

Characterization of adobe bricks used in developing countries: Mexico as a case of study

Caracterización de ladrillos de adobe usados en países en desarrollo: México como caso de estudio

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Abstract

In Mexico adobe masonry is a traditional building material common in rural areas with low economic development and a high degree of marginalization. In addition, a growing interest in adobe masonry is noticed in two ways: for rescuing the heritage and as a rediscovered environmentally friendly building material. The problems are found of how to carry out the conservation works of the great built heritage with this material, as well as the lack of skilled people at all levels, from designer to masons, because it is a forgotten technique. Hence, some recent investigations about the obtention of adobe mechanical properties and characterization of adobe bricks, including earth blocks, have been performed. This article investigates experimentally destructive and nondestructive tests used for this purpose, especially elastic mechanical properties, considering new sensors, systems and different techniques has led to the inspection of adobe bricks. The results show, compared destructive with nondestructive methods, a good correlation between both techniques. This study contributes towards a better understanding of the elastic mechanical properties of adobe bricks built in Mexico, considered as a developing country.

Adobe masonry, Destructive tests, Nondestructive tests

Resumen

En México, la mampostería de adobe es un material de construcción tradicional, común en áreas rurales con bajo desarrollo económico y alto de grado de marginación. Además, un interés creciente en la mampostería de adobe se ha desarrollado de dos maneras: como rescate de patrimonios y como redescubrimiento de un material de construcción amigable con el ambiente. La problemática se encuentra en cómo llevar a cabo trabajos de conservación en construcciones consideradas como patrimonios construidos con este material, así como la falta de personal capacitado en todos los niveles, desde el diseñador hasta los albañiles, por ser una técnica olvidada. Debido a esto se han realizado algunas investigaciones recientes sobre la obtención de propiedades mecánicas del adobe y la caracterización de ladrillos de adobe, incluidos los de tierra. Este artículo investiga experimentalmente ensayos destructivos y no destructivos utilizados para tal fin, especialmente para obtener las propiedades mecánicas elásticas, considerando nuevos sensores, sistemas y diferentes técnicas que se han llevado para la inspección de ladrillos de adobe. Los resultados obtenidos de la comparación entre métodos destructivos y no destructivos muestran una buena correlación entre ambas técnicas. Este estudio contribuye a una mejor comprensión de las propiedades mecánicas elásticas de los ladrillos de adobe construidos en México, considerado como un país en desarrollo.

Mampostería de adobe, Ensayes destructivos, Ensayes no destructivos

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Introduction

The lack of territorial planning due to the disorderly growth of the population and the migratory flow generates a problem in the basic services for the integral development of a family. Housing is one of the human needs of great concern, one of the reasons why many people do not build their homes with industrialized materials that provide good structural security such as concrete, brick masonry and steel is due to the lack of economic resources. According to the CONEVAL (2015) the population living in poverty in Mexico was 55.3 million people. At the same time, the population in extreme poverty was 11.4 million people, which is equivalent to 44%, and 9% respectively of the total population of the country. (CONEVAL, 2015).

An alternative in the construction of a house is a building process with an adobe masonry that despite being traditional is considered a symbol of poverty. However, in several states of the country, programs for the construction of adobe houses have been implemented with the purpose of achieving decent housing in the social context.

Adobe housing is a traditional type of construction in many developing countries due to that the materials used in adobe houses are earth, straw (Salazar-Hernández, *et al.*, 2021), and water for the walls, with wood in the roof system, all items that are found in the local environment, making construction feasible. In Mexico, first, earth is excavated from an area near the place of construction.

That earth is then combined with straw and water until a uniform and malleable mixture is obtained. Finally, the mixture is placed in wooden molds to create the pieces of adobe, these are allowed to dry in the open air for approximately 30 to 60 days. Adobe has several disadvantages when compared to materials such as clay brick masonry and concrete. For example, adobe has low resistance to bending, shearing and axial compression forces (Bassoud *et al.*, 2021; De Filippi *et al.*, 2021). In addition, adobe degrades physically from the weathering to which it is exposed during its useful life.

