Construction and Building Materials 51 (2014) 295–302

Contents lists available at ScienceDirect

Construction and Building Materials

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

Failure of rammed earth walls: From observations to quantifications

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HIGHLIGHTS

- Experimental results on compressive, tensile strengths and Poisson's ratio of RE.
- Local failure tests were conducted on 1 m × 1 m × 0.3 m wallets.
- Shear strength was identified using a simple method based on Mohr's theory.
- FEM with nonlinearity and crack development, was used to confirm the results.

ARTICLE INFO

Article history:
Received 2 July 2013
Received in revised form 8 October 2013
Accepted 31 October 2013
Available online 27 November 2013

Keywords:
Rammed earth
Tensile strength
Shear strength
Failure

ABSTRACT

Nowadays, rammed earth construction is attracting renewed interest throughout the world thanks to its "green" characteristics in the context of sustainable development. Firstly, using a local material (soil on site or near the site), rammed earth constructions have very low embodied energy. Secondly, rammed earth houses have an attractive appearance and present advantageous living comfort due to substantial thermal inertia and the "natural regulator of moisture" of rammed earth walls. This is why several research studies have been carried out recently to study the mechanical and thermal characteristics of rammed earth. However, to our knowledge, there are not yet sufficient studies on the tensile strength and the shear strength of rammed earth. The tensile strength of rammed earth is neglected in general due to its very low value, but in extreme conditions (e.g., seismic conditions), knowing the tensile strength is necessary for structural design. Moreover, the shear strength is required in many cases to check the local failure of rammed earth quickly, which has been observed in old structures (especially those submitted to concentrated loads). This paper presents experimental results on tensile strengths and the Poisson ratio of rammed earth specimens. Local failure tests were also conducted on 1 m × 1 m × 0.3 m wallettes manufactured in the laboratory. The shear strength was then identified using a simple method based on compressive strength, tensile strength and Mohr's circle theory. The approach proposed was validated by tests on the wallettes. Finite Element (FE) modeling was also carried out to confirm the results. Last, the method presented was validated for stabilized rammed earth lintels presented in the literature.

1. Introduction

Rammed earth materials are ideally sandy-clayey gravels. The materials are prepared to their optimum moisture content and compacted inside a temporary formwork to form walls. The earth composition varies greatly and always contains clay but should not include any organic components. Clay acts as the binder between the grains, a mixture of silt, sand, and gravel up to a few centimeters in diameter. Compaction is undertaken on material prepared to its optimum moisture that provides the highest dry density for the given compactive energy [3]. The rammed earth wall is composed of several layers of earth. The earth is poured loose in layers about 10–15 cm thick into a timber or metal formwork, which is then rammed with a rammer (manual or pneumatic). After compaction, the thickness of each layer is typically 6–10 cm. The procedure is repeated until completion of the wall. A detailed presentation of rammed earth construction can be found in Walker et al. [28].

For traditional rammed earth construction, referred to as "rammed earth" (RE) or "unstabilized rammed earth," the only binder is clay. Other binders can also be added such as cement or hydraulic or calcium lime, were added. This is often called "stabilized rammed earth" (SRE). The main advantage of stabilization is the increase in durability and mechanical performance. However, stabilization increases the construction cost and environmental impact.

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http://dx.doi.org/10.1016/j.conbuildmat.2013.10.053

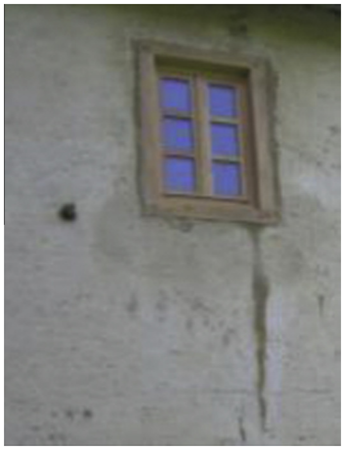

Fig. 1. Typical failure of an old rammed earth wall in France.

