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1 Optimum lime content identification for lime-stabilised
2 rammed earth

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8 **Abstract**

The rising price of energy and a recognition of the human impact on climate change has resulted in growing interest in environmentally-friendly construction techniques such as rammed earth. Modern rammed earth is generally stabilised with small quantities of Portland cement in order to improve its strength and durability, however an alternative is to use lime to stabilise the raw soil. This is common practice in road construction, for example, but is less common in RE. This paper presents experimental results illustrating the existence of an optimum lime content that maximises the unconfined compressive strength and stiffness of an engineered lime-stabilised rammed earth and the experimental procedures employed to determine it. The effect of curing regime (oven as opposed to natural drying) on the final unconfined compressive strength of the material was also investigated. An optimum lime content for the tested soil has been identified and several methods to determine its rough value presented which have the potential to reduce testing times and so associated costs.

9 *Keywords:* Lime stabilisation, rammed earth, unconfined compressive
10 strength, optimum lime content.

11 **1. Introduction**

12 Climate change, growing energy costs and the impact of human activities
13 on the environment have all become key concerns for future development in
14 recent years. As construction processes required to develop infrastructure
15 constitute major sources of carbon dioxide production and energy consump-
16 tion, alternative methods are beginning to be explored in order to reduce
17 their environmental impact. One such method is rammed earth (RE) con-
18 struction.

19 RE is an ancient building technique which utilises moist, sandy-loam
20 (USDA classification) subsoil compacted into formwork to form strong, durable
21 and free-standing structures [16, 20]. While the technique has changed little
22 since its inception, it is now common to stabilise RE materials with small
23 quantities of Portland cement in order to improve its strength and durability.
24 The incorporation of Portland cement, however, seems to reduce the sustain-
25 ability of RE and increases both its cost and environmental impact [8, 28].
26 Although a comparative analysis of the sustainability of lime versus that of
27 Portland cement in terms of their thermal and embodied energy finds con-
28 flicting results in the literature [28, 36], depending on the mineralogy of the

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29 clay, availability and transportation, lime stabilisation can represent a more
30 efficient solution than Portland cement for the improvements of the material
31 mechanical properties (it is well established that using Portland cement to
32 stabilise clayey soils does not always produce the expected enhancements in
33 terms of material performance). In Australia, the cost of lime and Portland
34 cement is fairly similar.

35 The interaction between lime and soil has been studied by several authors
36 and it is quite understood that lime stabilisation improves the strength, stiff-
37 ness, plasticity/workability and water adsorption of the raw soil [13, 14]. The
38 lime-soil reaction can be described by three general phenomena: *i*) cation ex-
39 change, *ii*) pozzolanic reaction and *iii*) carbonation. Cation exchange takes
40 place as soon as lime is added to soil in the presence of water. This reaction
41 produces free Ca^{++} ions and leads to an increase in the pH of the soil-lime
42 mix. pHs above roughly 12.4 (the pH of lime-saturated water), achieved
43 through significant lime addition, encourage the solubility of silica and alu-
44 mina present in the clay minerals and quartz [4]. The silica and alumina then
45 react with the Ca^{++} to form calcium silicates and aluminates. From here on,
46 in the presence of water, the reaction is very similar to the Portland cement
47 hydration process: calcium silicates become hydrates and form cementitious
48 compounds. This pozzolanic reaction is exothermic and temperature depen-
49 dent, with the rate increasing at higher temperatures. It is understood that
50 the pozzolanic reaction is affected by soil mineralogy and that the hydration
51 process might take place over a long period, potentially producing continuous

52 strength development for periods longer than the standard 28-day hydration
53 time for Portland cement concrete (for instance). The formation of cement-
54 ing agents (mainly the products of silica hydrates) is assumed to be the main
55 source of strength improvement in lime-stabilised soils [34].

56 Carbonation is another lime-soil reaction that happens when lime reacts
57 with carbon dioxide present in the air, mostly associated with hot-dry cli-
58 mates where control of curing is difficult. It is a phenomenon that should
59 be avoided because it inhibits the formation of cementitious products that
60 hence weakens the material strength. However, it has been shown that this
61 effect can be effectively mitigated through the proper design and control of
62 stabilisation regime and curing conditions [2].

63 Although several examples of historical lime-stabilised RE (LSRE) struc-
64 tures survive to this day, the use of lime in the earthen building construction
65 industry has not been exhaustively investigated so far [7]. This papers aims
66 to understand whether an Optimum Lime Content (OLC) that maximises
67 the Unconfined Compressive Strength (UCS) of a given soil mixture exists
68 for RE materials and outlines an experimental procedure for its determina-
69 tion. The effect of lime stabilisation on the stiffnesses of these materials is
70 also investigated in order to better characterise its elastic behaviour. The
71 details of the experimental programme used in this study are illustrated in
72 Section 2 and findings are extensively discussed in Section 3. The suitability
73 of those procedures used to approximately identify the OLC for an RE soil
74 are discussed in Section 4 and subsequent observations and recommendations

75 provided at the end of this paper in Section 5.

76 **2. Experimental procedure**

77 An engineered soil was prepared by combining known quantities of kaolin
78 clay powder, silica flour, sand and gravel, following guidelines available in
79 RE literature [7, 18, 27, 37]. The choice of using an engineered soil mixture
80 was desirable due to the need to control material grading and mineralogy for
81 testing. Individual component quantities were determined following recom-
82 mendations made by Houben and Guillaud [20] for the selection of a suitable
83 soil for RE construction, with the final Particle Size Distribution (PSD)
84 shown in Figure 1. The gravel component was sieved to pass a 10 mm sieve.

