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

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

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

2 Rammed earth material

Rammed earth materials are ideally sandy-clayey gravels. The materials are prepared to their optimum moisture content and compacted inside temporary formwork to form walls. The earth composition varies greatly and always contains clay but should not include any organic components. Clay acts as the binder between the grains, a mixture of silt, sand, gravel up to a few centimetres diameter. Compaction is undertaken on material prepared to its optimum moisture that provides the highest dry density for the given compactive energy (Mesbah et al. 1999). The rammed earth wall is composed of several layers of earth. The earth is poured loose in layers about 10-15 cm thick into a timber or metal formwork, which is then rammed with a rammer (manual or pneumatic). After compaction, the thickness of each layer is typically 6–10 cm. The procedure is repeated until completion of the wall. Detailed presentation of rammed earth construction can be found in Walker *et al.* (2005).

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

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

Concerning the influence of moisture content on characteristics of rammed-earth, Olivier and Mesbah (1995) first initiated the idea to use the suction concept to study the role of moisture in the compacted earth material. They showed that increasing the moisture content accompanied a decrease in the suction of compacted soil material. In a more recent study, Jaquin *et al.* (2009) studied the influence of suction on mechanical characteristics of rammed-earth material. This study found that suction was a source of strength in unstabilised rammed-earth, and that the strength increased as moisture content reduced. However, in that study, the moisture content only varied between 5.5% and 10.2% (by mass), while the moisture content of an unstabilised rammed-earth wall in normal conditions is around 1 to 2% (Bui *et al.*2009b). In addition, in that study, only one soil was tested and the mechanical strengths obtained were relatively low (fc ~ 0.5 MPa) compared to current values (1-2MPa, Walker *et al.* 2005). Hence, in this paper, the influence of moisture on the mechanical characteristics of rammed-earth material was studied, on several different soils and with a greater range of moisture contents: from the wet state just after manufacturing (11%) to "dry" state in normal atmospheric conditions (1-2%). Samples in this study were manufactured and tested in unconfined compression at different moisture contents which correspond to different values of suction. A simplified method to measure suction was also developed and validated.

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

3.1 Laboratory manufacturing process

3.1.1 Soils

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

In order to investigate the role of hydraulic binder, soils B and E were stabilized at 2% and 8% of natural hydraulic lime (NHL 3.5) by weight, respectively. Natural hydraulic lime is produced by heating calcining limestone which contains clay without adding. Number 3.5 indicates the minimum compressive strength at 28 days (which can vary from 3.5 to 10 MPa). Calcium reacts in the kiln with the clay minerals to produce silicates that enable the lime to set without exposure to air. Any unreacted calcium is slaked to calcium hydroxide. Hydraulic lime is used for providing a faster initial set than ordinary lime (calcium lime). Eight percent of lime was chosen because it was the maximum quantity observed in practice for stablized rammed earth; beyond this limit, stabilized rammed earth lost its interest of “green material”.

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%

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

3.1.2 Sample manufacturing

In the present study, to investigate the influence of moisture on the characteristics of rammed-earth material, reproducing the dynamic compaction and the layer superposition of rammed-earth technique was essential without regard the sample size effect. To achieve this, an automatic Proctor machine was adopted. The standard mold of the Proctor test was replaced by a mold 16 cm in diameter and 32 cm high. To obtain the dry density of *in-situ* rammed earth material (~1920 kg/m^3; Bui *et al.* 2009b), a series of preliminary tests were conducted to determine the manufacturing moisture content and the amount of soil to be poured into the mold for each layer. An 11% moisture content was chosen as the compaction moisture content and 2.2 kg of moist soil was weighed out for each layer. Each layer received the Proctor energy (E = 0.6 kJ/dm^3). There were six compaction layers in each specimen prepared. The final height of the cylinder after the release was 30 cm giving to the sample an aspect ratio of 2. It is very important to avoid smaller aspect ratio (Aubert *et al.* 2013). Prior to mixing, the soil was sieved through a 2-cm screen.

