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Compressive strength and microstructure evolution of lime-treated silty soil subjected to kneading action

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Highlights

- Behaviours of lime-treated silty soil subjected to kneading compaction are investigated.
- Kneading action enhances better lime-dispersion during soil compaction.
- Proper lime-dispersion contributes to enhanced UCS evolution in the long-term.
- Wet side compacted soil shows enhanced UCS during longer and accelerated curing.
- Accelerated-cured and 7 years in-situ cured soil, both kneaded, show UCS of similar level.

Abstract

Long-term improvement in behaviour of soil subjected to lime treatment depends on the mechanism of its implementation. In-situ lime-treated fine-grained soil is often subjected to ‘kneading action’ developed by Pad-foot roller. The mechanism underlying the effect of kneading on lime-treated soil remains less investigated. Unconfined Compressive Strength (UCS) and microstructural modification of the lime-treated soil subjected to kneading compaction are evaluated. Kneading action undergoes better lime-dispersion during compaction. This feature accompanied with available water favours the long-term pozzolanic-reactions and hence enhanced the UCS evolution, particularly in the kneaded soil compacted at Wet Moisture Content (WMC). Lime-treated kneaded soil compacted at WMC, which is slightly higher than the Optimum Moisture Content (OMC) is beneficial for enhanced UCS evolution in specimens subjected to longer and accelerated curing. The UCS evolution in the laboratory accelerated-cured kneaded soil is of a similar level as the average UCS measured in the in-situ 7 years atmospherically cured kneaded soil.

30

31 *Keywords: lime-treated soil; kneading compaction; Unconfined Compressive Strength; lime-dispersion;*
32 *pozzolanic-reactions*

33

34 **1. Introduction**

35

36 Efficient and effective management of natural resources such as soil is essential in any land
37 development project. Thus, several chemical stabilisation processes associated with suitable
38 implementation processes (compaction, soil-mixing, soil-chemical-mixing, *etc.*) are commonly practiced
39 for improving the engineering properties of natural soil. Chemical stabilisation involves the use of
40 inorganic or organic binders, such as slags [1–4], fly ashes produced from coal-burning [5,6], cement kiln
41 dust [7,8], alkaline activator [9,10], lime [11–15], *etc.*

42 The use of lime in the form of quicklime or hydrated lime is a widespread technique for such
43 improvement. Lime is one of the most versatile [16], low-cost [17], and easily available chemicals. It was
44 shown to be paramount in several applications using environmentally friendly techniques [16]. Soil treated
45 by lime can be used repeatedly, which is another cost-effective measure [18].

46 Soil improvement by lime consists of two primary modification mechanisms: a) the instant cation
47 exchange reactions and flocculation-agglomeration resulting in a reduction of soil plasticity and
48 improvement of workability, and b) the long-term pozzolanic-reactions leading to the development of the
49 cementitious compounds, thus increasing the soil strength [19–22]. Construction of earth structures such as
50 earth embankments for roads, airports, or railway lines, hydraulic structures, pavement subgrades is
51 successfully implemented because of improvement brought about by lime treatment [11,14,21,23]. One of
52 such examples of earthen hydraulic structures is the Friant-Kern Canal in California, United States. The
53 bottom and blankets of several sections of the canal, initially built with heavy plastic clays, were renovated
54 during the '70s using 4% quicklime by weight [24,25]. Study up to more than 40 years after the renovation
55 was conducted, which showed increased long-term strength, reduction in swelling potential, erosion
56 resistance, thus indicating good geo-mechanical stability of the lime-treated structure [11]. Another study
57 was recently reported by Das et al. [23], where the long-term effect of lime treatment on the mechanical,
58 physicochemical, and microstructural evolution of an embankment constructed and atmospherically cured
59 for 7 years were demonstrated. This study showed a significant evolution in average UCS of about $3.29 \pm$
60 (0.45) MPa due to the development of cementitious compounds because of the long-term pozzolanic
61 reactions. Thus, the durability and reliability of these structures throughout the service life are linked to the
62 hydromechanical performance of the soil.

63 Several studies have reported that lime treatment increases the permeability of soil due to the
64 flocculation of particles, which increases the inter-aggregates pore space [26-28]. Others have shown that
65 permeability increases at the beginning of treatment and decreases with increased curing due to the
66 evolution of cementitious compounds [29,30]. Makki-Szymkiewicz et al. [14] conducted a permeability
67 study on a 2.5% quicklime treated silty soil experimental embankment for about 6 months from the time of
68 construction. The study reported a similar level of permeability values in the lime-treated and untreated
69 soils over the 6 months of curing, concluding that conducting controlled mixing and compaction conditions
70 during the construction improves the hydraulic performance of lime-treated soil. As a result, the same
71 embankment, after 7 years from construction was also reported to have a uniform distribution of pH and
72 water content by Das et al. [23], which led to a significant evolution in compressive strength. Thus, the
73 long-term hydromechanical performance can be said to be associated with the compaction conditions
74 implemented during the construction of such structures.

75 Compaction conditions, such as compaction procedure, energy, and compaction water content,
76 were demonstrated to impact the hydromechanical improvement brought by lime treatment in the soil
77 through several controlled laboratory investigations [13,31-39]. Le Runigo et al. [34] and Mitchell et al.
78 [40] stated that lime-treated soil compacted with different initial moisture contents and compaction energies
79 show different magnitudes of initial permeability coefficient, k . A greater magnitude of k indicates a greater
80 quantity of water percolation through the compacted soil. Water flow could enhance the dissolution of
81 cementitious compounds, consequently decreasing the UCS of the lime-treated soil [13,32,34,36]. This is
82 because k of a soil depends on the pore size distribution (PSD) of the soil, which was shown to be a direct
83 function of compaction conditions by several studies [41-43]. However, how well the above laboratory
84 conditions represent the realistic field conditions is still an important question.

85 On the field, the usual design-construct of an earthwork project is as follows: The proposed soil
86 materials are initially subjected to a laboratory test to define the compaction parameters required for the
87 design. During the construction, these compaction parameters are achieved by implementing the
88 compaction procedure, which is often adjusted according to the type of soil. All soil types except for rocky
89 soil are compacted by Smooth-wheeled roller [44], while fine-grained soil, particularly clayey soil, is
90 preferred to be compacted by Padfoot roller [45-47]. Lekarp et al. [48] demonstrated that Smooth-wheeled
91 roller develops two types of compaction mechanisms in the soil, *i.e.*, generation of stress tensors at the point
92 of contact of the roller and the soil and a continuous rotation of these stress tensors due to the cyclic passes
93 of the roller wheel. However, Padfoot roller, in addition to the rolling action of the wheel, produces a
94 kneading action by the pad foot present on the drum surface of the roller. Thus, penetration of the pads
95 occurs in the soil during compaction [47,49].

96 Though the effect of roller compaction was detailed by Lekarp et al. [48], and recently its
97 implementation was shown in le Vern et al. [50], the effect of kneading action has not been well
98 investigated. Clegg [51] urged the importance of implementing kneading compaction at a laboratory scale
99 to produce realistic laboratory compacted fine-grained specimens by showing a similar generation of soil
100 structure and residual interparticle stresses with the in-situ soil. Kouassi et al. [45] confirmed that soil
101 properties, including the dry density and elastic stiffness obtained under kneading effect at a laboratory
102 scale, were close to those obtained in the in-situ compacted soil. Cuisinier et al. [31] and Herrier et al. [24]
103 highlighted that the magnitude of k obtained from kneaded lime-treated silty soil was lower compared to
104 the soil compacted statically.

105 However, apart from these studies, the effect of kneading compaction on mechanical behaviour is
106 less investigated. The consideration of compaction energy is not available in the previous studies, which is
107 essential to analyse the soil mechanical behaviour. Moreover, since kneading compaction was shown to
108 bring a difference in k , which correlates with microstructural characteristics, the contribution of the
109 kneading effect to the mechanical behaviour must be evaluated.

110 In this context, the present study investigates how the kneading mechanism contributes to the
111 mechanical performance and microstructural modifications of lime-treated soil at a laboratory scale. The
112 first section of the study highlights the compressive strength of kneaded soil by comparing the same with
113 soil compacted by a reference standard method. The second section describes the contribution of kneading
114 compaction at microstructure levels. Finally, comments are made on how the generation of mesopores
115 because of lime treatment contributes to the evolution of UCS.

116
117

118 **2. Materials and Methodologies**

119

120 *2.1. Soil and Lime properties*

121 The material used in this study is silty soil. Details regarding the geotechnical properties of the soil
122 were obtained from the study reported by Makki-Szymkiewicz et al. [14]. The soil was composed of 12%
123 clay content, 82% silt fraction, and the content of soil passing through 80 μm sieve was 99.5%. The liquid
124 limit and plasticity index of the soil was 31% and 11%, respectively. The Methylene value was 2.5 g/100
125 g. The mineralogy of the soil, obtained by X-ray diffraction, showed the presence of Illite, Kaolinite, and
126 Chlorite as clay minerals along with Quartz and Feldspars [15].