Adobe houses built in Mexico are one-story dwellings (Figure 1). The rectangular floor plans have average areas of 30 to 50 m², the longitudinal walls are 2.4 to 2.7 m high and the transverse walls are 3.0 to 3.9 m high. Wall thickness is typically 28 to 35 cm. Adobe houses do not usually have intermediate dividing walls (Figure 1). They have one or two access doors, located on the longitudinal walls, 0.7 to 1.2 m wide and approximately 2 m high. Typically, there is a 0.3 to 1 m² window on a longitudinal wall. Wooden lintels, 3 to 5 cm thick with supports approximately 20 to 30 cm long, are placed on the doors and the windows.



Figure 1 Typical adobe houses in Mexico
Self-Authorship

The pieces of adobe are joined with a mortar composed of soil, water and dry grass to form a sludge; the joints are approximately 2.5 to 3.5 cm thick. The foundation is usually constructed of basalt masonry and the same mortar that is used for the pieces of adobe. The foundation starts 60 to 80 cm beneath the surface and continues up to 30 to 40 cm above the ground to avoid weathering of the bottom of the adobe walls (Arroyo, 2010).



Figure 2 Roof system in adobe houses
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The roof system (Figure 2) is either flat or pitched at an inclination anywhere from 15 to 30 degrees. The roof cover is fabricated from annealed clay tile mounted on a robust longitudinal wooden beam that rests on the transverse walls (head walls) and on two wooden struts; the latter are connected to a transverse beam, equally spaced, and resting on the longitudinal walls.

Wooden rafters, also known as "madrinas" or battens, are placed approximately 60 cm apart on the walls and longitudinal beam rest. Transversing the rafters, wooden laths are placed every 25 cm to support the annealed clay tiles (Figure 2).

For the fabrication of adobe bricks, the mixture of the materials is done by hand, it is the materials (Figure 3a) and auxiliaries with a hoe, as a result a more uniform and malleable mixture is obtained. To this was added more water for use in wooden molds (Figure 3b).

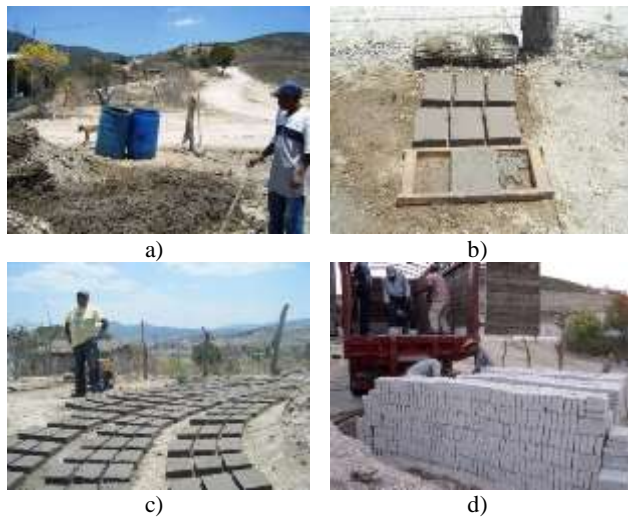


Figure 3 Fabrication and transportation of adobe bricks: a) mixture of materials; b) wooden molds; c) adobe bricks are dried under the sun; d) Transportation of adobe bricks. Self-authorship

The mold is well filled, it is compacted with the fists until it is sure that there are no air spaces. It is recommended to pair with a metal or wood ruler the wooden molds for the adobes, following the traditional procedure for the elaboration of the pieces. We let it stay in water for a day so that it absorbs enough water. Later, they were placed on the ground, this has to be flat, dry and outdoors in a place (Figure 3c) where they received direct sunlight and plenty of air to dry completely during 1 to two months approximately. Then the pieces are transported to use them (Figure 3d).

The adobe constructions must comply with several important aspects of construction, such as low cost, safety to live, comfort and, at the same time, must be sustainable. Fortunately, historical monuments and heritage conservation have also been important to them, for that reason there have been several works to study forms to know their structural and superficial health.

