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# Evaluation of the long-term effect of lime treatment on a silty soil embankment after seven years of atmospheric exposure: Mechanical, physicochemical, and microstructural studies

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1 Evaluation of the long-term effect of lime treatment on a silty soil embankment after  
2 seven years of atmospheric exposure: mechanical, physicochemical, and microstructural  
3 studies  
4

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13

14 **Abstract**  
15

16 The long-term effect of lime treatment was evaluated on a 2.5 % lime-treated experimental  
17 embankment after seven years of atmospheric exposure. The evaluation was done by comparison of (i) the  
18 mechanical performance of the field sampled specimens with laboratory cured specimens, and (ii) the  
19 physicochemical and microstructural properties of the samples from the lime-treated embankment with  
20 specimens obtained from an untreated embankment constructed near to it as a reference embankment.

21 An average Unconfined Compressive Strength (UCS) level of 3.29 MPa was measured in the  
22 lime-treated specimens sampled from the core of the embankment. This UCS level was found to be  
23 comparable to the UCS of accelerated-cured specimens obtained at a laboratory scale. Thus, such levels of  
24 UCS can be expected after long-term in-situ curing. Scanning electron microscope images evidenced the  
25 contribution of the formation of cementitious bonding towards such UCS evolution in the lime-treated  
26 specimen. The persistence of the lime effect within the core of the embankment was confirmed by the  
27 presence of a pH greater than 11. However, a relative decrease in the pH and water content was observed  
28 in the upper layer compared to the core of the lime-treated embankment. This indicates that the effect of  
29 lime was lost in the upper layer under constant soil-atmosphere interaction and due to the development of  
30 vegetation roots. Pore structure observations made by Mercury Intrusion Porosimetry (MIP) and Barrett-  
31 Joiner-Halendapore (BJH) methods highlight the formation of smaller pores (diameter < 3000 Å) under  
32 lime effect. These smaller pores have contributed towards the evolution of suction in the core-sampled  
33 specimens of the lime-treated embankment. This has led to the long-term water retention capacity of the  
34 lime-treated soil. BJH was able to detect mesopore-formation (25-500 Å) under the lime effect in a more  
35 precise manner compared to MIP. The evolution of mesopores was found to be coincident with the  
36 development of strength and specific surface area of the lime-treated soil.

37

38 *Keywords: lime treatment; compressive strength; embankment; mesopores; atmospheric exposure.*

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## 1. Introduction

Management of natural resources is a critical challenge in any land development project, especially for projects related to earthworks. A cost-effective way to conserve natural resources is to use soil located directly in the land reserved for the project. This makes it essential to improve the engineering properties of the available soil. In this regard, soil improvement by lime is known to be an efficient and economical technique that leads to improved bearing capacity, strength, modulus, etc. (Al-Mukhtar et al., 2012; Bell, 1996; Diamond and Kinter, 1965; Little, 1995; Osula, 1996). Additionally, the lime-treated soil structure is also known to be eco-friendly as the material can be entirely reused after the deconstruction of the structure (Hopkins et al., 2007).

Most studies conducted on soil improvement by lime treatment were obtained from laboratory test results (Ali and Mohamed, 2019; Lemaire et al., 2013; Verbrugge et al., 2011) while the feedback from field performance is less investigated. It is worth noting that the conditions faced by the lime-treated soil under the laboratory- and field-testing environments are relatively different.

Several studies have reported long-term strength improvement in pavement layers stabilized with lime (Aufmuth, 1970; Cardoso and das Neves, 2012; Little, 1995; McDonald, 1969). Aufmuth (1970) concluded that the in-situ California Bearing Ratio (CBR) value observed in lime stabilized pavement layers significantly rises with age and tends to appear permanent if compared to the CBR value of the same soil without stabilization. McDonald (1969) confirmed the effectiveness of lime treatment through a study made on pavements subjected to low, medium, and heavy traffics flow after about 13 years from construction. This was in terms of improved smoothness or rideability and better structural response as indicated by deflection measurements. Cardoso and Neves (2012) demonstrated the effectiveness of lime in reducing the overall settlement rate of an embankment built with marls. They showed how lime treatment induced a decrease in the secondary consolidation of the marls with increased curing, reduced the swelling potential, and increased its stiffness.

So far, few studies have reported the behaviour of lime-treated specimens sampled from real or experimental earth structures submitted to long-term environmental exposure. Rosone et al. (2018) studied the effect of seasonal wetting and drying cycles for over 18 months on specimens obtained from lime-treated expansive clay soil embankment. The suction value measured at the top layer of the embankment was reported to be three times higher than that measured at 0.45 m depth from the surface. Below 0.45 m, the total suction value stabilized at about 1.40 MPa. The high value of suction measured on the top of the embankment was attributed to evapotranspiration, leading to water loss, a rise of suction, and crack development.

Bicalho et al. (2018) described a similar observation with respect to the rise in suction and water content loss in specimens sampled up to a depth of 0.75 m from the surface of a 2 % lime-treated silty clay experimental embankment due to climatic variation. However, with increased curing time, this impact of seasonal variation in the variability of water content and soil suction was minimised, thus indicating the good stability of the lime-treated soil.

The Friant-Kern Canal construction in California, United States, was based on 4 % quicklime by weight to stabilize a highly plastic clay soil in permanent contact with water (Herrier et al., 2012; Knodel, 1987). More than 40 years after construction, the study evidenced the increased long-term strength, reduction in swelling and shrinkage potential, as well as significant resistance to erosion, thus showing the improved geo-mechanical stability of the structure (Akula et al., 2020).

All these studies have demonstrated the effectiveness of lime treatment over time and, to an extent, the effect of the soil atmosphere interaction on the modification of properties of lime-treated soil. Beyond the general behaviour mentioned herein, more investigation is needed with respect to strength and microstructural modifications induced by long-term lime treatment on structures cured in the open atmosphere.

The purpose of this study was to thoroughly evaluate the influence of lime treatment in an atmospherically cured lime-treated embankment after seven years of exposure to wet environmental

91 conditions. The climatic condition of the construction region can be referred to in Makki-Szymkiewicz et  
92 al. (2015), who investigated the embankment at an early age (up to 1 year from construction) to assess its  
93 hydraulic performance. They demonstrated that if proper mixing and compaction process is maintained  
94 during construction, a permeability of  $10^{-9}$  m/s can be obtained, which was similar to the untreated soil.  
95 The present study demonstrates an extended investigation regarding the effectiveness of lime treatment in  
96 the long-term. The examination of the lime-treated structure was made in terms of strength,  
97 physicochemical characteristics, and microstructure, which was lacking in the studies reported above.

98 The first part of the study focuses on (i) evaluating the UCS of the lime-treated soil, (ii)  
99 examining the presence of cementitious bonding within the fabric of the lime-treated soil, and (iii)  
100 investigating the long-term effect of lime treatment on water content, suction, and pH. The second part  
101 presents the effect of lime treatment on pore structure and specific surface area modifications.  
102

## 103 **2. Studied embankment, samples, and methods**

### 104 *2.1. Materials and implementation of the embankment*

106 The soil used is a silty soil from Marche-Les-Dames (MLD), Belgium, with the following  
107 mineralogy: Illite, Kaolinite, and Chlorite as clay minerals along with Quartz and Feldspars. All  
108 information about the embankment construction can be obtained from Makki-Szymkiewicz et al. (2015).

109 The lime-treated embankment was built with 2.5 % of quicklime (CaO), a Proviacal ® DD CL 90-  
110 Q supplied by Lhoist. For reference purposes, an untreated embankment was constructed under the same  
111 conditions. The maximum dry densities,  $\rho_{d\ max}$  of the untreated and 2.5 % lime-treated soil obtained by  
112 Standard Proctor test (as per ASTM D698-12e2) were  $18.2\ \text{kN/m}^3$  and  $17.3\ \text{kN/m}^3$ , respectively, and the  
113 Optimum Moisture Contents (OMCs) were 14.6 % and 17.8 %, respectively. Both embankments were  
114 compacted by a vibratory sheep foot roller at a moisture content of about 1.1 times of optimum. The lime-  
115 treated and the untreated embankment were compacted in 6 and 3 layers, respectively. The average water  
116 content recorded after completion of compaction of the untreated and the lime-treated embankment was  
117 17.0 % and 19.4 %, respectively.  
118

### 119 *2.2. Specimens sampling from the embankment and sample preparation for laboratory test*

121 During deconstruction, at first, few specimens were gathered at different depths from the surface  
122 up to a depth of 0.12 m (i.e., in the regions close to the surface) to understand the impact of seasonal  
123 variation and vegetation roots in the lime-treated embankment. Then the soil near the surface was  
124 removed to limit the effect of weathering and plant roots. Later, trenches were excavated (Fig. 1) for  
125 sampling soil specimens at different depths throughout the core of the embankment.

