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Physical-chemical, mechanical and durability characterization of historical adobe buildings from the State of Michoacan, Mexico

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ABSTRACT

Most earthen historical buildings have been abandoned for decades, exposed to the weathering and the passage of time. In Mexico, the low status of earthen constructions has increased these deterioration processes, resulting into the risk of disappearance of this significant architectural heritage. Historical adobes from monumental buildings in the State of Michoacan were sampled and collected in the localities of La Huacana (H) and Santa Cruz de Morelos (SC). The specimens were characterized in the materials laboratory, assessing their physical-chemical, mechanical and durability properties. An interdisciplinary methodology was designed through institutional cooperation and the application of different test methods.

The adobes showed totally different compositions and proportions, and stabilizers like vegetal fibers, nevertheless, the mechanical performance of both samples was very similar, achieving respectable values in the context of historical adobe structures. Several correlations were found through the analyses: the physical properties like the density, the color or the electrical resistivity were related with the mechanical and durability ones; the non-destructive testing (NDT) allowed to calculate the dynamic elasticity modulus and infer the mechanical behavior; the chemical characterization enabled to obtain the elemental and mineralogical composition; and the Atterberg limits gave the soil classification.

The research showed the broad diversity of earthen solutions and demonstrated how the granulometry is not a limitation to the adobe production, since the local soils can achieve similar mechanical and durability behaviors. Furthermore, H presented very different composition than the guidelines for earthen construction; nevertheless, the samples showed better durability performance and lower capillarity absorption rates. It is hoped that the results obtained with this research can help the further development of the earthen materials characterization and the decision-making process for the restoration and conservation of historical and vernacular constructions.

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1. Introduction

Earthen architecture is one of the first and most important cultural manifestations of humankind, being found in all the inhabited continents. The oldest structures found date back from 10000 to 8000 B.C. [1], and the first sedentary civilizations, like Mesopotamia, moulded their local soils into different earthen techniques to build their first long-lasting structures [2]. Considering that the development and momentum of civilizations was different depending on the geographic regions of the world, we can identify similar construction stages in uneven locations and chronological time periods [3]; with specific techniques, like the adobes or the rammed earth, being developed at the same time in remote regions, demonstrating the rationality of these solutions.

Adobes, also known as mud bricks or earth blocks, are the regular unfired masonries moulded in formworks that constitute construction elements like walls and vaults. These components consist of a mixture of clayey soils, sands and coarse material, blended with the required amount of water to acquire the plastic consistency [4]; additionally, the blocks can embed different stabilizers, frequently vegetal fibers to reduce the shrinkage. The variations of the technique are countless, and the properties of these blocks together with the fact of being a masonry system caused the spread and popularity of adobe buildings around the world.

The first found and dated adobes in the American continent trace back to at least the 5100 B.C., in the archaeological site Los Morteros, in Peru, while some vestiges suggest an earlier origin of the technique [5]. It was the most common earthen technique in Mexico, Peru, Bolivia and Chile [6], and almost all the Pre-Columbian civilizations were familiar with it [7]. The presence in the Mesoamerican[1, 2 and 3] region was strong, being a relevant feature for the development of the cities and the construction culture found in all the territory [8]. In Mexico, the technique has been identified in relevant archaeological sites like Teotihuacan, Cholula [9], La Venta or La Joya. Daneels (2015) reports the first identified adobes (1150-700 B.C.) in Oaxaca from the Early Preclassic Period; while in the State of Michoacan, in the Balsas River Basin, evidence of ancient adobes and lime coatings has been found with an expected antiquity of 1500 years [10].

The proven durability of these structures demonstrates the great qualities of earth as a construction material as long as the earthen materials are well protected and repaired [11,12]. Nevertheless, the abandonment of the traditional techniques and the lack of maintenance of these constructions have accelerated the decay of earthen buildings, since the intervention processes are inappropriate or nonexistent [13,14]. In Mexico, this situation is notorious, since adobe buildings are perceived as outdated and unsafe, and often related with the lower social levels [15]. However, the preservation of this historical buildings is essential, as they still integrate the historic centers and neighborhoods of many cities [16], Notwithstanding the current situation of earthen architecture, the environmental potential of these construction techniques is unlimited [17], since earth can be one of the main materials for the future sustainable building industry [18]. Therefore, the necessity of a more technical and specialized approach to earthen architecture is evident, finding a general absence of official standards and guidelines regarding these techniques. Regulations often avoid the specialization [19], publishing documents that ignore the traditional materials and systems, even though they constitute our architectural heritage. Additionally, from the restoration and conservation of the archaeological and architectural heritage a better analysis and knowledge of the earthen buildings is needed, to protect, retrofit and preserve this vernacular and historical heritage [2].

1.1. Characterization of earthen structures

With the primary focus on the characterization of materials and construction systems based on earth, a more specialized literature has been developed in recent years. At global level, we can find review papers and chapters regarding earthen construction materials and techniques dealing with different specific aspects and approaches: like the hygrothermal properties [12,20–22], the characterization with non-destructive methods [23,24], the physical and mechanical properties of different techniques [22,25–28], the analysis and use of natural local fibers [29–31], the durability of the earthen buildings [32–35], the life-cycle assessment (LCA) [36–38], or the soils selection process [39].

