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1 The effects of lime content and environmental temperature on the mechanical and
2 hydraulic properties of extremely high plastic clays

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29 The effects of lime content and environmental temperature on the mechanical and
30 hydraulic properties of extremely high plastic clays

31 Hatim Ali and Mostafa Mohamed

32 **Abstract:**

33 This paper focuses on monitoring the evolution of lime-clay reactions using geotechnical parameters
34 as a function of lime content and environmental temperature. Lime contents of 5, 7, 9, 11 and 13%
35 by dry weight of expansive clay powder were added to prepare lime-clay specimens. The specimens
36 were prepared at the same dry unit weight of 12.16 kN/m^3 and moisture content of 40% except for
37 tests aimed at the determination of dry unit weight as a function of mellowing period. Prepared
38 specimens were mellowed or cured at two different ambient temperatures of 20°C and 40°C . Results
39 attained from Unconfined Compressive Strength and permeability tests were employed to assess the
40 impact of lime content on the mechanical and hydraulic properties of lime treated expansive clays.
41 The results revealed that at the beginning the rate of strength gain is remarkably fast for a particular
42 period of time which is dependent on lime content. Furthermore, the strength gain on specimens
43 cured at 40°C is 8 times higher than that observed on specimens cured at 20°C which highlights
44 significant effect for the environmental temperature on accelerating the chemical reactions.
45 Reduced dry unit weight due to increased resistance to compactability is observable with increasing
46 lime content and higher environmental temperature. Accelerated pozzolanic reaction at higher
47 environmental temperature resulted in permeability coefficient of specimens mellowed for 24 h at
48 40°C to be higher than those mellowed at 20°C . The results also highlighted that the permeability
49 coefficient would be relatively stable when expansive clays were treated with small amounts of lime
50 e.g. 5%.

51

52 **Keywords:** Lime treatment, expansive clay, mechanical behaviour, hydraulic behaviour, swelling
53 pressure, unconfined compressive strength

54

55

56 1. Introduction

57 The presence of expansive clays in construction sites poses major concerns to both design and site
58 engineers due to their substantial volumetric changes with drying and wetting cycles. As a result of
59 this volume change, distress and damage of infrastructures may be inevitable. Montmorillonite
60 minerals group that has a voracity to absorb water is responsible for the volumetric behaviour of
61 such expansive clay (Sridharan and Prakash, 2000; Estabragh et al., 2014 and Thyagaraj et al., 2016).
62 Over the past few decades, a number of preventative techniques have been proposed and
63 implemented to reduce and/or limit potentially destructive impacts of the volumetric change of
64 expansive clays on structures such as; replacement of near surface expansive clay, control of
65 compaction and water content, addition of fibrous materials (Mirzababaei et al., 2013), stabilisation
66 using chemical agents (Mirzababaei et al., 2009 and Soltani et al., 2017) and traditional chemical
67 treatment using lime, cement and fly ash (Schanz and Elsaywy, 2015 and Thyagaraj et al., 2016). Due
68 to its low cost, technical efficiency and abundant availability; lime treatment is by far the most
69 common way to suppress volumetric change and enhance strength of expansive clays. Quick lime
70 (CaO) and hydrated lime Ca(OH)_2 are typically considered for stabilization of expansive clays. The
71 reactions following the addition of lime to such a clay in the presence of water have been
72 extensively described by many researchers (Diamond and Kinter, 1965; Diamond and Kinter, 1966;
73 Rogers and Roff, 1997; Boardman et al., 2001; Di Sante et al., 2014; Beetham et al., 2015 and Zhao et
74 al., 2015). There is a consensus that cation exchange, flocculation and agglomeration, carbonization
75 and pozzolanic reaction are responsible for the changes in the clay characteristics. The added lime
76 decomposes partially into hydroxyl ions and calcium ions. Calcium ions tend to replace the
77 monovalent cations such as sodium or any native cations in a process called cation exchange which
78 takes place on the clay particle surfaces. Thus, the surface of clay particle could be balanced by
79 lesser number of hydrated cations (Strawn et al., 2015). This leads to a reduction in the thickness of
80 diffuse double layer that surrounds the clay particles which in turn enhances the bonding with each
81 other to form the flocs (Beetham et al., 2015). Hydroxyl ions increase the pH value in the pore water

82 to nearly 12.4 and as the pH value increases the number of negatively charged sites rises (Al-
83 Mukhtar et al., 2014). The aggressive alkaline environment in the pore water partially destroys the
84 clay layers launching silica and alumina anions in the pore water. Concentration and availability of
85 silica and alumina ions are dependent upon the mineralogy of clay (Cristelo et al., 2012). Alumina
86 and silica anions react with calcium and hydroxyl ions forming desirable cementitious compounds in
87 the form of calcium-silicate-hydrates (CSH), calcium-aluminate-silicate hydrates (CASH) and calcium-
88 aluminate-hydrates (CAH). The formation of the cementitious compounds strengthens the
89 convergence points between particles within the flocs and between the flocs within the aggregates.
90 The immediate formation of such compounds and their role in enhancing the flocculation and
91 agglomeration were reported by (Diamond and Kinter, 1965 and Vitale et al., 2017). This is
92 contradictory to the outcomes of studies that refer to the late formation of the cementitious
93 compounds (see for example; Boardman et al., 2001). Disagreement is also notable with the concept
94 of initial lime consumption which is still used in the British Standard, BS 1942-2 (1990) for the
95 determination of the minimum required percentage of lime to satisfy the cation exchange
96 phenomenon based on the pore water alkalinity as an indicator. Of note, the British Standard, BS
97 1942-2 (1990) assumes that the reactions are to occur as distinct processes. This assumption was
98 one of the main criticisms that were raised by Rogers and Roff (1997). In contrast, Rogers and Roff
99 (1997) used the plastic limit as an indicator rather than the pH value and proposed a new concept
100 called modified initial lime consumption that is based on simultaneous occurrence of all reactions.
101 More recently, these main reactions have been examined and monitored by many studies (see for
102 example; Al-Mukhtar et al., 2014; Tran et al., 2014; Zhao et al., 2015 and Vitale et al., 2017) using
103 chemical and geotechnical parameters but conflicting opinions still exist.

