Hydromechanical triaxial behaviour of unfired compacted earth for building construction

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Abstract

Considering the context of sustainable building, energy consumption and greenhouse gas reduction, compacted earth is regarded as a promising non-industrial construction material. However, due to lack of scientific knowledge, there is currently no clear recognized guidance for their set-up, or means of measurement to guarantee their performance. In particular, the mechanical behaviour of earthen materials is strongly influenced by the water molecules which are adsorbed on the pore surfaces. In that context, in order to explore the hydro-thermo-mechanical behaviour of compacted earth, triaxial apparatus at controlled temperature and equipped with non-contacted sensors measuring system, was developed. The results show that the relative humidity at which the samples were stored have a strong impact on the mechanical characteristics of earthen material: both the maximum deviator stress fc and Young's modulus E decrease with the increase of relative humidity, meanwhile, more plastic characteristics are observed. Non negligible swelling/shrinkage phenomena induced by variations of relative humidity are also observed. These results are eventually analysed in the light of a fully coupled poromechanical model which allows quantifying the evolution of the mechanical behaviour induced by daily variations of temperature and humidity.

Keywords: Earthen constructions, Poromechanics, Couplings in porous media.

1. INTRODUCTION

Crude earth is composed of clays, silts, sands and possibly gravels and fibers. One particularity of this material is the presence of micro- to nano- connected pores. Thanks to these several levels of porosity, as well as their strong affinity water molecules, which is due to their clayey content (Murad et al. (2012)), earthen based materials are classically classified as good to excellent hygroscopic materials. Its denotes their ability to buffer moisture and improve indoor air quality while keeping the internal temperature relatively stable. This affinity with water molecules also significantly impacts their mechanical behavior. For example, the decrease in strength with moisture, which is well known in soil mechanics (see for example Morvan et al. (2010)), has been demonstrated for compacted earth by Chamipré et al. (2016), while hygrometry variations may lead to quite significant swelling/shrinkage phenomena.

It follows that a proper assessment of the global performance of earthen materials should take into account these thermo- hydro-mechanical couplings. In that context, this paper aims at assessing the couplings between the stress, strain, humidity and temperature fields in the partially saturated compacted earthen material through a poromechanical approach. To reach this goal, the impact of hygrothermal processes, which already identified by Soudani et al., (2016), on the mechanical behavior (hardening/softening and swelling/shrinkage phenomena) are estimated through experimental investigation on centrimetric samples in a temperature and hygrometry controlled triaxial cell. The obtained relations are implemented in a fully coupled poromechanical approach.

2. HYDROMECHANICAL BEHAVIOR

2.1. Materials and methods

The earthen material considered in this study came from an existing construction located in ''Rhône-Alpes" region in the South-East of France. Decimetric blocks were sampled from rammed earth walls of this construction during operations of new doors and windows opening. This choice ensures that the studied material is suitable for building sustainable earth constructions. The blocks were manually crushed, first with a pick and then with a soft hammer.

Triaxial compression tests were performed with the electro-mechanical press (Z020TN, Zwick Roell, Ulm, Germany). The accuracy of the press sensor was about 20 N for the axial load and 2 µm for its displacement. Deformations were measured using a home-designed measuring system. Four non-contact sensors (accuracy of 0.4 µm) were installed on 1/3 and 2/3 of specimen's height, thereby measuring the axial deformation; meanwhile, three non-contact sensors were placed on the middle of the specimen with the included angle of 120° to measure the radial deformation. Through combining the axial and radial deformation, the volume changes during triaxial tests were estimated.
Three tests conditions (unconfined, 1bar of confinement pressure and 6bars of confinement pressures) are considered at two temperatures (23°C and 30°C) and 3 relative humidities (35%, 75% and 97%).

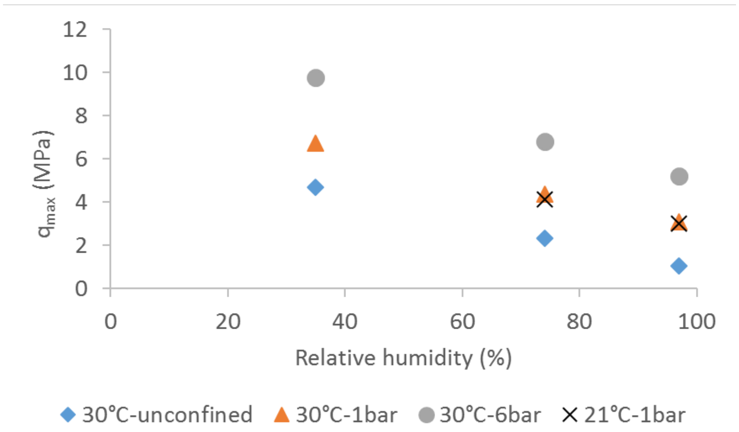

Figure 1. Evolution of the deviatoric strength at failure (q_{max}) with relative humidity

For all the test conditions investigated, the samples firstly exhibit a contraction, followed by a dilatancy. Under both loading and unloading cycles, the stress-strain relation is almost linear especially at lower stress levels (20% and 40% of deviatoric stress at failure, denoted by q_{max}). In consequence, the linear-elastic assumption could be adopted in order to determine the secants Young's modulus and Poisson's ratio.

