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

3 Hatim Ali[1] and Mostafa Mohamed[2*]

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5 [1] PhD research student, School of Engineering, Faculty of Engineering and Informatics, University of

6 Bradford, Bradford, West Yorkshire, BD7 1DP, UK.

7 [2] Senior Lecturer, School of Engineering, Faculty of Engineering and Informatics, University of Bradford,

8 Bradford, West Yorkshire, BD7 1DP, UK.

9 [*] Corresponding author

10 Dr Mostafa Mohamed

11 Email: m.h.a.mohamed@bradford.ac.uk

12 Phone: +44(0) 1274 233856

13 Fax: +44(0) 1274 2341111

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hydraulic properties of extremely high plastic clays

Hatim Ali and Mostafa Mohamed

Abstract:

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

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

1. Introduction

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

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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   compacability (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.

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/m^3. 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_2O_3	Fe_2O_3	MgO	Na_2O	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

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 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 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

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

7

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.

Mould   Hammer   Hammer's guide

All dimensions are in mm

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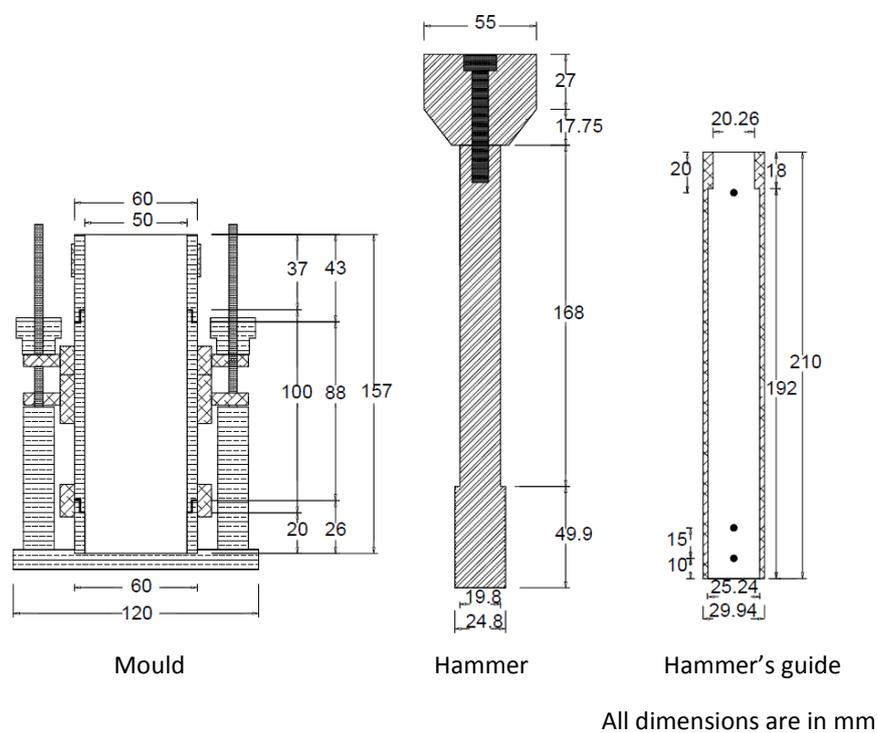
185   Figure 1: Sketch of the utilised mould and hammer

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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

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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.

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/m^3 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/m^2 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/m^3. 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/m^3 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.