85 Unstabilised RE materials are compacted at their optimum water con-
86 tent (OWC) in order to ensure the highest dry density and, by extension,
87 strength [22]. This practice is also used for stabilised RE materials. For
88 Portland cement stabilisation, the maximum amount of cement that can be
89 added to stabilise the soil then becomes strictly related to the compaction
90 OWC: it would be inefficient to increase the cement content if there was not
91 enough water to hydrate it. Water also plays a critical role in the stabilisa-
92 tion process of lime-stabilised RE materials, as was discussed in the previous
93 Section. In this study, the initial water content, that is the water content
94 at time of mixing and moulding of the specimens, was also taken as equal
95 to the compaction OWC. This choice is motivated by the fact that rammed
96 earth materials are always nominally compacted at their OWC during con-

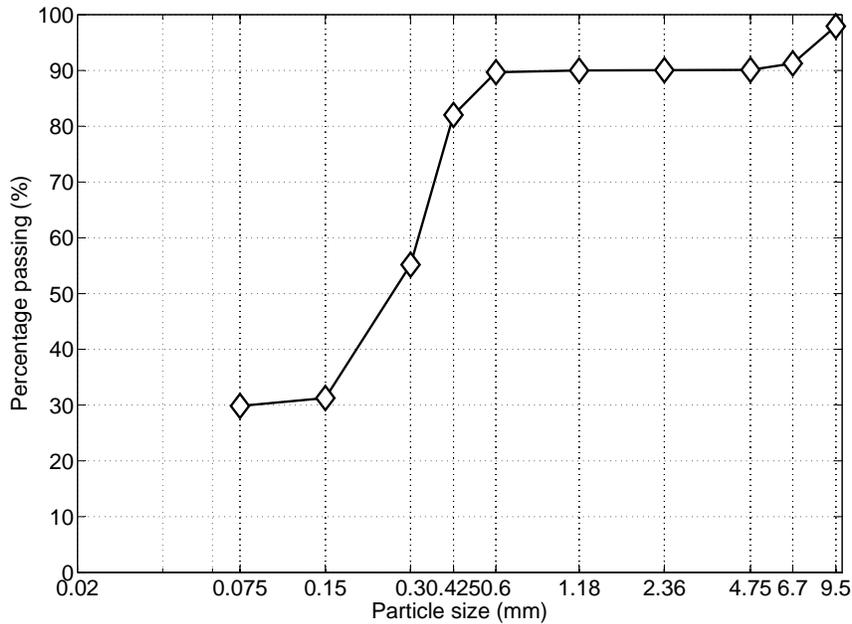


Figure 1: Particle size distribution of engineered soil mixture used in the experimental programme.

97 struction and it would be both unrealistic and impractical to use moulding
 98 water contents different from it. The assessment of stabilised soil mixes with
 99 other than optimum initial water contents is therefore beyond the purpose
 100 of this paper, but is discussed elsewhere [11, 12]. The focus of this investiga-
 101 tion is on the existence of an OLC for a soil mixture with a fixed amount of
 102 clay. Although the strength and stiffness of compacted lime-stabilised soils
 103 depend on many other factors (mineralogy, curing temperature, relative hu-
 104 midity and duration, for example), those factors were set constant in all tests
 105 performed in this study in order to obtain results that were only lime-content

106 dependent.

107 *2.1. Determination of optimum water contents*

108 Laboratory determination of the OWC is generally carried out using ei-
109 ther the Standard or the Modified Proctor Test (MPT) [31]. The MPT has
110 a compactive effort very similar to that used on-site and is a well specified,
111 codified and widely established test and hence repeatable in any laboratory.
112 For these reasons, the MPT was used in this study.

113 The MPT for the unstabilised material was performed according to AS 1289.3.2.1-
114 2009. Oven-dried (for 24 hours at 105°C) soil mix was wetted with water
115 and left to equilibrate for 7 days in sealed containers, in order to ensure a
116 uniform water content, $w\%$, prior to compaction testing. After compaction,
117 the samples were dried in an oven at 105°C to measure $w\%$ and so dry den-
118 sity. The procedure was repeated for different values of $w\%$ and the OWC
119 was found as the water content corresponding to the maximum dry density
120 $\rho_{d,max}$ achieved.

121 For the lime-stabilised material, the procedure specified by AS 1289.3.2.1-
122 2009 was slightly modified. Oven-dried soil material was combined with a
123 selected quantity of hydrated lime and dry-mixed thoroughly for a minimum
124 of five minutes. Then, batches were made with known values of $w\%$. As the
125 addition of water initiates the cation exchange, flocculation and pozzolanic
126 reactions, compaction was completed within 45 minutes of wetting in order
127 to prevent undesired soil fabric changes from interfering with the test. Un-

128 like for unstabilised materials, oven drying could not then be used to verify
 129 the material water content due to the loss of (non-evaporable) water via the
 130 above-mentioned reactions triggered by the high drying temperatures. Ma-
 131 terial water content was therefore taken to be the added water content $w\%$
 132 used during compaction and the OWC determined as described above. The
 133 OWC, water/lime ratio (w/L) and $\rho_{d,max}$ for each of the investigated lime
 134 contents are given in Table 1. Note that lime and water contents are given
 135 as a percentage of the dry soil mass (i.e. not inclusive of the lime mass).

Table 1: Lime content, OWC, $\rho_{d,max}$ and water/lime ratio results

Lime content (%)	0	2	3	4	5	6
OWC (%)	7.6	7.7	8.1	8.0	9.6	8.5
w/L ratio	N/A	3.85	2.70	2.00	1.92	1.42
$\rho_{d,max}$ (kg/m ³)	2190	2130	2070	2140	2060	2030

136 2.2. UCS specimen preparation

137 Material UCS is generally used to assess stabiliser effectiveness [27, 30,
 138 38]. UCS was determined for 100-mm diameter, 200-mm high cylindrical
 139 specimens tested in uniaxial compression between Teflon sheets [9]. Five
 140 specimens were prepared per lime content, prepared following the same mix-
 141 ing and compaction procedures used for OWC testing. Specimens were care-
 142 fully extracted from the mould immediately following manufacture and trans-
 143 ferred to wire racks to cure for 28 days under constant conditions of $94\pm 2\%$
 144 relative humidity (RH) and $21\pm 1^\circ\text{C}$. It is important to note that this allowed

145 specimen water contents to reduce with time. That being said, it is beyond
146 the purposes of this study to investigate the effect of the water content at
147 testing on the compressive strength. The aim of this paper is to discover
148 whether, for an initial water content equal to the OWC and under fixed cur-
149 ing conditions, samples made of the same soil but different lime contents
150 show an OLC that maximizes the compressive strength. The curing time
151 prior to testing was set to 28 days following the recommendations of AS
152 5101.4 [32] and other Australian guidelines for lime stabilisation practices
153 [1]. These curing conditions might not have represented those on-site, but
154 allowed for the repeatability of the procedure to be assessed in a systematic
155 manner. These specimens are hereafter referred to as “A-series” specimens.

