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ULTRASOUND TRANSMISSION METHOD TO ASSESS RAW EARTHEN

MATERIALS

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ABSTRACT

The feasibility of using ultrasound transmission method to assess raw earthen materials is investigated. Results indicate that this technique is effective at controlling the drying process of raw earthen materials. Near the hygrometric equilibrium, there is a linear relationship between the moisture content of the earthen material and the ultrasound transmission speed, which increases during the drying process. For the tested compressed earth, the hygrometric equilibrium is reached when the ultrasound transmission speed is over 1100 m/s. In addition, ultrasound transmission method is useful to reliably calculate the dynamic Young's modulus of raw earthen materials.

KEYWORDS

Ultrasound transmission method; Compressed earth; Young's modulus; Modal analysis.

1. INTRODUCTION

Earthen architecture has been traditionally analysed under the eye of the cultural heritage and preservation specialists. Earthen building techniques and their performance have been extensively documented (see the work by Miccoli et al. [1]) and there are several case studies (see, for example, [2,3]), which are oriented to analyse existing buildings, their origins and the conservation interventions performed on them. However, this ancient building material, which became sparse with the introduction of cheaper and more efficient concrete and steel structures, is gaining attention because of the increasing interest in sustainable building techniques (see the survey by Niroumand et al. [4]).

In this context, scientific research on earthen building materials is experiencing a remarkable diversification. There are studies aimed to discuss the optimum particle size distribution and the suitable moisture content to achieve the best mechanical performance (see [5–7]). Other researches deal with the mechanical characterisation of earthen materials (see [8–13]) or are focused on studying the structural response of elements made of earth (see [14–17]), mainly against in-plane dynamic loading. There is also a significant trend to research about the thermal inertia of earthen materials (see the clarifying work by Heathcote [18]), which is one of their main advantages.

However, among the different variables which influence the mechanical response of earthen materials, the moisture content is always highlighted as the most influent one. In fact, in-situ measured mechanical properties depend on the water content and matric suction, which are highly variable by changing environmental conditions. In this

line, the research conducted by Schroeder et al. [19] showed that the mechanical performance of rammed earth walls depended on both the initial moisture and the drying process. Similarly, Bui et al. [20] conducted unconfined compression tests at different moisture contents and concluded that the compressive strength of earthen materials depended on this parameter. Gerard et al. [21] added indirect tensile tests to the compression ones with the aim of evaluating the mechanical response of earthen samples characterised by a different suction levels. These authors pointed out that it is possible to predict the strength of an earthen building material from the environmental hygroscopic conditions. Finally, Champire et al. [22] introduced the analysis of the influence of the moisture content on the deformability of earthen materials measuring both axial and radial strains of compression tested samples.

Although there are several studies about the influence of the moisture content on the mechanical strength of earthen materials, there is little research about how to determine this influent parameter using non-destructive techniques or little invasive ones. In this line, it is worth highlighting the research conducted by Chabirac et al. [23], who used Time-Domain Reflectometry (TDR), based on measuring the travel time of an electromagnetic wave between two conductive rods of a specified length, to determine the moisture content of rammed earth. Another remarkable work is the research presented by Aubert et al. [24], who used ultrasound transmission tests to evaluate the hardening process of clayey soil blocks subjected to freezing-thawing cycles after increasing their initial moisture content. Their results showed that the freezing-thawing cycles reduce the moisture content of the samples, increasing the matric suction and consolidating the soil, thus obtaining higher transmission speeds.

However, the main application of the ultrasound method on earthen materials has been aimed to determine mechanical properties. It is the case of the study of Galán-Marín et al. [25] who studied the possibility of stabilising soils by adding alginate and wool. They used ultrasound transmission method to evaluate the stabilisation effect obtaining transmission speeds of longitudinal waves between 1000 m/s and 1800 m/s. Similarly, Ben Mansour et al. [26] used a low frequency acoustic pipe to determine the properties of CEB (Compressed Earth Blocks) and compared the results with the properties obtained performing destructive mechanical tests.