104

105 The efficiency of lime treatment is dependent on many factors such as mineralogical composition of
106 clay, curing time, ambient temperature, mellowing period and lime content. Over the past three

107 decades, contradictory conclusions were reached for the impact of adding various percentages of
108 lime on the mechanical and hydraulic properties of expansive clays. For instance, Bell (1996) stated
109 that the addition of lime to montmorilinitic soil beyond 4% leads to a decline in the strength
110 attributing this behaviour to the lime which is considered as a bad fill and does not have marked
111 cohesion or friction. Similarly; Dash and Hussain (2012) noted that strength gain declines on lime
112 stabilised bentonite specimens if they were treated by more than 9% of lime. In contrast, a study
113 conducted on bentonite clay by Al-Mukhtar et al., (2010) indicated that as the lime content (0-20%)
114 increases; the strength gain increases attributing the initial strength gain to the flocculation induced
115 by cation exchange whereas the long term gain was attributed to the pozzolanic reaction. Both short
116 and long term behaviours were considered as being distinct processes. Al-Mukhtar et al., (2010)
117 attributed the elevated strength gain after the first day to the pozzolanic reaction which was found
118 to be 6 times higher when the temperature is increased from 20°C to 50°C. Ali and Mohamed (2017)
119 observed that the strength gain measured on 7% lime treated expansive clay specimens was
120 temperature and mellowing period dependent in particular during the first day of treatment. This
121 corresponds with the observation made by (Vitale et al., 2017) that the formation of cementitious
122 compounds starts since the very short time from the addition of lime. The current study, therefore,
123 examines and evaluates the rate of strength gain under two different environmental temperatures
124 over a curing period of 7 days on specimens treated with various percentages of lime. Moreover,
125 since the ongoing formation of cementitious compounds causes an increased resistance to
126 compaction (Osinubi, 1998), the compaction test will be conducted with view to track down the
127 effects on dry unit weight as a function of lime percentage, temperature and compaction delay.
128 Furthermore, the changes in the hydraulic properties are investigated to assess the impact and
129 extent of growing cementitious compounds due to increased lime content. Earlier studies (see for
130 example; McCallister and Petry, 1992; Metelková et al., 2011; Al-Mukhtar et al., 2012) suggested
131 that the ongoing formation of cementitious compounds in the available pores leads to a gradual

132 decline in the permeability of treated expansive clays but further quantification of the time-
133 dependent changes is needed.

134 2. Materials

135 Expansive clay in the form of Pure Wyoming Sodium Bentonite powder was selected for the testing
136 programme. The used clay composed primarily of montmorillonite mineral in addition to a small
137 amount of non-clay minerals e.g. Quartz, calcite and feldspar. The used clay is classified as extremely
138 high plastic clay due to its high liquid limit of 330% and plastic limit of 43%. The used expansive clay
139 was supplied by Potclays Ltd, UK and its chemical analysis is illustrated in Table 1. The results of
140 standard Proctor Compaction tests revealed that as the water content increases the dry unit weight
141 decreases. Neither maximum dry unit weight nor optimum moisture content could be determined
142 by conduction of the compaction tests due to the expanding lattice of used bentonite clay with
143 increasing water content. An optimum water content was, therefore, estimated according to the
144 correlation suggested by Sridharan and Nagaraj (2005) as a function of the plastic limit. As a result,
145 moisture content of 40 % was taken as the optimum moisture content and the corresponding dry
146 unit weight was found to be 12.16 kN/m³. Fine hydrated lime which was passed through 425µm
147 sieve and stored in a sealed container, was utilized. In this investigation, percentages of lime were
148 selected to be 5, 7, 9, 11, and 13% of the dry weight of clay.

149 Table 1: Chemical analysis of used clay as provided by the supplier

Element and amount (%)								
SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	CaO	FeO	LOI*	Trace
63.02	21.08	3.25	2.67	2.57	0.65	0.35	5.64	0.72

150 *Loss of ignition

151

152 3. Experimental Programme

153 Lime-clay mixtures were prepared by the addition of specific percentage of lime to clay in a powder
154 form. Subsequently, a predetermined amount of water was added gradually whilst the mixture was
155 manually mixed and kneaded. To ensure high degree of pulverization and uniform treatment each

156 mixture was passed through 2 mm sieve. Furthermore, the mixture was mechanically mixed to
 157 ensure complete and thorough mixing. In this paper, three series of experimentations have been
 158 conducted to assess the evolution of reactions and impacts on physical, mechanical and hydraulic
 159 properties. Table 2 demonstrates the variable and fixed parameters in each series of tests following
 160 the initial mixing. In order for preparation of specimens under controlled laboratory conditions to be
 161 carried out, an environmental cupboard that is capable of controlling both temperature and
 162 humidity, is used in this investigation. In all experiments a relative humidity of 90% was maintained
 163 and found to be adequate to prevent loss of water from specimens during mellowing and curing
 164 periods.