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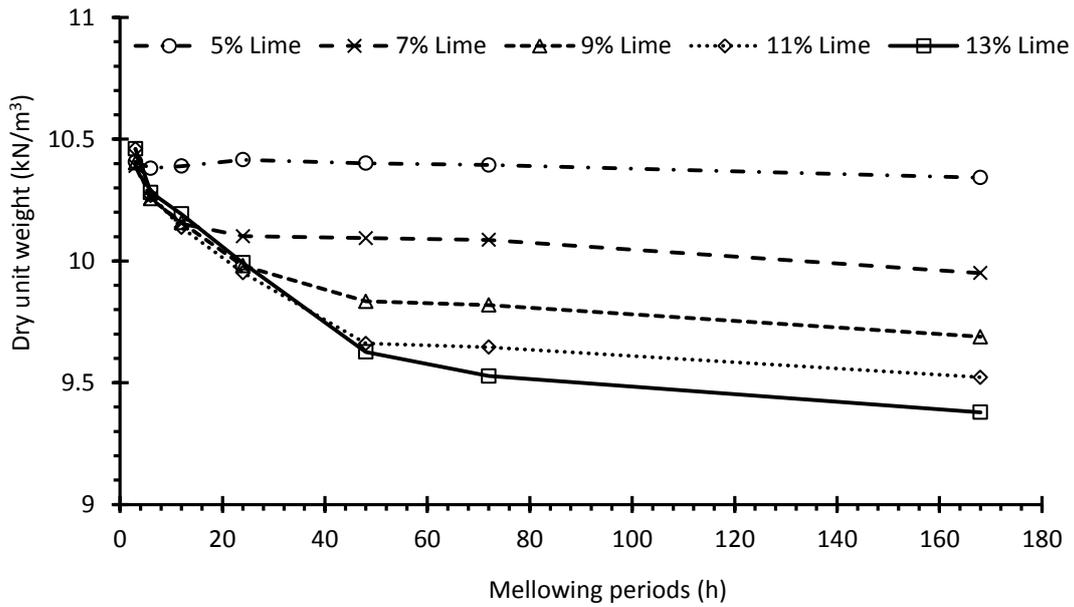
Figure 2: Dry unit weight of specimen mellowed at 40°C and prepared with various lime percentages

against mellowing period

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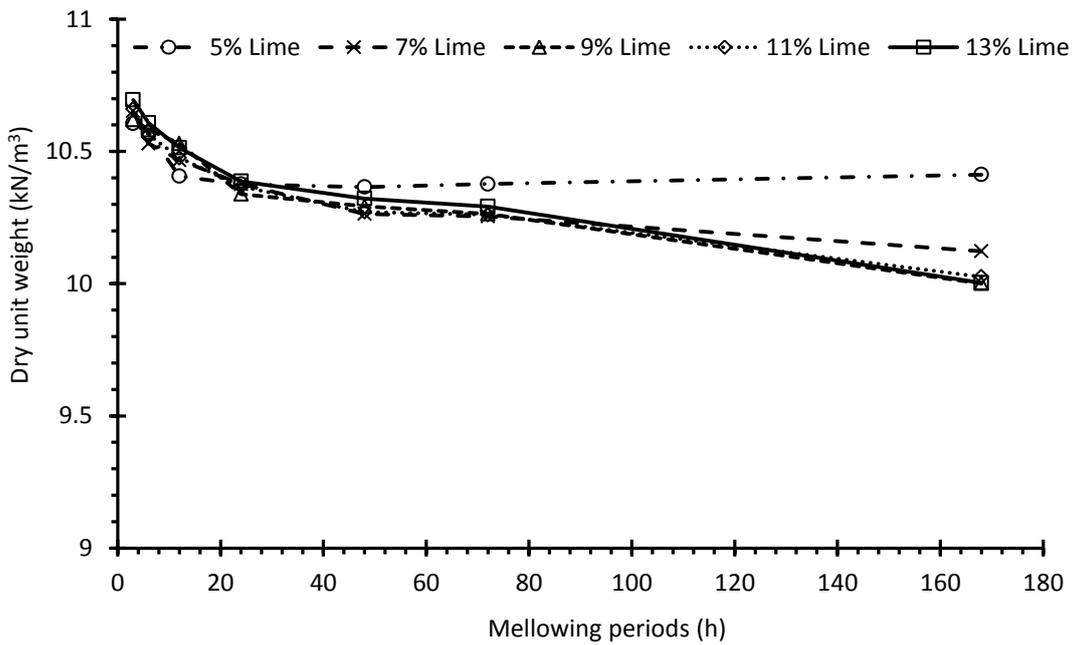
Figure 3: Dry unit weight of specimens mellowed at 20°C and prepared with various lime percentages against mellowing period