Despite the evident relationship between moisture content and ultrasound transmission speed in earthen materials, we found no research which uses this effect to control the evolution of the moisture content during the production process of earthen materials using ultrasonic non-destructive methods.

Besides ultrasound method, modal analysis has also been applied on earthen structures to characterise their mechanical response with a non-destructive approach. In this line, Bui et al. [27] performed dynamic measurements to obtain the natural frequencies and the damping ratios of four rammed earth buildings. In addition, they compared the results of the operational modal analysis with the predictions of a simplified analytical model obtaining the dynamic Young's modulus of rammed earth (between 100MPa and 500MPa). Four years later, Bui et al. [28] presented the modal analysis of rammed earth walls which were built 22 years before testing. These experimental results were used to adjust a numerical model. The Young's modulus which brought the best fitting between the experimental dynamic response and the

numerically predicted behaviour was compared with the one obtained performing uniaxial compression tests showing good correlation. In a similar way, Aguilar et al. [29] used operational modal analysis combined with numerical simulations to obtain rammed earth properties of a particular heritage structure.

The accuracy of the Young's modulus obtained adjusting numerical models to vibrational analyses on earthen structures has been always contrasted with destructive compression tests (for example, [28]). However, there are no studies which used another non-destructive method, e.g. ultrasound transmission technique, to validate a Young's modulus which was numerically adjusted from the experimental dynamic response.

Thus, the literature review reveals two main applications for ultrasound transmission method on earthen elements which need to be studied: (i) to control the drying process during the construction stage of massive earth structures (for example, rammed earth or cob) with the aim of setting a threshold value of the transmission speed which assured the safety of manufacturing the next batch over the controlled one, and (ii) to obtain the elastic properties (dynamic Young's modulus and Poisson's coefficient) in a reliable way. This second application requires proving that the values measured with ultrasound transmission method are coherent with the values obtained with other dynamic tests like modal analysis. The aim of this paper is to provide knowledge on these two particular topics for the specific case of compressed earth.

2. MATERIALS

Clayey-sand soil was used to produce cubic samples and a scaled wall. The cubic samples were used to study the drying process using ultrasound transmission method. The wall was used to assess the feasibility of using ultrasound transmission method to determine the Young's modulus of earthen materials: the numerical simulation of the vibrational response of the wall, which used the value of the dynamic Young's modulus which was obtained with ultrasound transmission technique as an input variable, was compared with the experimentally determined modal response with this purpose.

2.1. Materials. Soil mixture

The clayey-sand soil used in the experimental campaign was composed of 10.0% clay and silt, 65% of sand with particles up to 2mm diameter and 25% of sand with particles up to 5mm diameter. The most significant components of the clay were 40-45% SiO_2 , 10-13% Al_2O_3 and 3-5% Fe_2O_3 . Its silicate modulus was 2.53. The particle size distribution of the mixture is presented in Figure 1.

Figure 1. Particle size distribution of the clayey-sand soil used in the experimental campaign

The soil mixture preparation consisted in (i) mixing the solid components (clay-silt, and two types of sand with the previously presented dosage) until the earthen mixture was uniform, (ii) adding the necessary water to reach 12.6% of moisture content and (iii) mixing the water with the “dry” earth mixture for at least 3 minutes, obtaining a uniform material. The initial moisture content of each earthen component was measured before mixing them. The methodology consisted in drying specimens at 105°C for 24h and measuring the weight variation. The desirable moisture content of the mixture was set to 12.6% using the drop ball test like in a previous research [30].

2.2. Cubic specimens for drying process

Twenty rectangular prisms specimens (100mm width x 100mm thick x 90mm height) were produced. These are referred as cubic specimens in the rest of the text for a better understanding.

To produce these cubes, a tape-covered wood plate (10mm thick) was placed inside the cubic mould (100mm x 100mm x 100mm) whose bottom face had a hole to ease the un moulding process. After that, the mould was filled with the mixture and a low pressure was manually applied to assure the complete filling of the mould. Finally, a quasi-static increasing pressure was applied at a ratio of 2.5kPa/s up to 200kPa using an electro mechanic press. The specimen was un mould and the procedure repeated for the rest of the cubes.

