Methodology to study the suction effects on mechanical characteristics of rammed earth

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ABSTRACT. *Rammed earth is a construction material but also construction technique by which soil is dynamically compacted into a temporary formwork to form walls. This construction exhibits mechanical characteristics that vary according to their suction states. Despite its numerous advantages as a sustainable construction material, the strength characteristics show dependency on the environmental conditions. This link between the mechanical characteristics and the hygroscopic conditions is studied here with unconfined compression strength test with and without unload-reload cycles on homogeneously compacted samples conditioned at different suction states. This study shows that both unconfined compressive strength and Young modulus increase with suction. Complex mechanical behavior involving plastic strain and damage phenomenon was observed, depending on the activity of soil. The soil studied, is in fact slightly active and undergoes both damage and plastic strain influenced by suction.*

RÉSUMÉ. *La terre crue est un matériau de construction mais aussi une technique de construction par laquelle le sol est compacté dynamiquement dans un coffrage temporaire pour former des murs. Cette construction présente des caractéristiques mécaniques qui varient en fonction de leur état de succion. Malgré ses nombreux avantages en tant que matériau de construction durable, les caractéristiques de résistance montrent une dépendance aux conditions environnementales. Ce lien entre les caractéristiques mécaniques et les conditions hygroscopiques est étudié ici avec un test de résistance à la compression non confiné avec et sans cycles de décharge-rechargement sur des échantillons compactés de façon homogène conditionnés à différents états des succions. Cette étude montre que la résistance à la compression et le module d'Young augmentent avec la succion. Un comportement mécanique complexe impliquant des déformations plastiques et un phénomène d'endommagement a été observé, en relation avec l'activité du sol. Le sol étudié est en effet légèrement actif et subit à la fois de l'endommagement et de la déformation plastique influencés par la succion.*

KEYWORDS: *rammed earth, suction, unconfined compression strength, plastic strain, damage.*

MOTS-CLÉS : *terre crue, succion, résistance à la compression non confinée, déformation plastique, dommage*

1. Introduction

Traditional construction with raw earth is a sustainable solution for the growing energy and raw materials need. Rammed earth is basically sandy-clayey gravels but also a construction technique by which load bearing walls can be manufactured by dynamically ramming the soil between temporary formwork. It is recyclable and needs low embodied and operational energy. It offers acceptable strength, a part of which comes from the interlocking between the particles from compaction. In addition to this, due to partial saturation state of the walls, there exists additional suction induced strength which upon an increase in water content decreases. Since the environmental conditions are continuously evolving, the raw earth has a sensitivity to water with its consistency varying from brittle to plastic. Consequently, the mechanical characteristics are strongly affected by the hydric solicitations.

The sensitivity of raw earth leading to variation in mechanical capacity has been studied by many authors. Jaquin et al. [JAQ 09] studied the influence of variation of suction on the compressive strength and stiffness of rammed earth by performing triaxial test on samples air dried to different suction values. It was observed that an increase in suction leads to increase in strength, although finitely. Stiffness studies indicated that wetter samples have greater ductility whereas drier samples were brittle. Beckett and Augrade [BEC 12] also studied the effect of humidity and temperature condition on unconfined compressive strength on two soil mixes. It was found that for all temperature and humidity levels, higher compressive strength was achieved for samples containing lower clay content. Champire et al. [CHA 16] performed unconfined compressive strength test with and without unload-reload cycles. They observed that earth exhibits a complex mechanical behavior combining elasto-plasticity, damage, and partial saturation mechanism. Bui et al. [BUI 14] studied this moisture influence at a greater range of moisture content and observed that compressive strength decreases with increasing moisture content. However, when the moisture content is below 4%, the compressive strength is quasi-constant.

In the present study, the methodology to analyze this hydric influence on the mechanical properties such as Young's modulus, compressive strength, damage and plastic strains using the unconfined compressive strength is described. It is proposed here to work with homogenously compacted earth rather than classical layered samples which give an advantage of better result interpretation.

