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Research Article

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Experimental Evaluation of the Compressive and Shear Behavior of Unstabilized Rammed Earth

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Abstract

Sustainability is becoming an increasingly important concern for the construction sector, encouraging builders and researchers to investigate environmentally friendly construction techniques, such as rammed earth (RE). Despite this growing interest, there is still a lack of knowledge about the mechanical behavior of RE materials and specific standardized testing methods to assess their properties are yet to be developed. Considering this situation, the present study analyzes two of the main mechanical characteristics of RE, compressive and shear behavior, proposing a manufacturing and testing procedure which can be easily controlled and replicated. With this aim, uniaxial compression tests (UCT) were performed on four RE cylindrical specimens, and diagonal compression tests (DCT) were carried out on large panels. The average unconfined compressive strength obtained was equal to 1.40 MPa, with a shear strength of 0.14 MPa. The results of this study provide useful information about the mechanical behavior of unstabilized rammed earth (URE), as the assessment of the compressive and shear properties is the basis for the development, in future research, of numerical models of structures made with this technique. The manufacturing and testing procedure proposed in this study, including the use of a standardized mold and the control of the compaction energy, made it possible to significantly reduce the dispersion in the results, frequently quite high in the mechanical characterization of RE elements.

Keywords

Rammed earth, Unstabilized rammed earth, Mechanical characterization, Compressive strength, Shear strength, Sustainable construction.

Introduction

Earth has been used as a construction material since the beginning of human history, leading to the development of several building techniques. One of the techniques has been more widely used, and is still prevalent in modern architecture, is RE. RE consists in the compaction of layers of soil mixed with a certain amount of water between temporary formworks, that are removed when the desired height of the wall is reached. RE has been frequently used to build simple houses, but it has also been the technique chosen to build important constructions such as city walls or fortresses, which now form part of the architectural heritage of several countries [1-6].

The need to preserve the existing RE historical buildings is one of the reasons why this technique is attracting growing interest today, but not the only one. The increasing concern about the environmental impact of building activities has made the construction sector look for alternative eco-friendly housing solutions, and RE is shown to be a very good candidate.

Several additives can be included to the earth mixture with the aim of improving the mechanical and/or physical properties of RE constructions: since traditional materials such as lime, natural fibers, or ashes, to modern additives like cement, synthetic fibers, or polymer [7]. However, the most traditional RE technique – and also the most eco-friendly one – consists only of soil and water, with the clay present in the soil acting as the only binder; this is the so-called URE.

Structural design of RE buildings has traditionally been based on geometrical relationships and qualitative rules, but its use in modern construction requires ensuring the structural safety by means of more accurate design methods, meeting the requirements defined by the current construction standards. These modern design methodologies imply the development of complex behavioral models, which need a significant amount of input data. With this in mind, the present study was carried out with the aim of characterizing the compressive and shear behavior of RE materials, by performing UCT on cylindrical specimens and DCT on larger prismatic samples. Compressive behavior of URE is quite well known already, but there are very few studies regarding the shear behavior of this material [8-10], even though it is crucial to understand the vulnerability and failure mechanisms of RE, especially under extreme conditions (e.g., seismic event) [11, 12].

Materials and Method

Materials

A natural soil from Seggiano (Grosseto, Italy) was used in the present study. The soil was classified, after been passed through an 8 mm sieve in order to remove the coarser particles, as a well-graded sand, according to the European Soil Classification System (ESCS, ISO 14688-2:2018). The particle size distribution of the resulting earthen material, shown in figure 1, contained 14% clay, 31% silt, 42% sand, and 13% gravel, in agreement with several recommendations for URE construction [3, 5, 13, 14]. Regarding the mineralogical composition, the soil had 27% quartz and 25% calcite as the main component. RE are nanoscale materials.

The soil had a plastic limit equal to 18%, a liquid limit equal to 38% and a plastic index of 20, according to the methodology indicated in ASTM D4318 [15]. The Standard Proctor test (method C) was performed following the procedure indicated by ASTM D698 [16], obtaining an optimum moisture content of 13% with a maximum dry density equal to 1.83 g/cm^3.

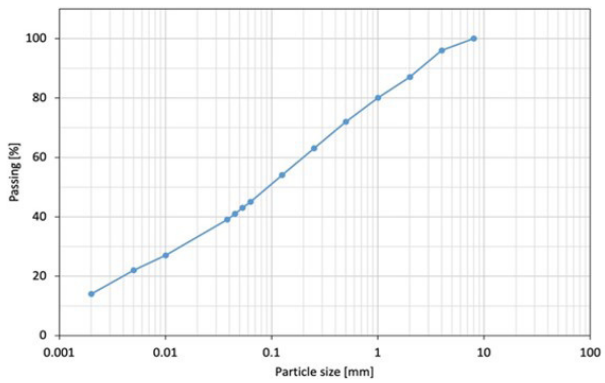

Figure 1: Particle size distribution of the soil.

