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A unified failure criterion for unstabilized rammed earth materials upon varying relative humidity conditions

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HIGHLIGHTS

- Impact of the hygroscopic conditions on the strength of earthen constructions is analyzed.
- Compressive and tensile strengths are determined on earthen materials upon varying relative humidity.
- Suction plays an important role on the strength of the material.
- A unified failure criterion including the effect of the suction inside the stress state is proposed.

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ABSTRACT

Uniaxial compression tests and indirect tensile tests are performed on compacted clayey silt samples upon varying suctions in order to assess the influence of changes in the relative humidity conditions on the strength of unstabilized rammed earthen building materials. The results show that suction plays an important role on the strength of the material. Also the ability of the Belgian clayey silt to develop sufficient mechanical strength to be used as an unstabilized earthen construction material is demonstrated whatever the relative humidity conditions, excepted the fully water saturated state. The experimental data are interpreted in the context of unsaturated soil mechanics using the generalized effective stress concept. This constitutive framework allows defining a unified failure criterion predicting the strength of the earthen building material as a function of the environmental hygroscopic conditions.

1. Introduction

Earthen construction is an ancient technique that is experiencing a renascence today thanks to the energy performance of this material and its potential for recycling. The material is locally available and the energy use for its manufacturing (i.e., embodied energy) is very limited [31,32]. Soil is one of the most predominant materials on earth. It is abundant and can be considered universal to some extents that avoid dependency on importation. Earth materials demonstrate a satisfactory thermal inertia and good hygroscopic properties that allows a natural hygrothermal regulation of buildings [2,7]. Those advantages open large perspective for the use of earthen materials in the field of building engineering.

In order to provide appropriate mechanical properties, the earthen materials, forming the wall, must be installed in a proper way in order to optimize the density and the water content. Among different kinds of earthen constructions (see [21] for an exhaustive review), rammed earth is the technique that consists in forming the wall by compacting moist soil between temporary forms. For "unstabilized" rammed earth, the system does not require any additional binder elements (such as cement or lime). A part of the cohesion is brought by the argillaceous materials in combination with the compaction process that provides the required density. The compaction should be performed at an adequate water content of the soil that allows optimizing the density for a given energy of compaction. In addition to the natural binding effect of the argillaceous material, capillary cohesion contributes, for a big part, to the total strength of the materials [17,28]. This is related to the internal suction which is related to the co-existence of gas and liquid phases in the void space.

However, after the construction, external rammed earth walls can be subject to large changes in humidity and incident wetting from rainfall. Those perpetual changes of environmental conditions induce continuous changes of the water retention conditions of the wall that affect the durability of the constructions. Characterization

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of the erosion has been performed on earthen walls in climatic chamber [19] or under in-situ conditions [11], but few studies focus directly on the impact of the change in relative humidity on the internal suction, and so on the strength of the wall.

The impact of those earthen constructions – atmosphere interactions on the strength has been investigated experimentally under laboratory conditions by Jaquin et al. [23], who performed unconfined compression tests on earthen materials samples air-dried to different target water contents. The suction (<1 MPa) was measured by means of high capacity tensiometers. This study quantified the increase in the strength and stiffness when the water content decreases. However, in that study, the water content varied between 5.5% and 10.2%, while the water content of an unstabilized rammed-earth construction subject to atmospheric conditions is generally lower (1–2%) [10]. Bui et al. [12] determined the unconfined strength of different soil samples (sand, clay) with a greater range of water content (from a wet state after manufacturing $w = 11\%$ to a dry state in atmospheric conditions $w = 1–2\%$). This study confirmed that suction plays an important role on the strength of the material, but highlighted also that a slight increase in moisture content of dry rammed-earth walls (water content not exceeding 4%) due to rainfall or change of relative humidity in the atmosphere is not followed by a sudden drop in the wall strength.

This literature review reveals therefore first the scarcity of experimental procedure replicating the prevailing climatic conditions in different regions of the world, and quantifying the evolution of the unstabilized earthen materials strength with the atmospheric conditions. On the other hand no unified failure criterion has been formulated to characterize the effect of the suction and capillary cohesion on the strength of these materials.

The first objective of the present study is to evaluate, from an experimental point of view, the ability of a representative Belgian clayey silt to develop sufficient mechanical strength under variable relative humidity conditions to be used as an unstabilized rammed earthen building materials. To do so, the optimum water content for dynamic compaction is determined and the evolution of the strength as a function of the atmospheric relative humidity is characterized through uniaxial compression tests and indirect tensile tests.