The data presented in Figures 2 and 3 show a significant drop in the measured dry unit weight with

increasing mellowing period up to a specific period of time. Beyond which a relatively reduced drop

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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

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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

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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

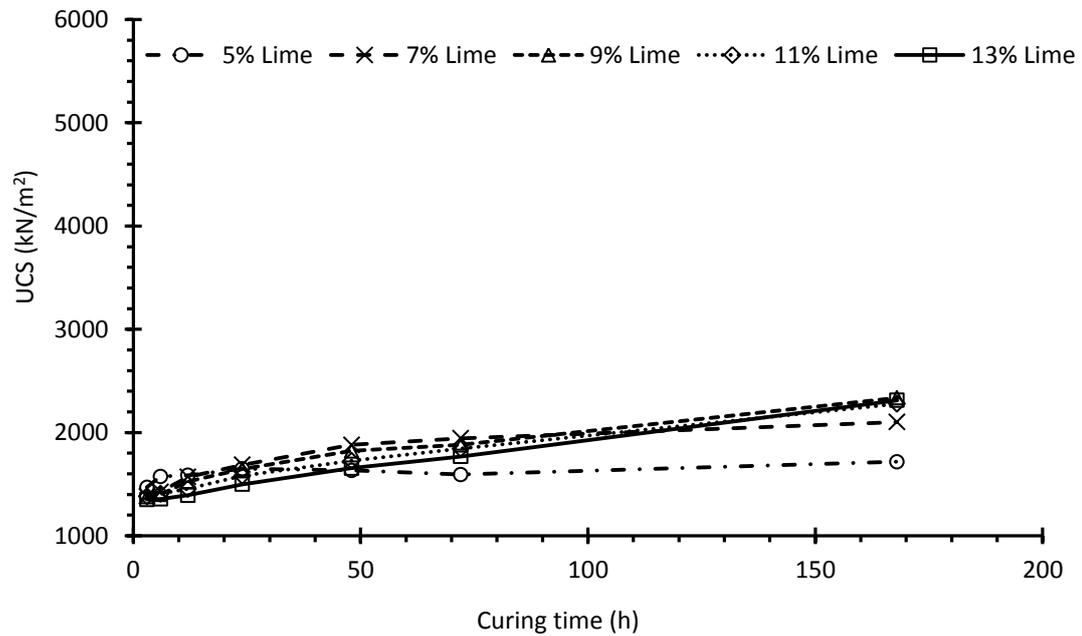307   rate of pozzolanic reaction as a function of available lime.
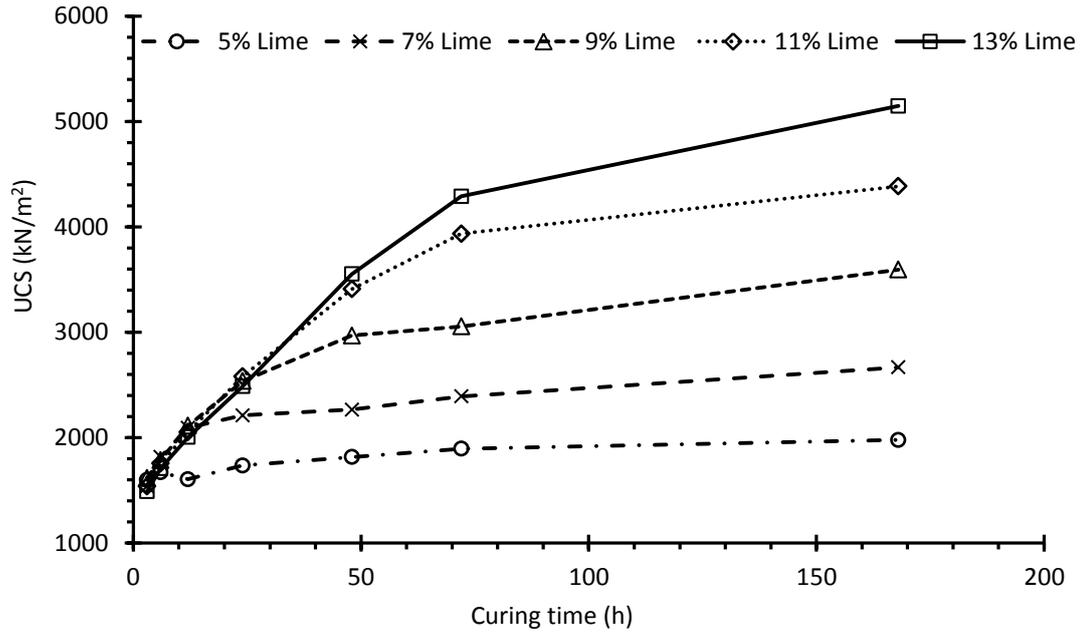
Figure 4: UCS on specimens prepared with various lime percentages and cured at 40°C against curing time
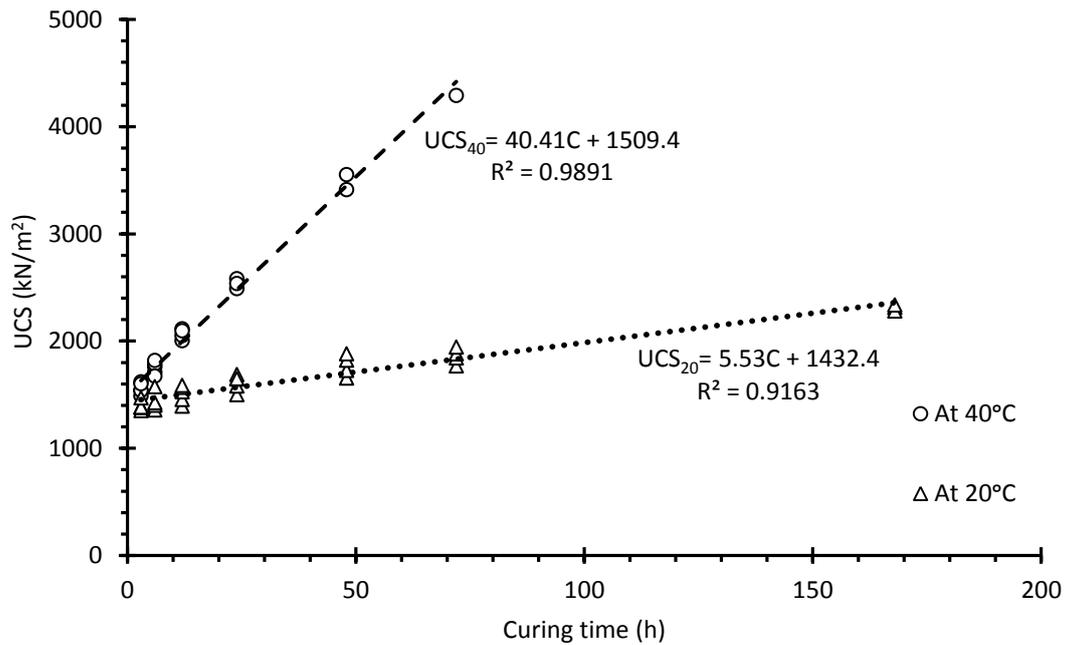

