Assessing the anisotropy of rammed earth

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Abstract

Rammed earth construction is an ancient technique that is attracting renewed interest throughout the world today. Since it is carried out by stacking layers of rammed earth, it is possible that the rammed earth material is anisotropic. This paper presents the first study of this anisotropy, carried out on two scales. The first is the scale of Representative Volume Elements (RVEs) of the rammed earth material, with dimensions close to those of the walls on site, manufactured and tested in the laboratory. The second is the microscopic scale, for which tests were carried out on equivalent Compressed Earth Blocks (CEBs). A conventional homogenization procedure was carried out to determine the relationships of the microscopic scale and the RVE scale. The compressive strengths, elasticity moduli and failure moduli are similar in both directions of the material: perpendicular and parallel to the layers. The sum of these results allows us to propose the hypothesis that the rammed earth material is an isotropic material of the first order, if the layers remain adherent to each other.

Key words: Sustainable development, rammed earth, anisotropy, compressive strength.

1 Introduction

Rammed earth construction is an ancient technique that is attracting renewed interest throughout the world today. Rammed earth walls are manufactured by compacting a clayey soil (earth) into a formwork. The earth's composition

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varies greatly but contains no organic components and a sufficient quantity of clay acting as a binder between the grains - a mixture of silt, sand, gravel and stones with a diameter of a few centimeters. The compaction is performed using a water content considered optimum, i.e. providing the highest dry density for a fixed compaction energy. This process is called the dry method, since the water content is about 10 %, while a paste (the case of adobes) should have a water content of about 25 %. The rammed earth is composed of several layers of earth roughly 15 cm thick, poured into a formwork (wooden or metal), and rammed with a rammer (manual or pneumatic). After compaction, each layer is 8-10 cm thick. This procedure is repeated until completion of the wall. Figure 1 on the left shows an example of a French house made of rammed earth.

Fig. 1. Left: a rammed earth house in France. Right: a rammed earth sample.

Thanks to its "green" characteristics in today's context of sustainable development, rammed earth construction is attracting renewed interest throughout the world (Walker et al. [1], Bruce [2]). Several studies have been carried out in recent years to study its characteristics: durability (Bui et al. [3], Hall and Djerbib [4], [5], [6]), environmental impact (Morel et al. [7]), thermal properties (Taylor et al. [8], Taylor and Luther [9], Paul and Taylor [10], Hall [11], Hall and Allinson [12], [13], Maniatidis et al. [14]), mechanical characteristics in compression (Maniatidis and Walker [15], Bui et al. [16], Jayashinghe and Kamaladasa [17], Walker and Dobson [18], Burroughs [19], Hall and Djerbib [20]), and paraseismic behavior (Hamilton et al. [21], Minke [22]).

A certain degree of complexity of the rammed earth material was observed and described by Bui et al. [16]. Since it is made by piling up layers of earth (Fig. 1 on the right), it is possible that the rammed earth material is anisotropic. Mechanical characteristic being different in directions perpendicular and parallel to the layers. However, to our knowledge, all of the previous studies of rammed earth's mechanical characteristics in compression only focused on the behavior of the rammed earth in direction perpendicular to the earth layers - i.e. the direction in which the wall supports load descent due to its own weight. No studies have yet examined the compressive behavior of rammed earth parallel to the earth layers.

Tests in this direction are of twofold interest. Firstly, the compressive behavior in this direction determines partly (only in the elastic state) the behavior of the walls during earthquakes or in general under horizontal loads (wind or roof effects, for example). However, in the vertical direction (perpendicular to the layers), rammed earth buildings often have safety coefficients (compressive strength of material divided by the maximal stress in the wall) of roughly 10 - the case for example of rammed earth buildings in France [23]. In the horizontal direction (parallel to the layers), the order of magnitude of the safety coefficient has not yet been studied. The tests in the direction parallel to the earth layers could clarify this question.
The second, more general interest would be the possibility to consider the material as homogenous and isotropic, but under what conditions and with what degree of accuracy? Indeed, these questions will determine the experimental procedures used to characterize this material in the laboratory and on site.

