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Characterizing the shear parameters of rammed earth material by using a full-scale direct shear box

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HIGHLIGHTS

- The cohesion and the friction angle of rammed earthen were determined.
- A full-scale shear box (0.5 m width × 0.5 m length × 0.45 m height) was developed.
- The friction angle and the cohesion of the intralayers were of 37.3° and 30.9 kPa.
- The friction angle and the cohesion of the interlayers were of 34.8° and 24.0 kPa.

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ABSTRACT

Rammed earth (RE) is one of the different techniques of earth constructions. The RE wall is built by compacting the soil in a formwork, layer after layer (about 10–15 cm thick for each layer). RE buildings are recognized for their very low embodied energy and their positive hygrothermal behaviour. Several recent studies have investigated RE material and among different aspects, the seismic performance remains an interesting topic that needs to be explored. In order to propose a robust model for seismic investigation, the shear characteristics of RE material should be appropriately determined. These shear characteristics include the cohesion, the friction angle of the intralayers and also the cohesion, the friction angle of the interlayers (between the layers) as a RE wall contains multilayers. However, few studies have directly identified these parameters by experiments. This is the first time, to our knowledge, that a full-scale shear box (0.5 m width × 0.5 m length × 0.45 m height) was specifically developed to study the shear parameters of the rammed earth. This full-scale shear box was designed to reproduce the manufacturing conditions of a current rammed earth wall in Europe (50-cm-thickness). Direct shear tests were performed both for intralayers and interlayers. The results showed that the shear strength obtained at the interlayers were about 80–90% of the corresponding values obtained at the intralayers. Finally, the influences of the moisture content and the size effect on the obtained results were also discussed.

1. Introduction

Rammed earth is a construction technique which consists on compacting the soil by layers (10–15 cm thick) inside a formwork. The compaction is performed with a rammer (pneumatic or manual) at an optimum moisture content which depends on the used soil and the compaction energy [1]. With the growing consciousness for seeking sustainable materials, rammed earth is receiving considerable interest from scientific researchers, because the material has a low embodied energy, a positive hygrothermal behaviour which offers an attractive living comfort during the dwelling and a recyclability at the end of the building life cycle [2–4].

Characterizing the rammed earth material is actually an important topic due to the renewed interests of this natural material. Scientific knowledge is necessary to have suitable and appropriate ways for the conservation and restoration of the existing RE building, and also to provide new recommendations for the design of new RE structures respecting actual regulations (for example durability exigencies, thermal or earthquake regulations).

A considerable number of studies on RE material is noted during the last decade, on several aspects: thermal and hygrothermal behaviours [3,4], durability [5,6], mechanical characteristics [7–11]. More details about the state of the art can be found in [12,13]. However, an important topic still needs more investigations is the seismic performance assessment of RE structures,

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although some preliminary studies can be cited [14–20]. To correctly characterize the seismic behaviour of complex RE structures, advanced numerical models with time history analysis seems to be a reasonable approach. However, the relevancy of the numerical models strongly depends on the input parameters used in the model. Therefore, the parameters such as the friction angle and the cohesion are the important characteristics for the shear behaviour of RE walls under earthquakes and need to be identified.

That was why several studies have tried to identify the cohesion and the friction angle of RE material by performing experiments or numerical modellings. For experimental studies, Cheah et al. [21] used triaxial tests and triplet tests on cement-stabilised RE specimens. The results showed different values for the cohesion of the stabilised RE between the two types of tests and a high variation of the results was noted. Jaquin et al. [22] carried out triaxial tests on compacted soil specimens, showing a relationship between the suction and the strength of compacted soil material; but in that study, the shear parameters were not presented. Other studies, not directly on RE materials but on fiber stabilised earths, are also interesting to be cited here. Bouhicha et al. [23] used direct shear tests to study the shear performance of a composite soil reinforced with barley straw; the tests were done using a Casagrande box of 6 cm × 6 cm × 3.6 cm and the results showed that the addition of straw increased the apparent cohesion by up to 50% but decreased the friction angle. Corbin and Augarde [24] also carried out direct shear tests on RE specimens (6 cm × 6 cm × 2 cm) stabilised by whool; however, an important variation of the results was observed due to the specimens representativeness, so no conclusion about the shear parameters could be done. Other studies used numerical approaches by performing parametric studies on the shear parameters and searching the best values which provided the numerical results closest to experiments [25,26].

