Construction and Building Materials 155 (2017) 164–175

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Structural behaviour of unstabilized rammed earth constructions submitted to hygroscopic conditions

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HIGHLIGHTS

- We study the structural response of rammed earth construction (two-storey building).
- We perform a transient modelling of hygroscopic transfer through the wall.
- We consider the evolution of strength of the wall with hygroscopic conditions.
- We evaluate the effect of annual hygroscopic change on the structural behavior.
- We demonstrate the ability of rammed earth to support conventional loading.

ARTICLE INFO

Article history:
Received 23 March 2017
Received in revised form 12 June 2017
Accepted 3 August 2017

Keywords:
Unstabilized rammed earth material
Relative humidity
Suction
Effective stress
Hygroscopic transfer
Structural behaviour

ABSTRACT

Rammed earth constructions exhibit strength and deformation properties that evolve as a function of the relative humidity of the air in contact with the walls. This effect must be considered in the structural design of the construction. This work studies, through finite element simulation, the impact of the hygroscopic transfers through the wall on the structural response of a classical two-storey rammed earth building. The coupling between the mechanical and the hygroscopic behaviour is considered by the concept of effective stress for unsaturated soils, in order to reproduce the effect of suction on the strength, the stiffness and the volumetric variations of the rammed earth. The simulations show classical deformation of the structure due to distributed load on the floors while the hygroscopic changes in the rammed earth (essentially drying) induce additional displacements of the walls that remain in a very acceptable range. Finally, an extreme case is envisaged in which the loads on the floors are increased excessively in order to study the plastic response of the wall.

1. Introduction

Nowadays, earthen construction experiences an evident renascence thanks to numerous advantages of this material. Traditional construction techniques remain still relevant today but modern experimental methods and numerical modelling open large perspectives for the development of adequate standards for the design and the construction. Although this material demonstrates moderate mechanical performance, it remains largely sufficient for two-storey buildings. The local availability of the raw material, the low embodied energy and its potential for recycling [26,30] make this construction technique very attractive in the context of the development of circular economy. Hall & Allison [21] and Beckett & Cianco [4] demonstrated the efficiency of earthen materials to provide a natural hygrothermal regulation of the building.

Among different kinds of earthen constructions (see Houben & Guillaud [22] for an exhaustive review), rammed earth consists of compacting successive layers of soil inside a formwork to obtain a continuous and relatively homogeneous wall formed with compacted earth. “Unstabilized” rammed earth means that there are no additional binder elements (such as cement or lime). The use of natural soil without additive reduces the embodied energy and improves the recycling potential of the construction.

The strength of the construction is brought, for a part, by interlocking of soil particles induced by the compaction process that provides the required density [17]. Also, in addition, capillary cohesion, induced by the partial saturation of the earth, contributes, for a big part, to the resistance of the wall [16,25]. Consequently, the mechanical response of the unstabilized rammed earth, in terms of strength and deformability, is strongly affected by the

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http://dx.doi.org/10.1016/j.conbuildmat.2017.08.012

hygroscopic conditions of the wall. All along the life of the building, the rammed earth wall will be submitted to evolving environmental conditions (the most important parameter being the air relative humidity) inducing transient hygroscopic transfers through the wall. The kinetics of water and vapor transfers through earthen walls was recently investigated numerically by Soudani et al. [34].

As a consequence of the continuous changes of water retention conditions, the stress-strain behaviour of the wall is permanently changing and their deformation and strength must be predicted as a function of the distribution of pore pressure conditions in the wall.

Since approximately one decade, the impact of the hygroscopic conditions on the mechanical behaviour of earthen construction is more and more investigated. Experimental studies show that the strength and the stiffness can be drastically increased when the earthen material is partially dried [7,8,24]. This effect of soil strengthening and stiffening is induced by internal suction that reinforces the contact between soil particles. Gerard et al. [18] deduced a unified failure criterion based on observed strength on unconfined compression and indirect tensile tests at different suction levels. The obtained failure criterion is based on the concept of effective stress for unsaturated soils that intrinsically includes the effect of suction and water retention properties inside the stress state [32].

The link between the mechanical behaviour of the rammed earth wall (in terms of strength and deformability) and the hygroscopic conditions should be considered in the design of such a structure through an approach that considers the hygro-mechanical coupling. Hygroscopic transfers through the wall control the suction distribution which, in turn, affects the mechanical response of the structure. Up to now, the design rules of rammed earth constructions are essentially based on empirical relations, physical properties of selected soil [13] or weak masonry guidelines that ignore those couplings. In most of the countries that established recommendations or standards, the only criterion related to rammed earth resistance consists in a characteristic value of unconfined compression strength under initial compacted conditions [29,33,35]. However, the evolution of this strength with the change of internal water content is never considered.