165 Table 2: Testing programme

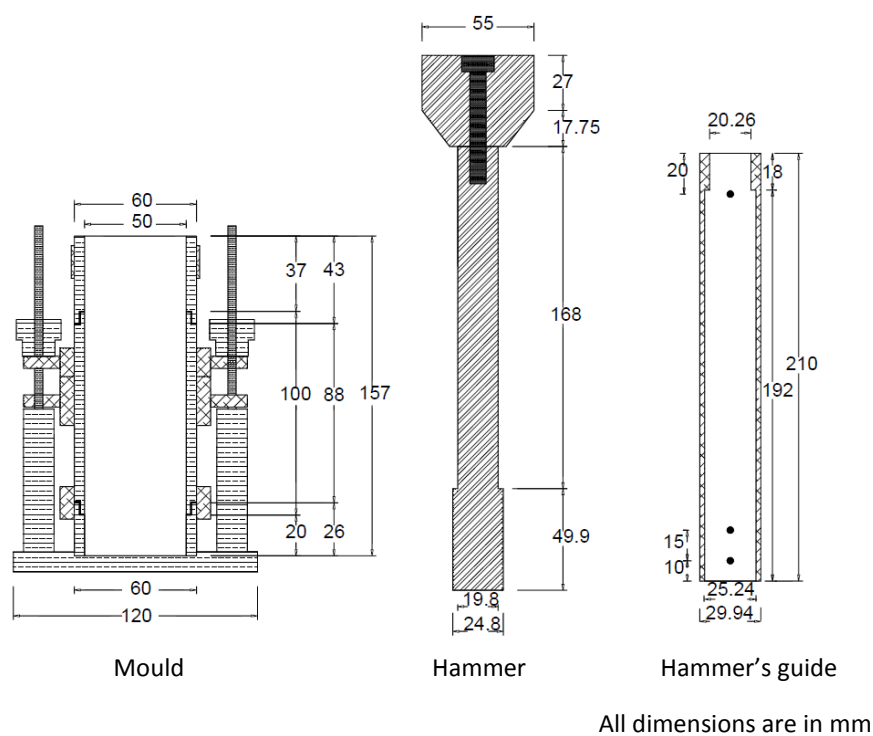
Series	Parameters	
	Variables	Fixed
Compaction tests	MP = 3, 6, 12, 24, 48, 72 and 168h T = 20°C and 40°C LP = 5, 7, 9, 11 and 13%	Compactive energy $w_c = 40\%$
Unconfined compressive strength tests	C = 0, 3, 6, 12, 24, 48, 72 and 168h T = 20°C and 40°C LP = 5, 7, 9, 11 and 13%	$Y_d = 12.16 \text{ kN/m}^3$ $w_c = 40\%$ MP = zero h
Permeability tests	T = 20°C and 40°C LP = 5, 7, 9, 11 and 13%	$Y_d = 12.16 \text{ kN/m}^3$ $w_c = 40\%$ MP = 24h

166 where; C = curing time, MP = mellowing period, LP = lime percentage, T = temperature, w_c =
 167 moisture content and Y_d = Dry unit weight

168 3.1 Compaction tests

169 A total of 70 compaction tests have been conducted in this series according to the parameters
 170 illustrated in Table 2. Figure 1 shows the newly developed purpose made mould and hammer by the
 171 authors and reported in Ali and Mohamed (2017). The newly developed mould and hammer were
 172 designed to prepare specimens under relatively comparable compactive energy as in the standard
 173 Proctor Compaction test whilst making significant saving in materials, time and effort. Specimens
 174 were compacted in 6 layers of which each layer has received 15 blows by 1.25 kg hammer falling
 175 from 150mm. It should be noted that the number of blows was increased from 13 to 15 blows to
 176 ensure preparation of specimens with the same dry unit weight to those obtained from the standard

177 Proctor test. All specimens were then compacted with the same compactive energy. The specimens
 178 prepared by the newly developed mould showed better density uniformity and repeatability.
 179 Following the preparation of lime and clay mixtures, each mixture was placed in double sealed bag
 180 and stored to mellow in the environmental cupboard under the desired temperature and a relative
 181 humidity of 90% for the predetermined period of time except for the mixtures that were compacted
 182 directly after mixing (zero h mellowing). Once the predetermined mellowing period is elapsed,
 183 mixtures were compacted and tested.



184

185 Figure 1: Sketch of the utilised mould and hammer

186

187 3.2 Unconfined Compressive Strength tests

188 Specimens for Unconfined Compressive Strength (UCS) tests were mixed and compacted statically
 189 with parameters illustrated in Table 2. The utilized compaction method was found efficient and
 190 effective in specimen preparation reducing the scattering of UCS results to less than 4% (Ali and
 191 Mohamed, 2017). Immediately upon completion of compaction process, compacted specimens were
 192 extracted from the mould and measurements of specimen's dimensions and mass were taken. Each

193 specimen was then wrapped promptly by cling film, put in a double sealed bag and stored for curing
194 in the environmental cupboard under a desired temperature (20°C or 40°C) and 90% relative
195 humidity for a specific period of time of 3, 6, 12, 24, 48, 72 and 168 h counted from the end of
196 compaction process. An automatic loading machine was used to perform the UCS tests. Data for the
197 axial stress and axial strain were recorded automatically every second. All specimens were tested at
198 a rate of 1mm/min.

199 3.3 Permeability tests

200 Permeability tests were performed to determine the permeability properties as a function of lime
201 content on specimens mellowed for 24h at two different environmental temperatures. The results of
202 Ali and Mohamed (2017) showed that increasing the mellowing period increases the permeability
203 coefficient. Furthermore, specimens mellowed for 24h showed less reduction in the permeability
204 coefficient over the testing period due to fast consumption of 7% lime. It was, therefore, decided to
205 select 24h mellowing period in order for the impact of lime content to be clearly observed. Following
206 the mellowing period the mixtures were statically compacted to produce specimens with 50 mm in
207 diameter and 10 mm high (half the ring's height) with a dry unit weight of 12.16 kN/m³ and water
208 content of 40 %. Upon completion of the compaction process, the specimens were placed in GDS
209 Automatic Oedometer System with hydraulic cell to initiate the permeability test. A pressure-volume
210 controller is connected to the base of the hydraulic cell in order to apply a base water pressure of 35
211 kN/m² on the bottom of the specimen whereas, the top of specimen was kept under water at
212 atmospheric pressure. The permeability tests were performed according to BS 1377-6 (1990).
213 Combining application of base pressure and halving the thickness of specimens was found effective
214 to speed up the flow of water through the specimen (Ali and Mohamed, 2017). As a result of which a
215 stable measurement of the swelling pressure can be reached in a shorter period of time. No vertical
216 deformation was permitted during the permeability tests by applying increasing load to prevent
217 swelling of specimens which means that all specimens maintained their initial dry unit weight
218 throughout the testing period of 3 days. Of note, all specimens were prepared with an initial degree

