

An investigation of the strength evolution of lime-treated London clay soil

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ABSTRACT The paper investigates the effect of hydrated lime on shear strength properties and behaviour of London clay, a soil extensively encountered in construction in the London area and the South Eastern England. Unconsolidated Undrained (UU) tests were performed to identify the effect of lime dosage, compaction water content and curing time on the shear strength and stress-strain behaviour of the treated soil. The mineralogical and physicochemical transformations occurring during the curing stage of the soil were also monitored to support the interpretation of the triaxial testing results and verify hypotheses made on the evolution of the chemical reactions and the development of cementation bonds.

The results showed that strengths gain was strongly influenced by lime content and the curing period, whereas the compaction water content was less influential. An interesting finding of practical relevance is that the strength evolution is likely to continue over long periods of time and result in very considerable strength gains upon the hardening of pozzolanic reaction products. At the same time, adequate early strength gains and adequate soil treatment can be obtained with reduced use of material consumption, thus further increasing the sustainability of the treatment processes. The paper has also highlighted the importance for engineering design of considering the brittle stress-strain response of the lime treated soil, and the benefit of using lower amounts of lime to alleviate this undesirable effect. The implications of various aspects of soil brittleness in different situations merit further attention and should be explored via modelling in future work.

1. Introduction

To meet sustainability requirements in the construction industry, improvement of unsuitable for construction ground and treatment of in situ soils for their use as fill materials, is a practice increasingly used by engineers. Lime treatment in particular is very commonly applied for road construction (subgrade and subbase stabilisation) and is also increasingly used for earthworks and foundations. It has been used since ancient times, yet an abundance of papers on the topic have been produced since the mid-twentieth century and keep being published to date (e.g., Cardoso and Maranha das Neves, 2012; Metelková et al., 2012; Russo and Modoni, 2013; Mavroulidou et al, 2013; Di Sante et al., 2014; Consoli et al, 2014; Chemedda et al, 2015; Beetham et al., 2015; Saeed et al., 2015; Zhang et al, 2015 and 2017; Belchior et al, 2017; Maubec et al, 2017; Giudobaldi et al, 2017 and 2018; Baldovino et al; 2018; Chakraborty and Nair, 2018 and 2020; Haas, S. and Ritter, H. J. 2019; Russo, 2019; Ismeik and Shaqour, 2020; Silvani et al., 2020; Cecconi et al , 2020; Akula et al, 2020; Vitale et al. 2016a,2016b, 2017, 2020, and 2021; Ma and Chen, 2021; Lavanya and Kumar, 2022; Ahmadullah and Chrysochoou, 2022; Das et al, 2022, amongst many other publications of the last decade), many of which still refer mostly to road pavement design, although well-documented specifications have been developed for the industrial application of the technique (see e.g. BSI 1990a and 1990b; NLA, 2004 and 2006; Britpave, 2017). The reason why the subject has not been exhausted is that a 'one size fits all' approach is not appropriate; the optimal application of treatments involves the case-by-case study and the understanding of the physico-chemical changes taking place through the lime–clay soil reactions so that material-specific recommendations are made for specific applications. Otherwise, this very common technique may prove inefficient as the expected modifications and transformations may not be achieved; natural soils comprise a variety of minerals as opposed to single clay minerals often used for research purposes, and their complex interactions with lime may lead to unexpected and often unsuccessful results of lime treatment (Maubec, 2010; Beetham et al., 2015).

Current standards and design specifications are based on basic physical and mechanical property testing. Monitoring of the progress of lime modification and pozzolanic reactions in time is commonly done in

26 terms of changes in the Atterberg limits, California Bearing Ratio (CBR) or unconfined compressive
27 strength (UCS) of the soil, which are insufficient for an extended use of the technique to applications other
28 than road pavements (for instance embankment stability, where knowledge of shear strength parameters is
29 necessary). In particular, for general geotechnical constructions information on the entire stress-strain
30 response of the ground is often required. This is made clear (for example) in the “Soft Soil Stabilisation
31 Design Guide” (Anon 2002) but this point has been ignored by the majority of researchers into lime
32 stabilisation over the last 30 years. On the other hand, more recent approaches are increasingly focusing on
33 the understanding of the dynamic, time-variable and complex chemistry of the treatments through
34 microscopic analyses, mineralogical studies and physico-chemical testing for example pH changes,
35 electrical conductivity changes, calcium concentration or soluble ion concentration measurements. These
36 properties initially increase as a result of the release of OH^- and Ca^{2+} ions upon lime addition; they then
37 remain constant, until finally a decrease in their values is observed as a result of the consumption of these
38 ions to form cementitious compounds during pozzolanic reactions (see e.g. Koliji et al., 2010, Al-Mukhtar
39 et al., 2010; and Metelková et al., 2012; Di Sante et al., 2014; Vitale et al., 2020, amongst many others).
40 This methodical examination and monitoring of the development of reactions and their products, can be
41 used to interpret the findings of standard soil mechanics tests so that informed recommendations for specific
42 materials are made.

43 This paper thus revisits the subject to provide a methodical study of the lime-treatment of London clay
44 involving useful mineralogical and physico-chemical testing beyond that included in the standards. This
45 information is used to interpret the findings of unconsolidated undrained (UU) triaxial testing. London clay
46 is a well-developed marine geological formation in the London Basin and Hampshire Basin, UK. It is
47 therefore extensively encountered in construction in the London area and the South-Eastern England
48 including high profile projects (e.g., Heathrow Terminal 5, Crossrail) and as earthwork material of existing
49 transport infrastructure earthworks, where lime treatment can be used for the maintenance of these assets
50 (see e.g., Lamont-Black et al., 2012). However, lime-treatment has been met with suspicion by UK

51 engineers until recently, in view of the high-profile failure of the Banbury section of the M40 that occurred
52 precisely due to the fact that site-specific chemistry was not considered in the design guidance. The
53 presented study can thus contribute towards the design of optimal targeted treatments for this commonly
54 encountered soil, useful for practicing engineers. The paper provides useful information on the effect of
55 lime percentage on the full stress-strain response in shear of the soil, which is generally lacking in the
56 literature, despite its importance in geotechnical design. The paper also reconsiders some of the common
57 practices in terms of lime dosage, curing times or compaction characteristics towards increased
58 sustainability of the technique. The above are the main new contributions of this paper to the substantial
59 corpus of literature on the subject.

60 2. Materials and methods

61 2.1. Materials used

62 The London clay soil used in this study was obtained in the form of bulk samples from a deep excavation
63 near Westminster Bridge in London, from a depth of approximately 26-30 m below ground level. The soil
64 was air-dried at an average temperature of $20 \pm 1^{\circ}\text{C}$ and a relative humidity of 60% for a month and was
65 subsequently pulverised using a mechanical grinder. The portion passing through the BS 425 μm sieve was
66 retained for testing as per BS 1377-1:1990 (BSI, 1990c). Table 1 shows salient properties of this soil.
67 Commercially available hydrated lime powder was used with a relative proportion of calcium hydroxide to
68 calcium oxide of 4.88:1.00 based on chemical analysis on the lime sample carried out in duplicate; the
69 suitability of this lime for soil stabilisation was verified according to BS 1924-2:1990 (BSI 1990b) (see
70 Mavroulidou et al., 2013). The required lime percentage for this soil was determined based both on the
71 “Initial Consumption of Lime” (ICL) and “Lime Fixation Point” (LFP) methods. The former test (Eades
72 and Grim, 1966, included in BS 1924-2-1990, BSI 1990b) specifies as ICL the minimum calcium lime
73 required to maintain a pH of 12.40 (the pH of $\text{Ca}(\text{OH})_2$ saturated solution at 25°C); this is a measure of the
74 amount of lime consumed by a soil due to immediate/rapid cation exchange reactions, which reduce clay
75 mineral effective surface area and affinity for water. For strength gain in time related to pozzolanic

76 reactions, higher lime dosages, beyond the ICL would be required, as widely discussed in the international
77 literature on lime stabilisation (see e.g., Diamond and Kinter, 1965; Locat et al. 1990; Sherwood, 1993;
78 Bell, 1996 amongst many others). The LFP method determines the optimum lime dosage required for the
79 maximum increase of the plastic limit of the soil (i.e. the Lime Fixation Point, LFP); lime in excess of the
80 LFP is used in the cementation process, increasing soil strength (Bell, 1989). Based on the ICL tests, the
81 minimum required amount of lime for this soil was determined as 3.45%. The plasticity tests of samples
82 treated with lime also indicated an LFP of approximately the same value i.e., 3.47% (for the detailed
83 processing of the data see Kichou et al, 2015 and Kichou, 2015). Based on these results, an amount of 4%
84 lime per dry soil mass would be sufficient for triggering both cationic exchange and short-term pozzolanic
85 reactions for this type of soil, as some small quantities of calcium silicate or calcium aluminate hydrate
86 phases can form due to the immediate reaction between the lime absorbed on the clay surface and the (Al-
87 OH) and (Si-OH) sites of the clay minerals (Eades and Grim, 1960 or Diamond and Kinter, 1965). To
88 assess the effect of lime dosage on the soil properties, this minimum percentage, as well as a second
89 percentage above this value were used (i.e., 6% per dry soil mass) to allow for long-term chemical
90 pozzolanic reactions to develop; these reactions require the supply of lime in excess of the complete
91 saturation in calcium of the clay. In this case, once immediate cationic exchange reactions have been
92 completed, any excess calcium will be available for pozzolanic reactions leading to the formation of
93 cementitious products (calcium silicate, calcium aluminate or calcium aluminosilicate hydrates) and thus a
94 soil strength increase over time.

95 **Table 1** Properties of London Clay soil used in this study

96

97 Preliminary testing on the lime-treated soil at these percentages of lime was then performed to assess the
98 effect of lime addition on (a) the soil plasticity and pH after 1 hour of mellowing; (b) the specific gravity,
99 G_s after lime addition and (c) the Standard Proctor Compaction characteristics (the latter were performed
100 after 24 hours of mellowing, according to BS 1924-2-1990 (BSI, 1990b) recommendations).

101

102 2.2. Equipment and specimen preparation for mineralogical and physicochemical tests on treated soil

103 The pH evolution of the treated soil in time was monitored to support the interpretation of the UU results,
104 as the dissolution of clay minerals is dependent on pH level. For pH measurements, the soil specimens were
105 crushed to fine powders after UU testing. The pH measurements were performed in the same fashion as for
106 the natural soil (see Table 1). Additionally, the free lime which was not consumed during treatment was
107 determined by calcium concentration measurements, using a spectrometer (Hitachi Z-8100). For this soil-
108 lime solutions (0.5g of treated soil dry powder in 40cc distilled water) kept in a sealed glass tube (to prevent
109 lime carbonation) were tested after 1, 7, 28 and 60 days of curing at $20\pm 1^\circ\text{C}$. The calcium concentration
110 was converted into lime percentage based on charts of calcium concentration for pure lime.