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

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

3.2 Unconfined compressive strength test

3.2.1 Test set-up

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

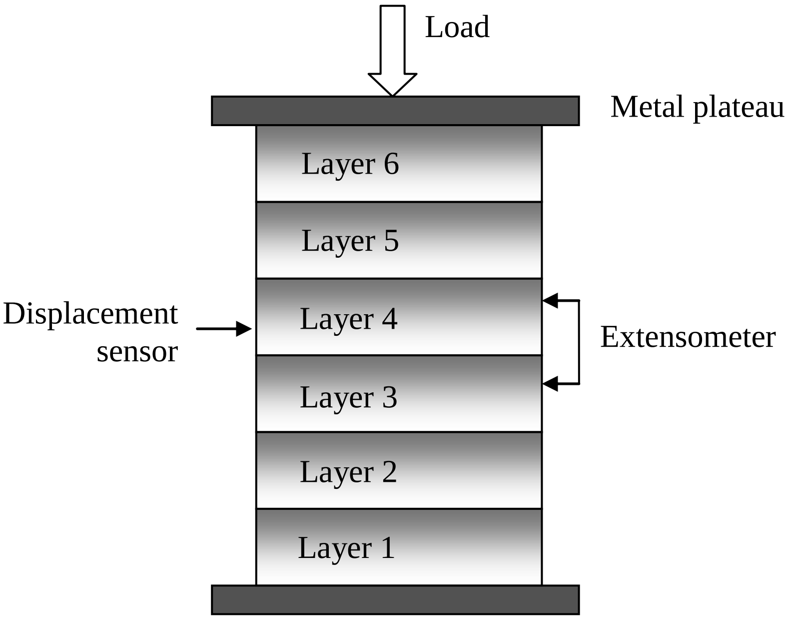

Figure 1 : Measurement device on a sample

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

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

3.2.2 Elasto-plastic behaviour

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

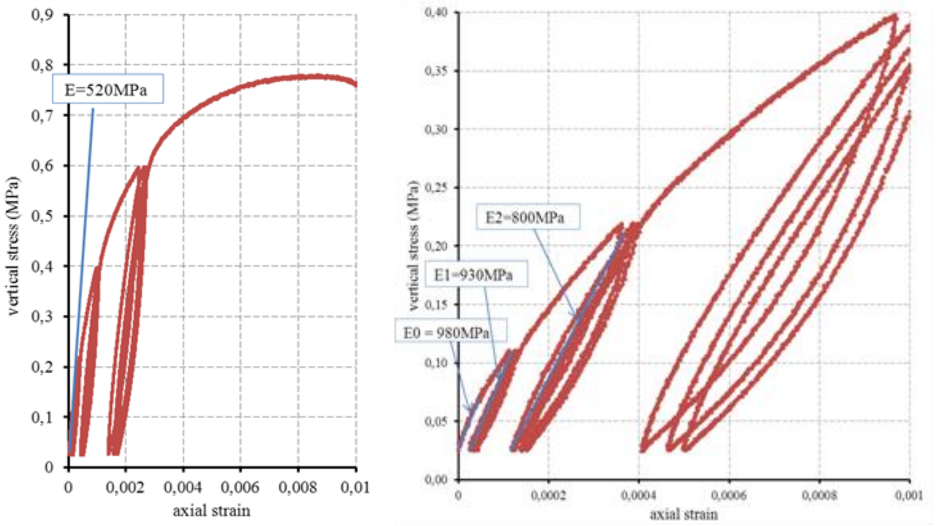

Figure 2 : Elasto-plastic behaviour of a soil A sample, at 9% in moisture content. On the right: a zoom of unloading-reloading cycles.

