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# Effect of moisture content on the mechanical characteristics of rammed earth

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## Abstract

In this paper, influence of moisture content on the mechanical characteristics of rammed-earth has been studied. Samples from different soils (sandy, clayey, stabilized) were manufactured and tested in unconfined compression at several moisture contents. Compressive strength, elastic modulus and Poisson's ratio were determined. A simplified method to measure the suction within rammed earth samples has been developed and validated. The variation of mechanical characteristics related to moisture content and suction are presented. This paper shows that a slight increase in the moisture content of dry rammed-earth is not followed by sudden drop in wall strength. Qualitative explanations at the nano-scale are presented.

**Keywords:** *Rammed earth, cohesion, suction, compressive strength, Young modulus, Poisson's ratio.*

## 1 Introduction

In the context of sustainable building, modern interest in earth as a building material is largely derived from its low embodied energy (Morel et al. 2001) and also because the material has good natural moisture buffering of indoor environments (Allinson and Hall 2010). On one hand, to act as a RH buffer, the material must be capable of adsorbing and desorbing moisture. However, if the moisture content of unstabilised earthen materials increases excessively, the material loses its

27 strength. Therefore the question is remains: what is the moisture buffering limit for a material  
28 without detrimental loss of mechanical strength?

29 On the other hand, the greatest difficulty for the application of earthen material in practice is the  
30 variability of soil characteristics. Indeed, because earth is not an industrial material, its mechanical  
31 characteristics vary from one site to another. The questions before every earth construction are: is it  
32 necessary to use a stabiliser, which type of stabiliser and how much to use? Although some  
33 empirical techniques exist (Walker *et al.* 2005, Burroughs 2001), to our knowledge, there are not  
34 yet scientific base for a fundamental understanding.

35 To answer these questions, it is necessary to study the source of the cohesion in rammed earth, to  
36 understand why earthen material is sensitive to water. The knowledge about fundamental  
37 phenomena will be useful to formulate material's composition. This paper deals with the  
38 quantification of suction inside rammed earth samples and a study of the limiting moisture values to  
39 maintain mechanical strength. The role of clay and hydraulic binder are also discussed. The  
40 experiments were carried out on rammed earth materials, but the analysis presented can be extended  
41 to other earthen materials such as adobe and cob for example.

## 42 **2 Rammed earth material**

43 Rammed earth materials are ideally sandy-clayey gravels. The materials are prepared to their  
44 optimum moisture content and compacted inside temporary formwork to form walls. The earth  
45 composition varies greatly and always contains clay but should not include any organic  
46 components. Clay acts as the binder between the grains, a mixture of silt, sand, gravel up to a few  
47 centimetres diameter. Compaction is undertaken on material prepared to its optimum moisture that  
48 provides the highest dry density for the given compactive energy (Mesbah et al. 1999). The rammed  
49 earth wall is composed of several layers of earth. The earth is poured loose in layers about 10-15 cm  
50 thick into a timber or metal formwork, which is then rammed with a rammer (manual or  
51 pneumatic). After compaction, the thickness of each layer is typically 6–10 cm. The procedure is

52 repeated until completion of the wall. Detailed presentation of rammed earth construction can be  
53 found in Walker *et al.* (2005).

54 For traditional rammed earth construction, referred to as “rammed earth” or “unstabilized rammed  
55 earth,” the only binder is clay. Other binders can also be added such as cement, hydraulic or  
56 calcium lime. This is often called “stabilized rammed earth” (SRE). The main advantage of  
57 stabilization is the increase in durability and mechanical performance. However, stabilization  
58 increases the construction cost and environmental impact.

59 Unstabilised rammed-earth is the focus of scientific research for two main reasons. Firstly, the  
60 heritage of rammed-earth buildings in Europe and the world is still important (Fodde 2009). The  
61 maintenance of this heritage needs scientific knowledge on the material to assess appropriate  
62 renovations. Secondly, the use of unstabilised rammed-earth in new constructions is possible in  
63 several countries, particularly in the current context of sustainable development (Bui *et al.* 2009a).  
64 The question "which conditions (soil suitability, weather) are suitable for the use of unstabilised  
65 rammed-earth?" awaits scientific answers. This question has a relation to the influence of moisture  
66 on rammed-earth wall behaviour, because moisture plays a role in the cohesion of earthen material,  
67 but it can also decrease the strength of the last one.

68 Concerning the influence of moisture content on characteristics of rammed-earth, Olivier and  
69 Mesbah (1995) first initiated the idea to use the suction concept to study the role of moisture in the  
70 compacted earth material. They showed that increasing the moisture content accompanied a  
71 decrease in the suction of compacted soil material. In a more recent study, Jaquin *et al.* (2009)  
72 studied the influence of suction on mechanical characteristics of rammed-earth material. This study  
73 found that suction was a source of strength in unstabilised rammed-earth, and that the strength  
74 increased as moisture content reduced. However, in that study, the moisture content only varied  
75 between 5.5% and 10.2% (by mass), while the moisture content of an unstabilised rammed-earth  
76 wall in normal conditions is around 1 to 2% (Bui *et al.* 2009b). In addition, in that study, only one  
77 soil was tested and the mechanical strengths obtained were relatively low ( $f_c \sim 0.5$  MPa) compared

78 to current values (1-2MPa, Walker *et al.* 2005). Hence, in this paper, the influence of moisture on  
79 the mechanical characteristics of rammed-earth material was studied, on several different soils and  
80 with a greater range of moisture contents: from the wet state just after manufacturing (11%) to  
81 “dry” state in normal atmospheric conditions (1-2%). Samples in this study were manufactured and  
82 tested in unconfined compression at different moisture contents which correspond to different  
83 values of suction. A simplified method to measure suction was also developed and validated.