126 A single trench was made on the untreated embankment (Fig. 2). Four trenches were excavated  
127 across the lime-treated embankment: T1 and T2 located towards the South-West, and T3 and T4 were  
128 located towards the North-East (Fig. 3). Specimens were collected throughout the trenches described in  
129 Fig. 2 and Fig. 3 for the untreated and lime-treated embankments, respectively.  
130



**Fig. 1:** Trench excavated in the lime-treated embankment (T2) for the sampling of specimens

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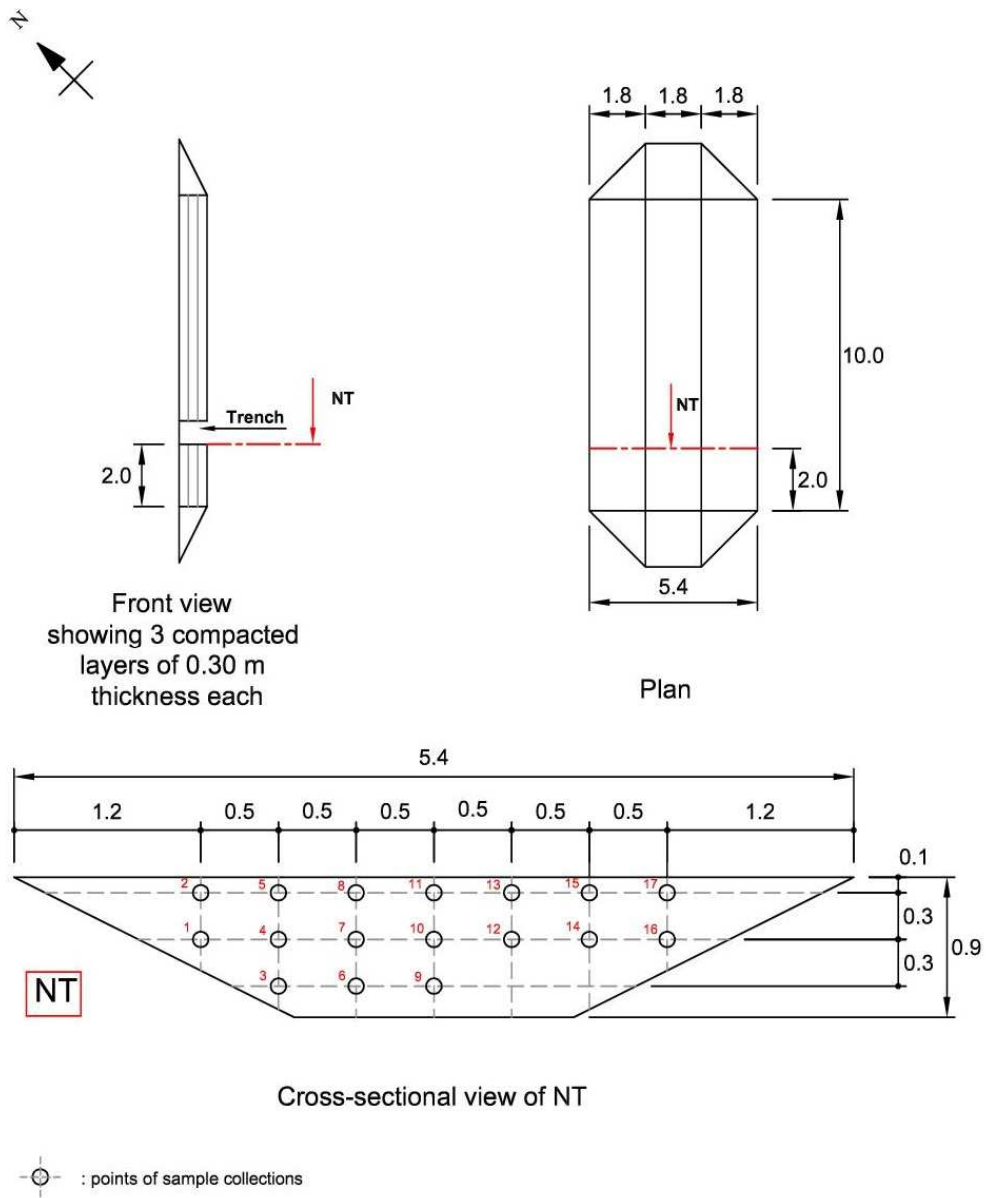
135 The following nomenclature is used here to identify the various specimens. The specimens  
136 collected from the trench excavated in the untreated embankment are referred to as 'Nat', followed by the  
137 number displayed in the cross-section (Fig. 2). Similarly, specimens collected from the trench of the lime-  
138 treated embankment are referred to as 'T1', 'T2', 'T3', and 'T4', followed by the number in the  
139 corresponding cross-section (Fig. 3).

140 The trenching of the untreated embankment was relatively easy to perform, as the compacted soil  
141 was damp and less cohesive. However, block-cutting was not possible due to the low cohesion of the soil.

142 In the lime-treated embankment, two types of sampling were carried out. A compacted cubic  
143 block of about 0.40 m<sup>3</sup> volume was cut from trenches using an excavator. It is worth noting that the  
144 process of block sampling was particularly complicated due to the rigidity of the soil. The second type of  
145 sampling consists of recovering smaller samples taken from each point of sample collection of the four  
146 trenches (Fig. 3). All specimens sampled were packed in a sealed bag and transported to the laboratory  
147 with care.

148 For strength measurement, two compacted cubic blocks were sampled from point T1-1 and T2-4,  
149 located at a depth of 0.30 m and 0.75 m normal to the slope, respectively (Fig. 3). These blocks were later  
150 trimmed at the laboratory to obtain specimens having dimensions of length (l) and diameter (d) with an l/d  
151 ratio of 2 and 1. The 'l' and 'd' of specimens corresponding to l/d ratio of 2 were 0.08 m and 0.04 m,  
152 respectively, and while it was 0.05 m for both 'l' and 'd' for specimens corresponding to l/d ratio of 1.  
153 Samples of dimension l/d = 2 were obtained as ASTM D 2166 (ASTM, 2006) recommends the standard  
154 size of specimens to be within l/d ratio of 2 and 2.5 for the UCS test. Additional samples of l/d = 1 were  
155 trimmed.

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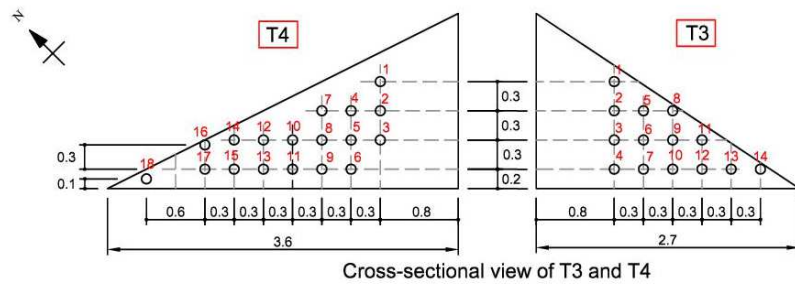
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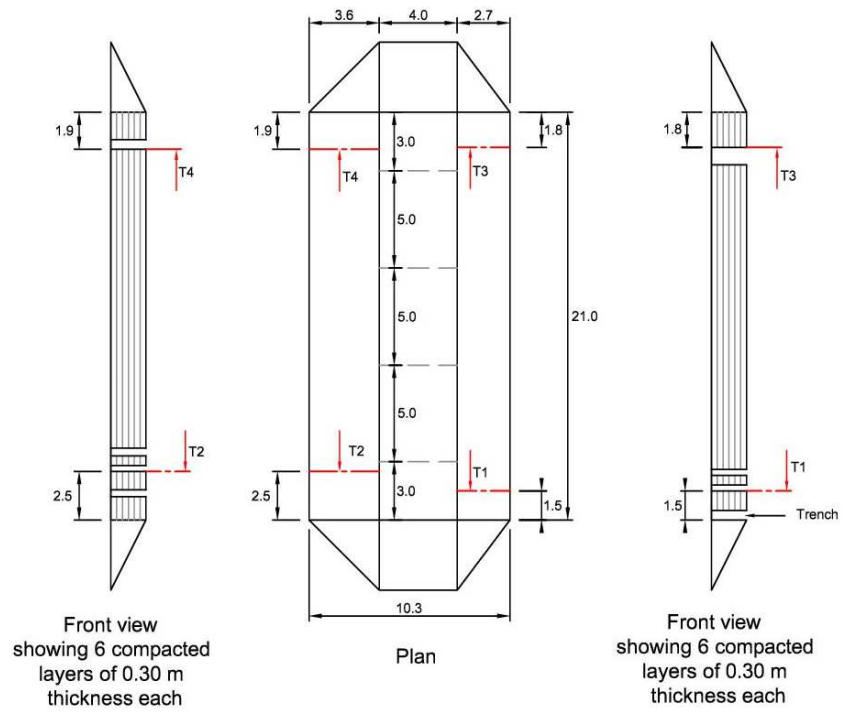
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**Fig. 2:** Plan view, Front view along with Cross-sectional view of the excavated trench made for sample collections from the Untreated embankment (All units in meter)



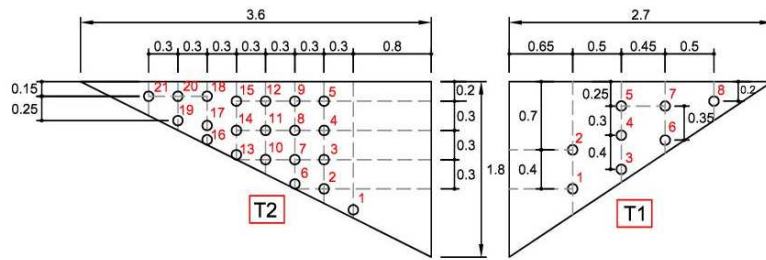
Cross-sectional view of T3 and T4



Front view showing 6 compacted layers of 0.30 m thickness each

Plan

Front view showing 6 compacted layers of 0.30 m thickness each



Cross-sectional view of T1 and T2

: points of sample collections

**Fig. 3:** Plan view, Front view along with Cross-sectional view of the excavated trenches made for sample collections from the lime-treated embankment (*All units in meter*)

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168 2.3. Laboratory tests

169 The UCS of the samples was measured using a mechanical press with a load sensor of 25 kN  
170 capacity. Measurements were performed at a constant deformation rate of 1 mm/min.

171 The soil fabric was assessed using a Scanning Electron Microscope (SEM) observation. The high-  
172 field emission Hitachi SU5000 SEM device was used for this purpose.

173 The physicochemical behaviour was investigated by measuring the water content, suction, and pH  
174 of the collected samples. Specimens sampled throughout the core of the trenches (Figs. 2 & 3) were  
175 subjected to all three tests. At the same time, the upper-layer-sampled specimens were subjected to water  
176 content and pH measurements. The water content measurement was carried out by oven drying at 105°C  
177 (ASTM, 2010), and the suction measurements were conducted using the WP4C Dewpoint Potentiometer  
178 (Decagon device). The pH measurement was executed by HI 2210 pH Meter. Samples collected were  
179 sieved through a 2 mm mesh size and then suspended in distilled water in a liquid-solid ratio of 5:1  
180 (volume fraction) for 1 hour. The pH of the suspended solution was then recorded.

181 The Specific Surface Area (SSA) of compacted freeze-dried samples were analysed by Brunauer–  
182 Emmett–Teller (BET) (Brunauer et al., 1938) test using Micromeritics TriStar II PLUS. Since SSA values  
183 were measured in compacted specimens, hence the measured values can be possibly lower than those of  
184 powdered samples under similar conditions.