Figure 5: UCS on specimens prepared with various lime percentages and cured at 20°C against curing time

The UCS values on specimens treated with various amount of lime were plotted as a function of curing time that had been recorded at the end of initial stage (stage 1) prior to the beginnings of 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.

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

The figure shows UCS (kN/m²) versus Curing time (h) with two data series:
- $UCS_{40} = 40.41C + 1509.4$, $R^2 = 0.9891$ (At 40°C, ○)
- $UCS_{20} = 5.53C + 1432.4$, $R^2 = 0.9163$ (At 20°C, △)

4.3 Permeability test

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

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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.
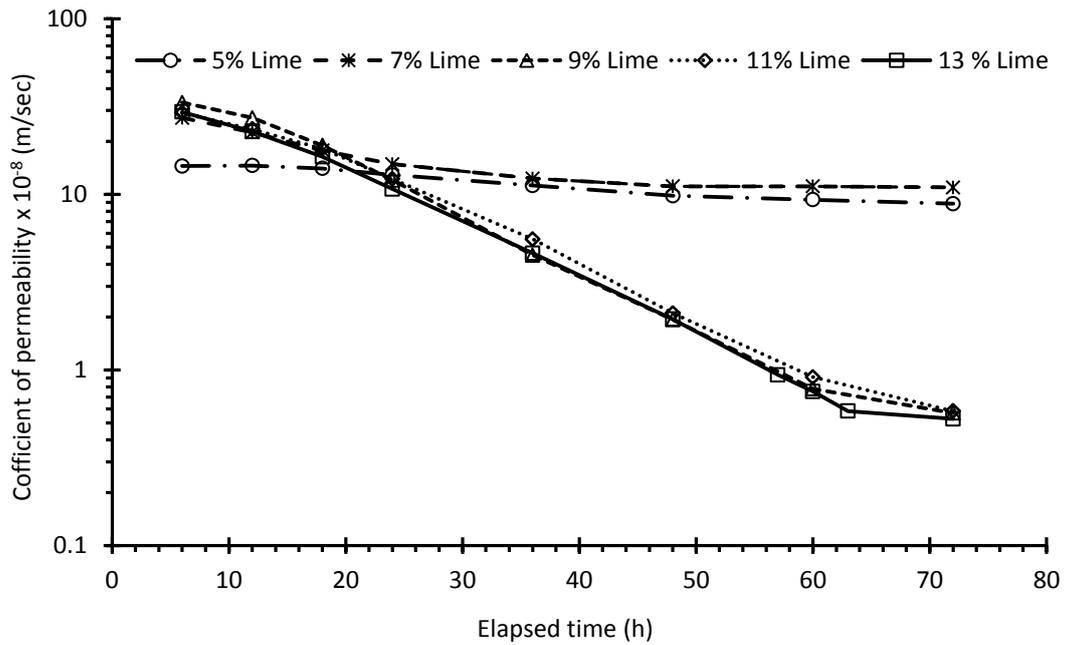
379