The apparent density of specimens was determined just after un moulding them by measuring their dimensions and weighting them.

The drying process of these cubic specimens was controlled with ultrasound transmission technique after five different curing procedures. Four of these curing procedures consisted in leaving the specimen in a high humidity environment (Temperature $20\pm 2^{\circ}\text{C}$, RH>95%) for four different times: 3days, 7 days, 14 days and 21 days. The last curing procedure consisted in no curing the specimen before drying. Four specimens were subjected to each curing process. The list of the cubic specimens and their initial density are summarised in Table 1.

Table 1. Cubic specimens

<i>Curing time (d)</i>	<i>Specimen</i>	<i>Density fabrication (kg/m³)</i>	<i>Density after curing (kg/m³)</i>
0	C0_1	1.894	---
	C0_2	1.829	---
	C0_3	1.805	---
	C0_4	1.836	---
3	C3_1	1.877	1.904
	C3_2	1.853	1.853
	C3_3	1.853	1.847
	C3_4	1.864	1.871
7	C7_1	1.898	1.824
	C7_2	1.862	1.880
	C7_3	1.859	1.985
	C7_4	1.872	1.976
14	C14_1	1.873	1.944
	C14_2	1.834	1.856
	C14_3	1.842	1.870
	C14_4	1.867	1.875
21	C21_1	1.853	1.894
	C21_2	1.838	1.959
	C21_3	1.829	1.835
	C21_4	1.855	1.982

2.3. *Wall specimen for Young's modulus*

The wall (900mm width x 160mm thick x 1200mm height) was produced by moulding the described mixture into a modular wood framework. Each earth layer was 130 mm thick before any compression and approximately 100 mm thick after applying a compressive stress of 200kPa. The compressive stress was applied using a manual press specifically designed for this purpose [31], which allowed controlling the applied force. This force was transmitted through an interchangeable steel plate of known dimensions (e.g. 330mm length of the plate oriented in the width direction of the wall x 135mm width of the plate oriented in the thick direction of the wall).

The bottom of the wall was built into a steel tool (see Figure 2a) which was 140mm width and 80mm depth. The top layer of the wall (corresponding to the top 80mm) was manufactured with a reduced width of 140mm to place an identical steel tool on this ending of the wall. These two steel tools were used later on to lift and move the compressed earth wall.

The wall was unmoulded 42 days after completing its construction and left for drying at indoor environmental conditions (defined by Temperature $20\pm 2^{\circ}\text{C}$, RH= $55\pm 15\%$).

Figure 2. a) Compressed earth wall with steel tools at both endings and position of the accelerometer for the modal analysis (point labelled 71). The localisation of the points where the ultrasonic transmission speed was measured is also visible. b) Geometric model and discretisation mesh for the numerical simulation.

3. METHODS

Moisture content changed inside the specimens along the time. Specimens experienced a continuous drying process from its construction until they found a stable state with the environment. Ultrasonic test was used to measure these changes along the time. On the other hand, numerical simulations and modal analysis were used to find an estimation of the Young modulus of the used compressed earth.

3.1. *Ultrasound transmission tests on cubic specimens*

Ultrasound transmission tests on cubic specimens started 3 days after their production in the case of specimens C0 and 3 days after removing them from the high humidity environment for the rest. Tests carried out at an earlier time provided no measurements because ultrasound transmission time was out of the measuring range

of the used equipment. In addition, performing ultrasound tests on samples just after producing them or removing them from humidity may cause them damage because of their little strength and the stacking effect of the petroleum jelly used as contact paste during the test.

Ultrasound wave travelling time was measured daily while specimens were drying at indoor environmental conditions until the measurements became stable.

Ultrasound transmission test method to determine the wave propagation time between a transmitter and a receiver is a well-known methodology.