Because their ancient value these buildings or monuments, in some cases, cannot be used in destructive or invasive tests so many non-destructive test systems have been developed as well as described by García-Diego (2012).

The study of ancient materials and technic is opportune to validate their mechanical properties and determine how convenient it is to build with them (García-Diego, 2012). In the field of construction, several studies have been carried out to try to identify the mechanical properties of adobe masonry and its structural behavior within contractions and. Adobe is a block made of earth and natural fiber and has been part of the construction since 1500 and 1000 BC in China and became popular in 206-220 AD. C. Today, it is used in countries such as China, India, Turkey, Mexico, etc. (Wu *et al.*, 2012). Invasive and destructive tests have been applied to this material with good results, which allows to determine the capacity of resistance, rigidity and deformation when the load increases, as explained in Silveira *et al.* (2012) and Lima *et al.* (2012).

However, there are buildings that cannot be exposed to regular breaks, due to their low resistivity, are impossible to transfer to a laboratory or only because of their historical value should not be touched (Křžan *et al.*, 2015). These are reasons to perform non-destructive tests (NDTs). The NDT methods are non-invasive and have been used for approximately forty years in the structural analysis of civil engineering and the determination of material mechanical properties. In this case, ultrasonic systems have been one of the best ways to study the properties of materials without damaging buildings (Niederleithinger *et al.*, 2015). Concrete is usually examined with destructive tests, but ultrasonic testing has also been used to measure the elastic properties of the concrete and assess degradation without damage, as shown in Niederleithinger *et al.*, 2015.

Lately, a new growing interest in adobe masonry has been noticed as an environmentally friendly building material (Laborel-Préneron *et al.*, 2016).

Main problems are found in using this material are how to carry out the conservation works of historical buildings, usually adobe masonry and rammed earth, as well as the lack of skilled people to produce adobe, from designer to masons, because it is a forgotten technique. Hence, in recent years some recent investigations about adobe mechanical properties and characterization of adobe bricks, including earth blocks, have been performed for some authors: Morel *et al.* (2007) described methodologies used to determine compressive strength of compressed earth blocks, including direct testing, the RILEM test and indirect flexural strength testing. In addition, the influence of block geometry (aspect ratio), test procedure and basic material parameters (dry density, cement content, moisture content) are also discussed.

Quagliarini and Lenci (2010) investigated the changes in the mechanical properties of ancient roman adobe earthen bricks by varying the percentage of an on-situ soil, straw and coarse sand into the mixture to produce those bricks. Comparisons were also taken with samples made of only soil. Later, Quagliarini *et al.* (2010) developed an experimental research, in order to characterize the mechanical behavior of adobe walls.

On the other hand, NDT methods have been used for determining the mechanical properties of materials. Some ultrasonic wave works have also been accomplished to measure steel thickness, connecting a wireless sensor network, which makes it for multiple measurement point technique such as explained in Kouche and Hassanein (2012), ultrasonic methods can be combine with other nondestructive techniques, where X-Ray, thermography and vibration systems are mentioned by Jolly *et al.* (2015). Special configuration is certainly required for some ultrasonic systems, for example there are tests that require material piece immersion, a setup such as those is presented for Kappatosa *et al.* (2017). Finally, a very important aspects to consider in some cases, is adobe piece porosity, permeability, the mortar or cement ratio and water content. Thus, cement and adobe are very similar as well. Fiber, soil and water are needed to prepare adobe mixture, which leads to different porosity levels and permeability as said by Lafhaj *et al.* (2006).

Destructive tests

Due to the inexistence of recommendations directed to adobe constructions in codes, some destructive tests have been carried out for determining mechanical properties (Aubert *et al.*, 2013) and the structural response of adobe bricks under loading (Illampas *et al.*, 2013) of adobe masonry: in Silveira *et al.* (2012) a study about the mechanical properties of adobe bricks collected from houses and land dividing walls in Aveiro district, Portugal, representative of existing traditional buildings, was performed. Some (lab-based) experimental tests were performed including cylindrical adobe specimens, which were subjected to simple compression and splitting tests.