2 Tests on Representative Volume Elements (RVEs)

The heterogeneity of rammed earth and the challenge of manufacturing samples that are representative of the rammed earth in situ are discussed in Bui et al. [16]. For simplification purposes, today most studies use tests on small samples: 10 cm cubes or cylinders 20 cm high $\times$ 10 cm in diameter (Hall and Djerbib [20], Burrough [19], Lilley and Robinson [24], Hamilton et al. [21]). Studies performed by Maniatidis and Walker [15] and Bui et al. [16] have shown that there is a difference between the results obtained with small samples and those obtained with samples closer in size to the walls in situ and thus more representative of the latter. Tests on RVEs are therefore indispensable.

2.1 Materials

The material used is referred to as "Thiers" material (after the name of a French town). The grain size distribution curve is shown in Figure 2. Its low binder content (4% clay) means that its compressive strength will be close to the lower limit for rammed earth material (Walker et al [1]).

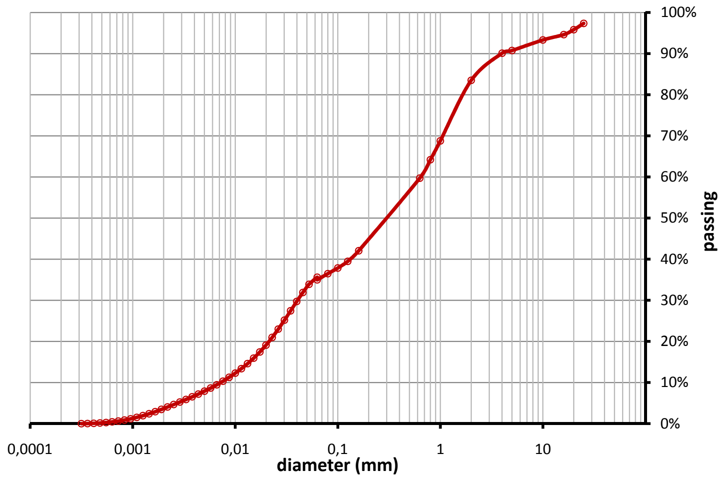

Fig. 2. Grain size distribution curve of the Thiers earth used.

2.2 Compression in the direction perpendicular to the layers

The manufacturing procedure and the uniaxial compression tests in this direction for RVEs were presented and discussed in Bui et al. [16]. We recall these results in this paper in order to subsequently compare them with the results of the tests performed parallel to the layers.
Three samples of Thiers earth measuring $(40\times40\times65)cm^3$ were manufactured. The uniaxial compression test in this direction on the RVEs was carried out in accordance with the procedure described in Bui et al. [16]. The summary of the results will be discussed in sections 2.4 and 2.5.

2.3 Compression in the direction parallel to the layers

2.3.1 Sample manufacture

The samples are manufactured in the same way as those tested in the direction perpendicular to the layers, in order to compare the results. The difference is that these samples are composed of only 3 layers. The sample dimensions are $40cm \times 40cm$ and roughly $20cm$ high. The last layer is given special attention during compaction to obtain a surface that is as flat as possible.
To achieve a slenderness ratio of 2, the samples are then cut with a table saw. Fig. 3 on the right represents a sample obtained after cutting. We manufactured two samples measuring $(40 \times 40 \times 20)cm^3$ which provided us 4 samples $(20 \times 20 \times 40)cm^3$ for testing in the parallel direction. Three samples were actually tested. Since the sample is tested in the direction parallel to the layers, surfacing is not necessary, because the two surfaces that were in contact with the formwork are sufficiently flat (Fig. 3 on the left).

Fig. 3. Left: uniaxial compression test parallel to the layers on samples measuring $(20 \times 20 \times 40)cm^3$. Right: samples measuring $(20 \times 20 \times 40)cm^3$, cut from a sample measuring $(20 \times 40 \times 40)cm^3$.

2.3.2 Uniaxial compression tests

These tests were performed in conditions similar to those of the uniaxial compression tests in the perpendicular direction, using the same hydraulic press, the same loading speed (0.01mm/s), and using no anti-friction system (Fig. 3 on left). With a slenderness ratio of 2 for the sample, the friction effect can be neglected. Unloading-reloading cycles were carried out respectively at the four stress levels: 0.06 MPa; 0.12 MPa; 0.22 MPa and 0.4 MPa (Fig. 4). Three cycles were carried out for each stress level.