111 X-Ray diffraction (XRD) mineralogical analyses were performed using a Bruker D2 Phaser diffractometer
112 with Cu-K α ($\lambda = 0.154 \text{ nm}$) X-Ray wavelength. The study was carried out on pulverised untreated & lime-
113 treated London clay samples which had been left to cure at constant moisture and a temperature of $20\pm 1^\circ\text{C}$
114 for different periods (1, 7, 28 and 60 days). The XRD results were analysed using Brucker DIFFRAC^{plus}
115 EVA software.

116

117 2.3. Specimen preparation for shear strength testing

118 The clay powder was first manually mixed with lime in a dry state for an approximate duration of 5 minutes
119 inside a sealed polyethylene bag, until the colour of the mixture became uniform. Distilled water was then
120 added as required and mixed in accordance with BS 1377-4:1990 (BSI, 1990e) for an average of 20 minutes
121 to ensure that lime was not exposed to the air for too long, thus avoiding lime carbonation. The soil-lime
122 mix was then left to mellow in a separate sealed polyethylene bag at constant moisture for 24h, as prescribed
123 in BS 1924-1:1990 (BSI, 1990a). Statically compacted cylindrical specimens of 38 mm in diameter and 76
124 mm in height were then prepared at an axial deformation rate of 1 mm/min. As the treated and untreated

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125 soils had different dynamic (Standard Proctor compaction) characteristics (see section 3.1 below), a point
126 of reference was needed for the static compaction characteristics of the different specimens, in order to
127 compare the triaxial test results of the different soils. It was decided to statically compact all specimens to
128 the same dry density of 1430 kg/m^3 , an intermediate value within the range of Standard Proctor MDD
129 obtained for three soil mixes (i.e., the MDD of 4% lime-treated soil). This dry density value was within the
130 range of Standard Proctor MDD values of the untreated clay at layers from different depths (see Zhang,
131 2011). Water content was kept to the respective Standard Proctor OMC for the untreated specimens and
132 4% lime-treated specimens but for the 6% lime treated specimens two different water contents were used
133 i.e., 27% and 32% (corresponding to OMC – 2.5% and OMC + 2.5% respectively) to assess the effect of
134 compaction water content (see Table 2). Note that the resulting specimens had similar degrees of saturation
135 S_r (thus excluding degree of saturation effects on the results) i.e., respectively an average S_r of 73%, 75%
136 and 76% for the untreated, 4% lime treated, and 6% lime-treated with water content of 27%, with the
137 exception of the 6% lime treated soil compacted wet of the OMC, whose average degree of saturation was
138 91%.

139 All specimens were consistently compacted in six equal layers, using the same amount of mass per layer,
140 as often recommended in the literature to limit the density variation with height thus ensuring uniformity
141 (e.g., Whitman et al., 1960; Booth 1975; Correia et al, 2013). After compaction the specimen dimensions
142 and masses were measured. All specimens used for triaxial testing were assessed to be within $38 \pm 0.5 \text{ mm}$
143 diameter and $76 \pm 1 \text{ mm}$ height at the time of the extraction from the brass mould. Specimens outside these
144 required ranges were discarded. It was also verified that they were within $\pm 1\%$ of the target dry unit weight,
145 as well as within $\pm 0.5\%$ of the required target water content. Furthermore, repeatability was verified on
146 randomly selected specimens, oven-dried to determine the dry mass and the initial water content. These
147 were generally found to be consistent within an acceptable margin variation $\pm 0.35\%$ and $\pm 0.75\%$ for the
148 water content and the dry unit weight respectively, confirming the good reproducibility specimen
149 preparation (Kichou, 2015). After extraction from moulds and measurements, specimens were immediately

150 wrapped in several cling film layers, inserted in a sealable polyethylene bag, and left to cure in insulated
151 cabinets at a controlled room temperature at $20 \pm 1^\circ\text{C}$. Unconsolidated Undrained (UU) triaxial tests were
152 then performed on the as cured specimens at curing periods of 1, 7, 28, 60, 120 and 250 days at a cell
153 pressure equal to 200 kPa.

154 **Table 2:** List of UU triaxial tests

155

156 **3. Results and discussion**

157 3.1 Physical, physicochemical and mineralogical tests

158 Table 3 summarises some physicochemical characteristics of the treated soil mixes (the plasticity
159 characteristics and pH of the lime-treated mixes were taken after one day of mellowing). The detailed
160 Standard Proctor Compaction testing results for each compacted mix (0%, 4% & 6% lime) are plotted in
161 Figure 1. The results show the clear effect of lime in reducing the plasticity index of the soil, as the
162 consequence of immediate reactions -cationic exchanges- and clay particle interactions (flocculation
163 agglomeration) at the microscopic scale (Eades and Grim, 1960 or Diamond and Kinter, 1965). Note that
164 in the literature the effect of the lime is variable and depends on soil type: whereas it normally reduces the
165 plasticity index (although not always, see e.g., de Brito Galvao et al, 2004), the individual effect of the lime
166 on the liquid limit and plastic limit respectively varies across soils. In the case on London Clay, it is seen
167 that both the liquid limit and plastic limit have increased, so that their difference shows a reduction in
168 plasticity index compared to the untreated soil. This can be attributed to the increased interparticle attraction
169 forces due to the addition of lime and early precipitation of bonding compounds, which is supported by the
170 XRD results shown in Figure 3. Concerning the specific gravity G_s , it was found to be the same for both
171 the 4% and 6% lime-treated soil mixtures, whereas if the theory of mixtures was used to estimate it, the
172 expected value for the 6% lime dosage would have been 2.73, considering the specific gravity G_s of the
173 untreated soil and that of the hydrated lime (2.34). As for the Standard Proctor Compaction results plotted

174 in Figure 1, it can be seen that increasing lime content resulted in increasingly flatter compaction curves,
175 higher OMC and lower MDD, consistently with the literature (see e. g., Bell, 1988).

176 Table 4 shows the consumed/available lime and Figure 2 matches it against the evolution of the pH of the
177 soil in time: most of the lime was consumed within the first day of treatment due to modification reactions;
178 lime consumption continued thereafter at a slower rate, throughout the monitoring period. Interestingly, the
179 4% lime dosage results show that after one day of treatment the consumed lime was lower than the identified
180 ICL or PFL; it is possible that this is due to the graphical identification of the ICL and PFL which can result
181 to some interpretation error. On the other hand, when 6% lime was provided, a higher percentage of
182 consumed lime than the ICL and PFL was recorded one day after treatment. As the dosage of 6% lime
183 provides more available lime, the lime consumption in time is higher but the differences in the consumption
184 rates compared to the 4% lime dosage are within 1.5-3%. Indeed, the slopes of the curves representing
185 available lime in time for 4 and 6% lime addition respectively (see Fig. 4) are quite similar, especially after
186 seven days of treatment. Interestingly, although most lime is consumed in the first few days, the remaining
187 available lime was still able to lead to further pozzolanic reactions (at a much slower rate) as evidenced by
188 the strength increase over time (see section 3.2); it was claimed that excess lime can keep triggering
189 pozzolanic reactions, as long as sufficient water and silica are available and pH is high enough to
190 maintain solubility of the silica and alumina (see e.g., Al-Mukhtar et al., 2010; Okyay and Dias, 2010)
191 which is the case here, as Figure 2 confirms. According to Figure 2, upon lime addition the pH values
192 increased to 12.4 for 4% lime and 12.5 for 6% lime, due to the dissolution of the clay and the release of
193 OH⁻; subsequently, the pH kept decreasing with curing time, as pozzolanic reactions consume calcium. For
194 4% lime the pH decreased fast between 1 and 7 days of curing to a value of 12 but was maintained above
195 11 up and to 250 days after curing started; this pH value is high enough to maintain some pozzolanic
196 reactions. For 6 % lime the pH was still above 12.0 even at 60 days of curing. The decrease in the available
197 lime shown in Figure 2 mirrors the pH decrease with curing time as calcium is participating in chemical
198 reactions, throughout the 60 days of measurements.

199 Figures 3(a), (b) and (c) represent respectively the XRD results of untreated and 4% and 6% lime-treated
200 London Clay samples for different curing periods. These show X-Ray intensity versus 2θ , where, by
201 convention, 2θ is the angle between the incoming and outgoing beam directions. The natural soil
202 diffractogram pattern shows principally the presence of illite and kaolinite clay minerals (i.e., no smectite
203 was detected in this layer, unlike in Zhang et al 2015 and 2017), in addition to quartz, feldspar, goethite and
204 some small amount of gypsum. Regarding the treated soil diffractograms, the investigation of lime-clay
205 reaction evolution is identified most clearly on the highest lime percentage (6%) by the changes observed
206 with the curing time (new phases appearing, and potential clay minerals destruction). The diffractions show
207 diminishing reflections at $2\theta=37.05^\circ$, indicating that lime is consumed with curing time, consistently with
208 the lime consumption tests presented in Table 4 and Figure 2. A similar decreasing peak reflection is
209 observed at $2\theta=54.03^\circ$ but at lower intensity. Note that the small amount of gypsum detected in the
210 untreated clay sample gradually disappeared from the first day of curing onwards for the 4% lime and 6%
211 lime-treated samples while a peak at an angle $2\theta=15.7^\circ$ was identified as ettringite in the lime treated
212 London clay samples. The presence of this peak while the gypsum disappeared indicates an early age
213 ettringite formation. Although the presence of ettringite could raise concerns for the suitability of lime
214 treatment, its quantity is small considering the intensity of the peak; moreover, its formation at an early
215 stage (before the hardening of the cementitious gels) would not be detrimental to the treatment and in fact
216 it could also contribute to the early strength gain noted in the following section.

217 For the 4% lime-treated sample, some small calcium silicate hydrate (CSH) peak can be seen in the form
218 of $\text{Ca}_3\text{HO}_9\text{Si}_3$ at 7 days of curing; a second reflection is noted at 28 days curing. In addition, a small Calcium
219 Aluminate Hydrate (CAH) in the form of $\text{Al}_2\text{Ca}_3\text{H}_{12}\text{O}_{12}$ appears on the 7th day of curing at $2\theta=32.1^\circ$; its
220 intensity increases with curing time, giving an indication of the progress of pozzolanic reactions between
221 lime and clay minerals. These observations are more clearly seen for the 6% lime addition, where four
222 reflections of CSH peaks of a higher intensity are observed as from the seventh day of curing. These
223 reflections increase with curing time, indicating that a higher number of cementation bonds formed at longer

224 curing periods. A CAH phase also formed at an angle $2\theta=32.08^\circ$ after the first day of curing onwards. At
225 60 days of curing period a very small Calcium Alumino-Silicate Hydrate (CASH) in the form of
226 $Al_{2.11}Ca_2H_{18}O_{16.25}Si_{1.11}$ appeared at an angle of $2\theta=13.44^\circ$ for both lime percentages; however, the peak is
227 rather too low for any firm conclusions. Arguably, some of the above stated decreases or increases are
228 difficult to visualise on diffractograms due to the small peaks.