The present study aims to investigate the experimental values of the cohesion and the friction angle. While the classical shear box tests or triaxial tests need to be performed on small specimens (compared to the thickness of in-situ RE walls), the manufacture of representative specimens within small moulds has several difficulties and the size effects cannot be evaluated [1,7]. That was why a full-scale shear box (50 cm width × 50 cm length × 45 cm height) was developed which enabled to perform direct shear tests on full-scale specimens. The specimens were fabricated in the same manufacturing process of an in-situ RE wall. Therefore, the representativeness of the specimens could be insured. This full-scale shear box was used to perform the direct shear tests which enabled to determine the cohesion and the friction angles of the intralayer (within an earthen layer) and the interlayer (frontier between two earthen layers).

2. Materials

The earth used in this study was provided by a RE manufacturer company, in the Rhone-Alpes region (France). This soil had been used to build numerous ancient RE buildings in this region. The grain size distribution of the earth is presented in Fig. 1, which shows that the soil used has 20% clay and does not contain gravels. The mineralogical composition was analyzed by X-ray powder diffraction (XRD) [27] which reveals the presence of quartz (72.6%), albite (15.1%), illite (11%), and traces of vermiculite were identified (1.3%).

To have an assessment of the quality and properties of the earth and the RE material tested, uniaxial compression tests were performed. Three prismatic specimens (25 cm × 25 cm × 50 cm height) were manufactured by using the same pneumatic rammer and the manufacturing water content as an in-situ RE wall. The specimens were compacted in five layers with a water content of 12% (by weight, determined following French Standard [28]). Then, the specimens were dried in laboratory ambient conditions (20 °C and 60% RH). The moisture content at the moments of test was about of 2.5% (by weight, determined after the compression tests by the oven-drying method) and the mean compressive strength obtained was of 1.1 ± 0.1 MPa. This value is usual for unstabilised RE, comparing to others values presented in the literature which were in the range from 0.5 to 2 MPa [1,7,12].

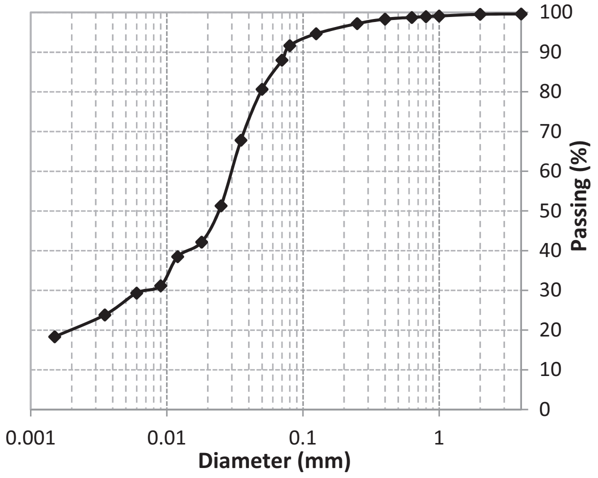

Fig. 1. Grains size distribution of the earth used.

3. Methods

3.1. The full-scale shear box

Casagrande shear test is a classical test in soil mechanics where a dry sand specimen is placed in a shear box that consists of two independent half-boxes; the sliding plane located at the frontier of the two half-boxes is also the shear plane of the specimen tested. To determine the friction angle and the cohesion of the material tested, at least two different tests are necessary and in general three different tests are recommended, in which each test is carried out with a different normal stress [29]. The test consists on firstly applying a vertical (normal) stress that is maintained constant during the test and then the shear force is generated by applying a horizontal displacement on one of the half-boxes.

The shear box used in this study (0.5 m × 0.5 m × 0.45 m) was specially designed and manufactured to test full scale RE specimens, in order to reproduce the same manufacturing process of an in-situ RE wall. Indeed, the 0.5 m-width is the current thickness of RE walls in France and Europe [5] and it has been explained above that the specimen size had important influences on the mechanical results.

The total height 0.45 m was chosen which enables to manufacture three earthen layers in the box (15 cm for each layer) where the horizontal shear plan is in the middle of the second layer. It is important to note that the last layer compacted (the top layer) is less representative than other layers since it receives only one compaction while other layers receive compaction several times. This observation was confirmed in a previous study [8]. For this reason, the last layer should not be tested in shear. In the present study, a specimen had three earthen layers and the shearing surface was located at the middle (intralayer) of the second layer.

The shear box is dimensioned with respect to various conditions imposed for direct shear tests indicated in the French Standard [29]. The standard was respected and adapted to the manufacturing process of the large box. In fact, several constraints were taken into account for the design of the full-scale shear box. The steel walls forming the full-scale shear box must be rigid enough to be considered as ‘‘undeformable” during the application of different loadings on the shear box. A maximum rotation of ±1° was imposed for the horizontal walls of the shear box. The application of the vertical load on the specimen must follow a vertical direction with a tolerance of ±1° and the vertical force applied must be constant.

Following the above constraints, the full-scale shear box designed is made of two steel boxes as shown in Fig. 2 where the