We can find a clear predisposition of the studies regarding the mechanical properties of the earthen materials and components [25, 27,40–49], since these are the most appreciated for construction and building purposes; a recent research reported that 92% of the works perform the compression test [25]. The most recent advances in the field come through the employment of Non-Destructive Testing methods (NDT). In the case of the earthen historical buildings, the NDT present the advantage of not altering these heritage constructions which can be delicate, while inferring and providing mechanical, electrical, thermal and acoustic properties of the analyzed materials. On the other hand, the mineralogical characterization in this field is still scarce, and more frequent in the works that come from archaeological approaches; in this sense, the review presented by Sánchez et al. (2022) found that only the 12% of the studies in the database performed these test methods [25].

Regarding the historical and vernacular constructions, in the last decades we can find recent research works analyzing historical earthen materials and components following inter and multidisciplinary approaches [41,50–56]. It must be outlined the work done in Portugal, where we can find several articles regarding the characterization of historical monuments and vernacular architecture built with earth, mainly with the techniques of adobe and rammed earth [43,46,57–61].

On the other hand, in Latin America and the specific case of Mexico, the existing literature is scarce, and most of the research works are only focused on the mechanical properties of the blocks, or analyzing the technique from typological and technological perspectives, with a theoretical approach to the vernacular architecture [62]. However, we can find some relevant references in the recent years; for instance, the important characterization efforts analyzing the historical adobes of the State of Morelos, heavily affected

[1] Mesoamerica is a historical and cultural region comprising part of North America in modern Mexico and Central America, related with the emergence of the first pre-Columbian civilizations.

during the 2017 Puebla earthquake [40,62–64]; or the works with archaeological earthen heritage including advanced chemical and mineralogical analysis [65,66]. Another instance could be the study by Puy-Alquiza et al. (2022), which compared the properties and composition of pre-Hispanic and colonial adobe blocks, finding interesting technical differences in the manufacturing techniques [67].

1.2. The historical earthen buildings of the Tierra Caliente region

The case studies of the research are the localities of La Huacana (H) and Santa Cruz de Morelos (SC), both situated in the State of Michoacan, in Mexico (see Fig. 1a), but specifically in the region called Tierra Caliente. Tierra Caliente is a geographical and cultural region which comprises municipalities and territories of the states of Michoacan, Guerrero and the State of Mexico. This territory stands out its extremely hot and dry conditions, since its nomenclature meaning is “hot land” [68]. According the Köppen-Geiger climatic classification, the region is considered as BSh, a hot semi-arid climate with extremely hot summers, warm winters and scarce precipitation [69]. The localities studied present an overall precipitation around 600 mm/year and average temperatures from 13 to 35 °C.

The vernacular architecture and the historical buildings of the region stand out for their adaptation to the aggressive environment and the extremely dry and hot climate, finding an extended use of local materials. The use of earth is extended in the region, since it provides great thermal performance due to the thermal mass of the thick adobe walls and the properties provided by the earthen plasters and coatings [70]. These refurbishments have two functions: provide hygrothermal comfort and protect the walls against the atmospheric agents; they were traditionally repaired through periodic maintenance actions, however, in the last decades most of the buildings have not been well preserved.

A really interesting feature of the vernacular architecture in Tierra Caliente is the presence and combination of different materials and traditional techniques, like the adobe masonry and the *bajareque* constructions [14]; *bajareque*, also known as wattle and daub in other regions of the world, is a mixed technique of wooden and earthen materials (see Fig. 1c). These dwellings adapt perfectly to the challenging local environment proportionating thermal comfort thanks to the materials employed and the natural ventilation strategies [68]. Both typologies are shown in Fig. 1b and c, however, it is interesting how some of these buildings interchangeably combine the two techniques: with stone foundations and adobe walls for the communal areas and bedrooms, and *bajareque* panels for the kitchens and storage rooms to provide better ventilation.

On the other hand, the monumental buildings of the region, like the temples or the *haciendas*, were built with stone and adobe masonry. The *haciendas* are rural estates buildings of colonial origin used for the production and control of the territory and the local resources [14], being big ensembles of constructions with larger dimensions. The encounter between different cultures and construction traditions in this region brough this local architecture with great variety of materials, typologies and solutions.

