

1 The effects of compaction delay and environmental temperature on the Mechanical and Hydraulic  
2 properties of lime- stabilized extremely high plastic clays

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27 The effects of compaction delay and environmental temperature on the Mechanical and Hydraulic  
28 properties of lime- stabilized extremely high plastic clays

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30 **Abstract:**

31 A comprehensive experimental programme was performed with the focus on assessing the  
32 effects of compaction delay and ambient temperature on the physical, mechanical and  
33 hydraulic properties of lime treated expansive clays. Specimens were mellowed for a period  
34 of 0, 3, 6, 12, 24 and 48 h at two different temperatures of 20°C and 40°C prior to being  
35 compacted, tested and/or cured for up to 28 days for evaluating the impacts on long-term  
36 strength development. All specimens were prepared with the same dry unit weight of 12.16  
37 kN/m<sup>3</sup> and moisture content of 40% except for tests aimed at determining dry unit weight  
38 as a function of mellowing period. The results revealed that as the mellowing duration  
39 increased the dry unit weight declined remarkably and the rate of reduction in dry weight  
40 was higher when specimens were mellowed at a temperature of 40°C during the first 12 h. A  
41 97% reduction in swelling pressure was obtained when the specimens were compacted  
42 upon mixing (zero hour mellowing period) and left to cure for 24 h prior to testing.  
43 Permeability coefficient of lime treated expansive clays was increased by up to 40 times  
44 when compaction was delayed for 24 h or when specimens were mellowed at 40°C.  
45 Specimens mellowed at a temperature of 40°C showed relatively stable values of  
46 permeability coefficient over the measurement period which could be attributable to  
47 accelerated pozzolanic reaction. The Unconfined Compression Strength tests revealed that  
48 strength of lime treated expansive clays is significantly affected by compaction delay. An  
49 increase of 234% and 282% in the UCS was achieved after 24 h of mixing with no  
50 compaction delay at 20°C and 40°C respectively. Gradual long-term gain in strength was

51 observable within the 28 days post mixing but the rate of strength gain becomes slower and  
52 independent of temperature after the first 24 h of mixing. The results suggested that the  
53 four key reaction mechanisms occur concurrently with the first 12-24 h after lime addition  
54 as being the most crucial period of time. Damaging the cementitious compounds by delayed  
55 compaction is harmful to strength and restraining of swelling potential of lime treated  
56 expansive clays.

57

58 **Keywords:** Lime treatment, compaction delay, ambient temperature, expansive clay,  
59 mechanical and hydraulic behaviour.

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64 **1. Introduction**

65 Problematic soils such as expansive soils are characterized by their significant volume  
66 change (Swelling/shrinkage) upon change in the water content. Ground movement due to  
67 their volume change could cause severe distress to structures erected above or within the  
68 expansive soil layers if appropriate measures are not undertaken. Expansive soils are  
69 encountered in arid and semiarid regions (Al-Rawas and Goosen, 2006) in more than 60  
70 worldwide countries including the UK (Shi et al., 2002). The Association of British Insurers  
71 estimated that losses caused by expansive soils are in the region of £400M per year in the  
72 UK (Driscoll and Crilly, 2000). Thus, it is imperative that treatment/stabilization measures  
73 are implemented to suppress the severity and consequences of potential ground movement  
74 associated with the swelling and shrinkage behaviour of expansive clays.

75

76 Several techniques are used to treat expansive soils including chemical additives and soil  
77 replacement. Chemical treatment using lime is by far the most common technique due to its  
78 low cost, technical efficiency and abundant availability of lime. Addition of lime to expansive  
79 soils in the presence of water causes a short term modification and long term stabilization  
80 effects resulting in structural and fabric change. The modification and stabilization changes  
81 are attributed to key reaction mechanisms namely; cation exchange, flocculation,  
82 agglomeration and pozzolanic reaction. These key reaction mechanisms were extensively  
83 investigated (Diamond and Kinter, 1965; Diamond and Kinter, 1966; Bell, 1996; Rogers and  
84 Roff, 1997; Boardman et al., 2001; Al-Mukhtar et al., 2012; Di Sante et al., 2014; Beetham et  
85 al., 2015; Zhao et al., 2015; Vitale et al., 2017) . Upon the addition of lime to expansive clays  
86 in the presence of water the lime decomposes partially into hydroxyl ions and calcium ions  
87 (Beetham et al., 2015). Calcium ions replace the exchangeable sodium ions on the surface of

88 clay particles. Instantly, adjacent clay particles become closer due to reduced thickness of  
89 double layer, interacting with each other and reconfiguring within clusters of clay floccs  
90 which in turn agglomerate together forming an open flocculated clay fabric. The hydroxyl  
91 ions sourced from the dissolution of lime hydroxide causes the creation of corrosive alkaline  
92 environment in the pores water (Beetham et al., 2015). This aggressive environment attacks  
93 the clay mineral lattice launching alumina and silica ions. In such environment the  
94 pozzolanic reaction initiates by reacting the available calcium ions the pores water with the  
95 alumina and silica ions forming the cementitious matters namely; calcium-silicate-hydrates  
96 (CSH), calcium-aluminate-hydrates (CAH), and calcium-aluminate-silicate  
97 hydrate(CASH)(Vitale et al., 2017). Due the continuity of forming these matter over long  
98 period of time the pozzolanic reaction is considered time dependent reaction(Bell, 1996).  
99 The temperature, unconsumed lime, mineralogy of the soil play a key role in controlling the  
100 kinetic of pozzolanic reaction(Al-Mukhtar et al., 2014). Unlike the agreement about the  
101 instant formation of cementitious matters upon the hydration of Portland cement  
102 (Bhattacharja and Bhatta, 2003; Rahman and Ojovan, 2016), in term of the lime it is still  
103 debatable that i)the key mechanisms occur sequentially(Boardman et al., 2001) or  
104 concurrently , ii) the place where the pozzolanic reaction takes place is in the solution (pore  
105 water) (Beetham et al., 2014) or on the surface or edge of clay particles(Boardman et al.,  
106 2001).

107

108 The efficiency of lime treatment was found to be dependent on many factors such as  
109 amount and type of lime, mineralogy composition of clay, water content, dry unit weight,  
110 temperature, compaction delay and degree of pulverization (Bozbey and Garaisayev, 2010;  
111 Beetham et al., 2014; Beetham et al., 2015). Compaction delay is considered as an integral

112 step to facilitate lime treatment in many engineering standards without adequate  
113 scientifically-based justifications (Holt and Freer-Hewish, 1998). Despite receiving less  
114 attention, some studies were conducted to pinpoint scientific elucidations for the  
115 consequences of compaction delay such as (Mitchell and Hooper, 1961; Sweeney et al.,  
116 1988; Holt and Freer-Hewish, 1998; Osinubi, 1998; Holt et al., 2000; Bhattacharja et al.,  
117 2003; Gallage et al., 2012; Adefemi and Wole, 2013; Ochepe et al., 2013; Di Sante et al.,  
118 2015). Compaction delay has been given different terminology e.g. mellowing period (Holt  
119 and Freer-Hewish, 1998; Holt et al., 2000), amelioration period (Gallage et al., 2012), rotting  
120 period, and aging period (Sweeney et al., 1988). Delaying the start of compaction process  
121 was found necessary in declining the size of clay clods before starting the compaction in  
122 order to meet the pulverization requirements (Holt and Freer-Hewish, 1998). Recently, the  
123 required pulverization is easy to reach by the use of stronger and more effective onsite  
124 plants. However, compaction delay sometimes cannot be controlled owing to several  
125 technical and logistical on site factors (Di Sante et al., 2015). Osinubi (1998) recommended  
126 based on his experimental results to undertake compaction immediately after the  
127 application of lime to avoid destruction of the slowly formed cementitious compounds,  
128 while others recommended to delay the compaction process to obtain quality workable  
129 material (Bhattacharja et al., 2003). To the best of the authors' knowledge, unlike the  
130 agreement about the role played by compaction delay in improving the workability and  
131 density reduction, no consensus was reached on the effects of compaction delay on the  
132 hydraulic and mechanical properties of lime treated expansive soils. For instance, although  
133 several standards require compaction delay of up to 48 h, Mitchell and Hooper (1961)  
134 reported that delaying compaction for 24 h has detrimental impact in curbing the swelling  
135 pressure of an expansive Californian soil and led to a reduce long-term strength. In contrast,

136 Sweeney et al. (1988) concluded that compaction delay of up to 24hr results in no significant  
137 effect on swelling pressure (Sweeney et al., 1988). Of note, both (Mitchell and Hooper,  
138 1961; Sweeney et al., 1988) utilized quick lime in the treatment of expansive clay soils  
139 giving rise to additional effects by the hydration process. Optimum mellowing period was  
140 recently introduced by Holt et al. (2000) to allow for enough reaction time between lime  
141 and soil prior to compaction in order to avoid the appearance of cracks that could lead to  
142 loss of strength.

143

144 The focus of most of the aforementioned studies was on the duration of compaction delay  
145 regardless of the effect of temperature on the progress of interaction before and after  
146 compaction except studies by (Holt and Freer-Hewish, 1998; Holt et al., 2000) in which  
147 compaction delay impacts were assessed at temperatures of 5 °C, 10 °C and 20°C. It was  
148 reported that there was no temperature effect on rate of strength up to 12 h of compaction  
149 delay, but thereafter the temperature effect during compaction delay depends on the type  
150 of soil. The effects of higher degree of temperatures were not assessed. The impact of  
151 ambient temperature on the strength gain was reported extensively (see for example; (Bell,  
152 1996; Boardman et al., 2001; Rao and Shivananda, 2005; Al-Mukhtar et al., 2010a; Al-  
153 Mukhtar et al., 2010b; Nasrizar et al., 2010; Nasrizar et al., 2012). Moreover, other studies  
154 exploited the impact of a higher temperature of 40°C to accelerate the strength gain in a  
155 week so as to predict the gain in strength in 4 weeks at 20°C (Mooney and Toohey, 2010;  
156 Toohey et al., 2013; Saldanha and Consoli, 2016) .