185 Pore characterization was done on compacted freeze-dried samples using MIP test and BJH  
186 method. MIP test was conducted using Micromeritics Auto Pore IV, while the BJH method analysed the  
187 pore structure from the data obtained by the BET test. The observed pore structure was classified based on  
188 the International Union of Pure and Applied Chemistry (IUPAC) (Rouquerol et al., 1994), which  
189 categorizes the pore-width as macropores ( $> 500 \text{ \AA}$ ), mesopores ( $20\text{-}500 \text{ \AA}$ ), and micropores ( $< 20 \text{ \AA}$ ).  
190 Lime treatment was shown to generate the development of smaller pores of diameter less than  $3000 \text{ \AA}$   
191 (Bhuvaneshwari et al., 2014; Cuisinier et al., 2011). This smaller pore includes a part of the macropores  
192 range and the total range of mesopores and micropores as per IUPAC classification. Thus, to obtain a  
193 more accurate description of the size of pore evolution, this study uses both the MIP test and the BJH  
194 method. In this study, the analysis of Pore Size Distribution (PSD) by BJH was made considering the  
195 desorption branch of the isotherm because the formation of the cylindrical meniscus is assumed to be  
196 stable in the desorption branch as reported by Bin et al. (2007) and Cai and Hu, (2019). The contribution  
197 of lime treatment on pore structure modification was investigated by a comparative analysis of pore  
198 characterizations made on four selected samples. These specimens were collected at two constant depths  
199 to avoid any possible additional stress impact: untreated specimens Nat 1, Nat 2, and lime-treated  
200 specimens T2-2, T2-3. Specimens Nat 1 and T2-2 were sampled at 0.15 m depth, whereas Nat 2 and T2-3  
201 are located at 0.45 m depth, normal to the slope (Figs. 2 & 3).

202 The distribution of moisture content, pH, and SSA of the specimens sampled from the core of the  
203 embankments are presented using contour plots obtained by using the mapping software: Surfer 13.

204 Table 1 summarizes the complete testing programs with the corresponding identifications and  
205 numbers of specimens.

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**Table 1:**  
Test programs with samples identifications and numbers

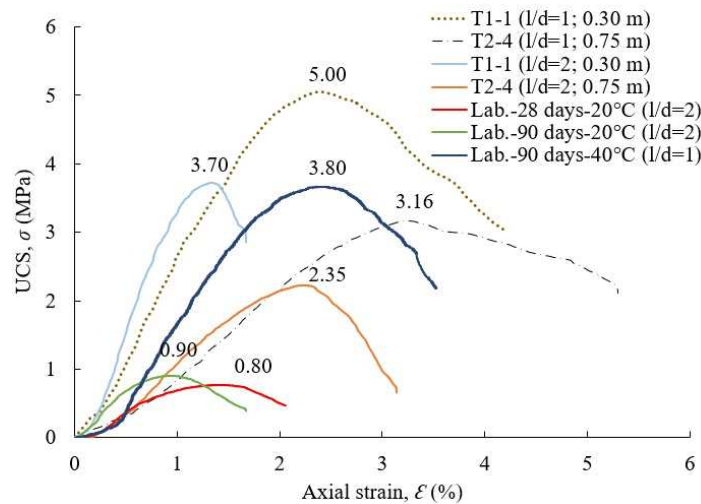
Sample type	Test name	No. of samples	Sample name
Laboratory (Lab.) specimens	UCS	3	Lab.-28days-20°C (l/d=2), Lab.-90days-20°C (l/d=2), Lab.-90days-40°C (l/d=1)
In-situ (upper layer-sampled) specimens	Water content, pH	13 each	T1 and T2
	UCS	4	T1-1 (l/d=2 ; 0.30 m), T2-4 (l/d=2 ; 0.75 m), T1-1 (l/d=1 ; 0.30 m), T2-4 (l/d=1 ; 0.75 m)
	SEM	2	Nat 2 (0.45 m), T1-1 (0.30 m)
	Water content, pH, SSA	78 each	All specimens shown in cross-sections of Fig. 2 & 3
In-situ (core-sampled) specimens	PSD by MIP	4	Nat 1 (0.15 m), Nat 2 (0.45 m), T2-2 (0.15 m), T2-3 (0.45 m)
	PSD by BJH	17	Nat 1 (0.15 m), Nat 2 (0.45 m), T1-1 (0.30 m), T2-2 (0.15 m), T2-3 (0.45 m), T2-4 (0.75 m), T1-2, T1-3, T1-6, T1-7, T2-13, T3-7, T3-9, T3-14, T4-8, T4-11, T4-12

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### 3. Results

#### 3.1. Unconfined Compressive Strength

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**Fig. 4:** UCS measured from the field- and laboratory-cured specimens

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The UCS values of the four trimmed core-sampled specimens from T1-1 (0.30 m) and T2-4 (0.75 m), as mentioned in section 2.2, are presented in Fig. 4. Specimens from T1-1 show UCS values of 3.70 MPa (l/d = 2) and 5.00 MPa (l/d = 1). Specimens from T2-4 show UCS values of 2.35 MPa (l/d = 2) and 3.16 MPa (l/d = 1). The corresponding water content of these specimens during the UCS test was measured to be around 11.0 %.

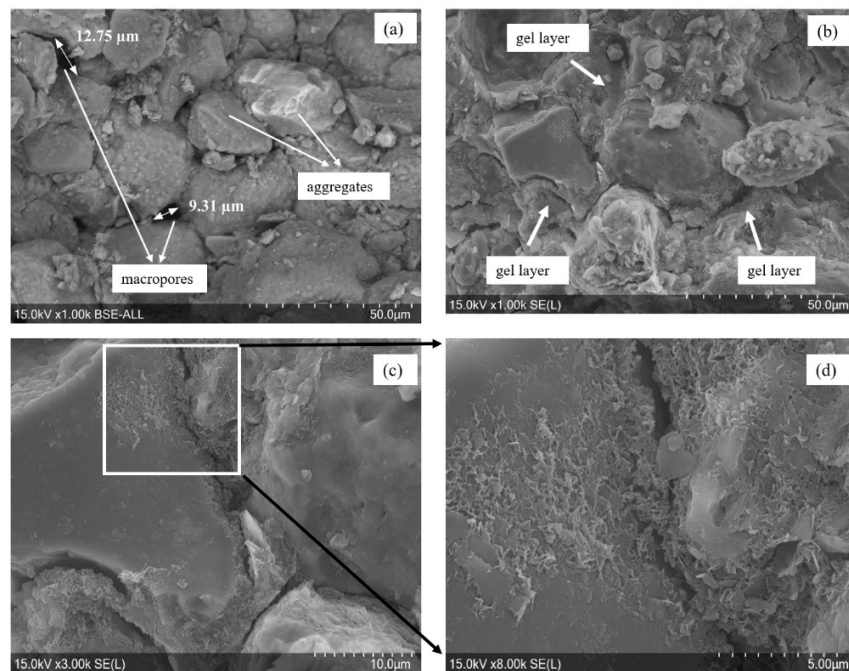
238 The UCS measured in the in-situ specimens was compared with three laboratory-cured samples  
 239 prepared with similar soil and the same lime content and water content as the field specimens. Two  
 240 laboratory compacted specimens of dimension having l/d ratio of 2 were cured for 28- and 90-days at  
 241 20°C. The 28-day curing was considered as a reference short curing period, whereas 90-day was the long  
 242 curing period at a laboratory scale. Since no laboratory study was made with specimens subjected to 7  
 243 years of curing, a third laboratory compacted sample was subjected to accelerated curing (at 40°C) for 90  
 244 days. Lemaire et al. 2013 and Zhang et al. 2020 have demonstrated that the increase in temperature  
 245 accelerates the soil-water-lime chemical reactions resulting in a rapid rise of UCS level in the lime-treated  
 246 soil.

247 Fig. 4 shows that the UCS measured for 28- and 90-days laboratory cured specimens at 20°C (of  
 248 dimension l/d = 2) were 0.80 and 0.90 MPa, respectively. While the UCS measured for the accelerated  
 249 cured specimens (of size l/d = 1) was 3.80 MPa.

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 251 *3.2. SEM observations*  
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253 Fig. 5 presents the SEM images showing the fabric structures of Nat 2 (untreated specimen  
 254 sampled at 0.45 m depth from the slope) and T1-1 (lime-treated specimen sampled at 0.30 m depth from  
 255 the slope) freeze-dried and gold-coated specimens. At a magnification of 1.00k, macropores and  
 256 aggregates were observed in Nat 2 (Fig. 5 (a)), while in T1-1, the aggregates, minerals, and pores were  
 257 found to be covered by a gel layer (Fig. 5 (b)).

258 At higher magnifications (Fig. 5(c & d)), the cementitious bonding was observed between  
 259 minerals and soil aggregates in T1-1, which is as reported in prior literature (di Sante, 2019; Jha and  
 260 Sivapullaiah, 2019; Lemaire et al., 2013).



