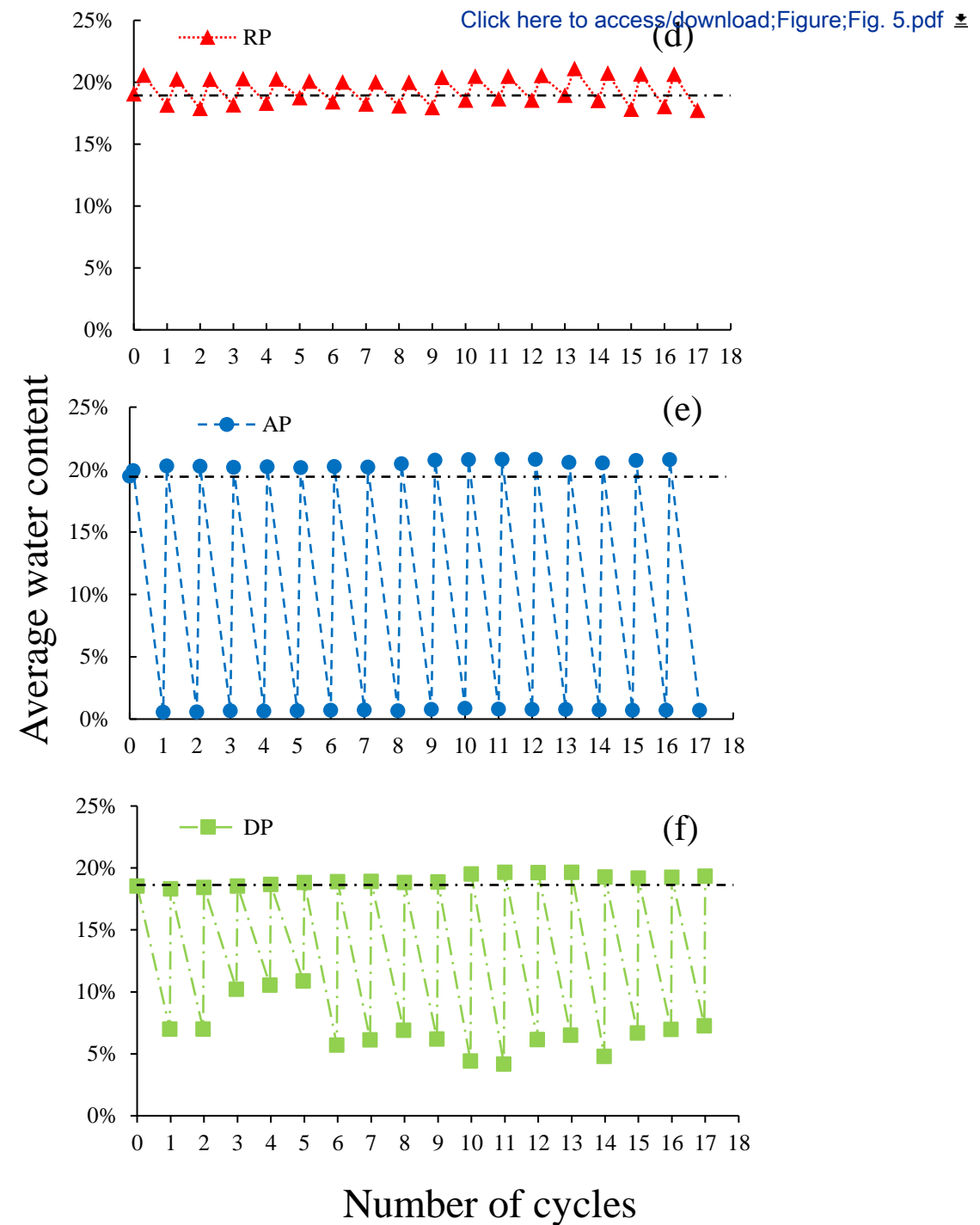