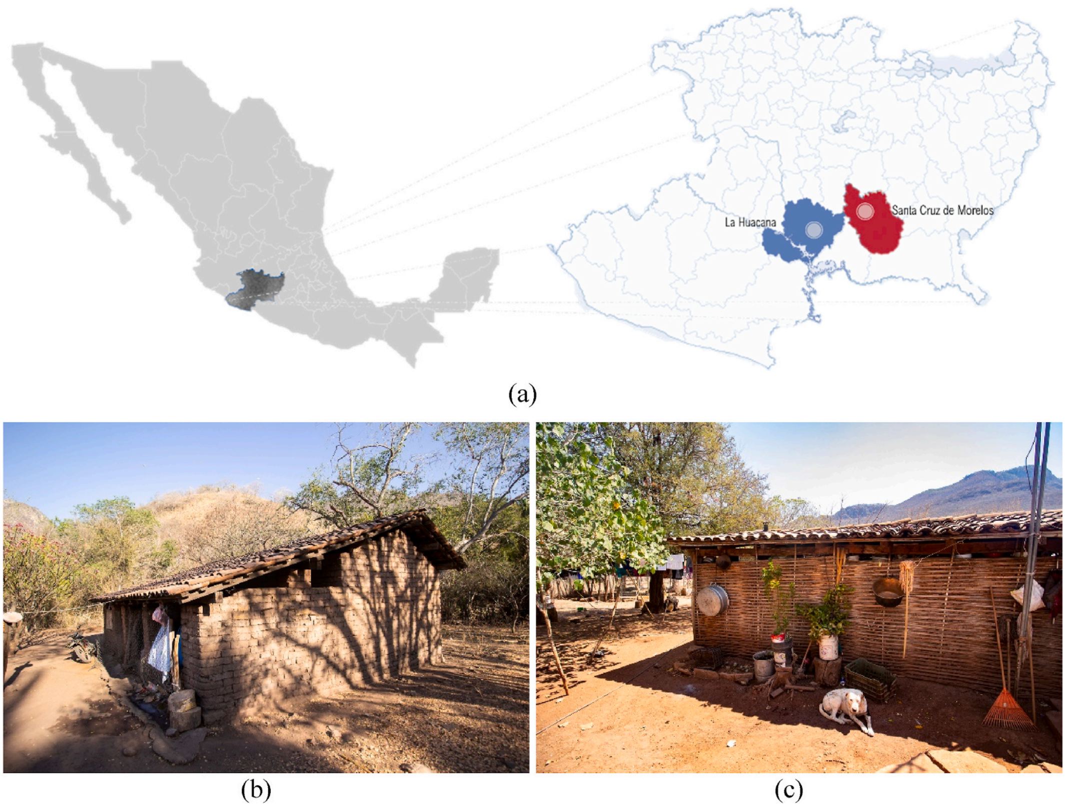

Fig. 1. Studied region and local vernacular architecture: (a) Location of Michoacan and the study cases of the research; (b) Adobe house; (c) Bajareque house.

A more detailed knowledge of the earthen materials and structures is required in this region, since they constitute the vernacular and historical heritage, and moreover they present excellent properties to be used in the contemporary construction sector. This work assesses the physical-chemical properties of historical adobes, their mechanical behaviour and their durability. The test methods applied to characterize these components are usually scarce and limited to simple mechanical trials; therefore, this proposal includes innovative approaches to study earthen materials. With this approach it will be possible to achieve better and more accurate restoration and conservation projects and actions.

2. Materials and methods

Recent works have joined efforts towards the unification of the characterization methods for earthen materials, especially for the design of new constructions due to its efficiency and potential [71]; nevertheless, historical earthen constructions present more difficulties to be assessed and a high degree of variability. For the present research work the adobe samples were collected and brought to the materials laboratory to be analyzed. The process started with a field campaign in the communities of Tierra Caliente, to collect the specimens, and later with the experimental analysis in the laboratory, which was designed to assess the physico-chemical, mechanical and durability properties of the heritage adobes.

2.1. Surveying and preparation of the samples

The adobe samples were collected in the Tierra Caliente region of Michoacan, being the selected buildings *haciendas*: The field campaign was done in the previously mentioned communities: SC, in the municipality of Turicato; and H, in the eponymous municipality. The field work also entailed the architectural and photographic survey of the vernacular constructions, to study the architectural typologies and the construction systems and techniques [72].

Some buildings presented an optimal conservation state, even that they were built for more than 200 years ago and some of them are no longer inhabited (see Fig. 2). It is important to note that the adobe walls had lost their coatings, which are the traditional preservation mechanism of these vernacular constructions. From these *haciendas* it was possible to collect some entire adobe blocks, as well as cylindric cores following the standard ASTM C42/C42M − 13 [73], although it was designed for concrete testing. Notwithstanding the abandonment of some of these buildings, the adobe walls presented great conditions and preservation state, facilitating the sampling process; in this field campaign about 15 blocks and 15 cylindric cores were extracted and collected.

After the field campaign, the adobes were transported to the Materials Laboratory "Ing. Luis Silva Ruelas" in the facilities of the Faculty of Civil Engineering of Universidad Michoacana de San Nicolás de Hidalgo (UMSNH). The samples were stored in the laboratory properly protected from humidity and environmental conditions to preserve their integrity, before being characterized as part of a research project on the durability of vernacular architecture.

Before starting the characterization procedures, the specimens were prepared to fulfill the test methods according to the respective regulations. From the complete adobes, regular cubes with dimensions of 8x8x8 cm^3 and beams of 4x4x16 cm^3 were cut using a disc cutter Additionally, cylinders of Ø3.5 cm and 8.75 cm of height were manually carved to perform the triaxial shear test. All the samples were classified and labelled. On the other hand, to perform the chemical and mineralogical analysis, representative samples of each study case were grinded with agate mortars till obtaining a powder which goes entirely through the sieve ASTM nº200 (<75 μm) to analyze the clayey binding agent of the adobes.