### 84 **3 Influence of moisture content on the mechanical characteristics of rammed-earth material**

#### 85 **3.1 Laboratory manufacturing process**

##### 86 **3.1.1 Soils**

87 Five different soils were used in this study which were taken from sites of rammed earth  
88 construction. Table 1 presents the composition of these soils that were obtained by sieving (for  
89 elements  $>80\mu\text{m}$ ) and the sedimentometric (for elements  $<80\mu\text{m}$ ). The clay contents of these soils  
90 were close to the interval proposed by Walker *et al.* (2005), 5-10%. The methylene blue tests were  
91 carried out following French Standard (NF P 94-068) to obtain methylene blue values. The clay  
92 activity index  $A_{CB}$  was calculated from the methylene blue values. That index enables to identify the  
93 soil’s mineralogical composition (Table 2) following an abacus given by Lautrine (1989) which  
94 was reused by Chiappone *et al.* (2004).

95 In order to investigate the role of hydraulic binder, soils B and E were stabilized at 2% and 8% of  
96 natural hydraulic lime (NHL 3.5) by weight, respectively. Natural hydraulic lime is produced by  
97 heating calcining limestone which contains clay without adding. Number 3.5 indicates the minimum  
98 compressive strength at 28 days (which can vary from 3.5 to 10 MPa). Calcium reacts in the kiln  
99 with the clay minerals to produce silicates that enable the lime to set without exposure to air. Any  
100 unreacted calcium is slaked to calcium hydroxide. Hydraulic lime is used for providing a faster  
101 initial set than ordinary lime (calcium lime). Eight percent of lime was chosen because it was the

102 maximum quantity observed in practice for stabilized rammed earth; beyond this limit, stabilized  
103 rammed earth lost its interest of “green material”.

104 **Table 1 : Soils used in this study**

Soil	Clay content (by weight)	Silt	Sand	Gravel
Soil A	5%	30%	49%	16%
Soil B	4%	35%	59%	2%
Soil C	9%	38%	50%	3%
Soil D	10%	30%	12%	48%
Soil E	10%	22%	43%	25%

105

106 **Table 2 : Clay’s mineralogical composition of the soils used**

Soil	Kaolinite (%)	Illite (%)	Montmorillonite (%)
Soil A	35	0	65
Soil B	15	0	85
Soil C	0	65	35
Soil D	18	18	64
Soil E	18	0	82

107

### 108 **3.1.2 Sample manufacturing**

109 In the present study, to investigate the influence of moisture on the characteristics of rammed-earth  
110 material, reproducing the dynamic compaction and the layer superposition of rammed-earth  
111 technique was essential without regard the sample size effect. To achieve this, an automatic Proctor  
112 machine was adopted. The standard mold of the Proctor test was replaced by a mold 16 cm in  
113 diameter and 32 cm high. To obtain the dry density of *in-situ* rammed earth material ( $\sim 1920 \text{ kg/m}^3$ ;  
114 Bui *et al.* 2009b), a series of preliminary tests were conducted to determine the manufacturing  
115 moisture content and the amount of soil to be poured into the mold for each layer. An 11% moisture  
116 content was chosen as the compaction moisture content and 2.2 kg of moist soil was weighed out

117 for each layer. Each layer received the Proctor energy ( $E = 0.6 \text{ kJ/dm}^3$ ). There were six compaction  
118 layers in each specimen prepared. The final height of the cylinder after the release was 30 cm giving  
119 to the sample an aspect ratio of 2. It is very important to avoid smaller aspect ratio (Aubert *et al.*  
120 2013). Prior to mixing, the soil was sieved through a 2-cm screen.

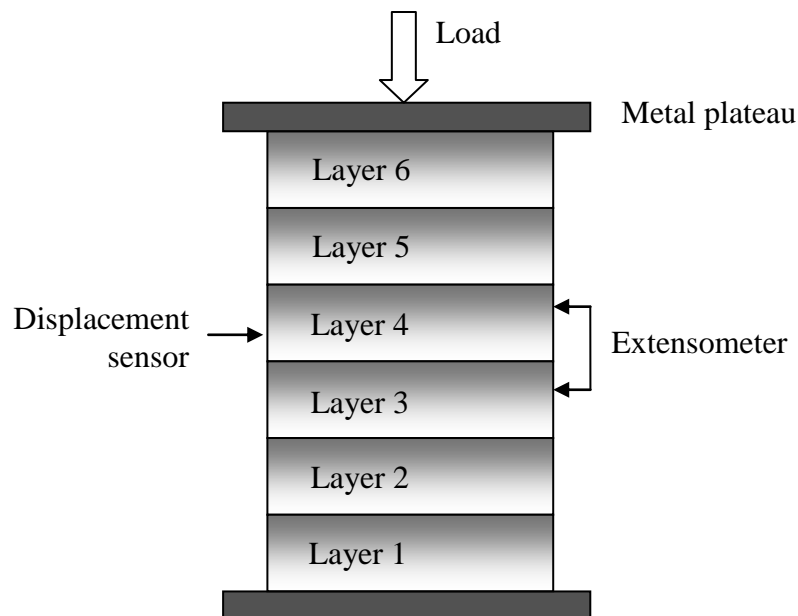
121 The compacted layer thickness in in-situ rammed earth walls is around 10 cm. Due to nature of  
122 compaction there is a density gradient in each layer, as the upper part of each layer is more  
123 compacted and therefore denser than the bottom (Bui *et al.* 2009b). The layer thickness of the  
124 laboratory samples is about 5 cm, meaning that the material is more evenly compacted over the  
125 entire layer thickness. The clear disadvantage of this laboratory manufacturing strategy is that the  
126 sample is not representative of typical *in-situ* material. Therefore, to correlate the results obtained  
127 from laboratory-fabricated cylindrical samples to the performance of *in-situ* walls, a *calibration* is  
128 necessary. This can be found by using a homogenisation process, presented in a previous study (Bui  
129 *et al.* 2009b).