261  
 262 **Fig. 5:** SEM images of specimens Nat 2 (0.45 m) (a) and T1-1 (0.30 m) (b-d) at different magnifications sampled from the core of  
 263 the embankments

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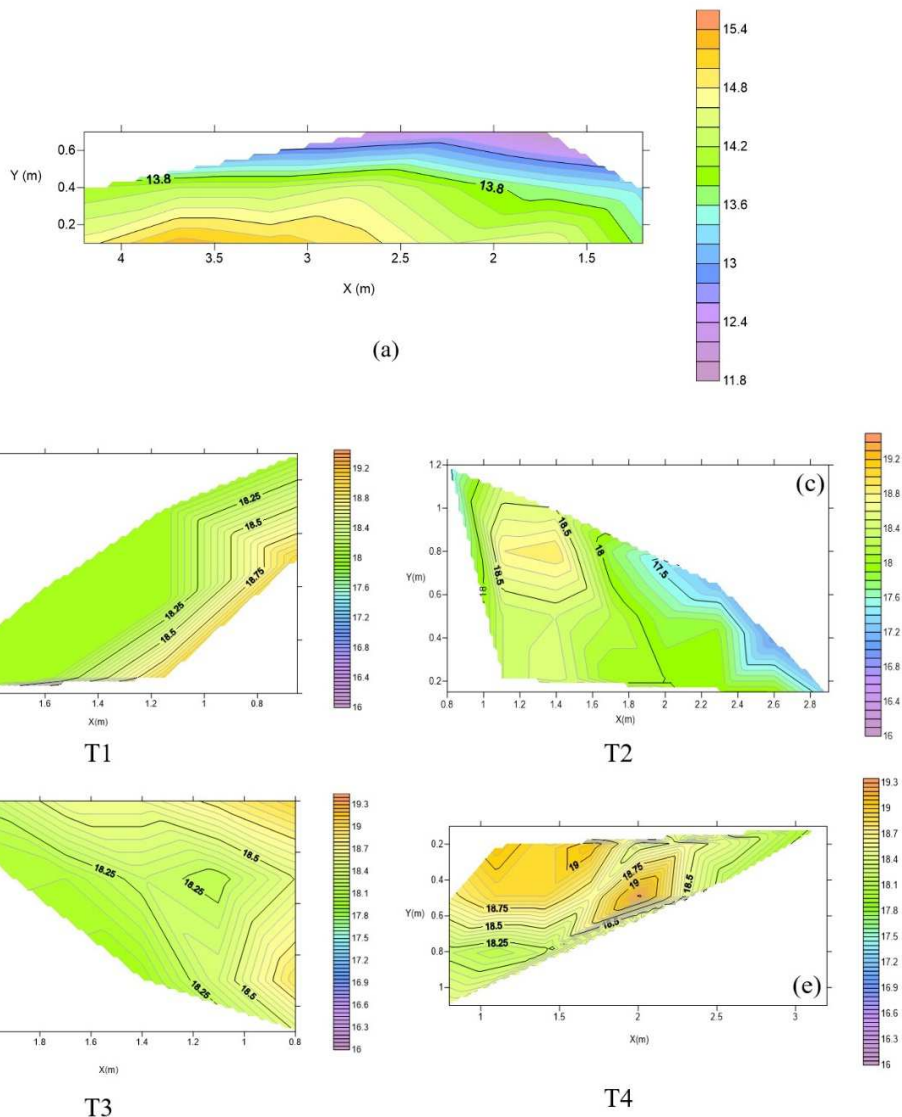
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### 3.3. Physicochemical properties

#### 3.3.1. Distribution of water content

Fig. 6 presents the distribution of water content throughout the core of the untreated and lime-treated embankments measured during deconstruction.

In the core of the untreated embankment, the water content was measured to be minimum at the surface, i.e., 11.8 %, and it gradually increased with depths reaching 15.4 % at the subgrade (Fig. 6(a)). While throughout the core of the lime-treated embankment, the water content measured was observed to be unevenly distributed in the range 17-19.3 % (Fig. 6 (b-e)).

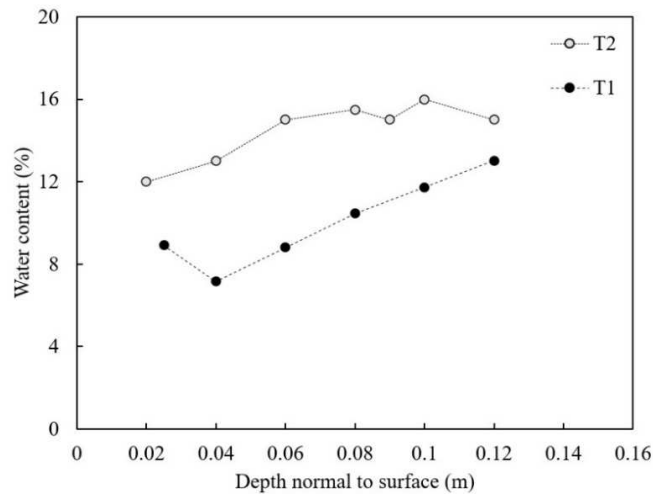


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281 **Fig. 6:** Contour plots showing the distributions of water content (%) in the untreated (a) and the cross-sections T1 (b), T2 (c), T3  
282 (d), and T4 (e) of the lime-treated embankments measured during deconstruction

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**Fig. 7:** Water content (%) measured on specimens sampled from the upper layer of the lime-treated embankment during deconstruction

Fig. 7 presents the water content measured on the upper layer-sampled specimens of the lime-treated embankment from the cross-sections T1 and T2 up to a depth of 0.12 m normal to the surface. The minimum water content observed in T1 was 7.0 %, while it was 12.0 % for T2. The water content then gradually increased with depth from the surface and reached a maximum value of 15 % for T2 and 13 % for T1.

### 3.3.2. Measurement of suction

The suction measured for all the untreated and the lime-treated core-sampled specimens is presented in Table 2. Due to the presence of 78 samples, measurement of suction was done sequentially, one after the other. This led to a slight variation between the water content measured during suction measurement and the one measured during deconstruction, as seen in Table 2. The suction range measured for the untreated specimens was 0.19-1.14 MPa, which corresponds to a water content range of 9.89-11.71 %. While for the lime-treated soil, the suction range measured was 0.17-2.71 MPa, corresponding to a water content range of 15.8-17.9 % (Table 2).

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311

**Table 2:**

Suction measured on untreated and lime-treated core-sampled specimens

Sample	Numbers	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
Untreated	WC (DC) <sup>1</sup> (%)	13.3	13.7	11.9	13.6	14.6	12.4	14.0	14.4	12.2	14.5	14.9	14.2	15.1	14.2	15.3	14.0	14.7					
	WC (SM) <sup>2</sup> (%)	9.89	11.2	9.73	10.8	12.9	9.71	11.9	11.6	9.38	11.7	11.4	12.7	12.6	12.3	12.3	11.5	12.1					
	Suction (MPa)	1.14	0.73	0.60	0.88	0.40	0.80	0.57	0.65	1.01	0.19	0.46	0.21	0.61	0.45	0.66	0.39	0.31					
T1	WC (DC) (%)	18.2	19.0	18.1	18.2	18.7	17.9	18.2	18.2														
	WC (SM) (%)	17.0	18.0	17.0	17.0	18.0	16.3	17.3	17.2														
	Suction (MPa)	1.15	0.80	1.29	0.76	0.72	1.47	0.78	0.71														
T2	WC (DC) (%)	17.4	18.4	18.8	18.3	18.3	18.5	18.9	18.4	18.5	17.8	18.2	18.0	17.4	17.8	18.0	17.2	17.9	18.0	18.0	17.0	17.3	
	WC (SM) (%)	14.1	16.0	15.2	16.2	18.2	16.4	15.2	16.3	17.2	17.0	16.0	15.4	16.4	17.0	17.5	16.8	16.4	16.6	16.3	16.0	16.4	
	Suction (MPa)	1.51	0.86	0.89	0.34	0.40	0.55	0.95	0.83	0.93	0.80	1.29	1.75	1.10	0.83	0.80	1.27	1.29	1.03	1.39	1.61	1.13	
T3	WC (DC) (%)	18.5	18.9	18.5	19.0	18.4	18.2	18.8	18.0	18.3	18.6	18.1	18.6	18.3	18.2								
	WC (SM) (%)	17.9	17.6	17.2	17.7	18.2	18.1	17.9	17.2	17.1	18.2	17.8	17.9	18.2	17.2								
	Suction (MPa)	0.42	0.63	0.51	0.71	0.56	0.41	0.53	0.71	0.68	0.18	0.40	0.17	0.35	0.85								
T4	WC (DC) (%)	18.5	18.2	18.7	18.1	18.9	19.1	18.2	18.9	18.9	18.6	19.1	19.3	18.4	18.5	18.6	18.1	18.4	17.9				
	WC (SM) (%)	17.9	14.5	18.0	17.3	17.6	16.6	16.9	17.1	15.3	16.5	16.6	18.5	14.5	15.8	17.2	16.1	17.5	16.9				
	Suction (MPa)	0.97	0.30	0.50	0.95	0.87	1.14	0.90	1.31	1.40	1.77	1.46	0.70	2.04	2.71	1.03	1.76	0.98	1.63				

312

<sup>1</sup>WC(DC): Water content measured during the deconstruction of embankments

313

<sup>2</sup>WC(SM): Water content measured during the suction measurement

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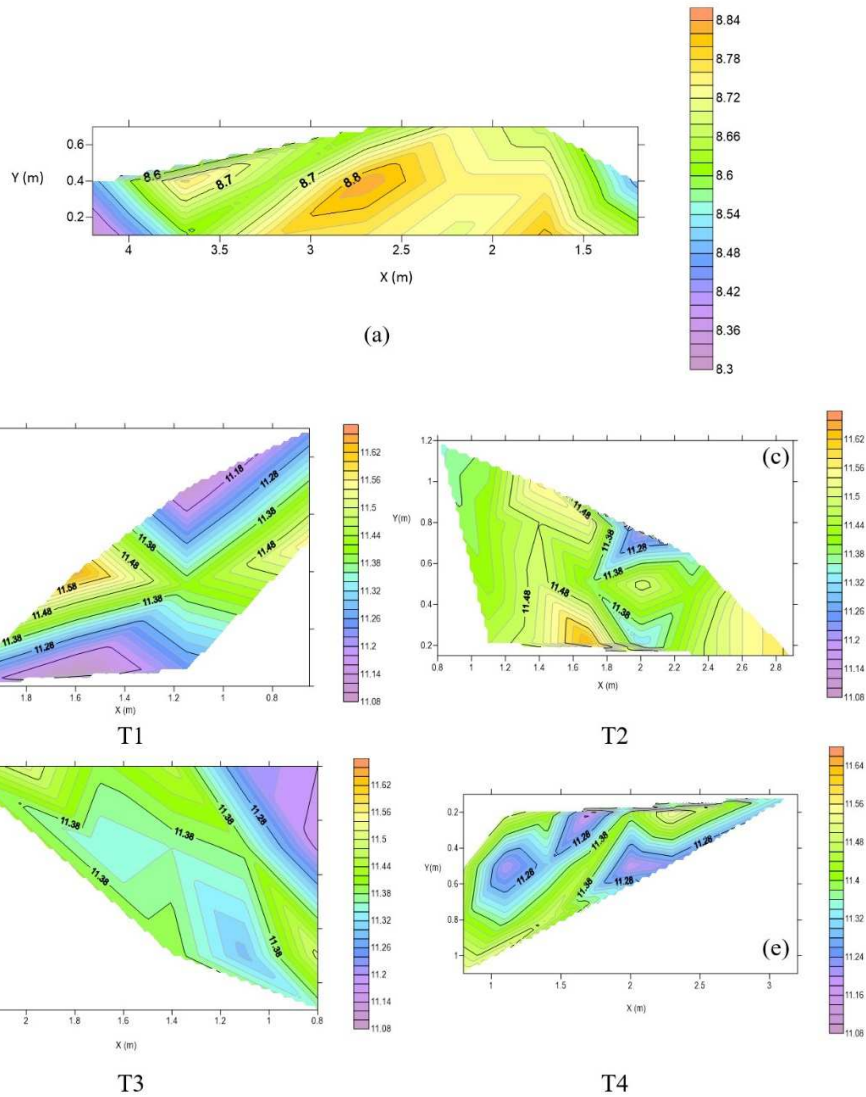
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### 3.3.3. Distribution of pH

Fig. 8 presents the distribution of pH throughout the core of the untreated and the lime-treated embankments measured during deconstruction.

