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1 **Influence of pore fluid-soil structure interactions on compacted lime-treated silty soil**

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7 **Highlights**

8

- 9 • Kneading-and static-compacted soil is percolated by demineralized water and a low-ionic
- 10 strength solution.
- 11 • Kneading action increases hydraulic tortuosity and pore fluid-soil structure contact.
- 12 • Effect of pore-fluid nature is more pronounced in kneaded soil than statically compacted soil.
- 13 • Demineralized water is relatively aggressive and enhances the leaching of lime.
- 14 • Pore volume flow is an important index to assess the durability of a hydraulic structure.

15

16 **Abstract**

17 The effects on hydromechanical performance due to chemical interactions between pore solution and soil
18 components in lime-treated soil are investigated. Static- and kneading-compacted soils are percolated by
19 demineralized water (DW) and a low-ionic strength solution. Kneading action causes aggregate
20 deformation, thus consequently reducing macropores of diameter 10^5 \AA . This increases the hydraulic
21 tortuosity and lengthens the pore fluid-soil structure contact, which favors the long-term pozzolanic
22 reactions. DW being relatively more aggressive than low-ionic strength solution accelerates the leaching of
23 Calcium, thus negatively impacting the hydromechanical performance. The study shows that the
24 hydromechanical evolution in lime-treated soil is governed by the duration of pore fluid and soil structure
25 contact, depending on the compaction mechanisms implemented. The extent of the effect of pore fluid-soil
26 structure interaction is regulated by the pore solution chemistry and the lime content. Thus, importance
27 should be given to the relevancy of the selected compaction procedure and the permeant solution at the
28 laboratory scale with respect to in-situ compaction mechanism and pore water.

29

30 *Keywords: lime-treated soil; kneading action; pore fluid; tortuosity; leaching.*

31

32 **1. Introduction**

33

34 Soil stabilization is a current practice for the efficient and effective management of natural
35 resources in any land and infrastructure development project. The process of soil stabilization involves two
36 main categories: mechanical improvement and chemical stabilization (Houben and Guillaud, 1994).
37 Mechanical improvement involves the use of proper implementation techniques such as proper mixing of
38 soil with chemical binder and water, compaction of soil through a suitable mechanism, and at an appropriate
39 water content and compaction energy (le Runigo et al., 2011, 2009; Little, 1987). Chemical stabilization
40 consists of the use of inorganic or organic binders, such as slags (Poh et al., 2006; Wild et al., 1998), fly
41 ashes produced from coal-burning (Kolias et al., 2005; Show et al., 2003), cement kiln dust (Miller and
42 Azad, 2000), and lime (Akula et al., 2020; Ali and Mohamed, 2019; Das et al., 2020; 2021; Makki-
43 Szymkiewicz et al., 2015).

44 Lime is one of the most versatile (Dowling et al., 2015), low-cost (Inkham et al., 2019), and readily
45 available chemicals. It was shown to be paramount in several applications using environmentally friendly
46 techniques (Dowling et al., 2015). Soil treated by lime can be used repeatedly, thus promoting its reuse and
47 improving cost-effectiveness (Hopkins et al., 2007). Upon mixing soil with lime, two effects are observed:
48 (i) instant reduction in moisture content and consequent flocculation/agglomeration of the clay particles,
49 further lowering soil plasticity and increasing workability of the lime-treated soil (Bell, 1996; Diamond and
50 Kinter, 1965; Little, 1995, 1987); (ii) long-term increase in strength of the lime-treated soil due to the
51 formation of cementitious compounds coming mainly from pozzolanic reactions (Das et al., 2020; Lemaire
52 et al., 2013; Pu et al., 2019; Verbrugge et al., 2011).

53 Several laboratory studies and few field studies are available that explain the importance of the
54 hydromechanical performances of the lime-treated soil towards the maintenance of the long-term durability
55 of lime-treated earth structures (Das et al., 2020; 2021; Deneele et al., 2016; le Runigo et al., 2011, 2009;
56 Lemaire et al., 2013; Verbrugge et al., 2011). The hydromechanical behavior is heavily influenced by
57 compaction conditions such as compaction procedure, energy, and water content (Cuisinier et al., 2011; le
58 Runigo et al., 2009; Mitchell et al., 1965; Watabe et al., 2000), which plays a central role in the mechanical
59 improvement process. According to le Runigo et al. (2011, 2009) and Mitchell et al. (1965), lime-treated
60 soil compacted at different initial moisture contents and compaction energies shows different magnitudes
61 of hydraulic conductivity, k . This is because the hydraulic conductivity of soil depends on the macropore
62 structure of the soil, which was shown to be a direct function of compaction conditions by Ranaivomanana

63 et al. (2018, 2017). A higher magnitude of k indicates a greater quantity of water percolation throughout
64 the compacted soil in a short time. This can enhance the leaching of cementitious compounds as well as the
65 available lime, which consequently decreases the compressive strength of the lime-treated soil, as reported
66 by Le Runigo et al. (2011) and Deneele et al. (2016).

67 Although the consideration of moisture content and the implemented energy during compaction
68 were shown to have a significant impact on the hydromechanical evolution, how well the laboratory-
69 implemented compaction mechanism represents the in-situ compaction mechanism is an important
70 question. In-situ fine-grained soil is often compacted by a pad foot roller, especially hydraulic earthen
71 structures (dikes, levees, dams, reservoirs). The pad-foot roller often consists of pads attached to the drum
72 surface of the wheel. During compaction, these pads generate a kneading action in the soil. The impact of
73 kneading action in natural soil was evaluated by Kouassi et al. (2000), who demonstrated an equivalent
74 generation of soil characteristics such as dry density and elastic stiffness between laboratory and field
75 compacted soil. A similar observation was also reported by Clegg, (1964). Cuisinier et al. (2011) evaluated
76 the evolution of hydraulic properties of lime-treated soil compacted by two procedures: static and kneading.
77 A lower k was observed in the lime-treated kneaded soil. Beyond these few studies, further evaluation of
78 the kneading mechanism, particularly with respect to lime-treated fine-grained soil, remains less
79 investigated. Thus, it is reasonable to investigate the influence of the kneading mechanism in the
80 hydromechanical evolution of lime-treated soil.

81 Another essential aspect that has remained less investigated with respect to the hydromechanical
82 evaluation is the effect of the chemistry of pore water solution during its percolation through lime-treated
83 compacted soil. Since lime-treated soil is susceptible to increased leaching, it may cancel out the
84 improvement brought by lime treatment (Deneele et al., 2016). Hence, the leaching mechanism of lime-
85 treated soil should be evaluated by considering the chemistry of porewater to which the selected soil is
86 subjected to. The effect of the chemistry of pore fluid such as leachates on the hydraulic behavior of natural
87 clay in the context of liner material used in underground nuclear disposal repository was widely
88 investigated. Several studies have shown how the aggressive effect of leachates induces cracks in clay-liner
89 and causes an increased hydraulic conductivity during the soil-leachate interactions (He et al., 2015; Sunil
90 et al., 2008; Vaverková et al., 2020). Currently, DW is used as a conventional permeant solution in most of
91 the existing studies to investigate the hydraulic and leaching behaviors of lime-treated soil, whereas in the
92 field, water from natural sources influences such behaviors. Thus, it is essential to consider the interactions
93 of pore solution chemistry with the lime-treated soil while investigating the soil's hydromechanical
94 evolution.

95 In this context, the present study investigates the influence of compaction modes and pore solution
96 chemistry on the hydromechanical performances of a lime-treated silty soil. The compaction modes

97 involved static and kneading compactions, and DW and a low ionic strength solution were used as pore
98 solutions. The investigation includes evaluating the hydraulic conductivity and mechanical performances
99 based on the leaching mechanism and microstructural modifications.

100

101 **2. Materials and Methodologies**

102

103 *2.1. Soil, Lime, and permeant solutions properties*

104 The soil selected in this study was silty soil imported from Marche-Les-Dames (Belgium). The
105 main geotechnical properties of the soil were obtained from the studies reported by Charles et al. (2012)
106 and Makki-Szymkiewicz et al. (2015). The soil is composed of 12% clay and 82% silt fraction. Its liquid
107 limit is 31%, and the plasticity index is between 8 to 12. The Methylene blue value is 2.5 g/100 g. The
108 mineralogy of the soil consists of Illite, Kaolinite, and Chlorite as clay minerals along with Quartz and
109 Feldspars.

110 The quicklime (CaO) used for the treatment was supplied by Lhoist. The lime consists of 90.9% of
111 available CaO and a reactivity (t_{60}) of 3.3 min. The Lime Modification Optimum (LMO) of the silt, which
112 defines the minimum lime content required to initiate the pozzolanic reactions, was determined by Eades
113 and Grim, (1966). The LMO was found to be 1% by weight of lime. Three different lime contents were
114 used, lime content equal to LMO, 2.5%, and 4%.

115 Two permeant solutions were chosen DW, and DW+10⁻³M NaCl. The latter has been used
116 previously by Razakamanantsoa and Djeran-Maigre (2016) and Sato et al. (2017) as a reference fluid to
117 highlight the negative effect of leachates on Bentonites in the context of landfill. The pH and Electric
118 Conductivity (EC) of the DW and DW+10⁻³ M NaCl, latter regarded as Low-mineralized Water (LW) is
119 presented in Table 1.

120

121 **Table 1**

122 The pH and Electric Conductivity of solutions

Permeant solutions	pH	Electric Conductivity ($\mu\text{S}/\text{cm}$)
DW	7.4	4.0
LW	6.5	172.0

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125 *2.2. Sample preparations*

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The maximum dry density, $\rho_{d(max)}$, and Optimum Moisture Content (OMC) of the untreated and the 3 different lime-treated silt were obtained by standard Proctor test as per ASTM, D698-12e2 and are presented in Table. 2.

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 1% lime	17.4	17.6
Silty soil treated with 2.5% lime	17.1	18.5
Silty soil treated with 4% lime	17.0	18.7

The silt was air-dried, sieved, and was then mixed with distilled water at OMC. The soil mixture was stored in sealed plastic bags for about 24 hours to allow moisture content homogenization. The wet soil and the respective lime were then mixed and were rested for 1 hour before compaction.