130 After the compaction process, the samples were removed from the mould. The bottom surface of  
131 the sample, as it has been in contact with the bottom face of the mould during compaction is smooth  
132 and did not require any further treatment before strength testing. However, the more uneven upper  
133 surface was capped with a mortar (2 lime : 3 sand by weight) to provide a flat smooth surface  
134 parallel with the bottom face. During drying, the sample was left in normal atmosphere until the  
135 moisture content obtained the desired value for the test. This moisture content was verified by  
136 weighing the specimen. Then, the specimen was covered in a plastic film for at least a week to  
137 maintain the desired moisture content. Within this time, as the moisture could circulate within the  
138 sample, the sample moisture content was considered to be more homogeneous. The sample was  
139 considered “*air-dry*” when moisture content remained constant, although there was still a *residual*  
140 moisture content which was around 2%. This “*air-dry*” state is the ambient condition of in-situ  
141 walls in service (Bui *et al.* 2009b).

142 **3.2 Unconfined compressive strength test**

143 **3.2.1 Test set-up**

144 The cylinders were tested in compression between two hardened steel platens. Three samples were  
145 tested for each series. To measure strains, extensometers were placed in the central part of the  
146 cylinders to minimize edge effects on strain measurement. To determine the Poisson's ratio, lateral  
147 strain measurements as well as vertical measurements were carried out. Figure 1 shows the  
148 configuration of a uniaxial compression strength test: extensometers measured the longitudinal  
149 strains and horizontal displacement sensors measure lateral displacements which help to calculate  
150 the lateral strains.



160 Figure 1 : Measurement device on a sample

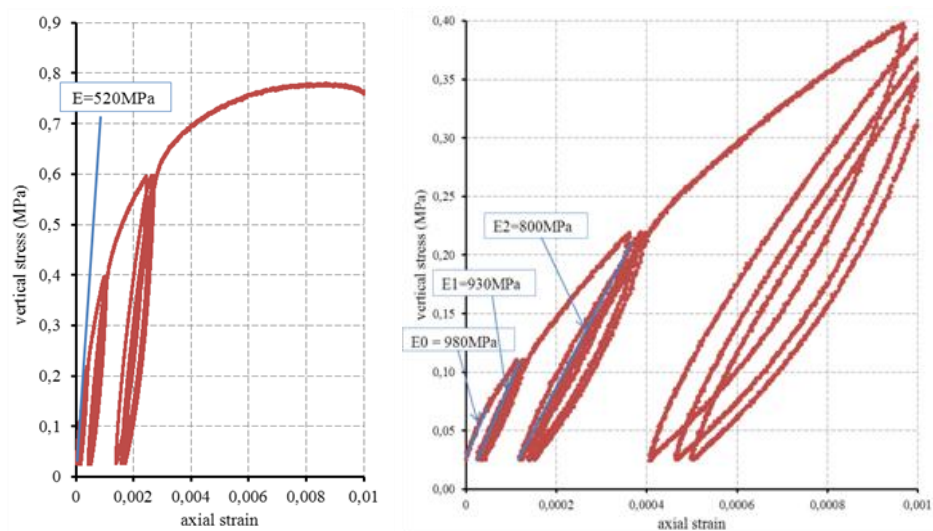
161 For each test, three extensometers and three displacement sensors, fixed at an interval of 120° on  
162 the radial plan, were used to verify the repeatability of results. An extensometer measures the strain  
163 between two points: one point at the center of a layer and the other point at the center of the upper  
164 layer. The distance between two points of extensometer is 6.2cm while the thickness of a layer of  
165 the sample is about 5cm. The cylinders were loaded by displacement control at a constant rate  
166 0.1mm/min until failure.



167 Some tests were under force control (3 kN/s) to observe the difference between failure modes of the  
168 two approaches, both of which are used for testing. For samples controlled by force, the failure  
169 plane was inclined whilst for samples controlled by displacement, fracture cracks were vertical.  
170 However, the maximum loads and stresses did not differ between two control modes. Indeed, in the  
171 case of force control, failure was brutal because sample reached quickly ultimate load, so the edge  
172 effect (friction between sample and press's metal plateau) played an important role, that caused the  
173 inclined failure. In the case of displacement control, loading rate was constant following imposed  
174 displacement, so the deformation of sample was more homogeneous. That was why sample could  
175 deform more uniformly in lateral direction. Sample's failure in this case was effectively due to the  
176 Poisson's effect which caused the vertical cracks. It is interesting to note that this difference in  
177 failure mode is well known for concrete cylinder tests (Eurocode 2).

### 178 3.2.2 Elasto-plastic behaviour

179 At the beginning of each test, a preload corresponding to 0.02MPa was applied to assure that entire  
180 upper face of sample was in contact with the press's plateau. Several unloading-reloading cycles  
181 were performed to observe the elasto-plastic behaviour of the material and the variation of the  
182 modulus following stress levels of the cycles (Figure 2).