229 In summary, the evolutions in pH and lime consumption as well as the mineralogy changes continue beyond
230 the 28 days for both lime dosages; 28-day curing has been the industry standard for concrete curing and by
231 extension, it has been regularly also applied for lime treatment, despite the differences in reaction kinetics
232 of Portland cement, used in regular concrete, and those of lime-treated soils. Conversely, the results show
233 that the evolution of the lime-treated soil properties continues beyond this point, and this is reflected in the
234 soil strength, as discussed below. This agrees with the literature (see e.g. Brandl, 1981; Baldovino et al,
235 2018; Haas and Ritter, 2019; Ahmadullah and Chrysochoou, 2022), who claimed that reactions and strength
236 increase could continue for many months or even years after the treatment due to the slow diffusion of lime
237 within clay particles, affecting the mineralogy and fabric of the soil and creating bonding between particles.

238

239 **Table 3:** Physicochemical characteristics of the untreated and treated soils

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241

242 **Table 4:** Consumed lime during the curing period in days

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245

246 **Figure 1.** Standard Proctor compaction test on lime treated & untreated London Clay

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248 **Figure 2.** Available lime and pH evolution with curing time

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251 **Figure 3:** XRD results: (a) XRD result on untreated clay; (b) 4% lime-treated clay; (c) 6 % lime-treated
252 clay (G: Goethite, K: Kaolinite, I: Illite, Q: Quartz, F: Feldspar, g: Gypsum; E= Ettringite)

253

254

255 3.2 Strength evolution and stress-strain behaviour

256 Figure 4(a) -(c) shows the stress-strain curves from the UU triaxial tests performed at 200 kPa confining
257 pressure at different curing times. The labels 1D, 7D, etc. on the figure refer to the curing time in days (D).

258 The untreated London Clay presented a ductile behaviour with a deviator stress levelling at high strains.

259 The 4% lime-treated London Clay specimen showed a strain softening behaviour but for curing times

260 between 1-60 days it maintained the maximum deviator stress value for a large range of strains between

261 approximately 1.5% and 5% (traditionally the test would have stopped within this range, after measuring

262 the same deviator stress for several repeated measurements - here testing was continued until strain

263 softening was observed). This is advantageous, as the behaviour is not very brittle, which would result to

264 an abrupt strength loss within a very narrow strain range. However, for long curing times (120 and 250

265 days) the specimens became increasingly brittle, with a more pronounced peak in a narrower strain range

266 and strain softening observed after about 2% and 1.5% strain for the 120- and 250-day specimens

267 respectively. The post-peak stress gradually decreased to reach a constant low deviator stress at a value

268 close to the one of untreated soil. Compared to the 4% lime-treated specimen, the 6% lime-treated

269 specimens, (except for the 1 day cured sample) showed a much more pronounced brittle behaviour with an

270 abrupt loss in strength in the post-peak stress zone (after strains of 3.5%, 2.5%, 1.5% and 1% for the 7 day,

271 28-60 day, 120 and 250 day-cured specimens respectively, i.e., decreasing with curing time, consistent with

272 the more brittle behaviour). This is similar to the behaviour of heavily over-consolidated or highly

273 structured natural soils (Leroueil and Vaughan, 1990). Note that the initial concave portion of stress-strain

274 curves which is a known artifact in materials testing, attributed to apparatus compliance and seating errors

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275 as discussed in the literature or material testing standards (e.g. Suescun-Florez et al, 2015; ASTM D695)
276 has had some influence on the stated strain values where peak stresses were noted, but overall the
277 observations and trends are consistent.

278 From the above it transpires that for geotechnical design it is of major importance to consider the
279 implications of the brittle nature of the stress-strain curves and the effect of the increasing lime percentage
280 on this. It was shown that increasing lime from 4% to 6% makes the response much more brittle, which is
281 undesirable in many geotechnical engineering applications, where post peak behaviour could be critical.
282 Considering (for example) the case of slope stability: different points on a developing slip surface (such as
283 A, B, C in Figure 5) will be at different points on the stress-strain curve (i.e., plot of shear stress versus
284 shear strain). Thus, at the time of failure the average shear strength will be much less than half the peak
285 UCS value measured in standard testing in the available literature. This effect is discussed in detail in Potts
286 (2003), which demonstrates that the sudden and catastrophic failure of the Carsington Dam can be explained
287 by finite element models, which incorporate the brittle response of an underlying layer of yellow clay. Thus,
288 depending on the application, the high increase in brittleness of the soil could be a major issue, a point that
289 the majority of works and guidelines on lime treatment (most of which refer to pavement design) tend to
290 ignore/overlook but this could be of extremely high practical relevance.

291 Figure 6 plots the peak deviator stresses obtained from all UU tests to assess comparatively the effects of
292 lime percentage, curing time and water content; to acquire a clearer picture of the strength evolution with
293 curing time and its likely causes, the results of Figure 6 are plotted again in two separate graphs (Fig. 7(a)
294 and 7(b) for 4 and 6% lime-treated soils respectively), with the strength gain marked. From Figure 6 and 7
295 (as well as 4), it can be noted that for both lime percentages and all compaction water contents used, the
296 peak strength of lime treated soils was over twice as much as that of the untreated soil, as early as after one
297 day of curing. Doubling of the strength of the untreated soil is usually considered to be the minimum
298 expected strength gain for chemical soil stabilisation. For 4% lime-treated soil the strength was
299 approximately 2.45 times that of the untreated soil after 7 days of curing. This is close to three-fold strength

300 gain, which Sherwood (1993) attributes to modification reactions. The strength then remained essentially
301 the same until 60 days of curing. This is consistent with the XRD results which show no considerable
302 differences in the treated soil spectra between 7 and 60 days (see Fig. 3(a)). At very later curing times
303 however (120-250 days) there is a remarkable increase in strength gain amounting to a value almost double
304 than that achieved in the previous curing time measurements. The progressive hardening of the cementitious
305 gels in time can be responsible for this. Due to practical reasons, it was not possible to perform XRD
306 measurements at these longer curing times to attest the mineralogy evolution. However, the pH of the soil
307 showed a considerable decrease between 60 and 120 days of curing, implying that presumably some further
308 reactions were also occurring during these longer curing times, supporting the UU results of Figure 6 (see
309 also Fig 8).

310 Specimens treated with 6% lime showed a similar sharp increase in peak strength at the two longest curing
311 periods. However as opposed to the 4% lime treated specimens, they also showed a continuous peak
312 strength gain with curing time (although at a much slower rate up to 60 days of curing). Within 28 days of
313 curing this amounted to an approximately 300% strength gain compared to that of the untreated soil and
314 about 960% after 250 days of curing compared to that of the untreated soil (see Fig 7). Overall, other than
315 on the first day of curing, the 6% lime treated specimens (irrespective of moisture content) developed much
316 higher strengths compared to the 4% lime treated ones, amounting to more than twice the value of the
317 strength of the latter specimens (especially in the longest curing time of 250 days). Sherwood (1993) also
318 reported a substantial strength gain for London clay treated with 10% lime at long curing times, after a
319 period of almost no strength increase. Due to the different lime percentage, the different location from
320 which samples originated and possibly also due to different specimen preparation and testing procedures,
321 the strength magnitudes shown in Sherwood were different to the ones recorded in this study, but the trends
322 were similar. This finding is interesting as it contradicts the common belief that, similarly to concrete, most
323 strength gain upon lime treatment would be achieved within the first 28 days and that henceforth any
324 strength gain would be very small. This could be due to the fact that cementing material is slowly formed,

325 initially around contacts between agglomerations of clay particles; it then gradually spreads around the
326 surface of these agglomerations. When this spreading is complete, a full matrix of cemented material exists
327 and higher strengths are observed (here observed after 60 days), whereas at intermediate times after
328 treatment, failure would take place through the weaker clay particles.

329 The higher and continuous strength gain for 6% lime treated specimens compared to that of 4% lime-treated
330 soil (which had a lower and almost constant strength between 7 and 60 days of curing) is consistent with
331 the XRD results (Fig. 3) which showed clearer peaks corresponding to CAH and CSH after 7 days of curing
332 compared to the 4% lime treated soil; it is also consistent with the pH measurements and the available lime
333 for reactions consistently, with Figure 2 and Table 4. Beyond 60 days of curing, it is reasonable to assume
334 that due to the higher amount of available lime (as evidenced also in Figure 8), pozzolanic reactions in the
335 6% lime-treated soil continued for longer curing times, as evidenced by other works (Brandl, 1981;
336 Baldovino et al, 2018, Haas & Ritter 2019 and Akula et al., 2020).

337 Concerning the influence of compaction water content, it can be seen that the strength values of the 6%
338 lime-treated specimens compacted at different water contents were initially similar but that at later times
339 the specimens compacted at the $OMC + 2.5\%$ developed higher strengths than those prepared at $OMC -$
340 2.5% , despite the initially higher degree of saturation. This shows the beneficial effect of water availability
341 for the progression of long-term chemical reactions. Generally, however, the effect of the lime percentage
342 was much more considerable compared to that of the compaction water content (Fig 6); slightly lower water
343 contents than the OMC could therefore be used without apparent issues, for savings in terms of water
344 consumption.

345

346

347 **Figure 4.** Strength evolution of lime-treated London Clay with curing time. (a) 4% lime, (b) 6% lime
348 ($OMC - 2.5\%$); (c) 6% lime ($OMC + 2.5\%$)

349

350 **Figure 5.** Relevance of full stress strain response in slope stability applications

351

352 **Figure 6.** Peak deviatoric stress evolution with curing time

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356 **Figure 7.** Annotated strength changes in time (a) 4% lime treated soil; (b) 6% lime-treated soil

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358

359 **Figure 8.** Correlation between mechanical performances and lime consumption at different curing times

360

361 **4. Conclusions**

362 This work investigated the influence of lime dosage, curing period and the compaction water content on
363 the evolution of the strength and stress-strain behaviour in shear of lime-treated London clay. The
364 interpretation of the results was supported by physicochemical and mineralogical analyses.

365 XRD, pH and calcium consumption results all confirmed that higher curing times lead to the formation of
366 an increasing number of cementitious compounds (CSH, CAH and CASH hydrates), causing a increase
367 for the soil. An interesting finding of practical relevance is that the strength evolution is likely to continue
368 over long periods of time and result in very considerable strength gains upon the hardening of pozzolanic
369 reaction products.

