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EXPERIMENTAL DIAGNOSIS OF EARTHEN CONSTRUCTION: CHARACTERIZATION AND IN-SITU ESTIMATION

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ABSTRACT

Earthen buildings form one of the largest building stocks worldwide. This is true for more humble buildings, whilst of the 563 cultural sites that were inscribed on the World Heritage list, 17% are fully or partially built with earth (UNESCO).
Conservation and sustainable development are two disciplines that seem to be uncomfortably far from one another. However, there are several advantages in conserving earthen buildings: reduction of carbon footprint, improvement of occupant health due to building quality, and keeping with cultural continuity. The environmental credential of earth as building materials relates to the fact that manufacturing and conservation does not deplete significantly finite natural resources, but also that handmade, air-dried materials have the lowest embodied energy and recycling or disposal does not require high levels of energy. Earth materials create low levels of waste and generally cause no direct environment pollution during the whole life cycle.
However, if not properly protected, earthen materials can be vulnerable to decay and damage. In fact, earthen buildings present a very low tensile strength, a low compressive strength and a fragile behaviour, and are generally speaking vulnerable to earthquakes. These considerations, and the present lack of guidelines for the

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conservation of earthen buildings, point to the necessity of studying proper diagnosis techniques with the objective of being the basis for adequate intervention methods.
The aim of this paper is to provide an overview of available tests both for earth material characterization (chemical, physical and mechanical) in the laboratory, and in situ estimation of its morphology and its mechanical behavior.

Key words: Earthen Construction, Rammed Earth, Earth Material Characterization, Diagnosis Techniques, Mechanical Behaviour.

Introduction

An important part of the world population live or work in earthen buildings (Figure 1). Earth, as construction material, it has been used since ancient times. As a result, we dispose of a large stock of architecture built on earth. As a reference, from the 563 cultural sites that UNESCO includes in its "World Cultural Heritage List", 96 (17%) are fully or partially built on earth (UNESCO World Heritage Centre).

FIG 1. World distribution of the earthen construction (Houben and Guillaud 1989).

Earthen construction is located virtually all over the world1 (Figures 2-7) showing a particular impact on developing countries, where other building materials have limited use and traditional building are still rooted.
There are many good reasons to use earth masonry or maintain the existing constructions. The main ones are environmental sustainability, occupant health, building quality and cultural continuity (Morton 2008). The manufacture of earth masonry materials does not significantly deplete finite natural resources. Hand-made, air-dried materials have the lowest "embodied energy". Long-term inputs, such as processes of recycling or disposal of earth masonry materials, do not require high levels of energy. Earth materials create extremely low levels of waste, all of which is benign and easily disposed of, and generally cause no direct environment pollution during the whole life cycle.

FIG 2. City wall of Khiva (Uzbekistan).

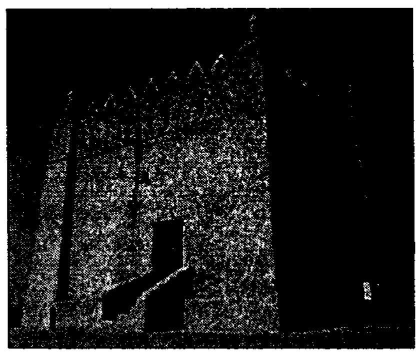

FIG 3. Hili Tower (Al Ain, United Arab Emirates).

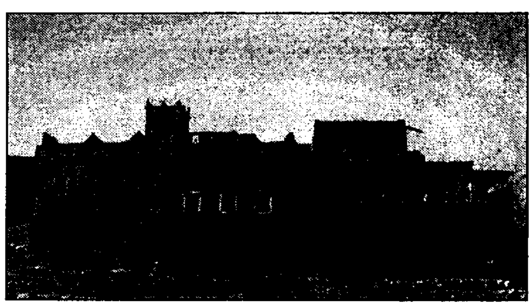

FIG 3. Ksar in the Draa valle (Morocco).

Nevertheless, earthen materials are usually more sensitive than modern ones, since they are more vulnerable to external aggressive agents. In fact, earthen materials present a very low tensile strength, a low compressive strength and a fragile behaviour, making the earthen structures, for example, strongly vulnerable to earthquakes (Blondet and Villa 2004; Silva et al. 2009). These considerations point the necessity of taking in account diagnosis techniques with the objective to evaluate the state of conservation of the earthen built heritage and adopting methodologies of intervention in order to preserve these constructions.

FIG 5. Moulded earth in Moenjodaro (Pakistan).

FIG 6. Mud brick building in Serramanna (Sardinia, Italy).