127 The quicklime (CaO) used for the treatment was supplied by a commercial supplier. The lime
128 consists of 90.9% of available CaO and a reactivity (t_{60}) of 3.3 min. The Lime Modification Optimum

129 (LMO) of the silt, which defines the minimum lime content required to initiate the pozzolanic-reactions
 130 [52], was determined by Eades and Grim test as per the ASTM D 6276-99a [53]. The LMO was found to
 131 be 1% by weight of lime. Three different lime contents were used, lime content equal to LMO, 2.5%, and
 132 4%.

133

134 *2.2. Sample preparations*

135 The maximum dry density, $\rho_{d(max)}$, and OMC of the silt obtained as per the standard Proctor
 136 compaction test mentioned in ASTM D698-91 [54] are presented in Table. 1. Once the characteristics of
 137 compaction were deduced, the silt was then air-dried and sieved using 5 mm-sieve. Soil mixtures for both
 138 the kneading and static compaction were prepared at OMC (Table 1) and the wet of OMC, i.e., at WMC (= $1.1 \times$
 139 OMC) and stored in sealed plastic bags for about 24 hours to attain moisture content homogenization.
 140 Thus, the initial compaction characteristics (Table 1) of the soil mixture subjected to both types of
 141 compactions were kept constant. The wet soil and the respective lime were then mixed and rested for 1 hour
 142 before compaction. This above process of soil preparation was as per the procedure mentioned in the French
 143 GTS Technical Guide for soil treatment [55], which is also a reference for in-situ construction of lime-
 144 treated structures.

145

146 **Table 1**

147 Maximum dry density and OMC of untreated and lime-treated silty soil using Standard Proctor test

148

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

149

150

151 Cylindrical specimens of dimensions having a length of 10cm and a diameter of 5cm were prepared
 152 by both kneading and static compactions. The static compaction involves compression of the specimens
 153 from top and bottom, as demonstrated by Holtz et al. [44]. This was considered as the standard reference
 154 compaction method.

155 In this study, the kneading compaction was conducted by a laboratory-developed kneading tool,
 156 which was equipped with a dynamic load, as presented in Fig. 1. The application of the dynamic load was

157 made successively with the rotation of the 3-kneading feet by an angle of 45° between 2 successive
158 loadings. This procedure was demonstrated by Kouassi et al. [45]. The applied compaction energy was
159 adjusted as recommended by ASTM D698-91 (Equation 1).

160
161

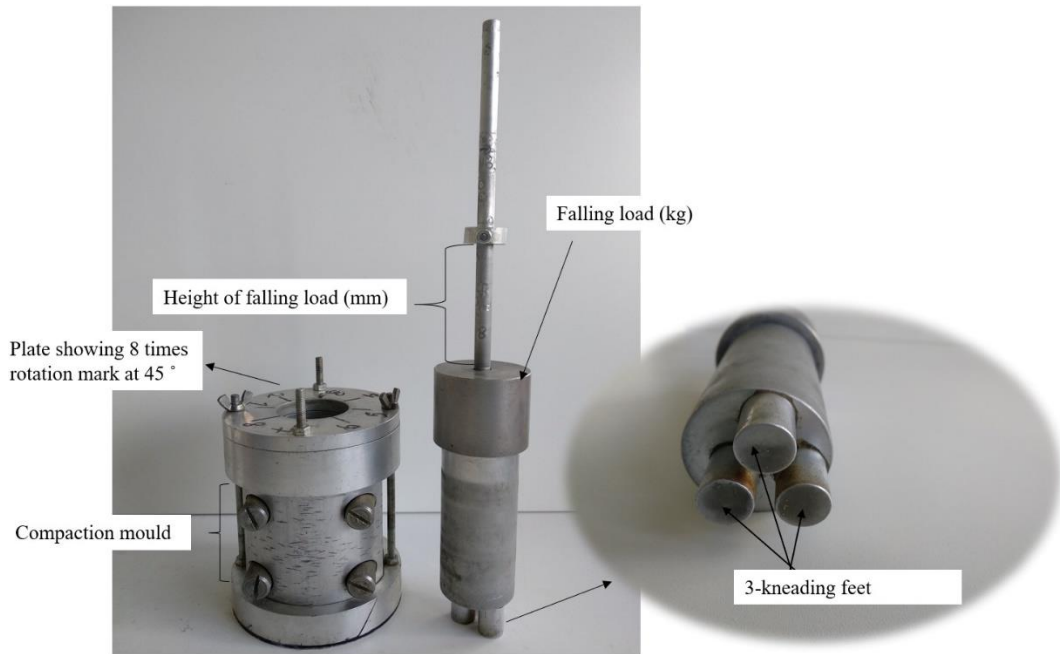
$$162 \quad E = \frac{N \times H \times n \times m \times g}{V} \quad (1)$$

163

164 where, E is the compaction energy (kN-m/m³); $N = 16$, which is the number of blows per layer; $H = 0.14$
165 m, i.e., the height of the falling load; $n = 5$, the number of compacted layers; $m = 1.042$ kg, the mass of the
166 falling load (kg), $g =$ acceleration due to gravity (m/s²), $V = 187$ cm³ i.e., the volume of the mould.

167

168



169

170

Fig. 1. Laboratory Kneading Compaction tool

171

172 After compaction, the bulk density of each specimen was evaluated. The average bulk density of
173 all the kneading and statically compacted specimens was 20.0 kN/m³ and 19.7 kN/m³, respectively. Thus,
174 the average bulk density obtained using both compaction methods was similar. Hence, the precision of the
175 kneading tool developed in the laboratory in achieving the targeted bulk density (*i.e.*, obtained from the
176 standard static tool) can be justified.

177 A total of 72 specimens, including duplicates for each soil configuration, were prepared for strength
 178 and microstructural investigations by both compaction methods (Table 2).

179
 180
 181
 182

Table 2
 Types and number of specimens prepared by static-and kneading-compactions

Compaction modes	Curing conditions		Compaction moisture content	Lime contents	Number of specimens (including duplicates)
	Curing time (days)	Curing temperature (°C)			
Static	28	20	OMC	1%, 2.5%, 4%	6
			WMC		6
	90	20	OMC	1%, 2.5%, 4%	6
			WMC		6
	180	40	OMC	1%, 2.5%, 4%	6
			WMC		6
Kneading	28	20	OMC	1%, 2.5%, 4%	6
			WMC		6
	90	20	OMC	1%, 2.5%, 4%	6
			WMC		6
	180	40	OMC	1%, 2.5%, 4%	6
			WMC		6

183
 184 Forty-eight of the total specimens were cured for 28- and 90-days at a laboratory temperature of
 185 about 20°C, and the remaining were cured for 180 days at 40°C, *i.e.*, under accelerated curing (Table 2).
 186 After curing, specimens prepared for microstructural analysis were freeze-dried and then stored in vacuum
 187 bags to avoid atmosphere interactions until further analysis.

188 The following nomenclature is used for specimen's identification: lime content (1/2.5/4)-Static
 189 compaction method/Kneading compaction method (S/K)-compaction moisture content (OMC/WMC)-
 190 curing time (28/90/180) days. For example, 1-K-OMC-28 means 1% lime-treated soil subjected to kneading
 191 compaction (K) at OMC and then cured for 28 days.

192

193 *2.3. Laboratory tests*

194 After curing, specimens were subjected to UCS test using a mechanical press with a load sensor at
195 a constant displacement rate of 1mm/min.

196 Pore characterization was made by Mercury Intrusion Porosimetry (MIP) test and Barrett-Joiner-
197 Halenda pore (BJH) method [56] on freeze-dried specimens. The motive behind operating both these
198 methods was to investigate the influence of lime treatment on pore structure modifications more
199 elaboratively. MIP is generally used for macropore investigation [23,57,58], while BJH for measuring
200 mesopores and micropores [23,59].

201 The procedure of MIP test involves the evacuation of freeze-dried samples via heating inside a
202 sealed penetrometer. Mercury was then progressively introduced into the samples through incremental
203 hydraulic pressure. The volume of mercury intruded, and the applied pressure, p (MPa), was registered
204 [60]. By measuring the pressure p required to be applied to force the mercury into a cylindrical pore of
205 diameter, D , pore sizes can be obtained according to the Washburn equation (Equation 2) [60].

206
207

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

209

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

212 The BJH method involves analysing pore structure from the isotherms obtained by Brunauer-
213 Emmett-Teller (BET) test [61], which uses nitrogen gas. Freeze-dried samples were evacuated or degassed
214 at 50°C. Nitrogen gas at temperature, T of 77K, and pressure (p) lower than the equilibrium/saturation gas
215 pressure (p_0) was then injected. Pore structure is determined by using the Kelvin equation (Equation 3)
216 [62].

217
218

$$r_k = \frac{2 \cdot V_m \cdot \gamma \cdot \cos \theta}{R \cdot T \cdot \ln \left(\frac{p}{p_0} \right)} \quad (3)$$

220

221 where r_k is the radius of curvature of the condensed gas inside the pore, γ is the surface tension, V_m is the
222 molar gas volume of an ideal gas, θ is the contact angle, and R is the gas constant. In this study, the pore
223 structure analysed by BJH was presented in the form of isotherm plots and cumulative mesopore volume.
224 The cumulative mesopore volume corresponding to the desorption branch of isotherm was used.