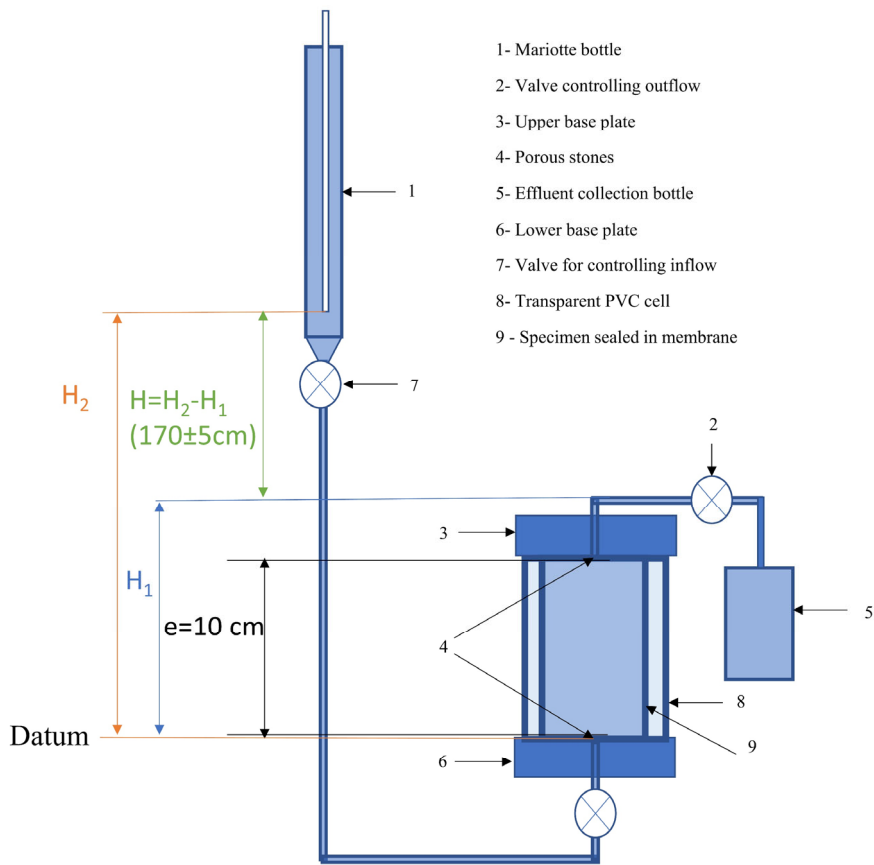
Cylindrical specimens of dimensions 0.05 m in height and 0.05 m diameter were prepared by Static (S) and Kneading (K) compaction methods at the constant compaction parameters mentioned in Table 2.

The static compaction involves compression of the specimens from top and bottom, as demonstrated by Holtz et al. (1981). The kneading compaction was performed by a laboratory-developed kneading tool. The process of kneading compaction was conducted, as demonstrated by Kouassi et al. (2000) for natural soil. Kouassi et al. (2000) does not consider compaction energy during kneading compaction, whereas, in the present study, compaction energy corresponding to the one mentioned in ASTM D698-91 was applied for specimens preparation. The application of the compaction load was made successively with the rotation of the 3-kneading feet by an angle of 45° between 2 successive loadings.

A total of 18 specimens was prepared, 9 specimens corresponding to each compaction method. After compaction, specimens were wrapped in plastic film and cured for 28-days at a laboratory temperature of 20 ± 1 °C.

2.3. Laboratory tests
2.3.1. Hydraulic conductivity test
2.3.1.1. Percolation setup

154 Hydraulic conductivity test was performed with flexible wall permeameter by a constant hydraulic
 155 head. The percolation system established was similar to the one used by Ranaivomanana et al. (2017). A
 156 schematic design of the permeability setup is presented in Fig. 1.
 157



158
 159 **Fig. 1** Schematic diagram of flexible wall permeameter setup (*Dimensions are not as per scale*)

160
 161 At the end of the curing time, specimens were sealed in a cellulose membrane and placed inside
 162 cylindrical transparent Polyvinyl chloride (PVC) cell with porous stones on its top and bottom (Fig. 1). A
 163 water inlet valve was equipped at the center of the PVC cell for applying the confining stress. The PVC
 164 cell, along with the membrane and specimen, was then placed within an upper and a lower base plate to
 165 avoid vertical deformation. Both the base plate are accompanied by a hole at its center for allowing outflow
 166 and inflow of solution in and from the specimen, respectively. The valve connected to the hole at the lower
 167 base plate was linked with the Mariotte bottle (Fig. 1). During the hydraulic test, the solution from the
 168 Mariott bottle passes through the base of the specimen. This is to ensure uniform flow throughout the

169 specimen by reducing any presence of entrapped air within the compacted specimen. The percolated fluid
170 was collected in an effluent collection bottle linked with the valve connected to the hole in the upper base
171 plate (Fig. 1).

172 A total of 12 setups for hydraulic conductivity tests were designed, of which 6 setups consist of
173 specimens submitted to DW, and the remaining were submitted to LW.

174

175 2.3.1.2. Hydraulic conductivity test protocol

176 During the hydraulic conductivity test, a confining pressure of 88 ± 2 kPa was applied for at least
177 24-48 hours before the application of hydraulic head pressure to ensure the homogeneity of the stress
178 distribution. The hydraulic head applied (H) was 170 ± 5 cm. Thus, the applied confining stress was about 5
179 times higher than the hydraulic head pressure. This was done (i) to maintain the structure of the compacted
180 specimen against any microstructure change due to the hydraulic head, and (ii) to avoid any preferential
181 flow between the soil and the membrane (Ranaivomanana et al., 2017).

182 The hydraulic conductivity test was conducted in accordance with the flow conditions provided by
183 Darcy's law. According to Darcy, the hydraulic conductivity, k (m/s) in terms of the total discharge, $Q =$
184 dV/dt , through a specimen; the cross-sectional area of the flow, A (m^2); and the hydraulic gradient, $i = H/e$
185 can be expressed as follows (Equation 1).

186

187

$$188 \quad k = \frac{dV * e}{dt * A * H} \quad (1)$$

189

190

191 where $H = H_2 - H_1$ is the hydraulic head (elevation datum) in m, and e is the specimen thickness in m; dV is
192 the incremental volume of percolated water between two measurements in m^3 ; dt is the time elapsed
193 between two measurements in seconds.

194 The hydraulic conductivity test was carried out in two phases: saturation and percolation. The
195 saturation phase involves the wetting of specimens until full saturation, and the percolation phase involves
196 the renewal of the entire porewater in the specimens. During the saturation phase, the outlet of the
197 permeability setup was kept closed until a volume of influents corresponding to 1 Pore Volume Flow (PVF)
198 of each specimen enter the specimens. One PVF is defined as the volume of pore water required to fill and
199 renew the total volume of pore water and void initially present in the soil once (Katsumi et al., 2008). This
200 level of PVF was selected to ensure about 90-95% saturation of the specimens before initiating the
201 percolation phase. Mathematically, 1 PVF is the product of the volume of soil solids, V_s , and the void ratio,

202 e of a given specimen. Then the accumulated volume of flow passing through the soil is denoted in terms
203 of PVF by dividing the total flow by the volume corresponding to 1 PVF.

204 The concept of PVF was proposed to consider the duration of contact between the permeant
205 solution and the lime-treated soil. Longer contact between soil and the permeant solution might be favorable
206 to the development of dissolution or precipitation mechanism inside the soil structure. Thus, the PVF can
207 be called an important index to assess the durability of the lime treatment. PVF was less often used for
208 hydraulic performance studies related to lime-treated soil. However, it was widely implemented in the
209 literature related to the hydraulic performance of Bentonite used in waste storage management (Katsumi et
210 al., 2008; Shackelford et al., 2000).

211 The hydraulic conductivity measurements were stopped in accordance with the following
212 termination criteria: (i) after 40 PVF was reached; and (ii) the last 5 values of EC measured during
213 percolation became almost stable. Such termination criteria were also referred to in a study reported by
214 Shackelford et al. (2000).

215

216 *2.3.1.3. Calcium analysis*

217 During the percolation phase, effluents were collected at different PVF. The effluents were then
218 filtered using 0.45 μm syringe prior to Inductively Coupled Plasma Optical Emission Spectrometry (ICP
219 OES) analysis for determining the elementary concentrations of Calcium (Ca). The analysis of Ca
220 concentration was made to investigate the difference in the concentration of Ca leached from the lime-
221 treated soil under the influence of DW and LW.

222

223 *2.3.2. Unconfined compressive strength (UCS) test*

224 Specimens after 28 days of curing and at the end of the percolation phase were subjected to
225 compressive strength analysis using a mechanical press with a load sensor of 10 kN. The load was applied
226 to the specimens at a constant axial displacement rate of 1 mm/min.

227 *2.3.3. Pore structure determination*

228 Soil specimens sampled from 28 days cured soil and from specimens at the end of hydraulic
229 conductivity test were freeze-dried and then subjected to Mercury Intrusion Porosimetry (MIP) test using
230 Micromeritics Auto Pore IV.

231 In the MIP test, specimens were first evacuated via heating inside a sealed penetrometer. Through
232 incremental hydraulic pressure, mercury was then progressively introduced into the specimens. The applied
233 pressure, p (MPa), and the volume of mercury intruded were registered progressively (Romero and Simms,
234 2008). Pore diameter, D was obtained according to the Washburn equation (Equation 2):

235

236

$$D = \frac{4\gamma \cos \theta}{p} \quad (2)$$

237 D is the diameter of the entrance pore where mercury intrudes, γ is the surface tension of mercury, and θ
 238 represents contact angle.

239 In this study, pore classifications were made as per the International Union of Pure and Applied
 240 Chemistry (IUPAC) (Rouquerol et al., 1994), which classifies pores based on their pore-width as
 241 macropores ($> 500 \text{ \AA}$), mesopores ($20\text{-}500 \text{ \AA}$), and micropores ($< 20 \text{ \AA}$).

242 The following nomenclatures are referred to for specimens' identifications: type of specimen
 243 (untreated, 1%/2.5%/4% lime-treated)-compaction mode (S/K)-type of permeant solutions (DW/LW). For
 244 example, 1%-S-DW represents 1% lime-treated statically compacted soil submitted to DW percolation.

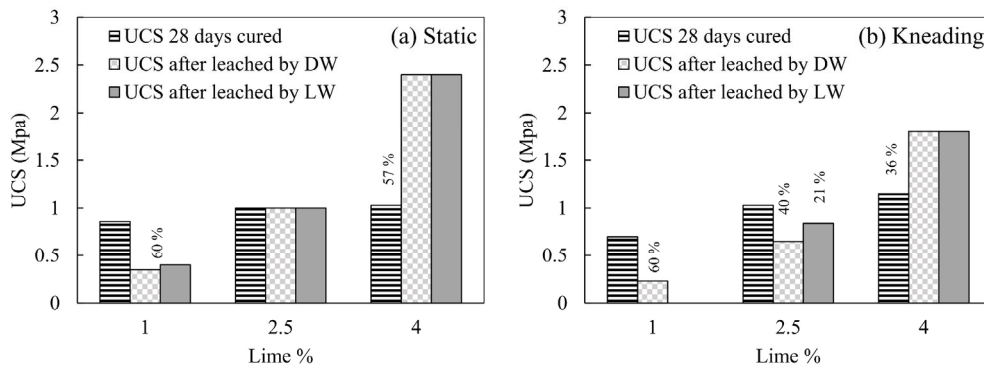
245

246 3. Results

247 3.1. Comparative evaluation of UCS in the lime-treated unleached and leached soil

248 The UCS obtained from the lime-treated 28 days cured specimens (unleached) were compared with
 249 the UCS obtained from the lime-treated leached soil at the end of the hydraulic conductivity test (Fig. 2).
 250 The testing conditions during UCS test for each specimen were kept similar.