370 Lime content higher than the ICL would cause more cementitious compounds to form; in this case 6% of
371 hydrated lime showed evidence of sustained chemical reactions, responsible for the formation of the
372 cementitious bonds during the curing time. However, even the minimum amount of 4%, which was

373 identified as suitable to modify this soil, resulted in high strengths (2.45 times that of the untreated soil)
374 already within a week of the treatment. It therefore appears possible that unlike common usage, for adequate
375 strength gains according to the application requirements it may not be necessary to provide much higher
376 lime percentages than a minimum. This finding is important for an efficient design, increasing the
377 sustainability of the treatments in terms of cost and material consumption (resulting to a lower carbon
378 footprint), as less lime is used. Likewise, the study shows that although beneficial, supplying water over
379 the OMC (often recommended for encouraging further strength evolution) may not be necessary, as the
380 benefits in terms of strength gain were small in comparison to the effects of lime dosage and curing time.
381 This finding can also lead to an increased sustainability of the treatment process, reducing water
382 consumption.

383 Finally, the paper has highlighted the importance for engineering design of considering the brittle stress-
384 strain response of the lime treated soil, and the benefit of using lower amounts of lime to alleviate this
385 undesirable effect. The implications of various aspects of soil brittleness in different situations merit further
386 attention and should be explored via modelling in future work.

387 Based on the above observations, the overall conclusion is that, although the lime treatment technique is
388 well established and documented, future practices and specifications can further increase the sustainability
389 of the ground treatment techniques, if based on targeted studies for every different soil type and an improved
390 understanding of the underlying physico-chemical processes, in addition to the conventional UCS or CBR
391 testing, commonly used to select appropriate treatments for practical applications. These can contribute
392 towards the design of optimal targeted treatments, minimising costs, material and energy input and the
393 overall carbon footprint of the practices.