Transmitting/receiving probes of longitudinal waves of 55kHz were used in this campaign. The pulse generator unit supplied a 1Hz frequency, 1000V amplitude oscillating voltage. The testing methodology followed the specifications of ASTM standard D 2845–05 [32].

Specimens were measured and weighed before and after every ultrasound test in order to take into account the effect of the contact paste (petroleum jelly) on the moisture of the specimens. Thus, the calculated moisture contents are not influenced by the ultrasound testing.

3.2. Ultrasound transmission tests on wall specimen

Ultrasound transmission test method was also applied on the wall to control its drying process and to obtain the dynamic Young's modulus of the used compressed earth.

The ultrasound transmission speed (V) was measured in three points. The top point was placed at 180mm from the top of the wall, the middle point at mid-height of the wall and the bottom point at 180mm from the bottom of the wall (see Figure 2a).

206 Ultrasound measurements were performed at five ages after removing the framework.
 207 In addition, a single measurement at mid-height was performed before carrying on the
 208 modal analysis. This last measurement was used to obtain the dynamic Young's
 209 modulus ($E_{ultrasound}$) applying equations (Eq. 1) and (Eq. 2).

$$E_{ultrasound} = \frac{\rho V^2}{K} \quad (\text{Eq. 1})$$

$$K = \frac{1 - \nu}{(1 + \nu)(1 - 2\nu)} \quad (\text{Eq. 2})$$

210 where ν is Poisson's ratio, ρ the density of compressed earth and V the transmission
 211 speed of ultrasonic wave.

212 3.3. Numerical simulation of the wall

213 A numerical modal analysis of the wall was implemented using ANSYS® Workbench
 214 platform to compare its results with the modal experimental data. This approach was
 215 aimed to validate the feasibility of using ultrasound transmission technique to obtain
 216 the Young's modulus of earthen materials. With this purpose, the dynamic Young's
 217 modulus obtained using ultrasound transmission technique ($E_{ultrasound}$) was introduced
 218 as an input variable of the model. Then, the simulated vibrational response (modal
 219 shapes and frequencies) was compared with the experimental modal analysis.

220 A three-dimensional geometric model of the wall was defined using its real
 221 dimensions. The geometry of the steel tools was simplified maintaining its volume and
 222 position of the centre of gravity (see Figure 2b).

223 Compressed earth was defined as an isotropic linear elastic material for this modal
 224 simulation. The density of the compressed earth of the wall was experimentally

determined obtaining a value of 1780 kg/m^3 . The Young's modulus, determined using ultrasound transmission technique, was set to 1418 MPa . This was calculated using (Eq. 1) and (Eq. 2) for a Poisson's ratio of 0.35 and the corresponding ultrasound transmission speed (see section 3). The value of the Poisson's coefficient (0.35) was selected within the range (0.22-0.4) proposed by Bui et al. [27] and also within the range (0.1-0.4) studied by Miccoli et al. [17,33] for earthen materials. In fact, this value (0.35) was selected because our wall was built with a procedure defined as a mix of rammed earth and earth compressed blocks. Rammed earth, characterised by the compaction of different earth layers applying several impacts, have a Poisson's ratio of 0.27 according with Miccoli et al. [33] or 0.22 according with Bui et al. [28]. Earth compressed blocks, produced in a single batch compacted with an increasing pressure, have a Poisson's ratio of 0.45 according with Miccoli et al. [33] or 0.5 according with Guillaud et al. [34]. Hence, the Poisson's coefficient of our wall was supposed to be between 0.27 and 0.45, or between 0.22 and 0.5, being 0.36 the central value of both ranges. In addition, other authors recommended values around 0.33 (see [35]) or 0.35 (see [36]) for modelling earthen materials.

In addition, a numerical analysis on the influence of the Poisson's ratio was performed. It consisted on: a) defining several values of this variable ($\nu=0.20$, $\nu=0.25$, $\nu=0.30$, $\nu=0.35$, $\nu=0.40$ and $\nu=0.45$); b) for each value, the corresponding Young modulus (E) was calculated using (Eq. 1) and (Eq. 2); c) for each pair of values (ν, E) the numerical simulation was performed and the frequencies corresponding to the first two vibration modes of the modal analysis were compared with the experimental ones.