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

381   percentages
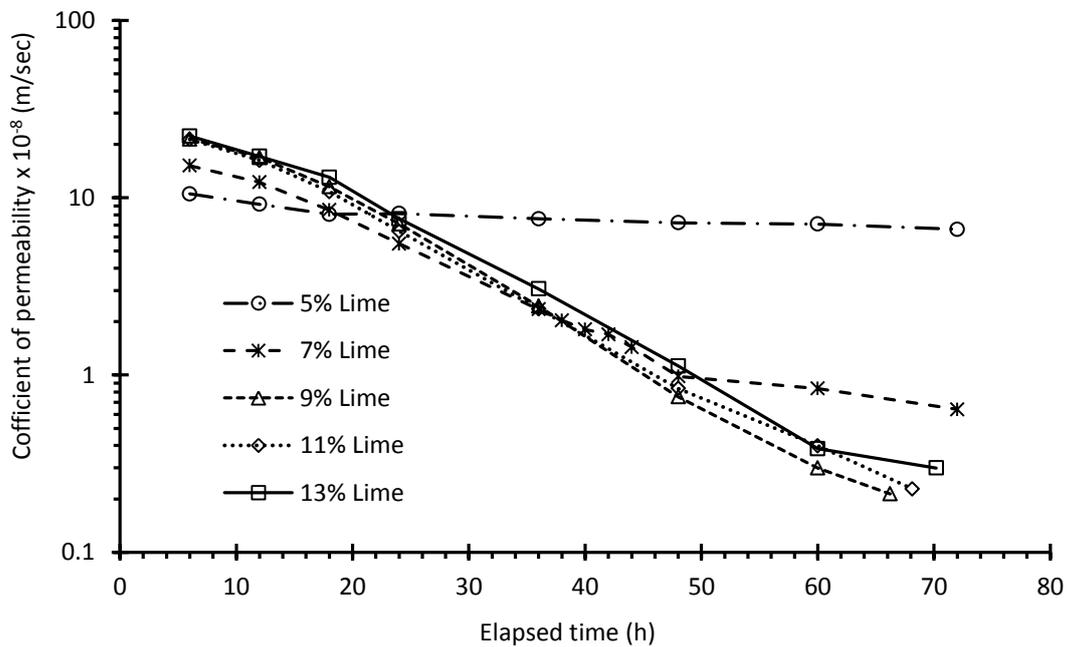
382

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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411   References:
412   Al-Mukhtar, M., Khattab, S., Alcover, J.-F., 2012. Microstructure and geotechnical properties of lime-
413   treated expansive clayey soil. Engineering Geology, 139: 17-27.
414   Al-Mukhtar, M., Lasledj, A., Alcover, J.-F., 2010. Behaviour and mineralogy changes in lime-treated
415   expansive soil at 50 °C. Applied Clay Science, 50(2): 199-203.
416   Al-Mukhtar, M., Lasledj, A., Alcover, J.F., 2014. Lime consumption of different clayey soils. Applied
417   Clay Science, 95(0): 133-145.
418   Ali, H., Mohamed, M., 2017. The effects of compaction delay and environmental temperature on the
419   mechanical and hydraulic properties of lime-stabilized extremely high plastic clays. Applied
420   Clay Science, 150: 333-341.
421   Beetham, P., Dijkstra, T., Dixon, N., Fleming, P., Hutchison, R. and Bateman, J., 2015. Lime
422   stabilisation for earthworks: a UK perspective. Proceedings of the Institution of Civil
423   Engineers - Ground Improvement, 168(2): 81-95.
424   Bell, F.G., 1996. Lime stabilization of clay minerals and soils. Engineering Geology, 42(4): 223-237.
425   Boardman, D.I., Glendinning, S., Rogers, C.D.F., 2001. Development of stabilisation and solidification
426   in lime–clay mixes. Géotechnique, 51(6): 533-543.
427   Bozbey, İ., 2017. Microfabric Evaluation of Lime-Treated Clays by Mercury Intrusion Porosimetry and
428   Environment Scanning Electron Microscopy. International Journal of Civil Engineering.
429   BS 1942-2, 1990. Stabilised Materials for Civil Engineering Purposes. British Standard Instituation,
430   London.
431   Cristelo, N., Glendinning, S., Fernandes, L., Pinto, A.T., 2012. Effect of calcium content on soil
432   stabilisation with alkaline activation. Construction and Building Materials, 29: 167-174.
433   Dash, S. K., Hussain, M., 2012. Lime Stabilization of Soils: Reappraisal. Journal of Materials in Civil
434   Engineering, 24(6): 707-714.
435   De Windt, L., Deneele, D., Maubec, N., 2014. Kinetics of lime/bentonite pozzolanic reactions at 20
436   and 50 C: Batch tests and modeling. Cement and Concrete Research, 59: 34-42.
437   Di Sante, M., Fratalocchi, E., Mazzieri, F., Pasqualini, E., 2014. Time of reactions in a lime treated
438   clayey soil and influence of curing conditions on its microstructure and behaviour. Applied
439   Clay Science, 99(0): 100-109.
440   Diamond, S., Kinter, E.B., 1965. MECHANISMS OF SOIL-LIME STABILIZATION. Highway Research
441   Record(92): pp 83-102.
442   Diamond, S., Kinter, E.B., 1966. Adsorption of calcium hydroxide by montmorillonite and kaolinite.
443   Journal of Colloid and Interface Science, 22(3): 240-249.
444   Estabragh, A.R., Rafatjo, H., Javadi, A.A., 2014. Treatment of an expansive soil by mechanical and
445   chemical techniques. Geosynthetics International, 21(3): 233-243.
446   McCallister, L., Petry, T., 1992. Leach Tests on Lime-Treated Clays. Geotechnical Testing Journal, Vol.
447   15(2): pp. 106-114.
448   Mirzababaei, M., Miraftab, M., Mohamed, M., McMahon, P., 2013. Impact of Carpet Waste Fibre
449   Addition on Swelling Properties of Compacted Clays. Geotechnical and Geological
450   Engineering, 31(1): 173-182.
451   Mirzababaei, M., Yasrobi, S., Al-Rawas, A., 2009. Effect of polymers on swelling potential of
452   expansive soils. Proceedings of the Institution of Civil Engineers - Ground Improvement,
453   162(3): 111-119.
454   Metelková, Z., Bohác, J., Sedlárová, I., Prikryl, R., 2011. Changes of pore size and of hydraulic
455   conductivity by adding lime in compacting clay liners, Geotechnical engineering: new