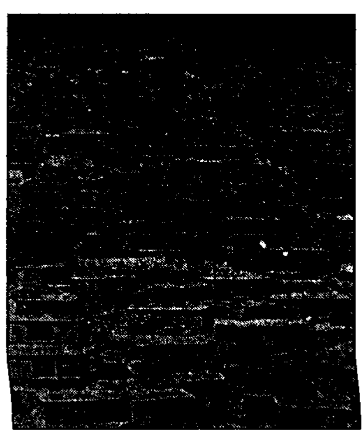

FIG 7. Mud brick terraced buildings in Upper Zerafshan (Tajikistan)

In recent years, several worldwide investigations have been conducted on this type of construction, leading to developments in the materials characterization, possible additions (stabilizers and fibers) to optimize its mechanical behavior, and structural assessment under static and cyclic loads. To a first approximation to the subject, the reader is referred to the bibliographic databases published by "The Getty Conservation Institute" (2002 and 2008).
More specifically, with regards to the materials characterization, studies have been devoted to the physical-mechanical and mineralogical characterization of earth material (Pagliolico et al. 2010), other studies have been focused to study possible stabilizers (Jayasinghe y Kamaladasa 2007; Venkatarama and Prasanna 2011), with or without fibers (Binici et al. 2005; Yetgin et al. 2008), and other aimed to the mechanical performance of earth performing on specimens at different scales (Bui et al. 2009; Piattoni 2011).

In terms of possible reinforcements applicable, several experimental campaigns, covering a wide type of reinforcement systems, have been conducted.

- Reinforced by plastic mesh in horizontal joints (Turanli and Saritas 2011).
- Reinforced by steel anchorages (Gomes et al. 2011).
- Reinforced by masonry (Gomes et al. 2011).
- Reinforced by concrete structures (Gomes et al. 2011).
- Reinforced by polymer mesh (Torrealva 2009 and 2009-a; Torrealva et al. 2008; Vargas et al. 2007).
- Reinforced by Integral Masonry System (IMS): Incorporating a three-dimensional structure through steel trusses. (Orta et al. 2009).
- Grouting (Silva et al. 2009)
- Reinforced by welded wire mesh protected with a cement mortar (Juárez et al 2005; Quiun et al. 2005; Yamin et al. 2007 and 2004).
- Confining reinforcement with wooden elements (Yamin et al. 2007 and 2004).
- Reinforced by FRP bars (Villa et al. 2004).
- Reinforced by steel bars (Lilley and Robinson 1995).

As already mentioned, earthen construction is strongly vulnerable to earthquakes. As a reminder may refer the earthquake in Bam-2003, Iran, magnitude 6.3 (Mehrabian and Haldar 2005) or the earthquake in Pisco-2007, Peru, magnitude 7.9 (San Bartolomé and Quiun 2008).
Because of mentioned disasters, several experimental campaigns have been undertaken in the last decade. They were devoted to evaluate the effectiveness against earthquake of several reinforcements applied to earthen structures (Blondet and Aguilar 2007; Ginell y Tolles 2000; Islam and Iwashita 2010; Leroy y Krawinkler 1990; San Bartolomé et al. 2009; Torrealva 2009 y 2009-a; Yamin et al. 2007 y 2004). Some of these experiences finish with earthquake shaking table tests on reinforced and unreinforced earth.

The case of Spain

Spanish Earthen Heritage is wide ranging: several of these buildings are included in the list of World Heritage of UNESCO (Alhambra monumental complex in Granada). In addition, more than fifty buildings are protected by different Spanish heritage Legislations.

Earthen architecture in Spain has been used since ancient times. The high density of structures of rammed earth in the Iberian Peninsula is due, primarily, to the presence of Muslims since the 8th century. In this sense, earth was used extensively in the construction of fortifications, defensive walls and towers. It was also widely used in religious buildings, like churches, synagogues and mosques.

There are many examples of earthen buildings that have survived for centuries such as those of Andalusia, Valencia, Castile-la Mancha, Murcia, Aragon, and Castile and León. As notable examples of earthen architecture in Spain one can refer to the Alhambra monumental complex (Figure 8), the castle of Baños de la Encina (Figure 9), the defensive walls of Niebla (Figure 10), the Moorish fortifications (Alcazaba) of Guadix and Almería, and the fortress (Alcázar) of Sevilla.

FIG 8. Alhambra (UNESCO World Heritage site since 1984).

FIG 9. Castle of Baños de la Encina.

FIG 10. Niebla defensive walls.

Some buildings, due to its significance, have been subject to conservation work, while smaller ones have suffered a gradual decline with the passing of the years (Figure 11). In Spain, despite its important set of heritage built with earth, scientific and technical research on the conservation of these structures is at its infancy. This is mostly due to practitioners' lack of knowledge of the material and of proper diagnosis. As a result, current interventions, on occasions, are inappropriate.

As it is the case for any other construction technique, the adequate conservation and rehabilitation of earthen architecture is obtained through proper diagnosis and subsequent understanding of applicable techniques of intervention.