394

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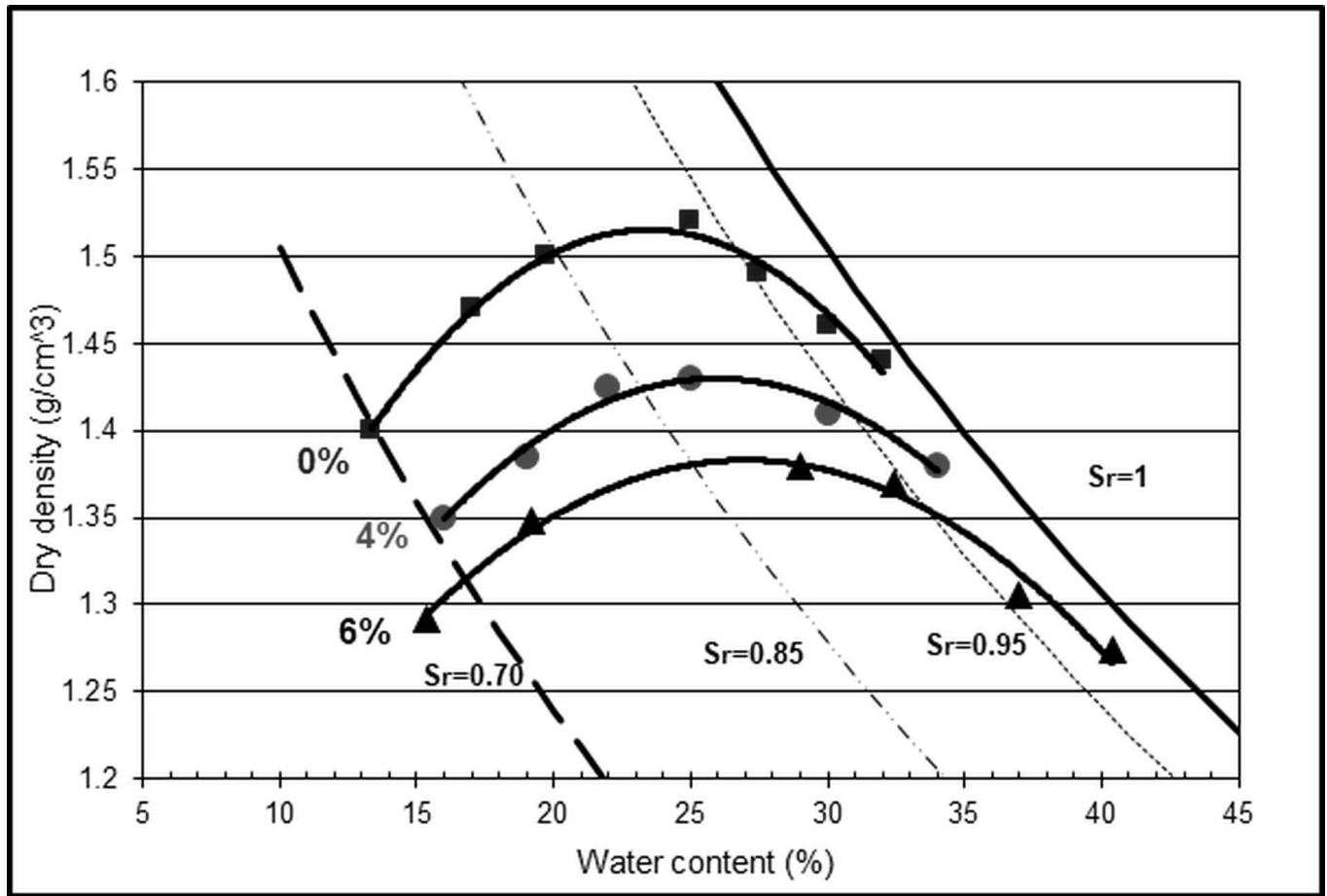
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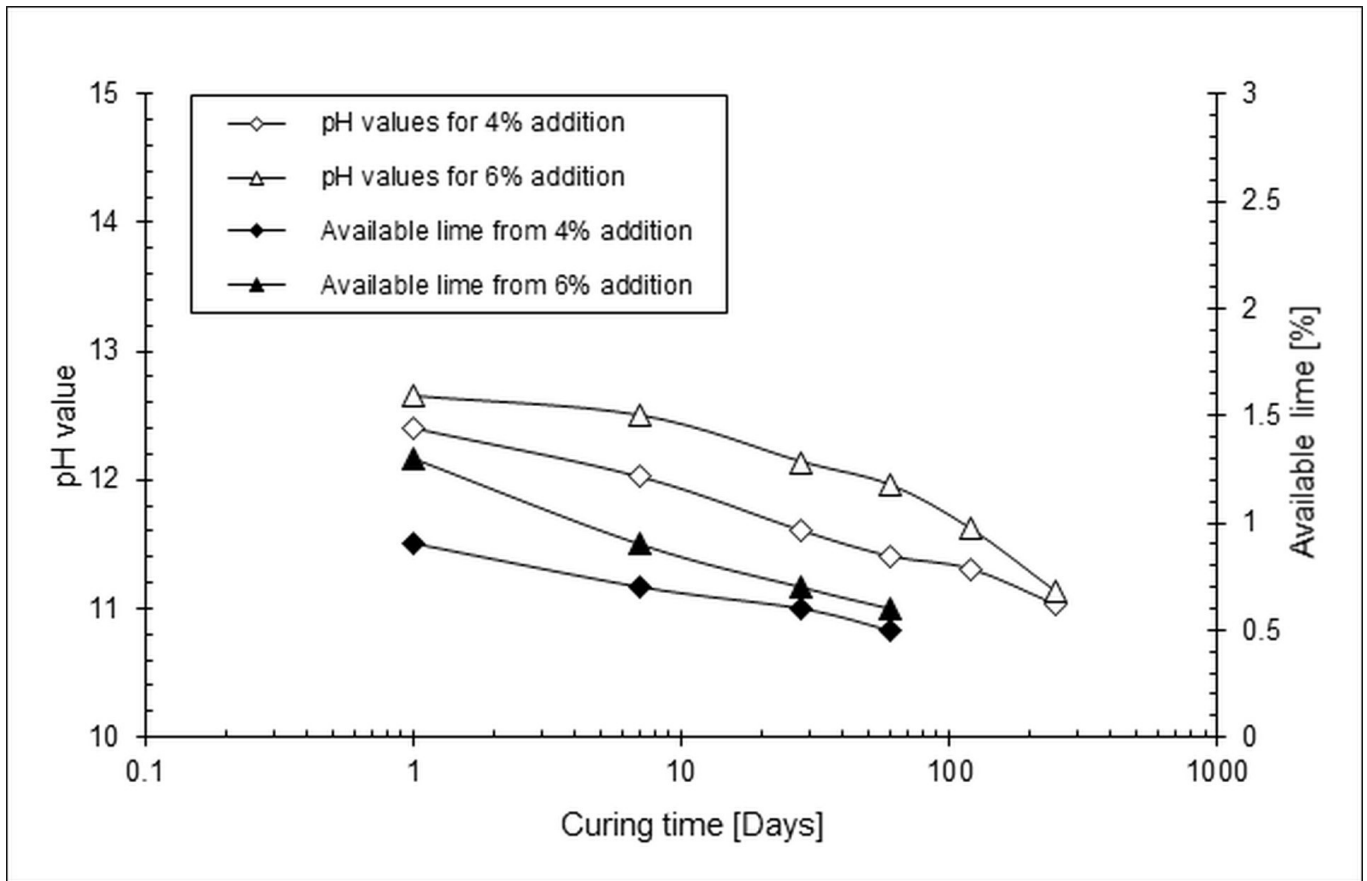
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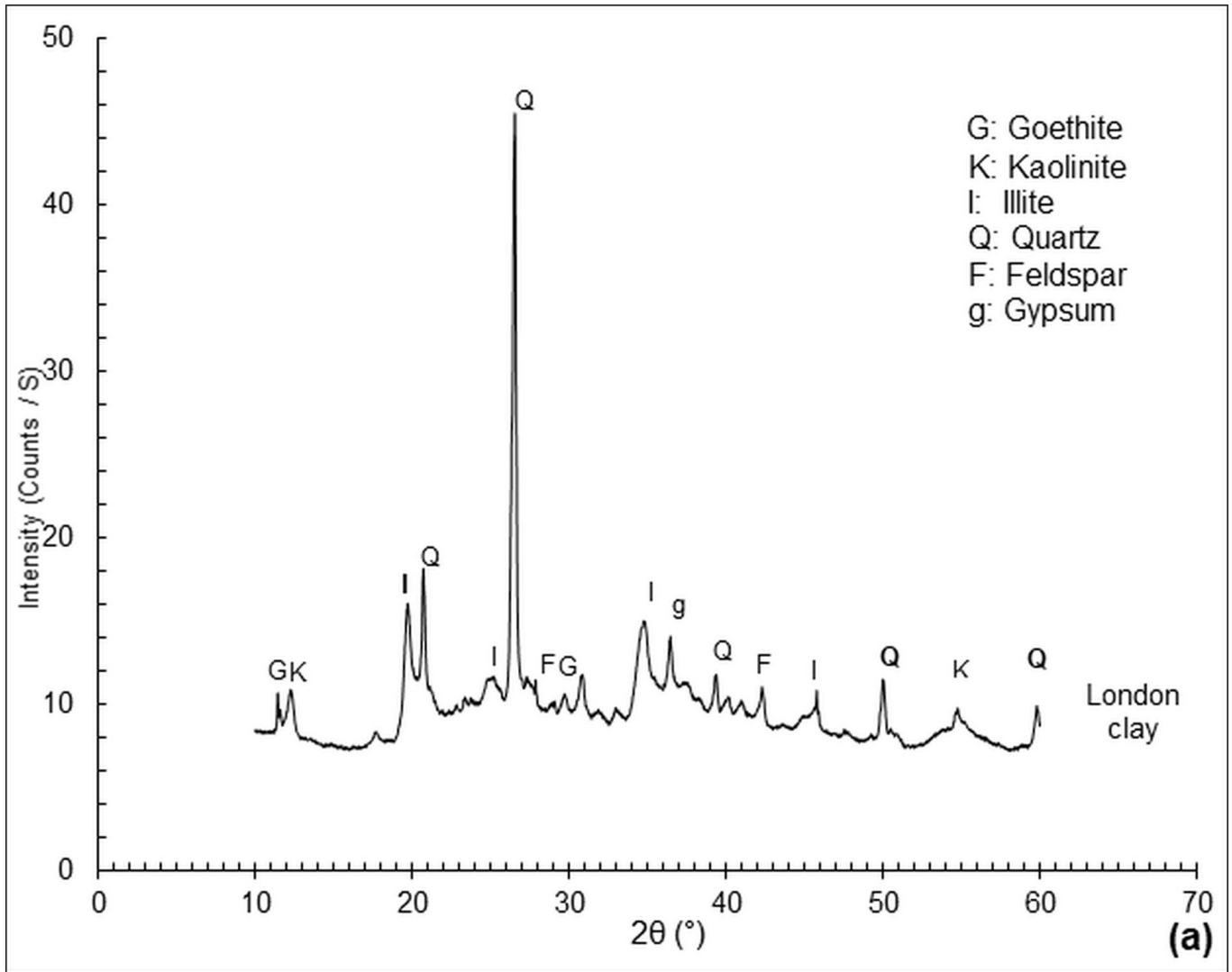