Then, the second objective is to propose a constitutive framework, based on the concepts of unsaturated soil mechanics, able to predict the failure criterion of unstabilized rammed earthen materials, including the effect of capillary and intrinsic cohesion through the generalized effective stress approach for unsaturated soil. Such a failure criterion will be useful to verify the stability of earthen constructions under the combination of various loadings (and so various applied stresses on the material) and various atmospheric conditions (and so various strength of the materials). So, this approach unifies the hygroscopic and mechanical effects on the rammed earth in a single failure criterion.

The paper is organized as follows. The first section presents the used soil and its geotechnical properties. Then, the different experimental techniques are described and the obtained results are presented. Finally, the results are interpreted in the context of unsaturated soil mechanics in order to provide a coherent constitutive framework that allows predicting the strength of the earthen building material as a function of the environmental hygroscopic conditions.

2. Materials

2.1. Identification parameters

The soil examined in this research is a clayey silt (Unified Soil Classification System (USCS): clay of low plasticity (CL)) from the region of Marche-Les-Dames (Belgium). This soil has already been the subject of many studies in the past for other applications [20,37]. So, it represents a referential material which has been already extensively characterized for other purposes. Its index properties are: liquid limit (w_L) = 32.5%; plasticity index (IP) = 15%. The grain-size distribution curve is reported in Fig. 1. The clayey fraction represents 13%, the silty one about 64% and the sandy one about 26%. Walker et al. [38] and Hall and Djerbib [18] summarized a series of recommendations on the grain-size distribution of soils particularly well adapted for earthen constructions. Even though most of the guidelines for a suitable rammed earth particle size distribution recommend an inert aggregate fraction of gravel, the Marche-Les-Dames silt used in this study does not contain any gravel. Nevertheless the particle size distribution of the Marche-les-Dames silt approaches the one proposed by Alley [1] and will show his relevance for earthen constructions (i.e., dry density, strength) in the next sections. Those good properties are due to the spread grain size distribution of this natural clayey silt that induces a good interlocking of grains after compaction.

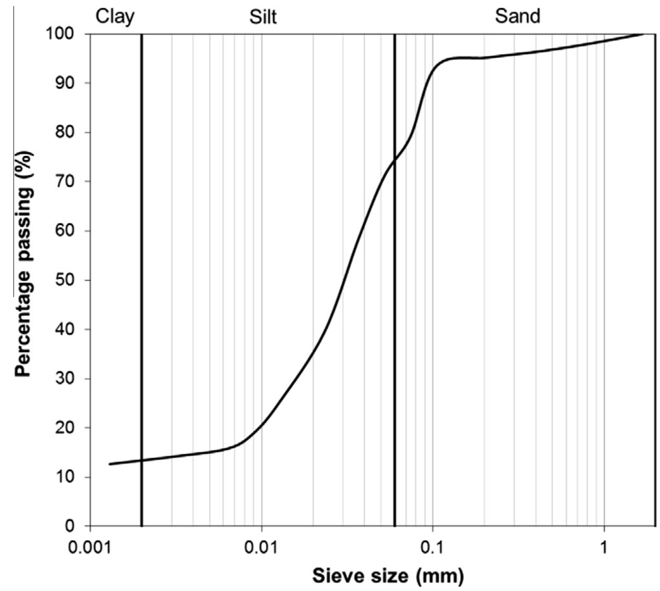

Fig. 1. Particle size distribution of the studied soil.

The normal Proctor compaction curve [4] is reported in Fig. 2. The optimum water content is 15% and the optimum dry density is 18.40 kN/m^3.

2.2. Optimized compaction conditions

Even if the normal Proctor compaction test constitutes a widely used standard for the geotechnical earthworks (e.g., embankment, road, etc.), this method is generally not considered in the context of earthen materials. Indeed, the targeted properties of an earthen wall largely differ from the properties expected for geotechnical works. To reach the target strength, we have to apply far greater compaction energy.

It is why other compaction methods have been already proposed as the heavy manual compaction test or the vibrating hammer test [34]. In this paper, a third compaction process has been used. The soil was dynamically compacted by sequentially ramming the soil in layers with a 2.5 kg Proctor hammer directly inside two kinds of mould: 36 mm in diameter and 72 mm in height for the uniaxial compression test (compacted in 3 layers) and 36 mm in diameter and 22 mm in height for indirect tensile test