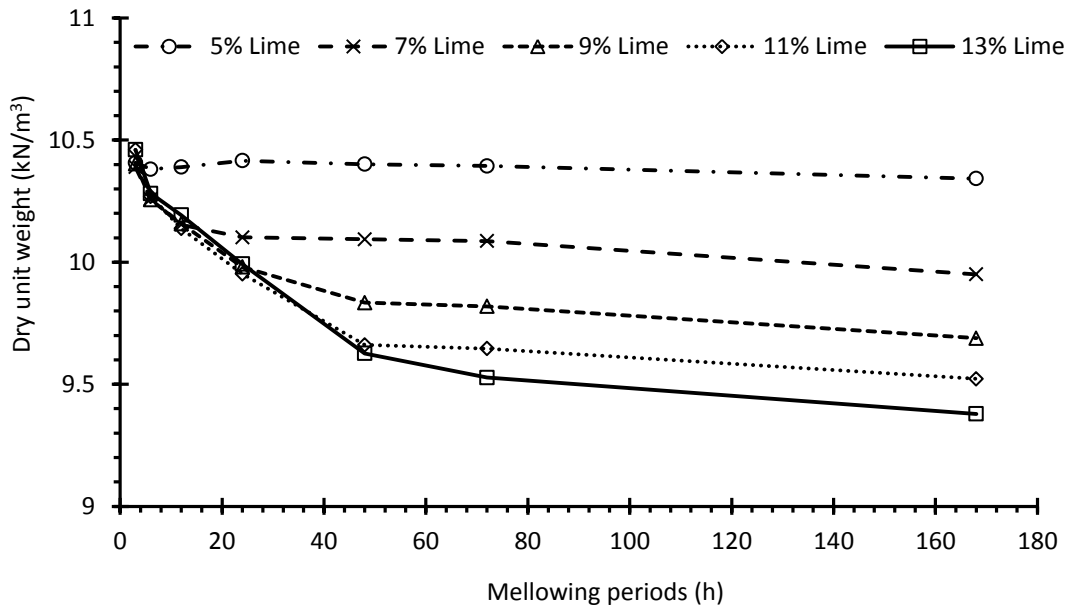
219 of saturation of 94.7%. Measurements of volume of water percolated into the specimens indicated
220 that during the first hour, the volume of water passed through the specimen was greater than the
221 volume of air in the specimen which confirms reaching full saturation within the first hour of testing.
222 The coefficient of permeability was then determined after 6, 12, 18, 24, 36, 48, 60 and 72 h from the
223 onset of test. A period of 6h deemed to be sufficient to ensure reaching full saturation and stable
224 reading of swelling pressure.

225 4. Results and discussion

226 4.1 Dry unit weight

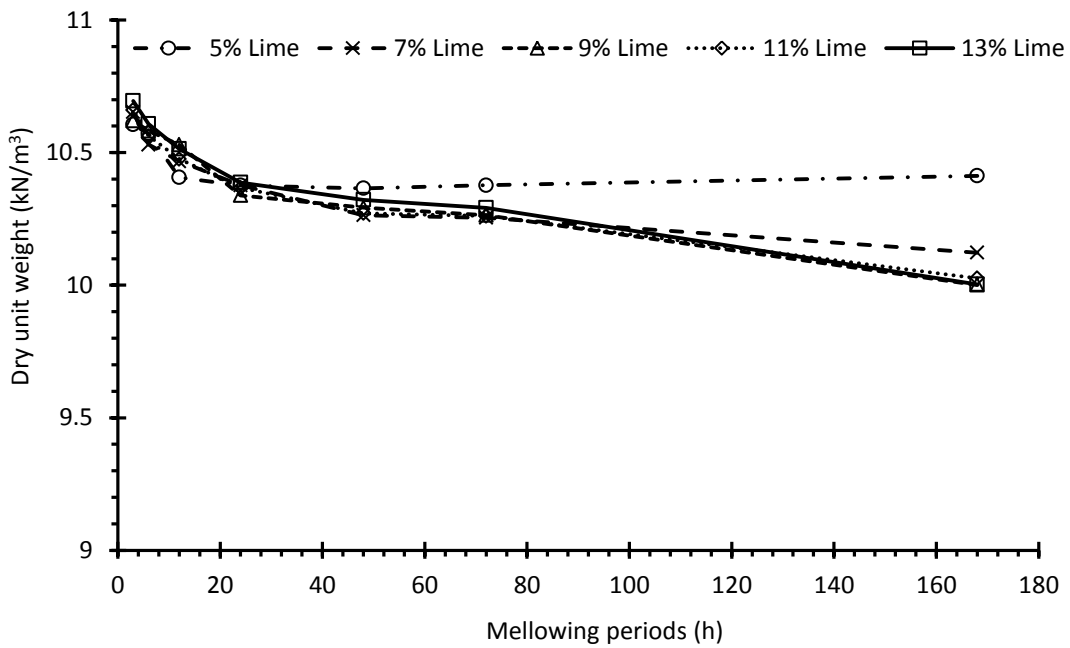
227 The dry unit weight of untreated clay specimens that were prepared with 40% moisture content was
228 found to be 12.16 kN/m³. The dry unit weight of specimens that were treated with 5, 7, 9, 11 and
229 13% lime and compacted and tested directly after mixing were 10.68, 10.75, 10.73, 10.70 and 10.71
230 kN/m³ respectively. These results show a decline by about 12% in the dry unit weight of treated
231 specimens compared with that of untreated specimen. This immediate reduction in the dry unit
232 weight can be attributed to the immediate changes due to the flocculation that is predominantly
233 induced by cation exchange phenomenon and the formation of initial cementitious compounds.
234 Lime content did not play a major role at zero h mellowing due to its quantity which seemed
235 sufficient to induce cation exchange. The resulting values of dry unit weight on specimens mellowed
236 at 40°C and 20°C were plotted against the mellowing period in Figures 2 and 3 respectively. The
237 effect of lime percentage on attained dry unit weight is very notable when mellowing was conducted
238 at 40°C. Whereas specimens mellowed at 20°C showed a lower declining rate in the dry unit weight
239 with increased mellowing period. In addition, no further drop in dry unit weight was observed on
240 specimens treated with 5% lime after 24h of mellowing which could be due to complete
241 consumption of lime.