251



252

253 **Fig. 2** Comparative evolution in UCS obtained in the 28 days cured and leached statically (a) and Kneading (b) compacted
 254 specimens

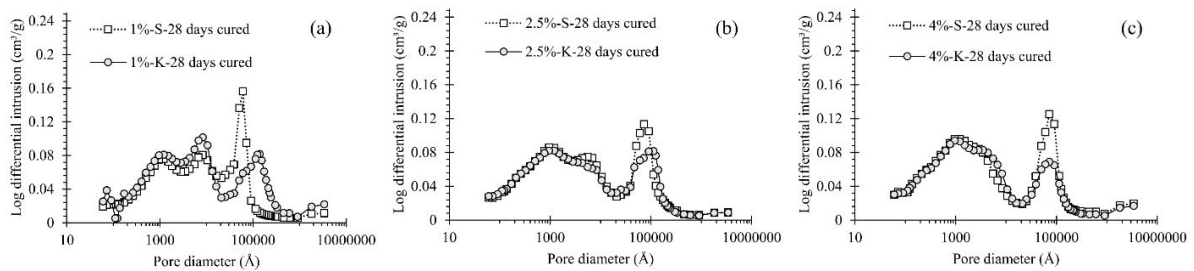
255 Fig. 2a shows that 1% lime-treated statically compacted specimens lost about 60% of the initial
 256 UCS on being leached by DW and LW. On the other hand, no significant change in the UCS was observed
 257 in the 2.5% lime-treated leached specimens. However, the UCS increased by about 57% for the 4% lime-
 258 treated leached specimens.

259 The UCS of 1% lime-treated kneaded specimens leached by DW decreased by about 60% (Fig.
 260 2b). The UCS measurement of the corresponding LW submitted soil was not possible as the specimen broke
 261 at the end of the hydraulic conductivity test. About 40% of the initial UCS was lost in the 2.5% lime-treated
 262 DW leached kneaded specimen, whereas this decrease in UCS was about 20% in the corresponding LW
 263 leached specimen. The UCS for 4% lime-treated leached specimens increased by about 36%.
 264

265 *3.2. Comparative evolution of Pore size distribution*

266 *3.2.1. In 28-days cured lime-treated specimens*

267 The Pore Size Distribution (PSD) of the statically and kneading compacted lime-treated 28-days
 268 cured specimens is summarized in Fig. 3.
 269



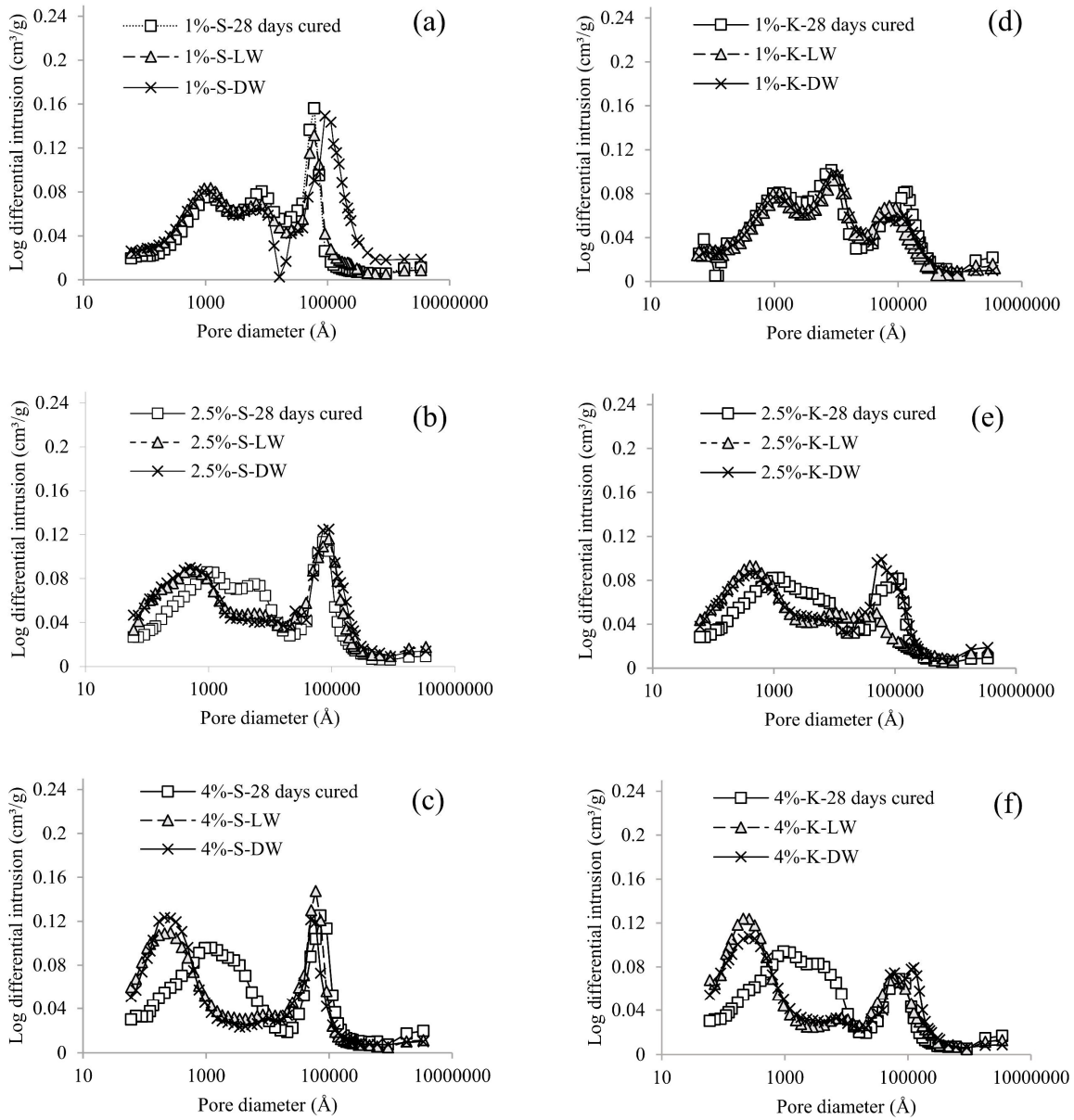
270
 271 **Fig. 3** Comparative evolution of PSD in the 1% (a), 2.5% (b), and 4% (c) lime-treated statically and Kneading compacted 28-
 272 days cured specimens

273 Three different peaks were observed at pore diameter 10^3 , 10^4 , and 10^5 Å. The total pores of
 274 diameter 10^3 Å were minimum in 1% lime-treated soil (Fig. 3a), slightly higher in 2.5% lime-treated soil
 275 (Fig. 3b), and maximum in 4% lime-treated soil (Fig. 3c). At the same time, pores of diameter 10^4 Å were
 276 minimum in 4% lime-treated soil and maximum in 1% lime-treated soil. This difference in the evolution of
 277 pores is attributed to the lime content used. At higher lime content, the evolution of cementitious
 278 compounds was enhanced (Lemaire et al., 2013; Little, 1987; Verbrugge et al., 2011), and hence more pores
 279 of diameter 10^3 Å were developed. The trend of pore evolution of diameters 10^3 and 10^4 Å remained at a
 280 similar level in both types of compacted soil.

281 However, the presence of the macropores of diameter 10^5 Å was comparatively significant in all
 282 the statically compacted specimens than the corresponding kneaded soil.
 283

284 *3.2.2. In unleached and leached lime-treated specimens*

285 At the end of the hydraulic conductivity test, the evolution of PSD in the two types of compacted
 286 soil after being leached by DW and LW was compared with the unleached specimens in Fig. 4.



288

289 **Fig. 4** Comparative evolution of PSD between 1%, 2.5%, and 4% lime-treated unleached and leached statically compacted (a-c)
 290 and kneading compacted specimens (d-f).

291 A decrease in the pores of diameter 10^4 Å and generation of pores of diameter lower than 10^3 Å in
 292 the 2.5% and 4% lime-treated leached specimens was observed compared to the unleached specimens (Fig.
 293 4b, c, e & f). This generation of pores lower than 10^3 Å was relatively significant in the 4% lime-treated
 294 soil.

295 However, the macropores of diameter 10^5 \AA increased in the 1% lime-treated statically compacted
 296 specimen after being leached by DW (Fig. 4a). At the same time, no significant change occurred in the
 297 corresponding LW leached specimen compared to the unleached specimen. In the 2.5% and 4% lime-treated
 298 soil, the evolution of macropores of diameter 10^5 \AA remained constant after being leached by both DW and
 299 LW (Fig. 4b & c).

300 In the kneaded specimens, a constant evolution of the macropores of diameter 10^5 \AA was observed
 301 in the leached and unleached 1% lime-treated specimens (Fig. 4d). On the other hand, the 2.5% lime-treated
 302 specimens showed an increase in the total 10^5 \AA diameter macropores after being leached by DW, whereas
 303 in the corresponding LW submitted specimen, the total macropores with a similar diameter decreased and
 304 were lower than that of the unleached soil (Fig. 4e). In the 4% lime-treated soil, the total macropores with
 305 a diameter of 10^5 \AA increased slightly in the DW leached specimen, while the total of this macropore feature
 306 remained almost constant in the corresponding LW leached specimen (Fig. 4f).

307

308 3.3. Hydraulic conductivity measurements in untreated and lime-treated soil

309 The analysis of the hydraulic conductivity was conducted after verifying the level of saturation in
 310 the lime-treated 28 days cured soils and at the end of the hydraulic conductivity test, *i.e.*, on completion of
 311 the renewal of 40 PVF. The measured degree of saturation, S_r is summarized in Table 3.