2.2. Methodological framework for the characterization procedure

Starting from the previous research work done in the materials laboratory with adobe blocks [62,74,75], and considering the most similar and relevant research works of heritage earthen constructions at global level [43,46,50,53,54,57–60,65,76]; the following methodology was designed, incorporating new methods to assess the substantial properties and adjusting to the available infrastructure. Three groups of test methods are delimited, in function of the properties wanted to know for the adobe blocks: the physical-chemical properties, the mechanical behaviour and the durability (see Table 1). All the trials were performed a minimum of three times to obtain a representative mean value.

Fig. 2. Case study of hacienda in Santa Cruz de Morelos, Michoacan.

Table 1
Test methods performed on the adobes.

Test method	Standard/Regulation/Scale
Physical-chemical characterization	
Bulk density	ASTM D7263-21 [77]
Water content	ASTM D4643-17 [78]
Colorimetry analysis	CIE Color Space
Potential of hydrogen (pH)	ASTM D6276-19 [79]
Sieve analysis	NMX-C-496-ONNCCE-2014 [80]
	ASTM C136/C136M – 19 [81]
Atterberg limits	NMX-C-493-ONNCCE-2018 [82]
	ASTM D4318-17e1 [83]
X-Ray Fluorescence (XRF)	UNE-EN ISO 12677:2012 [84]
X-Ray diffraction (XRD)	UNE-EN 13925-1:2006 [85]
	UNE-EN 13925-2:2004 [86]
	UNE-EN 13925-3:2006 [87]
Scanning Electron Microscope (SEM)	–
Electrical resistivity (ER)	NMX-C-514-ONNCCE-2019 [88]
	ASTM G57-20 [89]
Mechanical characterization	
Uniaxial Compressive Strength (UCS)	NMX-C-083-ONNCCE-2014 [90]
	ASTM C39/C39M – 21 [91]
Point Load Test (PLT)	ASTM D5731-16 [92]
Flexural strength test	BS EN 12372:2022 [93]
Unconsolidated-Undrained Triaxial Compression Test	NMX-C-432-ONNCCE-2002 [94]
	ASTM D2850-15 [95]
Ultrasonic Pulse Velocity (UPV)	NMX-C-275-ONNCCE-2020 [96]
	ASTM C597-16 [97]
Stress-strain and Modulus of Elasticity	NMX-C-128-ONNCCE-2013 [98]
	ASTM C469/C469M – 22 [99]
Durability characterization	
Capillarity absorption	NMX-C-504-ONNCCE-2015 [100]

The samples were tested with the normal laboratory ambient conditions (20 °C and 60% humidity), to replicate the behaviour of the adobes found in the historical buildings. The experimental campaign was performed in the Materials Laboratory of the UMSNH, starting with the NDT, then with the mechanical tests and ending with the soil mechanics trials. On the other hand, the chemical and mineralogical tests were performed in the Universitat Politècnica de Catalunya (UPC) in Barcelona, and the Universidad de Navarra in Pamplona, Spain.

2.3. Methodological framework for the characterization procedure

Starting with the NDT, the colorimetric analysis was performed following the standardized system CIE, based in three parameters: the luminosity L* and the chromatic coordinates a* (red to green axis) and b* (yellow to blue axis) [101]. The models relying on Cartesian axis are really useful for the numerical and predictive analysis [102], helping to achieve a comparative analysis between study cases; this allows to obtain the objective value of the color of the samples, being very useful for the analysis of heritage materials and the feasible restoration actions [74,103]. The equipment utilized was the colorimeter CRLM-200, it was previously calibrated with a white reference. To analyze the adobes, multiple measurements were taken for all the surfaces of the samples to obtain representative values of each study case.

For the UVP test, the 10 cm diameter cylinders extracted *in situ* following the standard ASTM C42/C42M – 13, were utilized with the equipment V-Meter MK IV from James Instruments, to later determine the dynamic elasticity modulus (E_d) [96,97]. Conversely, the pH was measured by two different methods: indicator pH strips CVQ2051 from the brand CIVEQ, and a portable pH meter Waterproof Tester Combo pH & EC from Hanna Instruments. The reference for the measurement was the standard ASTM D6276-19 for soils stabilization [79], with solutions in the same quantities of the earthen materials and water. The dynamic elasticity modulus can be calculated with other NDT like the vibration or resonant frequency [23,24,104], but for this specific research this method did not work well.

To assess the durability of the adobes, the capillarity absorption test was performed [100], applying the same process designed for concrete specimens to the adobe cubes. Before starting the test, the samples were dried for 8 days in the oven at 50 °C and all the surfaces of the cubes were sealed except the inferior and upper ones in contact with water (See Fig. 3). The procedure consisted in the measuring of the weight variation of the samples at the specific intervals given by the standard. For the electrical resistivity (ER) test [88,89],the equipment utilized was Soil Resistance Meter, Model 400 from Nilsson Electrical Laboratory Inc. To perform the procedure, the cubic samples were tested in saturated state, just after the capillarity absorption test.