242



243

244 Figure 2: Dry unit weight of specimen mellowed at 40°C and prepared with various lime percentages
 245 against mellowing period



246

247 Figure 3: Dry unit weight of specimens mellowed at 20°C and prepared with various lime
 248 percentages against mellowing period

249

250 The data presented in Figures 2 and 3 show a significant drop in the measured dry unit weight with
 251 increasing mellowing period up to a specific period of time. Beyond which a relatively reduced drop

252 in the dry unit weight would be observed. The measured data, therefore, suggest that the declining
253 pattern in dry unit weight is a two-stage process namely stages 1 and 2. During stage 1, remarkable
254 drop in the dry unit weight was observable and accelerated at high temperature of 40°C but the
255 behaviour relied on the lime content. Subsequent stage (stage 2) was characterised by a slower rate
256 of declining dry unit weight which was also dependent on lime availability in particular when
257 mellowing was conducted at 40°C. The fast declining in the dry unit weight during stage 1 can be
258 attributed to all chemical reactions including pozzolanic reaction which occur upon the addition of
259 lime in the presence of water. Recent results by Vitale et al., (2017) indicated that the ongoing
260 growth of cementitious compounds starts shortly after the addition of lime. Al-Mukhtar et al., (2014)
261 observed an accelerating rate of lime consumption with increasing temperature. Accordingly, the
262 mild decline in the dry unit weight in the second stage indicates that most of the lime was consumed
263 during stage 1 in particular when mellowing was carried out at higher temperature.

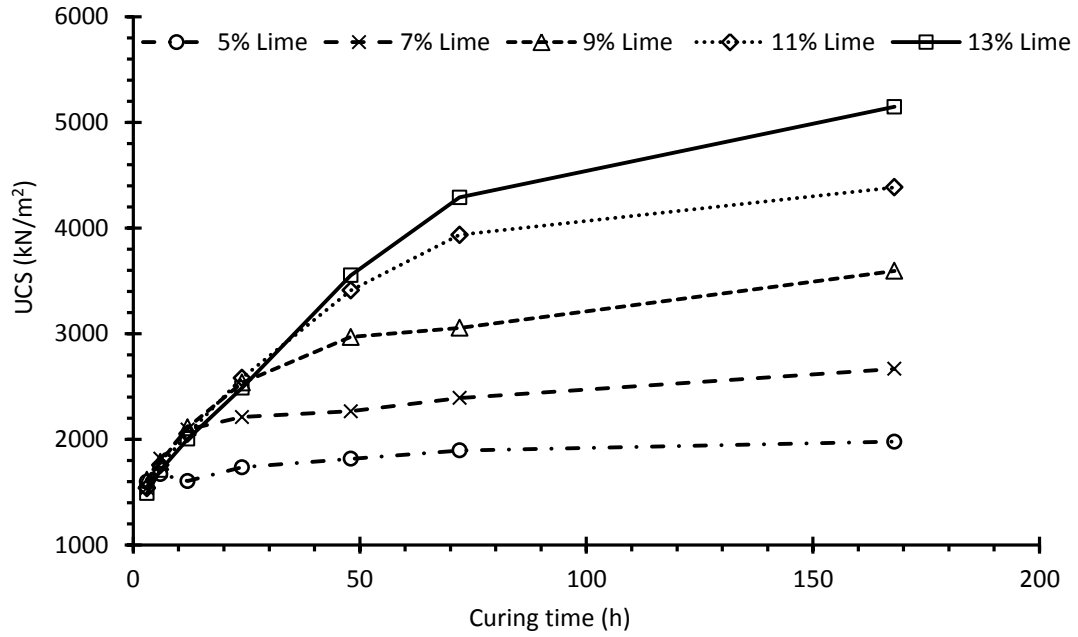
264 Careful inspection of the data presented in Figures 2 and 3 clearly shows that during stage 1, the
265 decline in the dry unit weight for specimens mellowed at 20°C is not as substantial as those
266 measured on specimens mellowed at 40°C. This is due to the impact of temperature on the kinetic of
267 pozzolanic reaction as suggested by De Windt et al., (2014). The pozzolanic reaction would be
268 accelerated in the loose mixture leading to increased amount of cementitious compounds formed at
269 40°C which in turn provides more resistance to compactability than that experienced on specimens
270 mellowed at 20°C. As a result, substantial drop in the dry unit weight was observable when
271 specimens were mellowed at 40°C. The period of time taken for the fast reaction (stage 1) was lime
272 content dependent in particular when mellowing was carried out at higher temperature. Mellowing
273 at low temperature of 20°C though resulted in a slight difference in the measured dry unit weight
274 even with increasing lime content. The start of the slowdown period (stage 2) was found to occur
275 after 6, 12, 24, 48, and 72 h for specimens treated with lime content of 5, 7, 9, 11, and 13%
276 respectively at 40°C. Since the same compactive energy was used, the decline in dry unit weight can
277 be attributed to an increased utilisation of the compactive energy in destroying the ongoing growth

278 of cementitious compounds with increasing mellowing period. Therefore, the decline and
279 subsequent steadiness in the value of dry unit weight can be used as an indicator to reflect the
280 ongoing growth of cementitious compounds over the mellowing period.