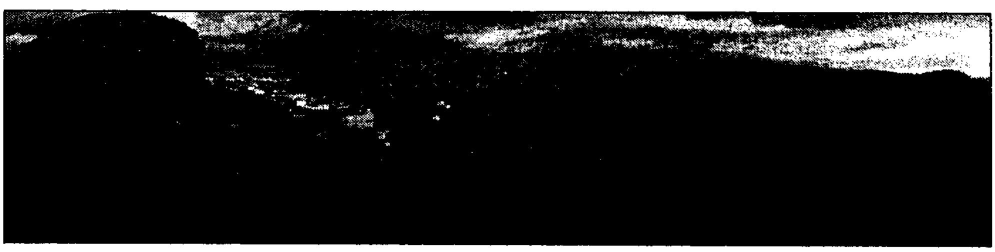

FIG 11. Samples of constructions in rammed earth in Aragonese village of Daroca.

In this regard, in the following sections, a brief enumeration of several applicable laboratory techniques for the characterization of the earth material is explained. Several Non/Minor Destructive Tests (N-MDT), which are useful in masonry structures diagnosis, will be explained because the authors think that these in situ diagnosis techniques could be useful to study both earth masonry (mud brick) and rammed earth. The suggested techniques will be completed with references to the key literature. Finally, some experimental results reached through some of the mentioned techniques will be briefly presented.

Experimental diagnosis of Earthen Construction

In order to give support to interventions to be adopted in old buildings, accuracy, detail and a special training in the development of diagnostic studies are required.

In this process, the survey-analysis phase is essential, because it is at this stage where hypotheses are set out and verified through calculations and tests. Within this phase, special attention should be paid to experimental surveys, since such inspection contributes to obtain input parameters for creating the model of analysis. The experimental survey also contributes to model calibration using the experimental verification of the results obtained analytically at certain checkpoints.
The aim of this section is to provide an overview of available tests both for earth material characterization in laboratory, and in situ estimation through minor destructive tests (MDT).

Laboratory tests

These tests usually are focused to identify chemical, physical and mechanical properties of materials (Fodde 2007; Fodde et al. 2007), and to know the mechanical performance of medium or large scale specimens. In TABLE 1 are listed the most commonly used laboratory tests.

TABLE 1. Laboratory tests mostly used for characterization of earthen materials.

<table>
<tr><th>Characterization</th><th colspan="2">Technique</th></tr>
<tr><td>Chemical</td><td colspan="2">Soluble salts content
Carbonates content
Measurement of pH
Elemental microanalysis with energy dispersive X-ray spectroscopy (EDAX)
X-ray fluorescence (XRF)
Mineralogical analysis by X-ray diffraction (XRD)
Microscopy</td></tr>
<tr><td>Physical</td><td colspan="2">Density
Porosity
Capillary absorption
Soil colour
Particle size distribution curve
Atterberg limits (plastic limit, liquid limit, and plasticity index)
Proctor test</td></tr>
<tr><td rowspan="2">Mechanical</td><td>Small scale specimens</td><td>Compressive strenght (σ_r, E y v)
Bending strenght</td></tr>
<tr><td>Medium and large scale specimens</td><td>Compression / Shear / Bending tests
Combined compression and shear tests
Test walls construction
Earthquake shaking table tests</td></tr>
<tr><td>Durability</td><td colspan="2">Freeze and thaw test
Wetting and drying test
Abrasion test
Erosion test
Shrinkage test</td></tr>
</table>

Non/Minor Destructive diagnostic Techniques (N-MDT) for in situ estimation

It is desirable often those experimental surveys are performed in the least intrusive way, especially in the case of monumental constructions. With this objective in mind, this section insists on the on-site experimental survey stage, through Non/Minor Destructive Methodologies (N-MDT). TABLE 2 lists some N-MDT techniques which may be used for the in situ estimation of earthen materials.

TABLE 2. Some N-MDT techniques which may be used to the in situ estimation of earthen materials.

Group	Technique	Foundation	Objectives	References
Techniques based in mechanical criteria	**Simple flat jack**	Relaxation of stress.	Local stress associated to a determinate cutting plane.	Binda et al. 2003; Binda & Tiraboschi 1999a; de Veckey 1995; Lombillo 2010; Noland et al. 1990; Ronca et al. 1997; Rossi 1987
	Double flat jack	In situ compressive test of a specimen.	Deformational parameters (Elasticity modulus and Poisson's ratio). Estimation of the compressive strength.	
	Shear Test	In situ shear test of a specimen for different levels of vertical load.	In situ measurement of shear strength index. ζ-σ relationship.	Abrams & Epperson 1989; Atkinson et al. 1988; Lombillo 2010
	Hole drilling	Relaxation of stress.	Local stress.	Lombillo 2010; Sánchez-Beitia & Schueremans 2009
	FreD	Relaxation of stress and in situ compressive test of a specimen.	Local stress. Deformational parameters (Elasticity modulus and Poisson's ratio). Estimation of the compressive strength.	Gutermann & Knaack 2008
	Dilatometer	Probe exerces a known radial stress versus the surrounding material.	Deformational parameters (Elasticity modulus and Poisson's ratio). Estimation of the compressive strength.	Almeida 2000; Lombillo 2010; Mónaco & Santamaria 1998
Techniques based in (acoustic and electromagnetic) waves propagation	**Ultrasonic test**	Measure of the ultrasonic wave's propagation time. It's not suitable to assess heterogeneous materials	Test allows the physical and mechanical properties estimation through correlations with ultrasonic wave speed. Speed range is linked with material quality.	Abbaneo et al. 1996; Binda et al. 2003a; Binda et al. 2001; Binda et al. 1999c; Carino 2001; Colla et al. 1997; Lombillo et al. 2009; Sadri 2003; Valluzzi et al. 2009
	Sonic test	Measure of the sonic wave's propagation time. It's more suitable than ultrasonic test to assess heterogeneous materials	Qualifying masonry structures, detecting internal voids and defects, controlling effectiveness of injection processes in structures, etc.	