156 For many years and due to the lack of proper standards, stabilised earthen
157 materials have been viewed and treated as weak forms of concrete. As a con-
158 sequence, no distinction is commonly made between the strengths obtained
159 from specimens tested under saturated, ambient or oven-dry conditions (for
160 example as in Walker and Standards Australia [37]). However, given the
161 strong relationship between water content, suction and strength (well es-
162 tablished for earthen construction materials), such distinction must be con-
163 sidered as recently confirmed in several studies [3, 10, 22]. Furthermore, the
164 temperature-dependent nature of the lime stabilisation process indicates that
165 the performance of specimens tested at ambient conditions will be different
166 to those of oven-dried specimens [17]. For this reason, additional specimens
167 were manufactured (using the same procedures discussed above) and allowed

168 to cure under identical conditions to A-series specimens for 28 days before be-
169 ing oven-dried at 105°C for additional 24 hours prior to UCS testing. These
170 are hereafter referred to as “O-series” specimens. Again, five specimens were
171 tested per lime content.

172 **3. Results and discussion**

173 *3.1. Effect of curing conditions on 28-day UCS*

174 Results from UCS testing on A- and O-series specimens are shown in
175 Figure 2 in terms of mean UCS values and standard deviations (s) (error
176 bars denote $\pm 1s$). Figure 2 shows that a significant increase in mean UCS
177 occurs between A- and O-series specimens. For unstabilised material (i.e. 0%
178 lime content), it is well understood that this increase is due to a significant
179 increase in total suction on oven drying to a lower water content [3, 22]. For
180 the stabilised samples, the reasons behind the increase in strength are less
181 straightforward.

182 One reason relates to the temperature effect; it is well established that
183 the formation of pozzolanic compounds in lime-stabilised soils depends on
184 temperature [17, 35]. Curing time is another factor that significantly affects
185 the strength of soil-lime mixtures. Croft [14], and later Consoli et al. [11],
186 presented results for the UCS of lime-stabilised soils as affected by curing
187 time. Unlike cement-stabilised soils and concrete, which achieve UCSs ap-
188 proaching their mature values after 4 weeks, these authors demonstrated that
189 curing times between 7 and 60 weeks might be required for lime-stabilised

190 soils to reach maturity, depending on soil mineralogy, stabiliser content and
191 compaction water content. Therefore, the pozzolanic reaction after 4 weeks
192 might be incomplete for materials tested in this study. The significant in-
193 crease in O-series UCS might therefore be attributed to a combination of
194 increased suction, as mentioned above, and also to a dramatic acceleration
195 of the pozzolanic reaction on exposure to elevated temperatures. All other
196 factors being the same, the higher the curing temperature, the greater the
197 extent of the pozzolanic reaction (and, by extension, strength) that can be
198 induced in a soil-lime mixture [35].

199 Figure 2 shows that, in some cases, values of s increased dramatically
200 between A- and O-series specimens. Given the severity of the oven drying
201 process, it might be that, had specimens been constantly wetted during the
202 24 hours in the oven, less scatter (i.e. lower values of s) would have been
203 observed in the O-series results despite the higher temperatures. In contrast,
204 the A-series samples were exposed to a highly humid environment for 28
205 days, allowing the hydration process to happen more uniformly and thus
206 producing more consistent results.

207 Results given in Figure 2 therefore suggest that ambient and oven-dried
208 specimens should not be assessed in the same way nor should their results
209 be indistinctively used for the same purpose. Instead, specimens should be
210 tested under conditions representative of those likely to be encountered dur-
211 ing their lifetime for UCS determination [3]. Results for O-series specimens
212 will therefore no longer be used in this paper to investigate LSRE properties.

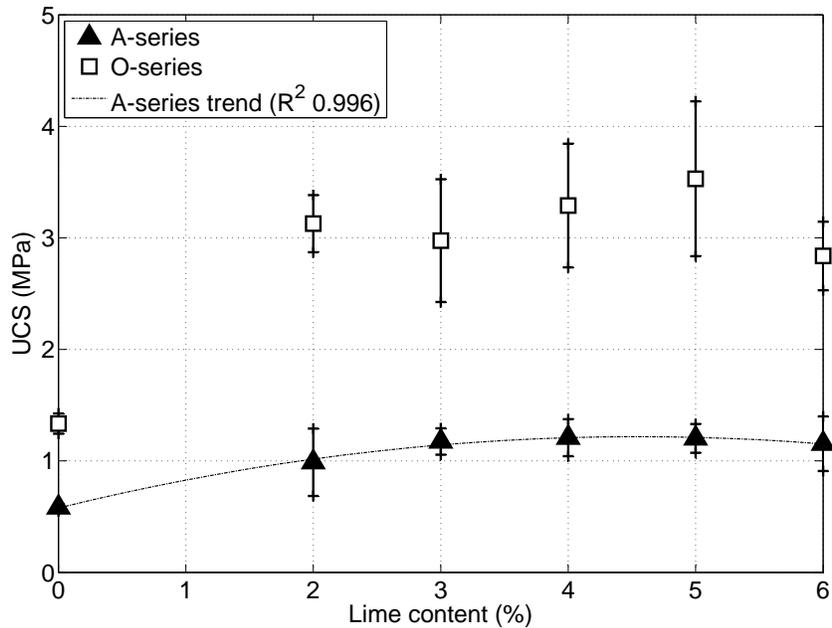


Figure 2: UCS results in terms of mean values and standard variation for (Ambient) A- and (Oven-dried) O-series specimens.

213 *3.2. Effect of lime and water content on 28-day UCS*

214 As shown in Figure 2, 28-day UCS values increase with increasing lime
 215 content up to an “Optimum Lime Content” (OLC) around 4%, above which
 216 no additional beneficial changes in UCS are observed. A similar trend to
 217 that found for A-series specimens shown in Figure 2 was also found by Bell
 218 [4], who demonstrated that this phenomenon was due to the limited amount
 219 of water available to hydrate the amount of lime, so that the material was
 220 effectively “lime saturated” for lime contents above the OLC; this is discussed
 221 in more detail later in this paper. It might be worth to notice again that, as

222 mentioned in the previous section, specimens tested in this study were not
223 sealed following manufacture but were instead allowed to cure in a highly
224 humid environment. For this reason, the water content at 28 days at testing
225 is different to the initial water content at mixing. It is beyond the purposes
226 of this study to investigate the effect of the water content at testing on the
227 compressive strength.