Therefore, it was possible to evaluate, using cylinders: the stiffness, strength capacity and deformation evolution for increasing loading. Later, Silveira *et al.* (2013) performed a study related to the influence of testing procedures in the mechanical characterization of adobe bricks traditionally used in Aveiro district, Portugal. Cylindrical and cubic adobe specimens were subjected to simple destructive tests (compression tests), adobe bricks to flexural tests, and cylindrical adobe specimens to splitting tests.

On the other hand, Turanli and Saritas (2011), using additives and plaster mesh in adobe wall panels, performed an experimental investigation by means of destructive tests. Ultimate load capacities, deformability, and energy absorption characteristics were evaluated. These authors concluded that, the combined use of plaster mesh with additives enhances the structural response significantly. Other authors have included fibers (Cassese, *et al.*, 2021) in their studies about of adobe masonry using this type of tests, for evaluating the changes in the mechanical properties of this material: Yetgin *et al.* (2008) performed uniaxial compressive tests for five different adobe mixtures done with natural fiber mixtures. According to this study as fiber content increases, compressive and tensile strengths decrease, and shrinkage rates decrease. On the other hand, Piattoni *et al.* (2011) concluded that with the presence of the straw fibers, the final strain is the double in comparison with the strains corresponding to the maximum stress for all the compositions tested.

Some authors (Piattoni *et al.*, 2011; Vega *et al.*, 2011; Millogo *et al.*, 2014) have mentioned that traditional adobes with different fibers (straw and Hibiscus cannabinus fibers) can be used as an adequate construction material. Some fibers can increase of the mechanical properties due to the nonpropagation of cracks for the presence of these (Millogo *et al.*, 2014).

Other materials or techniques (e.g. corn plant, bamboo particles or “synthetic termite saliva”) used to improve the mechanical properties of adobe have been proposed for some authors (Ribeiro Corrêa *et al.*, 2015; Serrano *et al.*, 2016). As it is possible to observe there are many investigations, with traditional adobe or adobe considering fibers, that use lab-based experimental tests by means of destructive tests. However, seldom “in situ” investigations have been carried, e.g. in Adorni *et al.* (2013) an in situ mechanical characterization of 2000 years old adobe bricks from the archaeological site of Nisa Partica in Turkmenistan was performed. In this study, a portable instrument was designed to perform three point bending, compression and ‘Brazilian’ tests. Hence, it is important to measure the mechanical properties of adobe bricks even in critical in situ conditions, because of this, NDT’s are proposed. This type of tests has been used in some materials like concrete or steel. However, in adobe masonry they are not frequently used.

Nondestructive tests (ultrasonic methods)

In ultrasonic tests, high frequency sounds waves are employed, in the range between 500Hz and 15 MHz. Ultrasound tests are based on the sense and quantification of sound waves transmitted and reflected pulses called echo. Those waves are divided into two groups, longitudinal waves and transverse waves (shear waves). These tests are classified in five different types and they are the most normally used (McCann and Forde, 2001; Hola and Schabowicz, 2010; Schabowicz, 2014). These methods are listed below:

Sonic transmission method. In this method, compressional wave transmission through the thickness of a structure using frequencies between 500Hz and 50 kHz is employed.

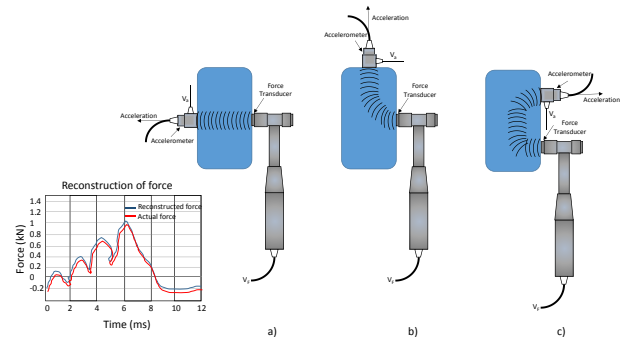


Figure 4 Ways of ultrasonic wave measurement (a) direct, (b) semidirect and (c) indirect.