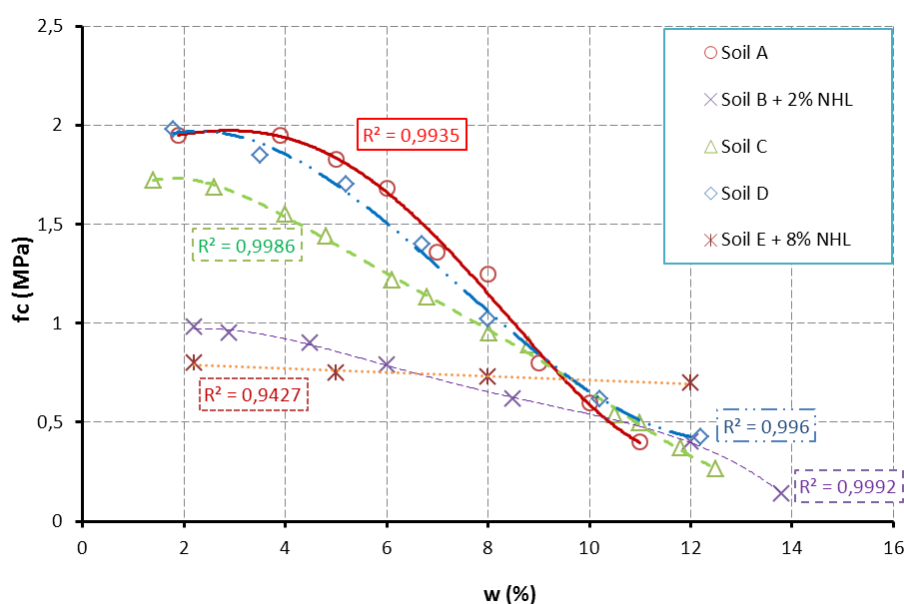
183  
184 Figure 2 : Elasto-plastic behaviour of a soil A sample, at 9% in moisture content. On the right: a  
185 zoom of unloading-reloading cycles.

186

187 Fig 2 shows that for stresses below 15% of maximum stress and strain below  $10^{-4}$ , the material is  
188 close to linear elastic behavior. Beyond this limit, the plastic (non recoverable) strain component  
189 increases and the linearity is also lost. In general, the elastic domain is considered when modulus  
190 does not decrease more than 20% of the initial strain (Eurocode 2, 2005). For example, the  
191 concrete's modulus usually used is the secant which is measured from the 0 stress level to 40% of  
192 the maximum compressive stress, because it represents approximately the elastic part of that  
193 material. However, in the case of rammed earth, the elastic part is shorter: when the stress is more  
194 than 20% of the maximum stress, the decrease of modulus is more than 20% of the initial modulus  
195 (Fig 2 right). That is why the secant modulus is calculated for stress levels between 0 and 20% of  
196 the maximum stress (Fig 2 left).

### 197 3.2.3 Variation of mechanical characteristics with moisture content

198 Figures 3, 4 and 6 show variation of the compressive strength, the elastic secant modulus and  
199 Poisson ratio with moisture content of the samples. The presented results are the mean values of  
200 three samples. For the measurements of the elastic modulus, Poisson's ratio and suction, only three  
201 soil types A, B and C were investigated in detail.

