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Impact of relative humidity on the mechanical behavior of compacted earth as a building material

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HIGHLIGHTS

- Three earthen materials have been tested in unconfined tests with cycles.
- Each earthen material have been confined at three different relative humidity.
- Axial strain has been measured by image correlation.
- Radial strain has been measured by non-contact sensors.
- Compacted earth exhibits a complex volumetric behavior.
- Its mechanical behavior appears to be strongly changed by the curing humidity.

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ABSTRACT

Earthen buildings can provide an answer to face difficulties in modern constructions in both terms of sociology, economics as well as ecology. However, the difficulty to understand and to predict their long term behavior represents an obstacle to their spreading. In some cases for example, unsuitable repairs on old constructions can lead to catastrophic situations.

More specifically, during their lifetime, earthen walls have to face important variations of indoor and outdoor relative humidity, which induces variations and gradients in their water content. In this context, this paper aims at addressing an important aspect, not yet fully understood: the impact of these variations on the deformability and the strength of unstabilized earth. To that purpose, unconfined compression tests, with and without unload–reload cycles, were performed on different compacted earth samples conditioned at different relative humidities. Tested samples were prepared from materials coming from different existing constructions and sieved at 10 mm. During the tests, the axial and radial strains were measured using non-contact sensors and an image correlation system. This study shows that earthen materials have a complex mechanical behavior, involving the phenomena of plastic straining and mechanical damage. Moreover, both of these phenomena show a strong dependence on the relative humidity at which the samples were stored, as well as on the activity of the clayey portion of the earth.

1. Introduction

A recent growing interest in earthen constructions in occidental countries is observable, mostly due to their low environmental impact [1]. Indeed, earth materials need few or no transformation to be used as a construction material and can be extracted close to the construction site. Moreover, the wall thickness, ranging from 30 cm to 50 cm, and the affinity of raw earth for water molecules bring a well-known quality for interior comfort for both acoustic, hygric and thermic aspects [2–5]. Water in the wall plays a crucial part: it confers a cohesion to the material, through suction effects, and also acts as a buffer to buffer temperature variations through liquid/vapor phase change phenomena, thus increasing the apparent thermal inertia of the wall [2–5]. However, the development of this ancestral building technique notably suffers from the lack of appropriate standards for construction and restoration, dealing accurately with mechanical, hydraulic, and even mineralogical characteristics of the earthen materials.

To fill this gap, many laboratory tests have been performed on earth samples and walls [6–8]. These studies underline an important variability of the common parameters such as the compression

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strength and the Young's modulus, which depend on the sample geometry, the type of earth used as well as test conditions. More importantly, the knowledge of only these two parameters are found to be largely insufficient to properly model the complex behavior of earthen walls [9–11]. For example, assumptions considering a constant Poisson's ratio equal to 0.33 (i.e. like a soil material [12]), and elastic moduli independent of the water content are known to be inconsistent with respect to experimental observations [13]. Furthermore, the material strength is usually evaluated through the compressive strength using unconfined compression tests and sometimes through the tensile strength using splitting or three points bending tests [14]. Measuring these parameters with no temperature nor relative humidity regulation may be acceptable for conventional materials such as concrete and stone. However, when it comes to the earth behavior and knowing its strong interaction with water molecules, it will be interesting and necessary to check the impact of ambient temperature and relative humidity [15]. As already discussed by many authors, the inherent variability of earth types and the influence hygrothermal conditions, make the identification of the key parameters (i.e. whose determination should be sufficient to qualify the mechanical performance of the material) even more difficult.

This paper aims at quantitatively studying the mechanical behavior of different unstabilized earth materials used for building constructions, and more precisely, at identifying main global trends, each of them investigated considering the impact of the relative humidity. It is a preliminary but essential step toward the development of a well-adapted constitutive model of earthen materials.

For that purpose, unconfined compression tests with and without unload-reload cycles and at different relative humidities were performed. The tested samples were made of earth sieved at 10 mm and sourced from three existing rammed earth constructions. During the test, the axial and radial strains were measured using non-contact sensors and an image correlation system so that the elastic parameters (namely Young's modulus and Poisson's ratio), the unconfined compressive strength, the residual strains and the volume variations can be measured with accuracy for all test conditions.