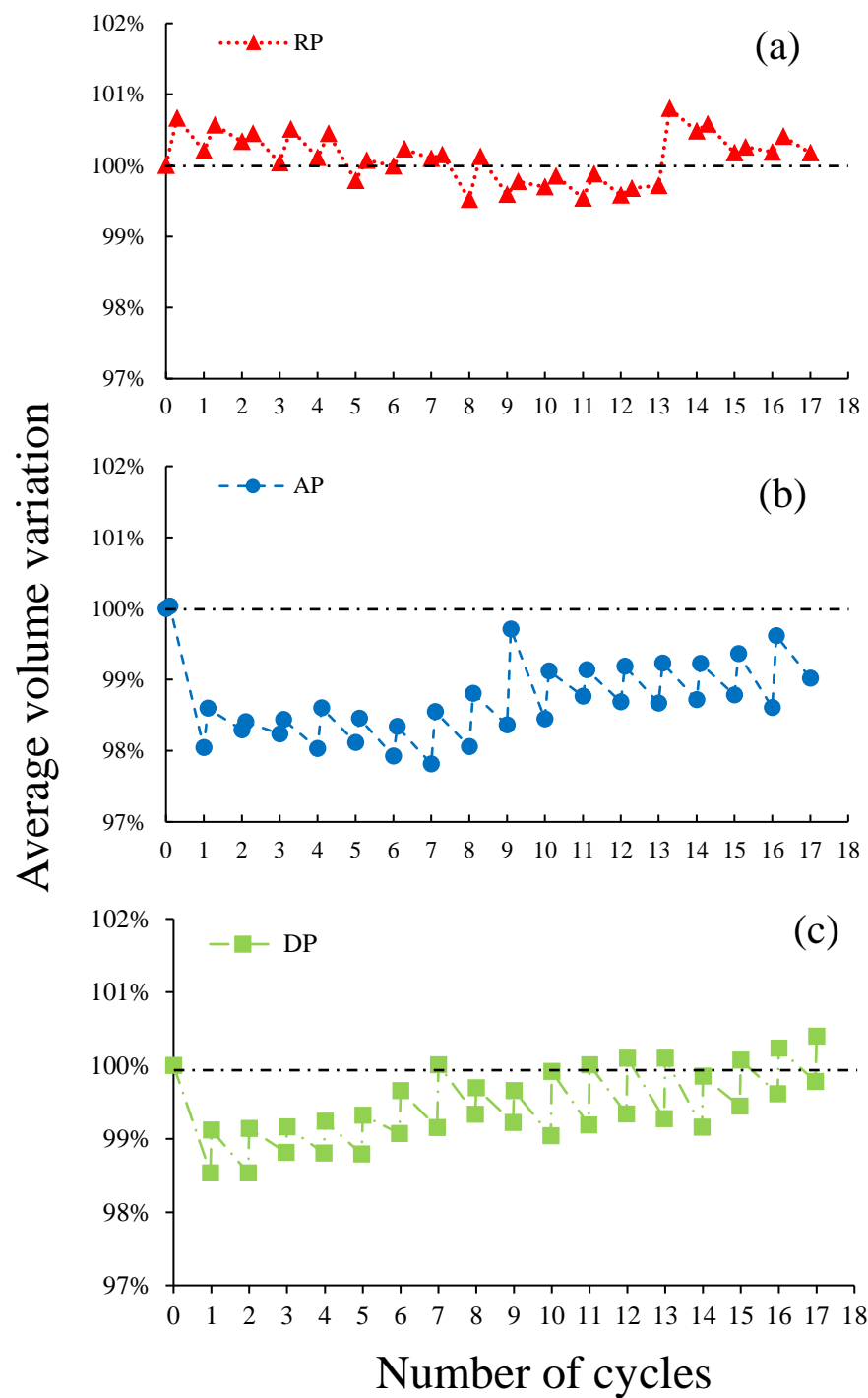
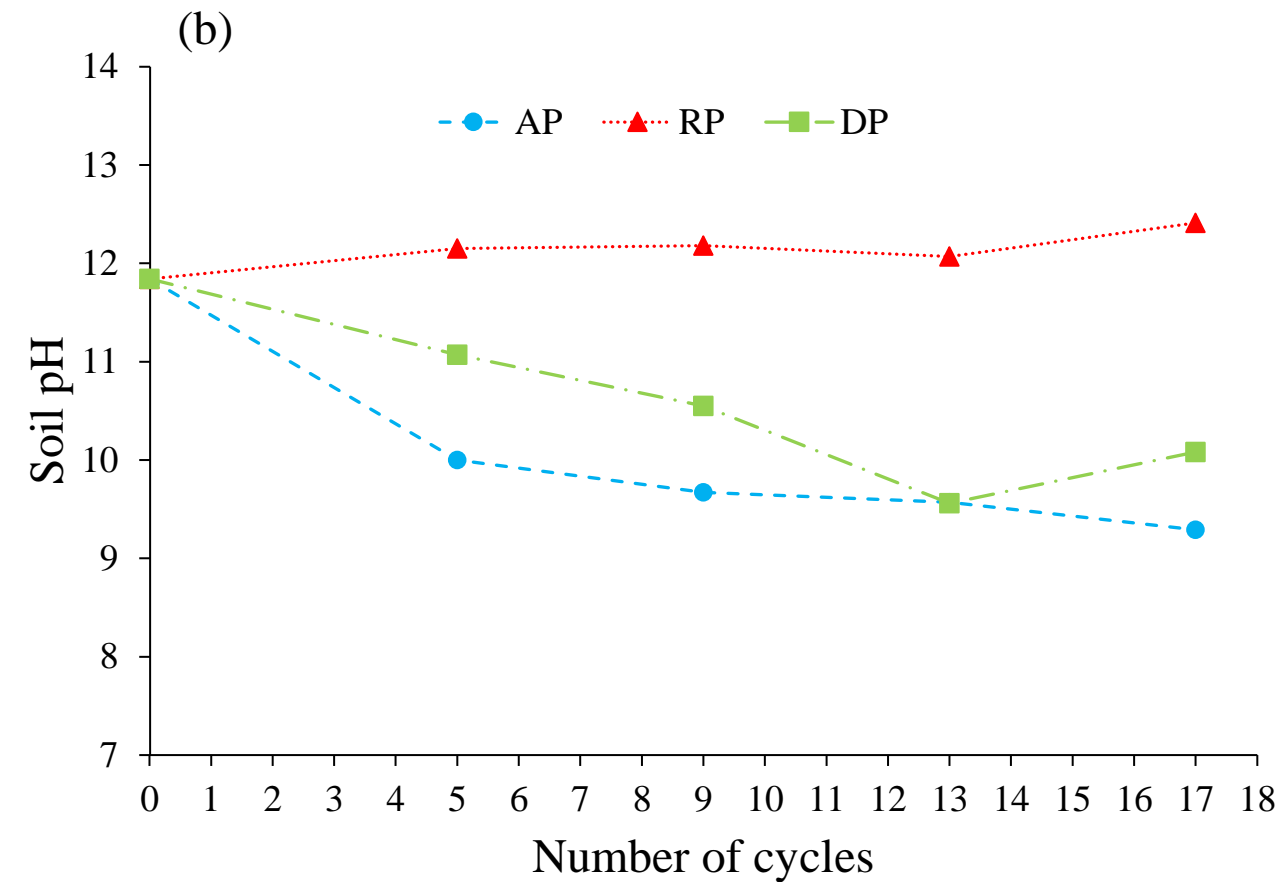