As it is showed in the Figure 1, an increase of relative humidity and/or a decrease of the confinement pressure induce both an obvious reduction of deviatoric stress at failure. On its side, temperature difference between 23°C and 30°C does not bring any significant variation.

Similarly, the Young modulus, estimated from the loading and unloading cycle at 20% of q_{max} significantly decrease with an increasing relative humidity, whatever the test condition and it does not seem to be impacted by the small variation of temperature considered in this study (cf. Figure 2).

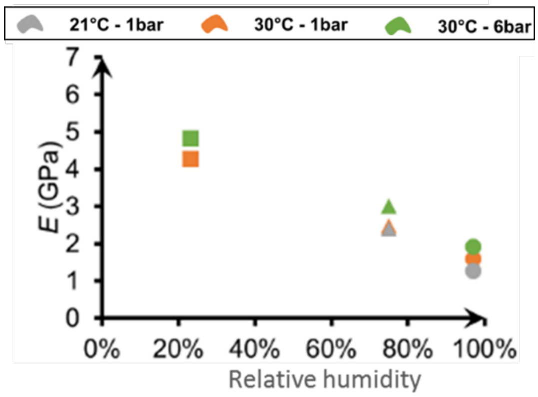

Figure 2. Evolution of the Young's modulus with relative humidity.

2.2. Swelling behavior

The swelling behavior was investigated following two experimental protocols. The first consists in an unjacketed test at increasing imposed relative humidity. This test is called "homogeneous swelling test", since, at each step, the relative humidity within the sample is homogeneous. The second one consists in circulating a moist air of increasing relative humidity through a jacketed sample. In this configuration, called the "continuous swelling test" the sample is under a gradient of relative humidity. To draw the relation between the volumetric strain and the relative humidity, this latter is calculated at the displacement measurement points using an adaptation of the hygrothermal model developed by Soudani et al., (2016). These two experiments lead to the results which are reported in the Figure 3.

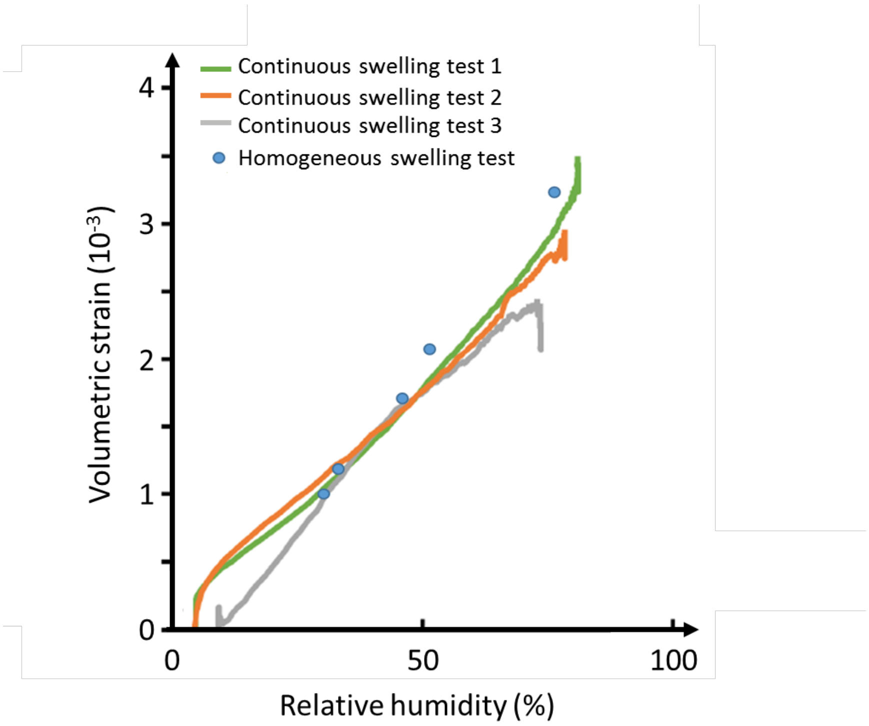

Figure 3. Volumetric strain induced by the increase of relative humidity within earthen samples

A good consistency is observed between all the swelling tests. This result gives some confidence on the accuracy of the hygrothermal model which is used to estimate the relative humidity within the sample for the "continuous swelling test".

These tests underline that the swelling process in the hygroscopic regime of saturation is not negligible. Indeed, this experience leads to swelling strains in the range of 1mm/m for a variation of relative humidity from 30% to 50%. This phenomenon should thus be taken into account for a proper design of earthen constructions.