The pH value of the untreated embankment was between 8.3 to 8.8 (Fig. 8 (a)). In the lime-treated embankment, the measured pH value ranges between 11.08 and 11.66 (Fig. 8 (b-e)).



324

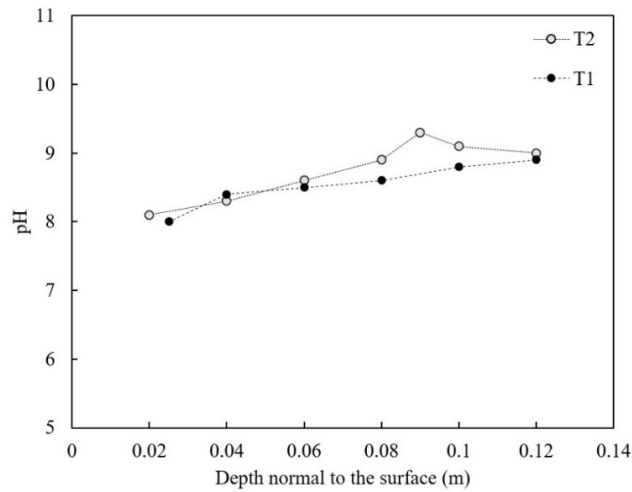
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**Fig. 8:** Contour plot showing the distribution of pH in the untreated (a) and the cross-sections T1 (b), T2 (c), T3 (d), and T4 (e) of the lime-treated embankments measured during deconstruction

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The pH measured from the specimens sampled at the upper layer (up to 0.12 m depth from the surface) of T1 and T2 was observed to be between 8.0 and 9.0 (Fig. 9). The trend of pH distribution in the upper layer of T1 and T2 appears to be almost similar.



331  
332 **Fig. 9:** pH measured on specimens sampled from the upper layer of the lime-treated embankment during deconstruction

333

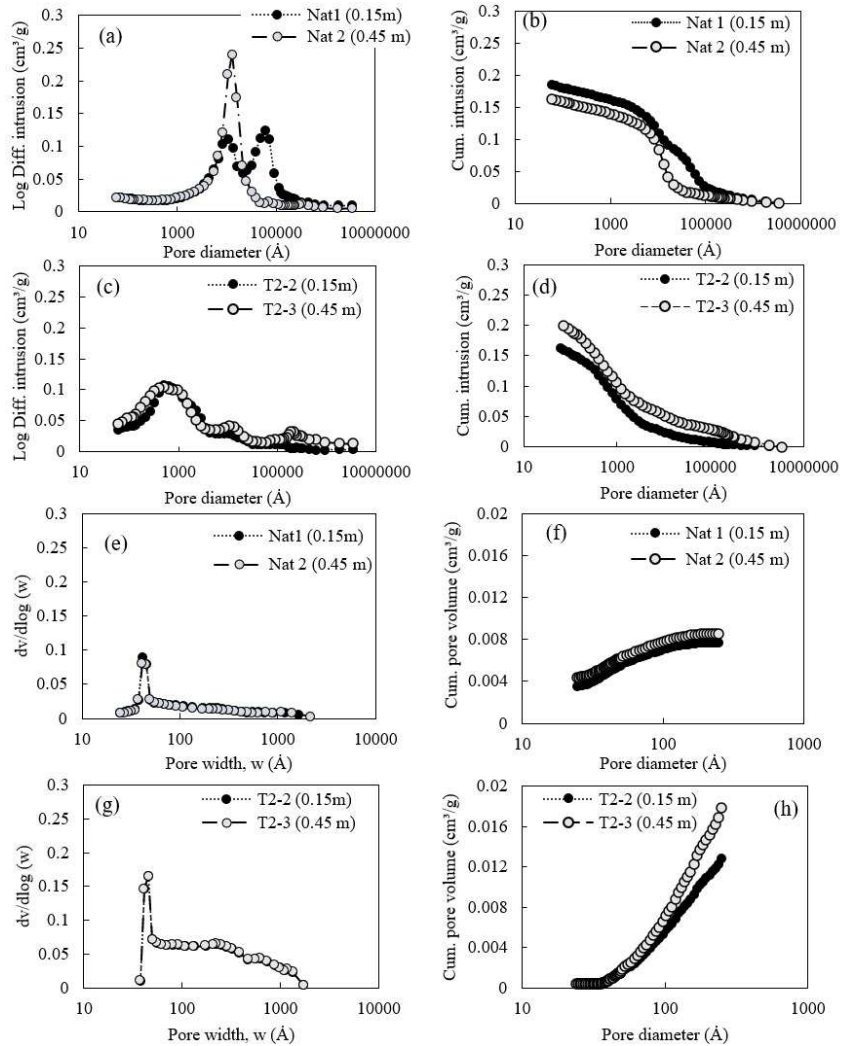
334 *3.4. Pore size distributions*

335 Fig. 10 (a-h) presents the PSD and cumulative pore volume of the untreated (Nat 1 and Nat 2) and  
336 the lime-treated specimens (T2-2 and T2-3) core-sampled at two different depths using MIP test and BJH  
337 method.

338 On investigating the pore structure of the untreated specimens by MIP, Nat 1 (0.15 m), and Nat 2  
339 (0.45 m) a bimodal and unimodal PSD were observed, respectively (Fig. 10 (a)). Nat 1 shows the higher  
340 intensity of macropores diameter of around  $10^4$  and  $10^5$  Å, while Nat 2 shows the same around pore  
341 diameter  $10^4$  Å. The cumulative pore volume measured for Nat 1 was about 19 % higher than Nat 2 (Fig.  
342 10 (b)). On observing the PSD and cumulative pore volume (in the range of pore diameter 20-250 Å) of  
343 the same untreated specimens by BJH, no significant presence of pores was observed in the mesopore  
344 range of pore diameter 50-500 Å (Fig. 10 (e & f)). Moreover, a similar narrow peak was seen at the pore  
345 diameter of 40 Å for both Nat 1 and Nat 2 (Fig. 10 (e)).

346 For the lime-treated specimens, the MIP results of both samples T2-2 (0.15 m) and T2-3 (0.45 m)  
347 show a broad unimodal peak at 625 Å with the development of smaller pores lower than pore diameter of  
348 3000 Å (Fig. 10 (c)). The trend of PSD remains the same for T2-2 and T2-3. However, T2-2 shows 20 %  
349 lower total pore volumes than T2-3 (Fig. 10 (d)). While analysing the pore structure of these specimens  
350 by BJH, the trend of the PSD in the mesopore range of pore diameter 40-500 Å remains the same for both  
351 the lime-treated samples Fig. 10 (g). Both the specimens show a significant presence of mesopores of pore  
352 diameter in the range 50-500 Å. Specimen T2-2 shows a 27 % lower cumulative pore volume in the  
353 mesopore range of pore diameter 20-250 Å than T2-3 (Fig. 10 (h)). Additionally, a similar narrow peak at  
354 the pore diameter of 40 Å was observed for both T2-2 and T2-3 (Fig. 10 (g)).

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**Fig. 10:** PSD and Cumulative (Cum.) pore volume observed between untreated (Nat & Nat 2) and lime-treated specimens (T2-2 & T2-3) at a depth of 0.15 m & 0.45 m normal to the slope by MIP (a-d) & BJH (e-h) methods

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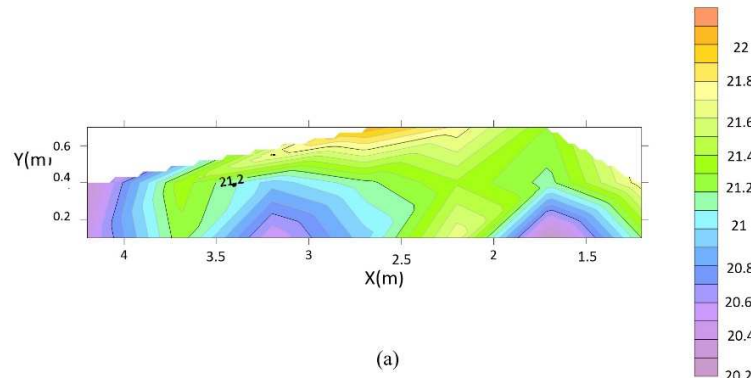
### 3.5. Distribution of SSA

Fig. 11 (a) shows the distribution of SSA throughout the core of the untreated embankment, which remains almost similar.

The SSA measured throughout the core of the lime-treated embankment appears to be unevenly distributed in all the cross-sections presented in Fig. 11 (b-e). The maximum range of SSA measured was between 40 m<sup>2</sup>/g and 45 m<sup>2</sup>/g, which was observed in few specimens sampled from T1 (Fig. 11 (b)), while other specimens show SSA values within 11 m<sup>2</sup>/g and 39 m<sup>2</sup>/g (Fig. 11 (b-e)).