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The wave transmission starts on one side of the wall, when the structure is hit by a force hammer and the reception of the wave is received by an accelerometer placed on the other side of the wall. This measurement can be performed in three different ways, as shown in Figure 4.

Sonic/seismic tomography. With this method, measurements are performed perpendicular to the surface of the wall or crossed by to have a set of readings, this group of structure values are related to measure specific times of ultrasonic wave travel, which are computed and with a series of iterations, structure mechanical properties can be estimated as it is observed in Figure 5.

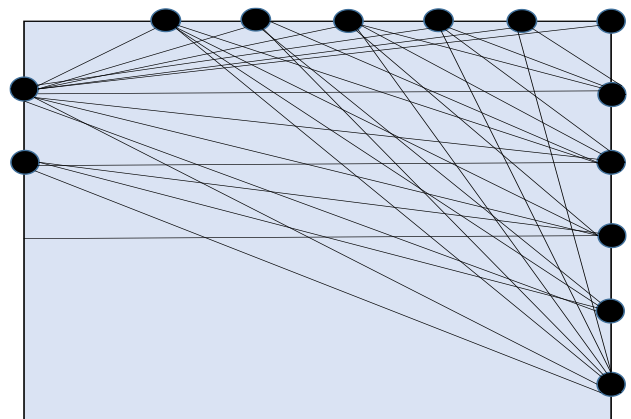


Figure 5 A structure is measured from different points and a set of several values is obtained

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Sonic/seismic reflection method. According to this method. The beginning and the reception of ultrasonic waves start on the same side of masonry, which is the case for indirect transmissions, but the path that is travelled by the wave is the direct same path where the reflected wave passes back, so the time it takes to go and come has to be divided between two.

In order to have only the time that sounds takes to go through the wall and calculate the material mechanical properties. The common frequencies used by the method are between 100 Hz and 1 kHz. Some problems, this method can have, are the dimensions and shape of the structure, cracks and voids within internal material structure and material surface, those issues can affect measurements.

Ultrasonic reflection method. In this case, the masonry structure thickness that can be measured is between 50 and 100 mm. It can be used for the detection of cracks and flaws in metal pieces casting. This method is the main technique employed for NDTs in concrete. There is a need for coupling agents to connect ultrasonic sensors to the surface and it is alike to method mentioned before. Basically, it is the method used in this purposed work.

For this study about adobe masonry non-destructive tests, the method used for this research is based on the ultrasonic reflection method. This method consists of an ultrasound generating source and two piezoelectric transducers (Figure 6), one set as a transmitter and the other as a receiver. In this process, ultrasonic waves are generated by a transducer with operating frequencies above 20 kHz, this means wavelengths between 50–100 mm in adobe masonry as in Fortineau *et al.* (2017). In this research work, a transducer of 50 kHz, such as the one shown in Figure 6b, is used.

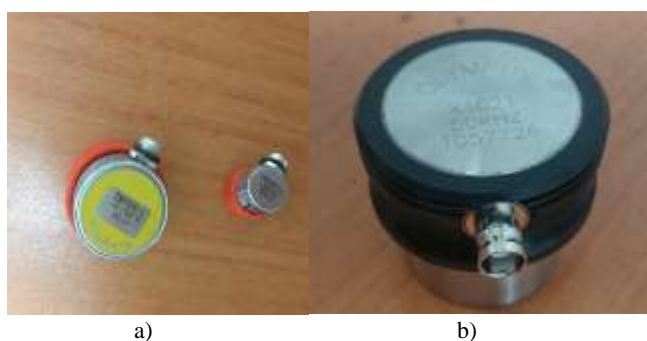


Figure 6 Piezoelectric transducers: a) transducers of 5000 kHz; b) transducer of 50 kHz
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Experimental tests

This section is divided in two parts. In the first part, destructive tests were carried out to obtain the elasticity modulus of adobe masonry used in the southeastern of Mexico.

The tested pieces were half-scale of typical adobe bricks built in this part of the country. Whilst, the second part consisted on using NDTs for the characterization of adobe masonry in this zone. Once the validation was performed, NDTs were used for the characterization of adobe bricks built central zone of Mexico. In this way, a comparison between two types of bricks were performed. It should be noted that for performing the destructive tests adobe pillars were built due to the complexity of testing a single adobe brick.