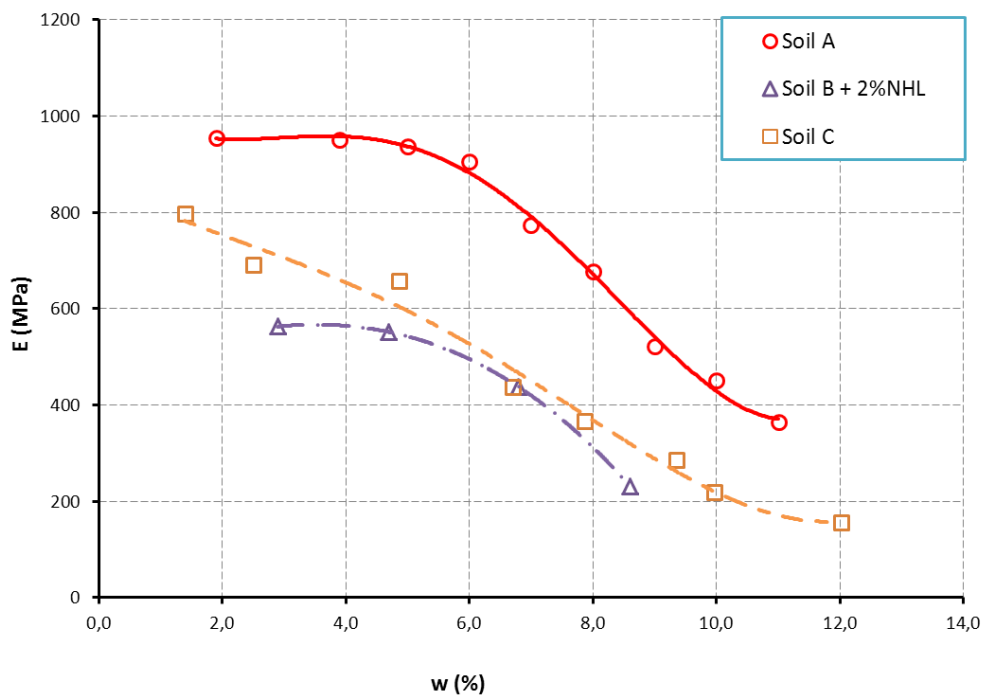


202

203 Figure 3 : Variation of compressive strength  $f_c$  with moisture content  $w$  of all soils studied.

204

205 Figure 3 presents the variation of compressive strength with moisture content of all soils studied.  
206 Following these results, compressive strength decreases with increasing moisture content that is  
207 logical. However, when moisture content is below 4% (close to air dry), the variation of  
208 compressive strength was not significant: compressive strength was quasi-constant for sandy soil A  
209 (classified following French Standard NF P 11-300) and stabilized soils B and E, it decreased about  
210 10% for clayey soils C and D (classified following French Standard NF P 11-300). When moisture  
211 content is greater 4%, the compressive strength decrease quickly for all studied soils, except soil E  
212 stabilized by 8% NHL. It is noted that the stabilization by hydraulic lime can decrease the  
213 sensibility to water of RE material but it does not always accompany an increase in compressive  
214 strength. Here the compressive strengths of stabilized samples (soils B and E) were lower than that  
215 of other unstabilized samples (at the same moisture contents). Soils B and E have important  
216 presence of Montmorillonite (85% and 82% of elements  $<2\mu\text{m}$ , respectively), that may play an  
217 unfavorable role for compressive strength of samples. In addition, specific curing of lime stabilized  
218 samples could give better results.



219

220 Figure 4 : Variation of secant modulus  $E$  with moisture content  $w$ .

221

222 For elastic modulus (Figure 4), there is only a slight variation for samples with moisture content up  
223 to 5% for the cases of sandy soil (A) and stabilized soil (B). Modulus decreased with increasing  
224 moisture contents above 5%. For the clayey soil C, the elastic modulus is more sensitive to moisture  
225 content where a decrease of 15% can be observed at 4% of moisture content.

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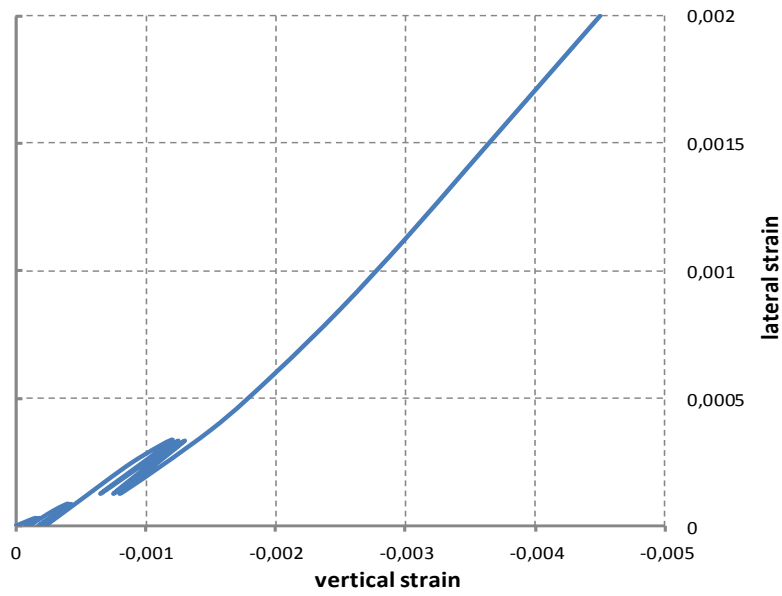
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Figure 5 : Measurement of Poisson's ratio from vertical and lateral strains

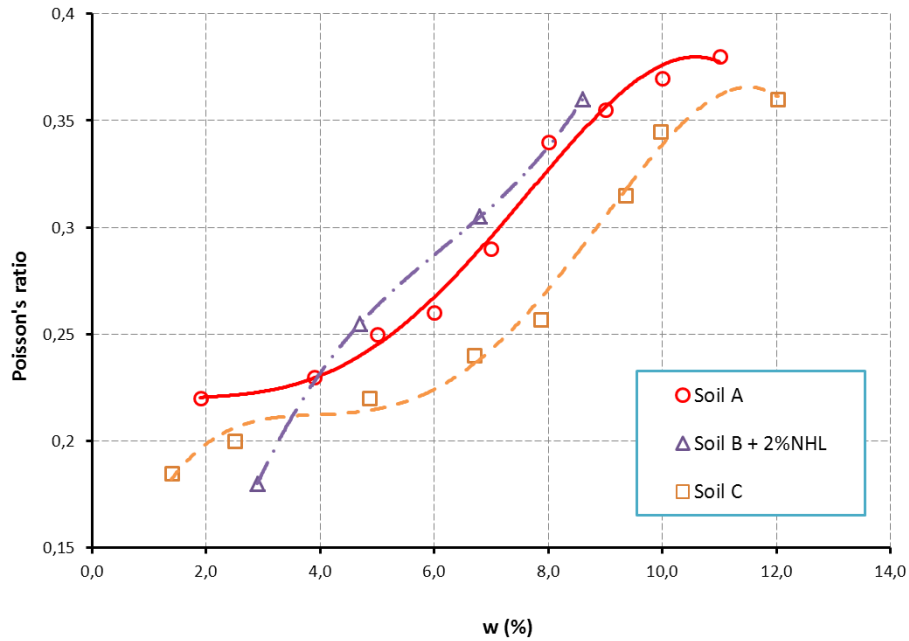
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237 The Poisson's ratio was calculated by devising the vertical strain by the lateral strain (Figure 5).