157

158 Conflicting recommendations were also found concerning the hydraulic properties of lime  
159 treated expansive clays. In general, addition of lime increases the permeability coefficient

160 as found by (Nalbantoglu and Tuncer, 2001; Tran et al., 2014) who attributed the increase in  
161 permeability to the increase in the size of inter-floc pores as a result of lime addition.  
162 However, the results of (Metelková et al., 2011; Al-Mukhtar et al., 2012) showed an initial  
163 increase in the permeability coefficient followed by a gradual decline due to the ongoing  
164 formation of cementitious compounds that partially fill the pore voids. However, potential  
165 effects of compaction delay was not seriously taken into consideration. Di Sante et al.  
166 (2015) concluded that there is no significant change in the value of coefficient of  
167 permeability with delayed compaction based on tests conducted on six specimens only.  
168 Further research would, therefore, be required to reach deeper understanding and  
169 informed conclusions for the role of compaction delay on hydraulic properties.

170

171 Comprehensive and critical review of the technical literature demonstrated that most of the  
172 previous studies on compaction delay were conducted on soils with liquid limit of less than  
173 90%. Soils with liquid limit higher than 90% are not suitable for engineering works unless  
174 treated (Highways-Agency, 2009) which magnifies the importance of treating high plastic  
175 clays to increase land use. Therefore, further research is still necessary to study the impact  
176 of compaction delay on problematic soils with higher values of liquid limit and plasticity  
177 index. The focus of the current study is to investigate the immediate and long-term effects  
178 of delayed compaction on the mechanical and hydraulic properties of lime treated  
179 extremely high plastic clays under two different environmental temperatures.

## 180 **2. Materials**

181 The expansive clay selected for this investigation is pure Wyoming Sodium Bentonite  
182 powder supplied by Potclays Ltd., UK. The clay comprises mainly Montmorillonite mineral in  
183 addition to a small amount of non-clay minerals e.g. Quartz, calcite and feldspar. Table 1

184 illustrates the chemical analysis of used clay that was provided by the supplier. The utilized  
 185 clay in this investigation has a liquid limit and plastic limit of 330% and 43% respectively. The  
 186 clay is therefore classified as extremely high plastic clay. Standard Proctor Compaction tests  
 187 revealed that neither maximum dry density nor optimum moisture content can be obtained.  
 188 The results showed continuous decline in the recorded dry density with increasing moisture  
 189 content. A moisture content of 40% was then estimated as an optimum moisture content  
 190 according to the correlation developed by Sridharan and Nagaraj (2005). Accordingly, the  
 191 corresponding dry unit weight was found to be 12.16 kN/m<sup>3</sup>.

192 Table 1: Chemical analysis of used clay

Element	SiO <sub>2</sub>	CaO	Na <sub>2</sub> O	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	Al <sub>2</sub> O <sub>3</sub>	LOI*	Trace
Percentage (%)	63.02	0.65	2.57	3.25	0.35	2.67	21.08	5.64	0.72

193 \*Loss of ignition

194

195 The utilized lime in this research is a hydrated lime with 95% ~ 97% lime in the form of  
 196 Ca(OH)<sub>2</sub>. It was difficult to determine the Initial Lime Consumption (ILC) according to BS  
 197 1924-2 (1990) due to the formation of a thick sludge which prevented the pH  
 198 measurements. Similar observation was previously made by Boardman et al. (2001).  
 199 Therefore, 7% lime was selected and added by dry weight of clay in order to induce  
 200 pozzolanic reactions in sodium- bentonite clay based on ILC that was recommended by  
 201 Boardman et al. (2001).

202 **3. Methodology**

203

204 All specimens were prepared by adding 7% of lime by dry weight of predetermined amounts  
 205 of clay powder. The clay and lime powders were initially mixed using a mechanical mixer  
 206 until obtaining a homogenous powder mixture recognized by the uniformity of mix colour. A

207 required amount of water was then added and mixing was continued to ensure uniform  
 208 distribution of moisture. The mixture was thoroughly mixed, kneaded manually and passed  
 209 through 2 mm sieve to ensure high degree of pulverization and uniform treatment of clay as  
 210 recommended by (Bozbey and Garaisayev, 2010). Subsequently, the mixture was thoroughly  
 211 mixed using a mechanical mixer. To avoid the detrimental effects of carbonization and loss  
 212 of moisture from the lime stabilized clay, mixtures were quickly stored in double sealed bags  
 213 and kept in a controlled environmental cupboard at a predetermined desired temperature  
 214 and relative humidity of 80%. This relative humidity was adequate to aid prevention of  
 215 moisture loss during the mellowing period. Mixtures were left in the environmental  
 216 cupboard for the intended mellowing period according to the test condition. Three series of  
 217 testing were conducted to study the effects of compaction delay on dry unit weight,  
 218 swelling pressure, permeability and unconfined compressive strength. Table 2 summaries  
 219 the testing programme.

220 Table 2: Testing programme

Series	Parameters		Notes
	Variables	Fixed	
Compaction tests	MP = 0, 3, 6, 12, 24, 48 h T = 20°C and 40°C	Compactive energy $w_c = 40\%$	Additional specimen prepared of pure expansive clay
Swelling pressure and permeability tests	MP = 0, 3, 6, 12, 24 h T = 20°C and 40°C G1 = testing upon compaction G2= testing after 24 h of mixing	$Y_d = 12.16 \text{ kN/m}^3$ $w_c = 40\%$	Two additional specimens of pure expansive clay and lime-treated clay
Unconfined compressive strength tests	MP = 0, 3, 6, 12, 24, 48 h T = 20°C and 40°C ET = 1, 7, 14 and 28 days	$Y_d = 12.16 \text{ kN/m}^3$ $w_c = 40\%$	Six additional specimens of pure clay and lime-treated clay

221 where; MP = Mellowing Period, T = Environmental Temperature, ET = Elapsed time from mixing,  $w_c$  =  
222 Moisture Content,  $Y_d$  = Dry unit weight, G1 = Group 1 and G2 = Group 2

223

### 224 **3.1 Compaction tests**

225 A preliminary investigation was carried out using Standard Proctor Test and showed that i.  
226 compaction of extremely high plastic clays in a standard proctor test is cumbersome, ii.  
227 Extraction of three specimens from the compaction mould results in significant distortion  
228 and variation of density along the specimen height and iii. Substantive amounts of materials  
229 were wasted. A new purpose made mould and hammer were, therefore, designed and  
230 manufactured to overcome all the aforementioned drawbacks. The designed mould has an  
231 internal diameter of 50 mm and height of 120 mm. mixtures were compacted in six layers  
232 using a 1.25 kg hammer falling from 150 mm. All specimens have received the same  
233 compactive energy as in the Standard Proctor Compaction. Initial validation exercise was  
234 conducted to ensure that convergence of density and even better uniformity of density  
235 along specimen height were achievable.

236

### 237 **3.2 Permeability and swelling pressure tests**

238 As illustrated in Table 2, tests were conducted to determine the permeability characteristics  
239 and swelling pressure as a function of predetermined delayed compaction periods on  
240 specimens mellowed at two different environmental temperatures. Of note, two groups of  
241 testing (G1 and G2) were conducted on specimens that were tested i. immediately after  
242 compaction and ii. After 24 h from the end of mixing process, respectively. For the latter  
243 group, specimens were mellowed for 3, 6, 12, 24 h under the intended temperature and  
244 then compacted, sealed and stored in the environmental cupboard at the same  
245 temperature for the remaining period of 24h and then tested. As a result, all specimens in  
246 this group (G2) were given 24 h to chemically react until testing, which was thought to be

247 fair. Of note, the temperature was maintained the same during mellowing and storage after  
248 compaction until testing.