Manufacturing and testing methodology

Two types of RE specimens were manufactured: small cylinders and large panels. The cylinders were manufactured using the mold and following the compaction process defined in standard ASTM D698 (Proctor compaction test with standard effort, method A) [16], widely used in civil and geotechnical engineering, resulting in specimens with a diameter of 10.1 cm and a height of 11.5 cm. Using this well-known standard procedure to manufacture the specimens made it possible to fully control the manufacturing process, including the compaction energy transferred to the soil, increasing the homogeneity between the samples.

The panels (50 cm x 50 cm x 10 cm) for the diagonal compression tests were made of six layers of soil and compacted in a wooden formwork applying the same Proctor compaction energy used for the smaller cylindrical specimens (Figure 2a). These samples are a scaled version of the specimens used in the standard test method for diagonal compression in masonry assemblages, as suggested in previous studies [17, 18].

For all the samples, the soil was mixed with the optimum moisture content +1%, according to the recommendations of several authors and standards about RE construction [19, 20]. The samples were cured under constant temperature and humidity conditions for 28 days before testing.

UCT were performed for the cylindrical samples, applying a homogeneous load on their upper face, perpendicularly to the soil layers, following the procedure described in ASTM standard D1633 [21], in the absence of specific standards for RE. Also, for the DCT carried out for the prismatic specimens, there are currently no standards specifically designed for RE constructions, so the ASTM standard for diagonal tension in masonry assemblages (ASTM E519 [22]) was followed. In these DCT, a vertical load was applied on a steel shoe placed at the top corner of the sample, in the direction parallel to one of the diagonals of the specimen. The relative displacements in both directions (parallel and orthogonal to the applied load) were measured between points placed opposite to the center

(a) (b)

Figure 2: Large panels for DCT: **(a)** Manufacturing and **(b)** test setup.

of the specimen using displacement transducers, as it can be observed in the setup of the test shown in figure 2b.

From the DCT it is possible to obtain the shear stress (S_s [MPa]) and shear strain (γ [m/m]), according to the formulation indicated in the aforementioned standard, where P [N] is the applied load, A_n [mm]^2 is the net area of the sample, Δx and Δy are the displaces in the two diagonals (measured at the center of the specimen), and g is the gage length:

$$S_s = 0.707 P / A_n$$

$$\gamma = (\Delta x + \Delta y)/g$$

Results and Discussion

Uniaxial compression tests

The compressive stress-strain behavior obtained from the UCT (Figure 3) showed a behavior which was initially linear, mainly elastic, although the formation of microcracks since the beginning of the test makes this linear branch not fully elastic [18, 23, 24]. The formation and propagation of the microcracks continues with increasing stresses leading to a plastic behavior of the material until the peak stress is reached. A softening branch follows the peak until the failure of the specimen.

The main parameter obtained in the UCT, however, is the compressive strength, very significant for RE constructions as they are generally designed to work mainly under compression. An average uniaxial compressive strength (UCS) of 1.40 MPa was obtained from the tests. This parameter is essential to characterize RE behavior, as these constructions are generally designed to work mainly under compression. A coefficient of variation (CV) 1.8% was obtained for the UCS, showing a remarkably low dispersion, especially considering the heterogeneity of this kind of materials, that usually leads to a significant dispersion in the results [12]. In fact, the whole stress-stress behavior of the specimens, shown in figure 3, is very homogeneous. This demonstrates the effectiveness of the methodology proposed in this study for manufacturing RE specimens.

Regarding the value of the UCS obtained, 1.40 MPa, it falls within the typical range observed for URE, which shows compressive strengths usually between 1.00 and 2.50 MPa [11, 12, 14, 25-28]. Authors have typically used both cubic and cylindric specimens of various dimensions but, although these parameters are known to influence the UCS results (together with the water content, the particle size distribution, or the compaction energy), the large number of possible combinations between them makes it very difficult to assess clear relationship between each of them and the UCS [12, 27, 29].

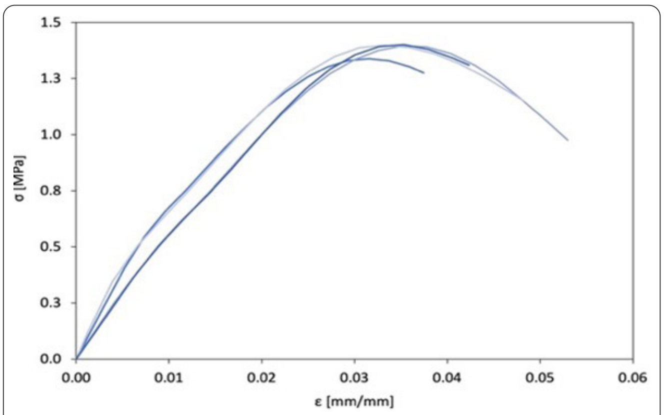

Figure 3: Stress-strain curves from UCT.