These tests in the parallel direction of the layers are a priori done on non homogenous material. Firstly, the stress is not uniform in the sample during the test due to the heterogeneity of the dry density, which increases from the bottom up within a same layer and is discontinuous from one layer to another. The stress value determined is thus an average value (the load applied by the press divided by the section of the sample). Secondly, layer separation occurs fairly early on during the test, notably the first crack in the last layer (Fig. 4 on left), meaning that the sample is no longer a continuous medium. However, these separations do not seem to significantly alter the sample's mechanical capacities, since each layer continues to support the load alone. There is no change in slope even after the abrupt loss of adhesion due to the separation (Fig. 4 on left).

During the test, the first crack appeared fairly early on, due to the separation of the last manufacturing layer (Fig. 5 on left), which corresponds to the first

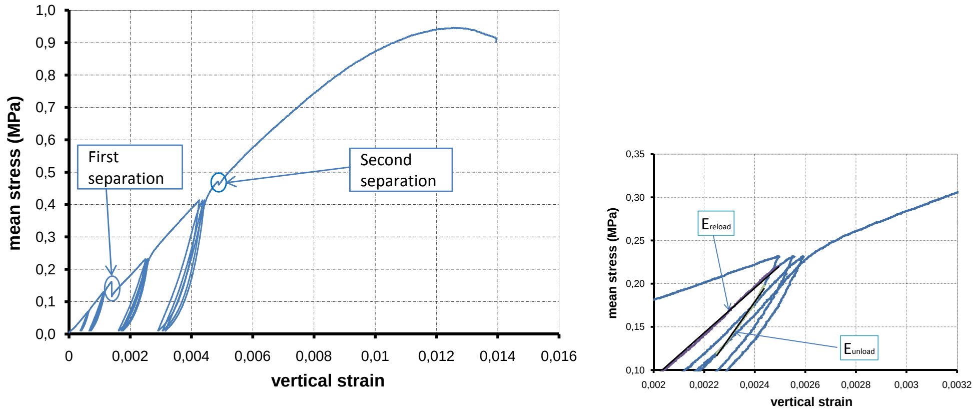

Fig. 4. Stress-deformation curve for the uniaxial compression test parallel to the layers, on the sample measuring $(20 \times 20 \times 40)cm^3$. Right: a closer look at the third pre-load level.

drop in stress in Fig. 4a, after the first loading-unloading cycles. This phenomenon is often observed in practice: the quality of the last layer is inferior to that of the other layers. This is perhaps due to the confinement of other layers and to a higher compacting energy of the next-to-last layers. The separation of the last layer corresponds to a strain that is 11 to 17 % of the failure strain and a stress that is 17 to 20 % of the failure stress.

The complete failure of the sample occurs at the level shown in Fig. 4 on the left, when the third vertical crack appears (on the right in Fig. 5b). It corresponds to the maximum extension of the material (the strain corresponds to the maximal stress) and to the internal failure within a layer leading to the failure of the entire sample.

In the case of the first two preloading levels (0.06 MPa and 0.12 MPa), the unloading-reloading cycles are identical (Fig. 4 on left), and $E_{unload} = E_{reload}$. However, for the cycles at the levels of 0.22 MPa and 0.4 MPa, the unloading-reloading cycles are no longer identical (Fig. 4 on right). In these cases, $E_{unload} \neq E_{reload}$. For these cases we determine the modulus using the average of E_{unload} and E_{reload}.

2.4 Comparison of the moduli in the two directions

The comparison of the moduli obtained from uniaxial compression tests perpendicular to the layers on samples measuring $(40 \times 40 \times 65)cm^3$ with the moduli obtained from uniaxial compression tests parallel to the layers on samples measuring $(20 \times 20 \times 40)cm^3$ is presented in Fig. 6.

Fig. 5. Cracks during the uniaxial compression test in the parallel direction to the two layers. (a) Left: the first crack that appears fairly early on in the test is located between the second and the third (last) layer. (b) Right: the second crack that appears towards the end of the test is located between the first and the second layer.