249

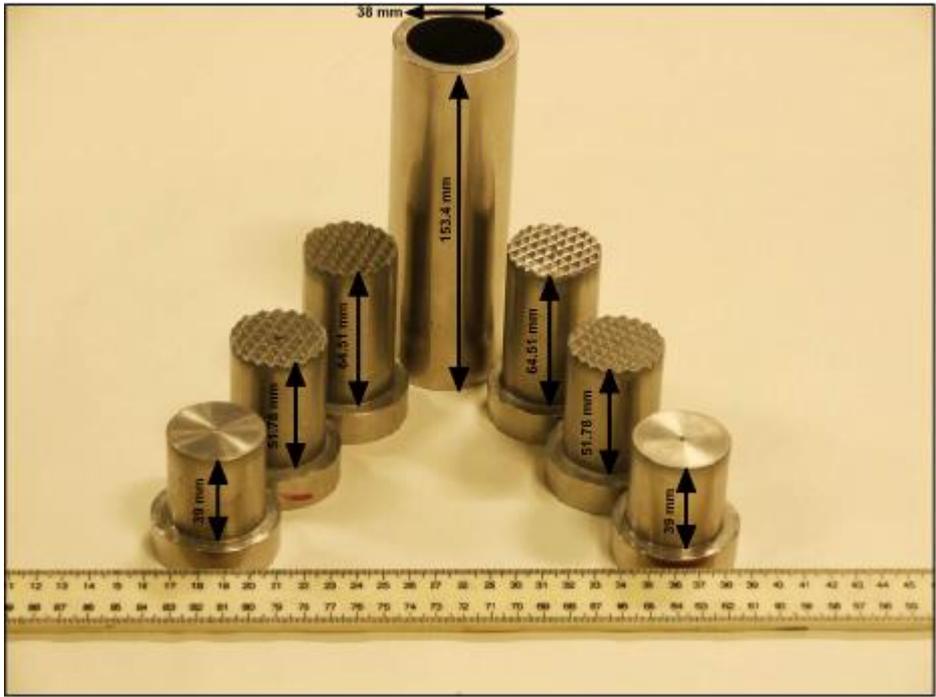
250 Untreated and treated specimens were prepared at dry unit weight of 12.16 kN/m<sup>3</sup> and  
251 water content of 40%. This means that specimens have an initial degree of saturation of  
252 94.7%. Measurements of water flow into the specimens indicated that the volume of water  
253 flow during the first hour is significantly higher than the volume of air in the specimens. This  
254 confirms that specimens have reached full saturation prior to determination of permeability  
255 coefficient. In addition, water content was measured at the end of each test and the  
256 increase in the water content was in the range of 2 to 3%. Therefore the specimens were  
257 fully saturated during the permeability tests. GDS Automatic Oedometer System with  
258 hydraulic cell was used to conduct swelling pressure and permeability tests simultaneously.  
259 The base of the hydraulic cell is connected with a pressure-volume controller so that a  
260 target base pressure of 35 kN/m<sup>2</sup> was applied on the bottom of specimen since the start of  
261 the test while the top of specimen was kept under water at atmospheric pressure. All tests  
262 were conducted at room temperature according to BS 1377-6:1990-4. Initial experiments  
263 showed that water only interacted with and penetrated a thin layer from the top and  
264 bottom of the specimen which prevented water ingress into central area of the specimens.  
265 This would lead to swelling pressure being measured inaccurately. Therefore, it was decided  
266 to run the tests on 10 mm thick specimens as suggested by (Al-Mukhtar et al., 2012) to  
267 shorten the flow path of water. In addition, the base pressure was increased to speed up  
268 the percolation of water and to ensure that all specimens were tested under comparable  
269 conditions. The swelling pressure was determined by applying incremental load to prevent  
270 swelling of specimens which means that all specimens maintained their initial dry unit

271 weight throughout the testing period. The Permeability coefficient were determined after 6,  
272 12, 18, 24, 36, 48, 60 and 72 h from the start of test to ensure reaching maximum value of  
273 swelling pressure and full saturation.

274

### 275 **3.3 Unconfined compression strength**

276 Unconfined Compressive Strength (UCS) tests were performed to assess the impacts of  
277 mellowing periods on evolving of strength of lime stabilized extremely high plastic clay  
278 specimens in the short and long term as illustrated Table 2. Of note; specimens for UCS  
279 were tested after 1, 7, 14 and 28 days from mixing. It should be noted that all results  
280 presented for UCS represent the average of three replicate specimens to ensure capturing  
281 accurate trends for the gain in strength of lime stabilized clays. A total of 142 specimens  
282 were prepared and tested to capture the effect of different mellowing conditions. Mixtures  
283 of lime stabilized clays were left in the controlled temperature and humidity environmental  
284 cupboard to mellow for predetermined periods as per testing programme. Mellowed  
285 mixtures were compacted in five layers under static load. Plunger with an indented surface  
286 was used to compact intermediate layers to ensure strong welding surface between the  
287 layers and to avoid scratching/disturbing the specimens. Compacted specimens were  
288 extracted promptly and measurements of dimensions and mass were taken. Specimens  
289 were then warped by cling film, put in double sealed bags and stored in the environmental  
290 cupboard until testing. This method of specimen preparation has shown to minimise and/or  
291 eliminate discrepancy between measurements (Saad et al., 2012).The developed mould that  
292 was used in this study is as illustrated in Figure 1. An automated loading machine was used  
293 to perform UCS tests at a rate of 1mm/min. Readings of axial load and vertical deformation  
294 were recorded automatically every 1 s.



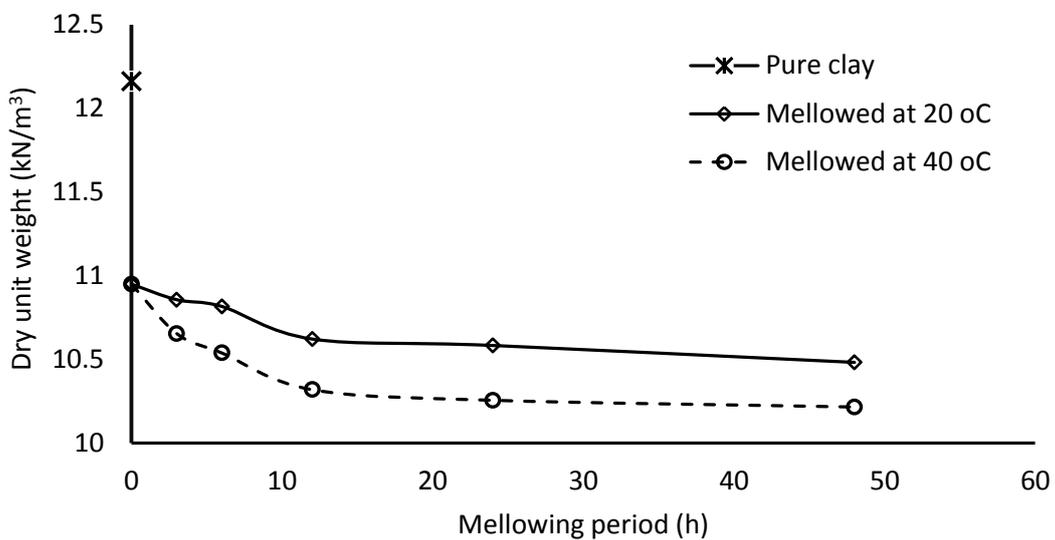
295  
296 Figure 1: Developed mould that was used in preparing the UCS specimens

297 **4 Results and Discussion**

298 **4.1 Dry unit weight**

299 The effect of compaction delay and environmental temperatures on the dry unit weight of  
300 lime treated extremely high expansive clay is shown in Figure 2. It is evident that the dry  
301 unit weight of lime-treated clay specimens that were mixed and compacted immediately  
302 was found to decline appreciably to  $10.95 \text{ kN/m}^3$  compared to the dry unit weight of pure  
303 clay specimen ( $12.16 \text{ kN/m}^3$ ). The reduction in compactability and hence the 10% drop in  
304 the dry unit weight can primarily be attributed to the flocculation of lime treated clay  
305 caused by cation exchange processes and instant formation of cementation compounds that  
306 bind the flocs. The growing of such cementitious compounds in lime treated bentonite was  
307 observed to occur very shortly after addition of lime (Vitale et al., 2017). Delaying  
308 compaction of mixtures led to further drop in the dry unit weight, in particular, mixtures  
309 that were mellowed for up to 12 h. The trend for the measured dry unit weight nearly  
310 flattened up with further increase in the mellowing period. This can be explained by the  
311 ongoing formation of cementitious compounds in a loose state offering an increased

312 resistance to compaction. With further delay in compaction, clay agglomeration and  
 313 bonding of clay particles would be stronger which would cause further resistance to  
 314 compactability. Since same compaction effort was used, the portion of energy that was  
 315 exhausted in destructing the cementitious compounds, would increase with their ongoing  
 316 formation in a loose state causing further resistance to compactability. This in turn leads to  
 317 further reduction in the dry unit weight as the compaction delays. It is worth noting that  
 318 specimens mellowed at a temperature of 40°C showed higher reduction in the dry unit  
 319 weight than those mellowed at 20°C due to the higher rate of the formation of cementitious  
 320 compounds as observed by (Al-Mukhtar et al., 2014; De Windt et al., 2014) . The rate of  
 321 reduction in dry unit weight for both temperatures slowed down after 12 h of mellowing.  
 322 This gives an indication that the formation of cementitious compounds slowed down  
 323 generally and lost its dependence on the ambient temperature after the first 12h of  
 324 mellowing.



325

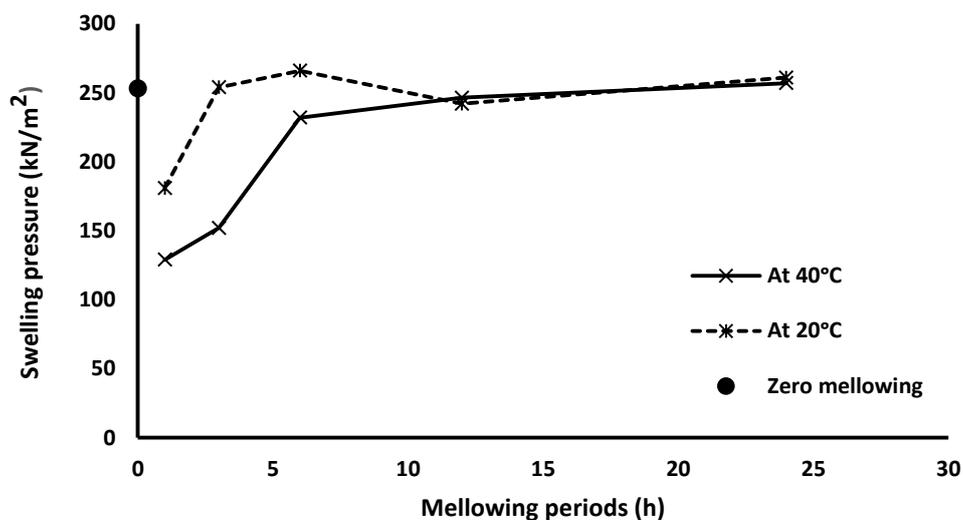
326 Figure 2 : Effect of mellowing and temperature on the dry unit weight

327

328 4.2 Swelling pressure and permeability tests

329 4.2.1 Swelling pressure

330 Results on untreated expansive clay specimens showed that the swelling pressure of pure  
331 clay was as high as 750 kN/m<sup>2</sup>. However, that of lime treated specimens declined to 250  
332 kN/m<sup>2</sup> when the specimens were compacted without delay and directly tested resulting in  
333 67% reduction in the swelling pressure. This significant reduction in the measured swelling  
334 pressure can be attributed to declining specific surface area of treated clay particles in  
335 contact with the pores water due to flocculation, agglomeration, initial cementitious  
336 matters (Beetham et al., 2015). Figure 3 shows results for the swelling pressure as a function  
337 of mellowing period for the first group of specimens that were tested immediately upon  
338 compaction as a function of compaction delay.



