Construction and Building Materials 175 (2018) 804–814

Contents lists available at ScienceDirect

Construction and Building Materials

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

Methodological issues for the mechanical characterization of unfired earth bricks

J.D. Rodríguez-Mariscal, M. Solís *, H. Cifuentes

Escuela Técnica Superior de Ingeniería, Universidad de Sevilla, Camino de los Descubrimientos, 41092 Sevilla, Spain

HIGHLIGHTS

- The complete stress-strain relationship in compression is obtained.
- Cubic, prismatic and cylindrical specimens are tested.
- Correction factors for obtaining the Unconfined Compressive Strength are analyzed.
- Different estimates of Young modulus are obtained and analyzed.
- Normalized stress-strain curves are provided.

ARTICLE INFO

Article history:
Received 8 February 2018
Received in revised form 12 April 2018
Accepted 13 April 2018

Keywords:
Earth bricks
Compressive behavior
Aspect ratio
Young modulus
Constitutive law

ABSTRACT

Earth is a traditional building material used through History in many areas around the world. Nowadays, there is also a significant revival of its use because of its ecological value and architectural performance. However, there is still a lack of knowledge about its actual mechanical behavior. This paper is aimed at providing experimental data for the development of consistent methodologies for the characterization of this building material. Compression tests of prismatic, cubic and cylindrical specimens were carried out. The compressive strength, Young modulus and the stress-strain constitutive law are obtained and analyzed. The paper shows that the Unconfined Compression Strength of the material should not be obtained by applying existing correction factors for other materials. The paper also analyzes the meaning and usefulness of different estimates of the Young modulus. Finally, the paper proposes a simplified method for estimating stress-strain relationships from the compressive strength and its corresponding strain of tested samples by using reference normalized curves.

1. Introduction

Earth is a construction material widely used throughout the world since ancient times. It is estimated that approximately 30% of the world population lives in earth buildings and that in developing countries this percentage rises to approximately 50% [1]. Earth exhibits several attractive features as a building material. It provides good thermal and acoustic isolation properties, it is cheap, easy to handle, and it is a zero polluting and ecological material. The main disadvantage of earth is its poor mechanical properties, which is specially critical in seismic areas [2–6]. This also limits the use of earth to low-rise buildings, although some exceptions can be found around the world as the well-known city of Shibam (Yemen), where buildings of more than 30 m high can be found.

Despite the advantages of the earth as a building material and its extensive use around the world, there is a lack of scientific knowledge about its structural behavior. Hence, there are no rigorous standards for its use, as they exist for other building materials. Only some qualitative and empirical standards currently exist for earthen construction [7–9]. The heterogeneity of the constituents of earth and the different building techniques around the world make even more difficult the development of building standards and recommendations. However, there is a need for investigating earth from a mechanical point of view in order to eventually address the needs for building safe and sustainable houses for the large population for which the earth is the only affordable or available building material and also the needs of the rapid developing of earthen modern architecture. Besides, this investigation is required for preserving the valuable existing earthen heritage sites and constructions. Fortunately, there is a increasing interest from

* Corresponding author.
E-mail address: msolis@us.es (M. Solís).

https://doi.org/10.1016/j.conbuildmat.2018.04.118
0950-0618/

the academic research community to address this issue and the numbers of related scientific papers has increased in the last years.

The methodology for the determination of the fundamental mechanical properties such as the compressive strength or the Young modulus of earthen materials is still an open issue. This paper is aimed at providing a new contribution for the development of knowledge about the mechanical behavior of earthen building materials and for the definition of standards for the characterization of its compressive mechanical properties.

There are different traditional techniques for using raw earth as a building material, and different compositions or additives may be used in different areas around the world. Adobe (unfired and air-dried earth blocks use for building adobe masonry constructions) is one of the most widespread technique. This paper is focused on the investigation of the properties of adobe, although it can be useful for future research on other traditional earthen building techniques such as cob or rammed earth, or modern type earthen masonry made of Compressed Earth Blocks (CEB). Although each building technique exhibit its own singularities, there are obviously strong similarities between all of them from a structural point of view.