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

3.2.3 Variation of mechanical characteristics with moisture content

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

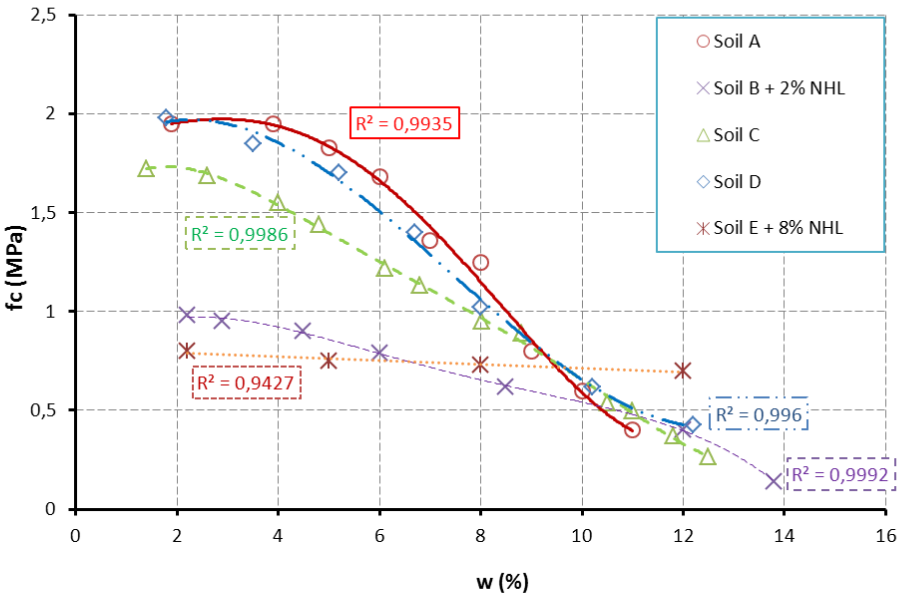

Figure 3 : Variation of compressive strength f_c with moisture content w of all soils studied.

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

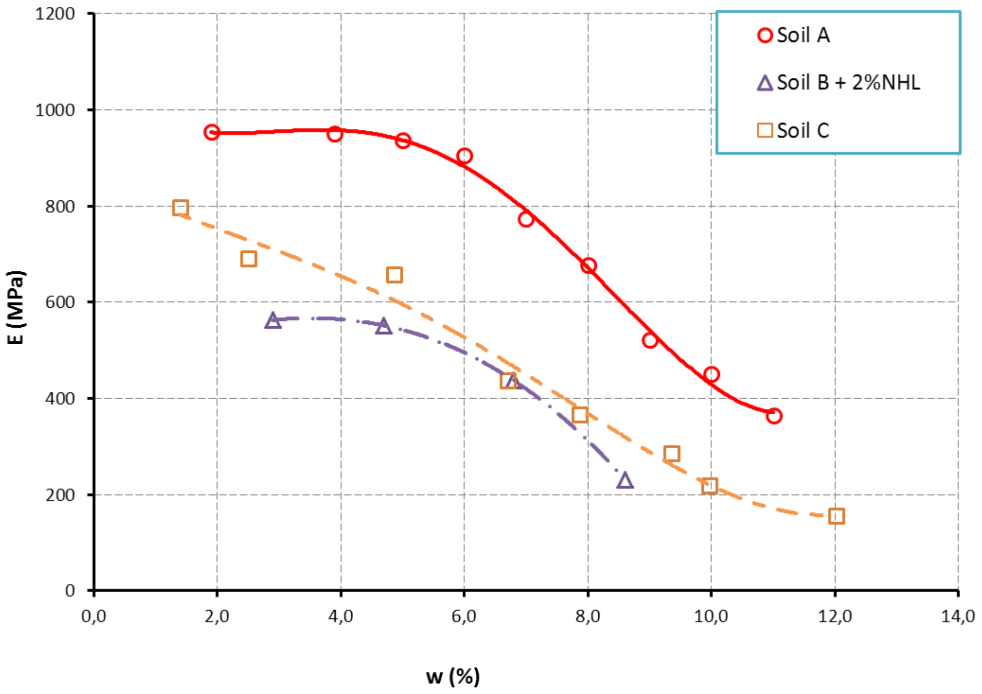

Figure 4 : Variation of secant modulus *E* with moisture content *w*.