339

340 Figure 3: Swelling pressures of specimens tested directly after compaction.

341

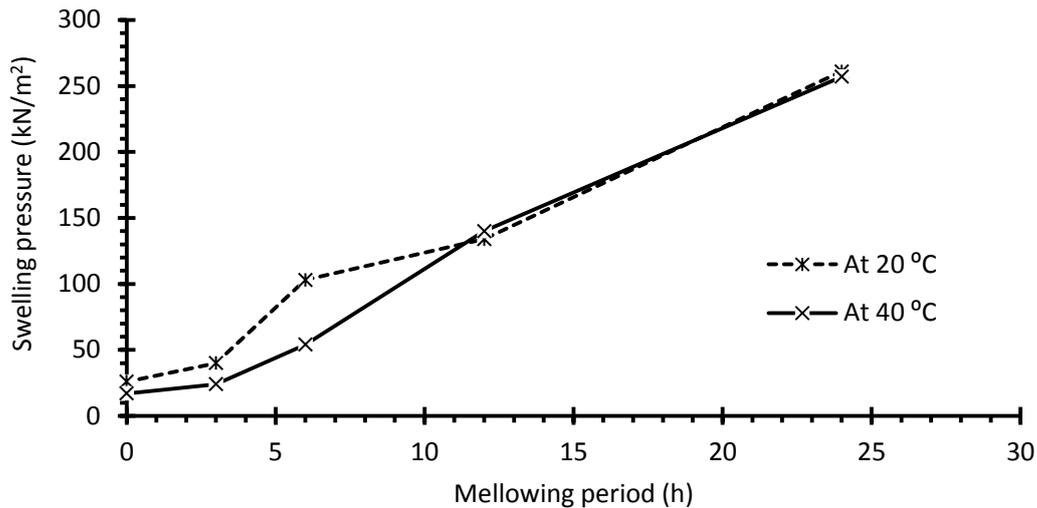
342 It is clear that swelling pressure of specimens mellowed at 20°C is more or less the same  
343 irrespective of mellowing period. The formation of cementitious compounds enhances the  
344 role of flocculation and agglomeration and binds the flocs together which would help  
345 further in curbing the swell. But hence, the aforementioned phenomenon took place in the

346 loose state during the mellowing prior to compaction, the subsequent compaction would  
347 cause partial destruction to the flocs and bonding between clay particles. Furthermore,  
348 illustrated data revealed that measured swelling pressure of the treated specimens which  
349 had been mellowed for different periods of time at 20°C and 40°C were very close apart  
350 from the specimen that was mellowed for 3 h at 40°C. The swelling pressure of the lime-  
351 treated specimen which had been mellowed for 3 h at 40°C was found to reaching a  
352 maximum of 150 kN/m<sup>2</sup>. It seem that the specimen was still retaining its temperature during  
353 the process of static compaction and before reaching the water. Despite the short duration  
354 of this periods, the rapid rate of formation of cementitious compounds during the first three  
355 hours under 40°C enabled substantial drop in the tendency to swelling. The mount of  
356 resistance to the compactability in the specimen that mellowed for 3 h under 40°C supports  
357 this interpretation. The results, therefore, suggest that compaction delay would have a  
358 minor or no effect on the swelling pressure. Due to testing immediately after compaction,  
359 one would note that the period of time given to the chemical reaction in these specimens  
360 were different. As a result, another group of testing was performed in which all specimens  
361 were given 24 h to chemically react until testing whilst compaction was conducted at an  
362 intermediate stage of 3, 6, 12, and 24. Therefore, group 2 of testing was characterized by  
363 being fair in terms of the period of time given to the lime to chemically interact with the  
364 clay.

365

366 Results for swelling pressure of the second group on specimens that were tested after 24 h  
367 from mixing irrespective of the mellowing period are shown in Figure 4. Measured swelling  
368 pressure on the lime treated specimens that were compacted immediately after mixing and  
369 tested after 24 h from mixing were found to be 17 kN/m<sup>2</sup> and 26 kN/m<sup>2</sup> respectively. The

370 results show clearly that the swelling tendency of lime treated extremely high expansive  
371 clay nearly abolished when specimens were not permitted to mellow prior to compaction  
372 but cured for 24 h. By comparing the values of swelling pressure with no compaction delay  
373 with those measured on 24h-mellowed specimens at both temperatures, it can be stated  
374 that the formation of initial cementitious compounds shortly after the addition of lime plays  
375 a significant role in restraining the swelling tendency. In other words, disturbance of the  
376 initial cementitious compounds by delayed compaction adversely affects the ability of lime  
377 to control expansion of expansive clay. Figure 4 shows remarkable reliance on the curing  
378 period after compaction for restraining the swelling potential rather than the mellowing  
379 period. There is a potential increase in the swelling due to the breaking down of the flocs  
380 and initial cementation that formed in loose state as a results of a subsequent compaction.  
381 It is also noticeable the deviation between those mellowed for 6 h. This can explained by the  
382 higher formation of cementitious matters at 40°C during the first 12 h helping in further  
383 curbing the swelling tendency. Since all the specimens in this group were tested after 24 h  
384 mixing. Both 6 h mellowing specimens at 20°C and 40°C were mellowed for 6 h and then  
385 stored for 18 h and then tested. During the first 6 h from 18 h, the rate formation of  
386 cementitious matter under 40°C is still fast compared with under 20°C. thus its ability to  
387 compensate for the partial destruction of the flocs as a result of the compaction is greater  
388 than that at 20C during this period. This explanation is supported by the swelling value of  
389 specimens mellowed for 12 at both temperatures that are close. Also it can be enhanced by  
390 the rate of the reduction in dry unit weight was generally fast and temperature dependent,  
391 further decline in dry unit weight at 40°C ,during the first 12 h, being slow after that  
392 regardless the ambient temperature.



393

394

Figure 4: Swelling pressures of specimens tested after 24h from mixing

395

396 4.2.2 Hydraulic properties

397 Of note, the untreated expansive clay specimen was found to be impermeable under the

398 applied difference pressure, hence, its coefficient of permeability could not be determined.

399 The coefficient of permeability on lime treated specimen, which was compacted directly

400 after mixing (zero hour mellowing period) and then submerged directly, reached a value of

401  $1.7 \times 10^{-9}$  m/s. The instantaneous increase in permeability can be attributed to the

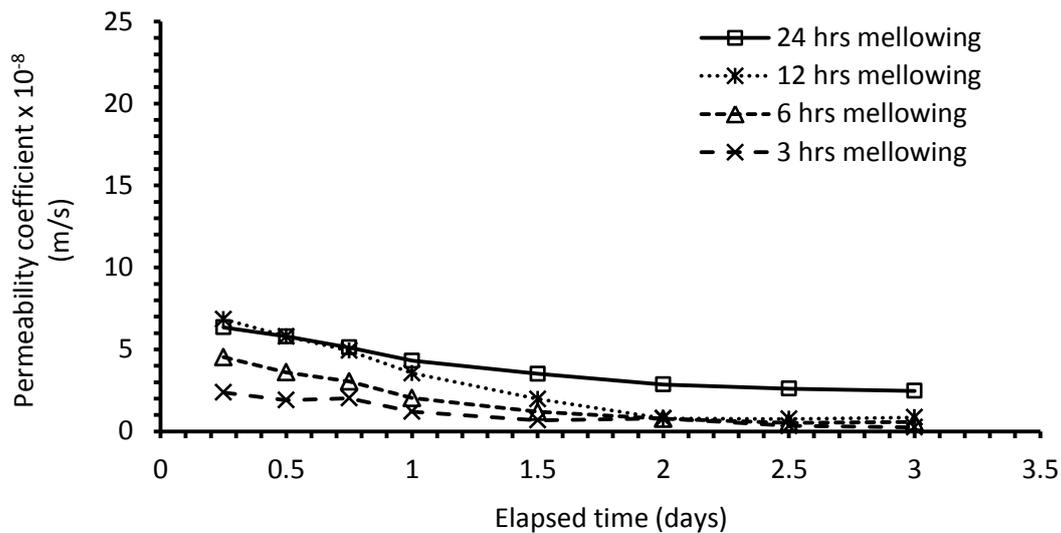
402 formation of inter-particle and inter-flocs pores. Figures5 and 6 present data for the

403 measured coefficient of permeability of lime treated clays for G1 specimens, which were

404 compacted and tested immediately after a period of mellowing at 20°C and 40°C