Values of fundamental mechanical properties of adobe (namely compressive and tensile strength and Young modulus) obtained by different authors have been summarized in [10,11] and an interesting state of the art review about the tests involved can be found in [12]. The scattering of the experimental results obtained up to now is significant. This is partly due to the different properties of the material (proportions and properties of each constituent, addition of fibers, moisture content, stabilizers, etc) [13–16], but also due to the different types of tests performed. For instance, the size and shape of the specimens for a standard compressive test is not established. Different sizes of cubic, cylindrical and prismatic specimens can be found in the literature, but the effect of specimen size and shape on the obtained results are not clear yet. Some research works [17–19,16] have highlighted the importance of considering the confinement effect on the specimens. They have even illustrated how a low aspect ratio (the ratio between the dimension parallel to the compressive loading direction and the minimum dimension of the cross-section of the specimen) can lead to unreasonable estimations of the compressive strength. In [18,19] the authors also investigated the application of correction factors (used for other materials) to obtain a consistent value from different types of specimens. This issue have been also addressed for adobe samples of existing constructions [20] and for compressed earth blocks [21].

The Young modulus is probably one of the most uncertain properties of earthen materials [10,14,20,22–24]. The stress-strain relationship is non-linear and the criteria for the determination of a reference value is not established yet. Moreover, the experimental procedure to measure strains definitely affects the results [20]. However, some empirical relationships between the compressive strength and the Young modulus have been proposed [7,8,24,20,10]. The stress-strain constitutive law has been also studied by several authors for adobe [20,25,12,23,26] and also for rammed earth and cob [15,22]. The complete stress-strain relationship, including not only the rising branch but also the post-peak or softening behavior after the compressive strength is reached, is needed for a complete understanding of the mechanical behavior of the material. This experimental information can be used to asses the compressive fracture energy and develop simplified elastic-plastic models for modelling masonry assemblages [23].

In this research work, simple compression tests are performed on brick, cubic, prismatic and cylindrical specimens. The specimens are made from soils from the riverbank of Guadalquivir river in Sevilla (Spain). To the authors' knowledge, the paper is the first research work about the analysis of mechanical properties from local materials and building techniques in this area. The compressive strength, Young modulus and complete constitutive law are obtained for each type of specimen. Normalized curves are provided and compared to others existing in the literature. The obtained average and normalized stress-strain curves can be useful for future analysis, building numerical models or comparison purposes. In addition, the paper analyzes the influence of the shape of the specimen, the confinement effect, the manufacturing process and the direction of loading (anisotropy) on the experimental results. It also illustrates the need of using a reliable method for the determination of the actual strains and it analyzes several approaches for characterizing the Young modulus.

2. Materials and methods

2.1. Experimental set-up

Specifications from standards for masonry characterization [27] were considered for conducting the tests. Two different loading directions were considered: the vertical (hereafter *longitudinal*) and horizontal (hereafter *transversal*) directions during the molding process (Fig. 1)). The *longitudinal* would be equivalent to the usual vertical compressive direction of the bricks as part of an adobe masonry wall, whereas the *transversal* direction would be equivalent to a horizontal compressive one. Thus, considering both directions, information about the anisotropic behavior of the adobe bricks can be obtained.

A universal mono-axial servo-hydraulic testing machine was used (50 kN load capacity and 200 mm stroke) and all tests were displacement controlled.The applied load and the displacement of the actuator was measured. Two LVDT type displacement sensors (12 mm range model DC-EC250 from Schaevitz company) measured the relative axial displacement between two points of the prismatic and cylindrical specimens. They were installed at opposite sides of the specimen in order to cancel out any bending effect by computing the average reading of the two sensors. All the output analog signals from the displacement sensors and the testing machine were recorded through a SCXI data acquisition system from National Instruments company.

From the displacement readings, the average strain can be computed. A global strain value for the whole specimen is estimated from the displacement of the actuator, whereas the displacement sensors provide a more local strain value which is not contaminated by the local effects near the contact areas between the specimens and platens of the testing machine. Because of their size, the LVDT displacement sensors could not be used for bricks and cubic specimens. The use of traditional strain gages for obtaining a more precise and local measurement of strains was not feasible because of the difficulty to obtain a proper and effective bond between the gage and the surface of adobe specimen.

The tilt movement of the upper platen of the testing machine was released in order to diminish the effects of irregularities and lack of flatness of the specimen sides, so the load is distributed as uniformly as possible on the specimen. The effect of irregularities is more significant at the first stages of loading [12], as it will be illustrated in next sections.

Table 1 and Fig. 2 summarize the description of the different types of specimens and tests performed. The loading direction is indicated as *T* for the *transversal* direction and *L* for the *longitudinal* direction. The type of measuring technique for strain readings is indicated as '*Mach.*' for the displacement of the actuator of the testing machine and *Sen.* for the displacement sensors. The tests were performed complying with the European Standard for the determination of the compressive strength of masonry units [27].