225 The discussion related to pore classifications was made as per the International Union of Pure and
226 Applied Chemistry (IUPAC) [63], which classifies pores based on their pore-width as macropores (> 500
227 \AA), mesopores ($20\text{-}500 \text{\AA}$), and micropores ($< 20 \text{\AA}$).

228 Calcium distribution evolution considering the Ca-mapping was shown to be a useful approach to
229 observe the distribution of lime in lime-treated soil by Lemaire et al. [64]. In this aspect, the μ -XRF images
230 are recorded for lime-treated kneading and statically compacted specimens to assess the effect of
231 compaction on the lime-dispersion. The μ -XRF analysis was performed on freeze-dried specimens,
232 impregnated with polyester resin (LR White [®]), and polished with ethanol. The device used equipped with
233 a rhodium RX source and an EDS system (using an SDD detector). Chemical maps of 2 mm square sample
234 sections were recorded.

235 The observed distribution of calcium was then quantitatively analysed by using imaging software
236 NIS-Elements Basic Research 3.1.

237

238

239 **3. Results**

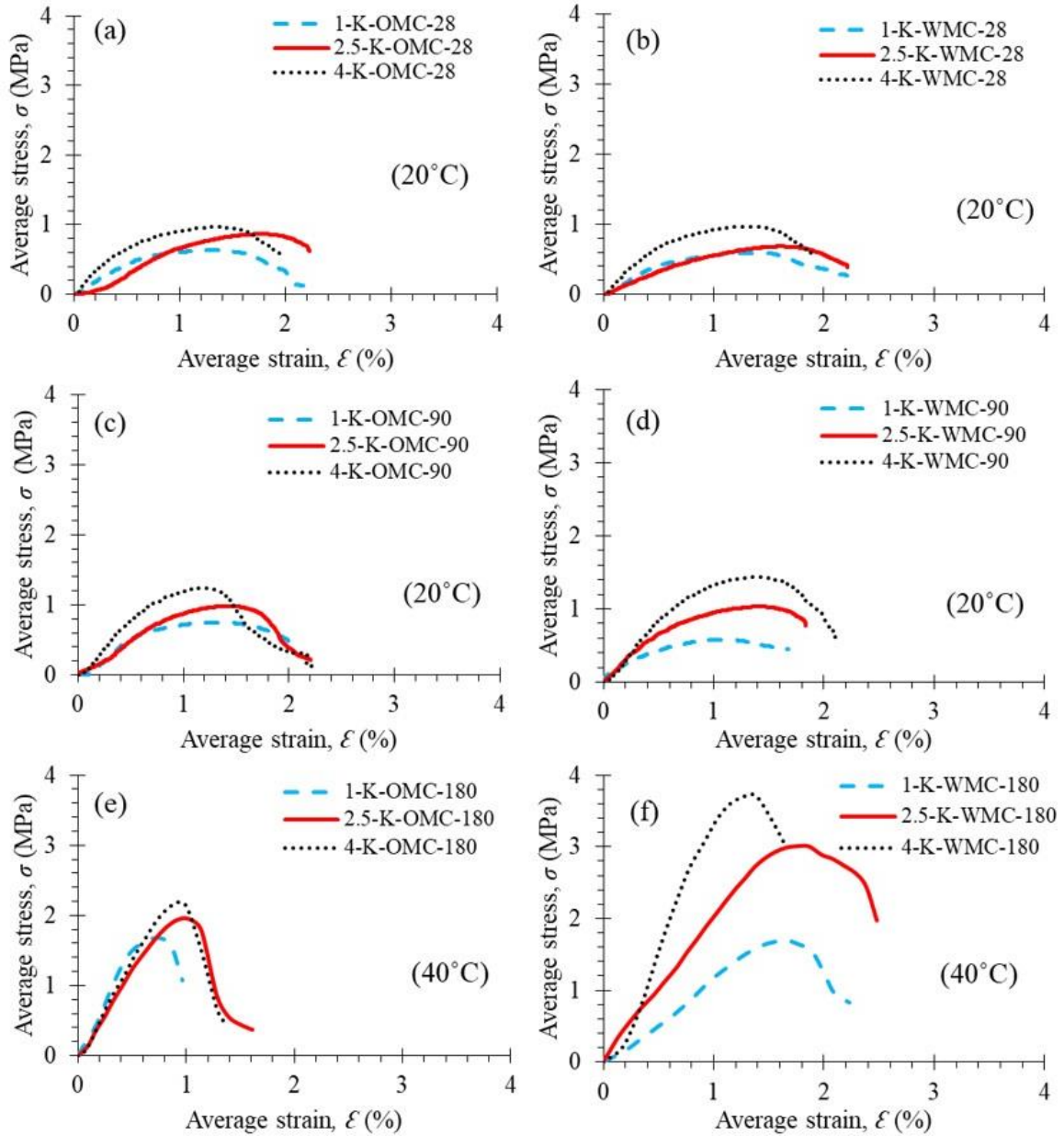
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241 *3.1. UCS of kneading compacted specimens*

242

243 Fig. 2 presents the trend of strength evolution in the lime-treated kneading compacted specimens
244 subjected to different curing periods and temperatures. The presentation was made in terms of the average
245 stress-strain obtained from duplicates of each soil configuration. The UCS value, representing the peak of
246 the stress-strain curve, is presented in Table 3.

247



248

249 **Fig. 2.** Strength evolution of 1%, 2.5% and 4% lime-treated kneading compacted specimens at OMC-28 days (a), WMC-28 days
 250 (b), OMC-90 days (c), WMC-90 days (d), OMC-180 days (e), and WMC-180 days (f)

251

252 **Table 3**

253 UCS measured in lime-treated kneaded soil subjected to different curing time and temperatures

254

	OMC-compacted specimens	WMC-compacted specimens
--	-------------------------	-------------------------

Lime content (%)	Curing time (days)	Curing temperature (°C)	UCS (MPa)	UCS (MPa)
1	28	20	0.60	0.60
	90	20	0.75	0.60
	180	40	1.70	1.70
2.5	28	20	0.86	0.70
	90	20	1.00	1.03
	180	40	1.95	3.00
4	28	20	0.96	1.20
	90	20	1.23	1.43
	180	40	2.20	3.70

255

256 The UCS of the lime-treated kneading compacted soil increased with the increase in lime content
 257 and curing time, as seen in Table 3 and Fig. 2. This increase in UCS was significantly higher for the
 258 accelerated cured specimens after 180 days of curing compared to the increase in UCS from 28 to 90 days
 259 of curing at 20°C.

260 Besides, the evolution of UCS was relatively higher in the WMC-compact specimens than the
 261 corresponding OMC-compact specimens treated with lime content higher than the LMO. The UCS
 262 measured was about 3% and 16% higher for 2.5% and 4% lime-treated specimens, respectively, for the 90-
 263 days cured WMC-compact specimens (Fig. 2d). Similarly, the UCS was about 50% and 70% higher for
 264 the 2.5% and 4% lime-treated accelerated cured specimens, respectively, compacted at WMC (Fig. 2f).