The XRF and XRD analyses were performed in the Chemical Department of the School of Sciences of Universidad de Navarra. For the fluorescence test, the samples were grinded till powder and tablets were made with potassium bromide (KBr). The equipment utilized to perform the test was the Nicolet-FTIR Avatar 360 and the software used to process the results was OMNIC E.S.P. The

Fig. 3. Capillarity absorption test of the adobe specimens.

resolution was 2 cm^{-1} and the spectrums obtained were the result of averaging 100 scans, providing the composition of the adobes as oxides. All the measurements were taken at a temperature of $20\pm1^{\circ}$ and a relative humidity of 40%. The SEM images were taken in the UPC with the high-resolution equipment JEOL JSM-7001F with energy dispersive X-ray spectroscopy (EDX), while the samples were treated with a palladium-platinum coating.

Following with the mechanical characterization, the UCS was calculated with the adobe cubes, utilizing the Universal Testing Machine FORNEY with a maximum capacity of 120000 kg, applying a constant velocity load of 0.20 $\pm$ 0.05 ton/min till the failure of the specimens (see Fig. 4a) [90]. Additionally, with the same equipment, the 4x4x16 cm beams were tried with the three-point bending test to obtain the flexural strength of the adobes (see Fig. 4b) [93].

An additional procedure to assess the mechanical compression resistance was the PLT, originally designed for the testing of uncarved rock fragments [105]. This method allows to determine the mechanical resistance of small size fragments and irregular samples, being very useful for heritage studies [106], although the previous experimentation with earthen materials is scarce and difficult to compare [62]. The PLT was performed with the portable equipment Digital Rock Strength Index Apparatus 100 kN from Controls Group (see Fig. 4c) [92].

The unconsolidated-undrained triaxial test (UU) was performed with the carved Ø3.5 x 8.75 cm cylinders to obtain the shear strength, cohesion and friction angle [94,95]. The equipment employed was the Triaxial Soiltest T-500, with a triaxial chamber of the brand Elvec with a load capacity of 500 kg, and a test velocity of 4.5 mm per minute. The carved cylinders were introduced in the triaxial chamber with a coupled pressure gauge and valves to measure the water pression. To calculate the static elasticity modulus, another compression test was performed to determine the stress-strain relation [98,98,99,99], assuming the stated Poisson's ratio for earthen materials. The equipment consisted in the ELVEC hydraulic press, model E659-2, series 100813, with maximum capacity of 120000 kg; a strainmeter with two rings; two strain gauges and a digital micrometer.

Finally, before the soil mechanics trials, the material was saturated into water to separate the vegetal fibers, specifically straw, by flotation. Then, the representative percentage by mass was calculated for both study cases. After that, the samples were dried in the oven for an average of two weeks at a maximum temperature of 50-60 °C, in order not to change the properties of the clay minerals. With the same drying process, the bulk density and the water content of the adobes were calculated [77,78]. The soil mechanics testing included the sieve analysis, which was executed with the dried material [80,81]; and also, the Atterberg limits, which were calculated with the material passing the sieve ASTM n°200 (<75 μm), separating the coarse and fine material [82,83].

3. Results and discussions

The summary of the characterization of the adobes is displayed in Table 2, distributing the results into the three mentioned categories: the physical and chemical, the mechanical, and the durability properties. For earthen materials and structures, the durability is conceived as the quality to resist the water-induced erosion [32], which is the main deterioration mechanism for these constructions. It can be noticed how other than the granulometric composition, the presence/absence of fibers and the color, the properties obtained for both study cases were very similar, with equivalent mechanical behavior and durability.

3.1. Physical-chemical characterization

The density presented coincides with the ranges proposed in other characterization studies for adobe masonries [1500-1900 kg/m^3] [25], also considering that the preservation state of the constructions can decrease this property [58], as it was found in previous research with pieces affected by earthquakes [62]. The H samples presented slightly major bulk density than SC, which later was translated into a better mechanical performance, since it expresses a greater degree of compaction of the blocks.

On the other hand, the water content presented more variability, The greater water content of H can be explained with the composition of the blocks, containing more fine material as it will be explained down below, and the absence of straw fibers, which tend to decrease the absorption rates of earthen blocks [107]. Both samples were exposed to the same environmental conditions for years, therefore the adobes from H are more prone to gain water and consequently suffer volumetric changes, which could have an affectation on their durability [34].

The moisture in earthen architecture components is essential, since it changes the consistency from solid to plastic to liquid, being this, one of the key features for the manufacturing the different techniques. Furthermore, the water content in earthen structures

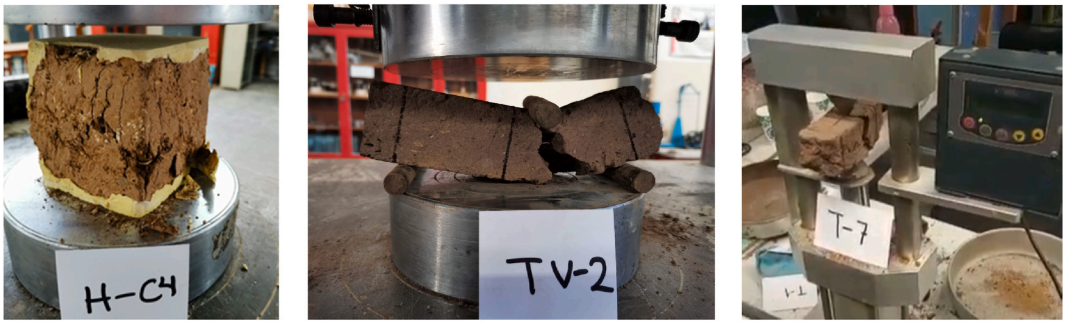

Fig. 4. Mechanical characterization of the adobe specimens: (a) Uniaxial compressive strength; (b) Three point bending test; (c) Point-load test.