228 In another study [29], UCSs were determined for unfired soil bricks man-
229 ufactured using two Botswanan soils (*Mahalapye* soil, clay soil (48.0% clay)
230 and *Tsabong* soil, sandy loam (14.5% clay) (USDA classifications)) stabilised
231 with a range of lime contents from 5% to 15%. An OLC was not identified
232 for those soils, with UCS values instead increasing as long as the lime content
233 increased. It is difficult to draw any conclusions on the comparison between
234 Ngowi's results and those presented here, however, due to the substantial
235 differences in compaction regime, significantly higher clay contents of those
236 materials tested and the lack of extra data in Ngowi's work, for example on
237 clay mineralogy and the moulding water content used. The lack of a distinct
238 OLC in Ngowi's work therefore does not invalidate the finding of an OLC for
239 the material tested in this study.

240 Some previous studies on lime-stabilisation of silt [12] indicated the initial
241 porosity/lime (n/L) ratio as a crucial parameter to evaluate the effectiveness
242 of lime stabilisation. It was found that the UCS decreased with increasing
243 n/L for specimens manufactured and maintained at a constant amount of
244 water (equal to 20% of the soil weight) with varying amount of lime and dry

245 unit weights. These conditions (constant water and varying dry unit weight),
246 however, imply that the compactive effort was not the same for all specimens.
247 In the study presented here, however, all specimens were manufactured using
248 the same compactive effort but at water contents equal to their OWC, which
249 varied with lime content.

250 Figure 3 presents A-series UCS vs. n/L where n has been calculated
251 assuming a specific gravity value of 2.65 for all material lime contents. Unlike
252 results found in Consoli et al., results shown in Figure 3 seem to display
253 a peak UCS vs. n/L value corresponding to lime contents of between 3
254 and 4%, similar to results shown in Figure 2 for the OLC. The lack of a
255 strong agreement between the results of this study and those in Consoli et
256 al. can again be attributed to factors such as different compaction energy, soil
257 composition and curing regime. In addition, samples in Consoli et al. had
258 constant but higher water contents (constant 20% of soil mass) than those
259 used in this work (between 7.6 and 9.6%) that guaranteed the hydration of
260 the lime present in the soil (between 3 and 9%) and were tested at higher
261 n/L values as found in this study. These results would therefore suggest that
262 a universal relationship between n/L and UCS cannot be derived; however,
263 within the confines of the material tested here, results for n/L might offer
264 some indication as to the location of the OLC. Clearly, this requires further
265 testing in order to be substantiated.

266 One last observation might be made regarding the effect of carbonation.
267 In a study on carbonation of stabilised soil-lime mixtures [2] it was found

268 that an increase in the amount of air voids present in a sample increases the
269 level of carbon dioxide that penetrates the soil. Unsealed samples cured in an
270 environment with 20°C and relative humidity of 100% showed no significant
271 loss of strength at 28 days as compared to the strength of sealed (hence no
272 carbonation allowed) samples. For the unsealed samples, water present in the
273 pores reduced carbon dioxide ingress and hence diminished the carbonation
274 process. Other samples exposed to higher temperatures (40°C) during the
275 same curing period showed an important loss of strength gain due to the
276 loss of water in the pores (i.e. an increase of air voids) that facilitated
277 carbonation. Since all specimens in this study were cured for a set time in
278 a curing room with a high relative humidity of 94% and a low temperature
279 of 20°C, it is assumed that carbonation did not play a major role in the
280 evolution of material strength.

281 *3.3. Effect of lime stabilisation on stiffness*

282 Material stiffness plays an important role in the prediction of structural
283 displacements and also in the structural analysis of composite elements (like
284 reinforced earth). This latter case became evident over recent years following
285 the destruction of the adobe town of Bam in Iran (A UNESCO World Her-
286 itage site) during the December 2003 earthquake, which was accompanied
287 by a severe loss of life. A study (unpublished) conducted after the disaster
288 showed the inappropriate use of steel beams to reinforce the existing build-
289 ings during conservation work prior to the earthquake. The beams were far

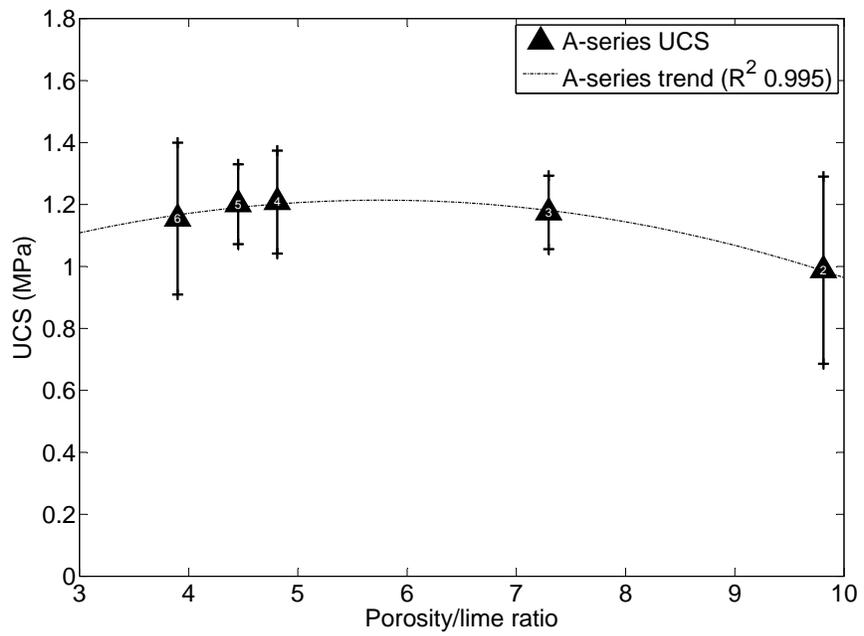


Figure 3: UCS versus initial porosity/lime ratio. The numbers inside the markers indicate the lime content in %.

290 too stiff ($E=205$ GPa) with respect to the adobe material ($E=85$ MPa) and
291 the two elements (the steel beam and the adobe wall in which the beam was
292 embedded) acted separately during the earthquake, with the wall crushing
293 and the steel beam not taking any load. The same study showed that the
294 use of polypropylene bars (with lower stiffness $E=850$ MPa) as tensile ele-
295 ments grouted in the wall improved the seismic performances. This example
296 illustrates the motivations behind evaluating the stiffness of RE in this study.