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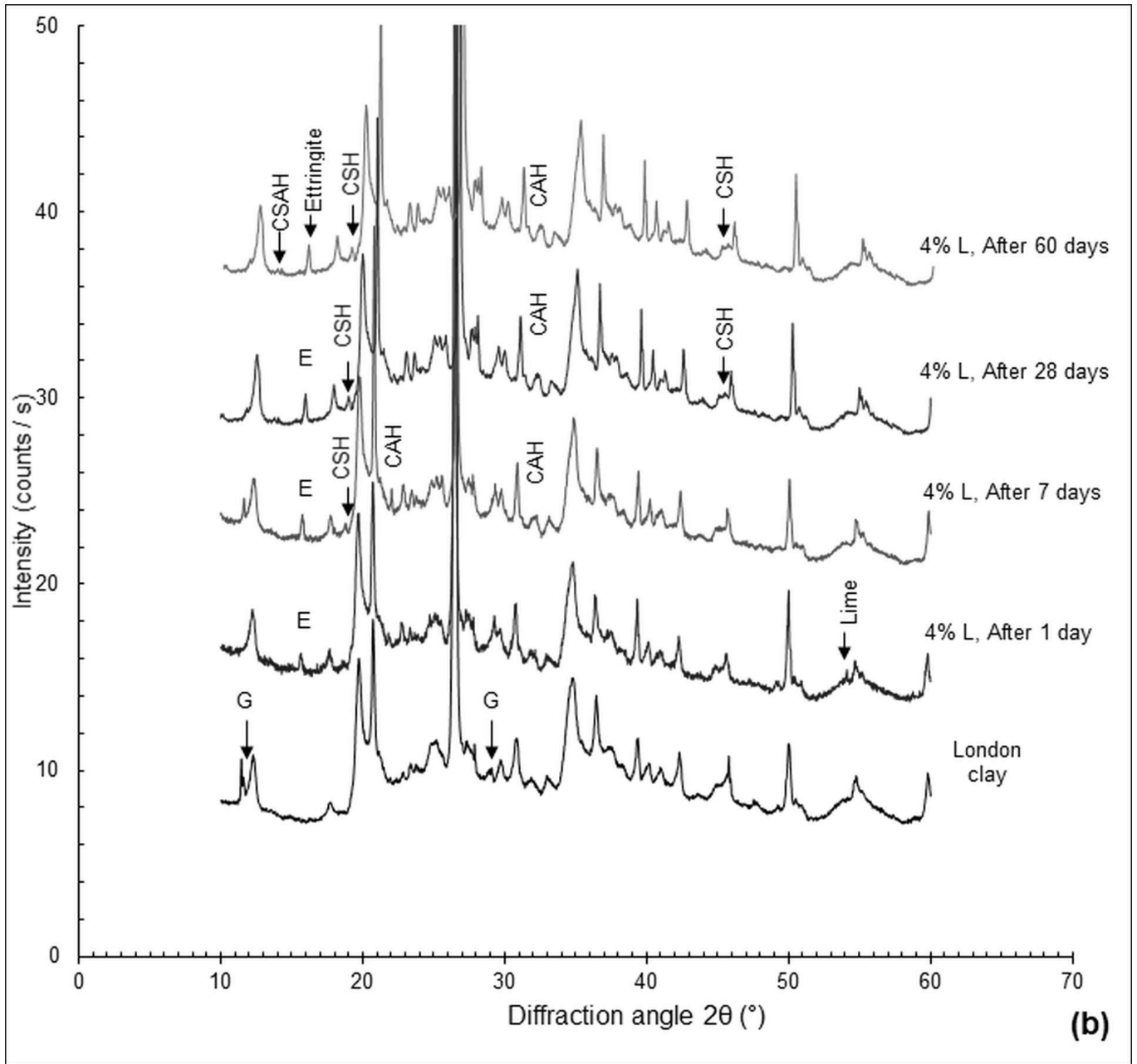
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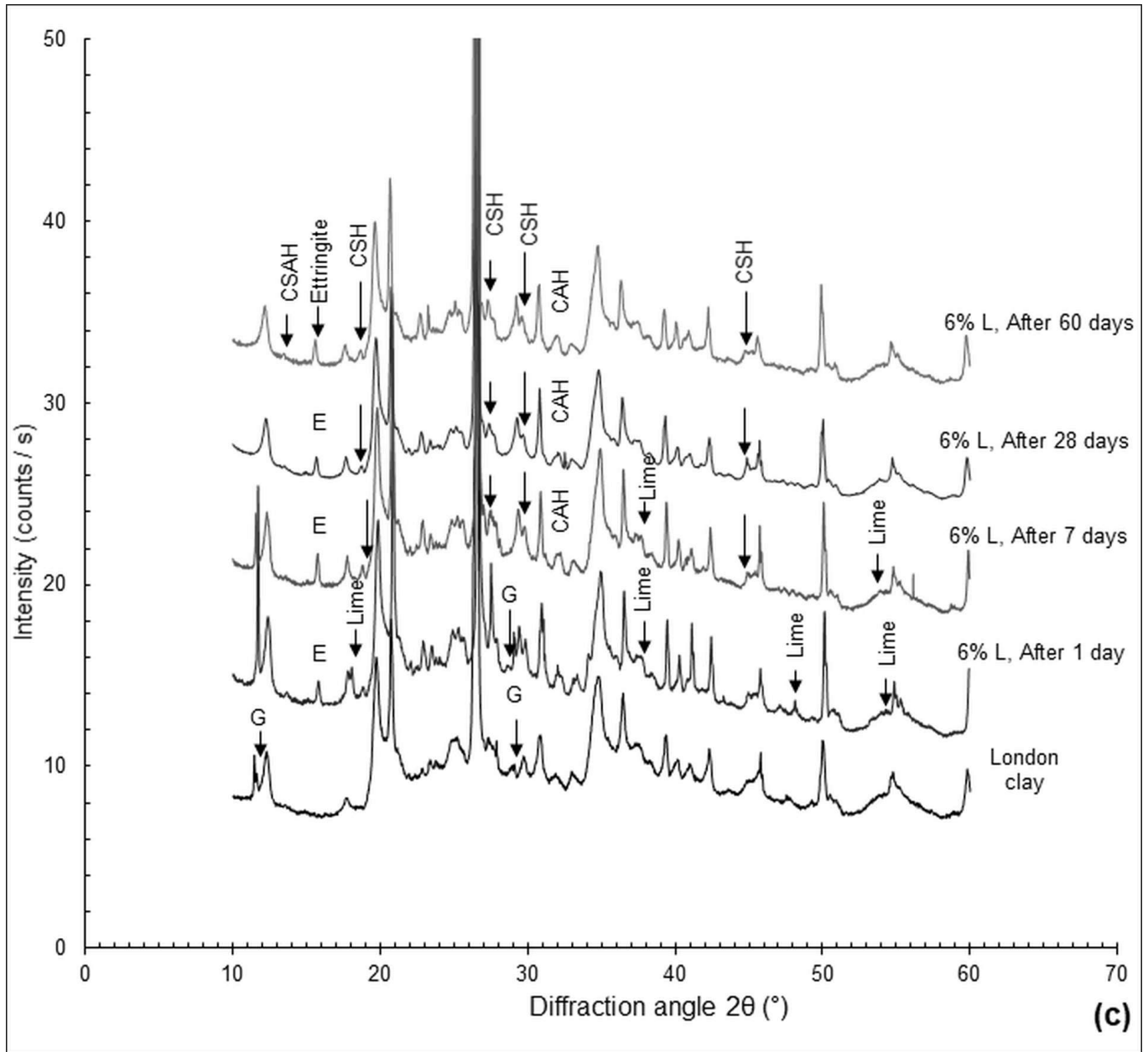
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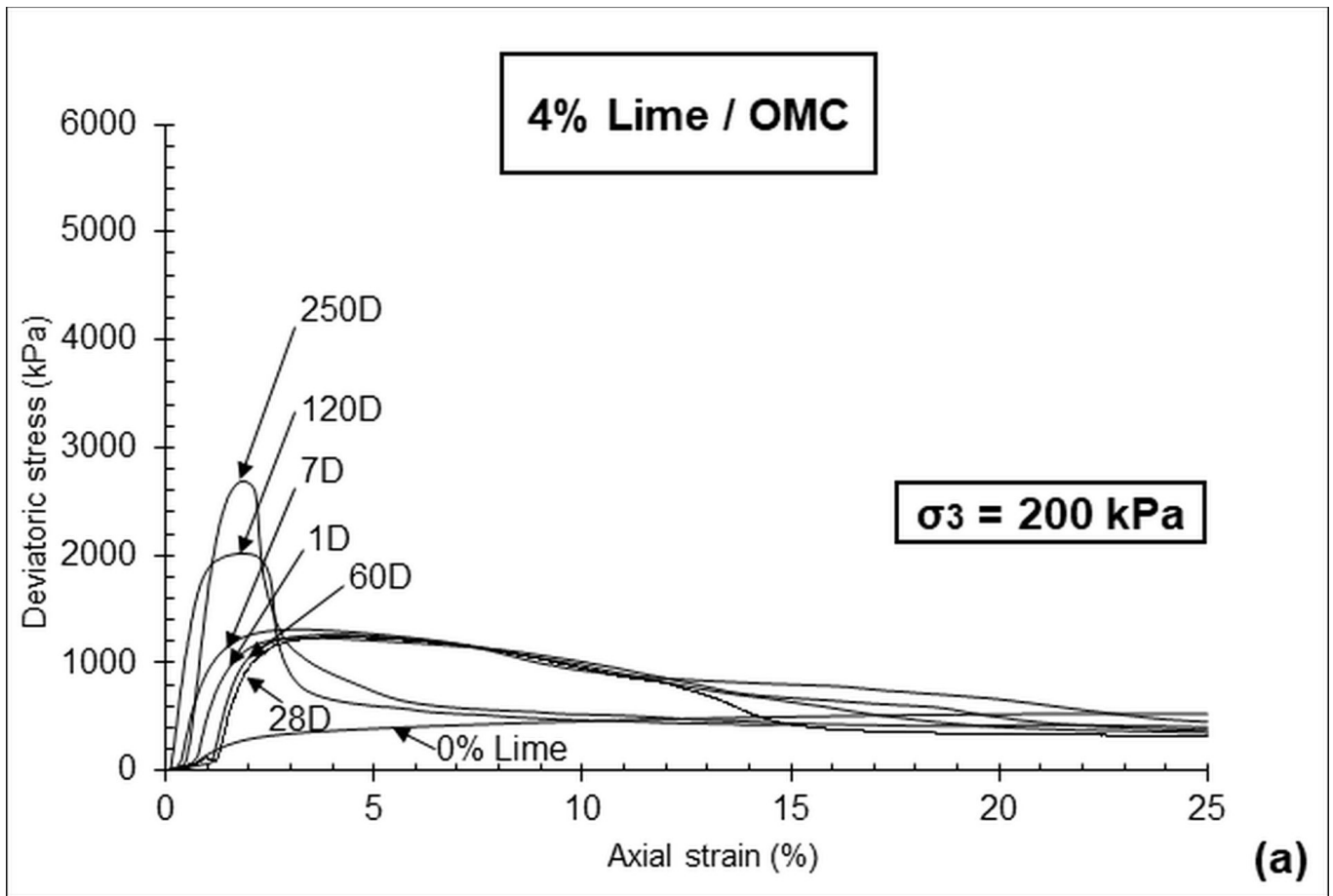