The wall was discretised using hexahedral elements whereas the complex geometry of the steel tools recommended using tetrahedral elements for these parts. The model had 5289 elements in total. In addition, the contact between the parts representing the steel tools and the wall were defined as perfectly bonded. Finally, no boundary conditions were introduced. This approach allows neglecting the rigid-solid movements from the numerical analysis.

3.4. Modal analysis of the wall

The wall was subjected to a modal analysis six months after its construction to assure a stationary hygrometric situation. A grid of 9 columns (separated 100mm) and 10 rows (separated 100mm) defined 90 points on one of the largest surfaces of the wall. A unidirectional accelerometer (*Brüel&Kjær piezoelectric charge accelerometer type 4370 with charge converter type 2646*) was placed in the point number 71 (see Figure 2a) oriented along the transversal direction (out-of-plane direction). This accelerometer was attached to a transmission plate which was bonded to the wall using cyanoacrylate. An impact hammer (*Brüel&Kjær type 8206 with rubber tip*) was used to excite the wall by impacting on all points in the out-of-plane direction. Two impacts were executed for each point, averaging the resulting signal and checking the coherence of the dynamic response. *Brüel&Kjær Multipurpose 6-channel input module type 3050* was used to acquire the data. A transient time weighting was defined to select the significant impact data from the hammer. An exponential time weighting was defined to select the significant oscillation data from the accelerometer just after the impact, discarding the data of the oscillation forced by the impact process. The cross-spectrum of the Fast Fourier Transformed (FFT) hammer and accelerometer

270 signals was calculated using *PULSETM* analysis platform. Data was post processed using
271 *ME'scopeVESTM* software to obtain the modal shapes and their corresponding
272 oscillation frequency and damping.

273 During the modal testing, the wall was hanged using an overhead travelling crane and
274 long chains so the boundary conditions were clear to compare with simulation results.

275 **4. RESULTS**

276 Figure 3 summarises the values of the moisture content of the cubes determined just
277 before performing ultrasound transmission tests. It is noticed that the drying process
278 (graphs of the left side in Figure 3) finished when the studied cubes reached a constant
279 moisture content of around 1% after an exponential decrease of this parameter along
280 time. In fact, the moisture content of the studied cubes can be considered constant 10
281 days after their removal from the high humidity environment or their production in the
282 case of specimens not subjected to high humidity curing. Ultrasound transmission
283 speed is between 1400 m/s and 1500 m/s for all specimens in the “dry” state
284 (moisture content around 1%). In addition, a linear relationship between the moisture
285 content and ultrasound transmission speed is envisaged when the moisture content is
286 below 3%.

Figure 3. Moisture content evolution during the drying process (left) and relationship between the moisture content and the ultrasound transmission speed (right).

In an analogous way, the evolution of the ultrasound transmission speed along time was determined for the compressed earth wall at three different heights. Different drying rate is observed depending on the position of the material. The bottom part of the wall showed lower ultrasound transmission speeds according with the data presented in Figure 4.

Finally, before modal analysis, the ultrasound transmission speed measured at mid-height of the wall was 1130 m/s, which corresponded to a dynamic Young's modulus of 1418 MPa, which was calculated with the general equations (Eq. 1) and (Eq. 2) considering a Poisson's coefficient of 0.35 and the measured density of 1780 kg/m^3 as mentioned in section 2.4. This value was used in the numerical simulations.

Figure 4. Ultrasound transmission speed at different heights of the compressed earth wall along the drying process.