	Impact echo test	Studying sonic or ultrasonic wave reflection in interfaces with different acoustic impedance.	Qualifying earthen structures, detecting internal voids, defects or interfaces between different materials, etc.	.
	Infrared termography	Display of the infrared radiations of electromagnetic spectrum which are invisible for the human eye	Humidity detection, location of blinded windows or doors, cracks identification, etc.	Clark et al. 2002; Grinzato et al. 2002; Maierhofer & Rollig 2009; Maierhofer et al. 2005
	Radar	Studying electromagnetic wave reflection in interfaces with different dielectric properties	It is useful for detecting zones with moisture, voids, or other discontinuities, as an alternative to ultra-sonic tests. It also allows for the detection of different materials, such as steel or wood, inside the construction.	Binda et al. 2003a; Binda et al. 1999b; Colla et al. 1997; Maierhofer & Wöstmann 2003; Maierhofer & Leipold 2001; Perez-Gracia et al. 2009; Vintzileou et al. 2004
	Geoelectric techniques	Changing of the electric resistivity	Detecting internal voids and defects, controlling effectiveness of injection processes in structures, etc.	Keersmaekers et al. 2004; Van Rickstal et al. 2008
Other Techniques	**Tomographic techniques**	It is a computational technique what supposes processing of a large amount of data. The aim is to reproduce the internal structure of an object through superficial measures (acoustic, radar, etc.)	Technique provides a distribution map of a physical property (for example acoustic wave's speed) in the interior of a structural element. Technique allows detecting voids and defects, etc.	Binda et al. 2003; Cardarelli 2005; Valle et al. 1998
	Endoscopy	Internal visualization of elements and the conditions of the materials around holes drilled in those elements, from outside.	Defects' size, internal voids, bearing wall's morphology (multi-leaves walls), etc.	Alavalkama et al. 1993 (eds.); Diez 2007; Vintzileou et al. 2004
	Dynamic characterization	Obtaining the main vibration frequencies	Evaluating dynamic properties of structural elements	Binda et al. 2000; Gallino et al. 2009; Gentile & Saisi 2007; Ivorra & Pallares 2006; Ramos et al. 2007; Roca 2007
	Monitoring	Control of the temporal evolution of a determinate property (through the use of sensors)	Knowledge of the temporal evolution of the structure movements, the temperature variation, etc.	Anzani et al. 2008; Marcos & San Mateos 2007; Oliveira et al. 2005; Roca et al. 2001

	Penetration resistance	Relationship between mechanical properties of the earthen component and its penetration resistance	Providing an idea about the earthen component quality	Magalhães & Veiga 2006; Tavares et al. 2008; Veiga & Carvalho 2000
	Sphere impact	Relationship between mechanical properties of the earthen component and its energy absorbed when a device impacts on its surface	Providing an idea about the earthen component quality	Magalhães & Veiga 2006; Veiga & Carvalho 2000
	Rebound tests	Relationship between mechanical properties of the earthen component and its energy absorbed when a device impacts on its surface	Providing an idea about the earthen component quality	Tavares et al. 2008
	Pull-out test or helix test	Relationship between mechanical properties of the earthen component and the pull-out force to extract a device which had been previously introduced in it.	Providing the pull-out strength of the earthen component and, as consequence, cumulative indication about its quality.	de Vekey & Sassu 1997; Tavares et al. 2008

Practical case:
Mechanical characterization of a rammed earth wall through MDT Techniques

FIG 12 to 14 illustrates the process of construction of the rammed earth wall (Lombillo 2010). Several compression tests were performed on cylindrical samples made with the same earth used in the construction of the wall. The following data were obtained: stress-strain curve, compressive strength and strain in fracture. FIG 15 and 16 illustrate one of the tests, as well as the stress-strain curve obtained. The results are summarized on TABLE 3.

FIG 12. Progressive dumping of earth and its compaction by ramming.

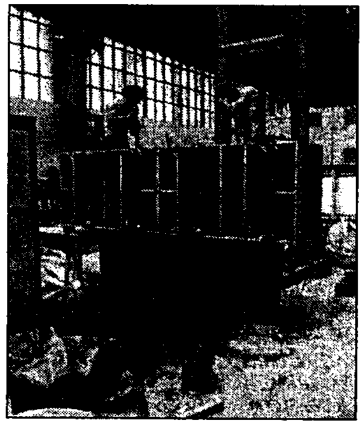

FIG 13. Progressive dumping of earth and its compaction by ramming.

