Effect of suction on the mechanical characteristics of uniformly compacted rammed earth

A El Hajjar, P Chauhan*, N Prime and O Plé

Univ. Grenoble Alpes, Université Savoie Mont Blanc, CNRS, LOCIE 73000, Chambéry, France
*Corresponding author. Email: parul.chauhan@univ-smb.fr

Abstract. Rammed earth, in the current environmental situation, is an alternative construction technique which can help in reducing energy and raw material consumption owing to its “sustainable” characteristics. To fully understand its behavior and properties, recent scientific investigations consider it as a compacted unsaturated material with suction as one of the main sources of strength. Eastern constructions face, over their lifetime, variations in the suction state which have a significant impact on their mechanical characteristics. In the present contribution, unconfined compression tests are performed, with and without unload-reload cycles, on homogeneously compacted samples subjected to various suction conditions. This study shows that both the unconfined compressive strength and Young modulus reduce with the reduction of suction states. Suction also seems to influence the amount of plastic strains and damage phenomenon. Indeed, the soils analyzed are slightly active and show both plasticity behavior and damage phenomenon.

1. Introduction

In the present scenario, it is crucial to reduce our energy and raw material consumption, notably concerning building construction which is responsible for large part of energy need and waste production. Traditional construction with raw earth responds to this concern. Rammed earth along with other raw earth construction techniques has more eco-friendly characteristics than steel or concrete. Indeed, it is recyclable and therefore inexhaustible, it needs low embodied and operational energy (thanks to thermo and hygro-regulator effects), and when manufactured properly can offer acceptable strength and numerous other advantages while remaining a low-cost material.

Despite these advantages, raw earth suffers from sensitivity to water with a consistency varying from brittle to plastic which has a direct influence on the mechanical capacity. Relative humidity variations thus lead to a variation of deformability and strength of the unstabilized rammed earth structure. Various researchers have studied this impact of relative humidity on the mechanical characteristics. Champiré et al. [1] performed unconfined compression strength tests, with and without unload-reload cycles on compacted earth samples conditioned at different relative humidities. They showed that compacted earth exhibits complex mechanical behavior, including plastic straining and mechanical damage both depending on the relative humidity at which the samples were stored and on the activity of the clayey portion. Bui et al. [1] also performed unconfined compression tests on samples from different soils (sandy, clayey, stabilized) and presented the variations with respect to water content and suction. This study showed that a slight increase of water content of rammed earth wall equilibrated in a classical ambient relative humidity is not followed by a sudden drop in the structural strength for a water content less than 4%.
Until recently, a new range of scientific investigation is being carried out considering rammed earth as highly unsaturated compacted material to fully understand its properties and behavior. In this frame, suction is considered to be one of the sources of strength. To establish a relation between strength and suction, unconfined compression tests at variable water contents achieved by air drying of the sample with suction measurement were done by Jaquin et al. [2]. Brittle behavior for low starting water content samples and ductile behavior for high water content samples was observed and a qualitative relation between stiffness of sample and suction was obtained.

The objective of this study is to extend the understanding concerning the influence of suction on mechanical behavior, and particularly on Young modulus, compression resistance and intensity of plastic strain, by mean of unconfined compression tests. We propose here to not work with classical rammed earth sample, organized in successive layers whose characteristics influence the mechanical response, but with homogeneously compacted samples which facilitate the result interpretation.

The organization of the paper includes the description of the earthen material tested, the sample preparation method, the hydric conditions imposition and finally the experimental procedures and mechanical response.

2. Material and Specimen Preparation

2.1 Material

The soil was collected from an existing construction site in the vicinity of Vienne in the Auvergne-Rhône-Alpes region in France. It was sieved at 5 mm. The particle size distribution by sieving and sedimentation analysis (figure 1) shows that the soil contains 40% sand, 53% silt, and 7% clay. Note that the particle size curve is not contained in the spindle proposed by British standard BS1377 [3] for earthen construction and is characterized by low clay content. Nevertheless, it is well known that the rammed earth material does not always follow this standard. The Atterberg limits are \( w_L = 27.42\% \) (Liquid limit) and \( w_p = 16.39\% \) (Plastic limit), leading to a plasticity index being \( I_p = w_L - w_p = 27.42 - 16.39 = 11.03\% \). According to the French GTR classification (‘Guide de Terrassements Routiers’) for fine soils (more than 35% of grains passing 80 \( \mu \)m, no soil grain-size over 50mm), it is classified as a low plastic silt (\( I_p < 12\% \)).