Very few attempts were initiated in the last years to quantify the structural behaviour of the wall taking hygroscopic conditions into account. Up to now, most of the approaches consider a constant and homogeneous water content profile in the whole structure [27,31]. In such a way, the mechanical properties of the wall are assumed homogeneous and the transient hygro-mechanical process is totally ignored. Furthermore, numerical modelling has also been used to quantify the structural behaviour of rammed earth wall submitted to seismic loading [6,27,28]. But still, the effect of hygroscopic conditions was not considered.

The present work proposes a hygro-mechanical finite element approach in order to reproduce those transient and highly non-linear processes. The computations use a consistent hygro-mechanical framework for unsaturated soils in which the stiffness and the strength are controlled by suction. Transient behaviour is taken into account through the modelling of hygroscopic transfers through the wall. The strength and deformability of the soil is based on the experimental study performed by Gerard et al. [18] on a clayey silt relevant for unstabilized earth construction. The key parameters are the stiffness evolution as a function of the suction, the water retention curve that links the suction with the degree of saturation and the relative permeability that considers the change of water permeability as a function of the degree of saturation. The mechanical response of a typical two-storey building is considered along six years with representative atmospheric conditions in Belgium as boundary conditions at the wall faces.

2. Materials

In this study a clayey silt soil that has shown its relevance for earthen construction [18] is used. It comes from the region of Marches-Les-Dames (Belgium) and it consists of a clay of low plasticity (CL) according to the Unified Soil Classification System (USCS). Its index properties are: liquid limit (w_L = 32,5%; plasticity index (IP = 15%. The grain-size distribution curve is presented in Fig. 1. The clayey fraction represents 13%, the silty one about 61% and the sandy one about 26%. The grain size distribution of this clayey silt is very similar to the one suggested by Alley [3] to reach after compaction relevant soil dry density and strength for earthen constructions. Indeed the large spreading of the particle size distribution provides a good interlocking of the grains, and therefore good mechanical properties. A full mechanical characterization of this clayey silt can be found in Gerard et al. [18]. Here only the most relevant results are summarized and interpreted for the calibration of material parameters needed for the hygro-mechanical computations.

For sample preparation, the soil was dynamically compacted in three layers by sequentially ramming the soil in layers directly inside a mold of 36 mm in diameter and 72 mm in height. The compaction of each layer was achieved until the handle of the hammer "rings" when dropped onto the compacted soil, which is considered as the indication of full compaction having being attained [20,37]. In order to ensure repeatability of the sample preparation, we prepared a first sample with the criterion of the hammer that rings when dropped on the soil; we measured the density of the obtained sample; and then we repeated always the same density for all the samples (by controlling the mass of soil and volume of sample. The optimum water content at compaction was determined in order to obtain the highest unconfined compression strength. Those conditions were reached for a water content of 8% and a dry density of 2000 kg/m^3. The suction of as-compacted samples, measured by the filter paper method [9], is equal to 2.4 MPa.

From those initial conditions, different suctions were applied to the samples through the control of relative humidity by different saline solutions [12]. Saturated saline solutions are installed at the bottom of a desiccator and adjust the water vapor concentration of the air (and so the relative humidity). Vapour exchange occurs between saline solution and soil samples placed in this desiccator (not in direct contact with the saline solution). The time necessary to reach equilibrium may be quite long. In our cases, it took from 5 to 25 days for the small samples and from 10 to 50 days for the biggest samples, depending on the imposed relative humidity.

The corresponding suction in the sample is obtained through the Kelvin's law:

$$s = -\frac{\rho_w RT}{M_w} \ln RH \tag{1}$$

where s is the suction, R is the constant of perfect gases (R = 8.3143 J/mol/K), T is the temperature in Kelvin (T = 293 K), M_w is the molar mass of water (M_w = 0.018 kg/mol), ρ_w is the bulk density of water (ρ_w = 1000 kg/m^3), and RH is the relative humidity.

Table 1 reports the different applied suctions at a temperature of 20 °C. Note that the samples that reach the highest suction (125 MPa) have been dried under ambient conditions in a room where the temperature and humidity are constant.

Fig. 2a and b present the soil water retention curve expressed in terms of water content, w, and degree of saturation, S_r, respectively. Only water retention properties for suctions higher than initial suction were investigated because, as it will be demonstrated in the numerical modelling, during the life of the building, the