297 UCS specimens were tested between Teflon sheets to reduce confinement
298 effects, following the work of Ciancio and Gibbings [9]. Thus, the displace-
299 ment between the loading platens divided by the height of the sample could
300 be regarded as the true axial deformation. Figure 4 shows the uniaxial com-
301 pressive stress-strain $\sigma - \varepsilon$ curves for A-series specimens tested in this work
302 (again, five specimens per lime content). The initial segment of the curves,
303 for very low values of stress, is characterised by a shallow slope due to any
304 re-alignment of the loading plates required to fully contact the specimen sur-
305 faces. Once the load is uniformly applied, the slope of the stress-strain curve
306 increases to a maximum value before decreasing again. The tangent slope of
307 the $\sigma - \varepsilon$ curve represents the tangent stiffness of the material, the maximum
308 value of which is hereafter designated E_0 .

309 Mean values of E_0 calculated for each group of specimens with the same
310 lime content are shown in Figure 5. These results suggest that E_0 significantly
311 increases with the initial addition of lime (i.e. between 0 and 2% lime content)
312 and then reaches a peak value of approximately 200 MPa at 4% lime content,

313 corresponding well to the OLC already identified for specimen UCS. Again,
314 this behaviour may be due to increasing rates of the lime-soil pozzolanic
315 reaction up to the point of lime saturation, whereupon the reaction rate
316 becomes stable [19].

317 It is important to state that E_0 does not coincide with the Young's mod-
318 ulus E of the material. The latter characterises the initial elastic relationship
319 between normal stress σ and strain ϵ , the former the incremental (and not
320 necessarily elastic) relationship between σ and ϵ . With this difference in
321 mind, a comparison is provided between the E_0 values obtained in this work
322 and the recommended values of Young's modulus available in the literature.
323 From Table 2 it can be seen that E_0 stiffnesses for lime-stabilised materi-
324 als given here fit well within the upper range expected for unstabilised RE
325 Young's modulus. A significant difference is seen, however, between values
326 of the stiffness for lime-stabilised and cement-stabilised RE.

327 In the absence of experimental data, Walker and Standards Australia [37]
328 recommend the use of a Young's modulus equal to 500 MPa for all RE materi-
329 als, regardless of the use of stabiliser employed. This value seems to overesti-
330 mate the data obtained in this study and by others in the available literature,
331 so that values of E lower than 500 MPa would seem to be more suitable for
332 unstabilised and lime-stabilised materials. A more flexible method to pre-
333 dict E is provided in NZS 4297:1998, whereby $E = 300 \times f'_c$, where f'_c is the
334 material characteristic compressive strength ($f'_c = 1 - 1.5x_1 \left(\frac{s}{\mu}\right)$, where s
335 and μ are the standard deviation and average of the series UCS and x_1 is the

336 lowest series UCS result). The experimental values found in this work for
 337 E_0 and f'_c are given in Table 3 alongside predicted values calculated using
 338 NZS 4297:1998. Results given in Table 3 indicate that the method proposed
 339 by NZS 4297:1998 is able to estimate the order of magnitude of the stiffness
 340 of the material, provided that f'_c has been accurately obtained. It should
 341 be noted that, as the calculation of f'_c depends on the mean and standard
 342 deviation of a tested series, the testing of a larger number of specimens might
 343 improve the match between predicted and experimental values. However, it
 344 is the authors' opinion that a single mathematical formulation to predict an
 345 accurate value of E from f'_c for LSRE would be difficult (if not impossible)
 346 to implement due to the high variability of existing soils and factors affecting
 347 their strengths and stiffnesses, so that preference should always be given to
 348 experimentally determined stiffness values.

Table 2: Stiffness values as reported by other authors and in this work for URE, LSRE (lime content in %) and CSRE (cement content in %).

Material type	Stiffness (MPa)	Author
URE	205	Maniatidis et al. [26]
URE	160	Maniatidis and Walker [25]
URE	160	Jaquin [21]
URE	75	Bui and Morel [5]
URE	95	This work
LSRE (2–6)	160–227	This work
CSRE (6–10)	500	Jayasinghe and Kamaladasa [24]

Table 3: Relationship between E_0 found in this work and E as recommended by NZS 4297:1998 for A-series specimens

	Lime content (%)					
	0	2	3	4	5	6
f'_c (MPa)	0.49	0.40	0.82	0.73	0.86	0.64
E_0 (MPa)	95	160	196	227	172	204
E (MPa) as per NZS [30]	147	120	246	219	258	192

349 4. Methods to identify the OLC

350 The existence of an OLC is a well known concept extensively applied in
351 the lime stabilisation of soils used in road-building, for example, however it is
352 a less well understood concept for RE applications. Results presented in this
353 paper indicate the existence of an OLC value, for those materials tested, that
354 allows for maximum material performance with the minimum use of lime.
355 A common procedure used by RE practitioners to identify the OLC would
356 be similar to the one presented in this paper, i.e. to manufacture several
357 specimens with different lime content, to measure their UCS and finally to
358 select the lime content that produces the maximum strength. There is no
359 doubt that this procedure is time consuming and requires the fabrication of
360 many specimens. Eades and Grim [15] and Hilt and Davidson [19] suggested
361 alternative methods to more quickly identify the OLC:

- 362 • *Eades and Grim [15]*: 20g of stabilised soil sieved to pass $425\mu\text{m}$ is
363 mixed with 100mL of distilled water and shaken for 30 seconds, and
364 then for another 30 seconds every 10 minutes for a total of one hour.
365 The pH of the resulting slurry is then tested with a pH meter calibrated

366 to a pH 12 buffer solution. The OLC corresponds to the lime content
367 required to produce a soil water pH of 12.4, lime saturated solution.
368 Although tests are conducted on the fine fraction of the stabilised ma-
369 terial, i.e. that fraction most reactive to lime stabilisation, results are
370 assumed to apply to the entire material grading.

371 • *Hilt and Davidson [19]* Stabilised soil, again sieved to pass $425\mu\text{m}$, is
372 wetted and allowed to cure for 24 hours prior to plastic limit (PL)
373 testing as per AS 1289.3.2.1-2009 [33]. The OLC corresponds to the
374 lime content above which no further change in PL occurs. Again, it
375 is assumed that tests conducted on the fine soil fraction apply to the
376 entire material grading.