Rammed earth is the focus of scientific research for two main reasons. Firstly, in the context of sustainable building, the modern interest in earth as a building material is largely derived from its low embodied energy, both for unstabilized rammed earth [21] and stabilized rammed earth [23], and also because the material has good natural moisture buffering from indoor environments [1]. Secondly, the heritage of rammed earth buildings in Europe and the world is still important [2]. Maintaining this heritage needs scientific knowledge to assess appropriate renovations.

Several research studies have recently been conducted to study the characteristics of rammed earth: durability and sensitivity to water [2,16], thermal properties [25,26], living comfort [22], mechanical characteristics in compression [3,4,19,17,13]; pullout strength [27] and dynamic characteristics [5]. However, there are not yet sufficient studies on the tensile strength and the shear strength of rammed earth [8]. The tensile strength of rammed earth is neglected in general due to its very low value, but in extreme conditions (e.g. seismic), knowing tensile strength is necessary for the structural design [12]. Shear strength is also required in many cases to check the punching strength of rammed earth walls quickly (Fig. 1), such as beams directly placed on a rammed earth wall (roof beams, lintel beams; [9] and vertical ties in anti-seismic devices [15].

This paper presents the experimental results on tensile strengths and the Poisson ratio of rammed earth. The shear strength is also identified using a simple method based on compressive strength, tensile strength, and Mohr's circle theory. The approach proposed was then validated by the tests on the (1 m × 1 m × 0.3 m) walls manufactured in the laboratory. FE modeling taking account the non-linear behavior of RE material was also conducted. The material studied in this paper is unstabilised rammed earth but the presented method is also applicable in the case of stabilized rammed earth.

2. Manufacture of specimens

2.1. Soils

Three different soils were used in this study (Table 1). These soils were taken directly from the RE building sites. The soils have the clay contents convenient for RE manufacture (5–10%, [28].

2.2. Different types of specimen

The representativeness of specimens manufactured in laboratory was discussed in a previous study [3]. In the present study, to identify several parameters that are useful for numerical and analytical models that will be presented in this paper, several tests in both directions with several types of specimen are necessary: cylindrical specimens for tests determining the Poisson ratio and the tensile strength within earthen layers (Brazilian test), prismatic specimens for compression tests, and wallettes for tests identifying the behavior and failure mode of RE walls under concentrated loading. The choice of each type of specimen will be explained in the corresponding section.

Table 1
Soils used in this study.

Soil	Clay (by weight) (%)	Silt (%)	Sand (%)	Gravel (%)
A	10	25	18	47
B	5	30	49	16
C	8	34	8	50

2.3. Cylindrical specimen manufacturing

To determine the tensile strength using the Brazilian test and measure the Poisson ratio, cylindrical specimens were needed. Extensometers were used on prismatic specimens without success because a square section did not enable homogeneous movements of the elastic wires that connected the extensometers (for greater detail, see Section 3.1)

The automatic Proctor machine was adopted (Fig. 2). The standard mold of the Proctor test was replaced by a mold 16 cm in diameter and 32 cm high. To obtain the dry density of in situ rammed earth material (~1920 kg/m^3; [3], a series of preliminary tests were conducted to determine the manufacturing water content and the amount of soil to be poured into the mold for each layer. An 11% moisture content was chosen as the compaction moisture content and 2.2 kg of moist soil was weighed out for each layer. Each layer received the Proctor energy (E = 0.6 kJ/dm^3). There were six compaction layers in each specimen prepared. The final height of the cylinder after the release was about 30 cm. Prior to mixing, the soil was sieved through a 2-cm screen.

After the compaction process, the specimens were removed from the mould. The bottom surface of the cylinder, since it was in contact with the bottom side of the mold during compaction, was smooth and did not require any further treatment before strength testing. However, the more uneven upper surface was capped with a mortar (2 lime: 3 sand by weight) to provide a flat smooth surface parallel with the bottom side. During drying, the specimen was left in the ambiant atmosphere.

Fig. 2. Automatic Proctor machine and modified mold.