265

266

267 3.2. Comparison of UCS evolution

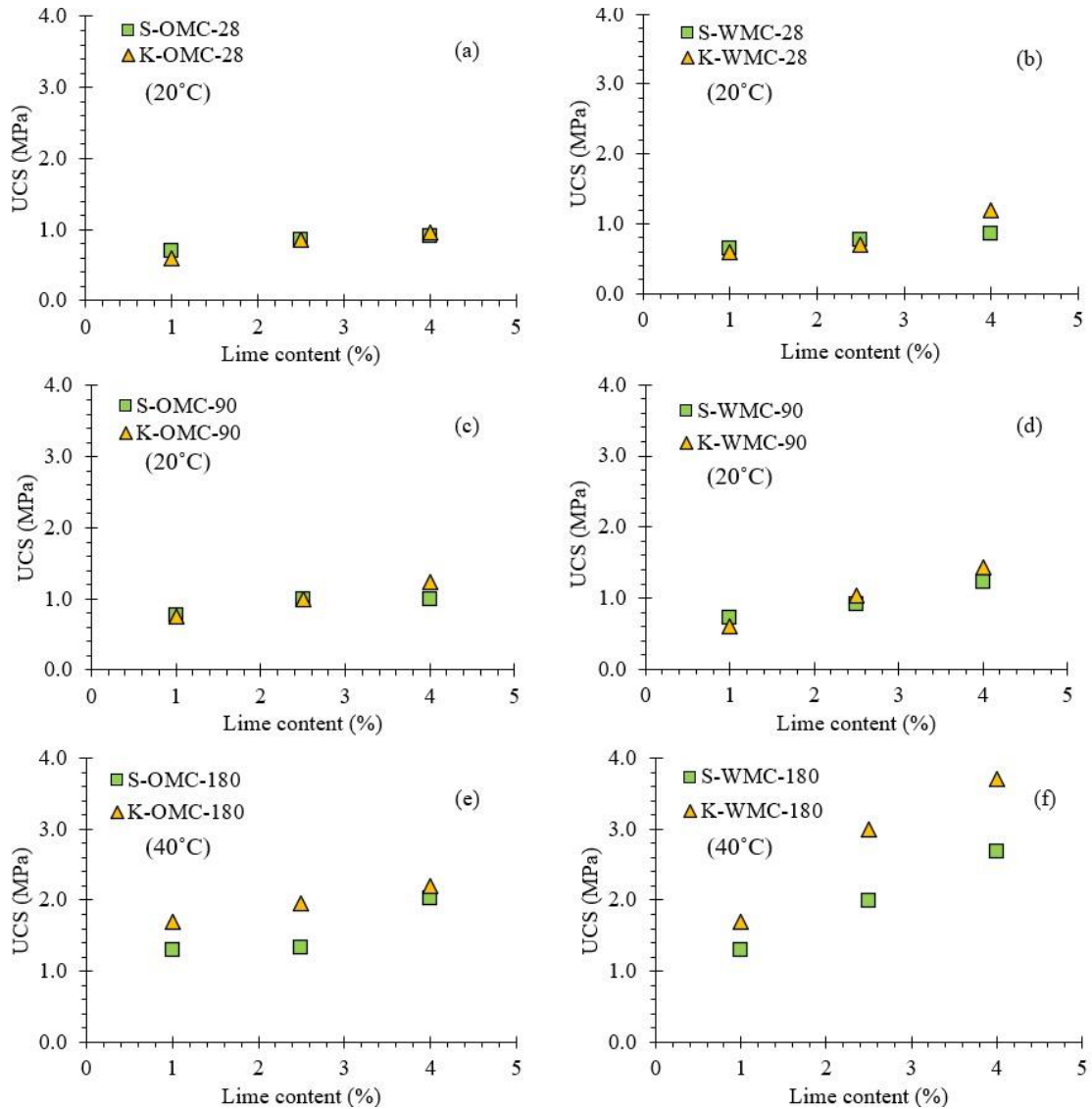
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269 The UCS measured from the kneaded soil, were plotted against the respective values obtained from
 270 the standard statically compacted specimens in Fig. 3. Comparisons are made between specimens prepared
 271 at the same compaction water content, lime content and subjected to similar curing conditions.

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Fig. 3. UCS measured from 1%, 2.5% and 4% lime-treated specimens subjected to static and kneading compactions at OMC-28 days (a), WMC-28 days (b), OMC-90 days (c), WMC-90 days (d), OMC-180 days (e), and WMC-180 days (f)

According to Fig. 3a-d, almost an equivalent UCS level was observed for all the 1% lime-treated compacted specimens, subjected to 28- and 90-days of curing at 20°C. However, this UCS was about 30% higher in kneaded specimens subjected to accelerated curing (Fig. 3e & f).

For the 2.5% lime-treated OMC-compacted specimens, the UCS level was similar for the 28- and 90-days cured specimens (Fig. 3a & c) and increased by about 45% in the accelerated kneaded specimen (Fig. 3e). For the corresponding WMC-compacted specimens, this UCS level remains almost the same after 28 days of curing (Fig. 3b); increased slightly in the kneaded soil after 90 days of curing (Fig. 3d), and increased by about 50% for the accelerated kneaded specimen (Fig. 3f).

287 At 4% lime treatment, all the kneaded specimens show about 6-40% greater UCS values.

288

289

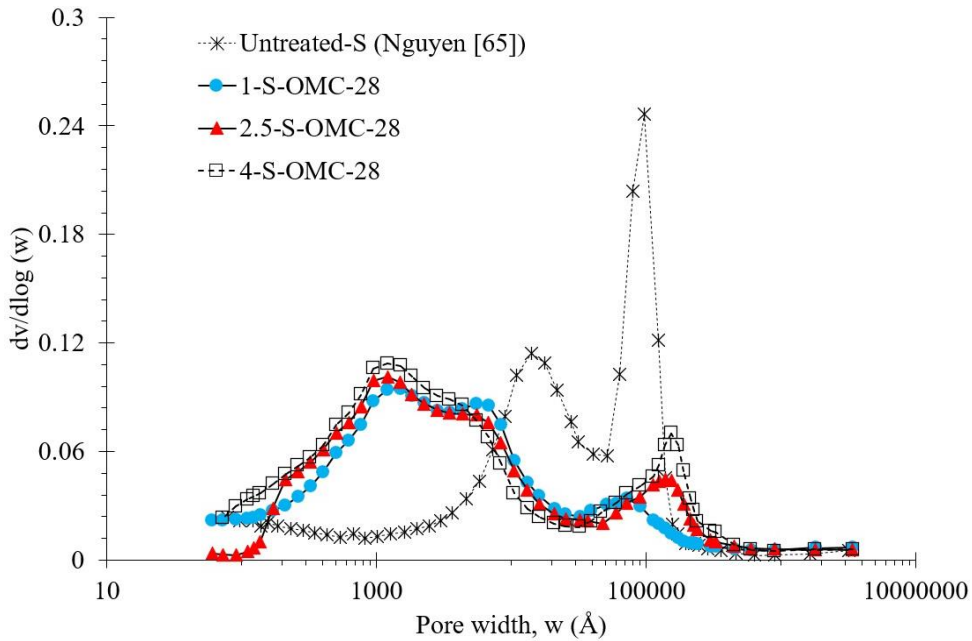
290 *3.3. Comparison of microstructural modifications*

291

292 *3.3.1. Pore size distribution by MIP*

293 Fig. 4 presents the pore size modification brought by lime treatment in the untreated statically
294 compacted specimens by MIP analysis. As expected, a significant decrease in the pores present at 10^5 and
295 10^4 Å and evolution of pores lower than 3000 Å was brought on lime additions. Such evolution was also
296 reported by Cuisinier et al. [31]. Besides, the evolution of pores lower than 3000 Å was enhanced with
297 increased lime contents due to the increased formation of cementitious compounds [23,31].

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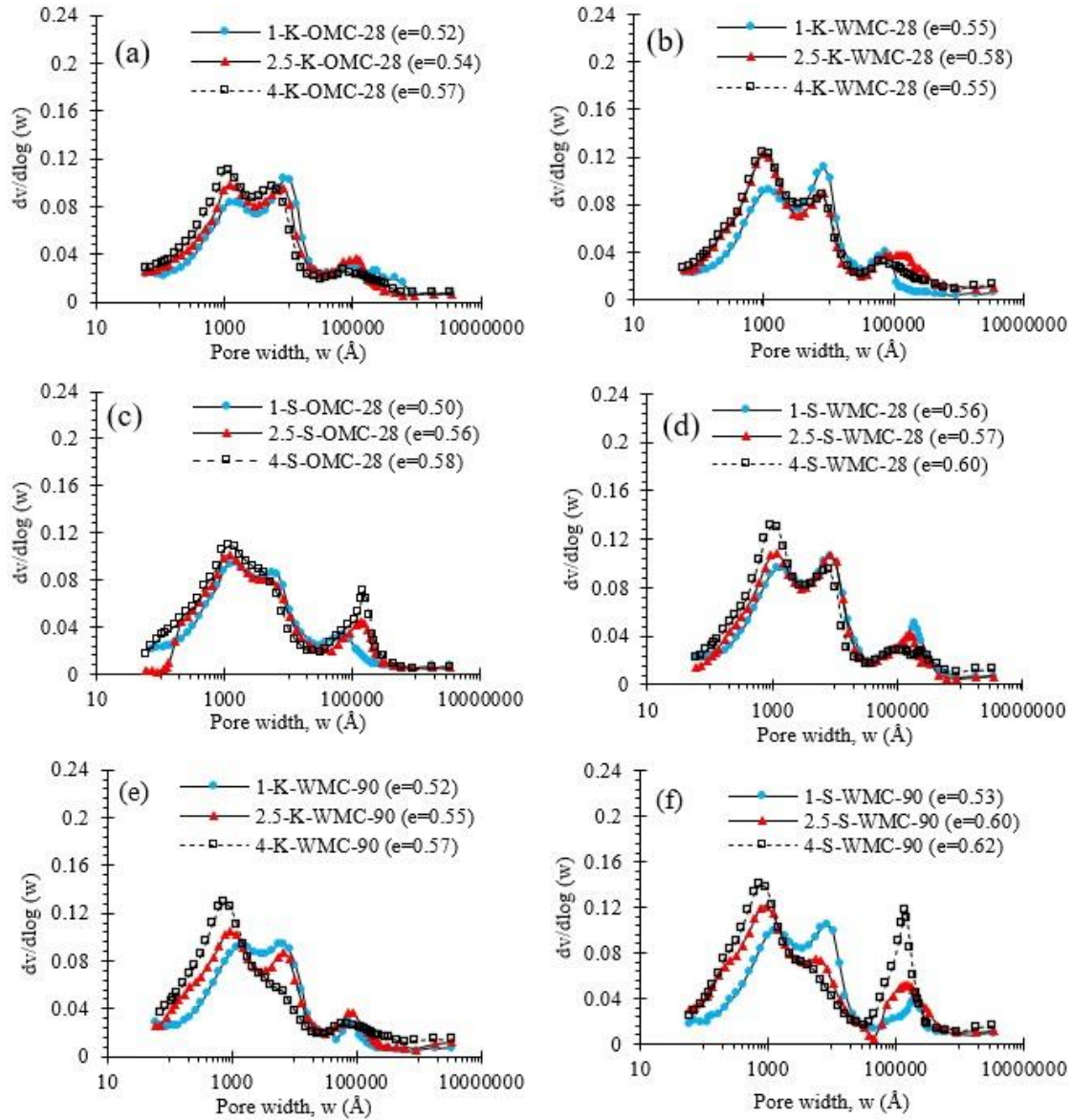


299

300 **Fig. 4:** Evolution of pore structure after addition of 1%, 2.5%, and 4% lime in the untreated statically compacted specimens at
301 OMC and after 28 days of curing

302 The evolution of pore structures in the lime-treated soil compacted by kneading- and static-
303 compactions at different lime contents were compared in Fig. 5. The comparison was presented in terms of
304 PSD for the OMC- and WMC-compacted 28 days cured and WMC-compacted 90 days cured specimens.