Setup for Destructive tests

In first place, to obtain adobe masonry mechanical properties, nine pillars, considering adobe masonry built in the southeastern of Mexico, were constructed to carry out axial tests, as shown in Figure 7. In this form, the elastic mechanical properties of adobe masonry from the southeastern of Mexico were obtained. The volumetric weight of the material was 13.24 kN/m³.



Figure 7 Specimens built for compressive tests: a) construction of pillars; b) planar surface for performing a uniform stress distribution; c) storage of pillars; d) numbering of pillars
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The specimens were tested in a Universal Machine whose maximum load was 2,200 kN, approximately. Instrumentation was performed using Displacement Transducers (LVDTs), as presented in Figure 8, and a Data Acquisition System (DAS). Thus, by placing the transducers on the specimen, it was possible to accurately know the displacement in that direction for each load step.

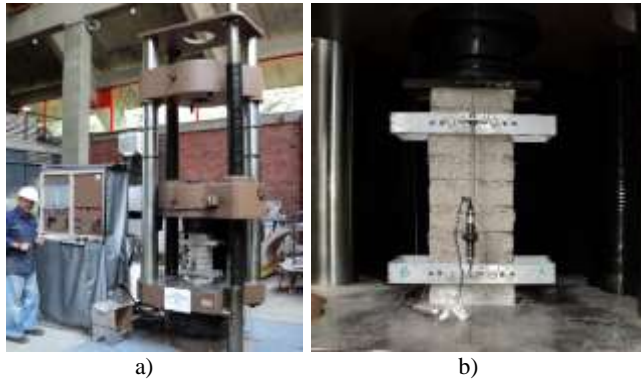


Figure 8 Adobe masonry pillar: a) Testing; b) Instrumentation
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The elasticity modulus E_m was obtained according to Mexican Norm (equation 1):

$$E_m = \frac{S_2 - S_1}{e_2 - 0.00005} \quad (1)$$

Where:

S_1 = Stress in MPa corresponding to strain $e_1 = 0.00005$

S_2 = Stress in MPa corresponding to 15-20 % of maximum adobe masonry stress

e_2 = Strain corresponding to S_2

From the measured elasticity in the specimens, average values were calculated (Table 1). The elasticity modulus E_m was 240.94 MPa.

| Specimen (Pillar) | E_m (MPa) |
|-------------------|-------------|
| Pillar-1 | 230.92 |
| Pillar-2 | 219.24 |
| Pillar-3 | 275.89 |
| Pillar-4 | 210.86 |
| Pillar-5 | 200.94 |
| Pillar-6 | 197.64 |
| Pillar-7 | 273.23 |
| Pillar-8 | 317.67 |
| Pillar-9 | 242.08 |
| Average values | 240.94 |

Table 1 Elasticity modulus (E_m), one of the adobe masonry elastic mechanical properties from the southeastern of Mexico

Setup for Non-Destructive test

For this part, Non-destructive tests were made with individual pieces of adobe masonry built in southeastern of Mexico, instead of pillars. In this way, a validation between both type of test was performed. Once the validation was carried out, adobe bricks built in central zone of Mexico were tested using NDTs.

The electronic equipment used for this experiment was the Olympus EPOCH 650, which is a rugged flaw detector. So due to rough surface, it was a necessity to couple the piezoelectric transducers to the adobe masonry pieces with a coupling agent. Coupling agents such as oil, grease or ultrasound gel commonly used in pregnancy ultrasounds can be used. In order to adhere the transmitter and the receiver to the piece surface, ultrasound gel was employed. It is important to understand, that two velocities need to be measured in order to obtain the strength capacity, stiffness and deformation with Poisson's ratio and elasticity modulus respectively. Longitudinal velocity that occurs along the piece and transversal velocity which represent the shear velocity. This concept is explained in Figure 6. In the shear velocity measurement, transducers need to be in 45° respect to the block surface with two wedges, they will be explained ahead, and this was well aimed in Hellier (2003).