![Figure 1. Particle size distribution and the British Standard BS1377 [3]](image_url)

The activity of the soil (\( A_c \)), which depends on the mineralogical nature, is defined as the ratio of plasticity index and percentage passing 2\( \mu \)m sieve. It is here equal to 1.48 which can be considered in the active range (1.25<\( A_c <2.0 \)). In order to more finely characterize the clays, the Cation Exchange
Capacity (CEC) and the specific surface area (\(S_{sp}\)) were determined. A CEC = 2.6 cmol/kg was obtained with a pH = 7.63, which is considered very low value. So, this soil has a low organic matter content, low water retention capacity, and high sand content. The measurement of the specific surface area gave a low value: \(S_{sp} = 14.7 \text{ m}^2/\text{g}\). It is difficult to determine the nature of the clays contained in this soil with CEC and \(S_{sp}\) because of the heterogeneity of the soil, but it can be predicted that this soil either does not contain or contains a very low amount of smectites or vermiculites (swelling clays with very high surface area and CEC).

2.2 Specimen Preparation

The normal proctor test demonstrated that the optimum moisture content to allow the best compaction is between 11.8 and 13.4\% (figure 2). Thus, the earth was mixed at 12.5\% water content and placed in a sealed container for 24 hours to allow homogenization of water content.

![Figure 2. Normal Proctor compaction of soil studied](image)

21 cylindrical samples were compacted in a stainless steel hollow cylindrical mold, designed to obtain specimens with a height of 10 cm and a diameter of 5 cm. The slenderness equal to 2 of the earth cylinders avoids the effect of shrinking (friction during the earth-press contact which hinders the deformation of the earth) and buckling. Indeed several studies have shown that for slenderness of about 2, the geometry does not influence the compressive strength obtained and depends only on the material and the method followed [4]. The samples were compacted by the means of two cylindrical pistons introduced in the upper and lower part of the mold. It was desired to achieve a compression pressure of 5 MPa, which is the pressure usually applied to press Compressed Earth Blocs (CEB). A displacement rate of 0.5 kN/s is chosen to allow air to escape and soil grains to be well managed. This pressure is applied in two stages, 80\% of the stress by pressing on one side and 100\% of this stress applied on both sides simultaneously, according to a methodology proposed by Bruno et al. [5]. This double compaction aims to increase the uniformity of the dry density in the material, in contrary to dynamic compaction which induces a density gradient due to lateral friction making the earth denser at the top surface of a layer and looser at the bottom. In addition, it has the advantage to perfectly control the pressure applied and thus the reproducibility of density is obtained (contrary to dynamical compaction used for rammed earth). Although this technique differs from real compacting processes (dynamic compaction for rammed earth, uniaxial static compaction for earth compressed brick), it leads to a realistic compacted state: the mean dry density obtained (1860 kg/m³) is a classical value for rammed earth structures (values ranging between 1700 and 2200 kg/m³ [7]. In this way, the material is like a model material which can be representative of CEB or Rammed earth structures.

3. Hydric Conditions
3.1 Control of Suction

The suction is controlled by liquid-vapor equilibrium method (also called relative humidity technique). In this method, the relative humidity of the atmosphere surrounding the sample is regulated by means of an aqueous solution of given chemical compound (different saturated saline solutions)[8]. Water is exchanged between the specimen and the surrounding in forms of water vapor according to the relative humidity of the air. When the equilibrium is reached, a particular value of suction is imposed on the sample. The relationship between the relative humidity of the air and the suction imposed at equilibrium is given by Kelvin’s equation (1).

\[ s = u_a - u_w = -\frac{R.T}{g.w_p}\ln(RH) \]  

(1)

where \( s \) is the suction at a particular temperature \( T \) (K), \( u_a \) is pore air pressure, \( u_w \) is the pore water pressure, \( R \) is universal gas constant, \( g \) is acceleration due to gravity, \( w_p \) is the molecular mass of water vapour and \( RH \) is the relative humidity, which is the ratio of partial vapour pressure \( P \) in the considered atmosphere and the saturation vapour pressure \( P_s \) at a particular temperature.