281 4.2 Unconfined Compression Strength

282 The measured Unconfined Compressive Strength (UCS) on untreated specimens was found to be
283 0.525 MPa. The UCS values on specimens that were treated by 5, 7, 9, 11 and 13% of lime and tested
284 directly after compaction were 1.35, 1.30, 1.30, 1.30 and 1.25 MPa respectively. The immediate
285 increase in strength reflects immediate changes in the clay characteristics due to fast interaction
286 between lime and clay in the presence of water. The immediate change in strength is consistent with
287 the observation made by Vitale et al., (2017). The results of UCS at 40°C and 20°C were plotted
288 against the curing periods in Figures 4 and 5 respectively. From Figure 4, it can be clearly seen that
289 the attained UCS values were increased substantially with the addition of more lime achieving 1.7,
290 2.7, 3.6, 4.4 and 5.2 MPa on specimens treated with lime content of 5, 7, 9, 11 and 13% respectively
291 after 7 days (168 h) of curing at 40°C. It is clear that fast strength gain was experienced with
292 increasing lime content. The rate of strength gain is nearly equal and fast during the initial stage. The
293 initial stage can be defined as the period of time after which the rate of strength gain begins to slow
294 down drastically. Increasing curing time has had a minor effect on the UCS beyond the initial stage
295 period which is significantly related to the lime content. The change in the strength gain behaviour
296 was recorded to occur at 6, 12, 24, 48, 72 h for specimens treated with lime content of 5, 7, 9, 11,
297 and 13% respectively which are exactly the same periods of time for the change in declining rate of
298 dry unit weight (see Figure 2). This confirms that the fast chemical reaction occurs whether in a loose
299 state during mellowing or after compaction during curing and results in aggregation and
300 cementation of the clay particles. It is also worth noting that elevating environmental temperature
301 to 40°C accelerated the consumption of available lime by pozzolanic reaction. In contrast, curing at
302 20°C led to a maximum strength gain of about 2.3 MPa after 7 days as it can be seen in Figure 5 for
303 specimens with lime contents of 9, 11 and 13%. The UCS measured on specimens treated with 5 and

304 7% of lime were even lower achieving only UCS values of 1.7 and 2.1 MPa respectively. Specimens
305 treated with 5% and 7% of lime showed a slower strength gain after 24 and 72 h respectively. This
306 reinforces the previous interpretation of the impact of temperature on the lime consumption and
307 rate of pozzolanic reaction as a function of available lime.



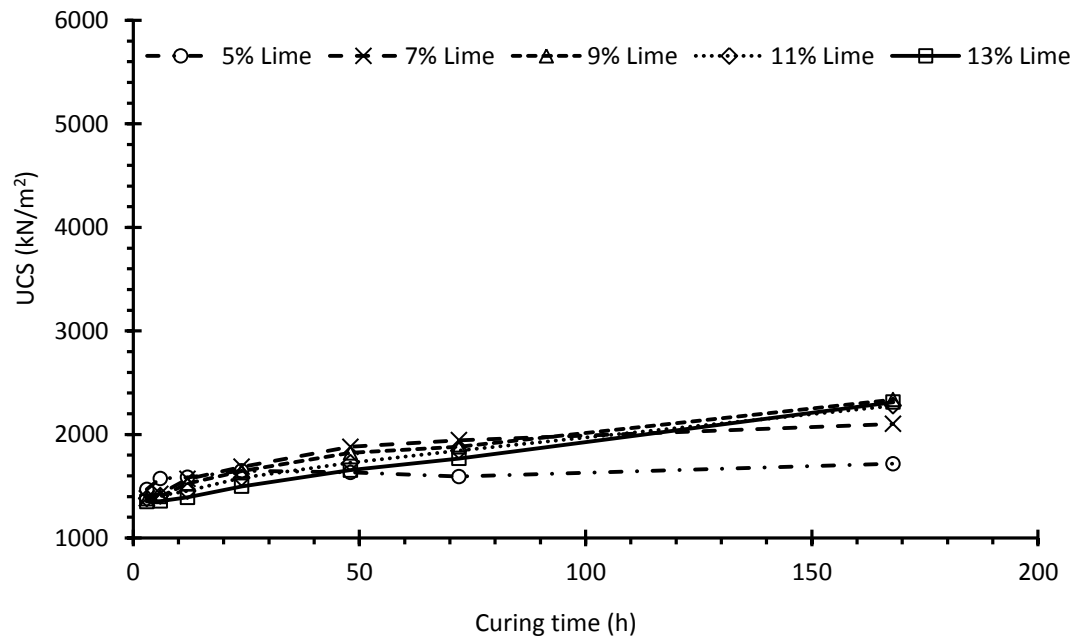
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Figure 4: UCS on specimens prepared with various lime percentages and cured at 40°C against curing time

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311



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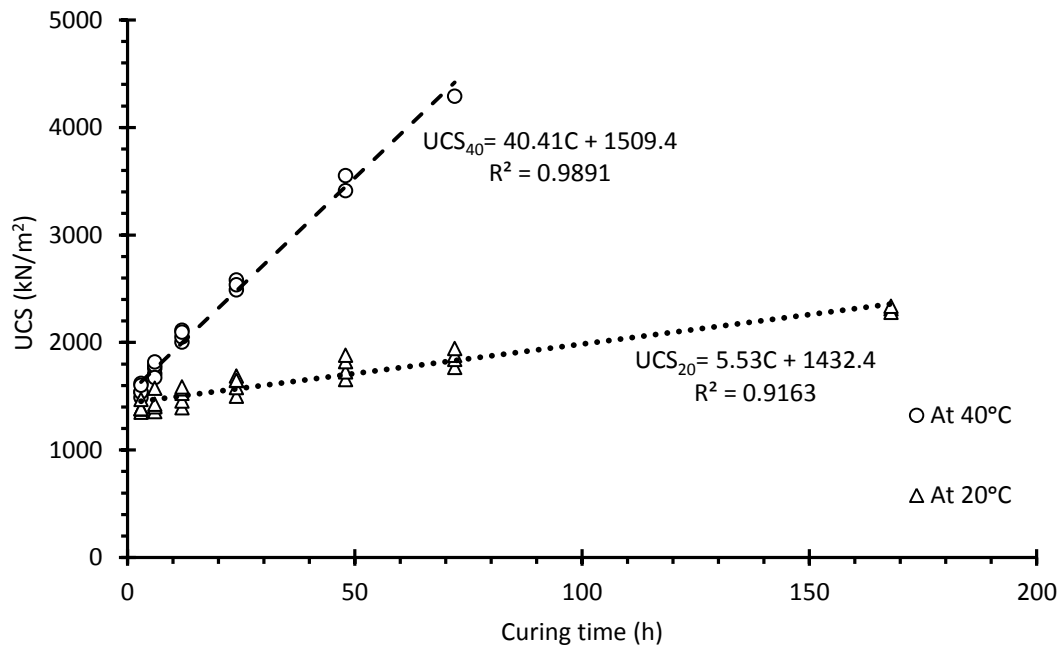
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Figure 5: UCS on specimens prepared with various lime percentages and cured at 20°C against curing time