Table 2
Complete characterization results.

Case	H	SC
Bulk density $\mathbf{P_{ap}}$ (kg/m^3)	1724.16 ± 0.05	1609.09 ± 0.03
Water content $\boldsymbol{\omega}$ (%)	6.37 ± 0.99	2.69 ± 0.48
CIE colorimetric representation		
a*	11.41 ± 0.41	7.01 ± 1.16
b*	22.71 ± 0.96	11.10 ± 0.25
L*	50.77 ± 0.52	43.04 ± 0.36
Electrical resistivity $\boldsymbol{\rho}$ (Ω·m)	22.94 ± 1.24	24.44 ± 3.38
Fine material percentage (%)	89.2 ± 1.46	44.67 ± 3.88
Fibres percentage (%)	0.32 ± 0.07	0.00 ± 0.00
USCS classification	ML	SM-SC
Hydrogen potential pH	5.5 ± 0.55	6.0 ± 0
Compressive strength $\boldsymbol{\sigma_{UCS}}$ (kg/cm^2)	10.48 ± 3.36	9.71 ± 1.69
Point-load strength $\boldsymbol{\sigma_{PL}}$ (kg/cm^2)	25.14 ± 11.72	20.50 ± 9.61
Shear strength $\boldsymbol{\tau_f}$ (kg/cm^2)	8.59	3.94
Flexure strength $\boldsymbol{\sigma_F}$ (kg/cm^2)	4.65 ± 2.48	3.85 ± 1.69
Dynamic elasticity modulus $\mathbf{E_d}$ (kg/cm^2)	4488.14 ± 1407.25	4299.83 ± 1025.50
Static elasticity modulus $\mathbf{E_s}$ (kg/cm^2)	4112.22 ± 1461.00	3781.46 ± 1975.72
Capillarity absorption coef. $\mathbf{C_{ABS}}$ (kg/m^2·min$^{1/2}$)	1.20 ± 0.25	0.88 ± 0.04
Initial absorption rate $\mathbf{T_{ABS.I}}$ (kg/m^2·min$^{1/2}$)	1.2906 ± 0.4451	1.0263 ± 0.0463
Secondary absorption rate $\mathbf{T_{ABS.S}}$ (kg/m^2·min$^{1/2}$)	0.0562 ± 0.0302	0.0453 ± 0.0210

directly affects their mechanical resistance and capacity while reducing the density [58]. Therefore, the conservation state of the samples is really important, and the abandoned or neglected structures present lower density values and higher humidity [108].

The colorimetric analysis allowed to quantify the clear difference of both samples, with H presenting more reddish tones and lighter color. The CIE system provides the parameters a* (red to green), b* (yellow to blue) and L* (luminosity), and these values can be converted with a color generator,[2] as it can be spotted in Table 2. The color is a very important aspect of earthen architecture, since it gives the aesthetic identity to the structures, even when the structures are layered with mortars that employ the same soils. Therefore, the restoration activities need to match the original aspect, and colorimetry is a NDT which can easily be applied *in situ*.

In addition, color allows to estimate some properties like the mechanical resistance, since adobes can contain iron oxides or hydroxides [57]; to assess the conservation or degradation degrees of built structures [109]; to identify the presence of some minerals and clay content [110]; or the stabilization with different additions [74,103]. In this case, the adobes from H presented a higher clay content which could be correlated with the natural soils of the region, while the tonality of SC could be more influenced by the sand proportion.

Following with the NDT of ER both cases showed similar ranges of results (ρ), with more variability in the case SC. It is difficult to find background research regarding this technique in earthen materials, with few examples of application [23,62]. The composition of the adobes plays an important role in the ER, since a higher content of coarse material tends to increase the values [111], which can be noticed in SC where the proportion of sand is higher. It has been reported a correlation between ρ and P_{ap} [23]; therefore, the ER is directly proportional to the bulk density, the UVP and the mechanical resistance among other properties. Moreover, it also can be used to estimate the damage levels of the samples, and research done with adobes affected by earthquakes showed much higher values and variability of ρ [62], on account of the damaged internal structure of the blocks.

[2] Generated with Free Color Converter from Nix Color Sensor: https://www.nixsensor.com/free-colorconverter/.