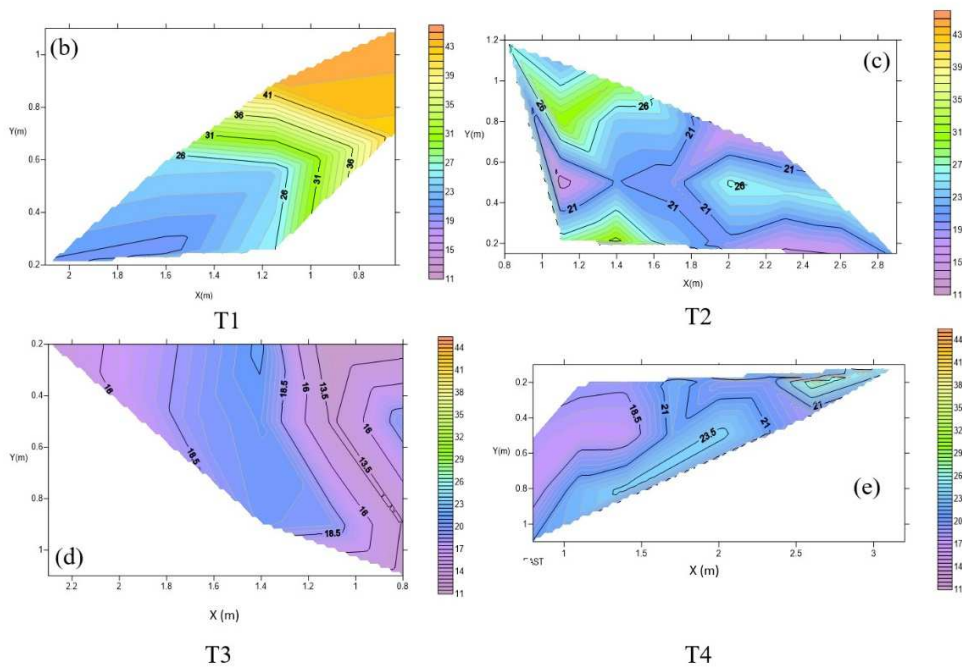
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(a)

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378

379 **Fig. 11:** Contour plot showing the distribution of SSA ( $\text{m}^2/\text{g}$ ) in the untreated (a), and cross-sections T1 (b), T2 (c), T3 (d), and T4  
380 (e) of the lime-treated embankments during deconstruction

381

## 382 4. Discussions

383

### 384 4.1. Evaluation of the UCS measured from the in-situ cured lime-treated specimens

385 Since specimens tested for the UCS had two different  $l/d$  ratios, a comparison between two  
386 samples of different ratios is made by applying a correction factor. According to ASTM-C42-77 (ASTM,  
387 1978), a correction factor of 0.87 should be applied to the UCS measured using specimens with  $l/d = 1$   
388 to obtain the corresponding UCS of a similar sample having  $l/d = 2$ . Thus, corrected UCS values of 4.35  
389 ( $5.00 \times 0.87$ ) and 2.74 ( $3.16 \times 0.87$ ) MPa (Fig. 4) were obtained for T1-1 and T2-4, respectively.  
390 Expectedly, these corrected values are nearly equal to the UCS of specimens (T1-1 & T2-4) having  $l/d = 2$   
391 (Fig. 4). Thus, considering different depths of sampling and different dimensions of the specimens, the  
392 UCS results can be assumed to be repeatable.

393 At the laboratory scale, the UCS measured from the accelerated cured specimen (Fig. 4) was  
 394 corrected to 3.31 ( $3.80 \times 0.87$ ) MPa using the correction factor. The UCS of the in-situ specimens (Fig. 4)  
 395 was observed to be about 2-4 times higher than what was measured after 28- and 90-days laboratory  
 396 curing at 20°C. This highlights the contribution of lime treatment in increasing the UCS of the soil after  
 397 long-term curing.

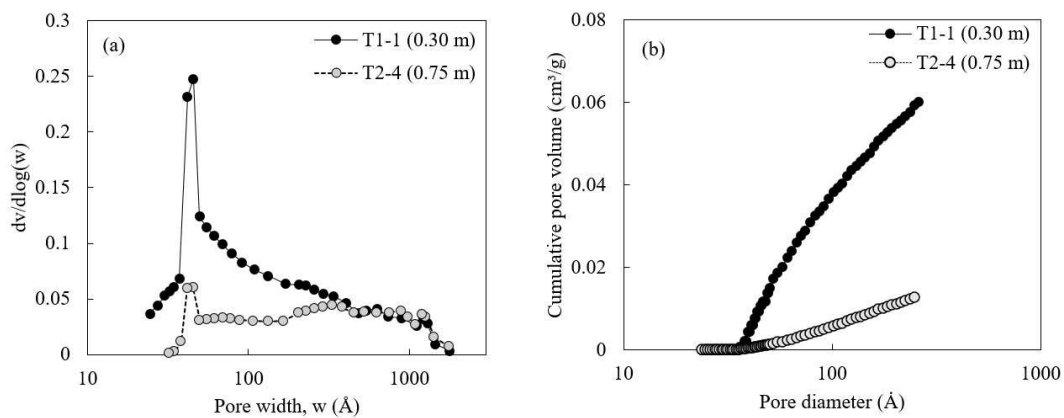
398 The average of the UCS value measured for the four in-situ cured specimens was 3.29 ( $\pm 0.45$ )  
 399 MPa. This average UCS value was found to be of comparable order to the UCS of the laboratory  
 400 accelerated cured specimen of dimension having  $l/d = 2$  (3.31 MPa). This implies that such UCS levels  
 401 can be expected after long-term curing. An inspection of the SEM images (Fig. 5 (b-d)) reveals that such  
 402 evolution of UCS in the in-situ samples can be attributed to the formation of cementitious bonds as a  
 403 result of pozzolanic reactions.

404 Another factor that can influence the in-situ measured UCS is the loss in water content. The water  
 405 content measured in T1-1 and T2-4 during the UCS test was found to be 7 % lower than what was  
 406 measured during the deconstruction period ( $\approx 18\%$ ) (Fig. 6 (b & c)). This loss of water occurred due to the  
 407 complications faced at the time of the trimming of the block-sampled specimens in the laboratory, as  
 408 mentioned in section 2.2. One might argue that this loss of water might have resulted in a higher UCS  
 409 level than expected. However, the evolution of a comparable level of UCS in the laboratory accelerated  
 410 cured specimens, the maintenance of pH greater than 11, and the formation of cementitious bonding  
 411 support the fact that the observed level of UCS was unlikely to have been influenced by the loss of water.  
 412  
 413

#### 414 4.2. Contribution of mesopores generation towards strength evolution in lime-treated soil

415 The UCS of specimens T1-1 and T2-4 differs by 2 MPa (Fig. 4) even after they show similar  
 416 water content during deconstruction ( $\approx 18\%$ ) and UCS test (11 %). Also, the pH measured during  
 417 deconstruction was of the same level (Fig. 8 (b & c)). Thus, it can be derived that the observed difference  
 418 in the UCS is not due to the difference in water content or pH. However, the suction measured for T1-1  
 419 corresponding to a water content of 17 % was 1.15 MPa, while it was 0.34 MPa for T2-4 at a water  
 420 content of 16 % (Table 2). This difference in suction level might be due to differences in microstructural-  
 421 development between T1-1 and T2-4 under the lime effect.

422 Lime treatment generates smaller pores (Cuisinier et al., 2011), which was shown to contribute to  
 423 the rise in cohesion and hence strength (Verbrugge et al., 2011). In this aspect, the difference in smaller  
 424 pores evolution between T1-1 and T2-4 was investigated by BJH method, as BJH method was observed to  
 425 measure ranges of pores relatively lower than the one measured by MIP test in Fig. 10.  
 426



427  
 428 **Fig. 12:** Evolution of mesopores distribution (a) and cumulative pore volume (b) between T1-1 & T2-4 by BJH method

429 Fig. 12 shows the mesopores distribution of T1-1 and T2-4. In Fig. 12 (a), a narrow peak at a pore  
430 diameter of 40 Å was observed, which is five times higher in T1-1 than in T2-4. Moreover, a relatively  
431 large number of mesopores of pore diameter 50-500 Å was found in T1-1 compared to T2-4.  
432 Cumulatively, specimen T1-1 shows about 5.5 times higher presence of pore volume in the mesopores  
433 range of pore diameter 25-250 Å than T2-4 (Fig. 12 (b)).

434 Thus, this higher number of mesopores development in T1-1 has led to the increased suction and  
435 consequently resulted in greater strength in T1-1 than in T2-4.

#### 436 437 438 *4.3. Long-term effect of lime treatment on the water content and pH distribution at the core of the* 439 *embankments*

440  
441 The average water content measured at the end of construction was 17.0 % and 19.4 % in the  
442 untreated and the lime-treated embankment, respectively. Thus, approximately a 5 % loss in water content  
443 was observed from the end of construction up to a depth of about 0.35 m normal to the surface of the  
444 untreated embankment (Fig. 6 (a)). This loss of water gradually decreases with depth. This was expected  
445 in the untreated embankment. The maximum loss of water in the core of the lime-treated embankment was  
446 about 2 % from the end of construction, comparatively lower than the untreated embankment.

447 Additionally, unlike the untreated embankment, the overall distribution of water content does not  
448 vary significantly with depth in the lime-treated embankment (Fig. 6 (b-e)). Most of the core-sampled  
449 specimens from the lime-treated embankment show water content ranging from 18.0 to 19.3 % (Fig. 6 (b-  
450 e)). Thus, this distribution can be said to be homogeneous. This can be attributed to the proper mixing and  
451 compaction process implemented during the construction time, as reported by Makki-Szymkiewicz et al.  
452 (2015). Thus, the presence of this homogeneous water content throughout the embankment and the lesser  
453 reduction in water content from the end of construction than the untreated embankment highlights the  
454 long-term water retention capacity of the lime-treated soil.

455 Lime treatment increases the pH of the natural soil due to the release of OH<sup>-</sup> ions in the soil-water-  
456 lime medium (Little, 1995). On evaluating the pH measured during deconstruction, the average pH  
457 measured in the untreated embankment was 8.5 (Fig. 8 (a)), which was found to be almost equivalent to  
458 the pH value of the present silty soil. However, all the lime-treated soil show pH greater than 11 (Fig. 8  
459 (b-e)) and lower than 12.3, which corresponds to the pH at Lime Modification Optimum (LMO) of the  
460 soil. This decrease in pH can be attributed to the consumption of lime during the curing time, as  
461 demonstrated by De Bel et al. (2013). Besides, the difference measured in the pH level between the  
462 untreated and lime-treated soil evidences the presence of pozzolanic products within the core of the lime-  
463 treated embankment.