377 Figure 6 shows results for plastic limit and pH testing as compared to
378 results found for UCS testing for material stabilised to the range of lime
379 contents used in this study. Note that results for pH at a lime content
380 of 0% are not shown for clarity. Figure 6 shows that OLCs determined
381 using the pH and PL methods show good agreement with the OLC of 4%
382 previously identified through UCS testing (pH=12.4 at 3.5% lime content
383 whilst PL becomes roughly constant above 4% lime content). Results given
384 in Figure 6 also support those observations made in the previous section that
385 soils prepared to lime contents $< 4\%$ had insufficient lime to saturate the pore
386 water, such that its capacity to dissolve the soil minerals into calcium silicates
387 is reduced, as these materials have pH environments less than the 12.4 limit

388 and so a reduced ability to dissolve the soil minerals into calcium silicates
389 and aluminates. The water is, however, sufficient to hydrate all calcium
390 silicate products but the hydration process is not enough to mobilise the
391 maximum strength of the material. On the other hand, materials prepared
392 to lime contents above 4% had sufficient lime to saturate the pore water, as
393 shown by pH conditions > 12.4 , but lacked sufficient water to fully hydrate
394 the available lime (as indicated by reducing w/L values with increasing lime
395 content in Table 1). The pozzolanic reaction in this case is governed by the
396 availability of water and not by the lime content, resulting in the production
397 of similar amounts of cementitious compounds for specimens of $> 4\%$ lime
398 content and, hence, similar compressive strengths at 28 days curing time.

399 For the materials tested in this work, the agreement between OLCs deter-
400 mined via pH, PL and UCS testing therefore indicates that pH and PL tests
401 are both suitable for determining the approximate value of the OLC of an
402 RE material. This conclusion, however, requires further testing to be fully
403 substantiated (for example the use of additional soil types, curing conditions
404 etc.). If proved to be reliable for RE, the *Eades and Grim* and *Hilt and*
405 *Davidson* tests could easily be performed to identify the rough location of
406 the OLC, so that the range of lime contents, and so testing time and costs,
407 required for confirmative UCS testing can be significantly reduced.

408 5. Conclusions

409 This paper has presented a series of tests investigating the existence of
410 an optimum lime content that maximises the compressive strength of a lime-
411 stabilised RE material. The tests produced several key findings:

- 412 • an OLC was found for the studied soil mixture such that, for a given
413 curing time, clay content and optimum water content at moulding (as
414 determined by the MPT), no beneficial change to strength or stiffness
415 is noticed with increased lime content;
- 416 • exposure of specimens to elevated temperatures resulted in a significant
417 increase (more than double the results of the A-series) of the UCS at
418 28 days;
- 419 • the formula $E = 300 \times f'_c$ proposed by NZS 4297:1998 seemed to be ap-
420 propriate for predicting the order of magnitude of the stiffness of LSRE.
421 It is therefore recommended when rigorous lab procedures for the de-
422 termination of the material stiffness are not available. The generic
423 value of $E = 500$ MPa proposed by Walker and Standards Australia
424 [37], however, overestimates the values found in this work for URE and
425 LSRE;
- 426 • a close agreement was found between UCS, PL and pH testing for
427 identification of the OLC.

428 It has been shown that the use of oven-dry conditions for UCS testing
429 results in a significant overestimation of the material UCS. Specimens should
430 therefore be tested under conditions similar to those to which they will be
431 exposed during their lifetime if an accurate assessment of their UCS is to be
432 made.

433 An OLC of 4% was found for the tested soil, above which no beneficial
434 change in UCS or stiffness was found with increasing lime content for the
435 testing conditions used. Subsequent pH testing suggested that this was due
436 to the lime saturation of the pore water for lime contents above 4%.

437 Given its lengthy duration, alternative testing methods to UCS testing
438 were investigated for OLC determination and a close agreement was found
439 between OLCs determined by UCS, PL and pH testing. Both pH and PL
440 testing might therefore offer suitable alternatives to extensive and time con-
441 suming UCS testing for more rapidly determining the OLC, which might, in
442 turn, offer significant cost savings to RE contractors.

443 It is important to stress, however, that results discussed in this work are
444 for a single soil type and that other factors, such as curing time, lime type,
445 curing temperature and water content at testing, should also be taken into
446 account before any general rule for lime stabilisation could be determined. It
447 would be inappropriate to extrapolate a general rule valid for any type of soil
448 from those results presented here. Further investigations are then necessary
449 to draw more general conclusions on this subject.

450 **6. Acknowledgments**

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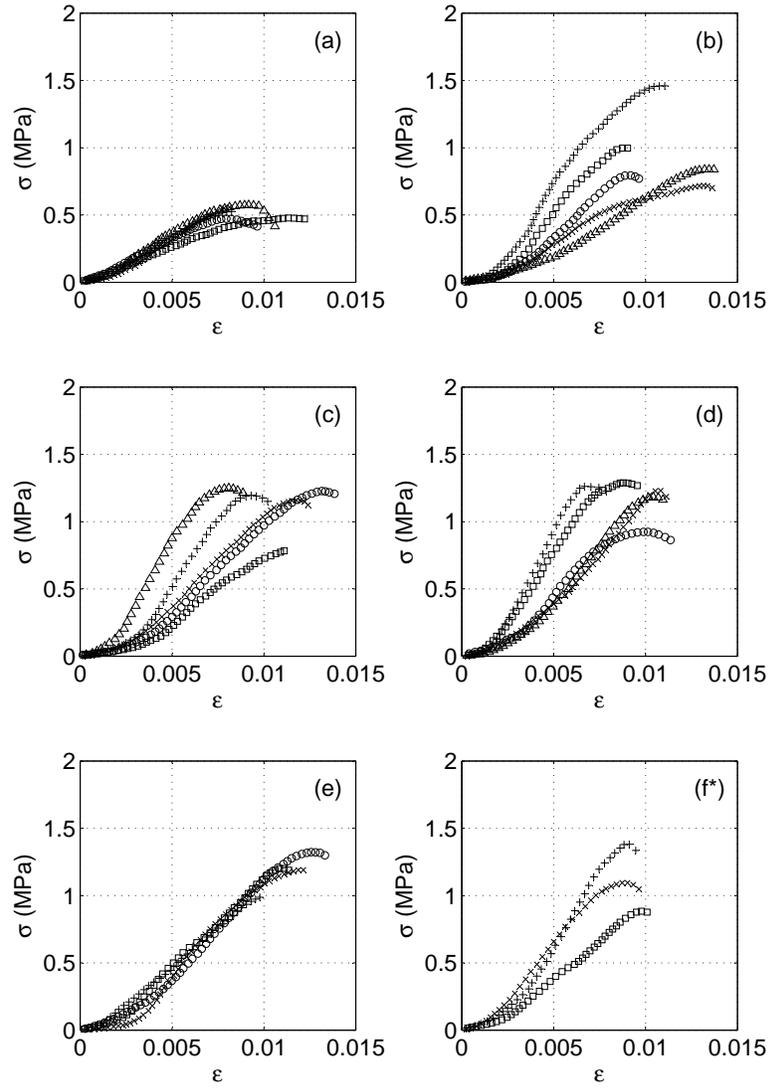