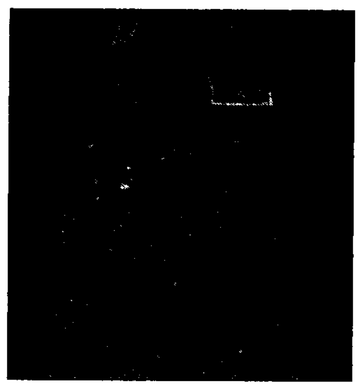

FIG 14. Progressive dumping of earth and its compaction by ramming.

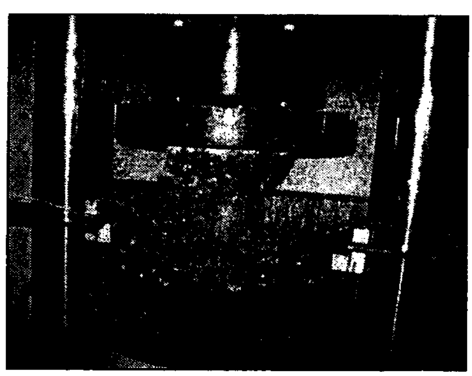

FIG 15. Test on specimen T2 and the stress-strain curve obtained.

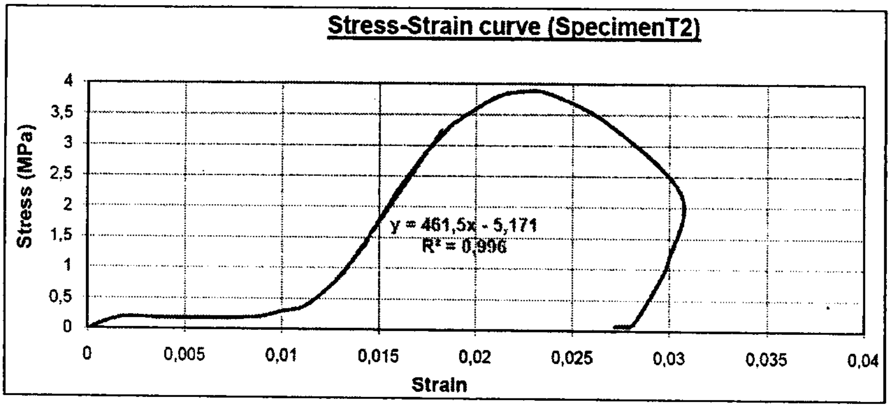

FIG 16. Test on specimen T2 and the stress-strain curve obtained.

TABLE 3. Compressive strength (σ_c), elasticity modulus (E) and strain in fracture (ε_r) of rammed earth specimens.

Specimen	Φ (cm)	H (cm)	σ_c (N/mm^2)	E (N/mm^2)	ε_r (%)
T1	15	15.8	3.4	386.55	2.59
T2	15	19.3	4.0	461.57	2.38
T3	15	19.5	2.7	296.84	2.45
T4	15	19	3.7	419.2	1.77
T5	15	14.6	2.0	127.22	2.97
T6	15	11.5	4.4	296.72	2.15
T7	15	28.5	2.7	549.76	0.63
T8	15	17.5	2.5	334.34	0.97
	Average:		3.2	359.0	2.0
	Coefficient of variation (%):		26.1%	35.4%	41.0%

Flat jack tests

On the rammed earth wall were developed a simple and a double flat jack test (FIG 17 and 18). The stress obtained in the simple flat jack test was contrasted with the theoretical stress in the same area of testing. For its part, the modulus of elasticity and the Poisson's ratio obtained in the double flat jack test were contrasted with the mechanical properties previously estimated by transducers for the registration of displacement. During the test, a clear convergence of the deformations' evolution in one point was recorded. This point, so-called point of residual displacement (Ronca et al. 1997), served to establish a stress of 1.45 MPa (FIG19). FIG 20 presents the stress-strain curves obtained through double flat jack tests, after of 4 cycles of loading and unloading.

FIG 17. Cutting process of the slot for the insertion of the flat jack. Pressurization process and control of the evolution of deformation.

FIG 18. Cutting process of the slot for the insertion of the flat jack. Pressurization process and control of the evolution of deformation.