314

315 The UCS values on specimens treated with various amount of lime were plotted as a function of
 316 curing time that had been recorded at the end of initial stage (stage 1) prior to the beginnings of
 317 slowdown period for both curing temperatures as shown in Figure 6. It can be clearly noted that

318 linear relationships between the UCS values and the curing time at 20°C and 40°C are attainable. The
319 rate of strength gain during stage 1 at 40°C is 8 times higher than that recorded on specimens cured
320 at 20°C irrespective of the lime content. Lime content affected the maximum strength in the initial
321 stage and the length of time until reaching stage 2 of the reaction in which the strength gain is
322 characterised by its low rate. These results also confirm the effect of curing temperature in
323 accelerating the strength gain in lime stabilized clays as observed previously by several authors (see
324 for example; Al-Mukhtar et al., 2010; Nasrizar et al., 2012; Toohey et al., 2013 and Saldanha and
325 Consoli, 2016). This can be attributed to the impact of temperature in increasing the kinetic of
326 pozzolanic reaction (De Windt et al., 2014) and thus on the rate of formation of cementitious
327 compounds. Moreover, the results suggest that lime content plays an important role in the
328 continuity of the fast rate of strength gain. Therefore, it can be stated that the accelerated rate of
329 strength gain is evident at high curing temperature for a specific period of time but it depends on
330 the availability of lime. The patterns for the UCS gain as a function of lime content and curing time
331 are in harmony with those observed earlier for the decline in the dry unit weight. It is therefore
332 reasonable to suggest that upon addition of lime in the presence of water, all chemical reactions
333 take place including pozzolanic reaction resulting in fast gain in strength which becomes remarkably
334 high with increased lime content and higher environmental temperature. Followed by another stage
335 in which a slower reaction occurs dependent on the availability of lime and temperature.



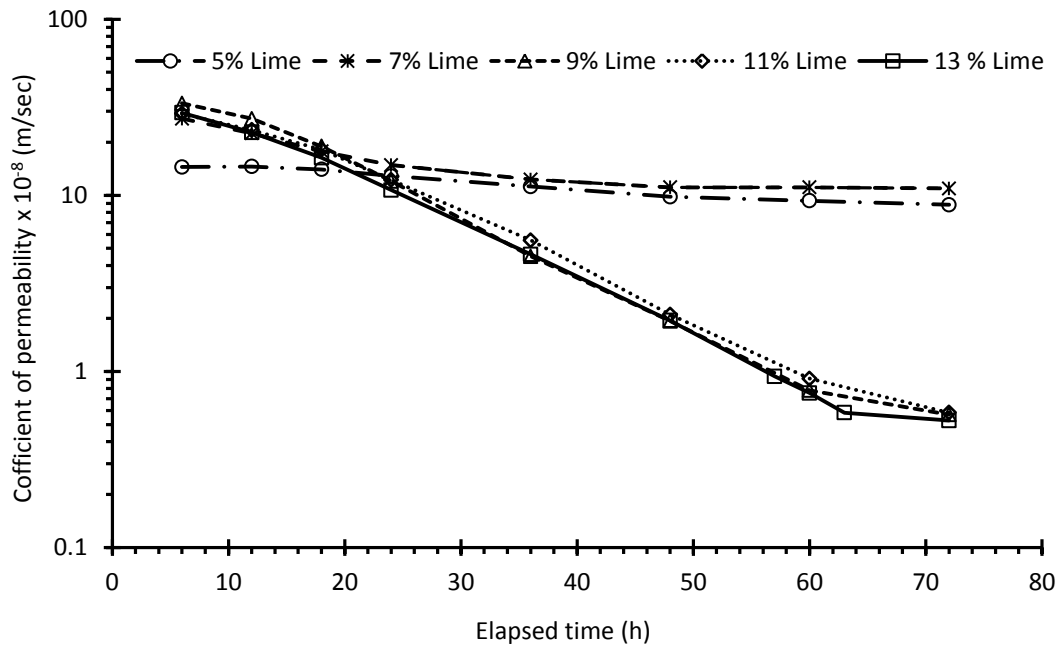
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337 Figure 6: Correlations for the strength gain rate during stage 1 at both temperatures