The soil mechanics characterization allowed to classify the material and obtain the composition of the adobe masonry. Table 3 displays the results of the sieve analysis (including the fiber content) and the Atterberg limits with the subsequent Unified Soil Classification System (USCS) definition. In the first instance, we can find a clear differentiation in the composition of the two study cases, with H presenting a really high content of silts and clays, and SC showing a more stratified granulometric distribution, similar to other characterized heritage and vernacular adobes [39,57,58,112]. These results demonstrate how earthen architecture does not follow a predefined formula and the different local soils and resources can be employed with different variation to obtain durable materials [113]. Additionally, it is interesting how other studies performed in Mexico reported similar compositions to H in colonial and postcolonial *haciendas*, with high contents of fine material [67].

The absence of fibers in SC is notorious, since it is a common feature for the adobe manufacturing around the world; in contrast, H presents 0.32% of fiber content by weight. The locality of SC presents a very dry landscape, it may be possible that the production of adobes during the dry season of the year makes difficult to find this resource. The fiber inclusion in earthen mortars and bricks has reported in some cases improvements in the uniaxial compressive strength, shear strength and tensile resistance to some extent [114]. Nevertheless, a high percentage of fibers is detrimental for mechanical purposes; interestingly, H and SC showed very similar behavior in the mechanical characterization. Conversely, the granulometric distribution of the soil particles is really important, since the optimal design of the pieces can achieve relevant resistances without any stabilizers [115], which is exactly the case of SC.

H was classified as CL-ML: lean clays or silts, while SC was ironically classified as SC: clayey sand, according to the standard ASTM D4318-17e1 and the USCS classification [116]. Nevertheless, it can be observed how both cases are located in intermediate areas of the chart (see Fig. 5), separating the high and low plasticity in the case of H, and the clays and silts in the case of SC.

The results of the pH suggest that the adobes were not stabilized, or diminished their pH over time, since the common values for clays range between 6.0 and 8.0 [117]. The natural pH of soil materials can be modified with the utilization of stabilizers, being lime the most common solution for earthen mortars and blocks [118], with the standard ASTM D6276-19 regulating the current procedure to achieve a value of 12.4 [79]. Additionally, other factors like the poor maintenance, the abandonment of the built structures or a high moisture ambient can provoke an alteration of the pH [119], and the antiquity of the samples from Tierra Caliente could be a relevant factor. The drop in the pH value could also be due to the carbonation processes which are very common in the traditional lime mortars; nevertheless, the XRF and XRD did not find significant amounts of this stabilizer in the samples.

Following with the chemical analysis, Table 4 presents the XRF and XRD results as well as the diffractograms for both study cases. The first provides the elemental composition of the samples identified by oxides, while the second identifies the existing minerals. SC reported a lower LOI[3] percentage, which may be due to the scarce quantity of vegetal fibers in the adobe mixtures. The determination of clay minerals with XRD is a complex process, and it is necessary to make specific preparations to the samples, by means of glycols to separate the clay minerals layers and later by calcination (see the corresponding diffractograms in Fig. 6).

Fig. 7 displays SEM images for both study cases, it can be visually observed how the clays envelop the silts with feldspar composition. In Fig. 7a the clays are deposited around an anorthite feldspar grain, also observing remains of vegetal fibers; Fig. 7b presents an anorthite grain (Spectrum 1) covered by kaolinite clays (Spectrum 2), it can be noted by its crystal habit, a triclinic pinacoidal system, as well as its elemental composition. Additionally, the EDX analysis allowed to validate the DRX results and help with the interpretation of the images (See Fig. 8).

3.2. Mechanical characterization

Table 5 presents a summary of the results of the mechanical characterization of the adobes from Tierra Caliente. The Uniaxial Compressive Strength (σ_{UCS}), the Flexural Strenth (σ_F) and the Point-Load Compressive Strengh (σ_{PLT}) are displayed in the first section of the table, finding the ratios between the different test methods. The second section contain the dynamic and static modulus and elasticity (E_d and E_s), calculated from the Ultrasonic Velocity Pulse test (UVP) and the stress-strain curve through compression test, as well as the ratio between E_d and E_s.

It is interesting how the relation with bulk density and mechanical resistance was fulfilled with all the tests, since H presented slightly higher results. The correlation between UCS and density has been proven, however the linear relation starts to plateau at a certain point [25]. In the case of the UCS, H and SC presented close values and low variability, within the global range of UCS for adobe blocks found in the literature review [25,27,28,45,47], and within the line of analogous research performed with heritage adobes in Mexico [62,64,67,120,121]. The longevity and aging of the pieces could be certainly a defining factor, as well as the preservation and maintenance of structures, as we can find much lower values for the study cases analyzing ancient and damaged pieces [62,67].

After the UCS test, the flexural strength is the most common trial to assess the mechanical resistance of adobe blocks [27]. H and SC reported σ_F of 4.65 and 3.85 kg/cm^2 respectively, with higher variability than σ_{UCS} and higher results for the fiber-stabilized adobes. An optimal fiber content has demonstrated to increase this mechanical parameter [47], in consequence it was expected to find a better performance of the adobes from H, as it was the case.