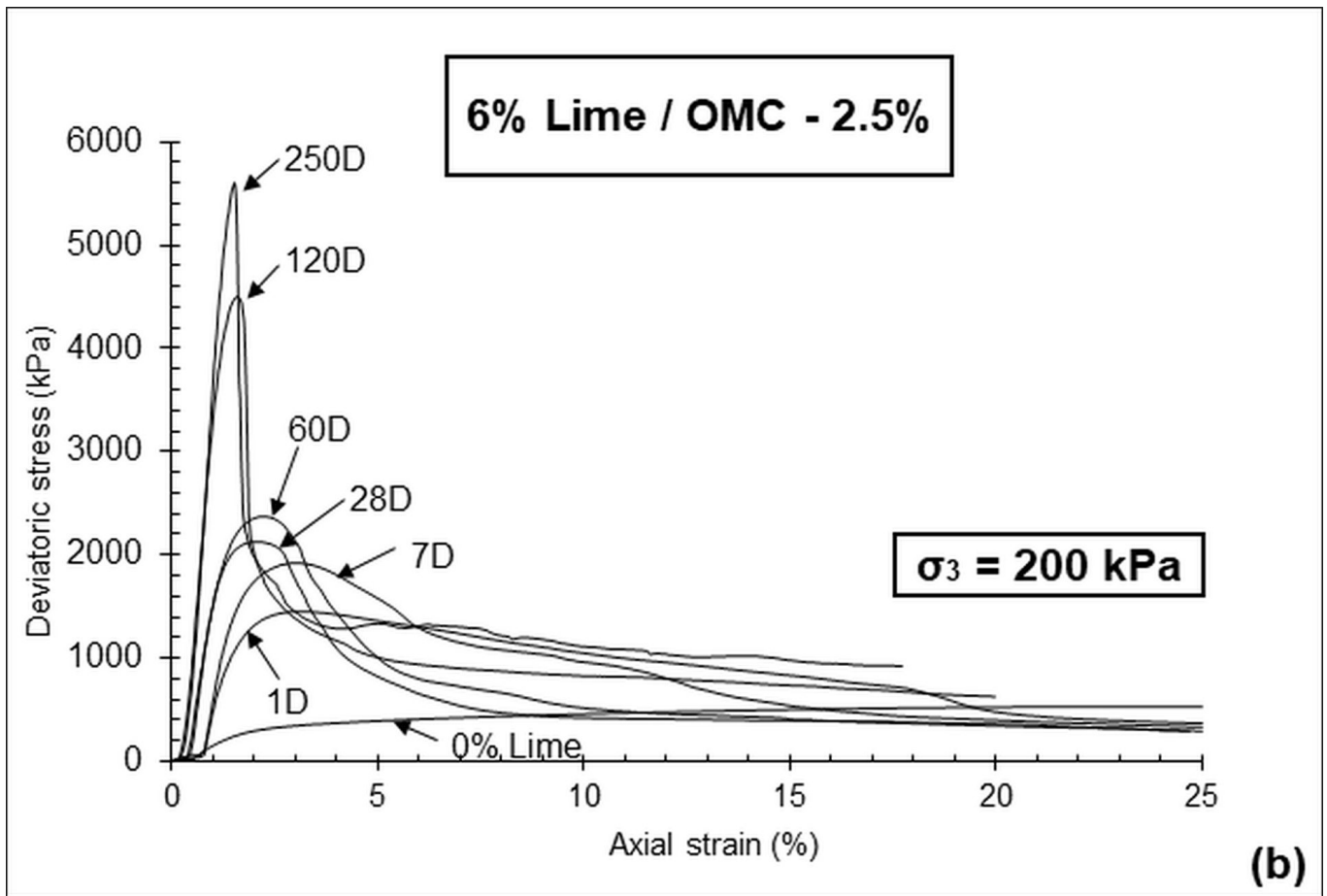


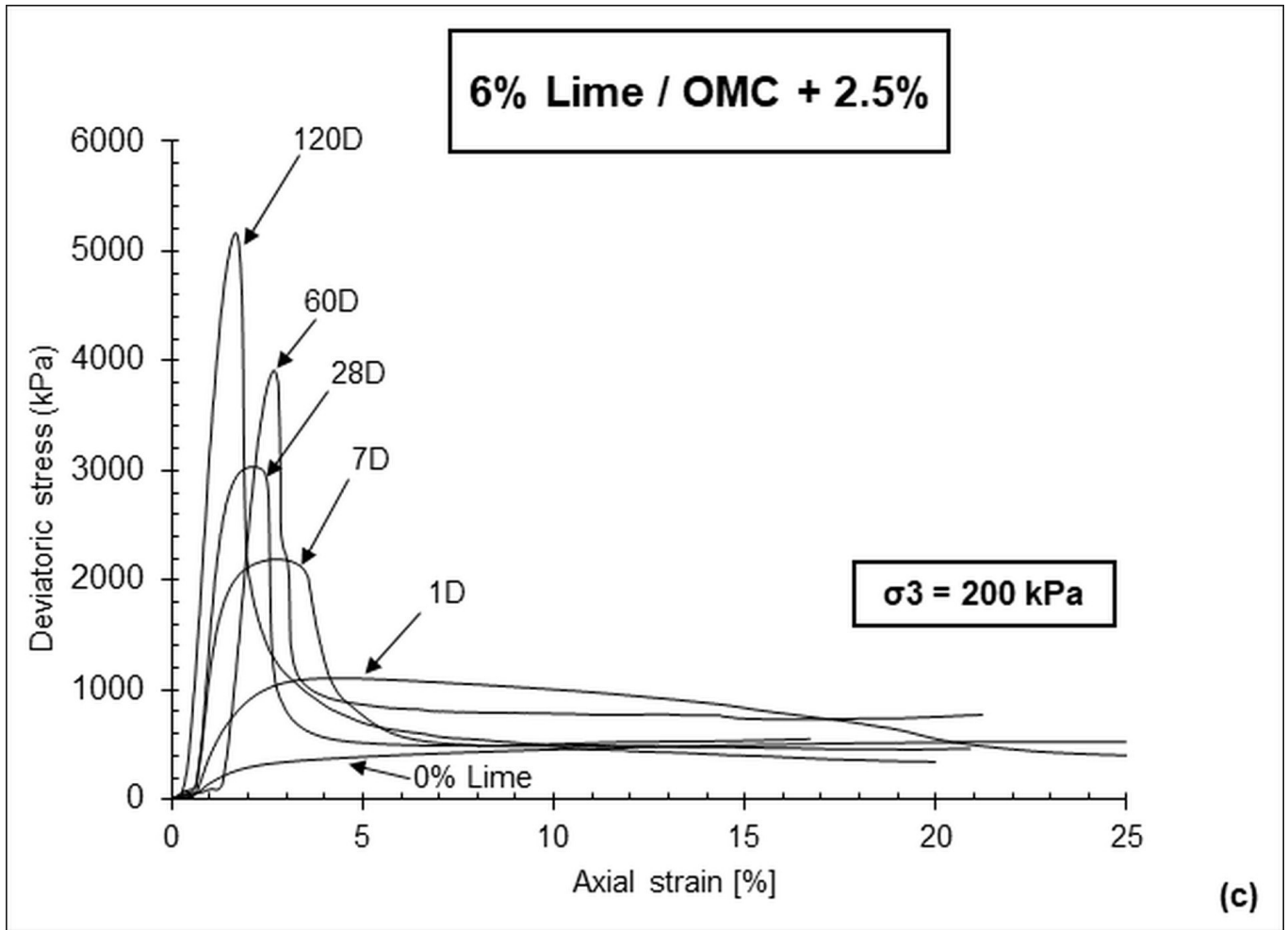


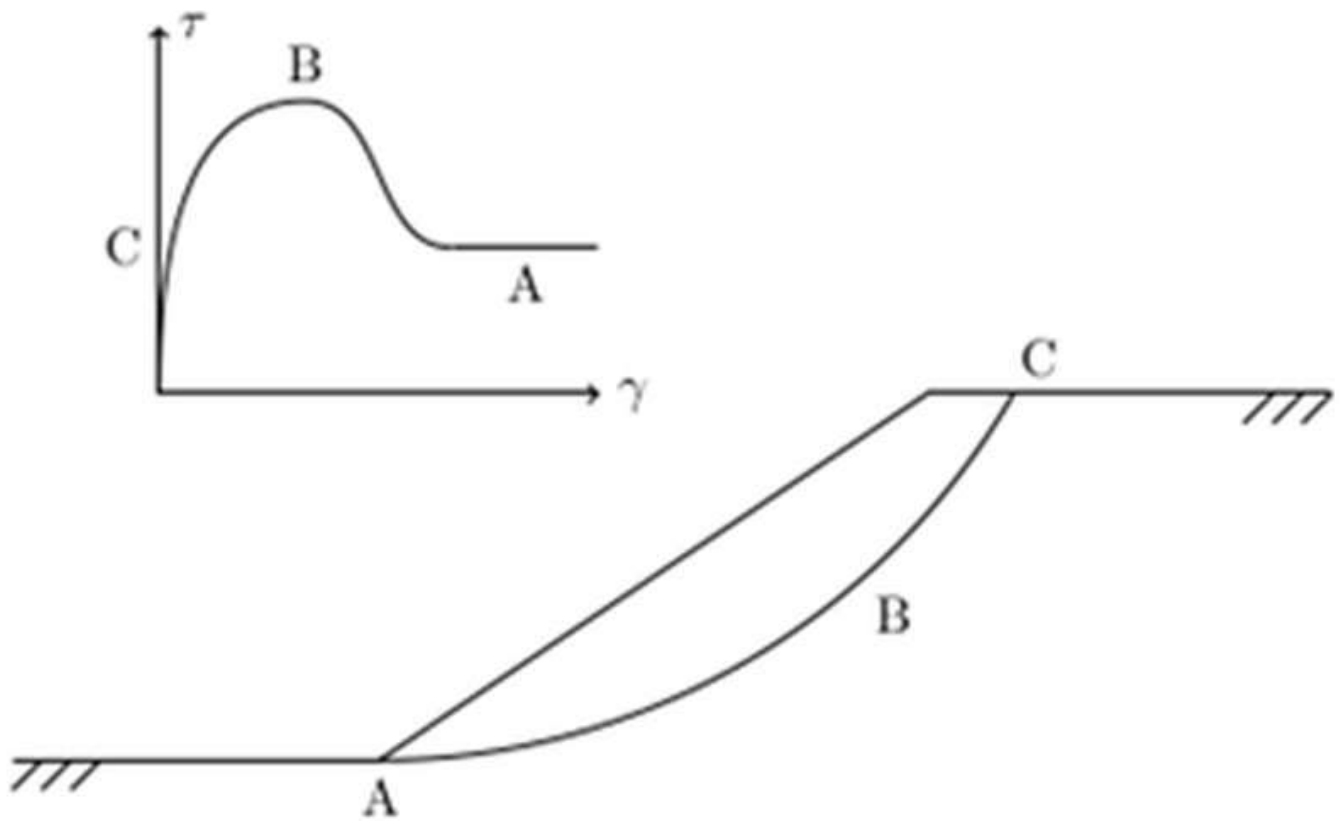


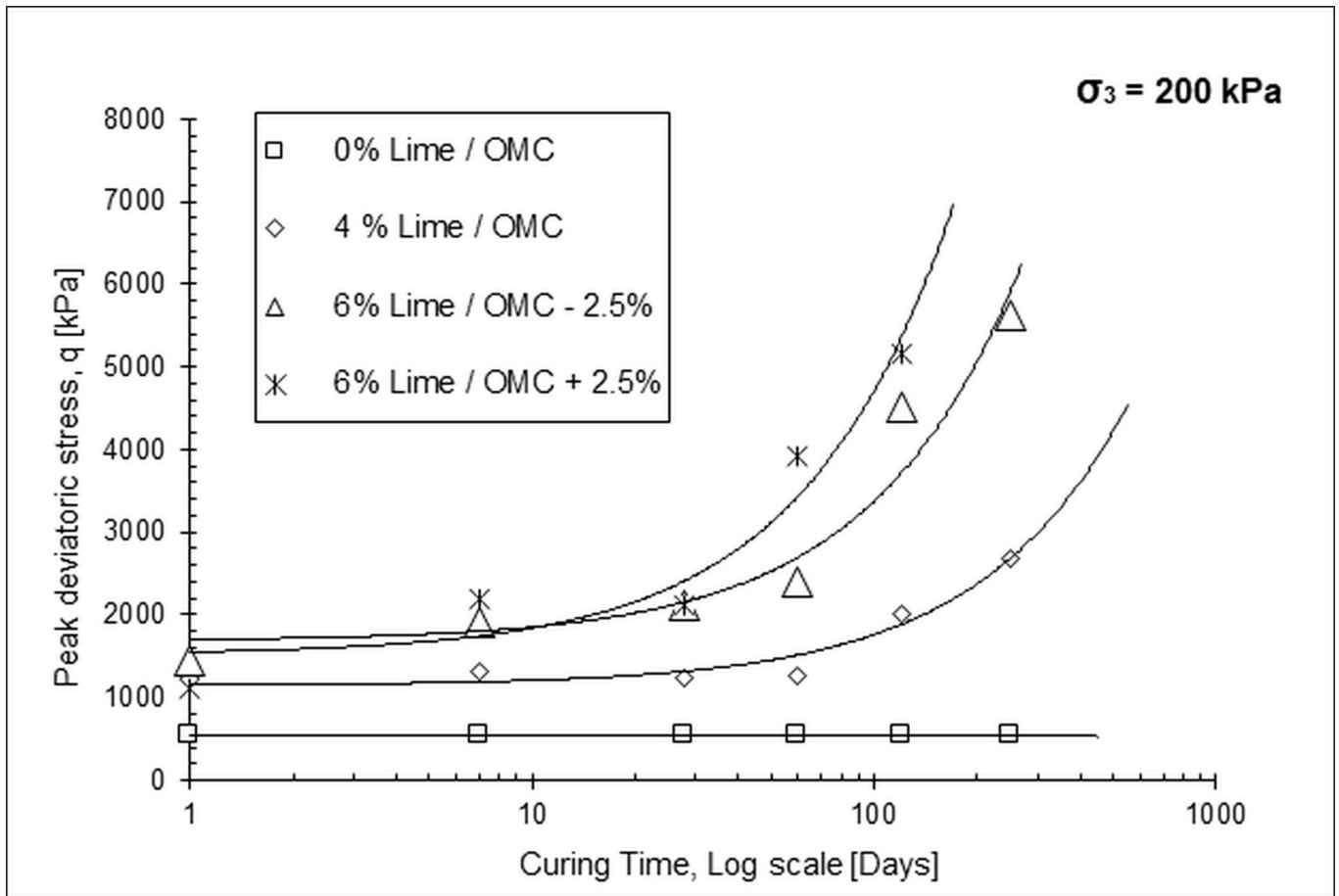


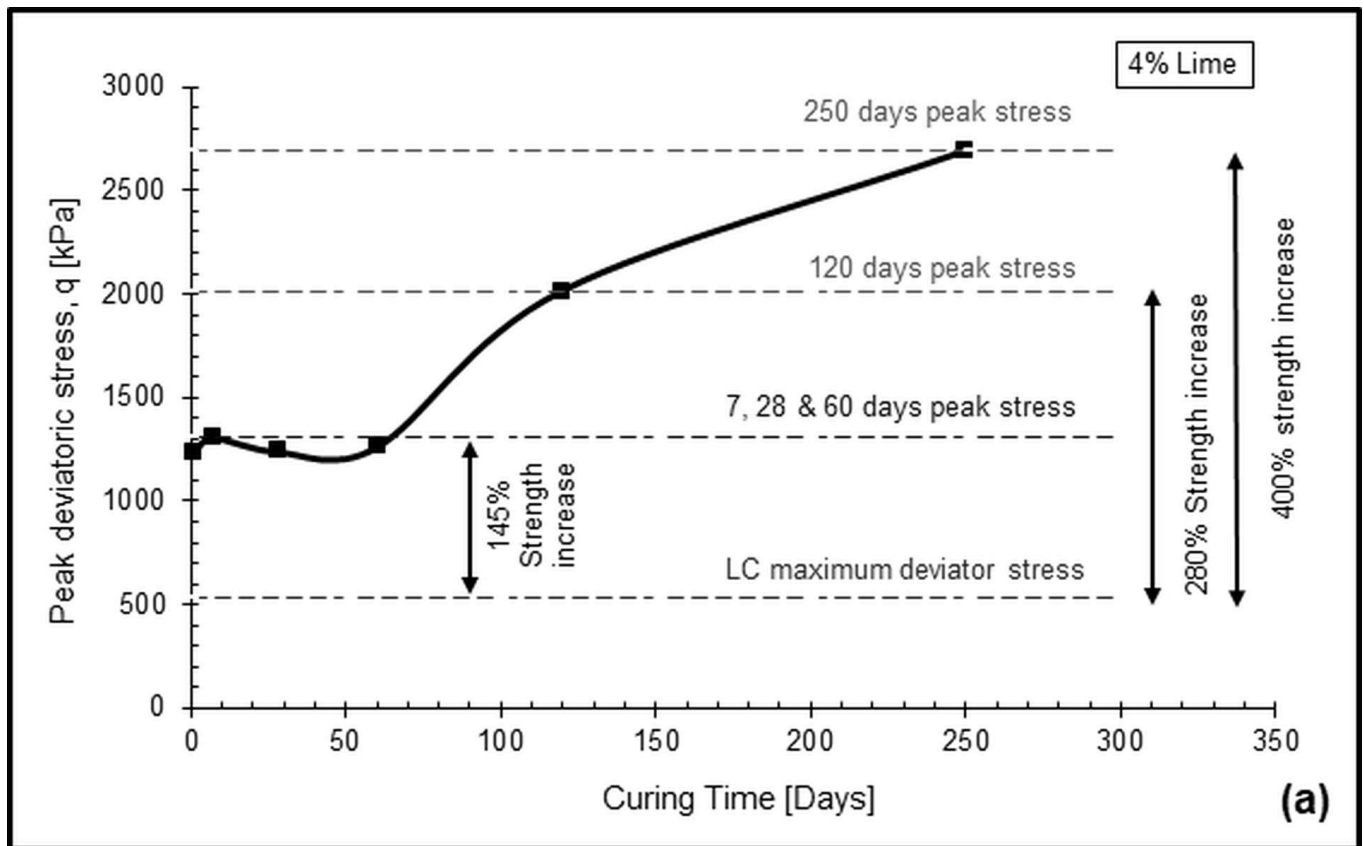


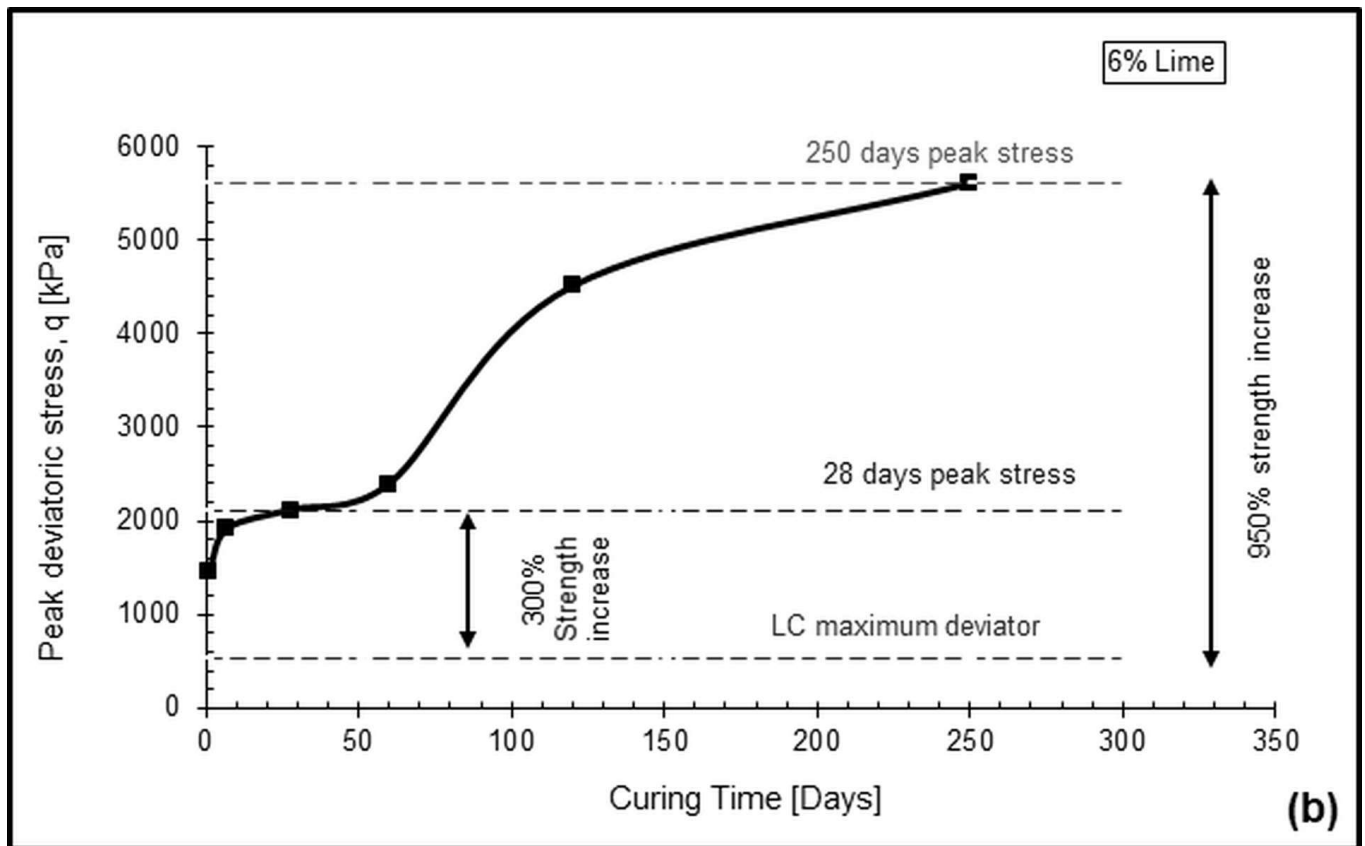












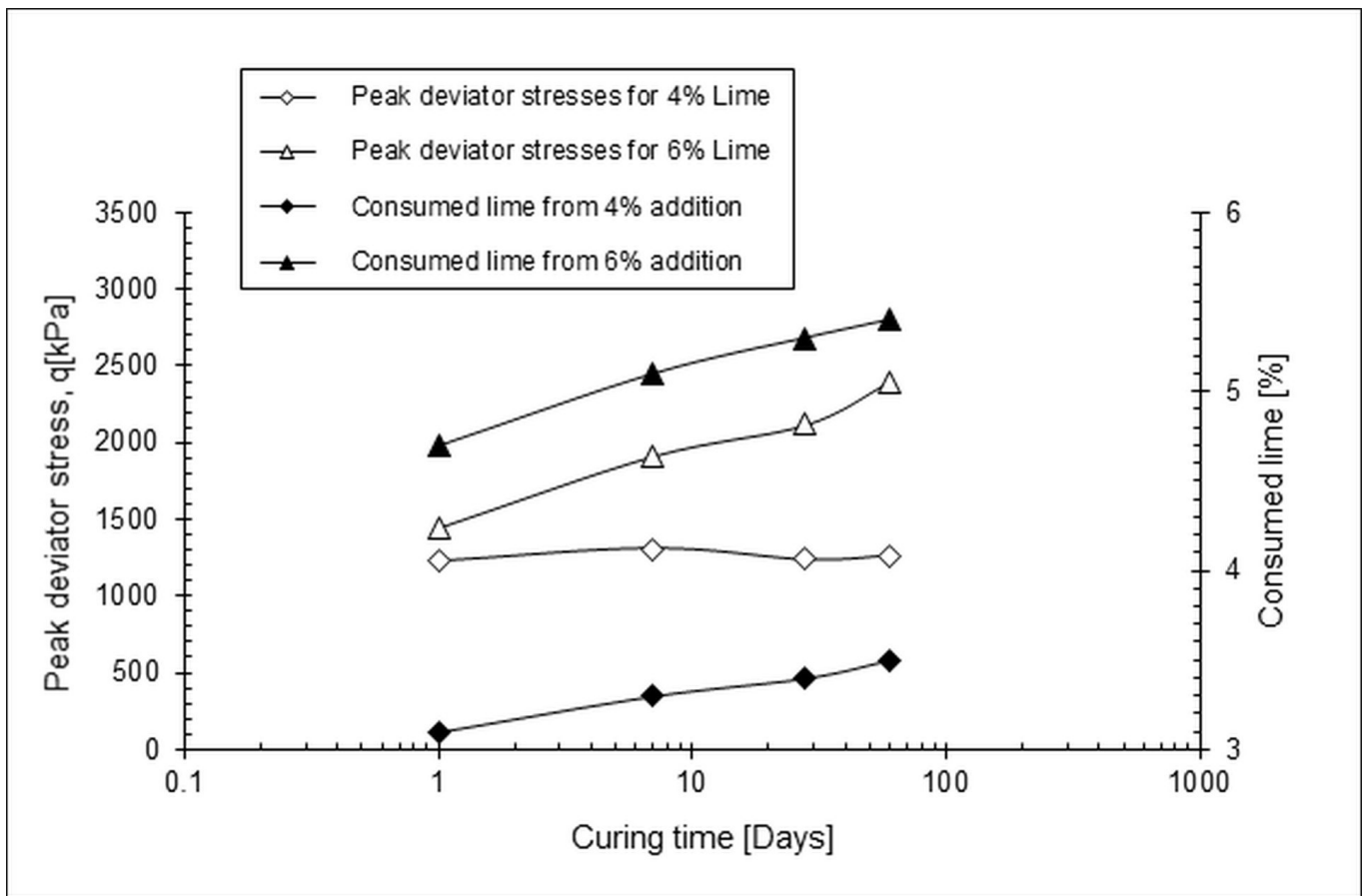


Table 1 Properties of London Clay soil used in this study

Property	Value	Test/Standard	Comments
Clay content %	51	Sieving followed by hydrometer testing according to BS 1377-2:1990 (BSI,1990d)	Duplicate samples
Sand (%)	4		
Silt (%)	45		
Liquid limit (%)	74	Cone penetrometer (liquid limit); thread tests (plastic limit) BS 1377-2: 1990 (BSI,1990d)	Three replicates; some variation at different depth
Plastic limit (%)	26		
Plasticity index (%)	48		
BS classification based on Atterberg limits	CH	BS 1377 -2 : 1990 (BSI,1990d)	
Specific gravity, G_s	2.75	Small pycnometer test BS EN ISO 11508:2017 (BSI, 2017)	Average of 3 readings of ± 0.005 difference
pH	7.2	Digital pH meter calibrated with two buffer solutions (pH = 4.01 & pH = 7). BS ISO 10390:2005 (BSI, 2005)	Average of 3 readings of 0.01-0.05 difference
Initial Consumption of Lime (ICL) %	3.45	BS 1924 – Part 2 (BSI 1990b)	As for pH above (the reported ICL value was based on graphical construction)