The results of the vibrational response (modal shapes and associated frequencies) calculated with the numerical simulation and experimentally determined with the modal analysis carried out on the compressed earth wall are presented in Figure 5. Only the first two modal shapes were experimentally determined. These shapes, their

307 associated frequency and the order they appear met the predictions of the numerical
308 simulation ($f_{EXP_mode_1} = 69.4\text{Hz}$ vs. $f_{SIM_mode_1} = 73.1\text{Hz}$ and $f_{EXP_mode_2} = 87.2\text{Hz}$ vs.
309 $f_{SIM_mode_2} = 86.6\text{Hz}$).

310 Figure 5. Modal shape of the first mode, experimentally determined (top left) and simulated (top right).
311 Modal shape of the second mode, experimentally determined (bottom left) and simulated (bottom
312 right)

313 In addition, modal analysis results indicated that the damping for the first mode (4.1%)
314 was greater than for the second mode (2.4%).

315 Finally, the results of using different values of the Poisson's coefficient showed (see
316 Figure 6) that the influence of this variable is significant. In Figure 6 the average
317 relative error of the predicted frequencies for the first two vibration modes are plotted
318 for each value of the Poisson's ratio considered.

319

320 Figure 6. Error of the eigenfrequencies predicted by the numerical simulation for each value of Poisson's
321 ratio

322

323

5. DISCUSSION

The feasibility of using ultrasound transmission method to (i) control the drying process of earthen structures and to (ii) obtain the dynamic Young's modulus of earthen materials is discussed on the basis of the presented results.

Specific concerns about using this non-destructive testing method on compressed earth are also commented.

5.1. *Ultrasound transmission method to control the drying process of earthen structures*

The plots in the right side of Figure 3 show there is a relationship between ultrasound transmission speed (V) and moisture content (w) of earthen cubes. It is observed that ultrasound transmission speed increases when the moisture content decreases during the drying process of the specimens. This phenomenon, which was previously observed by other researchers (see [24]), is related with the increase of the matric suction, which consolidates the soil and increases the transmission speed, although the apparent density of the material is decreasing due to the drying process.

Plots of ultrasound transmission speed (V) vs. moisture content (w) (right side of Figure 3) show two stages. When the moisture content is over 2% the speed transmission is almost constant during the drying process. At the threshold value of $w=2\%$ there is always a sudden increase of the ultrasound transmission speed. Finally, for values of moisture content under 2% there is a linear relationship between the ultrasound transmission speed and the moisture content up to the hygrometric equilibrium which is reached around 1%. This behaviour, together with empirical observations of the

specimens, suggest that there is a qualitative change in the state of the soil of the tested specimens when the moisture content is around 2%. At this moisture level, the soil turns from a malleable matter, which barely transmits ultrasound waves, to a stiff, fragile solid material. In addition, it has to be noticed that this sudden change always happens when the moisture descending rate along time shows an inflection (see plots in the left side of Figure 3). All these data indicates that the nature of the water dissipated at moisture content over 2% is free water which occupies the largest voids in the soil structure whereas the water dissipated at moisture content below 2% is interstitial water placed between particles. Matric suction is significantly increased when this second type of water dissipates until reaching the hygrometric equilibrium with the environment.

The linear relationship between ultrasound transmission speed (V) and moisture content (w) can be represented by a linear fitting ($V = Sw + b$) along the process of dissipation of the interstitial water ($w < 2\%$). The coefficients of this linear fitting (S and b) are summarised in Table 2. It is observed that the independent term (b) of the linearly fitted equations can be considered constant, with an average value of 1837.5 m/s (COV = 10%) for the tested cubes. In contrast, it is observed that the slope of the linear fitting (S) linearly depends on the time the specimens were cured into a high humidity environment (only for the specimens cured at high humidity environment). This fact can be observed in Figure 6, in which the average of the slopes of each type of specimen ($\bar{S}$) are plotted against the corresponding curing time (t) in a high humidity environment. These data is linearly fitted. Note that specimens C0 are excluded from this analysis.