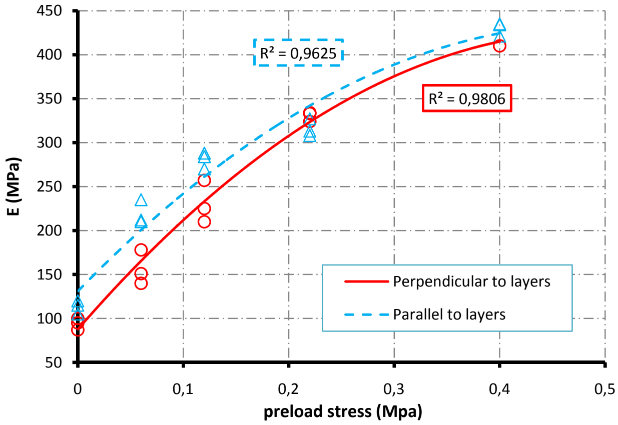

Fig. 6. Comparison of moduli in the perpendicular direction with samples measuring $(40 \times 40 \times 65)cm^3$ and in the parallel direction with samples measuring $(20 \times 20 \times 40)cm^3$.

We see that with low levels of preloading the moduli in the direction parallel to the layers are superior to those perpendicular to the layers (by about 25%), whereas with a preload of 0.4 MPa, the difference is insignificant. The greater difference at low levels of preloading is perhaps due firstly to the surfacing of the samples tested in the perpendicular direction, and secondly, it is also possible that in the first phase there were more microcrack closings in the perpendicular direction (compacting direction) than in the parallel direction.

2.5 Compressive strength and failure modulus

The compressive behavior of earthen material in general and rammed earth in particular is not linear elastic. In many cases the failure modulus is used rather than the elasticity modulus (e.g. Bruce [2]). The failure modulus is calculated using the ratio between the maximum stress and the deformation corresponding to this stress. The failure modulus used in this study is shown in Table 1. The failure moduli in the two directions of the test are equal to each other, at roughly 70 MPa.

The compressive strengths of rammed earth in the perpendicular and parallel directions to the layers, obtained through uniaxial compression tests on prismatic samples, are also shown in Table 1. The difference between the compressive strengths obtained in the two directions, perpendicular and parallel to the layers, is minor (<10%).

Test direction	R_c (MPa)	$E_{failure}$ (MPa)	w_{test} (%)
Perpendicular to layers	0.84 ± 0.03	74 ± 7	3.1 ± 0.8
Parallel to layers	0.92 ± 0.03	72 ± 4	2.5 ± 0.3

Table 1
Compressive strength and failure modulus results obtained with three tests on prismatic samples. w_{test} signifies the water content at the test moment.

2.6 Discussion

Before the separation of the layers (i.e. before crack opening) and after a preload, we showed the behavior of rammed earth material can be characterized by the following parameters: the elasticity modulus (reflecting the elastic stiffness below the preloading value), the compressive strength, and the failure modulus (reflecting the elasto-plastic stiffness at the time of failure), in both direction perpendicular and parallel to layers. After separation of the layers, this is still valid for a single layer.

However, for a whole wall, after separation of the layers, we feel it is relevant to treat the rammed earth material as a discontinuous material, with a friction interface law of the Coulomb type between each layer. This law is determined by the friction angle parameter φ.
In order to determine the crack apparition between the layers and the angle φ, we believe that it is necessary to use shear device as the direct shear box for example. Knowledge of this limit will allow us to determine which behavior

to model for the rammed earth material.
If the separation occurs close to the failure of the material, we can advance the hypothesis of an elasto-plastic isotropic behavior fully described in this article. If not, then structures made of rammed earth material are closer to those made of dry block masonry. If this is true, it will be necessary to determine the new parameter φ. However, one major difference with respect to dry block masonry that complicates modeling is the compressive strength of the rammed earth layers, which is finite, of an order of magnitude 20 to 200 times less than that of cut stone. Therefore we will not be able to advance the hypothesis of infinite compressive strength, a conventional hypothesis for these structures.