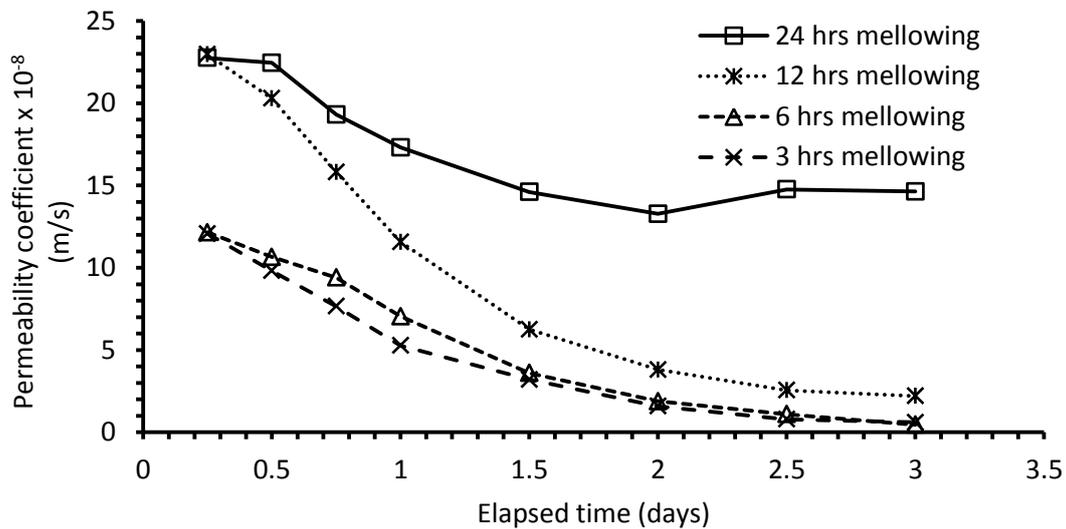
405 respectively, versus elapsed time from submersion in the odometer cell.

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407

408 Figure 5: Coefficient of permeability versus submersion period for GI at 20°C with 7% lime.



409

410 Figure 6: Coefficient of permeability versus submersion period for G I at 40°C with 7% lime

411

412 Inspection of illustrated data in Figures 5 and 6 showed that there is direct increase in the  
413 value of coefficient of permeability with increased mellowing period shortly after testing.

414 Nevertheless, gradual decline in the value of coefficient of permeability was evident for all

415 specimens over the 3-day measurement period reaching a relatively lowered coefficient of

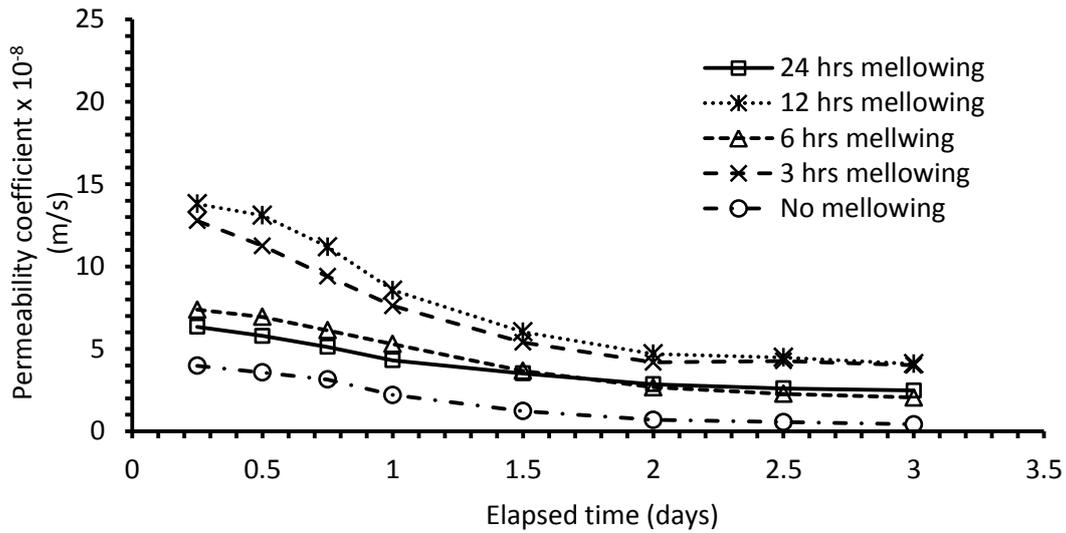
416 permeability value. The gradual decline can be explained by the ongoing formation of

417 cementitious compounds in the available pores leading to reduced size of interconnected

418 pores (Wild et al., 1987; Al-Mukhtar et al., 2012). The permeability coefficient of specimen  
419 mellowed for 24 h at 20°C was 1 order of magnitude higher than that measured after 3 h of  
420 mellowing. Mellowing at 40°C resulted in lime treated clay specimens being more  
421 permeable and followed by substantial reduction in permeability coefficient over the testing  
422 period. It was noted that specimens mellowed for 24 h had a permeability coefficient as  
423 high as 40 times as that measured on mellowed specimens for up to 6 h prior to testing. This  
424 could be due to the rapid consumption of lime prior to compaction and destruction of bond  
425 which leads to an open structure and enhanced connectivity between the pore voids.

426

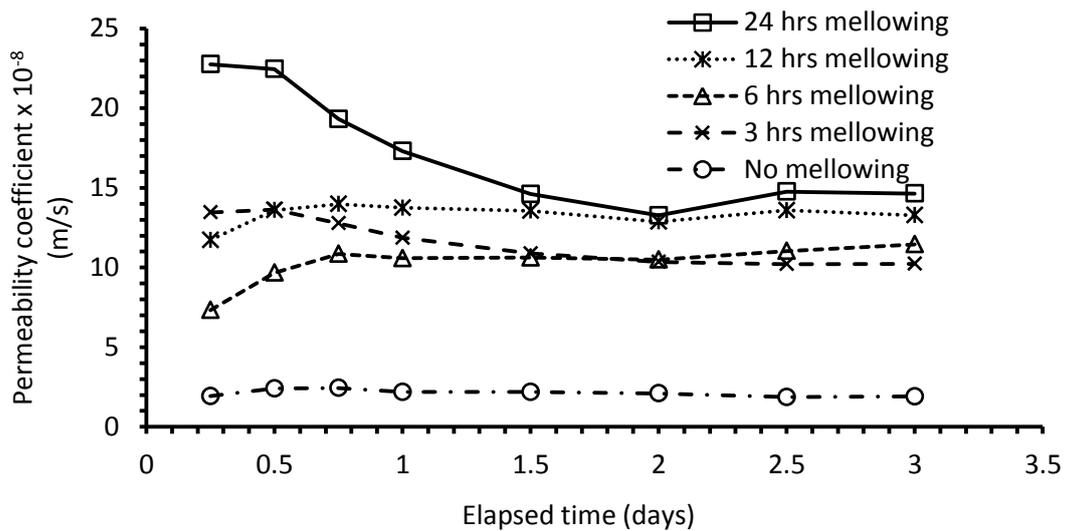
427 Results for the permeability coefficient of group 2 specimens that were tested after 24 h  
428 from mixing are presented in Figures 7 and 8 at 20°C and 40°C respectively. Generally, the  
429 results of specimens mellowed and cured at 20°C showed a gradual reduction in the  
430 coefficient of permeability with elapsed time. Among all specimens that were tested after  
431 24 h of mellowing at 20°C h, specimen with no compaction delay but cured for 24 h had the  
432 lowest value of coefficient of permeability. The other prevailing observation is that  
433 coefficient of permeability of all specimens that were tested after 24 h at 20°C were one  
434 order of magnitude higher in comparison with counter specimens that were tested upon  
435 compaction.



436

437 Figure 7: Coefficient of permeability versus submersion period for G2 at 20°C with 7% lime.

438



439

440 Figure 8: Coefficient of permeability versus submersion period for G2 at 40°C with 7% lime.

441

442 It is evident from Figure 8 that mellowing the specimens at a temperature of 40°C resulted

443 in coefficient of permeability being several times higher than that measured on specimens

444 mellowed at 20°C. Since all specimens were prepared with the same dry unit weight, the

445 difference in the coefficient of permeability values is likely to be due to distribution of pore

446 size and connectivity between pores. This can be attributed to the higher rate of formation

447 of cementitious matters at 40°C in loose state offering some resistance to the subsequent

448 compaction keeping the microstructure open and leading to an increased flow of water  
449 under the same water pressure. Careful inspection of Figures 7 and 8 indicates that unlike  
450 the measured coefficient of permeability values at 20°C which showed gradual decline over  
451 elapsed time, specimens that were mellowed and cured at 40°C and tested after 24 h of  
452 mixing showed a relative stable values of coefficient of permeability after 24 h of being  
453 submerged. This could be due to rapid consumption of the lime during the first 24h at 40°C.  
454 By and large, increasing the mellowing period leads to higher values of coefficient of  
455 permeability. The results, therefore, suggest that permeability of lime treated clays are  
456 mellowing period, temperature and lime availability dependent.