238 The last one is the ratio between the lateral dilatation (measured by horizontal displacement

239 sensors) and the sample's radius. The Poisson's ratio was calculated in the "elastic part" like Young

240 modulus.



241

242

Figure 6 : Variation of Poisson's ratio with moisture content  $w$ .

243

In Figure 6, Poisson's ratio values were about  $0.2 \pm 0.02$  for the dry samples (moisture content

244

$<4\%$ ), then increased with the moisture content increasing to  $0.37 \pm 0.01$  for the wet samples. This

245

variation is logical because when the material approaches the saturated state, the Poisson ratio

246

approaches the value of 0.5.

247

#### 4 Study of suction

248

Olivier and Mesbah (1995) found that suction could be a parameter that determined the mechanical

249

characteristics of compacted earth material. In the present study, a simplified method to measure the

250

suction was developed and the effect of suction on rammed earth was studied for three soil types

251

over a large moisture content range.

252

##### 4.1 Suction

253

Suction was first defined in soils as a potential energy (Delage 2002). The suction  $s$  is linked to the

254

relative humidity ( $RH$ ) of the pore air through Kelvin's equation, which can be expressed as:

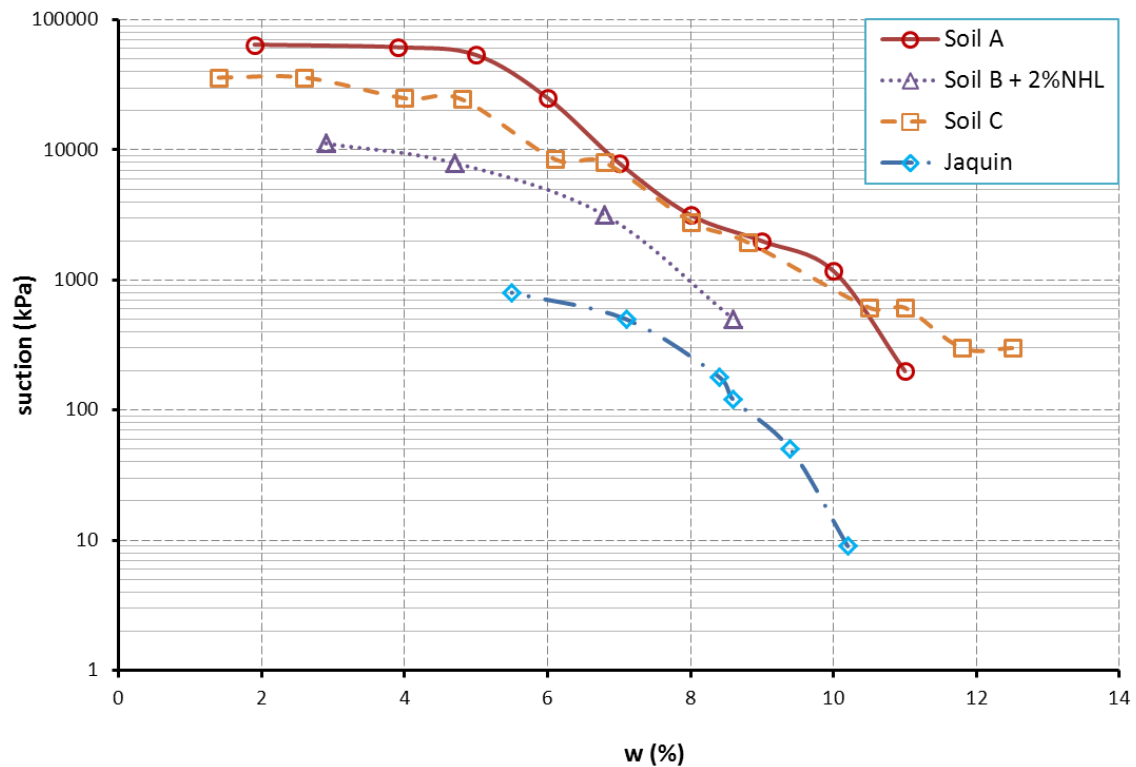
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$$s = u_a - u_w = -\frac{R \cdot T}{g \cdot w_v} \ln(RH)$$

256 with:  $u_w$  the pore water pressure;  $u_a$  the pore air pressure;  $RH$  relative humidity, which is the ratio of  
257 partial vapour pressure  $P$  in the considered atmosphere and the saturation vapour pressure  $P_0$  which  
258 depends on the temperature;  $w_v$  is the molecular mass of water vapour;  $g$  is the acceleration due to  
259 gravity ( $g=9.81m/s^2$ );  $R$  is the universal gas constant;  $T$  is the absolute temperature. Evaporation of  
260 pore water is affected by the  $RH$  of the pore air compared with that of the adjacent air outside the  
261 wall. In practice, drying of the wall will continue until the pore air humidity equals the humidity of  
262 the surrounding air.

#### 263 **4.2 Simplified method to measure the suction**

264 There are several techniques to measure suction in unsaturated soils. A review of these techniques  
265 can be found in Delage (2002). A technique using filter paper was developed. First, a triple layer of  
266 *Whatman n°42* filter paper was placed on the surface of the sample at the desired moisture content.  
267 *Whatman n°42* filter paper is frequently used for suction studies and its calibration curves are well  
268 known (Delage 2002). Then, the specimen was covered with plastic film to prevent any further  
269 evaporation. Samples were then stored for two weeks, so the moisture equilibrium was established  
270 between the sample and the filter paper. Then the filter paper was extracted and the moisture  
271 content of the middle sheet - which was not contaminated thanks to its non-contact with the  
272 specimen surface - was determined. Using the calibration curve of the *Whatman n°42* filter paper -  
273 which define a relation between suction and moisture content - the suction of the paper was  
274 determined and therefore the suction of the sample, which is the same, was established .