312

313 **Table 3:**

314 S_r measured in the lime-treated soil at the end of curing time and at the end of hydraulic test

	S_r (%) of statically compacted soil			S_r (%) of kneaded soil		
	1%	2.5%	4%	1%	2.5%	4%
	lime-treated	lime-treated	lime-treated	lime-treated	lime-treated	lime-treated
After 28 days of curing	74.6	78.5	74.4	74.4	69.3	71.7
After 40 PVF was renewed in DW submitted soil	98.2	100	99.8	100	90.2	98.8
After 40 PVF was renewed in LW submitted soil	100	99.4	100	–	100	98.8

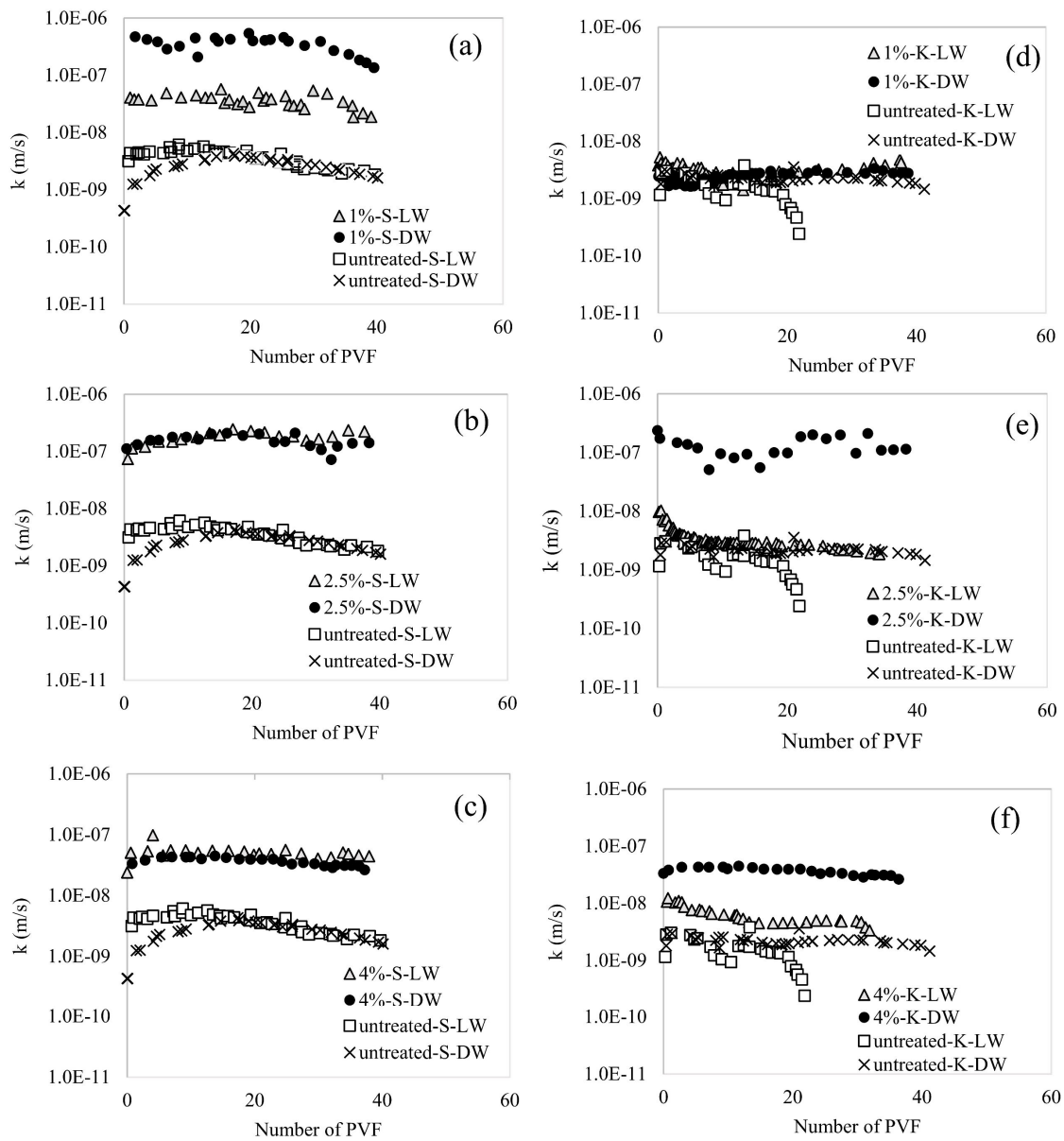
315

316 The S_r of all the 28 days cured lime-treated soils were less than 80%. This saturation level reached
 317 a value greater than 90%, when measured at the end of the hydraulic conductivity test. This difference in
 318 saturation values indicates that the hydraulic conductivity measurement was conducted in saturated
 319 specimens. It is worth noting that in-situ lime-treated soil may rarely reach a similar saturation level as the
 320 one obtained herein (Table 3) before the percolation happens.

321 The evolution in the k of the lime-treated and the untreated soil is presented in Fig. 5 with respect
 322 to the PVF measured during the hydraulic conductivity test.

323

324



325

326 **Fig. 5** Evolution in hydraulic conductivity of untreated and 1%, 2.5%, and 4% lime-treated DW and LW submitted statically (a-
 327 c), and kneading (d-f) compacted specimens

328 The duration taken by each specimen of the present dimensions to renew the volume of solution
 329 that corresponds to 40 PVF is provided in Table 4.

330

331 **Table 4:**

332 Duration of percolation phase in the lime-treated soil to renew 40 PVF of solutions

	Duration taken by statically compacted soil (days)				Duration taken by kneaded soil (days)			
	untreated	1% lime-treated	2.5% lime-treated	4% lime-treated	untreated	1% lime-treated	2.5% lime-treated	4% lime-treated
DW submitted soil	77	0.7	1.5	5	87	70	4	6
LW submitted soil	55	6	1.5	5	93	65	75	40

333

334

335 Fig. 5a shows that the magnitude of k in the untreated statically compacted specimens, submitted
336 to both types of solutions remained within the range of 10^{-8} to 10^{-9} m/s. This k then increased by about one
337 and two orders of magnitude in the 1% lime-treated LW and DW submitted soil, respectively. The duration
338 taken by the LW submitted soil to renew 40 PVF was about 5 days higher than the corresponding DW
339 submitted soil (Table 4). However, it took about 49 to 76 more days to circulate a similar volume of
340 solutions through the untreated soil.

341 In the 2.5% and 4% lime-treated statically compacted soil, the k was in between 10^{-7} to 10^{-8} m/s for
342 both DW and LW submitted soil. Thus, k was about one order of magnitude higher than the untreated soil
343 (Fig. 5b & c). The total duration corresponding to the percolation of 40 PVF was only 1.5 and 5 days for
344 the 2.5% and 4% lime-treated soil, respectively, which was much lower than the duration taken by the
345 corresponding untreated soil (Table 4).

346 For the lime-treated kneading compacted soil, the level of k measured for the untreated soil was in
347 the range of 10^{-8} to 10^{-9} m/s (Fig. 5d). In the untreated LW submitted soil, the level of k further decreased
348 after about 20 PVF. This decrease is attributed to the grain rearrangement within the soil matrix during the
349 percolation phase (Young, 2012). However, the obtained level of k in the 1% lime-treated kneaded
350 specimens submitted to DW and LW remained almost at a similar level as the untreated soil (Fig. 5d). At
351 the same time, the k increased by an order of magnitude in the 2.5% and 4% lime-treated kneaded specimen
352 submitted to DW, whereas it remained constant for the corresponding LW submitted specimen (Fig. 5e &
353 f). The 2.5% and 4% lime-treated kneaded soil took 75 and 40 days, respectively, to renew 40 PVF, whereas
354 the corresponding DW submitted soil took only 4-6 days to circulate the similar volume of solutions (Table
355 4). However, the duration of the percolation phase was relatively higher in the untreated kneaded soil than
356 in the lime-treated kneaded soil.

357 Based on the evolution of k obtained for each specimen in Fig. 5, Table 5 presents the estimated
358 hydraulic life expectancy of an in-situ lime-treated earth structure of a unit reference height if built with the

359 present soil configuration. The duration of life expectancy was expressed both in years and days (Column
 360 D) and was calculated by dividing the reference unit height of the structure by the average of the last 10
 361 values of k measured in each specimen (Fig. 5).

362 As per Table 5, the estimated hydraulic life expectancy was 14.5 years for 2.5% lime-treated
 363 kneaded soil percolated by LW (Column D), while it was just 1.1 years for the corresponding DW
 364 percolated soil. For the 4% lime-treated soil, the life expectancy of the LW percolated sample was 6 years
 365 higher than that of the DW percolated sample. The difference in life expectancy based on the types of
 366 solution percolated was less significant for the 1% lime-treated kneaded soil. In the statically compacted
 367 soil, the difference in life expectancy for soil treated with 2.5% and 4% lime and percolated by both types
 368 of the solution was less significant. However, the hydraulic life expectancy of 1% lime-treated soil
 369 percolated by LW was 0.9 years higher than the corresponding DW percolated soil. It is worth noting that
 370 the above-estimated life expectancy did not consider the soil structure-pore fluid interactions during
 371 percolation. The obtained duration represents the duration taken by a given pore fluid to reach the bottom
 372 of a unit height structure if percolated from the top, considering k as the flow velocity.

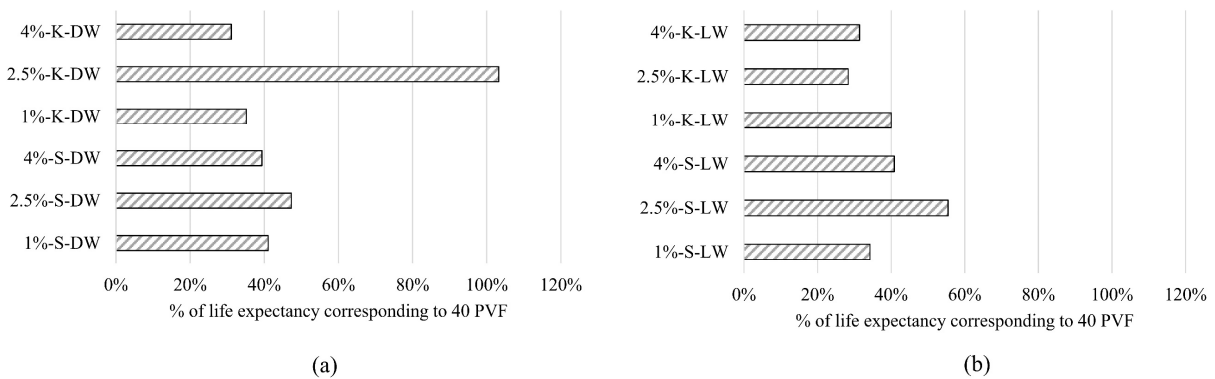
373
 374
 375

376 **Table 5:**
 377 Estimated life expectancy of a unit height in-situ earth structure, if built with the present soil configurations