Figure 4: Stress-strain ($\sigma - \varepsilon$) curves for A-series specimens under uniaxial compression at lime contents: a) 0%; b) 2%; c) 3%; d) 4%; e) 5%; f*) 6%. *Please note: due to some damage, only three of the five specimens with 6% lime content were tested.

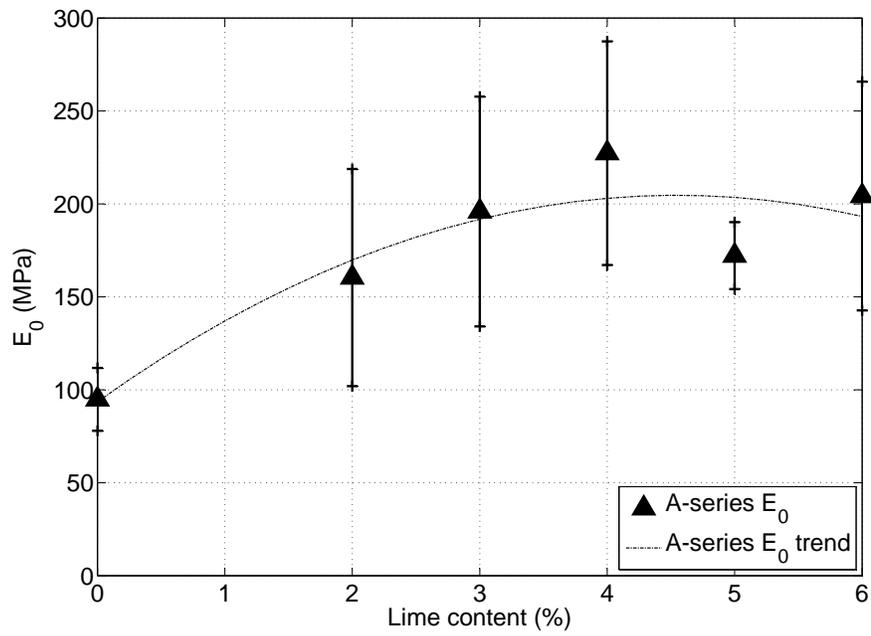


Figure 5: Maximum tangent stiffness modulus results in terms of mean values and standard deviation for (Ambient) A-series specimens.

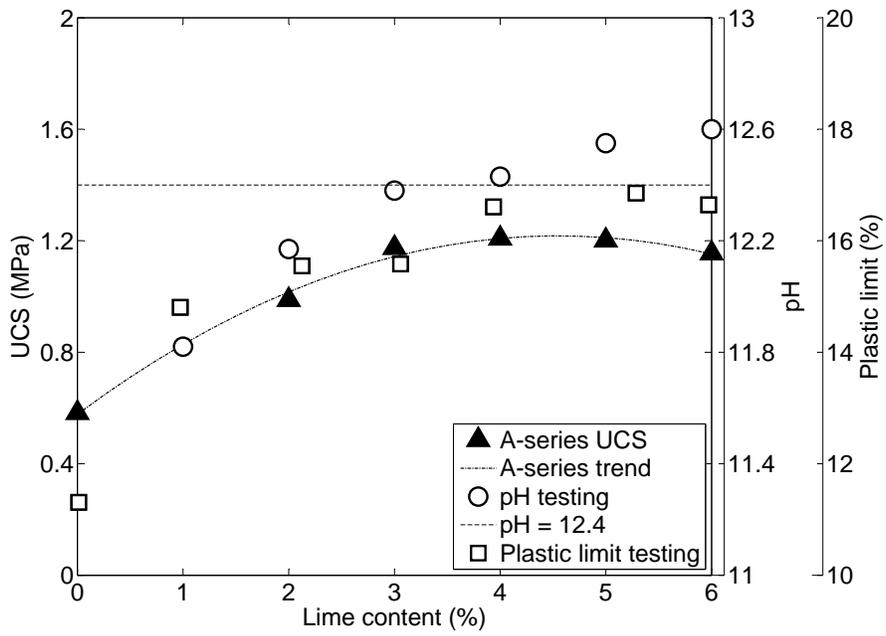


Figure 6: UCS, PL and pH testing results as compared to lime content.

- 454 [1] AustStab Technical Note, 2002. Lime stabilisation practice, AustStab
455 Pavement Recycling and Stabilisation Association 1, 1–8.
- 456 [2] Bargonaza, S., Peete, J.M., Freer-Hewish, R., Newill, D., 1987. Car-
457 bonation of stabilised soil-cement and soil-lime mixtures, Proceedings
458 of SeminarH, PTRC Transport and Planning Summer Meeting, Univer-
459 sity of Bath, 7-11 Sep 1987. London: PTRC Education and Reserach
460 Services, 29–48.
- 461 [3] Beckett, C. T. S., 2011. The role of material structure in compacted
462 earthen building materials: Implications for design and construction.
463 PhD Thesis, Durham University.
- 464 [4] Bell, F., 1996. Lime stabilization of clay minerals and soils. *Engineering
465 Geology* 42, 223–237.
- 466 [5] Bui, Q.-B., Morel, J.-C., 2009. Assessing the anisotropy of rammed
467 earth. *Construction and Building Materials* 23 (9), 3005–3011.
468 Burroughs2006
- 469 [6] Burroughs, S. 2006. Strength of compacted earth: linking soil properties
470 to stabilisers. *Building Research and Information* 34(1), 55–65.
- 471 [7] Burroughs, S. 2010. Recommendations for the selection, stabilization,
472 and compaction of soil for rammed Earth wall construction. *Journal of
473 Green Building* 5(1), 101–14.