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

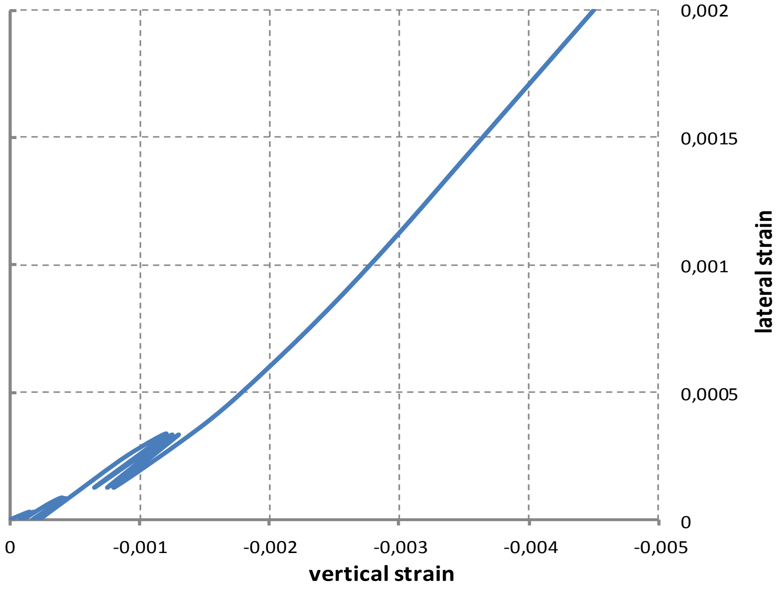

Figure 5 : Measurement of Poisson’s ratio from vertical and lateral strains

The Poisson’s ratio was calculated by devising the vertical strain by the lateral strain (Figure 5). The last one is the ratio between the lateral dilatation (measured by horizontal displacement sensors) and the sample’s radius. The Poisson’s ratio was calculated in the “elastic part” like Young modulus.

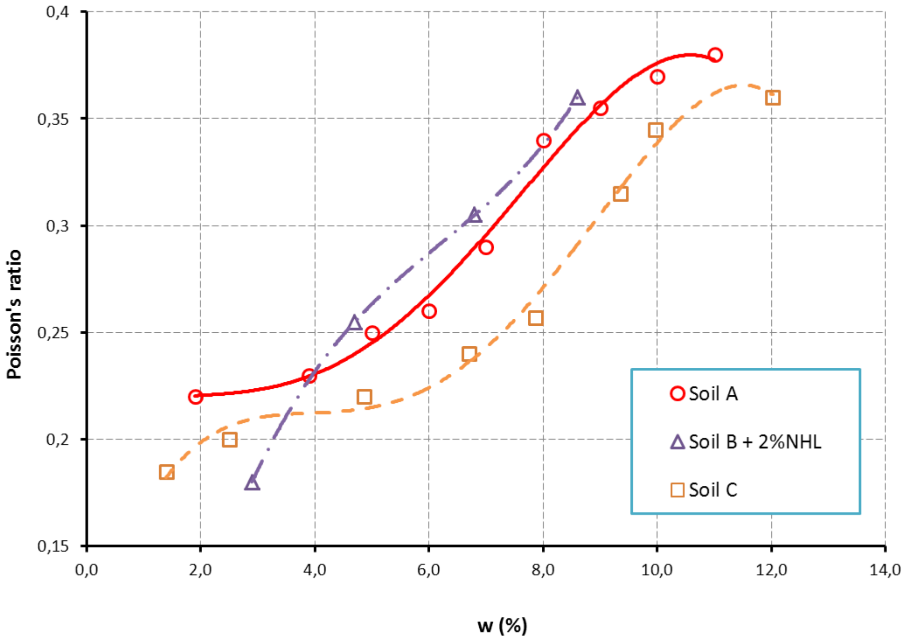

Figure 6 : Variation of Poisson’s ratio with moisture content *w*.

In Figure 6, Poisson’s ratio values were about 0.2 ± 0.02 for the dry samples (moisture content *<4%*), then increased with the moisture content increasing to 0.37 ± 0.01 for the wet samples. This variation is logical because when the material approaches the saturated state, the Poisson ratio approaches the value of 0.5.

4 Study of suction

Olivier and Mesbah (1995) found that suction could be a parameter that determined the mechanical characteristics of compacted earth material. In the present study, a simplified method to measure the suction was developed and the effect of suction on rammed earth was studied for three soil types over a large moisture content range.

4.1 Suction

Suction was first defined in soils as a potential energy (Delage 2002). The suction *s* is linked to the relative humidity (*RH)* of the pore air through Kelvin’s equation, which can be expressed as:

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

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

4.2 Simplified method to measure the suction

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

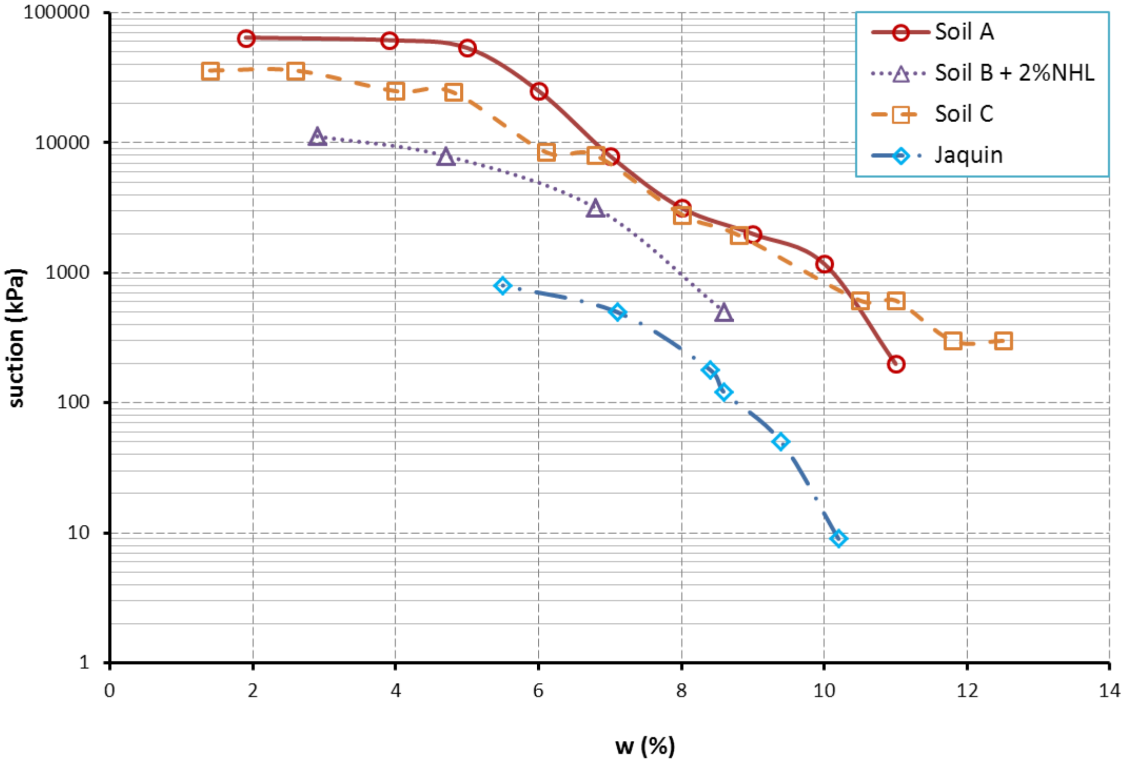

Figure 7 : Variation of suction *s* following moisture content *w*

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.

4.3 Validation of the simplified method and discussions

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.