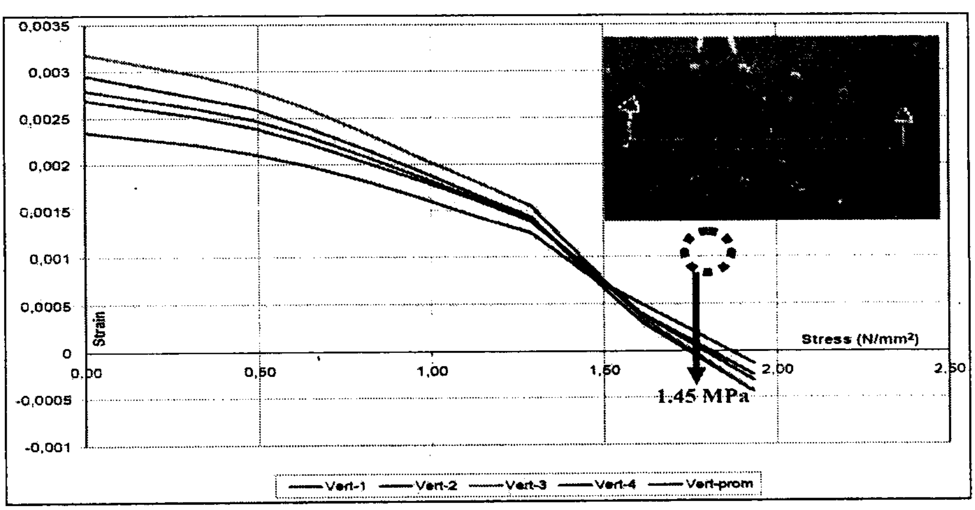

FIG 19. The stress obtained through simple flat jack was 1.45 MPa.

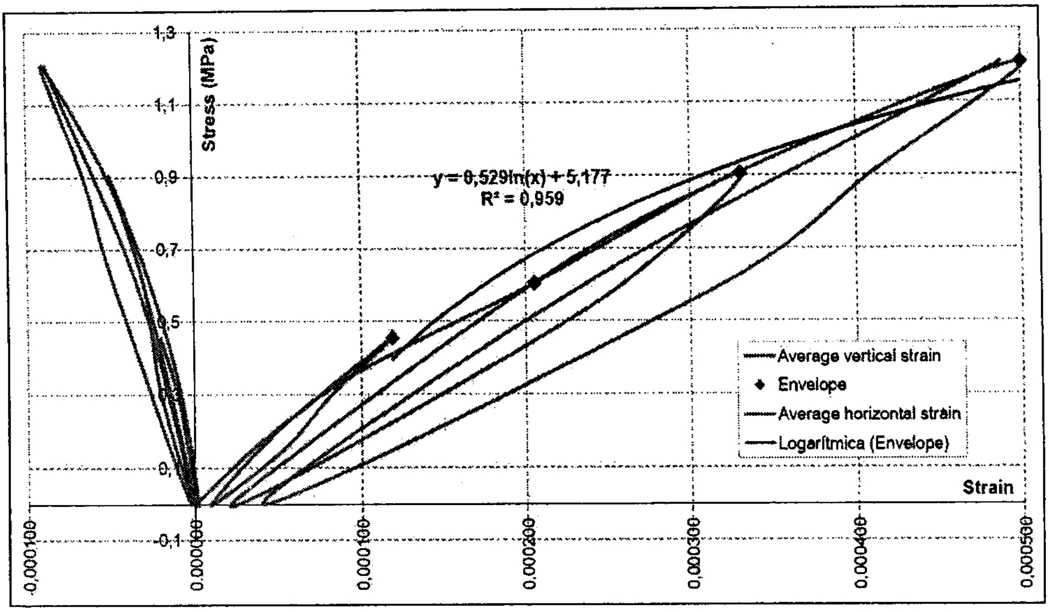

FIG 20. Obtained average σ-ε laws in the trial of flat cat double has done. It also represents a logarithmic fit (R^2 0.959) curve envelope of charge cycles.

These curves show a linear behavior of the rammed earth wall until 0.45 MPa. The non-linear behavior of the loading cycles was represented through a logarithmic envelope curve (Kubica 1996). Based on this envelope curve a stress associated to a strain of 2% was estimated. This strain corresponds to the strain in fracture obtained in the compression tests on cylindrical rammed earth samples as tested previously. The estimated stress reached a value of 3.10 MPa which is equivalent to the average compressive strength obtained in compression tests of cylindrical samples already referred to (TABLE 3). Also, from the curves could be obtained a secant modulus of elasticity of 3,170.66 MPa and a Poisson coefficient of 0.16. TABLE 4 summarizes the obtained results.

TABLE 4. Contrast of vertical stress and the mechanical properties of the rammed earth wall.

Flat Jack test	$\sigma_{exp.}$ (MPa)	$\sigma_{theor.}$ (MPa)	$\sigma_{exp}/\sigma_{theor}$	v_{exp}	E_{exp} (MPa)	$E_{transductors}$ (MPa)	$E_{exp}/E_{transductors}$
Simple	1.45	1.19	1.22	-	-	-	-
Double	-	-	-	0.16	3,170.66	1,394.00	2.27

The theoretical vertical stress at the level where the simple flat jack test was performed was 1.19 MPa. It can be seen that the error in the estimation of the vertical stress was 22%. On the other hand, the relationship between the modules of elasticity was 2.27.