457

## 458 4.2 Unconfined Compressive Strength test

### 459 4.2.1 Axial stress

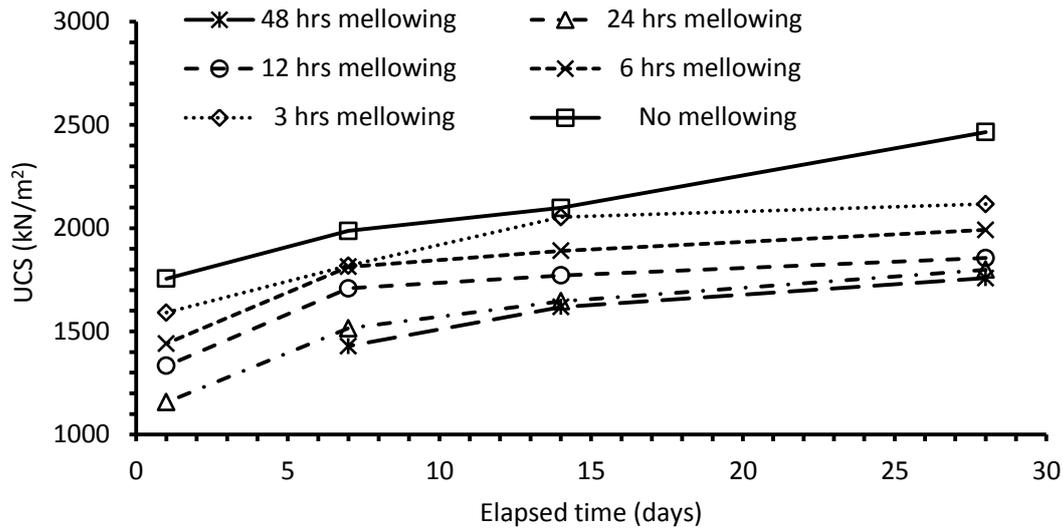
460 Tests were undertaken in this section to not only investigate the immediate effects of  
461 compaction delay on Unconfined Compressive Strength (UCS) of lime treated expansive  
462 clays but also to assess the gain in strength over the period of curing. Of note, identical  
463 environmental conditions were maintained during the predetermined periods of  
464 compaction delay and curing periods. It is also worth noting that the data presented  
465 hereafter for UCS represent the average peak strength that were measured on three  
466 replicate specimens. The variation of UCS from the average strength was found to not  
467 exceed  $\pm 4\%$  which was considered acceptable and reflects the effectiveness of specimen  
468 preparation method as the individual strength was not diverged from the average by more  
469 than  $\pm 10\%$  as recommended by Consoli et al. (2011) Measurements that were taken for  
470 dimensions of specimens and water content just before testing showed negligible change in  
471 specimen volume and in the value of water content.

472

473 Specimens tested under similar conditions of no mellowing and direct testing upon  
474 compaction showed that UCS on pure clay specimens was found to be 525 kN/m<sup>2</sup> whereas  
475 that of lime treated expansive clay was 1255 kN/m<sup>2</sup>. The immediate strength gain by lime  
476 addition gives an indication of the speed of lime interaction and its immediate effects on soil  
477 characteristics. This suggests that cation exchange and pozzolanic reaction occur  
478 concurrently from addition of lime which is in agreement with earlier observations by  
479 (Diamond and Kinter, 1965; Vitale et al., 2017). The UCS of lime treated specimens that  
480 were compacted directly after mixing and left for 24 h at 20°C and 40°C were found to be  
481 1756 KN/m<sup>2</sup> and 2009 KN/m<sup>2</sup> respectively. In contrast, the strength of specimens which  
482 were mellowed for 24 h and then compacted and tested directly were found to be 1156  
483 KN/m<sup>2</sup> and 1344 KN/m<sup>2</sup> at 20°C and 40°C respectively. The results clearly show that  
484 specimens mellowed for 24 h experienced significant loss in strength irrespective of the  
485 environmental temperature. The reduction in the strength illustrates the adverse effects of  
486 subsequent compaction resulting in a destruction of the cementitious compounds that were  
487 developed over 24 h of mellowing period.

488

489 Figures 9 and 10 show results for measured UCS on specimens treated with 7% of lime as a  
490 function of mellowing period at environmental temperatures of 20°C and 40°C respectively  
491 over of a period of 28 days from mixing. The results show clearly that irrespective of the  
492 ambient temperature, delaying the compaction of lime treated extremely high plastic clay  
493 mixture was found to be detrimental to achieving enhanced UCS. However, gradual increase  
494 in the value of UCS was noticeable over the period of curing. The results clearly show that  
495 UCS of specimens mellowed and cured at 40°C was higher by 25% in comparison to those  
496 mellowed and cured at 20°C.

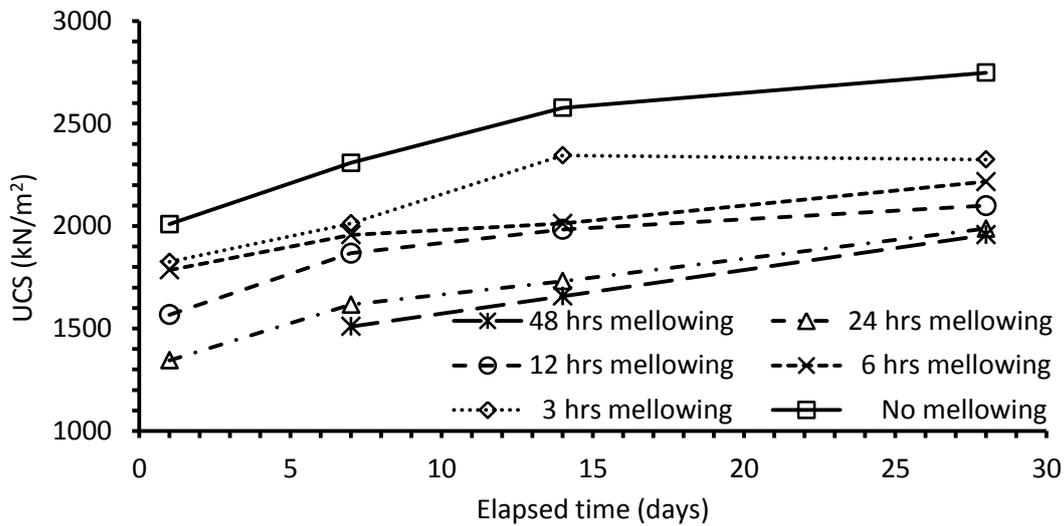


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Figure 9: Effect of mellowing periods on the development of strength gain at 20°C with 7% lime



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Figure 10: Effect of mellowing periods on the development of strength gain at 40°C with 7% lime

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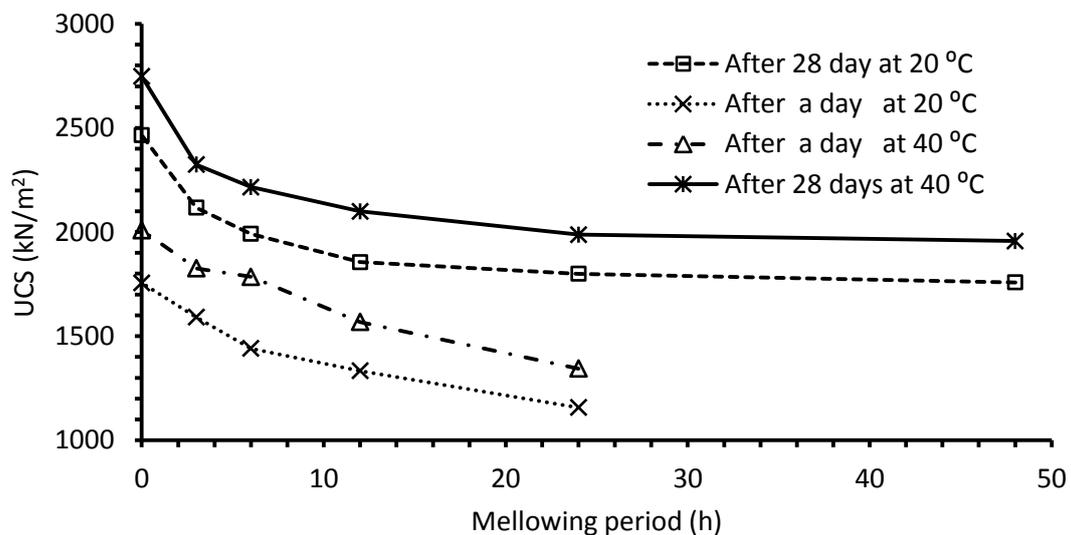
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To aid the discussion, Figure 11 was plotted for UCS measured after 1 and 28 days from mixing versus mellowing periods and Table 3 was presented to illustrate the strength gain in 24 h. Of note, UCS of pure expansive clay was taken as a control. It is evident that substantial drop in the measured values of UCS was observed as a result of increasing mellowing period in particular within the first 12 h. Figure 11 also reveals that the difference

509 in the strength gain occurred due to temperature appeared, to some extent, to remain the  
 510 same across the 28 days of curing period. This differences in strength is likely to be due to  
 511 the initial cementation matters and their rate of formations which is dependent on the  
 512 temperature. The formation rate of cementitious compounds are sharply lower regardless  
 513 the ambient temperature with prolonged curing period. Table 3 illustrates that the gain in  
 514 strength after 24 h from mixing was generally faster and higher at 40°C than those measure  
 515 at 20°C. The results confirm that zero mellowing gave a 234 and 282% increase in strength  
 516 when cured for 24 h at 20°C and 40°C respectively. Whereas those mellowed for 24 h  
 517 showed only an increase of 120.4% and 156.4% respectively.