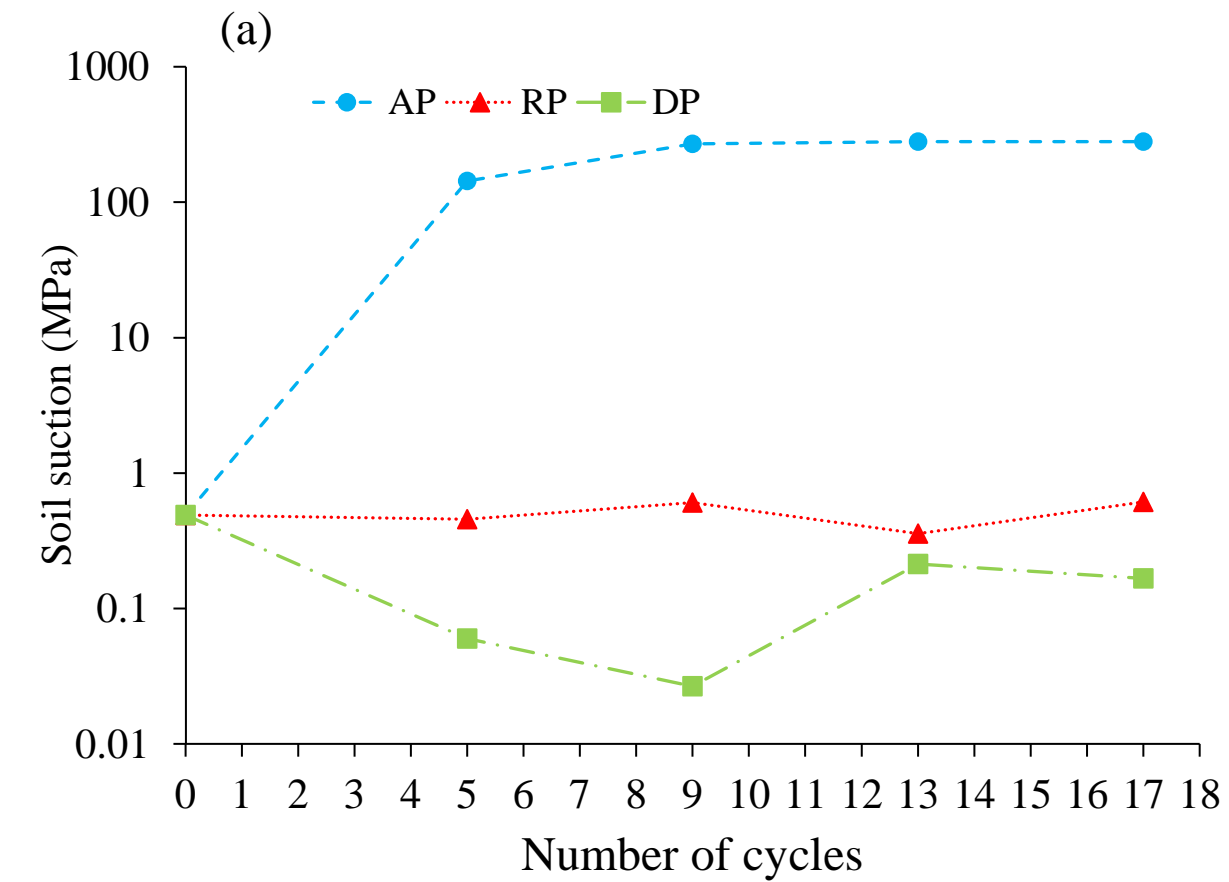


Fig. 5