275

276

Figure 7 : Variation of suction  $s$  following moisture content  $w$

277

Figure 7 shows the variation of samples' suction following samples' moisture content (desiccation phase). The variation of suction is slight for the case of dry samples ( $w < 4\%$ ). Then the suction steeply decreases following the increase of moisture content.

278

279

280

### 4.3 Validation of the simplified method and discussions

281

Figure 8 presents all of the data for this study as well as results from Jaquin et al. (2009), who used tensiometers to directly measure suction at the top of their specimens. For suction and corresponding compressive strength, the data are well correlated, showing that the simplified method is reliable. In fact, the suction may depend also on type of soil (percentage of clay, type of clay). But following these results (on four soils), the variation following soil's type was low (a correlation  $R^2=0.923$  was obtained). It will be interesting to check this point with a number more important of soil's type.

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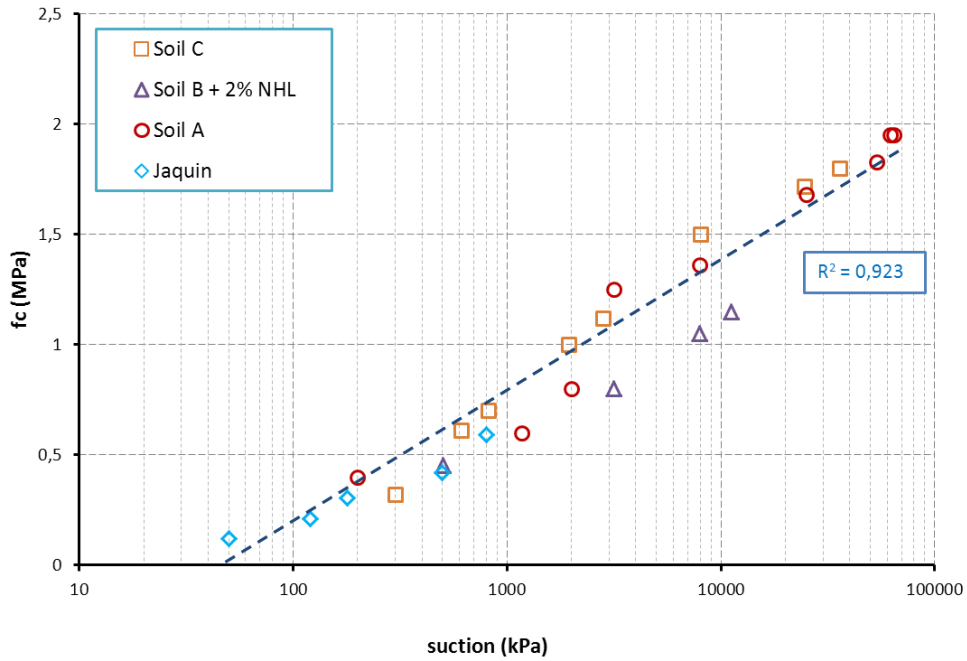
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288

Figure 8 shows also that suction (when presented logarithmically) is linearly correlated to the compressive strength for unstabilised rammed earth, even though the composition of the fourth

289

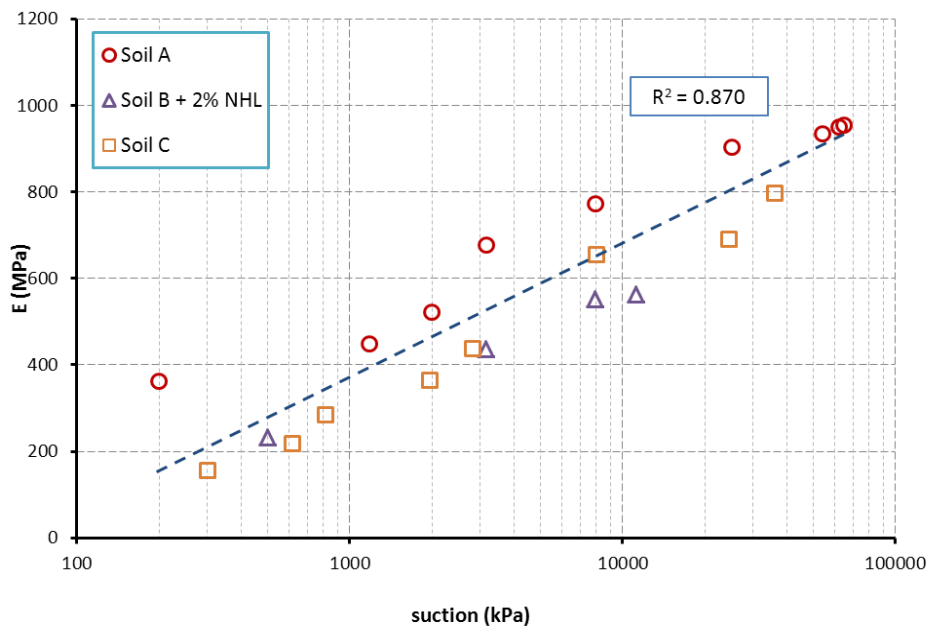
290 materials is quite different from the three others. Figure 9 presents the variation of secant modulus  
 291 following suction which shows the elastic modulus is dependent on the suction too.