The 21 cylindrical samples after compaction at optimum moisture content were distributed in batches of three samples within 7 different relative humidities 9%, 22.51%, 32.8%, 57.6%, 75.3%, 84.34% and 97.3% (see table 1) in order to achieve different moisture balance in each lot. Daily weighing was taken to follow the soil moisture content over time while saturation of the saline solution is checked every time, otherwise, the samples equilibrate at different relative humidity. Equilibrium is considered when the mass variation is less than 0.05% during 24 hours. It is noted that for low values of relative humidity (less than 60%), the samples reach the water balance in two weeks, whereas for high relative humidities they need more than a month to equilibrate, as shown in figure 3. From this graph, it appears that the batch equilibrated with MgCl₂ salt leads to a final water content which is greater than the batch equilibrated with NaBr salt, even if it applies a lower relative humidity. This observation being inconsistent, the saturation of the MgCl₂ saline solution has been re-checked a posteriori for all tests. It appears that it was not fully saturated, saturation being difficult to visualize with this salt. The suction applied being unknown in this batch, all the results obtained for this hydric condition have not been considered in the following analysis, and only 6 values of Relative Humidities are presented.

| Salt | KOH | CH₂CO₂K | MgCl₂ | NaBr | NaCl | KCl | K₂SO₄ |
|------|-----|---------|-------|------|------|-----|-------|
| RH (%) | 9 | 22.51 | 32.8 | 57.6 | 75.3 | 84.34 | 97.3 |
| Suction (kPa) | 331.3 | 205.3 | 153.4 | 75.9 | 39 | 23.4 | 3.8 |

3.2 Soil Water Retention Curve (SWRC)

The phenomenon of condensation/evaporation and sorption/desorption favors the water exchange between the porous medium and the environment of the microstructure of earth [9]. The water retention curve is used to study the behavior of water in the porous medium ranging from a dry state (high suction) and saturated state (zero suction). Water retention is affected by the direct contribution of the soil components such as clays, organic matter, and oxides, the soil structure i.e. the nature of soil constituents and their organization [10]. To demonstrate the behavior of water in raw earth, three samples (dry mass between 5g and 8g), with the same compacted state than the 21 earth cylinders, were dried at ambient temperature and relative humidity (T=25°C and RH=62%). The 3 samples were then heated in the oven at 70°C for several days until reaching a constant mass of solid particles. Then, they were placed in box containing KOH saline solution (RH=9%). Daily weighing was taken and when the samples are equilibrated (mass variation of less than 0.05% for 24 hours), the samples were placed in the next relative humidity box. Once equilibrium is reached in the last box (RH=97.3%), the samples are transferred again toward the lower RH boxes.
To draw the retention curve, mean of water contents of 3 samples was done for each suction state since standard deviation (σ) was less than 6% (except for samples placed in RH=9% box). For both sorption and desorption path, Fredlund and Xing retention curve model [11] was used and fitting parameters were calculated using SWRC fit which is a nonlinear fitting program [12]. In the figure 4, θ₀ and θᵣ are the saturated and residual volumetric water content, a, m and n are fitting parameters. We note that the path traveled during desorption is above the sorption path, which highlights the phenomenon of hysteresis, which is due to the influence of electrostatic potential in the pores [13]. As the relative humidity increases from nearly zero, first there occur adsorption to a single layer and then to multiple layers of water molecules occurs within the pore structure of the material. The metastable groups of adsorbed water vapor molecule can spontaneously nucleate into a meniscus of liquid water that is in equilibrium with the relative humidity for a given pore radius.

![Figure 3](image1.png)

**Figure 3.** Evolution of water content with time during the equilibration period.

![Figure 4](image2.png)

**Figure 4.** Soil water retention curve for sorption and desorption path along with Fredlund and Xing model

4. Mechanical Response
4.1 Unconfined Compression Strength

The 21 samples are submitted to unconfined compression tests. For each RH batch, 1 of the 3 samples is led to failure after performing 3 unload-reload cycles to calculate Young modulus. Unconfined Compressive strengths (UCS) are reported for the 21 samples in figure 5 with respect to the suction state.

First, it shows that UCS varies between 1.8 and 6.7 MPa. Then, it can be observed that a decrease of suction (an increase of relative humidity), induces a significant decrease of the resistance. In addition, it is noted that the samples which have undergone loading/unloading cycles, i.e. the samples represented in triangular marking in figure 5, have greater mechanical strength than those which have not undergone cycles. They appear in the graph as a curve outside the spindle formed by other samples. This must be due to the additional static compaction experienced by the samples during the three loading cycles, indicating that the mechanical strength of the raw earth is improved by the additional compaction. For classical relative humidity in our latitude (around 60%), the compressive strength is around 3MPa which is close to what is observed in the literature [14].