518  
 519 Figure 11: the effect of the mellowing period on UCS after 1 and 28 days at different  
 520 temperature with 7% lime

521 Table 3: Analysis of strength gain after 24 h from mixing at 20°C and 40°C

Mellowing period (h)	Temperature of 20°C		Temperature of 40°C	
	Strength gain at the end of first day (kN/m <sup>2</sup> )	% increase in UCS after 24 h from mixing	Strength gain at the end of first day (kN/m <sup>2</sup> )	% increase in UCS after 24 h from mixing
0	1230.7	234.4	1483.7	282.6
3	1066	203.0	1300.5	247.7
6	915.5	174.4	1260.3	240.0
12	808.1	153.9	1042.7	198.6
24	631.87	120.4	819.24	156.0

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#### 4.2.2 Axial strain

Data presented hereafter represent average values of axial strain that were measured at peak strength on three replicate specimens. The variation between measured strains from the three replicate specimens did not exceed  $\pm 5\%$ . Tests on specimens of pure expansive clay used in this investigation and lime treated clays showed that peak strength was experienced at an axial strain of 6% and 2.4% respectively. Of note, lime treated expansive clay specimens were compacted immediately after mixing and tested directly. The decline in measured strain is directly related to the development of cementation material at the particles contact. On the other hand, lime treated expansive clay specimens that were mellowed for 24 h and tested directly experienced axial strains of 3.0% and 2.5% at 20°C and 40°C respectively. The slightly higher strain measured on specimen mellowed at 20°C could be interpreted by the slow formation of gel cementitious compounds.

Figure 12 presents the response of axial strain measured at peak UCS versus compaction delay on specimens tested after 1, 7 and 28 days from mixing at two different temperatures of 20°C and 40°C. The results revealed that delaying compaction leads to increased axial strain irrespective of elapsed time for testing which means that lime treated expansive clays become more ductile. The environmental temperature was found to play a major role in the underpinning treatment process leading to changing axial strain behaviour over the curing period. For a short curing period of 1 day, the results revealed that specimens mellowed and cured at 20°C experienced higher axial strain than those at 40°C due to the accelerated pozzolanic reaction. This trend of behaviour was completely altered with extended curing periods to 7 and 28 days, resulting in, specimens being mellowed and cured

547 at 20°C experienced less strain. This could be attributed to the quick consumption of lime at  
 548 higher temperature whereas at 20°C lime stabilization continue over the prolonged curing  
 549 period which is contradictory to earlier conclusions made by Toohy et al. (2013).

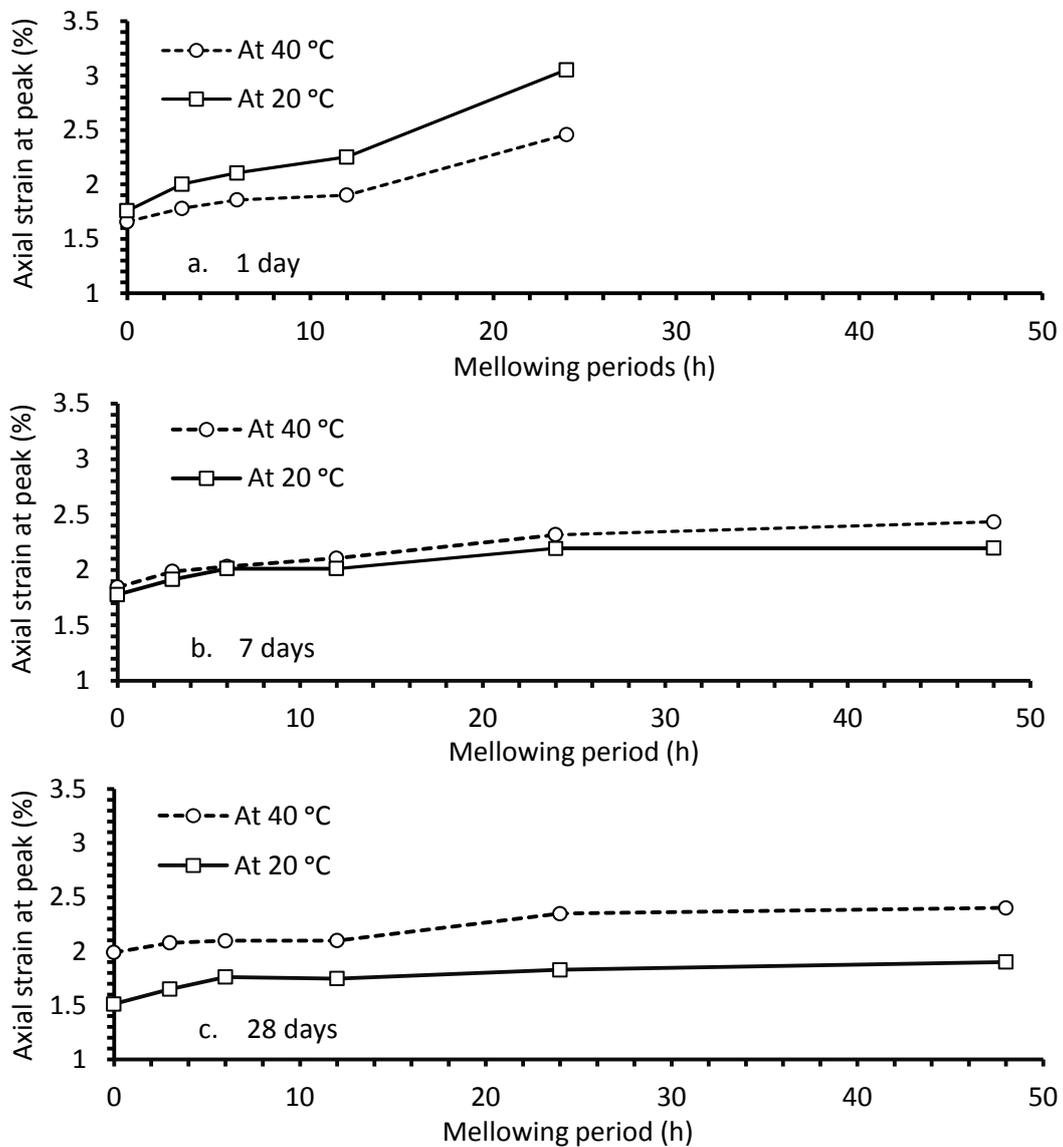


Figure 12: Strain behaviour a function of mellowing period after;  
 a. 1 day, b. 7 days and c. 28 days

550

:

551 **5. Summary and conclusions**

552 A comprehensive experimental programme was undertaken to investigate hydraulic and  
553 mechanical properties of lime treated expansive clays. The expansive clay used in this  
554 investigation has a liquid limit of 330% and is therefore classified as extremely high plastic  
555 clay. All lime stabilised clay specimens were mixed with moisture content of 40% and  
556 compacted to produce specimens with density of 12.16 kN/m<sup>3</sup>. A number of conclusions are  
557 drawn out of the investigation;

558

559 1. Delaying compaction of lime treated expansive clays was found be destructive to the  
560 development of cementation compounds at particles contact and between clay flocs  
561 resulting in a substantial decline in the measured dry unit weight within the first 12 h  
562 of compaction delay beyond which insignificant change in the measured dry unit  
563 weight was observed.

564 2. Lime treated expansive clay samples that were mellowed at higher temperature of  
565 40°C experienced elevated reduction in the dry unit weight than those mellowed at a  
566 temperature of 20°C due to the fact that higher temperature accelerates the rate of  
567 formation of cementitious compounds. The results suggest that the first 12 h is the  
568 most crucial period for development of bond and clay flocs. The decline in the dry  
569 unit weight was found to be independent of temperature after the first 12 h of  
570 compaction delay.

571 3. The results illustrated that compaction delay has harmful impact on the swelling  
572 tendency unlike, ambient temperature that has negligible impact on the swelling  
573 tendency. The results illustrated that both compaction delay and ambient  
574 temperature have negligible impact on the swelling tendency and attained swelling

575 pressure when specimens were tested without curing. However, the results revealed  
576 that specimens compacted immediately after mixing and left to cure for 24 h  
577 experienced remarkable reduction by 97% in the observed swelling pressure. This is  
578 due to the fact that produced cementitious compounds are undisturbed and  
579 undamaged by the compaction process.

580 4. In general, increasing mellowing period and environmental temperature led to  
581 increased coefficient of permeability of lime treated expansive clays. However,  
582 coefficient of permeability experienced a gradual decline with elapsed time from  
583 submersion due to the slow formation of cementitious compounds. Coefficient of  
584 permeability experienced an increase by one order of magnitude with long  
585 compaction delay and when mellowed at 40°C.

586 5. The results illustrated that UCS is directly related to the duration of mellowing with  
587 significant loss in UCS being occurred with prolonged delay of compaction with the  
588 first 12 h being recognized as the most crucial period affecting the long term  
589 strength of lime stabilized expansive clay. The results suggest that the bulk of  
590 modification and stabilization to the structure and fabric of expansive clay takes  
591 place shortly after the addition of lime.

592 6. The strength gain is fast and temperature dependent during first day, being relatively  
593 slow and time dependent after that. Thus, enhanced strength could be achieved if  
594 lime stabilized clay is cured carefully for first 24 h.

595 7. Axial strain of lime treated expansive clay was found to increase with delay of  
596 compaction and be dependent on ambient temperature and period of curing.

597 Based on this research work, delaying the compaction of lime treated extremely high plastic  
598 clay should be avoided to preserve the cementitious compounds as it appears to be the  
599 primary contributor for enhancing strength and reducing swelling pressure of lime treated  
600 expansive clays.