2. Material and Methods

The soil used was from existing construction site in the vicinity of Vienne in the Auvergne-Rhone-Alpes region of France. It contains 40% sand, 53% silt, and 7% clay. Its liquid limit, plastic limit, and plasticity index (I_p) are 27.42%, 16.39%, and 11.03% respectively. It is classified as low plastic silt, A1, (I_p<12%) according to French GTR classification ('Guide de Terrassement Routier'). The activity of clay (A_c) defined as the ratio of plasticity limit and percentage passing 2 µm sieve was determined to be 1.48 which is in active range ($1.25<A_c<2.0$). Cation exchange capacity (CEC) and specific surface area (S_{sp}) were determined to be 2.6 cmol/Kg and 14.7 m^2/g. Thus, the soil has low organic content, low water retention capacity and contains a very low amount of swelling clays such as smectites and vermiculites.

To determine the water content for preparation of samples, normal proctor test was conducted and the maximum dry density was achieved at water content between 11.8 to 13.4%. Thus, the earth was mixed at 12.5% water content and left for 24 hours for homogenization of water content. 21 cylindrical samples were compacted in a stainless steel hollow mold to obtain a specimen of height 10 cm, diameter 5 cm and hence a slenderness of 2. The samples were compacted to a compression pressure of 5 MPa in two stages. In the first stage, 80% of stress was applied on one side and in the second stage, 100% of stress was applied on both sides simultaneously as proposed by Bruno et al. [BRU 15]. This method of double compaction aids in the uniformity of dry density as compared to dynamic compaction which induces a density gradient with denser state at top of each layer and looser state at bottom. It also has the advantage of repeatability of dry density and allows to control the pressure applied. A mean dry density of 1860 kg/m^3 was obtained which is a classical value for rammed earth (between 1700-2200 kg/m^3) [ELN 17].

Suction was applied on samples using the liquid-vapor equilibrium method in which the relative humidity of the surrounding atmosphere was regulated using a saturated aqueous solution of different salts [DEL 98]. After reaching equilibrium the suction was calculated using Kelvins equation.

$$s = u_a - u_w = -\frac{R.T}{g.w_v}\ln(RH) \quad [1]$$

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_v 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_o at a particular temperature.

The 21 compacted samples were then placed in batches of three in boxes which imposed relative humidity of 9%, 22.51%, 32.8%, 57.6%, 75.3%, 84.34% and 97.3%, corresponding to suction values shown in table 1. Samples were left be equilibrated until the mass variation was less than 0.05% during 24 hours. Inconsistency was found for samples equilibrated with $MgCl_2$ as it leads to final water content more than NaBr. Thus, in the further section, the results from this hydric condition are not considered for analysis.

Table 1. Relative Humidity and Suction imposed by the saturated saline solutions

Salt	KOH	CH_3CO_2K	$MgCl_2$	NaBr	NaCl	KCl	K_2SO_4
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

The soil water retention behavior was analyzed using 3 samples (5-8 g dry mass), compacted in the same manner as the 21 cylindrical samples. The samples were heated in an oven at 70 °C to achieve constant mass and then placed in the humidity boxes one by one starting from KOH saline solution (RH=9%) and at last in K_2SO_4 saline solution (RH=97.3%). This helped to obtain the sorption curve. Once equilibrium is reached in the last box (RH=97,3%), the samples are transferred again toward the lower RH boxes to obtain the desorption curve. These data were fitted using Fredlund and Xing retention curve model.

3. Results

Unconfined compressive test was conducted on the 21 samples. For each RH batch, one of the three samples was compressed with unload-reload cycles to obtain Young's modulus. The unconfined compressive strength (UCS) varied between 1.8-6.7 MPa highly depending on the suction states since the decrease of suction-induced a significant decrease in the strength. It was noted that samples which have undergone unload-reload cycles have greater mechanical strength than those which did not undergo cycles highlighting that additional compaction might aid the mechanical strength.

Initial tangent modulus (E_{tan}) was calculated from the initial linear part of the stress-strain curve and secant Young modulus (E_{sec}) was determined from the test with unload-reload cycles. Initial tangent modulus decreased 3 times when the suction decreased from 331.3 kPa to 3.8 kPa corresponding to increase in RH from 9% to 97.3% (figure 1). Thus, the initial tangent modulus reduces as the suction state reduces.