![Figure 5. Evolution of UCS with suction for samples with and without loading-unloading cycles](image)

4.2 Young Modulus of elasticity

Initial tangent modulus ($E_{\text{tan}}$) was determined from the unconfined compression test using the slope of initial linear part of the curve and secant Young modulus ($E_{\text{sec}}$) was determined from tests with unloading-reloading cycles. In figure 6, the variation of axial stress with deformation along with the determination of both moduli for one test is shown. The evolution of Initial tangent modulus (evaluated as the mean of the 3 tests made with the same suction state) with suction highlights that suction state has a large effect on $E_{\text{tan}}$ (figure 7). A 3 fold decrease of initial tangent modulus is observed when the suction state at beginning of test changes from 331.3 kPa to 3.8 kPa (i.e. from a RH of 9% to 97.3). Thus, the initial Young modulus reduce as the suction state reduces which is consistent with literature [1],[1],[2],[15],[16],[16].
Figure 6. Determination of $E_{\text{tan}}$ and $E_{\text{sec}}$ with loading-unloading cycles for one test ($s=23.4$ kPa - RH=84.34%)

Figure 7. Variation of Initial tangent modulus with suction states (each point being the mean of the 3 values of the same batch)

The evolution of Secant modulus, once plastic behaviour is met, can be also characterized. In this objective, $E_{\text{sec}}$ is plotted along the ratio of maximum axial stress previously experienced and UCS (figure 8a). The graph shows a global reduction of $E_{\text{sec}}$, i.e. damage phenomenon, with increasing axial stress (except for the sample conditioned at 331.3 kPa). The stiffness degradation seems to be reduced as the suction state of the sample decreases (from more than 20% for samples conditioned at 205.3 kPa to 13% for samples at 3.8 kPa suction). The dependency of damage phenomenon on suction can be clearly seen from the decrease of the slope in figure 8(a). It means that the dryer the earth sample, the more sensitive to damage it is.

4.3 Evolution of plastic strains
The evolution of the plastic strain (residual strain at the end of the unloading cycles) with the ratio axial stress/ UCSs (figure 8(b)) shows that residual strain increases with axial stress level. Besides, the lower the suction, more is the plastic behaviour (figure 8(b)). This effect becomes more and more important when the axial load approaches the compression strength. It means that a humid pathology of an earthen structure leads to simultaneous degradation of the material stiffness correlated to an increase of the plastic strain.
The damage and plasticity behavior as discussed by Champiere et al. [1] suggest that the nature of the clay, notably its activity, is a more determining parameter as compared to the content of clay. More active clays experience strong irreversible strains and less damage and vice versa. The soil investigated in this work is considered to be slightly active and thus shows both plasticity (characterized by residual strains) and damage (characterized by stiffness degradation).

![Figure 8. Secant Modulus (a) and residual strain after unloading (b) as a function of stress level](image)

5. Conclusion
In this study, a consistent methodology to investigate hydric influence of the mechanical behaviour of compacted earth structures is proposed, based on a natural earth, compatible with construction project and being made with 7% of slightly active clay.

First, the double compaction process, with 5 MPa applied, allows to manufacture samples which are representative of raw earth structures, but with a reduced density variation inside the material. Then, matric suction is chosen as the state variable accounting for hydric state during the tests, since it represents the direct mechanical translation in the porous matrix of any kind of hydric solicitation applied. In this contribution, hydric state is chosen to be applied uniformly and permanently by mean of saline solution method, which makes it possible to apply 7 suction states, prior to the mechanical loading.

The unconfined compression tests, made with and without unload-reload cycles lead to the following conclusions with regards to mechanical strength, Young modulus, and plastic strain intensity. The samples which have undergone unload-reload cycle had greater mechanical strength indicating that the mechanical strength of the raw earth is improved by the additional compaction. As the suction state decreases, the resistance in simple compression, which is manifested by stress at break, decreases non-linearly, the slope being less steep for lower suction values. A global reduction of the initial Young modulus was observed as the suction state reduces. This highlights, that suction is one of the most important sources of strength and the influence of varying humidity conditions have an impact on the mechanical behavior. The evolution of the modulus during the test shows a global reduction. This stiffness degradation termed as damage phenomenon was significantly higher for samples conditioned at higher suction states.

The plastic straining in the material increased as the axial stress increased. This plastic behavior was more prominent in the samples at lower suction states. Generally, more active clays experience strong irreversible strains and less damage and vice versa. The soil analyzed in this work was slightly active and shows both plastic straining and mechanical damage.

Currently, the effect of hygrometry on the shear characteristics of the soil using Casagrande Direct shear test is being investigated and the effect of suction states on the parameters such as friction angle and cohesion will be analyzed.
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