3 Microscopic scale - Tests on Compressed Earth Blocks (CEBs)

3.1 Summary of the method

This scale is referred to as "microscopic" since we can take into account the heterogeneity in each layer of material (Fig. 1 on right). In our case, the microscopic size of the rammed earth is roughly 5 cm, or half the thickness of a layer. The samples used to enable a study at this scale are CEBs measuring $9.5 \times 14.0 \times 29.4 cm^3$.

The objective of this approach using equivalent CEBs is to facilitate the test procedure in the laboratory. This method was developed and described by Bui et al. [16]. This method has been validated only for cases of elasticity moduli in the direction perpendicular to the layers. In this paper we present the validation of this approach for elasticity moduli parallel to the layers as well as for the rammed earth's compressive strength in both directions, perpendicular and parallel to the earth layers.

In the homogenization, we assume perfect adherence between each layer and the possibility to apply Hooke's law.

3.2 Homogenization in the direction perpendicular to the layers

The homogenization procedure in the direction perpendicular to the layers is illustrated in Fig. 7.

It should be noted that:

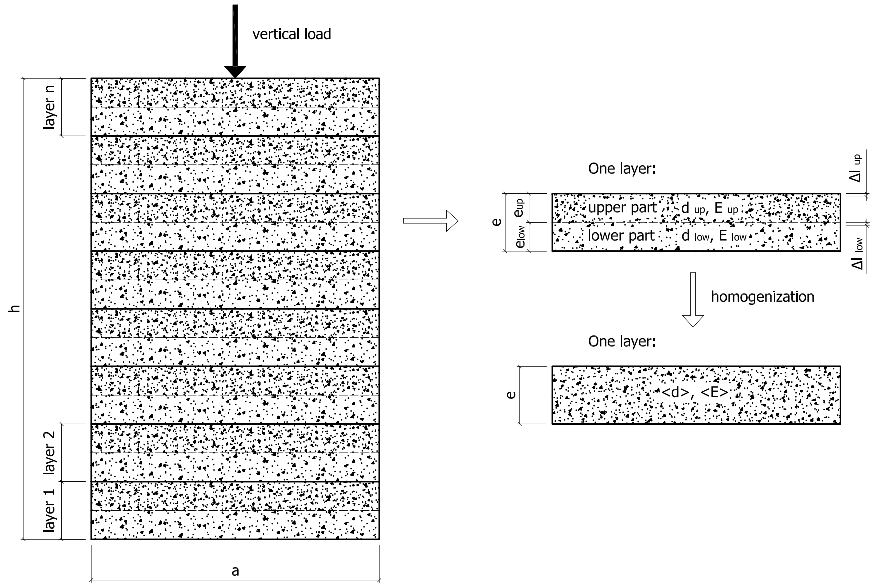

Fig. 7. Left: rammed earth sample at macroscopic scale. Right: microscopic scale on a rammed earth layer and homogenization.

- $< d >$ is the representative density of the material at the macroscopic level.
- $< E >_v$ is the representative elasticity modulus in the direction perpendicular to the layers of the material at the macroscopic level.
- $< E >_h$ is the representative elasticity modulus in the direction parallel to the layers of the material at the macroscopic level.
- σ is the average stress applied during the compression test ($\sigma = F/S$).

We then have the following classic relationship:

$$< E >_v = \frac{e_{up} + e_{low}}{\frac{e_{up}}{E_{up}} + \frac{e_{low}}{E_{low}}} \tag{1}$$

3.3 Homogenization in the direction parallel to the layers

The homogenization procedure in the direction parallel to the layers is illustrated in Fig. 8. We then have the following:

$$< E >_h = \frac{e_{up}E_{up} + e_{low}E_{low}}{e_{up} + e_{low}} \tag{2}$$

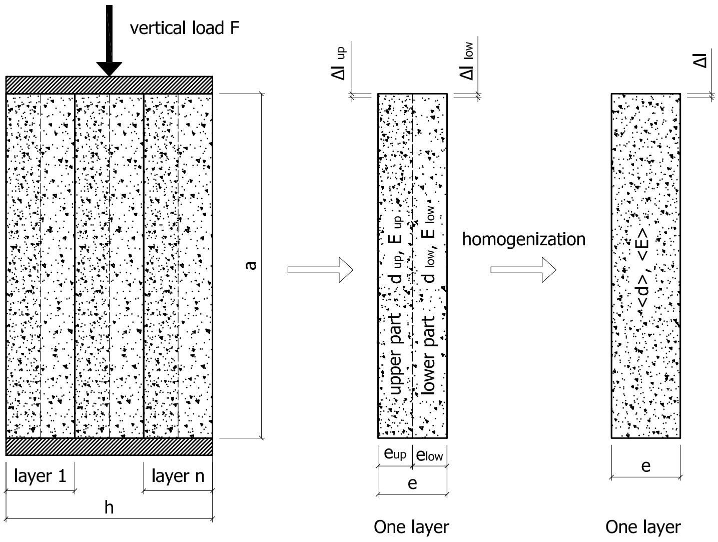

Fig. 8. Homogenization in the direction parallel to the layers.

3.4 Recall of the procedure used to implement this approach [16]

The strategy used for the study is to manufacture two types of CEBs with densities corresponding to d_{up} et d_{low} in Figures 7 and 8. By carrying out uniaxial compression tests on these CEBs, we can determine the corresponding moduli E_{up} and E_{low}. Based on the relationships presented in equations (1) and (2), we can determine the equivalent average elasticity modulus of the rammed earth, in the perpendicular and parallel directions respectively.

In the case of our rammed earth, we can reasonably choose: $e_{up} = e_{low}$. The values d_{up} and d_{low} were determined experimentally and are respectively 1980 and 1820 kg/m^3 (Bui et al. [16]).

If we replace $e_{up} = e_{low}$ in equations (1) and (2), we respectively obtain the following relationships:

$$< E >_v = \frac{2E_{up}E_{low}}{E_{up} + E_{low}} \tag{3}$$

and:

$$< E >_h = \frac{E_{up} + E_{low}}{2} \quad (4)$$

In the case of compressive strength homogenization in the direction perpendicular to the layers, we easily obtain:

$$< R >_v = \sigma_{low}^{max} \quad (5)$$

where σ_{low}^{max} is the compressive strength of the lower portion of the layers.

In the case of the compressive strength homogenization in the direction parallel to the layers, the stress is expressed according to (6):

$$< \sigma > = \frac{(E_{up}e_{up} + E_{low}e_{low})\varepsilon}{e_{up} + e_{low}} \quad (6)$$

On one hand, the upper portion of a layer (denser) has a higher compressive strength than the lower portion (less dense). On the other hand, when: $\varepsilon_{up} = \varepsilon_{low}$ and $E_{up} > E_{low}$, we obtain $\sigma_{up} > \sigma_{low}$. Thus we do not yet know in which portion the failure will first occur. There are two possibilities:

a. Case 1: either the upper portion reaches failure first:

$$< R >_h = \frac{(E_{up}e_{up} + E_{low}e_{low})\sigma_{up}^{max}}{(e_{up} + e_{low})E_{up}} \quad (7)$$

If $e_{up} = e_{low}$, we then obtain:

$$< R >_h = \frac{(E_{up} + E_{low})\sigma_{up}^{max}}{2E_{up}} \quad (8)$$

b. Case 2: or the lower portion reaches failure first:

$$< R >_h = \frac{(E_{up}e_{up} + E_{low}e_{low})\sigma_{low}^{max}}{(e_{up} + e_{low})E_{low}} \quad (9)$$

And if $e_{up} = e_{low}$, the equation (9) becomes:

$$< R >_h = \frac{(E_{up} + E_{low})\sigma_{low}^{max}}{2E_{low}} \tag{10}$$

3.5 CEB manufacture

The CEBs were manufactured according to the procedure described in Bui et al. [16]. The earth is poured into a mold and compressed using a double compacting manual press. In our case, the earth used to manufacture the CEBs was Thiers earth sieved at 3 cm.

The press used is a double compacting press that can produce samples that are quasi-homogenous and isotropic. An indirect verification of these properties is proposed by Morel et al. [25].