A	B	C	D	E
Compaction modes	Specimen's configuration	Average k (m/s)	Estimated life expectancy for a unit height structure (years (days))	Required duration to reach 40 PVF in a unit height structure (days)
Statically compacted	1-S-OMC-28-DW	2.97E-07	0.1 (39.0)	16
	1-S-OMC-28-LW	3.30E-08	1.0 (350.6)	120
	2.5-S-OMC-28-DW	1.71E-07	0.2 (67.7)	32
	2.5-S-OMC-28-LW	2.01E-07	0.2 (57.7)	32
	4-S-OMC-28-DW	4.56E-08	1.0 (254)	100
	4-S-OMC-28-LW	4.73E-08	0.7 (244.7)	100
Kneading compacted	1-K-OMC-28-DW	2.91E-09	10.9 (3983.5)	1400
	1-K-OMC-28-LW	3.56E-09	8.9 (3249.4)	1300
	2.5-K-OMC-28-DW	1.49E-07	0.2 (77.7)	80
	2.5-K-OMC-28-LW	2.18E-09	14.5 (5297.0)	1500
	4-K-OMC-28-DW	3.00E-08	1.1 (385.8)	120
	4-K-OMC-28-LW	4.54E-09	7.0 (2548.3)	800

378

379 Each hydraulic conductivity test subjected specimens of given configuration took different
 380 durations to renew 40 PVF (Table 4). This duration was used to calculate the required duration to renew 40
 381 PVF in a unit height hydraulic structure (Table 5, Column E). These obtained durations were further
 382 expressed in percentage with respect to the percentage of the total life expectancy estimated for the structure
 383 of unit height (*i.e.*, Column E/Column D) in Fig. 6.
 384
 385
 386



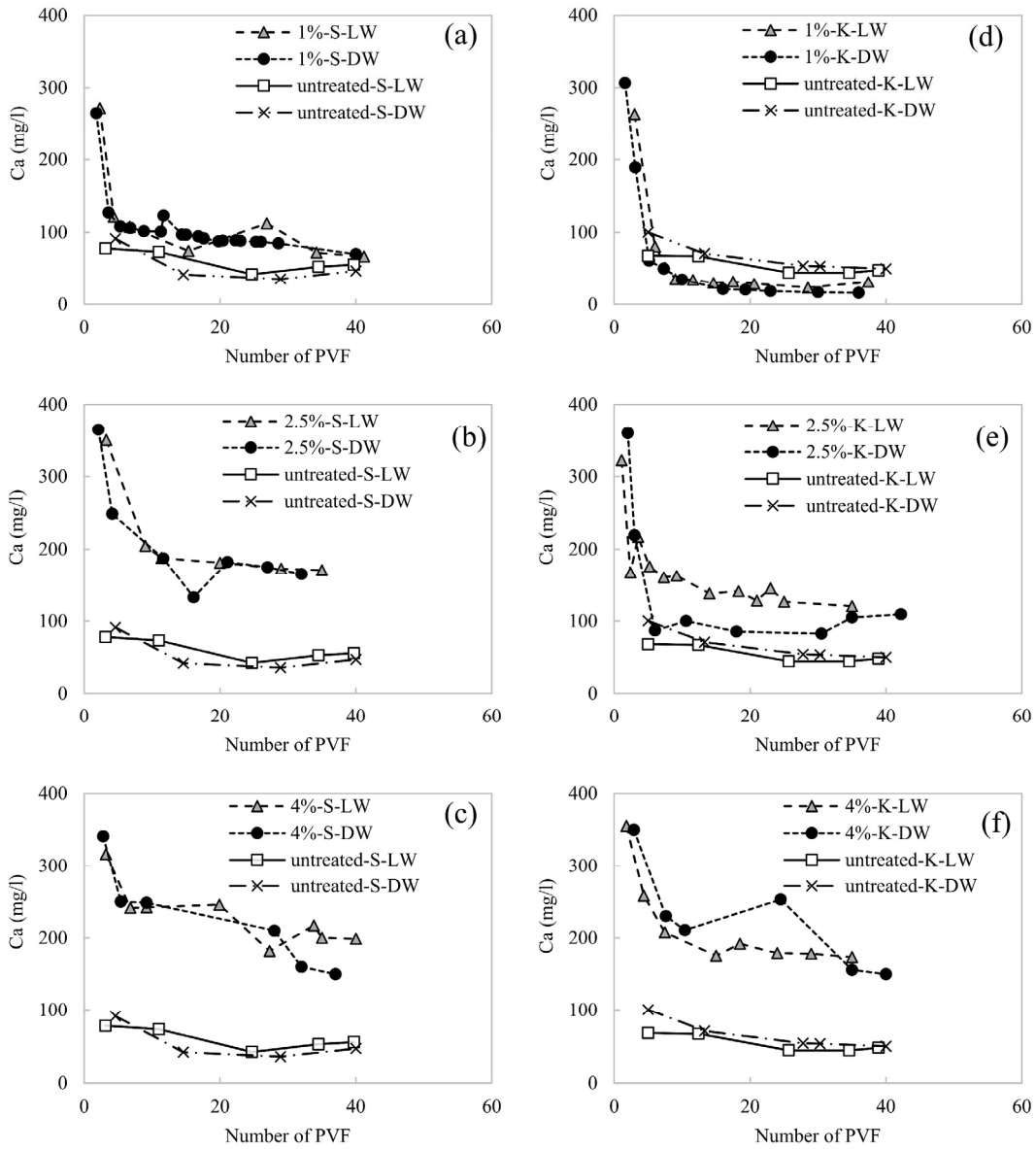
387
 388 **Fig. 6** Percentage of life expectancy that can be reached in a unit height earth structure if subjected to 40 PVF of DW (a) and LW
 389 (b) in kneading-and statically-compacted soil

390
 391 According to Fig. 6a, the estimated lifetime of the 2.5% lime-treated kneaded soil structure, if
 392 percolated by 40 PVF of DW, has reached its expected life values. The corresponding kneaded specimen
 393 on being submitted to 40 PVF of LW reached only 28% of its total life expectancy (Fig. 6b). Besides, the
 394 renewal of 40 PVF has reached about 30 to 50% of the total estimated life of the structure, built with the
 395 remaining configuration. The above evaluation of hydraulic performance was in terms of PVF, which
 396 presents the advantage of considering the pore fluid-soil structure interactions. Based on this evaluation, it
 397 was shown that the total life expectancy was yet to be reached even after the renewal of 40 PVF (Fig. 6).
 398 Thus, such an assessment helps to investigate the life scale of in-situ earth structures at laboratory scale.

399 However, it is worth noting that the above estimation of life expectancy was based on the hydraulic
 400 performances and did not consider the mechanical performances of the compacted soil.

401
 402 **3.4. Evolution of calcium concentrations in the effluents of untreated and lime-treated soils**

403 Fig. 7 presents the calcium concentration, *Ca* (mg/l) measured in the effluents collected at different
 404 PVF from the untreated and the lime-treated statically and kneaded specimens during the percolation phase.



406

407 **Fig. 7** Concentration of *Ca* leached from the untreated and 1%, 2.5%, and 4% lime-treated DW & LW submitted statically (a-c)
 408 and kneading (d-f) compacted specimens

409 Permeant solution flows mostly through the widest connecting pore available in soil (Hunt and
 410 Sahimi, 2017). Hence, the leaching mechanism in a saturated lime-treated soil (Table 3) is more likely to
 411 be pronounced on the available minerals around the inter-aggregate pores constituting the flow-path
 412 compared to the intra-aggregate pores.

413 In the 1% lime-treated statically compacted soil, most of the *Ca* from the available and added lime,
 414 particularly around the flow-path, was lost on renewal of 10 PVF of DW and LW (Fig. 7a). Further renewal

415 of solution triggered a release of soluble *Ca* from the soil. In the 2.5% and 4% lime-treated specimens, a
416 sharp concentration of *Ca* was leached up to about 10 PVF, and the rate of leaching then slowed down.
417 However, the overall trend of *Ca* leaching for the treated soil remained much above the trend obtained from
418 the untreated soil, thus, indicating that the loss of *Ca* was either from the cementitious compounds or
419 residual lime available, particularly the available *Ca* around the flow path (Fig. 7b & c).

420 For the kneading compacted soil, *Ca* available around the flow-path in the form of cementitious
421 compounds or residual lime was lost completely at about 5-7 PVF from the 1% lime-treated soil (Fig. 7d).
422 Then a concentration of soluble *Ca* was leached from the soil. The 2.5% lime-treated DW submitted
423 specimen leached a significant *Ca* concentration, particularly coming from the lime added during the
424 renewal of 40 PVF of DW. Besides, a part of soluble *Ca* was also lost from the soil (Fig. 7e). At the same
425 time, the trend observed in the loss of *Ca* concentration in the corresponding LW submitted soil remained
426 above the DW submitted soil, thus, indicating a part of *Ca* was lost only from the added lime (Fig. 7e).

427 For the 4% lime-treated kneaded soil, the evolution in the loss of *Ca* for the DW and LW submitted
428 specimens remained at about a similar level (Fig. 7f). The leached *Ca* comes from the added lime.

429 Besides, the 2.5% and 4% lime-treated DW submitted kneaded soil leached a significant *Ca*
430 concentration in just 4 and 6 days of percolation phase, respectively, whereas it took 75 and 40 days for the
431 corresponding LW submitted soil to leach the equivalent *Ca* concentration (Table 4).

432

433

434 **4. Discussions**

435 *4.1. Influence of pore fluid-soil structure interaction on the UCS evolution of lime-treated soil*

436

437 Soil treated at LMO was shown to have a limited contribution towards the development of
438 cementitious compounds (le Runigo et al., 2011). Hence, the addition of 1% lime to soil can be considered
439 insufficient to maintain its strength and lost almost 60% of its initial UCS, irrespective of the compaction
440 modes and the pore solutions the specimens were submitted to (Fig. 2).

441 The evolution of compressive strength in lime-treated soil enhances with the development of
442 cementitious bonding, which depends on the lime content used (higher than the LMO), water content, and
443 curing time (Das et al., 2020; Lemaire et al., 2013; Little, 1995; Verbrugge et al., 2011). Thus, in the 2.5%
444 and 4% lime-treated soil, due to the constant contact of the compacted soil structure with the pore solution,
445 particularly during the saturation phase, a significant evolution of cementitious compounds occurred. This
446 was confirmed by the decrease in the total pores with a diameter of 10^4 Å, which in turn increased the
447 formation of pores with a diameter lower than 10^3 Å in both the 2.5% and 4% lime-treated compacted

448 samples (Fig. 4b-c, e-f). As expected, the evolution of pore with a diameter lower than 10^3 \AA was more
449 pronounced in the 4% lime-treated soil due to the greater availability of lime than that of the 1% and 2.5%
450 lime-treated samples. As a result, the UCS of the 4% lime-treated soil increased by 57% and 36% in the
451 statically and kneaded specimens, respectively, at the end of the hydraulic conductivity test compared to
452 the 28 days cured specimens (Fig. 2a & b). The UCS remained unaffected in the 2.5% lime-treated statically
453 compacted soil (Fig. 2a); however, it decreased in the corresponding kneaded soil.

454 The decrease in UCS of the kneaded soil was about 20% higher in the DW submitted soil than the
455 LW submitted soil (Fig. 2b). This relatively significant decrease in UCS indicates the pronounced influence
456 of pore solution chemistry on the kneaded soil structure. These phenomena are detailed in the later sections,
457 which involve the mechanism of hydraulic conductivity and leaching as a result of the coupled influence
458 of soil structures and pore solutions.