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

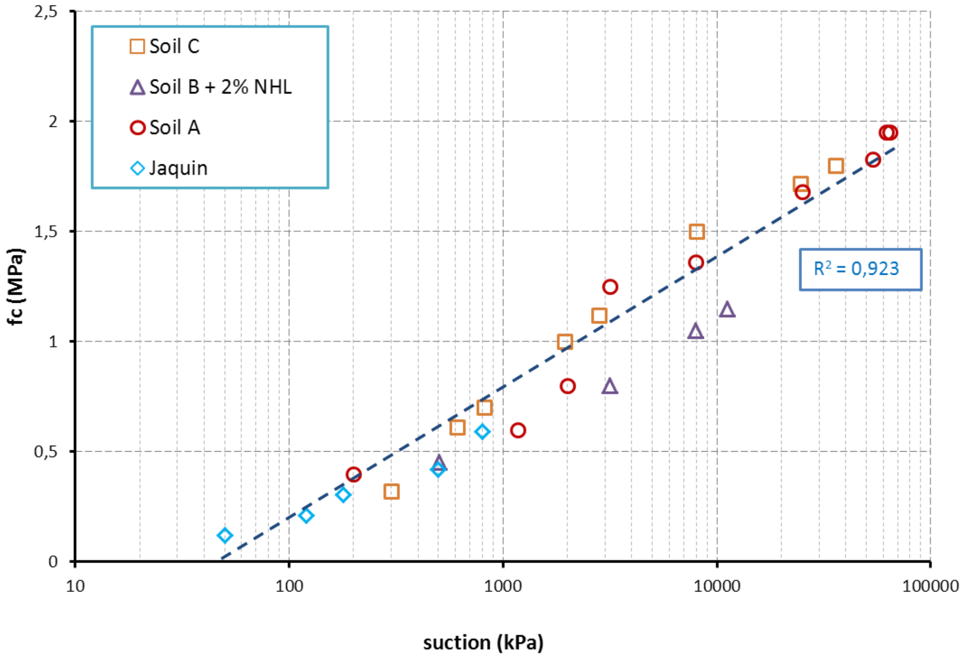

Figure 8 : Variation of compressive strength f_c following suction s

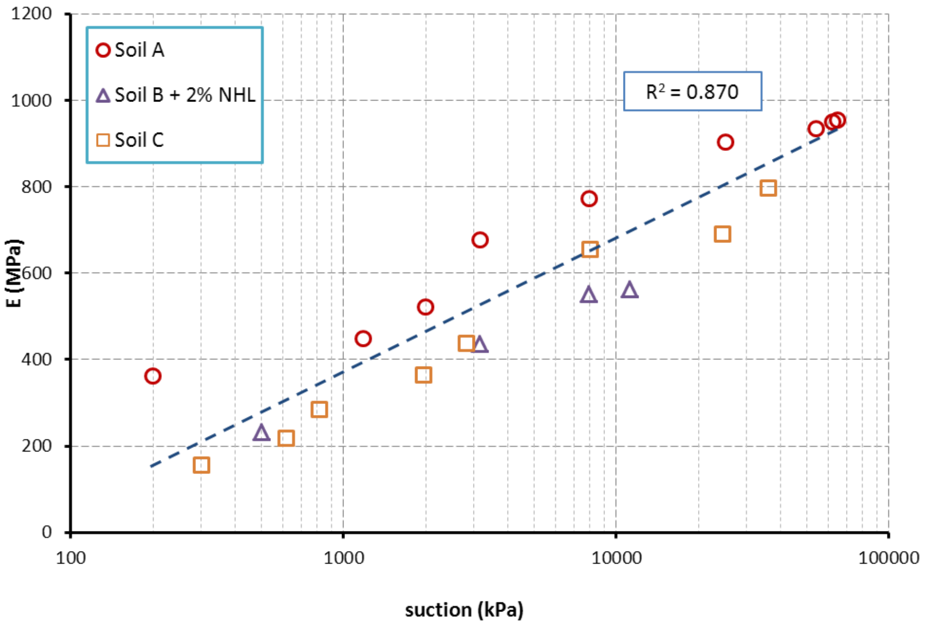

Figure 9 : Variation of secant modulus E following suction s. Note: Jaquin *et al.* (2009) did not present their elastic modulus values.

5 Discussions – Microscopic behaviour of earthen materials

5.1 Sandy soil

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

5.2 Clayey soil

The cohesion of clayey soil material was provided not only by the capillary force between particles but also by attraction forces of clay particles. Attraction between clay particles (plate shape) due to Van der Waals force whose radius is constant. The double layers (proposed by Gouy in 1910 and complemented by Chapman in 1913) surrounding each plate has a mutual action of electrical repulsion due to their positive charge. When the thickness of the double layer is low (high concentration and high valence of the cations), the attraction prevails, plates attract, so there is the cohesion. Otherwise, the thickness of the double layer is low (due to a decrease of the concentration and of valence of the cations, which is the consequence of a significant amount of water), the particles push one to the others, so clay loses its cohesion. This explains the sensibility to moisture of clayey material.

5.3 Stabilized soil

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

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

6 Conclusions and prospects

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

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

A simplified method to measure the suction of rammed earth samples has been developed and validated. This simplified method can be used for studies on suction of RE material. The suction studies were taken in the cases of a sandy soil, a clayey soil and a clayey soil stabilised by 2% NHL. The evolutions of mechanical characteristics following moisture content and following suction were presented. The results confirmed that suction was an important factor of the mechanical characteristics of the studied samples. Indeed, the suction may depend also on type of soil (percentage of clay, type of clay). But following the results in this study, the variation following soil’s type was low. It will be interesting to check this point with a number more important of soils.

The water sensitivity of the rammed-earth material and other earthen materials is a widely perceived weakness. However, this paper showed that a slight increase in moisture content of dry rammed-earth walls (moisture content not exceeding 4% by weight, e.g. due to rain fall or change of RH in the atmosphere) did not accompany a sudden drop in the wall’s strength. Indeed, in this domain, the compressive strength was quasi-constant for sandy soil and stabilized soils and a decrease about 10% for the clayey soil. Qualitative explanations at the microscopic level have been proposed to analyse the results, for all cases: sandy soil, clayey soil and stabilized soil. These interpretations are the fruit of the experiences of the authors and their Universities from 20 years (ENTPE Lyon, France and University of Bath, UK), accompanied by classical theories. The information presented in this paper will be useful to understand the behaviour at nano-scale of earthen material.

Acknowledgement

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