3.6 Unconfined compression test on CEBs

The CEBs were tested in the longitudinal direction (loaded according to the 29.4 cm length of the block). This arrangement gives a slenderness ratio of 3.1. Since we can consider the blocks to be homogenous-isotropic, this arrangement does not modify the results obtained.

3.7 Calculation of the equivalent parameters

The results of the uniaxial compression tests on the CEBs with dry densities of $1980 kg/m^3$ (3 blocks) and $1820 kg/m^3$ (4 blocks) were used to calculate the equivalent parameters according to the equations (3), (4), (5), (8) and (10).

3.7.1 Equivalent elasticity modulus

The calculation of the equivalent moduli in the directions perpendicular to the earth layers ($< E >_v$) and parallel to the earth layers ($< E >_h$) according to equations (3) and (4) was performed and is presented in Figures 9 and 10. The comparison of the variation of the rammed earth sample moduli and those of the equivalent CEBs, shown in Figs 9 and 10, shows a very good correlation between the homogenization results and those of the rammed earth samples manufactured in the laboratory.

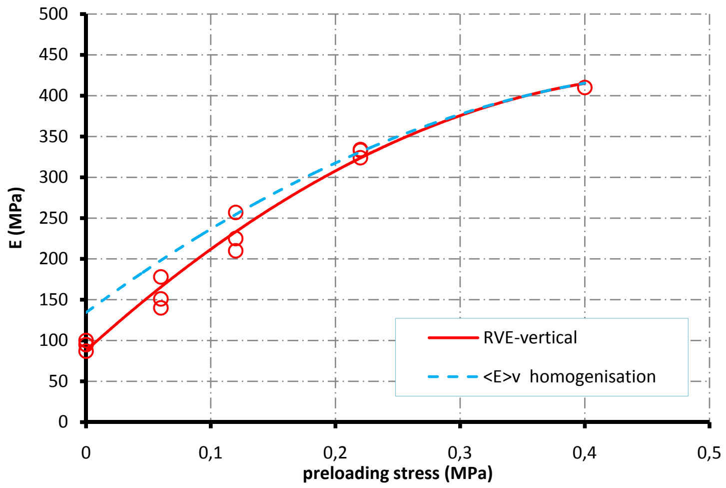

Fig. 9. Reloading-unloading modulus according to the pre-loading of the rammed earth samples tested in the direction perpendicular to the layers and of the equivalent CEBs.

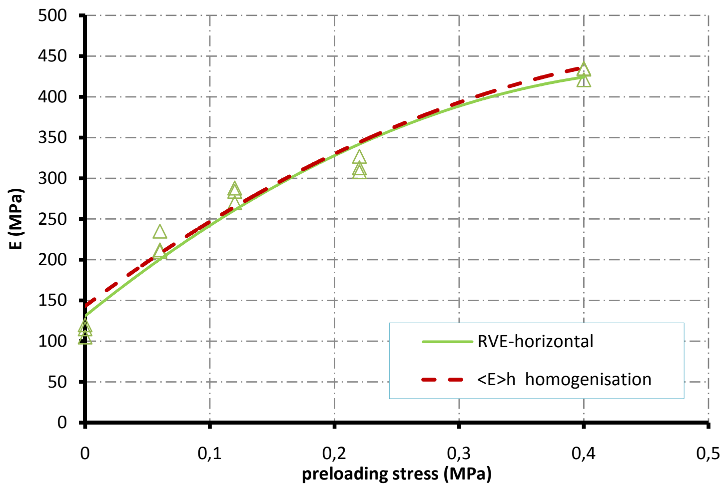

Fig. 10. Variation of the modulus according to the pre-loading of the rammed earth samples tested in the direction parallel to the layers and of the equivalent CEBs.

3.7.2 Equivalent compressive strength

The results are presented in Table 2, in which, $< R >_v$ and $< R >_h$ respectively represent the compressive strengths in the perpendicular and parallel directions to the layers of the rammed earth material. In accordance with the rammed earth compressive strength homogenization procedure, the moduli E_{up} and E_{low} in the equations (8) and (10) correspond to the failure moduli for the CEBs with dry densities of 1.98 and 1.82, respectively.