292

293

Figure 8 : Variation of compressive strength  $f_c$  following suction  $s$



294

295

296

Figure 9 : Variation of secant modulus  $E$  following suction  $s$ . Note: Jaquin *et al.* (2009) did not present their elastic modulus values.



## 297 **5 Discussions – Microscopic behaviour of earthen materials**

### 298 **5.1 Sandy soil**

299 The cohesion of low clayey soil material was primarily provided by the capillary force between  
300 particles. Fisher and Israelachvili (1981), Halsey and Levine (1998) showed that there was a range  
301 of moisture content in which the capillary force was constant (independent of the amount of  
302 moisture in the material). The attractive force due to the capillary condensation bridge between two  
303 spherical particles with a rough surface has four phases. In phase 1 (asperity phase), the  
304 condensation takes place between two asperities in contact with each other and the cohesive force  
305 increases non-linearly with the amount of moisture. In phase 2 (roughness phase) the force  
306 increases linearly with the amount of moisture due to the lateral spreading of the liquid bridge over  
307 several asperities. However, in this phase, the meniscus is not yet sensitive to the average spherical  
308 curvature of the particles. In phase 3 (classical phase), the meniscus is no longer sensitive to the  
309 roughness and the cohesive force is independent to the amount of moisture, as between two smooth  
310 spheres. For the samples whose moisture content is between 2 and 4%, its moisture contents fall in  
311 this third phase, which explains the constancy of the attractive force. When the moisture content  
312 increases, the samples are in phase 4 (saturation phase), neighbouring liquid bridges merge, the  
313 cohesion decreases. Our specimens were dried naturally and so do not fall within phases 1 or 2  
314 because there was a balance with the atmospheric pressure.

### 315 **5.2 Clayey soil**

316 The cohesion of clayey soil material was provided not only by the capillary force between particles  
317 but also by attraction forces of clay particles. Attraction between clay particles (plate shape) due to  
318 Van der Waals force whose radius is constant. The double layers (proposed by Gouy in 1910 and  
319 complemented by Chapman in 1913) surrounding each plate has a mutual action of electrical  
320 repulsion due to their positive charge. When the thickness of the double layer is low (high  
321 concentration and high valence of the cations), the attraction prevails, plates attract, so there is the

322 cohesion. Otherwise, the thickness of the double layer is low (due to a decrease of the concentration  
323 and of valence of the cations, which is the consequence of a significant amount of water), the  
324 particles push one to the others, so clay loses its cohesion. This explains the sensibility to moisture  
325 of clayey material.

### 326 **5.3 Stabilized soil**

327 In unstabilized earthen material, clay is the sole binder. In the case of stabilised earthen material (by  
328 lime or cement), pozzolanic material is also present due to hydraulic binder. The main element of  
329 the pozzolanic cohesion is C-S-H sheets which are not sensitive to water.

330 However, if hydraulic binders are not sufficient, as they can not coat all particles (including sand,  
331 silt, clay), and as such the soil remains water sensitive (case of soil B stabilised at 2% NHL).  
332 Beyond an amount of hydraulic binder which is sufficient to coat all grains, material can become  
333 few sensitive to water (case of soil E stabilised at 8% NHL). In concrete, this binder threshold can  
334 be determined by empirical formulas (Eurocode 2). For rammed earth material, an equivalent  
335 empirical formula is interesting but it should take into account the clay amount and the clay type.  
336 The way is complex and requires several future experimental results.

### 337 **6 Conclusions and prospects**

338 In this paper, the influence of moisture on the mechanical characteristics of rammed-earth material  
339 has been studied, on different soils (sandy, clayey, stabilized) and with a great variation of moisture  
340 content: from the wet state directly after manufacturing (11-13%) to “dry” state in atmospheric  
341 conditions (1-2%). Samples in this study were manufactured and tested in unconfined compression  
342 at different moisture contents which correspond to different values of suction.

343 In this study, the Poisson’s ratio was determined, it varied from about 0.2 for the “dry” samples to  
344 0.37 for the wet samples. This coefficient can be used in modeling structures, in static or dynamic.

345 A simplified method to measure the suction of rammed earth samples has been developed and  
346 validated. This simplified method can be used for studies on suction of RE material. The suction  
347 studies were taken in the cases of a sandy soil, a clayey soil and a clayey soil stabilised by 2% NHL.  
348 The evolutions of mechanical characteristics following moisture content and following suction were  
349 presented. The results confirmed that suction was an important factor of the mechanical  
350 characteristics of the studied samples. Indeed, the suction may depend also on type of soil  
351 (percentage of clay, type of clay). But following the results in this study, the variation following  
352 soil's type was low. It will be interesting to check this point with a number more important of soils.  
353 The water sensitivity of the rammed-earth material and other earthen materials is a widely perceived  
354 weakness. However, this paper showed that a slight increase in moisture content of dry rammed-  
355 earth walls (moisture content not exceeding 4% by weight, e.g. due to rain fall or change of RH in  
356 the atmosphere) did not accompany a sudden drop in the wall's strength. Indeed, in this domain, the  
357 compressive strength was quasi-constant for sandy soil and stabilized soils and a decrease about  
358 10% for the clayey soil. Qualitative explanations at the microscopic level have been proposed to  
359 analyse the results, for all cases: sandy soil, clayey soil and stabilized soil. These interpretations are  
360 the fruit of the experiences of the authors and their Universities from 20 years (ENTPE Lyon,  
361 France and University of Bath, UK), accompanied by classical theories. The information presented  
362 in this paper will be useful to understand the behaviour at nano-scale of earthen material.

363

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