<u>Hole drilling tests</u>

Three hole drilling tests were conducted on the rammed earth wall, but only one of them could be finished successfully for reasons which will be explained later. These tests had the purpose of estimating the vertical stress in different parts of the rammed earth wall. After the gluing of the strain gauges (FIG 21), the drilling was executed (FIG 22). FIG 23 illustrates an overview of the test.

FIG 21. Gluing of the strain gauges on the rammed earth wall.

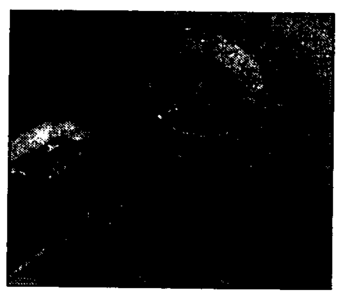

FIG 22. An instant during the drilling carried out on the wall.

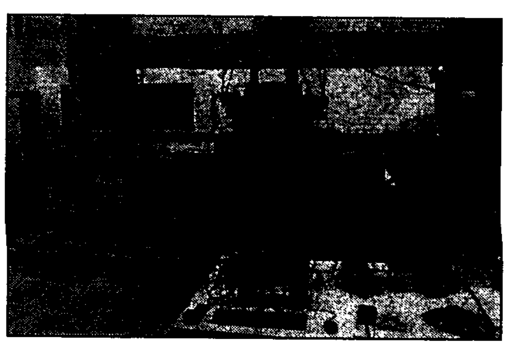

FIG 23. Overview of one of the hole drilling tests.

FIG 24 presents the deformations' evolution recorded by each of the eight strain gauges, before and after the drilling.

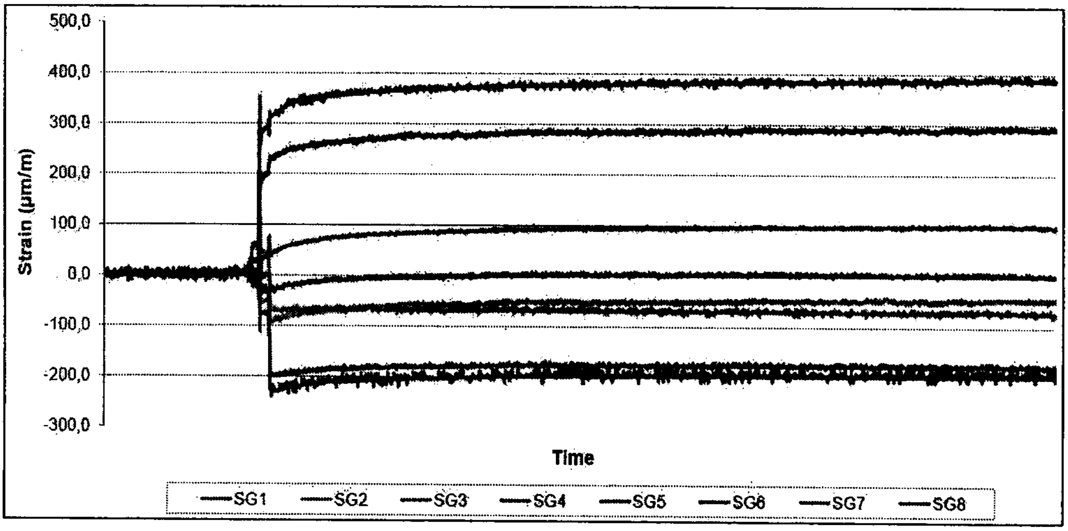

FIG 24. Final register for the processing of the hole drilling test. At the end of the test the eight strain gauges showed fluctuations less than ±5 μm/m, so the registry associated with each one of them was considered valid.

TABLE 5 shows the strain variation, from before to after the drilling, suffered by each of the eight strain gauges.

TABLE 5. Variation recorded by the strain gauges.

Strain Gauge	SG1	SG2	SG 3	SG 4	SG 5	SG 6	SG 7	SG 8
ε (μm/m)	290.2	-47.0	-70.3	98.6	385.5	-193.9	-176.2	3.6

From the above mentioned variations, Table 6 presents for each combination of three strain gauges, the maximum and minimum principal stresses, σmax and σmin, the angle (β), measured clockwise, between the maximum principal stress and the direction of the first strain gauge of the combination, and, finally, the vertical stress (σvert). The stress estimated in the test was 1.04 MPa (compression) with a coefficient of variation of 6.0%. The vertical theoretical stress existing at the testing point was 1.16 MPa. Therefore, the relationship between the experimental stress obtained by the hole drilling test and the theoretical one was 0.91. This circumstance seems to confirm that this methodology might be applicable to rammed earth structures. In turn, as it has already mentioned earlier, other two hole drilling tests were conducted. In both cases the presence of aggregates of appreciable size made impossible to get consistent results, because during the drilling process, these aggregates were intersected by the drill with the consequent chipping of the testing area. As a result the strain recorded by the strain gauges cannot be related with purely mechanical phenomena.