459

460 *4.2. Influence of pore fluid-soil structure interaction on the hydraulic behavior of lime-treated soil*

461

462 The observed hydraulic performances in the lime-treated soil appear to be in accordance with the
463 microstructural modifications brought about by a coupled effect produced between the compacted soil
464 structure and the chemistry of the solutions.

465

466 *4.2.1. Influence of soil structure on the hydraulic conductivity evolution*

467 Transport of pore fluid through a compacted soil matrix was shown to follow the pore geometry
468 constituted by the widest connecting pores (Hunt and Sahimi, 2017). Besides, previous studies have
469 demonstrated that lime treatment increases the size of inter-aggregates pores due to flocculation, and as a
470 result, increases the magnitude of hydraulic conductivity compared to the untreated soil (Nguyen et al.,
471 2015; Tran et al., 2014). This explains the increased k from about 10^{-9} m/s to somewhere in between 10^{-6}
472 and 10^{-8} m/s in all the lime-treated statically compacted specimens (Fig. 5a-c).

473 However, according to Mitchell and McConnell, (1965), under kneading action, flocculated
474 particles in natural soil break and transform into more likely a dispersed structure. This statement was
475 confirmed in the lime-treated soil studied herein. The large inter-aggregates formed due to lime treatment
476 were relatively deformed during kneading compaction, and consequently, the macropores were reduced.
477 Fig. 3 shows the presence of a relatively lower number of 10^5 \AA diameter macropores in all the lime-treated
478 kneaded soil compared to the corresponding statically compacted soil. Thus, the evolution of k remained
479 constant, *i.e.*, between 10^{-8} to 10^{-9} m/s in the 1% lime-treated kneaded soil submitted to both types of
480 solutions, as well as the 2.5% and 4% lime-treated kneaded specimens submitted to LW (Fig. 5d-f).

481 However, the magnitude of k for the 2.5% and 4% lime-treated DW submitted soil was between
 482 10^{-7} and 10^{-8} m/s, which was one order of magnitude higher than the corresponding untreated and LW
 483 submitted soil (Fig. 5e & f). This difference in k was because of the effect of pore solution chemistry, which
 484 is explained in the later section.

485

486 *4.2.2. Influence of soil structure on flow characteristics*

487 From the preceding discussion, different evolutions of 10^5 Å diameter macropores were observed
 488 under different methods of densification (*i.e.*, static and kneading actions). Hence it will be interesting to
 489 evaluate the flow path of the permeant solutions through both types of compacted structures, which is
 490 measured by hydraulic tortuosity.

491 The hydraulic tortuosity, T is defined as the parameter that characterizes the heterogeneity in the
 492 flow path of the solution in a porous media (Srisutthiyakorn and Mavko, 2016). In this study, T was
 493 calculated using the Kozeny-Carman equation (Equation 3), which considers T as a function of the pore
 494 geometry (Allen and Sun, 2017). Results of T calculated for the static and kneading compacted specimens
 495 are summarized in Table 6.

496

$$497 \quad T = \sqrt{\frac{\phi^3}{ckS^2}} \quad (3)$$

498

499 In Equation 3, k is the coefficient of permeability in m/s, ϕ is the porosity calculated from each specimen,
 500 c is the Kozeny constant assumed to be equal to 200 for calculation convenience, and S is the specific
 501 surface area in m^2/g measured with BET. The value of c was considered based on the plot provided by
 502 Allen and Sun, (2017), where c was shown to be a function of the porosity of the soil.

503

504 **Table 6**

505 Tortuosity calculated from statically and kneading compacted specimens

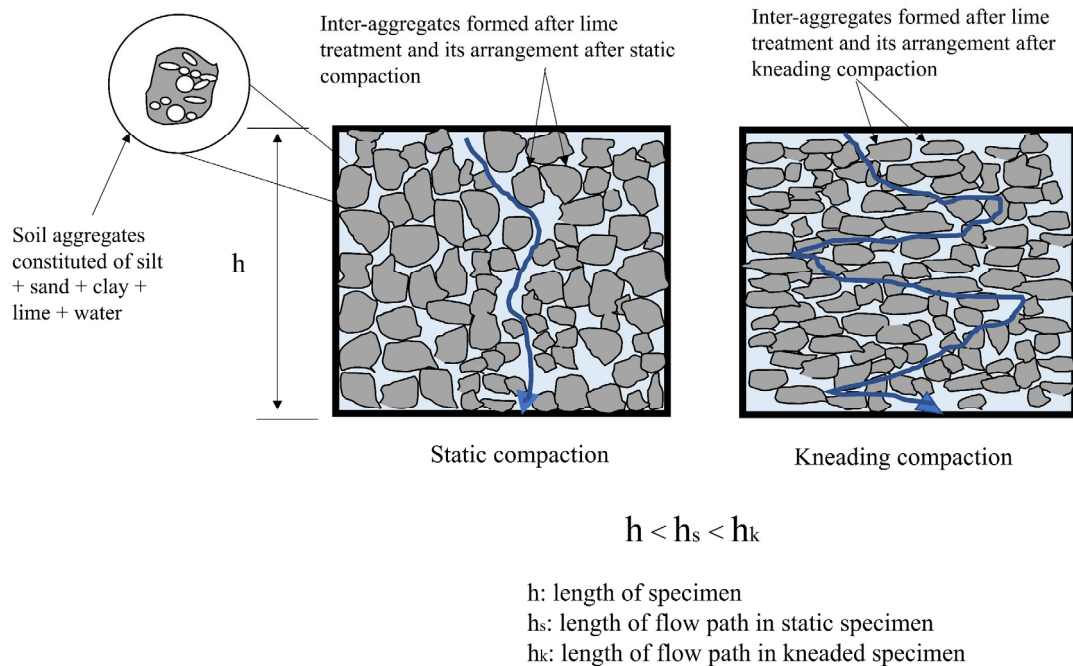
Specimen ID	k (m/s)	ϕ	S (m^2/g)	T	Specimen ID	k (m/s)	ϕ	S (m^2/g)	T
1%-S-DW	2.97E-07	0.38	13.16	2.32	1%-K-DW	2.91E-09	0.37	11.75	24.84
1%-S-LW	3.30E-08	0.35	12.02	6.81	1%-K-LW	3.56E-09	0.37	11.62	23.34
2.5%-S-DW	1.71E-07	0.38	19.78	2.04	2.5%-K-DW	1.49E-07	0.38	18.56	2.27
2.5%-S-LW	2.01E-07	0.39	18.42	2.08	2.5%-K-LW	2.18E-09	0.38	18.56	19.46
4%-S-DW	4.56E-08	0.38	22.93	3.36	4%-K-DW	3.00E-08	0.37	22.10	4.12
4%-S-LW	4.73E-08	0.37	23.73	3.12	4%-K-LW	4.54E-09	0.39	20.60	12.34

506

507 According to Table 6, almost all the statically compacted specimens showed a comparatively lower
 508 value of T than the corresponding kneaded specimens. Thus, the consequence of kneading action on
 509 reducing total macropores of diameter 10^5 \AA by deforming the flocculated particles was reflected in the
 510 greater value of T obtained in the kneaded soil. Hence, it can be said that the kneaded soil structure
 511 experiences an intimate and longer contact with the permeant solution, and the pore fluid within the kneaded
 512 soil structure has greater accessibility towards the available lime. Such intimacy is favorable for the
 513 development of pozzolanic reaction, and consequently, a significant formation of cementitious compounds
 514 can occur in the pores. This benefit of kneading action was confirmed by the observed decrease in the
 515 amount of 10^5 \AA diameter macropores in the 2.5% lime-treated LW submitted kneaded soil compared to
 516 the unleached soil (Fig. 4e). As a result, the estimated hydraulic life expectancy and the duration to renew
 517 40 PVF of LW through a unit height in-situ kneaded structure was relatively longer than the one obtained
 518 using the reference standard method (Table 5).

519 Based on the above discussion, Fig. 8 presents a synthetic schematic diagram that elaborates the
 520 flow paths within the lime-treated statically and kneading compacted soil.

521
 522



523
 524 **Fig. 8** Schematic diagram showing differences in lime-treated compacted soil matrices after being subjected to static and
 525 kneading compactions and the expected flow paths of permeant solution during hydraulic test

526

527 *4.2.3. Influence of pore solution chemistry on flow characteristics and leaching mechanism*

528 The mechanism of leaching was defined by the chemistry of the pore solutions the specimens were
529 submitted to. As evident from Fig. 7e & f and Table 4, the leaching of *Ca* was comparatively higher and
530 accelerated in the DW submitted kneaded specimens compared to the corresponding LW submitted
531 specimens. As described earlier, due to the constant contact of soil-lime with the pore solution during the
532 saturation phase of the hydraulic conductivity test, a significant formation of cementitious bonding occurred
533 in the inter-and intra-aggregate pores. Once the percolation phase was initiated, the renewal of the pore
534 solution occurred. Since DW is devoid of ions and has a low EC (Table 1), the DW dissolves a relatively
535 significant quantity of *Ca* from the cementitious compounds, particularly those present around the flow
536 path, and the soluble *Ca* from the soil. The dissolution of cementitious compounds from the macropores,
537 thus, in turn, increased the magnitude of *k* (Fig. 5e & f). As a result, 40 PVF of DW was percolated through
538 the 2.5% and 4% lime-treated kneaded soil only in 4 and 6 days, respectively. At the same time, the
539 corresponding 2.5% and 4% lime-treated LW submitted specimens took 75 and 40 days, respectively, to
540 percolate a similar volume of LW (Table 4). The above phenomena also explain the relatively significant
541 UCS reduction observed in the DW submitted kneaded specimen (Fig. 2b).

542 However, the influence of pore solution chemistry in the leaching mechanism inducing a
543 modification in the flow-path remained less pronounced in the 1% lime-treated kneaded specimen than in
544 the 2.5% and 4% lime-treated samples. As soil treated at LMO has limited contribution towards the
545 development of cementitious compounds, almost all *Ca* from the added lime was leached, and
546 consequently, a significant amount of soluble *Ca* was leached from the soil (Fig. 7d). Besides, under the
547 application of a constant load during kneading compaction, the flocculated particles in the 1% lime-treated
548 specimens tend to deform more than the deformation of the 2.5% and 4% lime-treated soil as the addition
549 of the higher lime dosages creates stronger flocculated particles. Thus, the evolution of *k* in the 1% lime-
550 treated remained at a similar level as the untreated kneaded soil (Fig. 5d).