Part	$d_{dry}(kg/m^3)$	w_{test} (%)	E_{fai} (MPa)	σ^{max} (MPa)	$< R >_v$ (MPa)	$< R >_h$ (MPa)
Up	1980	2.8	102 ± 4	1.53 ± 0.03	**0.88** ± 0.09	**1.06** ± 0.04
Low	1820	2.5	72 ± 3	0.88 ± 0.09		

Table 2
Calculation of the compressive strength homogenized on the basis of equivalent CEBs. $< R >_v$ and $< R >_h$ respectively represent compressive strengths in the perpendicular and parallel directions to the layers of the rammed earth material.

The comparison between the compressive strength results obtained on the basis of the equivalent CEBs and from prismatic samples of rammed earth is shown in Table 3.

Strength (MPa)	RVEs	Equivalent CEBs	Difference (%)
Perpendicular to layers	0.84 ± 0.03	0.88 ± 0.09	5
Parallel to layers	0.92 ± 0.03	1.06 ± 0.04	15

Table 3
Comparison of the compressive strength calculated on the basis of the equivalent CEBs with that resulting from the tests performed on rammed earth samples manufactured in the laboratory.

We see that the strengths calculated on the basis of the equivalent CEBs are higher than those of the rammed earth samples manufactured in the laboratory, both perpendicular and parallel to the layers. In the perpendicular direction, the difference is not significant(less than 5%), perhaps due to the inferior surfacing of the rammed earth samples manufactured in the laboratory.

In the direction parallel to the layers, the difference is significant (approximately 15%), which may be due to several reasons. First of all, the earth layers in the rammed earth sample are not really flat, due to friction in contact with the formwork, whereas in the homogenization we assume that these layers are flat. This assumption does not significantly influence the test results in the direction perpendicular to the layers, but it has a much greater influence in the direction where the applied load is parallel to the layers. Secondly, the separation of the layers during the uniaxial compression tests in the direction parallel to the layers was not taken into account in the homogenization, where it is assumed that the adherence between layers is perfect. These are the two main reasons why there is an "over-estimation" of the compressive strength in the horizontal direction by the homogenization.

4 Conclusions and prospects

In this paper, the anisotropy of rammed earth material was studied on two scales: first the scale of representative samples of rammed earth (with dimensions similar to those of the walls on site) manufactured and tested in the laboratory, and secondly the microscopic scale, the tests were performed on equivalent Compressed Earth Blocks (CEBs). A classic homogenization procedure was carried out to determine the relationships of the microscopic scale and the RVE scale.

On the scale of the representative rammed earth samples (RVEs), the anisotropy of this material was studied by using uniaxial compression tests in two directions, both perpendicular and parallel to the layers. Unloading-reloading cycles were added to study the non-elastic behavior of this material. These tests gave similar results in both directions tested for this material, for compressive strength, failure modulus and the elasticity moduli in the case of preload greater than 0,2MPa. In case of preload smaller than 0,2MPa, the difference between the elasticity moduli in two directions is from 5 to 25%. All of these results enable us to initiate the hypothesis that rammed earth is an isotropic material of the first order if the layers remain adherent to each other. These results have justified the successful application of the hypothesis of an isotropic material on the macroscopic scale (in-situ rammed earth walls on small deformation) in the study of Bui et al [16]. Further research will be established to examine this subject.

The tests with the equivalent CEBs were developed using a model of a composite material made of layers. They indicated a compressive strength, reloading moduli and a failure modulus consistent with those resulting from tests on rammed earth RVEs, in both test directions: perpendicular and parallel to the layers. This illustrates the reliability of the proposed model. The tangent moduli of the equivalent CEBs were observed to be superior to those of the rammed earth samples in the direction perpendicular to the layers (by roughly 50%). This is perhaps due above all to the surfacing, and also to more micropores closing in the rammed earth samples (in this direction of the test, i.e. the direction of the ramming during manufacture).

The advantage of the CEB method is that using the homogenization procedure on a quasi-homogenous-isotropic material such as a CEB, enables to determine the equivalent characteristics of rammed earth walls in both directions. The difficulty with this method lies in determining the corresponding dry densities d_{up} and d_{low}. Future studies will be necessary to identify a simple method to determine the dry densities of rammed earth walls.

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