There are different building techniques using clayey material: rammed earth, adobe, cob, earth masonry, compacted earth blocks (CEB), extruded earth blocks, wattle and daub [16]. The choice is mostly made based on the local know-how and on the nature of the soil. In any case, the material is composed of aggregates (sand, gravels, fibers, etc ...) bonded by a continuous clayey matrix, which is known to be responsible for the cohesion of the material and its complex mechanical behavior, such as swelling and shrinkage when subjected to hydric changes [17,18]. As a consequence, even though studied materials are CEB, the conclusions can be, up to a certain point and given an equivalent clay mass content, extended to other earthen construction technics. At last, many tests found in the literature study the impact of stabilizers (i.e. adding a binder, concrete or lime) on the mechanical behavior of the material [19–23], which are shown to be often responsible for an increase of the compression strength and a reduction of the impact of water on the mechanical behavior. If the existence of environmental side-effects has to be mentioned [15,24,25], the use of stabilizers has proven to be necessary for environmental (monsoon, etc ...) or specific structural constraints. However, the heritage of unstabilized earth buildings remains particularly important [11] and must be assessed, at least for maintenance and rehabilitation purposes. That is the reason why this study is limited to the behavior of the compacted earth without stabilizer (i.e. only composed by crude clayey soils).

The first part of the paper describes the earthen materials tested, the sample preparation and the experimental procedures. The results of the unconfined compression tests are presented in the second part. Finally, the last paragraphs focus on the most important factors governing the mechanical behavior: type of soil, relative humidity and the maximum applied stress (i.e. ratio between maximal stress level reached for different unloading–reloading cycle and the compression strength).

2. Materials and methods

2.1. Material

Three different materials were studied, named STR, CRA and ALX. They all came from existing centenarian rammed earth constructions located in "Rhône-Alpes" region in the South-East of France, thus ensuring that the studied material was suitable for building sustainable earth constructions [26]. The particle size distributions of all three earths were determined in accordance with the French Norms NF P94-056 and NF P94-057 and are reported in Fig. 1A. They showed a mass content of clays (particles with a diameter lower than 2 μm) equal to 15% for STR, 16% for CRA and 8% for ALX.

In parallel, the Atterberg limits and the Methylene Blue Value (MB) are measured on the 0–80 μm fraction of the soils. The choice has been made in order to increase the accuracy of the measurement and to provide a direct comparison between the activities of the fine components (clays + silts) of the tested materials. The measurement of the activity was made following the procedure reported in [27]. Finally, the clay minerals were identified using a Siemens D5000 powder X-ray diffractometer equipped with a monochromator having a Ka (lambda = 1.789 Å) cobalt anticathode on oriented aggregates and using three preparations: air dried or natural, after glycolation and after heat treatment at 500 °C. The clay characteristics are summarized in Table 1.

The X-ray diffraction (XRD) analysis shows that the clays of the three materials are quite stable (illite, Kaolinite, Chlorite and Vermiculite). These results are quite consistent with the common know-how which stipulates that the overall clay content should be sufficient to ensure a good material stiffness and strength, but the proportion of expansive clay must remain limited in order to avoid cracking.

The plasticity index and the Methylene Blue Value of the 0–80 μm portion of CRA are at least twice as high as the corresponding values for STR's ones, while their particle size distributions are similar. On the other hand, Methylene Blue Value of the 0–80 μm portion of STR and ALX are similar.

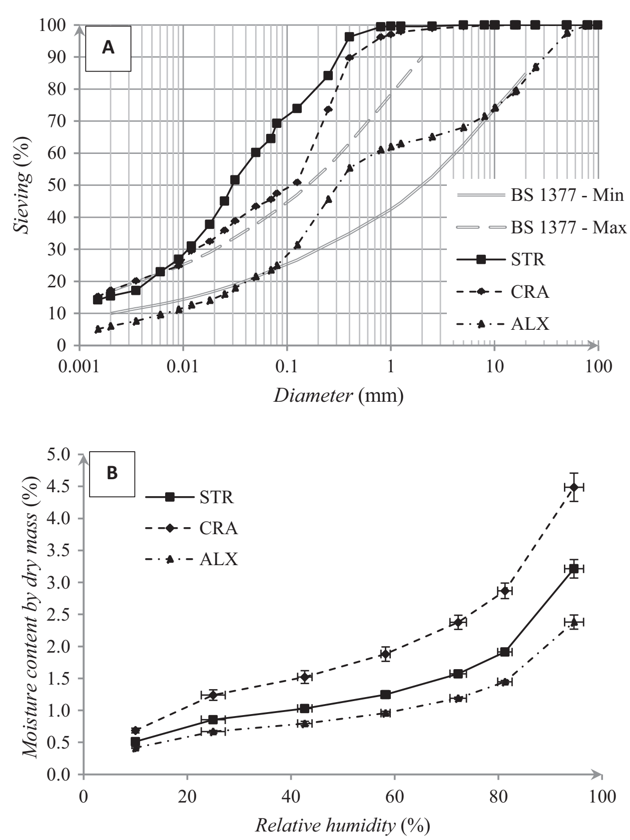

Fig. 1. Particle size distributions of the tested materials and their comparison with the upper and lower bounds of the BS 1377 Standard (A) and their sorption curves (B).