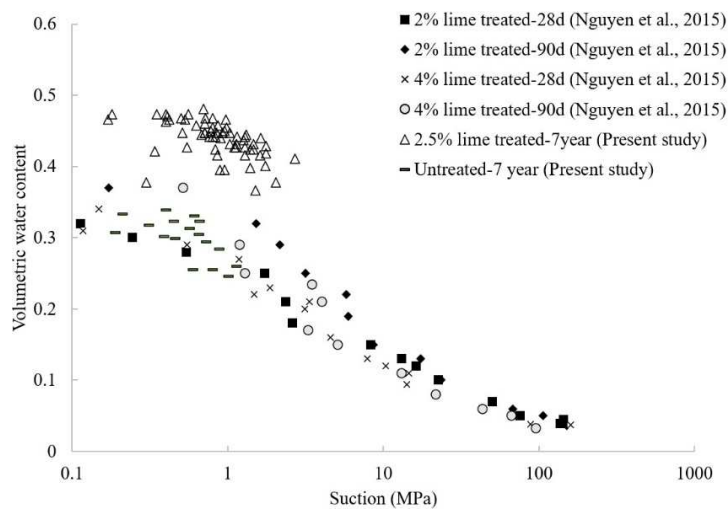
464 Like the homogenous distribution of water content observed throughout the core of the lime-  
465 treated embankment, the pH, too, was found to be uniformly distributed throughout, ranging from 11.08 to  
466 11.66 (Fig. 8 (b-e)). This can also be attributed to proper mixing, as mentioned previously.

#### 467 468 *4.4. Effect of lime treatment on the evolution of suction at the core of the embankments*

469  
470 Within the range of suction measured for the untreated embankment (0.19 MPa-1.14 MPa), a total  
471 variation of around 1.00 MPa in suction corresponds to a 2 % (9.89 %-11.71 %) variation in water content  
472 (Table 2). At the same time, this variation is around 2.50 MPa (0.17 MPa-2.71 MPa) for the lime-treated  
473 soil corresponding to the same percentage difference in the water content (15.80 %-17.90 %). Thus, the  
474 maximum suction measured for the lime-treated soil was about 1.57 MPa higher than the untreated soil,  
475 although the corresponding water content in the lime-treated soil was about two times higher than the  
476 untreated soil. The average minimum suction measured for the untreated specimens approximately  
477 corresponds to the average maximum measured water content and vice versa (Table 2). This behaviour of  
478 suction variation with water content was expected in the untreated specimens. While in the lime-treated  
479 samples, the variation of suction was less affected by the difference in the water content level.

480 Makki-Szymkiewicz et al. (2015) reported a suction level of 0.051MPa to 0.084 MPa at about an  
 481 average water content of 19.4 % in specimens collected up to 1 year from the end of construction in the  
 482 same lime-treated embankment. Thus, the present measured suction range (0.17 MPa-2.71 MPa) in the  
 483 lime-treated specimens increased by about 2 to 30 times with a maximum of 3 % difference in the level of  
 484 water content (15.80-17.90 %) during the additional six years curing period. This can be attributed to the  
 485 modification of the lime-treated soil microstructure illustrated by an additional generation of smaller pores  
 486 (< 3000 Å) (Fig. 10 (c)) in the present specimen compared to the MIP result reported by Makki-  
 487 Szymkiewicz et al. (2015) for the six months in-situ cured specimen.

488 Besides, the present variation of suction with respect to water content (Table 2) was also  
 489 compared with the water retention plot provided by Nguyen et al. (2015) for the same soil and are  
 490 presented in Fig. 13. Nguyen et al. (2015) showed the evolution of suction with respect to volumetric  
 491 water content for 28 days (28d) and 90 days (90d) laboratory cured specimens treated with 2 % and 4 %  
 492 quicklime.  
 493  
 494  
 495



496  
 497 **Fig. 13:** Water retention plot obtained from the present soil compared to the one obtained from Nguyen et al. (2015)

498  
 499 Fig. 13 shows that the volumetric water content corresponding to the suction range of about 0.1 -  
 500 5.0 MPa was slightly higher for 90 days cured specimens compared to the corresponding 28 days cured  
 501 specimens. Similar evolution of volumetric water content was observed in the present untreated soil  
 502 corresponding to the suction range of 0.19-1.14 MPa. However, the volumetric water content in the 7-year  
 503 cured specimens was about 50 % higher compared to all the specimens from Nguyen et al. (2015),  
 504 corresponding to a similar range of suction (0.17-2.71 MPa).

505 Thus, based on the above discussion, it can be concluded that the observed long-term water  
 506 retention capacity of the present lime-treated soil was due to this increased suction because of long-term  
 507 pozzolanic reactions. Literature, based on laboratory studies, has demonstrated how lime treatment  
 508 improves the water retention capacity of soil with the increase in curing time due to the modification of  
 509 soil microstructure resulting from the generation of cementitious compounds (Russo, 2005; Wang et al.,  
 510 2016).

511 Thus, the overall suction variation in the untreated soil follows the variation in the water content  
 512 level inversely. However, in the lime-treated soil, the evolution of suction was due to the development of  
 513 smaller pores as a result of pozzolanic reactions and was less affected by the variation in the water content  
 514 level.  
 515

516 4.5. Effectiveness of lime treatment on the upper layer of the embankment submitted to atmospheric  
517 exposure

518  
519 The minimum water content measured in the upper-layer specimens of T1 and T2 was 7 % and 12  
520 %, respectively (Fig. 7). This was about 12 % and 7 % less than the maximum water content measured in  
521 the core of T1 and T2, respectively (Fig. 6 (b & c)). The increase in loss of water as one moves from the  
522 core towards the upper layer emphasizes the effect of soil-atmosphere interaction. Besides, the  
523 development of vegetation roots (as observed during deconstruction) also contributes towards this water  
524 loss. Bicalho et al. (2018) and Rosone et al. (2018) reported a similar impact of soil-atmosphere  
525 interaction on the upper surface of an in-situ cured lime-treated embankment. They showed a significant  
526 loss of water from the surface to a depth of 0.45-0.75 m of the embankment. Thus, the present study  
527 shows that the influence of soil-atmosphere interaction is significant up to a depth of 0.12 m normal to the  
528 surface of the lime-treated embankment.

529 In addition to the loss of water, a maximum reduction in pH for T1 and T2 was observed to vary  
530 from 11.66 (Fig. 8 (b & c)) in the core to 8 in the upper layer (Fig. 9). This might be a consequence of  
531 carbonation (Xu et al., 2020) or dissolution of lime by leaching (Deneele et al., 2016; Khattab et al., 2007)  
532 under the long-term exposure of soil to the atmosphere. In the upper layer, the average pH for T1 and T2  
533 gradually increases from around 8 near the surface to 9 corresponding to the depth of 0.12 m. This  
534 indicates that the atmospheric effects are minimised with depth.

535 Thus, it can be concluded that although the effect of lime treatment remains within the core of the  
536 lime-treated embankment, it was lost up to a depth of 0.12 m normal to the surface.

537

538 4.6. Evaluation of pore structures measured between the untreated and the lime-treated soil

539 Unlike the MIP results of the untreated soil (Fig. 10 (a)), no significant macropores were found at  
540 a pore diameter of  $10^4$  Å and  $10^5$  Å in the lime-treated specimens (Fig. 10 (c)). Instead, both samples T2-2  
541 and T2-3 show the presence of smaller pores of diameter lower than 3000 Å (Fig. 10 (c)). Such smaller  
542 pores formation due to lime treatment was also reported by Cuisinier et al. (2011). Additionally, in the  
543 lime-treated soil, as per the BJH results, the observed development of mesopores in the range of pore  
544 diameter 50 Å to 500 Å (Fig. 10 (g)) was more significant than that in the untreated soil (Fig. 10 (e)). The  
545 narrow peak developed at the pore width of 40 Å for the lime-treated specimens (Fig. 10 (g)) was about  
546 1.8 times higher than what was observed in the untreated samples (Fig. 10 (e)). In the untreated  
547 specimens, this observed peak can be due to the presence of clay porosity (Bin et al., 2007; De Bel et al.,  
548 2013). The increase in this peak for the lime-treated samples might be due to the combined presence of  
549 clay porosity and cementitious bonding because of pozzolanic reactions.

550 The overall development of smaller pores in the lime-treated soil is attributed to the development  
551 of pozzolanic products (C-S-H, C-A-S-H, C-A-H, etc.), and not due to carbonation, as both T2-2 and T2-3  
552 exhibit pH greater than 11 (Fig. 8 (c)), while carbonation reactions lead to a decrease in pH below 9 (Xu et  
553 al., 2020). Besides, the observed increase in smaller pores in the present 7-year cured specimens when  
554 compared to that reported by Makki-Szymkiewicz et al. (2015) (as explained in section 4.4) underscores  
555 the contribution of the pozzolanic reactions towards the development of smaller pores in the long-term.

556 Specimen Nat 1 (0.15 m) shows a higher number of macropores of pore width  $10^5$  Å and 19 %  
557 greater cumulative pore volume than Nat 2 (0.45 m), as reported in section 3.4. This indicates that the  
558 untreated specimen collected at a lower depth (0.15 m) exhibits more macropores than the one sampled  
559 from a greater depth (0.45 m). Samples Nat 1 and Nat 2 were located within the 2<sup>nd</sup> and the 3<sup>rd</sup> layer of  
560 compaction normal to the surface of the trench, respectively, in the untreated embankment (Fig. 2). Thus,  
561 during the construction of the untreated embankment, the compaction effort achieved by Nat 2 in the 3<sup>rd</sup>  
562 layer was higher than the one obtained by Nat 1 in the 2<sup>nd</sup> layer. Lipiec et al. (2012) and Mossadeghi-  
563 Björklund et al. (2019) have demonstrated how an increase in compaction effort leads to a decrease in the  
564 diameter of macropores with depths from the surface of the pavement. Thus, the presence of more  
565 macropores in Nat 1 than Nat 2 can be partly due to this difference in the compaction effort achieved with

566 respect to depth during construction. In the lime-treated embankment, specimen T2-2, located at 0.30 m  
 567 above T2-3 (Fig. 3), shows a 27 % lower pore volume than T2-3 as per the BJH results (Fig. 10 (h)).  
 568 However, specimen T1-1 located 0.45 m above T2-4, shows 5.5 times greater pores volume in the same  
 569 pore range (Fig. 12 (b)).