- 474 [8] Ciancio, D., Boulter, M., 2012. Stabilised rammed earth: a case study in
475 Western Australia. *Proceedings of the ICE - Engineering Sustainability*
476 165 (2), 1–14.
- 477 [9] Ciancio, D., Gibbings, J., 2012. Experimental investigation on the com-
478 pressive strength of cored and molded cement-stabilized rammed earth
479 samples. *Construction and Building Materials* 28 (1), 294–304.
- 480 [10] Ciancio, D., Jaquin, P., Walker, P. 2013. Advances on the assessment of
481 soil suitability for rammed earth. *Construction and Building Materials*
482 *under press* DOI: 10.1016/j.conbuildmat.2012.12.049.
- 483 [11] Consoli, N., Prietto, P., Carraro, J., Heineck, K., 2001. Behavior of
484 compacted soil-fly ash-carbide lime mixtures. *J. Geotech. Geoenviron.*
485 *Eng.* 127 (9), 774–782.
- 486 [12] Consoli, N., Dalla Rosa Johann, A., Gauer, E.A., Dos Santos, V.R.,
487 Moretto, R.L., Corte, M.B. 2012. Key parameters for tensile and com-
488 pressive strength of siltlime mixtures. *Geotechnique Letters* 2, 81–85.
- 489 [13] Croft, J., 1967. The structures of soils stabilized with cementitious
490 agents. *Engineering Geology* 2 (2), 63–80.
- 491 [14] Croft, J., 1968. The problem in predicting the suitability of soils for
492 cementitious stabilization. *Engineering Geology* 2 (6), 397–424.
- 493 [15] Eades, J. L., Grim, R. E., 1966. A quick test to determine lime require-

- 494 ments for lime stabilisation. In: Proceedings of the 45th Annual Meeting
495 of the Committee on Lime and Lime-Fly Ash Stabilisation. pp. 61–72.
- 496 [16] Easton, D., 2007. The rammed earth house. Chelsea Green Publishing.
- 497 [17] George, S., Ponniah, D., Little, J., 1992. Effect of temperature on lime-
498 soil stabilization. *Construction and Building Materials* 6 (4), 247–252.
- 499 [18] Hall, M., Djerbib, Y., 2004. Rammed earth sample production: context,
500 recommendations and consistency. *Construction and Building Materials*
501 18 (4), 281–286.
- 502 [19] Hilt, G. H., Davidson, D. T., 1960. Lime fixation of clayey soils. In:
503 Highway Research Board, Bulletin 262, Washington D. C. (USA). pp.
504 20–32.
- 505 [20] Houben, H., Guillaud, H., 1996. Earth construction - a comprehensive
506 guide., Second Edition. Intermediate Technology Publications, London
507 (UK).
- 508 [21] Jaquin, P. A., 2008. Analysis of historic rammed earth construction.
509 PhD Thesis, Durham University.
- 510 [22] Jaquin, P. A., Augarde, C. E., Gallipoli, D., Toll, D. G., 2009. The
511 strength of unstabilised rammed earth materials. *Géotechnique* 59 (5),
512 487–490.

- 513 [23] Jaquin, P. A., Augarde, C. E., Gerrard, C. M., 2008. A chronological
514 description of the spatial development of rammed earth techniques. In-
515 ternational Journal of Architectural Heritage: Conservation, Analysis
516 and Restoration 2 (4), 377–400.
- 517 [24] Jayasinghe, C., Kamaladasa, N., 2007. Compressive strength character-
518 istics of cement stabilized rammed earth walls. Construction and Build-
519 ing Materials 21 (11), 1971–1976.
- 520 [25] Maniatidis, V., Walker, P., 2008. Structural capacity of rammed earth in
521 compression. Journal of Materials in Civil Engineering 20 (3), 230–238.
- 522 [26] Maniatidis, V., Walker, P., Heath, A., Hayward, S., August 2007. Me-
523 chanical and thermal characteristics of rammed earth. In: International
524 Symposium on Earthen Structures. Indian Institute of Science, Banga-
525 lore, pp. 205–211.
- 526 [27] Middleton, G. F., Schneider, L. M., 1992. Bulletin 5: Earth-wall con-
527 struction, 4th Edition. CSIRO Division of Building, Construction and
528 Engineering, North Ryde, Australia.
- 529 [28] Morel, J. C., Mesbah, A., Oggero, M., Walker, P., 2001. Building houses
530 with local materials: means to drastically reduce the environmental im-
531 pact of construction. Building and Environment 36 (10), 1119–1126.
- 532 [29] Ngowi, A.B., 1997. Improving the traditional earth construction: a case
533 study of Botswana. Construction and Building Materials, 11(1), 1–7.

- 534 [30] Standards New Zealand, 1998. NZS 4297:1998: Materials and workman-
535 ship for earth buildings incorporating amendment no. 1. Standards New
536 Zealand, Wellington.
- 537 [31] Standards Australia, 2003. AS 1289.5.2.1-2003 : Soil compaction and
538 density tests - Determination of the dry density or moisture content
539 relation of a soil using modified compactive effort. Standards Australia,
540 Sydney.
- 541 [32] Standards Australia, 2008. AS 5101.4-2008 : Methods for preparation
542 and testing of stabilized materials. Method 4: Unconfined compressive
543 strength of compacted materials. Standards Australia, Sydney.
- 544 [33] Standards Australia, 2009. AS 1289.3.2.1-2009 : Methods of testing soils
545 for engineering purposes - Soil classification tests - Determination of the
546 plastic limit of a soil - Standard method. Standards Australia, Sydney.
- 547 [34] Thompson, M. R., 1967. Factors influencing the plasticity and strength
548 of lime-soil mixtures. Tech. Rep. Bulletin 492, Engineering Experiment
549 Station, University of Illinois.
- 550 [35] Transportation Research Board, 1987. State of the art report 5 - Lime
551 Stabilization. Reactions, Properties, Design and Construction. TRB
552 Publication.
- 553 [36] Venkatarama Reddy, B.V. and JagadishThompson, K.S., 2001. Embod-

554 ied energy of common and alternative building materials and technolo-
555 gies. *Energy and Buildings* 35, 129–137.

556 [37] Walker, P., Standards Australia, 2002. *The Australian Earth Building*
557 *Handbook*. SAI Global Ltd., Sydney, Australia.

558 [38] Walker, P. J., 1995. Strength, durability and shrinkage characteristics
559 of cement stabilised soil blocks. *Cement and Concrete Composites* 17,
560 301–310.