Finally, the shape of the relation between the volumetric strain and the relative humidity appears to be almost linear. If the local equilibrium between the adsorbed water, the in-pore capillary water and the water vapor are assumed, this tendency can be reproducing using a Gibbs potential of adsorbed water similar to the one developed by Lei et al. (2014). It leads to the following expression for the swelling strain, denoted by ϵ_v:

$$\mathrm{d}\epsilon_v = \frac{\mathrm{d}m_{ads}}{\rho_L(1-\phi_0)} \tag{1}$$

were ρ_L is the liquid density and $\phi_0$is the initial porosity and m_{ads} is the mass of the interlayer water per unit of material initial volume. It is linked to the relative humidity (denoted by rh) through the relation:

$$m_{ads} \approx a\, rh \frac{\rho_d^0}{1-a\, rh} \tag{2}$$

where ρ_d^0 is the initial dry density and a is a positive dimensionless coefficient, between m_{ads}/m_s and 1, whose value increases with the swelling potential of the material.
A good correlation is observed between the experimental results of swelling tests and of the theoretical curve obtained from the relations (1-2) for a swelling coefficient a=0.0017.

3. POROMECHANICAL MODEL

3.1. Law of behavior

The experiments at several relative humidities have underlined that the Young's modulus (denoted by E) varies quite significantly with water content, while the Poisson's ratio (denoted by ν) seems to remain almost constant. On the other side, the tests at 23°C and 30°C do not exhibit strong differences in mechanical behavior. In consequence, using the general framework of poromechanics (Coussy, (2010)), the following linear law may be proposed for the stress tensor (ΔX stands for X-X_0):

$$\Delta\boldsymbol{\sigma} = \frac{E}{\nu+1}\left(\boldsymbol{\epsilon} + \frac{\nu}{1-2\nu}\epsilon_v\boldsymbol{\delta}\right) - \left(\Delta P_\phi + \frac{E}{3(1-2\nu)}\left(3\alpha\Delta T + \frac{\Delta m_{ads}}{\rho_L(1-\phi_0)}\right)\right)\boldsymbol{\delta} \tag{3}$$

were $\boldsymbol{\sigma}$ and $\boldsymbol{\epsilon}$ are the stress and strain tensors, P_ϕ is the equivalent pore pressure, α is the thermal dilatation coefficient and $\boldsymbol{\delta}$ is the second order unity tensor.

3.2. Comparison with experimental data

The model, composed by the conservation equations, is solved with COMSOL Multiphysics (coupling between PDE and linear elasticity modules). Its predictions are compared to swelling experiments at constant temperature under hydric gradients.

The cylindrical sample is initially under a confinement pressure of p_{conf} = 1,5bar above the atmospheric pressure and equilibrated at a relative humidity of 3% thanks to a dry air flow of Q = 50mL/min through the sample (from the bottom side to the top side). At t = 0, the relative humidity of the air injected into the sample increases from 3% to 90% while the flow rate is kept constant. Evolutions of axial and radial displacements are monitored, as well as gas pressures and relative humidity at top and bottom surfaces. The experimental results, in comparison with the numerical application, are reported in the Figure 4. All the material parameters used for the simulation have been measured independently.

The poromechanics model developed here leads to consistent results. In particular, the quite good correlation between both relative humidity and deformation evolutions gives some confidence on the ability of the simplistic form given for the inter-layer activity to reproduce the good tendencies.

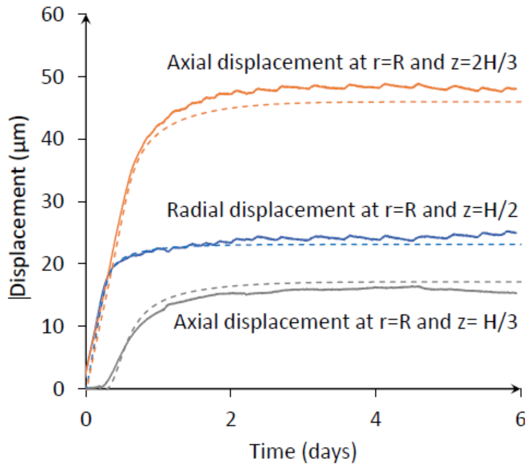

Figure 4. Comparison of the experimental results with model predictions. r and z are respectively the radial and the axial coordinates, R is the radius of the sample and H is its length.

4. CONCLUSION

Hydro-mechanical triaxial behavior of compacted earth at different temperatures (23°C and 30°C) was investigated. This study shows that mechanical characteristics of earthen materials have a strong dependence on the relative humidity at which the samples are stored, and in parallel yields some preliminary observations on their thermal mechanical behavior. In particular, dimensional variations of the sample under variation of air relative humidity have been experimentally investigated, and they were found to be not negligible.

These experimental results were then used to develop a thermo-hydro-mechanical model for unstabilized compacted earth. This former model was made on the framework of poroelasticity and consider the swelling-shrinkage phenomena through a semi-empirical approach. The comparison with experimental data underlines its ability to correctly reproduce the water mass transfer through the porous network and its consequence on the dimensional variations of the material.

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