305



306
 307 **Fig. 5.** Analysis of pore structure by MIP for 1%, 2.5% and 4% lime-treated specimens compacted by kneading and static
 308 compaction at OMC, and WMC and after 28 days (a-d) and 90 days (e, f) of curing at 20°C

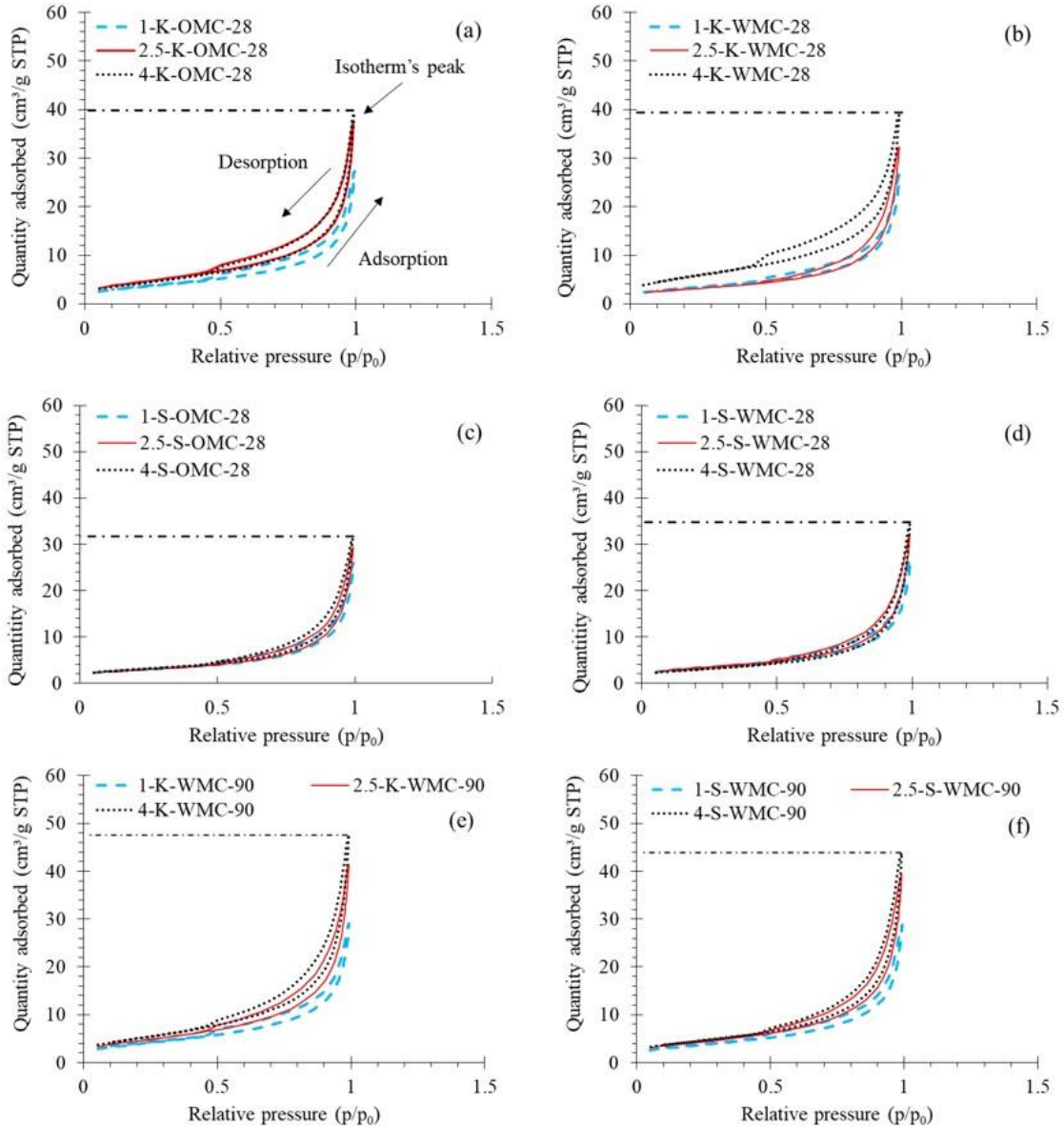
309
 310 A small number of macropores of pore diameter 10^5 \AA were observed in all three different lime-
 311 treated kneaded specimens compacted at both OMC and WMC (Fig. 5a, b & e). On the other hand, for the
 312 statically compacted specimens, an increase in the intensity of macropores of pore diameter 10^5 \AA was
 313 observed with the increased lime content (Fig. 5c, d & f).

314 Besides, almost a similar decrease in the presence of macropores of diameter 10^4 \AA and increased
 315 intensity of pores of diameter lower than 3000 \AA was observed in both types of compacted specimens, with
 316 increase lime content and curing time (Fig. 5a-f).

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3.3.2. Pore size distribution by BJH

Fig. 6 & 7 presents the pore structure analysis by the BJH method in terms of the generation of isotherms and cumulative pore volume evolutions, respectively, in the lime-treated kneading and statically compacted specimens.



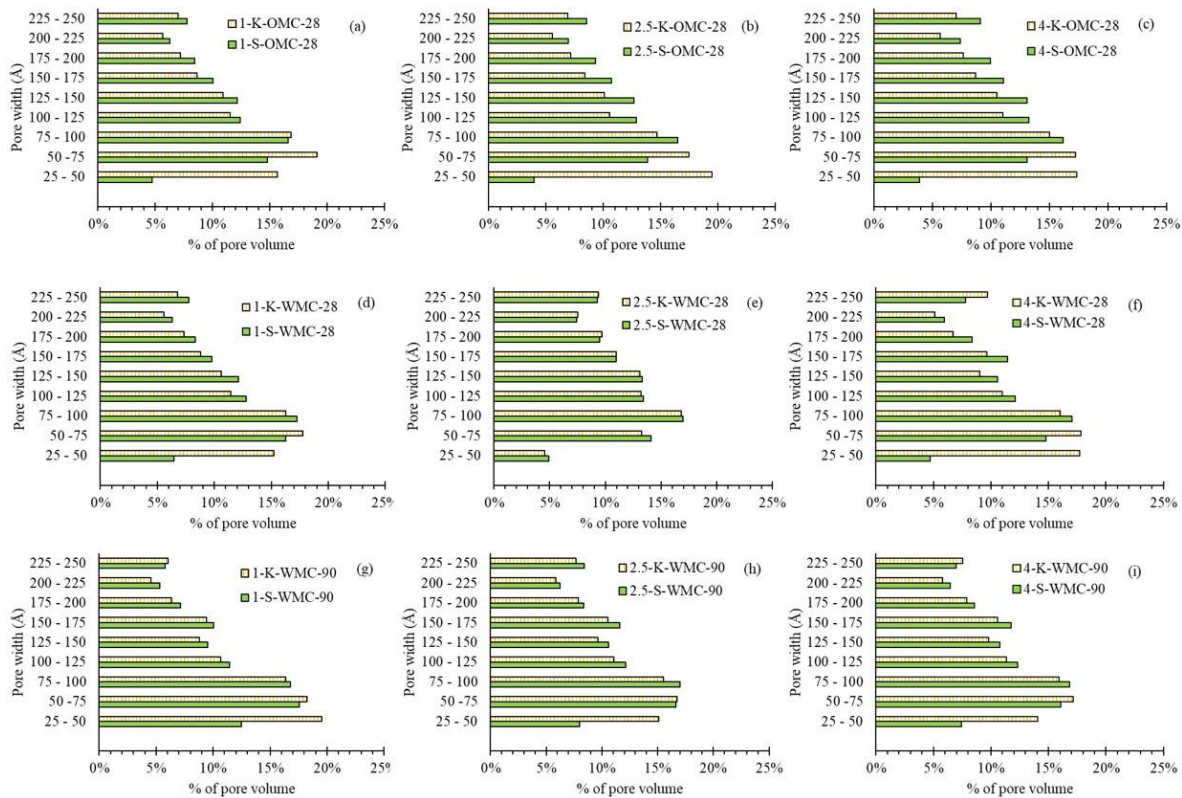
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Fig. 6. Evolution of isotherms in 1%, 2.5%, and 4% lime-treated OMC, and WMC kneading and statically compacted specimens after 28 days (a-d) and 90 days (e, f) of curing at 20°C

327 The peak of the isotherms, as seen in Fig. 6a, represents the total nitrogen adsorption capacity of
 328 the soil [66]. In the analysis made with the present soil, the PSD analysed by the BJH method was found to
 329 be in the range of pore diameter of about 20-2000 Å. Thus, the higher is the peak of the isotherm, the greater
 330 is the presence of pores of diameter 20-2000 Å in the soil.