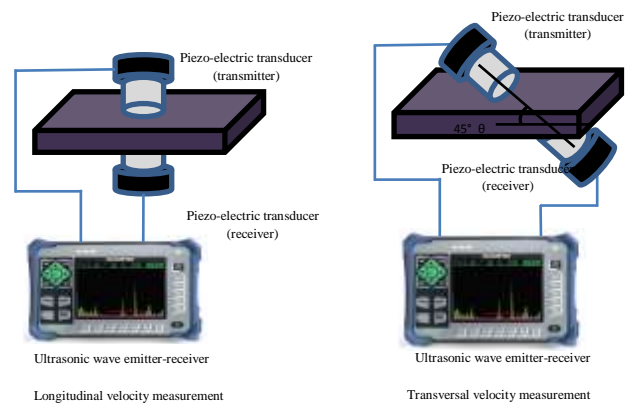


Figure 9 Setup for ultrasound velocity measurements
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Longitudinal velocity V_L and transversal one V_S were estimated by equations described in the following part and measurement data obtained from the ultrasonic pulse emitter-receiver system. So, it is called that form because its main application, which is to measure time that sound takes inside materials to go through. These equations are described in Moore (2007). They have been used to measure other materials such as concrete in Chang (2014), where other equipment such as 5077PR was used. Velocity can be determined from equation (2).

$$V = \frac{h}{t} \quad (2)$$

Where:

V = velocity

h = Thickness

t = Trip transit time

The units read on the instrument display were in inch/uS. Units had to be converted to cm/uS and multiplied by 1×10^6 to be expressed in cm/S. starting from this Poisson's ratio ν can be calculated using (3).

$$\nu = \frac{1 - 2 * \left(\frac{V_T}{V_L}\right)^2}{2 - 2 * \left(\frac{V_T}{V_L}\right)^2} \quad (3)$$

Where:

ν = Poisson's ratio

V_T = Shear (transversal) velocity

V_L = Longitudinal velocity

Now to calculate elasticity modulus E_m , both velocities are necessary as well. This time density is included. Using equation (4).

$$E_m = \frac{V_L^2 \rho * (1 + \nu) * (1 - 2\nu)}{1 - \nu} \quad (4)$$

Where:

V_L = Longitudinal velocity

ρ = Density

ν = Poisson's ratio

Validation and comparison of tests

NDTs were performed with Olympus EPOCH 650 system on adobe masonry. These tests took place in the Material Laboratory at the University of Guanajuato where five pieces (ten in total) of two different adobe bricks from different origin places were tested. Different construction forms were used to make those bricks. The first block is from the southeastern of Mexico (1:2 scaled-down adobe pieces), the second block is from the central part of the country (full scale adobe bricks).

Even though, they were almost the same material and they were made following the same procedure, they presented some differences such as type of fiber and water level during mixing but in spite of that, their mechanical properties stayed alike. The two bricks are shown in Figure 7. Their physical properties are listed in Table 2.



Figure 10 Adobe bricks from the southeastern of Mexico (half scale) and from central part of the country (full scale)

Self-authorship

| Physical properties | Brick from southeastern of Mexico (half scale) | Brick from central part of Mexico (full scale) |
|------------------------------|--|--|
| Dimensions (cm) | 21.5 x 5.3 x 14.5 | 30.5 x 7 x 26.5 |
| Mass (kg) | 2.175 | 7.425 |
| Volume (cm ³) | 1652.27 | 5657.75 |
| Density (kN/m ³) | 13.16 | 13.12 |

Table 2 Physical properties of typical adobe masonry bricks used in Mexico

Besides the EPOCH 650, two 50 kHz ultrasonic transducers were needed to performance the measurements, these transducers are suitable to work with this kind of materials such as concrete, brick and inconsistent materials. Measurements were done on a fixed surface to avoid vibrations or natural disturbances and not to affect instrument readings. For transversal velocity measurement is necessary to use the 2 plastic wedges. Transducers and wedges are shown in Figure 11.