456   horizons, Proceedings of the 21st European Young Geotechnical Engineers Conference,
457   Rotterdam, Amsterdam: IOS Press; 2011, pp. 93-8.
458   Nasrizar, A.A., Ilamparuthi, K., Muttharam, M., 2012. Quantitative Models for Strength of Lime
459   Treated Expansive Soil. American Society of Civil Engineers, GeoCongress: 978-987.
460   Osinubi, K.J., 1998. Influence of Compactive Efforts and Compaction Delays on Lime-Treated Soil.
461   Journal of Transportation Engineering, 124(2): 149-155.
462   Rogers, C.D.F., Roff, T.E.J., 1997. Lime modification of clay soils for construction expediency.
463   Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, 125(4): 242-249.
464   Saldanha, R.B., Consoli, N.C., 2016. Accelerated Mix Design of Lime Stabilized Materials. Journal of
465   Materials in Civil Engineering, 28(3): 06015012.
466   Schanz, T., Elsawy, M.B.D., 2015. Swelling characteristics and shear strength of highly expansive
467   clay–lime mixtures: A comparative study. Arabian Journal of Geosciences, 8(10): 7919-7927.
468   Soltani, A., Deng, A., Taheri, A., Mirzababaei, M., 2017. A sulphonated oil for stabilisation of
469   expansive soils. International Journal of Pavement Engineering: 1-14.
470   Sridharan, A., Nagaraj, H.B., 2005. Plastic limit and compaction characteristics of fine-grained soils.
471   Proceedings of the Institution of Civil Engineers - Ground Improvement, 9(1): 17-22.
472   Sridharan, A., Prakash, K., 2000. Classification procedures for expansive soils. Proceedings of the ICE
473   - Geotechnical Engineering, 143(4): 235-240.
474   Strawn, D.G., Bohn, H.L., O'Connor, G.A., 2015. Soil chemistry. John Wiley & Sons.
475   Thyagaraj, T., Samuel, Z., Kumar, K.S.R., 2016. Relative efficiencies of electrolytes in stabilization of
476   an expansive soil. International Journal of Geotechnical Engineering, 10(2): 107-113.
477   Toohey, N.M., Mooney, M.A., Bearce, R.G., 2013. Stress-Strain-Strength Behavior of Lime-Stabilized
478   Soils during Accelerated Curing. Journal of Materials in Civil Engineering, 25(12): 1880-1886.
479   Tran, T.D., Cui, Y.-J., Tang, A.M., Audiguier, M., Cojean, R., 2014. Effects of lime treatment on the
480   microstructure and hydraulic conductivity of Héricourt clay. Journal of Rock Mechanics and
481   Geotechnical Engineering, 6(5): 399-404.
482   Vitale, E., Deneele, D., Paris, M., Russo, G., 2017. Multi-scale analysis and time evolution of
483   pozzolanic activity of lime treated clays. Applied Clay Science, 141: 36-45.
484   Wild, S., Arabi, M., Rowlands, G.O., 1987. Relation between pore size distribution, permeability, and
485   cementitious gel formation in cured clay–lime systems. Materials science and technology,
486   3(12): 1005-1011.
487   Zhao, H., Liu, J., Guo, J., Zhao, C., Gong, B.-w., 2015. Reexamination of Lime Stabilization Mechanisms
488   of Expansive Clay. Journal of Materials in Civil Engineering, 27(1).

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