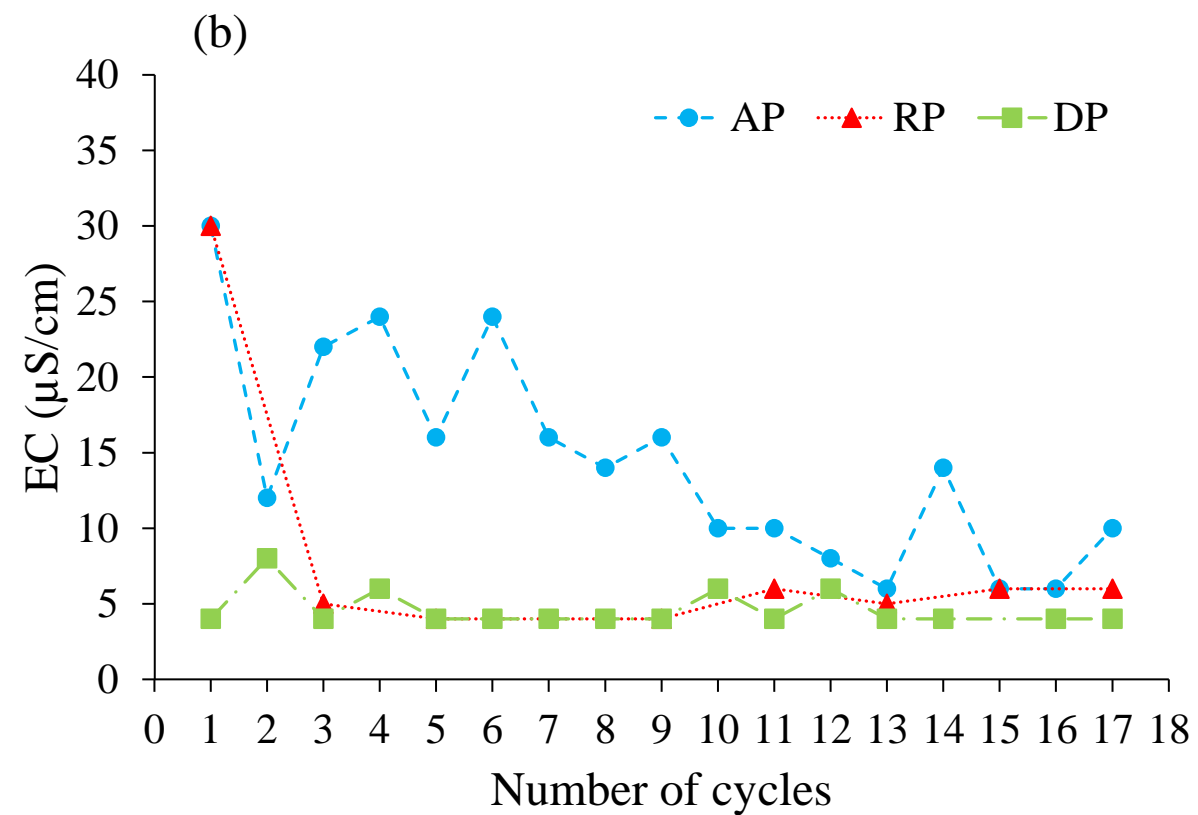
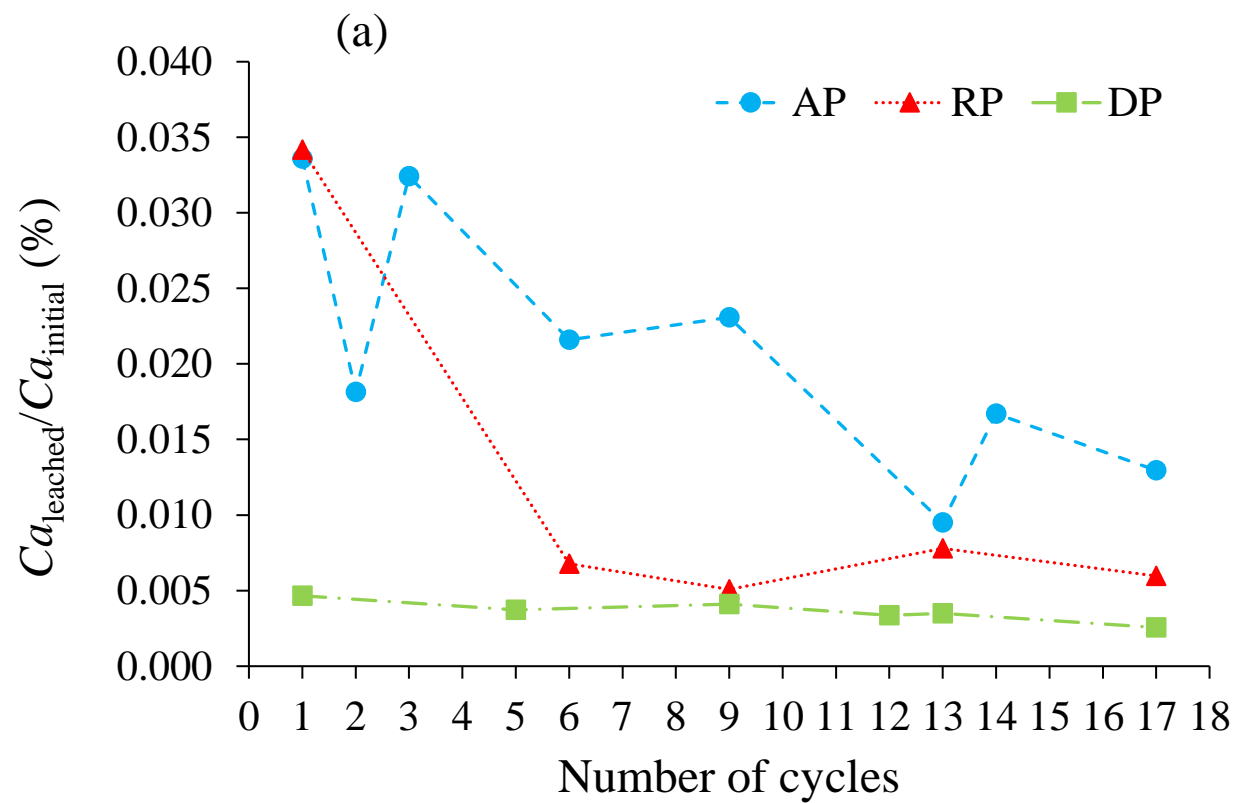