Figure 11 Measurement: a) 50 kHz transducer with plastic wedge; b) Setup for the brick from central part of Mexico

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Ultrasound pulse measurement were conducted using equations from (1) to (4), the setup for tests is presented in Figure 6. In this figure, a test performed on one of the pieces is shown. The 45° collation and coupling agent between the wedges and the piece. Another important thing is that sensor should be coupled with the same agent to the wedges otherwise signal can be attenuated.

Results of two pieces are reported in Table 3 and Table 4, the first piece from southeastern and the second one from central part of the country, respectively. Where the Poisson's ratio and elasticity modulus are listed and the density for both blocks is presented. The densities obtained in these two pieces, besides of being very similar, are close to values that were determined from destructive tests and other adobe pieces take from the same set of pieces.

| T_L (μ S) | V_L (in/ μ S) | V_L (cm/S) | Poisson's ratio ν | Elasticity Modulus E_m (MPa) |
|---------------------|------------------------|-----------------|--------------------------|---|
| 106.1 | 0.01885 | 47879.359 | 0.44 | 221.879 |
| T_T (μ S) | V_T (in/ μ S) | V_T (cm/S) | | |
| 185.3 | 15218.565 | 38655.154 | | |

T = sound flying time, L =longitudinal, T =transversal.

Table 3 Mechanical properties of southeastern adobe masonry brick

| T_L (μ S) | V_L (in/ μ S) | V_L (cm/S) | Poisson's ratio ν | Elasticity Modulus E_m (MPa) |
|---------------------|------------------------|-----------------|--------------------------|---|
| 157.2 | 0.01908 | 48473.282 | 0.43 | 227.385 |
| T_T (μ S) | V_T (in/ μ S) | V_T (cm/S) | | |
| 275.1 | 0.01540 | 39119.506 | | |

T = sound flying time, L =longitudinal, T =transversal.

Table 4 Mechanical properties of adobe masonry brick obtained from central part of the country

A comparison between experimental results obtained from two types of tests was performed (Table 5).

| Specimen | Density (kN/m^3) | Type of test | E_m (MPa) |
|----------------------------------|--------------------------------|------------------|----------------|
| Southeastern adobe masonry brick | 13.16 | NDT test | 226.54 |
| Central part adobe masonry brick | 13.12 | | 231.01 |
| Southeastern adobe masonry brick | 13.24 | Destructive test | 240.94 |

Table 5 Elasticity modulus of adobe bricks (E_m)

From values obtained, it is clear that results from NDTs and destructive tests are similar (6% of difference between both tests for the obtention of the elasticity modulus), it is possible to calculate adobe masonry mechanical properties with both methods with close values. As well as, Poisson's ratio and the elasticity modulus were closed in both types of adobe brick, 0.44 and 0.43 for southeastern and central part adobe masonry brick, respectively. Thus, the mixture (earth combined with straw and water) obtained to build adobe masonry bricks in these two parts of Mexico produces the same rigidity of this material.

Conclusions

Mechanical properties of adobe masonry can be obtained using destructive tests in pillars or cylinders (for obtaining elasticity modulus, Poisson's ratio and tensile and compressive strength) due to the complexity of testing a single brick. However, in some cases, destructive tests are not possible to apply for obtaining these properties. Such is the case of historical buildings, e.g. constructions carried out with adobe masonry. Thus, NDTs can be performed for rescuing the heritage of this type of constructions. The NDT system and the method used in this study to estimate the adobe masonry elastic mechanical properties showed good results compared to destructive tests, the elasticity modulus obtained was closed in both methods (6% of difference between both tests), which validates the alternative method proposed in this research. In addition, these NDTs can be used "in situ" to measure the elastic mechanical properties (elasticity modulus and Poisson's ratio) of adobe bricks even in critical conditions.

It should be noticed that both types of brick coming from different parts of Mexico (southeastern and central part of the country) present approximately the same elastic mechanical properties because of their construction process that is very similar in these two parts of the country. There no précised values about adobe Poisson's ratio and elasticity modulus, but according to this method in compare to the destructive one and other data obtained in other works, it is concluded that this NDT technique is suitable for the analysis of adobe pieces and structures.

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