331 Fig. 6 shows that the peak of the isotherm rises with increased lime content. However, this rise was
 332 relatively more significant in the 4% lime-treated kneaded soil (Fig. 6a, b & e) than the corresponding rise
 333 in statically compacted soil (Fig. 6c, d & f).

334 The hysteresis developed in the isotherm was relatively distinctive in the 4% lime-treated 28 days
 335 cured kneaded soil (Fig. 6a & b). This hysteresis was demonstrated to be associated with the delay in
 336 capillary condensation and evaporation that occurs in the mesopores by McGregor et al. [67] and Collet et
 337 al. [68]. Thus, an enhanced hysteresis indicates the presence of a greater volume of mesopores [69].
 338



339
 340 **Fig. 7.** Percentage of cumulative mesopores volume measured in 1%, 2.5%, and 4% lime-treated OMC, and WMC kneading and
 341 statically compacted specimens after 28 days (a-f) and 90 days (g-i) of curing at 20°C

342
 343 The cumulative mesopore volume measured in the lime-treated compacted soil was in the range of
 344 mesopore diameter 25-250 Å. The variation of these mesopore volumes is presented in terms of the

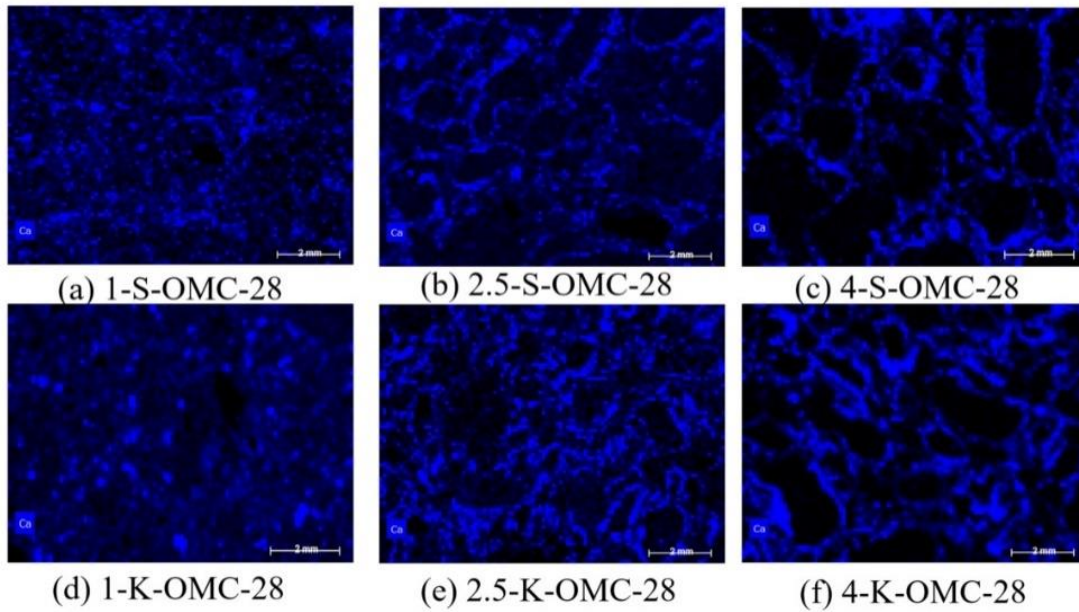
345 percentage of mesopore volume for a different interval of mesopore range (Fig. 7). It was observed that
 346 almost all the statically compacted soil exhibited a greater percentage of mesopore volume in the range of
 347 pore diameter of 100-250 Å. At the same time, the percentage of pore volume was relatively higher in the
 348 kneaded soil in the mesopore range of pore diameter lower than 100 Å, i.e., 25-75 Å.

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 350

351 *3.3.3. μ-XRF images*

352 Fig. 8 presents the distribution of calcium within the lime-treated soil matrix compacted at OMC
 353 and after 28 days of curing. The calcium distribution is represented by the blue region, while soil by the
 354 black region. The quantitative analysis of this calcium distribution is presented in Table 4.

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 356



357
 358 **Fig. 8.** μ-XRF image highlighting calcium distributions in 1%, 2.5%, and 4% lime-treated static (a, b, & c) and kneading
 359 compacted (d, e, & f) specimens prepared at OMC after 28 days of curing time at 20°C.

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 361

362 **Table 4**
 363 Percentage distribution of Calcium (Ca) within the polished surface area of the kneading- and statically-compacted specimens
 364

28 days cured specimens

Lime%-W.C ¹	TSA ² ($\times 10^{-12}$) (m ²)	Kneading	Statically
		compacted	compacted
		% of T.S.A covered by Ca	% of T.S.A covered by Ca
1-OMC	6.0	17.2	13.3
2.5-OMC	7.0	25.4	17.0
4-OMC	6.0	24.4	17.0

365 ¹W.C: compaction moisture content

366 ²T.S.A: Total Surface Area

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369 Table 4 highlights that, for a constant surface area, the percentage of calcium distribution was about
370 4 to 8% higher in the lime-treated kneaded specimens than the corresponding statically compacted
371 specimens.

372

373 4. Discussion

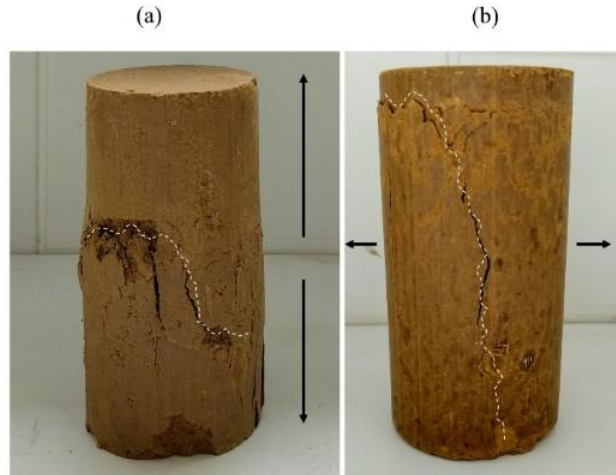
374

375 As expected, kneading compacted soil showed a rise in UCS with increased curing time and lime
376 content (Fig. 2). The significant UCS evolution for the accelerated cured specimens was attributed to the
377 acceleration of pozzolanic-reactions, as demonstrated by Lemaire et al. [64] and Verbrugge et al. [70] (Fig.
378 2e & f). At the same time, for soil treated with 2.5% and 4% lime, the UCS obtained was relatively higher
379 for the WMC-compacted 90 days cured specimens when compared to the corresponding OMC-compacted
380 specimens (Fig. 2c & d). This increase in UCS was more significant for all the accelerated cured WMC-
381 compacted specimens (Fig. 2e & f). Thus, kneaded soil, treated at lime content higher than LMO, cured for
382 a longer time, and under accelerated condition, shows enhanced UCS in WMC-compacted specimens when
383 compared to OMC-compacted specimens. However, the literature has shown that lime-treated soil
384 compacted at WMC, which is much higher than the OMC and cured for a shorter period, resulted in lower
385 UCS than OMC-compacted soil due to the loss in soil grain-to-grain contact with increased water content
386 [13,71-73]. In the present case, the soil treated at WMC is only 1.1 times higher than OMC and cured for a
387 longer time and under accelerated conditions. Thus, the generation of enhanced UCS in the WMC-
388 compacted specimens indicates an appropriate availability of water in the soil matrix, which might have
389 regulated a steady consumption of water by quicklime for the formation of cementitious compounds with
390 increased curing time and under accelerated conditions. Thus, compacting lime-treated soil at WMC
391 slightly higher than OMC is beneficial for long-term evolution of UCS.