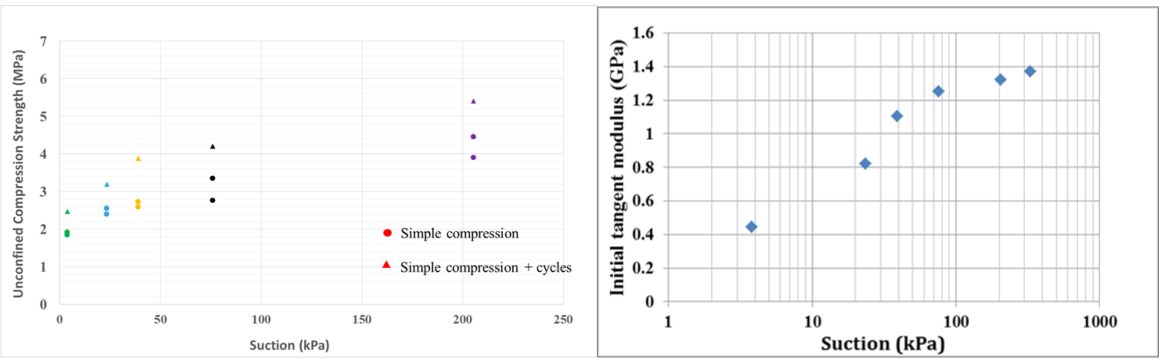

Figure 1. *Variation of UCS (left) and Initial tangent modulus (right) with suction*

The evolution of secant modulus during the test (figure 2a) with the ratio of maximum axial stress experienced to UCS show a global reduction of E_{sec} i.e. damage phenomenon. As the suction state reduces, the damage decrease which is clear from the decrease of slope (figure 2a). Thus, wetter samples are less sensitive to damage phenomenon. The evolution of residual strain at the end of unloading cycles (termed as plastic strain) with axial stress/ UCS ratio show that plastic behavior was more prominent at lower suction states (figure 2b). Also, during the course of the test, the plastic strain increases for all samples. Champire et al. [CHA 16] suggested that the nature of clay is much more important parameter than the amount of clay (as long as it is sufficient to ensure material cohesion). More active clays experience less damage and more plastic strains and vice versa. The soil studied here is slightly active in nature and in fact experience both damage which is characterized by stiffness reduction and plasticity characterized by plastic strains.

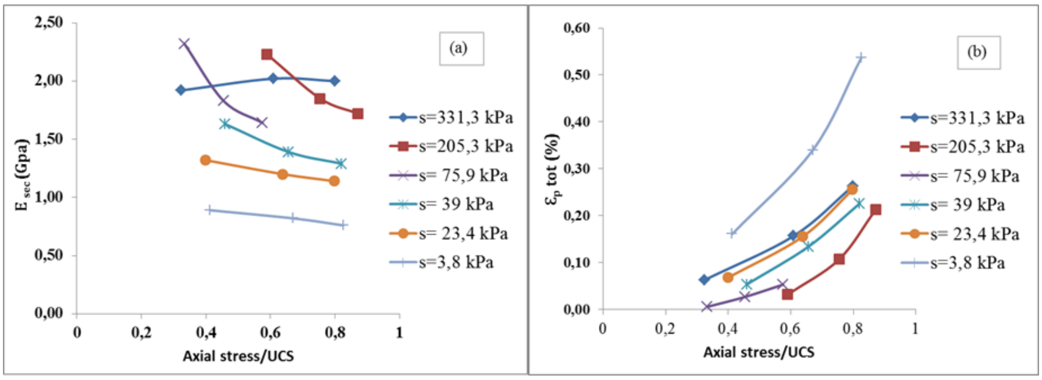

Figure 2. *Secant Modulus (a) and residual strain after unloading (b) as a function of stress level*

4. Conclusions

In this study, a methodology to analyze the effect of suction state on the mechanical characteristics was proposed. A method of double compaction with a compaction pressure of 5MPa was used to obtain more uniformly compacted specimens than for classical layered ones. Prior to the mechanical testing, the samples were conditioned at different relative humidities by means of saline solutions. The Unconfined Compressive Strength and initial Young's modulus decreased as suction state decreased. This suggests that suction is one of the most important sources of strength and the hydro-mechanical coupling behavior of rammed earth is essential to characterize. Samples tested with unload-reload cycles showed higher mechanical strength, indicating that strength of rammed earth can be improved by additional compaction. Damage phenomenon was observed during the test and this stiffness degradation was found higher for drier specimen conditioned at high suction. Plasticity was observed progressively increasing upon loading and the residual strain was higher for wetter samples. In general, soils containing more active clays, are highly plastic and suffer less damage and vice versa. The soil analyzed in this study being slightly active show both these phenomenon.

Presently, this influence of hydric solicitations is being analysed on the shear behaviour using the direct shear test.

5. References

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