551 Although the impact of pore solution chemistry on the mechanical and hydraulic evolution was
552 pronounced in the kneaded soil, it remained less significant in the statically compacted soil. Due to the
553 presence of additional macropores (Fig. 3) in all the lime-treated statically compacted specimens, statically
554 compacted soil can be said to have undergone preferential flow, which was reflected in the relatively lower
555 value of *T* than that in the kneading compacted samples (Table 6). In the process of preferential flow, the
556 pore solution-soil structure interaction remained less significant, and thus the leaching mechanism remained
557 at a similar level irrespective of the types of pore solutions the specimens were submitted to (Fig. 7a-c).
558 This explains the evolution of a similar level of *k* in the 2.5% and 4% lime-treated statically compacted soil
559 regardless of the types of pore solution they were submitted to (Fig. 5b & c). It also explains the difference
560 in UCS observed between the statically and kneading compacted soil (Fig. 2).

561 However, the k increased by 10 times in the 1% lime-treated DW submitted soil compared to the
 562 LW submitted soil (Fig. 5a). Considering that the leaching mechanism in 1% lime-treated statically
 563 compacted soil remained at a similar level (Fig. 7a), and 1% lime-treated soil has limited contribution
 564 towards the deposition of cementitious compounds around the flow path; hence, the observed increase in
 565 the k value in the DW submitted soil was due to the partial disintegration of inter-aggregates around the
 566 flow path, which in turn increased the quantity of 10^5 Å diameter macropores (Fig. 4a).

567

568 *4.2.4. Comparison of hydraulic evolution in laboratory and in-situ cured soil*

569 The hydraulic evolution and the estimated hydraulic life expectancy of the 2.5% lime-treated LW
 570 percolated kneaded soil (Table 5) were compared with the atmospherically cured specimens. In-situ
 571 specimens were sampled from a 7-years atmospherically cured embankment built with the same soil
 572 configuration, as reported by Das et al. (2020). The embankment was previously studied by Makki-
 573 Szymkiewicz et al. (2015), who reported a k of 2.00E-09 m/s after 6 months of atmospheric curing. The
 574 hydraulic conductivity was evaluated again after 7 years of atmospheric curing by subjecting the sample to
 575 LW at the laboratory, and the k value was found to be 9.18E-10 m/s. The estimated hydraulic life expectancy
 576 and the evolution of k in the laboratory and the in-situ cured specimens are compared and are presented in
 577 Table 7.

578

579 **Table 7**

580 Comparison of k and life expectancy obtained for in-situ and laboratory cured 2.5% lime-treated kneaded soil, percolated by LW

Type of specimens	Duration of curing	k (m/s)	Life expectancy (years)
Laboratory-cured	28 days	2.18E-09	14.5
	6 months	2.00E-09	15.9
In-situ cured	7 years	9.18E-10	34.5

581

582 Table 7 shows that the obtained values of k and hydraulic life expectancy evolved in a positive
 583 manner. The k value decreased while the hydraulic life expectancy increased with curing time. The decrease
 584 in k was due to the evolution of cementitious compounds, which increased the mesopores by decreasing the
 585 available macropores, as reported by Das et al. (2020). The increased mesopores positively contribute to an
 586 increase in UCS, which has led to an average UCS of 3.29 MPa in the 7 years atmospherically cured soil,
 587 as reported by Das et al. (2020).

588 Thus, in addition to the positive evolution of k with increased curing time, an enhanced mechanical
 589 behavior can also be expected with time. Such an evolution can contribute to the increased hydromechanical

590 life expectancy of the structure. This underlines the relevance of kneading compaction and the use of LW
591 to evaluate the long-term hydromechanical performance of lime-treated soil.

592

593 **Conclusions**

594

595 This study investigates the hydromechanical evolution in lime-treated soil based on the leaching
596 mechanism and microstructural modifications brought about by a coupled pore solutions-soil structure
597 interaction. Based on the analysis, the following conclusions are derived:

598

599 1) The evolution of UCS in the lime-treated leached specimens was impacted by combined influence
600 created by (i) the availability of lime, (ii) the quality of the interaction of the pore fluid with the soil-lime
601 component and, (iii) the impact of compaction mechanism on the extent of deformation of larger-sized
602 flocculated particles. Thus, the UCS increased by 57% and 36% in the leached 4% lime-treated statically
603 compacted and kneaded specimens, respectively, compared to the unleached specimens. The UCS remained
604 unchanged in the 2.5% lime-treated statically compacted specimen, while it decreased by 21% and 40% in
605 the 2.5% lime-treated kneaded soil, percolated by LW and DW, respectively.

606

607 2) Evaluation of hydraulic conductivity in terms of PVF helps to determine the percentage of life expectancy
608 that can be reached in an in-situ hydraulic structure by considering the pore fluid-soil structure interactions.
609 The renewal of 40 PVF corresponds to the deterioration of about 30 to 50% of the total estimated life of the
610 lime-treated structure, built with the present soil configurations.

611

612 3) Kneading action reduced the number of macropores of diameter 10^5 \AA in the compacted soil structure,
613 which consequently reduces the magnitude of k . Thus, the magnitude of k was 10^{-8} to 10^{-9} m/s in the LW
614 submitted kneaded soil, while it was 10^{-6} to 10^{-8} m/s in the corresponding statically compacted soil.

615

616 4) Higher hydraulic tortuosity obtained in the kneaded soil demonstrated the longer contact duration
617 between the pore solution and the soil and lime component. This feature favored the development of
618 cementitious compounds and lowered the macropores of diameter 10^5 \AA in the 2.5% lime-treated LW
619 submitted kneaded soil, which is favorable for the long-term performance of lime-treated earth structure.

620

621 5) The chemistry of pore fluid caused a significant modification in the hydromechanical evolution of lime-
622 treated soil based on its accessibility to the soil and lime component. DW, being relatively more aggressive
623 than LW, dissolved a significant amount of Ca from the cementitious compounds, thus resulting in an

624 increase in the k of 2.5% and 4% lime-treated kneaded soil. This influence of DW on the leaching
625 mechanism and the hydraulic conductivity evolution remained less pronounced in the statically compacted
626 soil than the kneaded soil due to the limited accessibility of pore fluid to the soil components.

627

628 6) The hydromechanical behavior of lime-treated kneaded soil evolved with curing time, which in turn
629 increased the life expectancy of an in-situ earth structure. The hydraulic evolution and the life expectancy
630 of 28 days laboratory cured 2.5% lime-treated kneaded soil, percolated by LW was $2.18\text{E-}09$ m/s and 14.5
631 years, respectively. After 7 years of atmospheric curing, the hydraulic evolution and the life expectancy
632 evolved to $9.18\text{E-}10$ m/s and 34.5 years, respectively. Such observations were due to evolution of
633 cementitious compounds, which also increased the UCS to 3.29 MPa. This underlines the relevance of the
634 use of kneaded soil and LW to evaluate the long-term hydromechanical performance of the lime-treated in-
635 situ structure.

636

637 7) Soil treated at LMO (1%) has limited contribution towards the development of cementitious compounds.
638 Thus, the influence of pore solution-soil structure interaction remained less significant in the hydraulic,
639 leaching, and compressive strength evolution of the 1% lime-treated soil, whereas significant modifications
640 in these properties can be observed in soil treated with lime content of 2.5% and 4%.

641

642 Thus, the above findings showed that the hydromechanical evolution in lime-treated soil is
643 governed by the mechanism created during the pore fluid-soil structure interactions. The duration of the
644 pore fluid-soil structure interaction is defined by the compaction mechanism implemented, and the extent
645 of influence is determined by the pore solution chemistry and the lime content added. Implementation of
646 kneading compaction accompanied with 10^{-3} M of NaCl concentration, a low ionic strength solution brings
647 a significant modification in the hydromechanical performance. Thus, the selected compaction procedure
648 and the permeant solution in the laboratory scale must be representative of the compaction mechanism and
649 pore water that the structure is likely to be subjected to in the field. This will help to have a close prediction
650 of the long-term hydromechanical performance of in-situ lime-treated structures. Such a prediction can
651 contribute effectively to the efficient management of construction resources. Besides, to have a considerable
652 modification in the hydromechanical performance, the addition of lime content higher than LMO is
653 essential.

654

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656

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661

662 **References**

- 663 Akula, P., Hariharan, N., Little, D.N., Lesueur, D., Herrier, G., 2020. Evaluating the Long-Term
664 Durability of Lime Treatment in Hydraulic Structures: Case Study on the Friant-Kern Canal.
665 Transportation Research Record 2674 (6), 431–443. <https://doi.org/10.1177/0361198120919404>.
- 666 Ali, H., Mohamed, M., 2019. Assessment of lime treatment of expansive clays with different mineralogy
667 at low and high temperatures. Construction and Building Materials 228, 116955.
668 <https://doi.org/10.1016/j.conbuildmat.2019.116955>
- 669 Allen, R., Sun, S., 2017. Computing and comparing effective properties for flow and transport in
670 computer-generated porous media. Geofluids. <https://doi.org/10.1155/2017/4517259>
- 671 A. ASTM, D698-12e2 (2012), Standard Test Methods for Laboratory Compaction Characteristics of Soil
672 Using Standard Effort (12 400 Ft-Lbf/Ft³ (600 KN-m/M³)). American Society for Testing and
673 Materials, West Conshohocken, PA.
- 674 Bell, F.G., 1996. Lime stabilization of clay minerals and soils. Engineering geology 42, 223–237.
- 675 Charles, I., Herrier, G., Chevalier, C., Durand, E., 2012. An experimental full-scale hydraulic earthen
676 structure in lime treated soil, in: 6th International Conference on Scour and Erosion, Paris. pp.
677 1223–1230.
- 678 Clegg, B., 1964. Kneading compaction. Australian Road Research Board Bulletin 1.
- 679 Cuisinier, O., Auriol, J.-C., le Borgne, T., Deneele, D., 2011. Microstructure and hydraulic conductivity
680 of a compacted lime-treated soil. Engineering geology 123, 187–193.
681 <https://doi.org/10.1016/j.enggeo.2011.07.010>
- 682 Das, G., Razakamanantsoa, A., Herrier, G., Saussaye, L., Lesueur, D., Deneele, D., 2020. Evaluation of
683 the long-term effect of lime treatment on a silty soil embankment after seven years of atmospheric
684 exposure: Mechanical, physicochemical, and microstructural studies. Engineering Geology 105986.
685 <https://doi.org/10.1016/j.enggeo.2020.105986>.