369 Table 2. Coefficients of the linear fitting of the relationship ($V = Sw + b$) between moisture content (w)
370 and ultrasound transmission speed (S)

<i>Curing time (d)</i>	<i>Specimen</i>	<i>S (m/s)</i>	<i>b (m/s)</i>
0	C0_1	-561	1948
	C0_2	-386	1836
	C0_3	-542	1891
	C0_4	-354	1686
3	C3_1	-498	1894
	C3_2	-616	2098
	C3_3	-560	1973
	C3_4	-560	2010
7	C7_1	-604	1664
	C7_2	-519	1629
	C7_3	-503	1641
	C7_4	-520	1646
14	C14_1	-494	1895
	C14_2	-660	2061
	C14_3	-373	1845
	C14_4	-341	1842
21	C21_1	-341	1769
	C21_2	-423	1559
	C21_3	-249	1626
	C21_4	-464	2237

371

372

373 Figure 7. Relationship between the slope (S) of the curve “ultrasound transmission speed vs. moisture
374 content” in Figure 3 and the curing time in high humidity environment (t)

375 Thus, for the tested cubic specimens the relationship between the ultrasound
 376 transmission speed (V) and the moisture content (w) follows the equation (Eq. 3)

$$V = 1837.5 - S \cdot w \quad (\text{Eq. 3})$$

377 where, w is expressed in % and S is calculated according with (Eq. 4), which is obtained
 378 by linear fitting of the experimental data (see Figure 7).

$$S = 10.6 \cdot t - 602 \quad (\text{Eq. 4})$$

379 t is the curing time in days ($0 < t < 21$) limited to the available information to adjust the
 380 equation.

381 Specimens C0 showed different response than the rest of the cubes. The general trend
 382 is that specimens C3, C7, C14 and C21 increased their moisture content when cured at
 383 high humidity environment (see Table 1). The water availability during the curing
 384 process allowed these specimens not only to increase the free water contained in their
 385 voids, but to modify the interstitial water. In contrast, specimens C0 had not available
 386 water because these cubes were not subjected to any curing process before the drying
 387 stage. Thus, the initial distribution of the water content between voids and interstitial
 388 spaces may be influenced by the fact of curing or not the specimens. It seems that
 389 curing specimens for a short period of time contributes to increase their interstitial
 390 amount of water, whereas long curing periods in a high humidity environment
 391 contribute to reduce the interstitial water increasing the proportion of free water in
 392 the voids.

In addition, although the initial moisture content increases with the time that specimens remained in high humidity environment (see Table 1), at the end of the drying process, when the hygrometric equilibrium was reached, all specimens showed similar moisture content independently of their initial curing period. Thus, if all specimens reached a similar final state in an analogous time but departing from different moisture contents, the rate of water dissipation had to be different, being faster in those specimens subjected to longest curing times. This statement supports the idea that specimens subjected to long periods of curing in high humidity environment had larger ratio of free water out of interstitial water. These cases showed faster initial drying because free water is easier to dissipate than interstitial water.

Not only curing time in high humidity environment affects the evolution of water dissipation. Observing Figure 4 it is noticed that the drying process of compressed earth is affected by the gravity, which tends to concentrate water in the voids of the lower area of the tested wall. Thus, ultrasound transmission speed is lower in the bottom of the wall and maximum at the top until the hygrometric equilibrium is reached. This analysis is supported by results from other researches like the ones presented by [23]. Moreover, in Figure 4 it can be noticed that the hygrometric equilibrium in the top half of the wall was reached around 50 days after removing the framework, when the ultrasound transmission speed at the top point and middle height point was stabilised.

Drying process of an earthen structure depends on its geometry, the earthen mixture composition, its production moisture content and the environmental conditions. Thus, ultrasound transmission method needs to be calibrated for every particular application if it has to be applied to quantify the moisture content of the material. The threshold value for the ultrasound transmission speed is set at 1100m/s for the tested compressed earth. Therefore, it can be considered that structures produced with the studied compressed earth are close to reach the hygrometric equilibrium when the transmission speed is over this threshold value.

However, from a general point of view, it is feasible to directly apply ultrasound transmission method to control the drying process and check that the hygrometric equilibrium has been reached by means of the stabilisation of ultrasound transmission speed. Checking the hygrometric equilibrium should be performed at the lower area of each earth batch because it is the part which requires more time to evaporate the water.