TABLE 6. For each combination of three strain gauges are presented: The maximum and minimum principal stresses, σ_{max} and σ_{min}, the angle (β), measured clockwise, between the maximum principal stress and the direction of the first strain gauge of the combination, and the vertical stress (σ_{vert}).

Combination	Strain Gauges	σ_{max} (MPa)	σ_{min} (MPa)	β (°)	σ_{vert} (MPa)
1	1, 3, 6	0,44	-1,6	60	-1,09
2**	2, 4, 7	0,48	-0,76	35	-0,72
3**	3, 5, 8	-0,04	-1,62	17	-1,48
4**	4, 6, 1	1,31	-0,81	-57	-0,72
5**	5, 7, 2	0,37	-1,47	76	-1,36
6*	6, 8, 3	0,79	0,21	-7	0,57
7	7, 1, 4	0,38	-0,98	-5	-0,97
8	8, 2, 5	1,29	-1,06	-47	-1,06

* The combination n° 6 has not been taken into account because it leads to a tensile stress of 0.57 MPa, which is entirely discordant with the other combinations. With the other 7 combinations is obtained a mean stress of 1.06 MPa (compression) with a coefficient of variation of 27.49%.
** With the objective of getting a coefficient of variation less than 10%, the combinations 2, 3, 4 and 5 have not been taken into account to obtain the mean stress. The sign - indicates compression.

Mini-presurometer tests

The experimental work through mini-presurometer consisted of two tests. Once the drilling was performed, the probe was introduced (FIG 25). Then the probe was pressurized to different levels of pressure, registering the volume of water injected into the probe at each pressure (FIG 26).

FIG 25. Mini-presurometer test on the rammed earth wall.

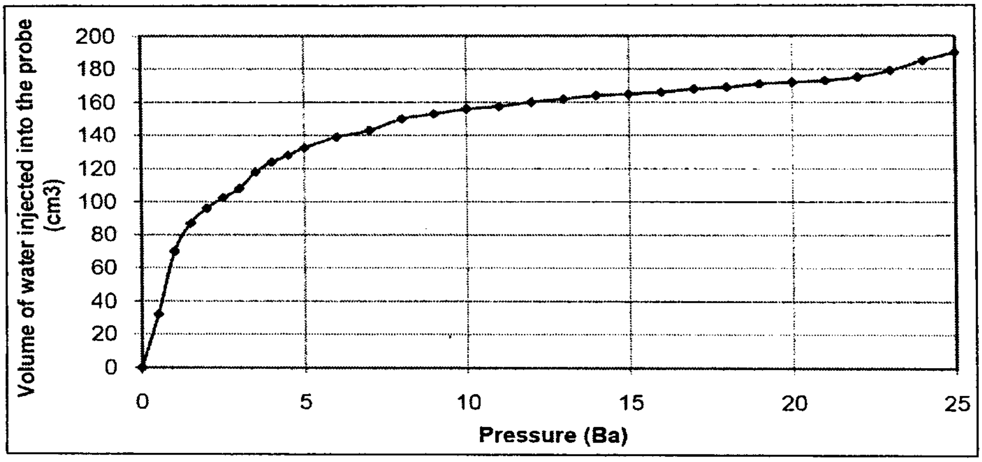

FIG 26. Injected volume – Pressure curve obtained in one of the tests.

After the tests, the presiometric modulus (E_{PMT}) could be obtained and the compressive strength (p_L) of the rammed earth component was estimated. Tests results are summarize in TABLE 7.

TABLE 7. Compressive strength (p_L) and presiometric modulus (E_{PMT}) estimated for the rammed earth wall.

Test	p_L (MPa)	E_{PMT} (MPa)
1	3.4	49.7
2	4.9	42.1
	4.2	**45.9**

The value obtained for the compressive strength is substantially of the same order as in the previous tests. On the other hand, the so-called presiometric modulus does not seem to correspond directly with the longitudinal modulus of elasticity, because of the value is much lower than the retrieved with other tests.

Conclusions

A significant catalogue of possible Non/Minor Destructive Methodologies (N-MDT) for implementation in earthen constructions diagnosis was explained. The main aim was to lead to more accurate and less aggressive diagnosis of buildings. As a result, interventions on these constructive types could be optimized.

By way of example, some of these N-MDT techniques have been applied in laboratory on a rammed earth component, and the results achieved have been exposed. On the basis of the limited number of tests carried out, it can be argued that the estimation of the stress in earthen components could be estimated with relative accuracy using both the simple flat jack technique and the hole drilling test. However, in relation to this last technique, difficulties associated with the dispersion of aggregates of appreciable size in the volume of the rammed earth makes complicated its practical applicability. In addition, it would be required to perform further testing to endorse the suitability of both methodologies.

With regard to the estimation of the compressive strength, the results reached through double flat jack and mini-presurometer tests were congruent, ranging around 3.5 MPa. Worst results were obtained for the modulus of elasticity. This fact points to the need to delve into this line of work in future research.

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