- 686 Das, G., Razakamanantsoa, A., Herrier, G., Deneele, D., 2021. Compressive strength and microstructure
687 evolution of lime-treated silty soil subjected to kneading action. *Transportation Geotechnics*, 29,
688 100568. <https://doi.org/10.1016/j.trgeo.2021.100568>
- 689 Deneele, D., le Runigo, B., Cui, Y.-J., Cuisinier, O., Ferber, V., 2016. Experimental assessment regarding
690 leaching of lime-treated silt. *Construction and Building Materials* 112, 1032–1040.
691 <https://doi.org/10.1016/j.conbuildmat.2016.03.015>
- 692 Diamond, S., Kinter, E.B., 1965. Mechanisms of soil-lime stabilization. *Highway Research Record* 92,
693 83–102.
- 694 Dowling, A., O’Dwyer, J., Adley, C.C., 2015. Lime in the limelight. *Journal of cleaner production* 92,
695 13–22. <https://doi.org/10.1016/j.jclepro.2014.12.047>
- 696 Eades, J.L., Grim, R.E., 1966. A quick test to determine lime requirements for lime stabilization.
697 *Highway research record*.
- 698 He, J., Wang, Y., Li, Y., Ruan, X., 2015. Effects of leachate infiltration and desiccation cracks on
699 hydraulic conductivity of compacted clay. *Water Science and Engineering* 8, 151–157.
700 <https://doi.org/10.1016/j.wse.2015.04.004>
- 701 Holtz, R.D., Kovacs, W.D., Sheahan, T.C., 1981. *An introduction to geotechnical engineering*. Prentice-
702 Hall Englewood Cliffs, NJ.
- 703 Hopkins, T.C., Beckham, T.L., Sun, C., 2007. *Stockpiling Hydrated Lime-Soil Mixtures*.
704 <http://dx.doi.org/10.13023/KTC.RR.2007.12>
- 705 Houben, H., Guillaud, H., 1994. *de l’article/du chapitre Earth construction. A comprehensive guide*.
706 distributeur Craterre-Eag.
- 707 Hunt, A.G., Sahimi, M., 2017. Flow, transport, and reaction in porous media: Percolation scaling, critical-
708 path analysis, and effective medium approximation. *Reviews of Geophysics* 55, 993–1078.
709 <https://doi.org/10.1002/2017RG000558>
- 710 Inkham, R., Kijjanapanich, V., Huttagosol, P., Kijjanapanich, P., 2019. Low-cost alkaline substances for
711 the chemical stabilization of cadmium-contaminated soils. *Journal of environmental management*
712 250, 109395. <https://doi.org/10.1016/j.jenvman.2019.109395>

713 Katsumi, T., Ishimori, H., Onikata, M., Fukagawa, R., 2008. Long-term barrier performance of modified
714 bentonite materials against sodium and calcium permeant solutions. *Geotextiles and Geomembranes*
715 26, 14–30. <https://doi.org/10.1016/j.geotexmem.2007.04.003>

716 Koliass, S., Kasselouri-Rigopoulou, V., Karahalios, A., 2005. Stabilisation of clayey soils with high
717 calcium fly ash and cement. *Cement and Concrete Composites* 27, 301–313.
718 <https://doi.org/10.1016/j.cemconcomp.2004.02.019>

719 Kouassi, P., Breyse, D., Girard, H., Poulain, D., 2000. A new technique of kneading compaction in the
720 laboratory. *Geotechnical testing journal* 23, 72–82. <https://doi.org/10.1520/GTJ11125J>

721 le Runigo, B., Cuisinier, O., Cui, Y.-J., Ferber, V., Deneele, D., 2009. Impact of initial state on the fabric
722 and permeability of a lime-treated silt under long-term leaching. *Canadian Geotechnical Journal* 46,
723 1243–1257. <https://doi.org/10.1139/T09-061>

724 le Runigo, B., Ferber, V., Cui, Y.-J., Cuisinier, O., Deneele, D., 2011. Performance of lime-treated silty
725 soil under long-term hydraulic conditions. *Engineering geology* 118, 20–28.
726 <https://doi.org/10.1016/j.enggeo.2010.12.002>

727 Lemaire, K., Deneele, D., Bonnet, S., Legret, M., 2013. Effects of lime and cement treatment on the
728 physicochemical, microstructural and mechanical characteristics of a plastic silt. *Engineering*
729 *Geology* 166, 255–261. <https://doi.org/10.1016/j.enggeo.2013.09.012>

730 Little, D.N., 1995. Stabilization of pavement subgrades and base courses with lime.

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

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

735 Miller, G.A., Azad, S., 2000. Influence of soil type on stabilization with cement kiln dust. *Construction*
736 *and building materials* 14, 89–97. [https://doi.org/10.1016/S0950-0618\(00\)00007-6](https://doi.org/10.1016/S0950-0618(00)00007-6)

737 Mitchell, J.K., Hooper, D.R., Campenella, R.G., 1965. Permeability of compacted clay. *Journal of the*
738 *Soil Mechanics and Foundations Division* 91, 41–65.

739 Mitchell, J.K., McConnell, J.R., 1965. Some Characteristics of the elastic and plastic deformation of clay
740 on initial loading. Institute of Transportation and Traffic Engineering, University of California.

- 741 Nguyen, T.T.H., Cui, Y.J., Herrier, G., Tang, A.M., 2015. Effect of lime treatment on the hydraulic
742 conductivity of a silty soil.
- 743 Poh, H.Y., Ghataora, G.S., Ghazireh, N., 2006. Soil stabilization using basic oxygen steel slag fines.
744 Journal of materials in Civil Engineering 18, 229–240. [https://doi.org/10.1061/\(ASCE\)0899-1561\(2006\)18:2\(229\)](https://doi.org/10.1061/(ASCE)0899-1561(2006)18:2(229))
745
- 746 Pu, S., Zhu, Z., Wang, H., Song, W., Wei, R., 2019. Mechanical characteristics and water stability of silt
747 solidified by incorporating lime, lime and cement mixture, and SEU-2 binder. Construction and
748 Building Materials 214, 111–120. <https://doi.org/10.1016/j.conbuildmat.2019.04.103>
- 749 Ranaivomanana, H., Razakamanantsoa, A., Amiri, O., 2018. Effects of cement treatment on
750 microstructural, hydraulic, and mechanical properties of compacted soils: Characterization and
751 modeling. International Journal of Geomechanics 18, 04018106.
752 [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0001248](https://doi.org/10.1061/(ASCE)GM.1943-5622.0001248)
- 753 Ranaivomanana, H., Razakamanantsoa, A., Amiri, O., 2017. Permeability prediction of soils including
754 degree of compaction and microstructure. International Journal of Geomechanics 17, 04016107.
755 [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0000792](https://doi.org/10.1061/(ASCE)GM.1943-5622.0000792)
- 756 Razakamanantsoa, A.R., Djeran-Maigre, I., 2016. Long term chemo-hydro-mechanical behavior of
757 compacted soil bentonite polymer complex submitted to synthetic leachate. Waste management, 53,
758 92-104. <https://doi.org/10.1016/j.wasman.2016.04.023>
- 759 Romero, E., Simms, P.H., 2008. Microstructure investigation in unsaturated soils: a review with special
760 attention to contribution of mercury intrusion porosimetry and environmental scanning electron
761 microscopy. Geotechnical and Geological engineering 26, 705–727.
- 762 Rouquerol, J., Avnir, D., Fairbridge, C.W., Everett, D.H., Haynes, J.M., Pernicone, N., Ramsay, J.D.F.,
763 Sing, K.S.W., Unger, K.K., 1994. Recommendations for the characterization of porous solids
764 (Technical Report). Pure and Applied Chemistry 66, 1739–1758.
- 765 Sato, K., Barast, G., Razakamanantsoa, A.R., Djeran-Maigre, I., Katsumi, T., Levacher, D., 2017.
766 Comparison of prehydration and polymer adding effects on Na activated Ca-bentonite by free swell
767 index test. Applied Clay Science 142, 69–80. <https://doi.org/10.1016/j.clay.2016.10.009>
- 768 Shackelford, C.D., Benson, C.H., Katsumi, T., Edil, T.B., Lin, L., 2000. Evaluating the hydraulic
769 conductivity of GCLs permeated with non-standard liquids. Geotextiles and Geomembranes 18,
770 133–161. [https://doi.org/10.1016/S0266-1144\(99\)00024-2](https://doi.org/10.1016/S0266-1144(99)00024-2)

771 Show, K.-Y., Tay, J.-H., Goh, A.T.C., 2003. Reuse of incinerator fly ash in soft soil stabilization. *Journal*
772 *of materials in civil engineering* 15, 335–343. [https://doi.org/10.1061/\(ASCE\)0899-](https://doi.org/10.1061/(ASCE)0899-)
773 1561(2003)15:4(335)

774 Srisutthiyakorn, N., Mavko, G., 2016. Hydraulic tortuosity: From artificial packs to natural rocks, in:
775 SEG Technical Program Expanded Abstracts 2016. Society of Exploration Geophysicists, pp. 3133–
776 3137. <https://doi.org/10.1190/segam2016-13966753.1>

777 Sunil, B.M., Shrihari, S., Nayak, S., 2008. Soil-leachate interaction and their effects on hydraulic
778 conductivity and compaction characteristics, in: 12th International Conference on Computer
779 Methods and Advances in Geomechanics. pp. 2380–2386.

780 Tran, T.D., Cui, Y.-J., Tang, A.M., Audiguier, M., Cojean, R., 2014. Effects of lime treatment on the
781 microstructure and hydraulic conductivity of Héricourt clay. *Journal of Rock Mechanics and*
782 *Geotechnical Engineering* 6, 399–404. <https://doi.org/10.1016/j.jrmge.2014.07.001>

783 Vaverková, M.D., Elbl, J., Koda, E., Adamcová, D., Bilgin, A., Lukas, V., Podlasek, A., Kintl, A.,
784 Wdowska, M., Brtnický, M., 2020. Chemical Composition and Hazardous Effects of Leachate from
785 the Active Municipal Solid Waste Landfill Surrounded by Farmlands. *Sustainability* 12, 4531.
786 <https://doi.org/10.3390/su12114531>

787 Verbrugge, J.-C., de Bel, R., Correia, A.G., Duvigneaud, P.-H., Herrier, G., 2011. Strength and micro
788 observations on a lime treated silty soil, in: *Road Materials and New Innovations in Pavement*
789 *Engineering*. pp. 89–96. [https://doi.org/10.1061/47634\(413\)12](https://doi.org/10.1061/47634(413)12)

790 Watabe, Y., Leroueil, S., le Bihan, J.-P., 2000. Influence of compaction conditions on pore-size
791 distribution and saturated hydraulic conductivity of a glacial till. *Canadian Geotechnical Journal* 37,
792 1184–1194. <https://doi.org/10.1139/t00-053>

793 Wild, S., Kinuthia, J.M., Jones, G.I., Higgins, D.D., 1998. Effects of partial substitution of lime with
794 ground granulated blast furnace slag (GGBS) on the strength properties of lime-stabilised sulphate-
795 bearing clay soils. *Engineering Geology* 51, 37–53. [https://doi.org/10.1016/S0013-7952\(98\)00039-8](https://doi.org/10.1016/S0013-7952(98)00039-8)

796 Young, R., 2012. *Soil properties and behaviour*. Elsevier.

797