570 Thus, it can be said that the presence of macropores in the untreated specimens are affected by the  
 571 sampling-depth of the embankment, while the formation of mesopores in the lime-treated samples under  
 572 the lime effect remains less affected by the same.

573

#### 574 4.7. Comparison between the volume of mesopores measured by MIP and BJH

575 The discussions in the preceding section show how lime treatment brings about the formation of  
 576 pores smaller than 3000 Å in diameter, including mesopores. On comparing this formation of smaller  
 577 pores detected using MIP (Fig. 10 (c)) and BJH (Fig. 10 (g)), it was observed that BJH results give a more  
 578 precise distribution of intensities showing a narrow peak at 40 Å and a broad peak at 50-500 Å. This was  
 579 missing in MIP results for the same specimens. Based on this observation, Table 3 is presented to show  
 580 the percentage difference of cumulative pore volume in the mesopore range that can be accessed by both  
 581 MIP and BJH methods. It includes specimens T2-2 and T2-3 in the pore range of mesopore diameter 60-  
 582 250 Å (i.e., the intersection of the ranges accessible through MIP and BJH). Table 3 shows that the  
 583 cumulative pore volume measured by BJH for T2-2 and T2-3, in the mesopore range (60-250 Å) was  
 584 about 3.5 and 3.2 times higher than that measured by MIP, respectively.

585

586 **Table 3:**

587 Difference in pore volume measured in the mesopore range of pore diameter 60-250 Å by MIP and BJH methods

Sample name	Total $V_{cum}^1$ measured by MIP (60-3.5 × 10 <sup>6</sup> Å) (cm <sup>3</sup> /g)	Total $V_{cum}$ measured by BJH (25-250 Å) (cm <sup>3</sup> /g)	$V_{cum}$ measured by MIP (60-250 Å) (cm <sup>3</sup> /g)	$V_{cum}$ measured by BJH (60-250 Å) (cm <sup>3</sup> /g)	Calculated $V_{cum}$ (60-250 Å) as a percentage of total measured by MIP (%)	Calculated $V_{cum}$ (60-250 Å) as a percentage of total measured by BJH (%)
T2-2 (0.15 m)	0.160	0.013	0.029	0.010	17.8	81.0
T2-3 (0.45 m)	0.200	0.018	0.040	0.015	19.8	84.0

588

<sup>1</sup> $V_{cum}$ : cumulative pore volume

589 These results, thus, show the effectiveness of the BJH method in quantifying the mesopores  
 590 formed under long-term lime effect.

591

592

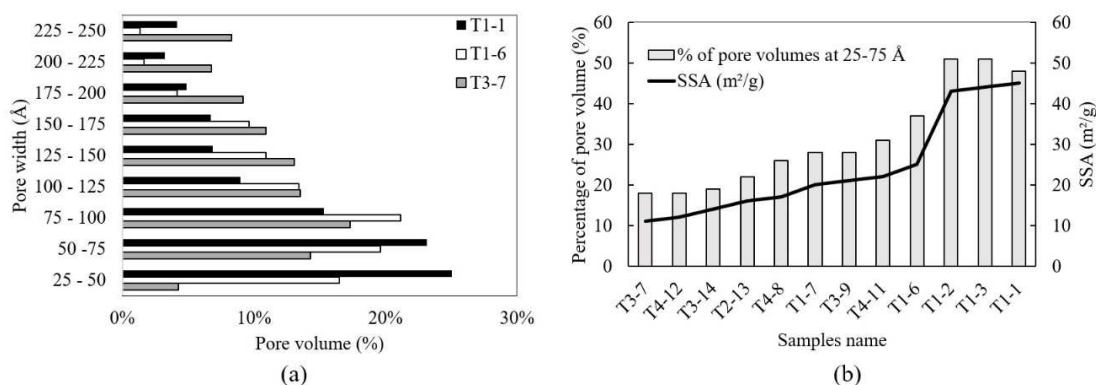
#### 593 4.8. Long-term effect of lime treatment on the SSA

594 Lime treatment is known to decrease the SSA of highly expansive soil based on laboratory  
 595 investigations (Bhuvaneshwari et al., 2014; Cherian and Arnepalli, 2015). So far, the long-term effect of  
 596 lime treatment on the SSA of lime-treated low plastic soil, such as silty soil, remains less investigated.

597 De Bel et al. (2013) conducted SSA by BET of the present MLD soil and stated that 3 % quick  
 598 lime-treated MLD soil shows a decrease in SSA from 23.0 m<sup>2</sup>/g to 13.3 m<sup>2</sup>/g after 7 days of curing. At the  
 599 same time, this SSA value rises to 21.6 m<sup>2</sup>/g after 400 days of curing at a laboratory scale. The former  
 600 behaviour was attributed to the flocculation effect, while the latter to the formation of pozzolanic products  
 601 (CSH and CAH). Considering this, it can be derived that the uneven distribution of SSA, as reported in  
 602 Fig. 11 (b-e), could be linked to the development of cementitious compounds in the different specimens  
 603 sampled at varying depths throughout the lime-treated embankment. As the evolution of cementitious

604 compounds leads to the formation of mesopores, the correlation between the range of mesopores  
 605 generation and the evolution of SSA was evaluated by BJH.

606 Using BJH data, the percentage of cumulative pore volume present in the pore diameter range 25-  
 607 250 Å was evaluated for specimens showing the maximum (T1-1 = 45 m<sup>2</sup>/g), the intermediate (T1-6 = 25  
 608 m<sup>2</sup>/g), and the minimum (T3-7 = 11 m<sup>2</sup>/g) SSA values. Fig. 14 (a) presents the percentage of pore volume  
 609 for specimens over the range of pore diameter 25-250 Å at 25 Å intervals. It was observed that T1-1  
 610 shows about 11 % and 30 % higher pore volume in the range of pore diameter 25-75 Å than T1-6 and T3-  
 611 7, respectively. T1-6 shows about 19 % higher pore volume in the same pore range than T3-7. For the  
 612 remaining range of pore diameter (75-250 Å), the pore volume was observed to increase for T3-7, while it  
 613 decreased more for T1-1 than T1-6. This indicates that the specimen with maximum SSA shows the  
 614 presence of more pores of pore diameter 25-75 Å and vice versa.  
 615



616  
 617 **Fig. 14:** Evolution of SSA with respect to the presence of pore volume in the mesopore range of pore diameter 25-75 Å  
 618

619 Based on this observation, the SSA of a few selected lime-treated specimens was plotted with  
 620 respect to the evolution of pore volume in the range of pore diameter 25-75 Å (Fig. 14 (b)). An increase in  
 621 the trend of pore volume was observed with the gradual rise in SSA. It can thus be derived that there exists  
 622 an apparent correlation between the two quantities.  
 623

#### 624 4. Conclusions

625  
 626 The long-term effect of lime treatment on a silty soil embankment was evaluated in terms of  
 627 mechanical, physicochemical, and microstructural properties after 7 years of atmospheric exposure in a  
 628 wet climate. The evaluation was made by undergoing laboratory investigations using several specimens  
 629 gathered in the upper layer as well as throughout the core of the embankment. Based on the study, the  
 630 following conclusions are derived:

- 631 1. An average UCS level of 3.29 MPa was obtained from the in-situ cured lime-treated specimens.  
 632 Comparison of this UCS level with the UCS obtained from the accelerated-cured sample (at 40°C  
 633 after 90 days) at laboratory scale confirms that such UCS level can be expected from the in-situ  
 634 cured specimens after 7 years of curing.
- 635 2. SEM images evidenced the presence of cementitious bonding formed because of pozzolanic  
 636 reactions under the lime effect in the core-sampled specimens of the lime-treated embankment.
- 637 3. The lime effect persists throughout the core of the lime-treated embankment as the pH  
 638 measurement was greater than 11 despite 7 years of curing in a region that receives significant  
 639 rainfall throughout the year.

- 640 4. A maximum loss of 12 % and 18 % in the water content and pH, respectively, was observed in the  
641 upper layer-sampled specimens compared to the core-sampled specimens. This shows that the  
642 effect of lime was lost in the upper layer of the lime-treated embankment due to long-term  
643 exposure of the soil to the atmosphere and due to the development of vegetation roots.
- 644 5. The relevance of the combined MIP- and BJH-pore structure analysis is shown by their efficiency  
645 in representing the complete range of macropores and mesopores affected by lime-treatment. MIP  
646 highlights the reduction in macropores ( $10^4$ - $10^5$  Å) and an increase in the number of smaller pores  
647 ( $< 3000$  Å) in the lime-treated soil when compared to the untreated soil. Simultaneously, BJH  
648 shows the formation of mesopores (50-500 Å) in the lime-treated specimens, which was missing  
649 in the untreated soil. BJH method happens to define the evolution of mesopores under the lime  
650 effect more precisely than MIP.
- 651 6. The formation of smaller pores enhances the evolution of suction in the lime-treated core-sampled  
652 soil when compared to the untreated soil. This has led to a lower reduction in the water content  
653 during this 7-year curing period, and the distribution of water content remains less affected by  
654 depth. Thus, lime treatment improves the long-term water retention capacity of the soil.
- 655 7. The formation of mesopores in lime-treated specimens was less affected by the depth of sampling  
656 in the lime-treated embankment. These mesopores contribute to the evolution of strength and  
657 SSA. An increase in mesopores results in increased strength, while the SSA was found to be  
658 correlated to the presence of mesopores in the range of pore diameter 25-75 Å.

659  
660 Thus, the study confirms the long-term persistence of the effect of lime within the core of a lime-  
661 treated silty soil embankment even after its exposure to a damp climate for 7 years. Based on the  
662 physicochemical and microstructural observations, a good and persistent mechanical performance was  
663 evidenced to be achieved at a lime content of 2.5 %.

664

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666

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671

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