5.2. Determining the dynamic Young's modulus of earthen materials using ultrasound transmission technique

The dynamic Young's modulus of the compressed earth used in the wall was correctly predicted by using the results of ultrasound transmission technique to compare numerical simulations with the experimental modal analysis. The simulation carried out considering a Poisson's ratio of 0.35 and calculating the Young's modulus from the ultrasound transmission speed correctly met the experimental results obtained with modal analysis. The average error on the eigenfrequencies is around 3%, supporting

the idea that combining ultrasound transmission method with modal analysis is an easy non-destructive technique to evaluate the dynamic Young modulus of massive earthen materials and their corresponding Poisson's ratio. Table 3 summarises the results of the influence of Poisson's ratio.

Table 3. Comparison between the frequency of the 1st and 2nd vibrational modes of the compressed earth wall obtained with modal analysis and numerical simulation ($\nu=0.35$).

	<i>Frequency of 1st modal shape (Hz)</i>	<i>Frequency of 2nd modal shape (Hz)</i>	<i>Error of 1st modal shape (%)</i>	<i>Error of 2nd modal shape (%)</i>	<i>Average error (%)</i>
<i>Modal analysis</i>	69.4	87.2	---	---	---
<i>Simulation ($\nu=0.20$)</i>	92.0	103.2	32.56	18.35	25.46
<i>Simulation ($\nu=0.25$)</i>	87.1	99.5	25.50	14.11	19.80
<i>Simulation ($\nu=0.30$)</i>	80.9	94.2	16.57	8.03	12.30
<i>Simulation ($\nu=0.35$)</i>	73.1	86.6	5.33	0.69	3.00
<i>Simulation ($\nu=0.40$)</i>	62.4	75.3	10.09	13.65	11.87
<i>Simulation ($\nu=0.45$)</i>	46.4	56.9	33.14	34.75	33.94

Regarding the modal analysis implemented to study the feasibility of using ultrasound transmission method to obtain the dynamic Young's modulus, it is observed that the damping value of the first vibrational mode (torsion) is greater than for the second one (bending). This particular result would indicate that the second modal shape might define the vibrational response of the wall at long-term because the amplitude of the first mode decreases faster.

The theoretical first six modes calculated with the simulation had eigenfrequencies below 5mHz and corresponded to solid rigid movements, which provided no information about the Young's modulus. The seventh simulated mode corresponded to the first vibrational mode which was related with the structure deformation and matched to the first vibrational mode measured with modal analysis. In addition, the shape and order of the first and the second vibrational modes are the same in simulation than in modal analysis, supporting the idea that choosing clear boundary conditions is essential to obtain experimental results to be compared with a numerical simulation.

6. CONCLUSIONS

This study about the feasibility of applying ultrasound transmission method to assess earthen materials concluded that:

- Ultrasound transmission method is useful to identify the hygrometric equilibrium of earthen materials but requires a specific calibration process to correlate ultrasound transmission speed with moisture content.
 - Ultrasound transmission speed increases along the drying process of earthen materials although their apparent density decrease.
 - Gravity affects the water distribution in earthen structures, thus results of ultrasound transmission method depend on the position of the measurement.
- To make conservative decisions on the drying process it is recommended to perform the ultrasound measurements at the bottom part of the structure or production batch.

- A methodology combining ultrasound transmission method and modal analysis is suitable for determining the dynamic Young's modulus of earthen materials and their corresponding Poisson's coefficient.

In addition, the results of the study pointed a future research hypothesis, whose demonstration was out of the scope of the present paper:

- The relationship between the ultrasound transmission speed and the moisture content during the drying process shows an inflection point, which might correspond to a change in the source of the water being dissipated, from free water in the voids to interstitial water.

Finally, it is worth remarking that ultrasound transmission method has proved to be efficient at determining mechanical properties of raw earthen materials and controlling the typical drying process which characterise their production.

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