601 Reference

- 602 Adefemi, B.A., Wole, A.C., 2013. Regression Analysis of Compaction Delay on CBR and UCS of Lime  
603 Stabilized Yellowish Brown Lateritic Soil.
- 604 Al-Mukhtar, M., Khattab, S., Alcover, J.-F., 2012. Microstructure and geotechnical properties of lime-  
605 treated expansive clayey soil. *Engineering Geology*, 139: 17-27.
- 606 Al-Mukhtar, M., Lasledj, A., Alcover, J.-F., 2010a. Behaviour and mineralogy changes in lime-treated  
607 expansive soil at 20 °C. *Applied Clay Science*, 50(2): 191-198.
- 608 Al-Mukhtar, M., Lasledj, A., Alcover, J.-F., 2010b. Behaviour and mineralogy changes in lime-treated  
609 expansive soil at 50 °C. *Applied Clay Science*, 50(2): 199-203.
- 610 Al-Mukhtar, M., Lasledj, A., Alcover, J.F., 2014. Lime consumption of different clayey soils. *Applied*  
611 *Clay Science*, 95(0): 133-145.
- 612 Al-Rawas, A.A., Goosen, M.F.A., 2006. *Expansive soils: recent advances in characterization and*  
613 *treatment*. Taylor & Francis, London.
- 614 Beetham, P., Dijkstra, T., Dixon, N., 2014. Lime diffusion and implications for lime stabilization  
615 practice, *Compendium of Papers from the Transportation Research Board 93rd Annual*  
616 *Meeting*, Washington DC. TRB, USA .
- 617 Beetham, P. et al., 2015. Lime stabilisation for earthworks: a UK perspective. *Proceedings of the*  
618 *Institution of Civil Engineers - Ground Improvement*, 168(2): 81-95.
- 619 Bell, F.G., 1996. Lime stabilization of clay minerals and soils. *Engineering Geology*, 42(4): 223-237.
- 620 Bhattacharja, S., Bhattya, J.I., 2003. Comparative performance of portland cement and lime  
621 stabilization of moderate to high plasticity clay soils. RD125, Portland Cement Association,  
622 Skokie, USA: 26 pages.
- 623 Bhattacharja, S., Bhattya, J.I., Todres, H.A., 2003. Stabilization of clay soils by Portland cement or lime-  
624 A critical review of literature. *Research and Development Serial No. 2066*, Portland Cement  
625 Association, Skokie, USA(2066): 60.
- 626 Boardman, D.I., Glendinning, S., Rogers, C.D.F., 2001. Development of stabilisation and solidification  
627 in lime–clay mixes. *Géotechnique*, 51(6): 533-543.
- 628 Bozbey, I., Garaisayev, S., 2010. Effects of soil pulverization quality on lime stabilization of an  
629 expansive clay. *Environmental Earth Sciences*, 60(6): 1137-1151.
- 630 Consoli, N.C., Lopes Jr, L.d.S., Prietto, P.D.M., Festugato, L., Cruz, R.C., 2011. Variables Controlling  
631 Stiffness and Strength of Lime-stabilized Soils. *Journal of Geotechnical and*  
632 *Geoenvironmental Engineering*, 137(6): 628-632.
- 633 De Windt, L., Deneele, D., Maubec, N., 2014. Kinetics of lime/bentonite pozzolanic reactions at 20  
634 and 50 C: Batch tests and modeling. *Cement and Concrete Research*, 59: 34-42.
- 635 Di Sante, M., Fratolocchi, E., Mazzieri, F., Brianzoni, V., 2015. Influence of delayed compaction on the  
636 compressibility and hydraulic conductivity of soil–lime mixtures. *Engineering Geology*, 185:  
637 131-138.
- 638 Di Sante, M., Fratolocchi, E., Mazzieri, F., Pasqualini, E., 2014. Time of reactions in a lime treated  
639 clayey soil and influence of curing conditions on its microstructure and behaviour. *Applied*  
640 *Clay Science*, 99(0): 100-109.
- 641 Diamond, S., Kinter, E.B., 1965. Mechanisms of soil-lime stabilization. *Highway Research Record(92)*:  
642 pp 83-102.
- 643 Diamond, S., Kinter, E.B., 1966. Adsorption of calcium hydroxide by montmorillonite and kaolinite.  
644 *Journal of Colloid and Interface Science*, 22(3): 240-249.
- 645 Driscoll, R.M.C., Crilly, M., 2000. *Subsidence damage to domestic buildings: lessons learned and*  
646 *questions remaining*. CRC.
- 647 Gallage, C., Cochrane, M., Ramanujam, J., 2012. Effects of lime content and amelioration period in  
648 double lime application on the strength of lime treated expansive sub-grade soils. *Advances*  
649 *in Transportation Geotechnics II*: 99-104.
- 650 Highways-Agency, 2009. *Manual of Contract Documents for Highway Works*, The Stationary Office,  
651 London, UK.

652 Holt, C.C., Freer-Hewish, R.J., 1998. The use of lime-treated British clays in pavement construction.  
653 Part 1. The effect of mellowing on the modification process. *Proceedings of the Institution of*  
654 *Civil Engineers-Transport*, 129(4): 228-239.

655 Holt, C.C., Freer-Hewish, R.J., Ghataora, G.S., 2000. The use of lime-treated British clays in pavement  
656 construction. Part 2: The effect of mellowing on the stabilization process. *Proceedings of the*  
657 *Institution of Civil Engineers - Transport*, 141(4): 207-216.

658 Metelková, Z., Bohác, J., Sedlářová, I., Prikryl, R., 2011. Changes of pore size and of hydraulic  
659 conductivity by adding lime in compacting clay liners, *Geotechnical engineering: new*  
660 *horizons*, Proceedings of the 21st European Young Geotechnical Engineers Conference,  
661 Rotterdam, Amsterdam: IOS Press; 2011, pp. 93-8.

662 Mitchell, J.K., Hooper, D.R., 1961. Influence of time between mixing and compaction on properties of  
663 a lime-stabilized expansive clay. *Highway Research Board Bulletin*(304).

664 Mooney, M.A., Toohey, N.M., 2010. Accelerated curing and strength-modulus correlation for lime-  
665 stabilized soils, Colorado Department of Transportation, DTD Applied Research and  
666 Innovation Branch.

667 Nalbantoglu, Z., Tuncer, E.R., 2001. Compressibility and hydraulic conductivity of a chemically  
668 treated expansive clay. *Canadian Geotechnical Journal*, 38(1): 154-160.

669 Nasrizar, A., Muttharam, M., Illamparuthi, K., 2010. Effect of placement water content on the  
670 strength of temperature cured lime treated expansive soil, *GeoShanghai 2010*, pp. 174-180.

671 Nasrizar, A.A., Illamparuthi, K., Muttharam, M., 2012. Quantitative Models for Strength of Lime  
672 Treated Expansive Soil. *American Society of Civil Engineers, GeoCongress*: 978-987.

673 Ochepe, J., Osinubi, K.J., Sadeeq, J.A., 2013. Statistical Evaluation of the Effect of Elapse time on the  
674 Strength Properties of Lime-Bagasse Ash Treated Black Cotton Soil. *ESRSA Publications*.

675 Osinubi, K.J., 1998. Influence of Compactive Efforts and Compaction Delays on Lime-Treated Soil.  
676 *Journal of Transportation Engineering*, 124(2): 149-155.

677 Rahman, R.O.A., Ojovan, M.I., 2016. Recent Trends in the Evaluation of Cementitious Material in  
678 Radioactive Waste Disposal, *Natural Resources and Control Processes*. Springer, pp. 401-448.

679 Rao, S.M., Shivananda, P., 2005. Role of curing temperature in progress of lime-soil reactions.  
680 *Geotechnical & Geological Engineering*, 23(1): 79-85.

681 Rogers, C.D.F., Roff, T.E.J., 1997. Lime modification of clay soils for construction expediency.  
682 *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, 125(4): 242-249.

683 Saad, S., Mirzababaei, M., Mohamed, M., Miraftab, M., 2012. Uniformity of density of compacted  
684 fibre reinforced clay soil samples prepared by static compaction, *The 5th European*  
685 *Geosynthetics Congress*. Valencia, Spain

686 Saldanha, R.B., Consoli, N.C., 2016. Accelerated Mix Design of Lime Stabilized Materials. *Journal of*  
687 *Materials in Civil Engineering*, 28(3): 06015012.

688 Shi, B., Jiang, H., Liu, Z., Fang, H.Y., 2002. Engineering geological characteristics of expansive soils in  
689 China. *Engineering Geology*, 67(1): 63-71.

690 Sridharan, A., Nagaraj, H.B., 2005. Plastic limit and compaction characteristics of fine-grained soils.  
691 *Proceedings of the Institution of Civil Engineers - Ground Improvement*, 9(1): 17-22.

692 Sweeney, D.A., Wong, D.K.H., Fredlund, D.G., 1988. Effect of lime on highly plastic clay with special  
693 emphasis on aging. *Transportation Research Record*, 1190: 13-23.

694 Toohey, N.M., Mooney, M.A., Bearce, R.G., 2013. Stress-Strain-Strength Behavior of Lime-Stabilized  
695 Soils during Accelerated Curing. *Journal of Materials in Civil Engineering*, 25(12): 1880-1886.

696 Tran, T.D., Cui, Y.-J., Tang, A.M., Audiguier, M., Cojean, R., 2014. Effects of lime treatment on the  
697 microstructure and hydraulic conductivity of Héricourt clay. *Journal of Rock Mechanics and*  
698 *Geotechnical Engineering*, 6(5): 399-404.

699 Vitale, E., Deneele, D., Paris, M., Russo, G., 2017. Multi-scale analysis and time evolution of  
700 pozzolanic activity of lime treated clays. *Applied Clay Science*, 141: 36-45.

701 Wild, S., Arabi, M., Rowlands, G.O., 1987. Relation between pore size distribution, permeability, and  
702 cementitious gel formation in cured clay–lime systems. *Materials science and technology*,  
703 3(12): 1005-1011.

704 Zhao, H., Liu, J., Guo, J., Zhao, C., Gong, B.-w., 2015. Reexamination of Lime Stabilization Mechanisms  
705 of Expansive Clay. *Journal of Materials in Civil Engineering*, 27(1).

706