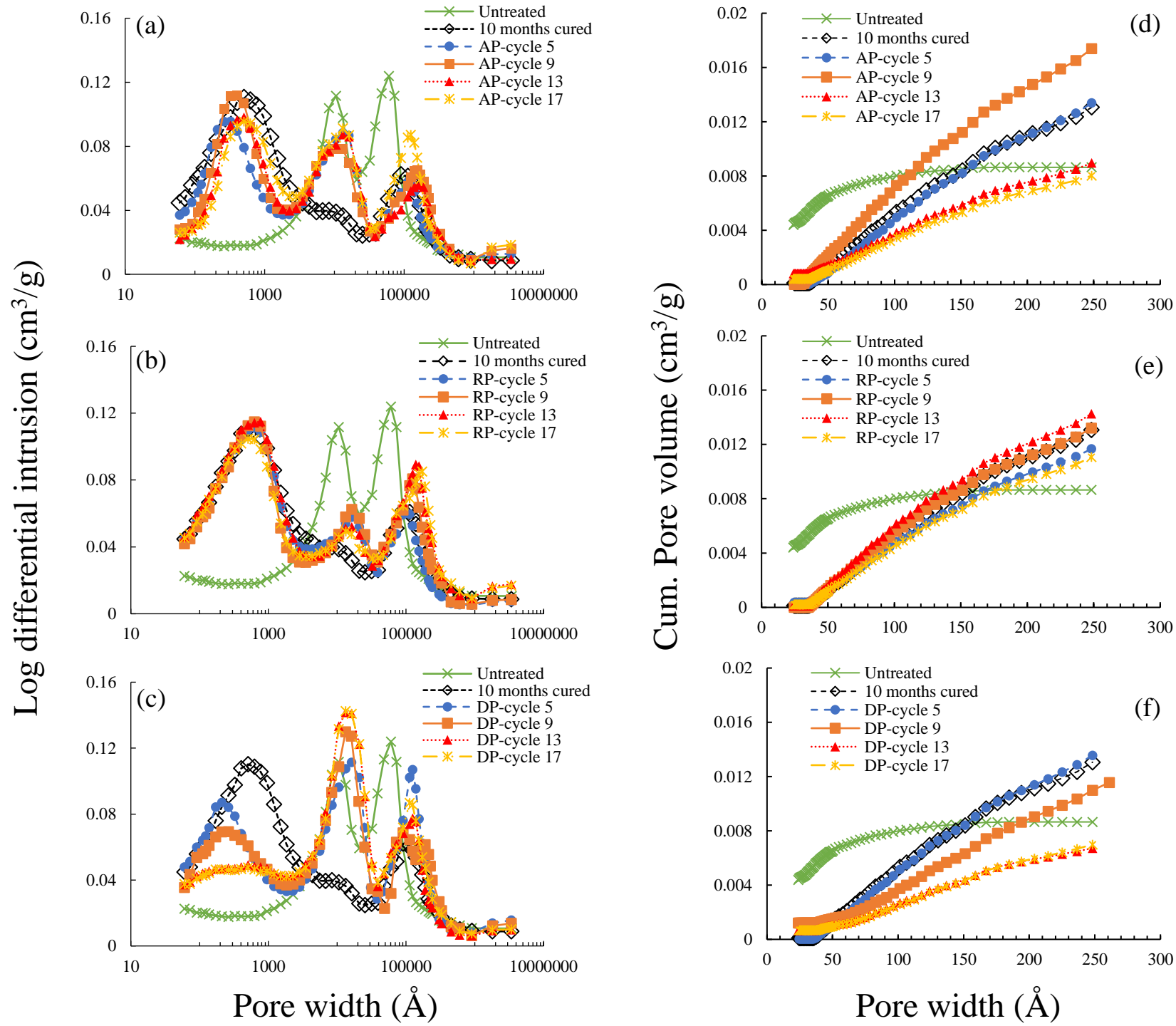


Fig. 8



[Click here to access/download;Figure;Fig. 8.pdf](#)