Natural gravimetric moisture content (%)	25-30	BS EN ISO 17892: Part 1: 2014 (BSI, 2014)	Triplicate; scales of $\pm 0.01g$ accuracy
Unit weight (kN/m^3)	1950-2000	BS 1377-2:1990 (BSI,1990d)	Triplicate; scales of $\pm 0.01g$ accuracy
Optimum Moisture Content (OMC)%	25	Standard Proctor Compaction BS 1377 – 4: 1990 (BSI,1990e)	Compaction 12 h after mixing soil dry powder with water
Maximum Dry Density (MDD) (kN/m^3)	1520		

Table 2: List of UU triaxial tests

Lime (%)	Curing time (days)	Water content (%)
0	N/A	OMC = 25
4	1	OMC = 27
4	7	OMC = 27
4	28	OMC = 27
4	60	OMC = 27
4	120	OMC = 27
4	250	OMC = 27
6	1	OMC - 2.5 = 27
6	7	OMC - 2.5 = 27
6	28	OMC - 2.5 = 27
6	60	OMC - 2.5 = 27
6	120	OMC - 2.5 = 27
6	250	OMC - 2.5 = 27
6	1	OMC + 2.5 = 32
6	7	OMC + 2.5 = 32
6	28	OMC + 2.5 = 32
6	60	OMC + 2.5 = 32
6	120	OMC + 2.5 = 32

Table 3: Physicochemical characteristics of the untreated and treated soils

Soil type	Liquid limit, w_L (%)	Plastic limit, w_P (%)	Plasticity Index, I_P (%)	pH	Specific gravity, G_s	OMC (%)	MDD kg/m^3
+ 4% lime	86	51	35	12.41	2.74	27	1430
+ 6% lime	90	54	36	12.62	2.74	29.5	1380

Table 4: Consumed lime during the curing period in days

Lime (%)	Curing period (Days)			
	1	7	28	60
	Consumed lime content (%) / (Percentage of supplied lime dosage)			
4	3.1 / (77.5%)	3.3 / (82.5%)	3.4 / (85%)	3.5 / (87.5%)
6	4.7 / (78.5%)	5.1 / (85%)	5.3 / (88.5%)	5.4 / (90%)