338 4.3 Permeability test

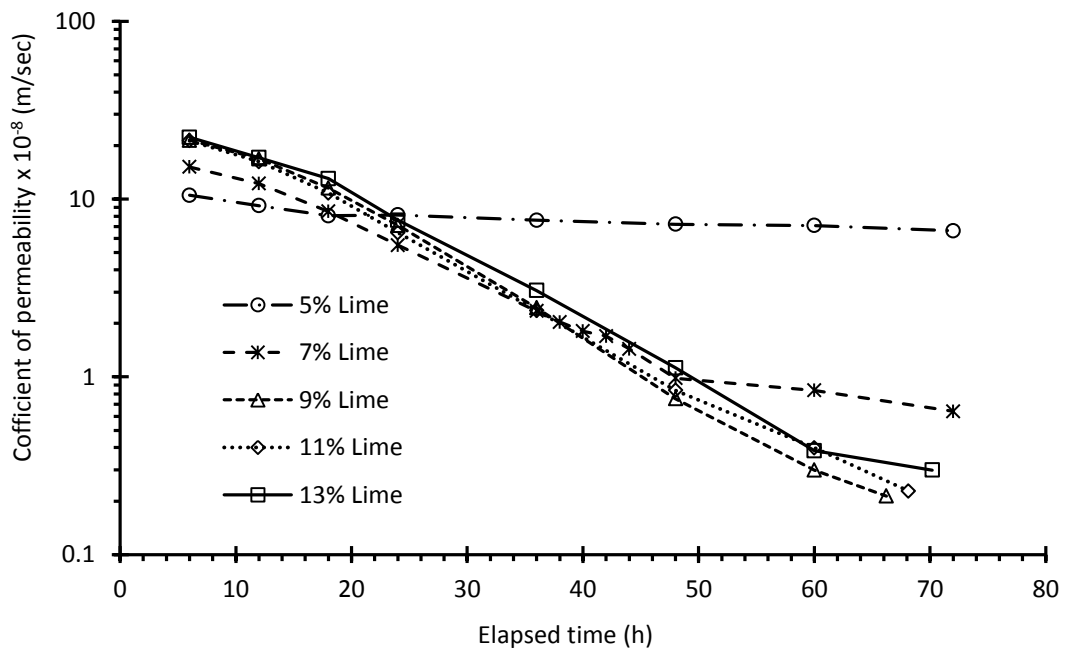
339 The coefficient of permeability was measured over a period of three days from the onset of the
 340 test on specimens that were mellowed for 24h at 40°C and 20°C. Figures 7 and 8 show data for the
 341 coefficients of permeability against time elapsed from the start of test for specimens with different
 342 lime percentages at 40°C and 20°C respectively. Of note, the coefficient of permeability of pure clay
 343 could not be determined indicating that it is exceptionally impermeable clay. Whereas, the
 344 coefficients of permeability of lime treated specimens were observed to be initially in the order of
 345 (10^{-7} m/s). This is generally corresponded to the impact of cation exchange phenomenon that causes
 346 flocculation upon the addition of lime. Flocculation which occurs in a loose state before compaction
 347 process, is enhanced by the initial cementitious compounds (Diamond and Kinter, 1965 and Vitale et
 348 al., 2017). These cementitious compounds that have developed at the sites of contact between the
 349 particles within the flocs and between the flocs within the clusters causing the formation of intra-
 350 floc and inter-floc pores (Beetham et al., 2015). Therefore, the fabric of lime-treated specimens
 351 became more porous than untreated specimen even after the compaction. The measured values for
 352 the coefficient of permeability for specimens that were mellowed at 40°C were higher than those

353 mellowed at 20°C. This is due to the effect of temperature of 40°C on accelerating the kinetic of the
354 pozzolanic reaction during the first day rendering the fabric of treated clay more open structure than
355 that formed at 20°C. However, the coefficient of permeability reduced substantially as the time
356 elapsed due to the ongoing formation of cementitious compounds. This behaviour manner was
357 reported previously in some studies (Wild et al., 1987; Metelková et al., 2011 and Al-Mukhtar et al.,
358 2012). Moreover, the microfabric investigation conducted by Bozbey (2017) using Mercury intrusion
359 porosimetry indicated that lime stabilized clay specimens had lesser total porosity in the long term
360 compared with that measured in the short term due to the ongoing growth of cementitious
361 compounds in the available pores causing a gradual reduction in the effective porosity. Data in
362 Figures 7 and 8 suggest that coefficient of permeability on specimens treated with lime contents of
363 9, 11 and 13% declined exponentially with the elapsed time reaching lower values by two orders of
364 magnitude after 72 h than their initially attained permeability coefficient due to the ongoing growth
365 of cementitious compounds. In contrast, the hydraulic behavior of specimens treated by 5% and 7%
366 at both temperatures was different. With lime content of 7%, the coefficient of permeability for the
367 specimen that was mellowed at 20°C showed exponential decline as seen in Figure 8 but the decline
368 in the permeability slowed down after 48 h. Whereas the permeability coefficient of 7% lime treated
369 clay specimen that was mellowed at 40°C, declined remarkably during the first 24 h and then
370 became nearly steady for the rest of the testing duration. These results indicate that there is not
371 enough amount of lime to sustain formation of cementitious compounds during the rest of
372 submerging period unlike treatment with higher lime contents. This can be attributed to the effect
373 of temperature in accelerating the consumption of lime which was previously reported by Al-
374 Mukhtar et al., (2014). Moreover, the coefficients of permeability on 5% lime treated specimens at
375 both temperatures were nearly steady during the 3-day duration. This indicates that the lime was
376 consumed during the mellowing period. It can be stated the permeability results correspond to a
377 great extent with the results of strength and dry unit weight. The formation of such compounds is
378 dependent on the availability of lime while the temperature controls the rate of lime consumption.



379

380 Figure 7: coefficient of permeability on specimens mellowed at 40°C and prepared with various lime
 381 percentages



382

383 Figure 8: Coefficient of permeability on specimens mellowed at 20°C and prepared with various lime
 384 percentages

385 5. Conclusions

386 In this investigation three series of experimentations were conducted to assess the impacts of lime
387 content and environmental temperature on the physical, mechanical and hydraulic properties of
388 lime treated expansive clays. A number of conclusions can be drawn from this investigation;

389 1- Mellowing specimens at temperature of 40°C results in higher drop in the attained dry unit
390 weight providing availability of lime. Furthermore, drop in the dry unit weight when
391 specimens were mellowed at 20°C is not as substantial as that measured at 40°C during the
392 initial stage due to the accelerated formation of cementitious compounds at higher
393 temperature.

394 2- It is apparent that strength gain and dry unit weight follow clearly a two-stage process
395 irrespective of the environmental temperature. Initially a fast change occurs for a specific
396 period of time depending on the availability of lime and environmental temperature.
397 Subsequently, the change gets relatively slow and is lime dependent after that. This
398 behaviour should be taken into consideration when using the accelerated regime to predict
399 the strength gain under normal condition.

400 3- The rate of strength gain on specimens cured at 40°C is found to be significant at 8 times
401 higher than that measured on specimens cured at 20°C.

402 4- Results attained for the strength gain and dry unit weight give a strong indication of
403 concurrent chemical reactions in particular during the early stage of lime addition.

404 5- The lime content and environmental temperature have a great impact on the hydraulic
405 behaviour performance of lime treated clay. The decline in permeability coefficient is found
406 to be exponentially over the duration of test.

407

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