392 On comparing the dispersion of calcium measured from the polished surface area of the compacted
393 specimens in Fig. 8, it was observed that this dispersion was enhanced under kneading compaction. The
394 percentage of the polished area covered by calcium was about 8% higher in the 2.5%, and 4% lime-treated
395 OMC kneaded specimens compared to the corresponding statically compacted specimens (Table 4). The
396 observed calcium can either be the calcium from the available lime or the cementitious compounds
397 developed because of pozzolanic-reactions. This provides evidence that kneading action enhances lime-
398 dispersion. This feature of enhanced lime dispersion, accompanied by water availability, would contribute
399 to the enhanced pozzolanic-reactions, particularly in the long-term. Thus, kneading compaction acts in
400 favour of pozzolanic-reaction, which consequently leads to better development of cementitious compounds.
401 This was confirmed by a relatively greater generation of mesopores of diameter 20-2000 Å as indicated by
402 the enhanced isotherm peak, by the hysteresis developed (Fig. 6), and by the presence of a greater
403 percentage of mesopore volume in the pore range 25-75 Å (Fig. 7). Increased development of cementitious
404 compounds can increase the overall stiffness of the kneaded soil. This explains the relatively greater UCS
405 obtained in all the 4% lime-treated kneaded soil (Fig. 3), in the 2.5% lime-treated 90 days cured kneaded
406 soil, compacted at WMC (Fig. 3d), and in all the lime-treated accelerated cured kneaded soil (Fig. 3e & f).

407 Kneading effect was shown to bring more significant deformation in the natural soil aggregates
408 compared to statically compacted specimens by Mitchell and McConnell [38]. Thus, upon kneading
409 compaction of the lime-treated soil at OMC/WMC, a greater aggregate deformation accompanied by
410 enhanced lime-dispersion occurred in comparison to the one that was statically compacted. Such a
411 phenomenon lowered the availability of macropores of diameter 10^5 Å (Fig. 5a, b & e) and enhanced the
412 mesopores evolutions (Fig. 6 & 7) in the kneaded soil. At the same time, macropores of diameter 10^5 Å
413 increased with lime content in the statically compacted specimens (Fig. 5c, d & f), which was due to the
414 formation of greater inter-aggregate pores at higher lime content, as reported by Tran et al. [75] and Wang
415 et al. [76]. The same specimens after curing and on being subjected to UCS showed failure due to
416 consumption of water for cementitious compounds formation. However, owing to the above-mentioned
417 differences produced in soil structure due to the difference in the effect of compactions, kneaded soil
418 showed a higher ductile failure characteristic during UCS test, as evidenced by the differences in the crack
419 development observed between the lime-treated kneading and statically compacted specimens in Fig. 9.
420 The diagonal and vertical crack developed in the kneaded and statically compacted specimens (Fig. 9a &
421 b) represents the shear and tensile crack, respectively, as reported by Kichou Z [74].

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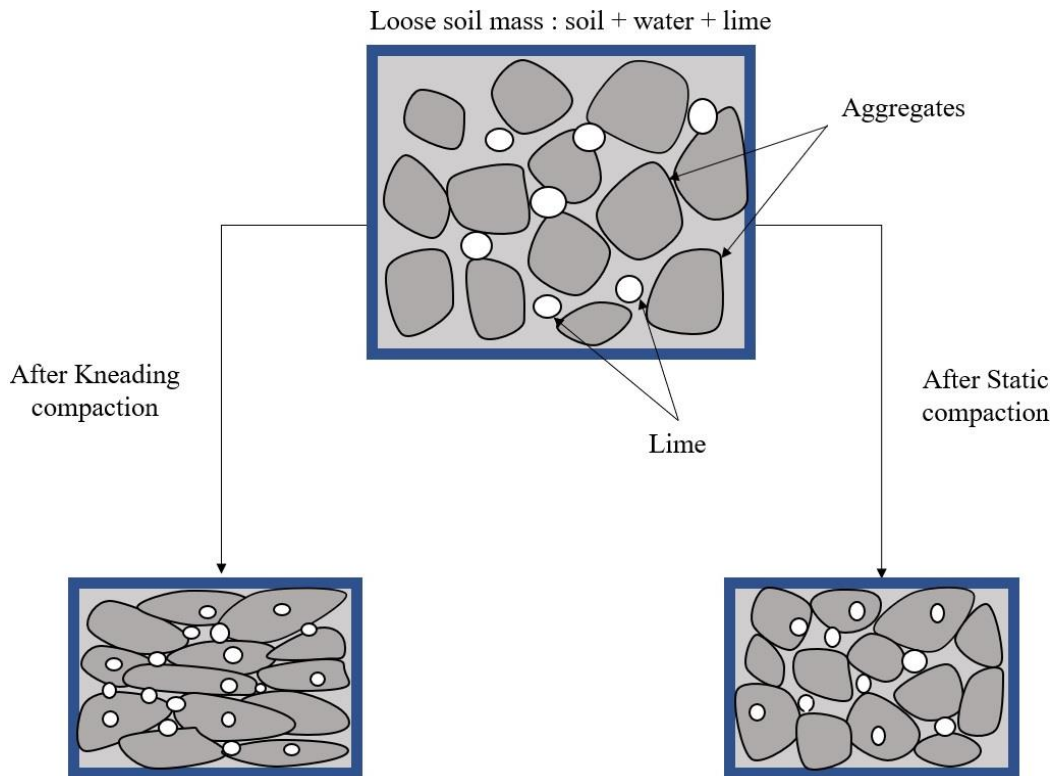
423

424 **Fig. 9.** Diagonal Crack in kneading compacted (a), and vertical crack in statically compacted (b) specimens after UCS test at 1%
 425 lime treatment, compacted at OMC and after 28 days curing

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427 Based on the initial findings, the difference in the effect of compaction on aggregates deformation
 428 and lime-dispersion in specimens subjected to kneading and static compaction is explained through the
 429 schematic diagram presented in Fig. 10.

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Fig. 10. Schematic diagram showing the difference in the effect of kneading and static compaction on aggregates deformation and lime-dispersion

The present 2.5% lime-treated and WMC-compacted silty soil was used in the construction of an embankment using a vibrating padfoot roller that produces kneading action during compaction [14,72]. The process of construction was as per GTS Technical Guide for soil treatment [55]. After 7 years of atmospheric curing, the embankment was deconstructed, and the UCS of four core-sampled embankment's specimens, namely, T1-1 & T2-4 of length (l)/diameter(d) ratio of both 1 and 2 was evaluated, and the average UCS of these specimens was reported to be 3.29 (\pm 0.45) MPa [23]. The obtained in-situ UCS was also shown to be repeatable using the correction factor recommended by ASTM-C42-77 [78]. The average UCS of in-situ extracted samples was shown to be comparable with a 90-day laboratory accelerated-cured specimen of similar configuration and of the dimension of l/d=1. The UCS obtained from in-situ and laboratory accelerated cured specimen that has been reported by Das et al. [23] are compared with the trend of UCS obtained with the present accelerated kneaded soil in Fig. 11 a & b.

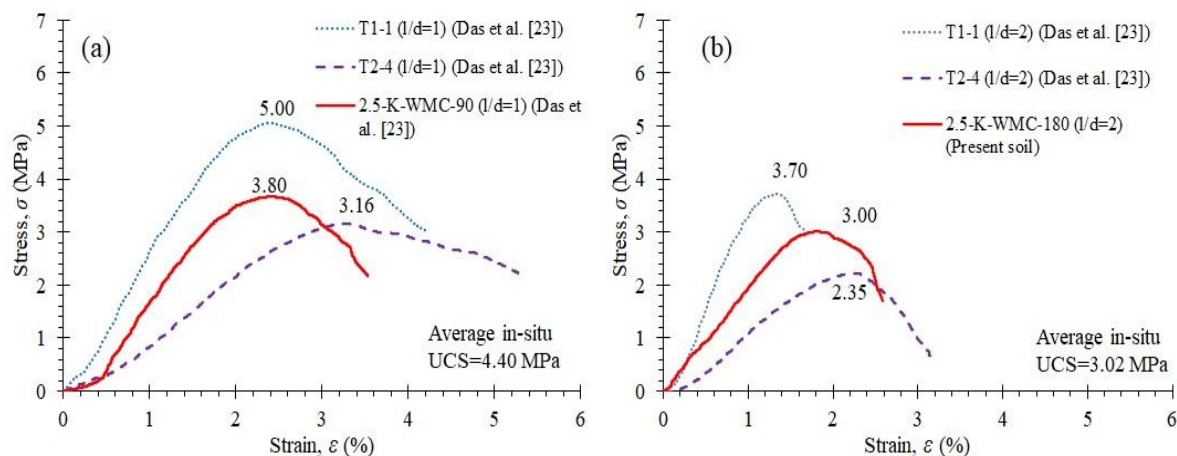
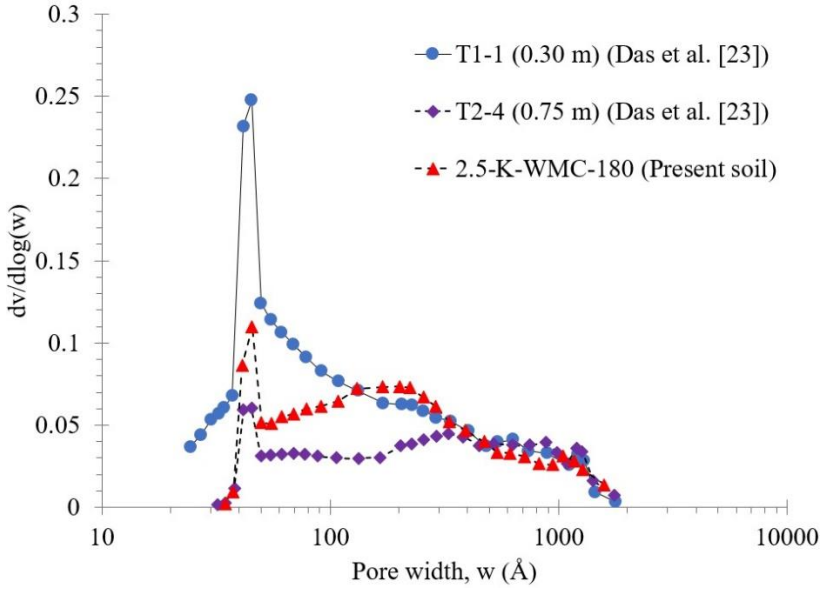


Fig. 11 Comparative evolution of UCS in in-situ core sampled and laboratory-accelerated cured soil of dimension of l/d ratio of 1 (a) and 2 (b).