Diagonal compression tests

The DCT carried out on three 50 x 50 x 10 cm specimens provided the shear behavior shown in figure 4, with the shear stress and strain calculated as described in the previous section. The specimens were tested until total failure, and the crack development process was observed. Cracks began near the center of the samples and spread following a diagonal orientation, initially with an inclination of about 45° and then reorienting towards the border of the loading shoes (Figure 5). Small cracking was also observed near the interfaces between layers at border of the panels.

The shear strength and its corresponding strain for each specimen is shown in table 1. The table also includes the initial modulus of rigidity (G_0), defined as the initial slope of the shear stress-strain curve. With the value of the modulus of rigidity and estimating a common Poisson's ratio (ν) of 0.27 [12, 18, 29, 30], assuming an isotropic behavior of the material, it is possible to obtain an elastic modulus E = 655 MPa, according to the expression $E = 2G(1 + v)$.

There are few examples in literature regarding the value of the shear strength of URE, but the one obtained in the present study (0.14 MPa) is in agreement with the results shown by some previous studies [11, 30]. This shear strength corresponds to 10% of the compressive strength; a similar ratio between the tensile and the compressive strength of RE has already been indicated by other researchers [11, 18, 25, 30, 31]. Very low dispersion is obtained in the S_s results, but higher for the strain at peak shear stress and modulus of rigidity.

The value of the elastic modulus (655 MPa) from the DCT, is within the usual range for URE, typically between 350 MPa and 1000 MPa [1, 8, 13, 25, 27], although the existing studies in literature show a very significant dispersion in the E values for RE, from values below 100 MPa [11, 14, 28, 32] to results above 1000 MPa [30, 33]. This dispersion is related to the wide variety of soils used and the differences in the sample manufacturing and testing procedures [12].

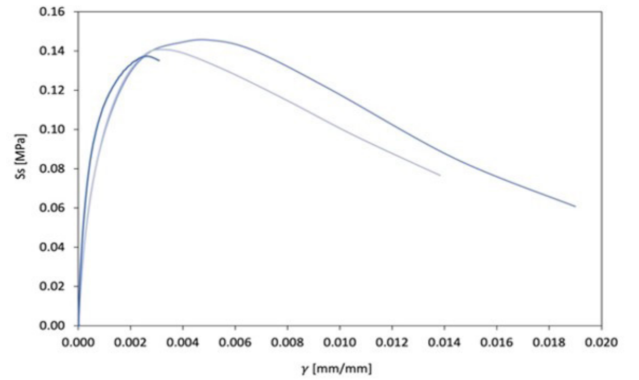

Figure 4: Shear stress-strain curves from DCT.

Figure 5: Failure of an URE specimen subjected to DCT.

Table 1: Mechanical parameters obtained from the DCT.

Specimen	S_s [MPa]	γ_{ss} [mm/m]	G_0 [MPa]
Panel 1	0.15	4.9	236.5
Panel 2	0.14	2.9	251.3
Panel 3	0.14	2.8	288.2
Mean	0.14	3.6	258.6
CV	3.2%	33.2%	10.3%

Conclusion

Expanding the use of unreinforced RE construction technique in new constructions requires a thorough understanding of its mechanical behavior. This is also essential to preserve the large number of heritage buildings that are made with this technique. In this regard, this paper presents an evaluation of compressive and shear behavior of unreinforced RE, evaluated by performing UCT and DCT on RE samples. Also, a manufacturing methodology for the specimens is proposed, using the procedure for the Proctor test (with standard mold and controlled compaction energy), in order to obtain more homogeneous samples and significantly reduce the dispersion in the results. By performing the uniaxial tests, a compressive strength of 1.40 MPa was obtained, a value similar to the ones commonly reported in literature for this kind of material. On the other hand, the diagonal tests allowed to obtain a shear strength of 0.14 MPa, equal to 10% of the compressive strength (relationship previously observed in literature between the compressive and tensile strength of RE). The crack development process under the shear load exhibited a diagonal pattern, beginning at the center of the specimen and growing to both supports. The results obtained regarding the compressive and shear behavior of RE will be the basis to develop numerical constitutive models of this material with the aim of predicting the behavior of existing and newly designed constructions with this material.

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Conflict of Interest

The authors declare that they have no known conflict of interest that could have appeared to influence the work reported in this paper.

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