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Fig. 11a & b presents the comparative trend in UCS evolution in the in-situ and laboratory kneaded specimen of dimension l/d=1 and l/d=2, respectively. The average of the in-situ UCS values, if compared with the UCS of the corresponding 2.5% lime-treated accelerated cured laboratory kneaded soil, was found to be of a similar level for both dimensions. The difference in UCS observed between the laboratory 90- and 180-days accelerated cured kneaded specimens was due to the difference in dimension which is in accordance with ASTM-C42-77 [78]. Besides, Das et al. [23] reported that the difference in UCS of the two in-situ cured core-sampled specimens was linked with the intensities of mesopores evolution by BJH.

458 The mesopore evolution of the present accelerated cured soil was compared with the one obtained from the
459 in-situ cured core sampled kneaded specimens and are presented in Fig. 12.
460



461
462 **Fig. 12.** Comparison of PSD obtained by BJH in 2.5% lime-treated kneaded specimens obtained between laboratory accelerated
463 cured specimen and 7 years in-situ atmospherically cured specimens
464

465 Fig. 12 shows that the present accelerated cured kneaded specimen exhibits intensities of
466 mesopores greater than T2-4 and less than T1-1. Thus, the trend observed in the evolution of mesopores
467 between the accelerated-cured and in-situ cured soil, both kneaded, corresponds well with the level of UCS
468 measured. This confirms the fact that the soil cured under laboratory-accelerated condition and the soil
469 sampled after 7 years of environmental exposure, both submitted to kneading action, exhibit a similar level
470 of UCS. This shows evidence of the relevancy of the accelerated condition in the laboratory to access to
471 the long-term UCS level similar to the sample submitted to field condition.

472 Additionally, Das et al. [23] reported a uniform distribution of pH above 11 and water content
473 throughout the lime-treated embankment after 7 years of atmospheric curing. This evolution was due to the
474 controlled mixing and compaction condition conducted during the construction of the embankment by
475 Makki-Szymkiewicz et al. [14] and Charles et al. [77], which again involves the kneading action due to the
476 use of padfoot rollers. Considering the enhanced dispersive action created by kneading compaction in Fig.
477 8, a uniform evolution of lime and lime components might have resulted throughout the embankment, thus
478 giving all pH values of the sampled specimens above 11 and a homogeneous water content.

479 Fig. 4 & 5 showed that lime treatment has led to the generation of pores lower than the pore
480 diameter of 3000 Å, and such generation was shown to increase soil cohesion and enhance UCS by

481 Verbrugge et al. [70]. However, pores diameter lower than 3000 Å includes a part of macropores, total
 482 mesopores, and micropores as per IUPAC (1994). In the present soil, BJH measured the evolution of pores
 483 under the lime effect in the range 20-2000 Å (Fig. 6), which includes macropores and mesopores, and the
 484 cumulative pore volume in the range 25-250 Å that includes only mesopores (Fig. 7). Hence, to identify the
 485 contribution of different classes of pores to the UCS evolution, a regression equation was developed.

486 The proposed equation (Equation 4) considers compacted specimens cured at 20°C. The input data
 487 of the proposed equation involves the isotherm peak which indicates the total volume of nitrogen injected
 488 in pores of diameter 20-2000 Å, and the cumulative pore volume measured in the mesopore range 25-250
 489 Å. The input data is provided in Table 5.

490
 491
$$\text{UCS} = -0.034 + 0.015 \times (\text{pores of diameter 20-2000 Å}) + 27.7 \times (\text{mesopores of diameter 25-250 Å}) \quad (4)$$

492
 493
 494 **Table 5**
 495 Isotherm peak and cumulative pore volume measured in lime-treated soil
 496

Samples name	Isotherm peak (cm ³ /g)	¹ V _{cum} in pore range (25-250 Å) (cm ³ /g)	UCS (MPa)	Samples name	Isotherm peak (cm ³ /g)	V _{cum} in pore range (25-250 Å) (cm ³ /g)	UCS (MPa)
1-K-OMC-28	27.3	0.008	0.60	1-S-OMC-28	26.0	0.011	0.70
2.5-K-OMC-28	37.6	0.015	0.86	2.5-S-OMC-28	29.3	0.013	0.86
4-K-OMC-28	39.3	0.018	1.00	4-S-OMC-28	31.3	0.014	0.90
1-K-WMC-28	26.6	0.010	0.60	1-S-WMC-28	27.0	0.010	0.64
2.5-K-WMC-28	32.2	0.012	0.68	2.5-S-WMC-28	32.0	0.012	0.77
4-K-WMC-28	38.9	0.014	0.96	4-S-WMC-28	34.4	0.012	0.87
1-K-OMC-90	31.4	0.011	0.75	1-S-OMC-90	28.8	0.010	0.77
2.5-K-OMC-90	39.3	0.015	0.98	2.5-S-OMC-90	42.5	0.016	1.00
4-K-OMC-90	46.8	0.020	1.23	4-S-OMC-90	43.0	0.019	1.00
1-K-WMC-90	29.0	0.009	0.60	1-S-WMC-90	28.8	0.011	0.72
2.5-K-WMC-90	41.4	0.017	1.03	2.5-S-WMC-90	39.3	0.016	0.91
4-K-WMC-90	47.7	0.020	1.43	4-S-WMC-90	43.8	0.018	1.23

497 ¹V_{cum}: Cumulative pore volume

498
 499 Equation (4) demonstrates accurately (R²= 0.90) that the mesopore range 25-250 Å makes the maximum
 500 contribution to the rise in UCS in the range of pores lower than 2000 Å developed under the lime effect.

501 This indicates how lime treatment brings greater development of mesopores due to the cementitious
502 bonding formed because of pozzolanic-reactions and how this contributes towards the strength evolution.

503

504

505 **5. Conclusions**

506

507 The effect of the kneading mechanism on the UCS evolution and microstructural properties of lime-
508 treated silty soil was investigated. Based on the studies, the following findings are derived:

509 1. Lime-treated kneaded soil, particularly compacted at WMC, prepared at lime content higher than LMO
510 and subjected to longer and accelerated curing, showed enhanced evolution of UCS. With appropriate
511 availability of water in the soil matrix, a steady consumption of water by quicklime was regulated for the
512 formation of cementitious bonding with increased curing time and under accelerated conditions.

513 2. The kneading action caused relatively greater deformation of large aggregates and decreased the
514 macropores of diameter 10^5 \AA , compared to the corresponding statically compacted soil.

515 3. Kneading compaction enhanced better dispersion of lime during compaction. When accompanied by the
516 available water, such configuration works in favour of long-term pozzolanic-reactions. This resulted in up
517 to about 50% greater UCS in the kneaded soil than the statically compacted soil prepared at lime content
518 greater than LMO, compacted at WMC, and subjected to longer and accelerated curing.

519 4. The UCS obtained from the laboratory accelerated kneaded soil was of a similar level as the average
520 UCS obtained from in-situ specimens sampled from the 7-year atmospherically cured embankment. The
521 mesopores generation showed a positive trend with respect to the evolution of UCS between the laboratory-
522 accelerated cured, and in-situ cured sampled soil.

523 5. Increased lime content and curing time resulted in increased isotherm peak, which indicated the greater
524 generation of pores in the range of pore diameter 20-2000 \AA . Among the pore ranges produced under the
525 lime effect, the contribution of mesopores in the pore range 25-250 \AA towards the evolution of UCS was
526 shown to be most significant, as highlighted by a regression equation relating UCS with pore size.

527 Thus, the above findings are part of a holistic investigation into the mechanical behaviour and
528 microstructural modification of lime-treated silty soil subjected to kneading action. The kneading action
529 caused compressive strength gain, particularly in the long-term and for WMC-compacted soil. These results
530 were evidenced by UCS and microstructure evaluated from 7 years in-situ cured core-sampled soil. Further

531 studies are required to be conducted to understand the hydraulic characteristics of lime-treated soil
532 subjected to the kneading effect.

533

534

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536

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541

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