Reviewing the scientific literature and equivalent study cases, the adobes from Tierra Caliente showed a satisfactory mechanical behavior. The review by Abhilash et al. (2022) compiled eight research works from six different countries [27], with a σ_F range of [1.0-9.5 kg/cm^2]. The variability was higher for adobes from Cyprus, manufactured in different regions of the country [122], while the precedents from Mexico were more delimited [2.0-4.3 kg/cm^2] [121]. The archaeological samples from Nisa Partica in Turkmenistan also presented a similar range [1.3-4.9 kg/cm^2], slightly lower considering the degradation experimented due to the passing of time [53].

[3] LOI (Loss-on-Ignition) represents the percentage of material lost on the ignition process of the test at 1050 °C.

Table 3
Composition of the adobes, index properties and USCS Classification.

	Gravel	Sand	Fines	Fibers	LL	PL	PI	USCS group	
H	2.49	7.98	89.2	0.32	49.58	34.10	15.48	CL-ML	Lean clay/silt
SC[a]	2.08	53.25	44.67	0.00	25.73	20.28	5.45	SC	Clayey sand

[a] The SC adobes contained negligible amounts of vegetal fibers, consequently they could not be separated from the rest of the material and its weight was not considered.

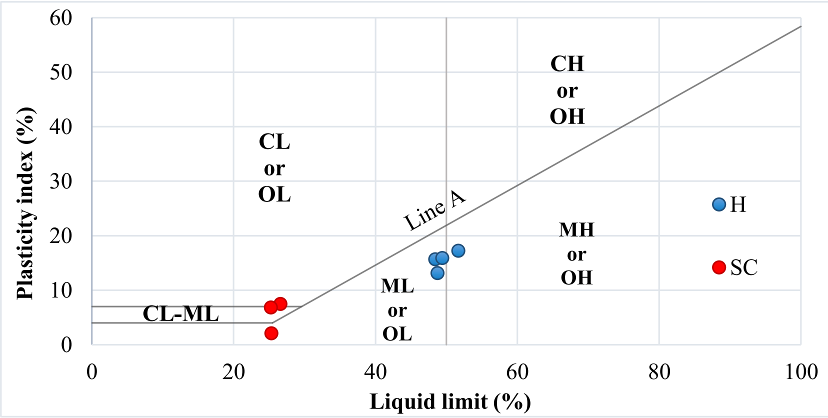

Fig. 5. Casagrande plasticity chart and location of the samples.

Table 4
XRF and XRD analysis of the adobes.

FRX Analyses										
(%)	CaO	MgO	Fe_2O_3	Al_2O_3	SiO_2	K_2O	Na_2O	P_2O_5	TiO_2	MnO	LOI
H	1.320	1.260	17.720	28.067	33.571	0.720	0.120	0.326	1.800	0.309	14.435
SC	3.460	2.605	19.952	14.610	48.630	2.937	0.361	0.190	1.483	0.276	5.145

DRX Analyses					
(%)	Anorthite	Metahalloysite	Quartz	Cristoballite	Hematite
H	56	22	10	7	5
(%)	Anorthite	Kaolinite	Quartz	Hematite	
SC	60	18	16	6	

Additionally, the ratio between σ_{UCS} and σ_F was calculated, with a variability between both study cases of 12%. The review of scientific works and regulations estimates the value of σ_F in a range between the 20 and the 50% of the σ_{UCS} [25]. Furthermore, Costi de Castrillo et al. (2022) presented the following equation for flexural strength: $f_f = 0.449 f_c$ [107], which would have the values of $0.443 f_c$ for H and $0.396 f_c$ for SC; all of them very close to the simplified (2:1) ratio.

Regarding the PLT, there are still very few references with earthen materials to compare the results. In previous research done with adobes from Jojutla, in Mexico, the ratio σ_{CSU}/σ_{PL} was very different, with a value of 1.39 [62]. One of the main causes for this disparity could be the original design of the test method to assess mainly sandstone rocks [92], and the correction factors for earthen materials don't yet exist. Nevertheless, the σ_{CSU}/σ_{PL} ratio was very similar for H and SC, being and encouraging aspect to continue exploring the PLT for the assessment of earthen materials, since studies with other rock materials have found almost linear correlations and reliable regression equations [123]. The advantages of performing *in situ* analysis and the possibility to test irregular fragments are really engaging for the heritage studies.

The UPV is one of the most helpful NDT to analyze heritage objects or materials and acquire information about the internal structure, while indirectly obtaining the porosity and the inhomogeneities, including the presence of damage [124]. Few research works have experimented with UPV directly calculated on adobes or other earthen techniques [24,54,58,62,124–126], since the current regulations are designed for the analysis of concrete structures. The results for H and SC presented low variability, and comparing them with the other precedents the values were higher, entailing a good manufacture and preservation of the blocks.

Additionally, the UVP is utilized as an indirect method to calculate the dynamic elasticity modulus (E_d) with the parameters of density and the Poisson's ratio (ν). The E_d is a direct representative property of the material stiffness and help to understand the stress-strain behavior of building structures [127]. A Poisson's ratio of $\nu = 0.46$ was calculated taking in consideration the results of the static elasticity modulus while being consistent with the literature [128]. The standards do not include procedures to calculate this parameter for earthen materials, and other analyses have calculated the ratio previously with the testing of control specimens by

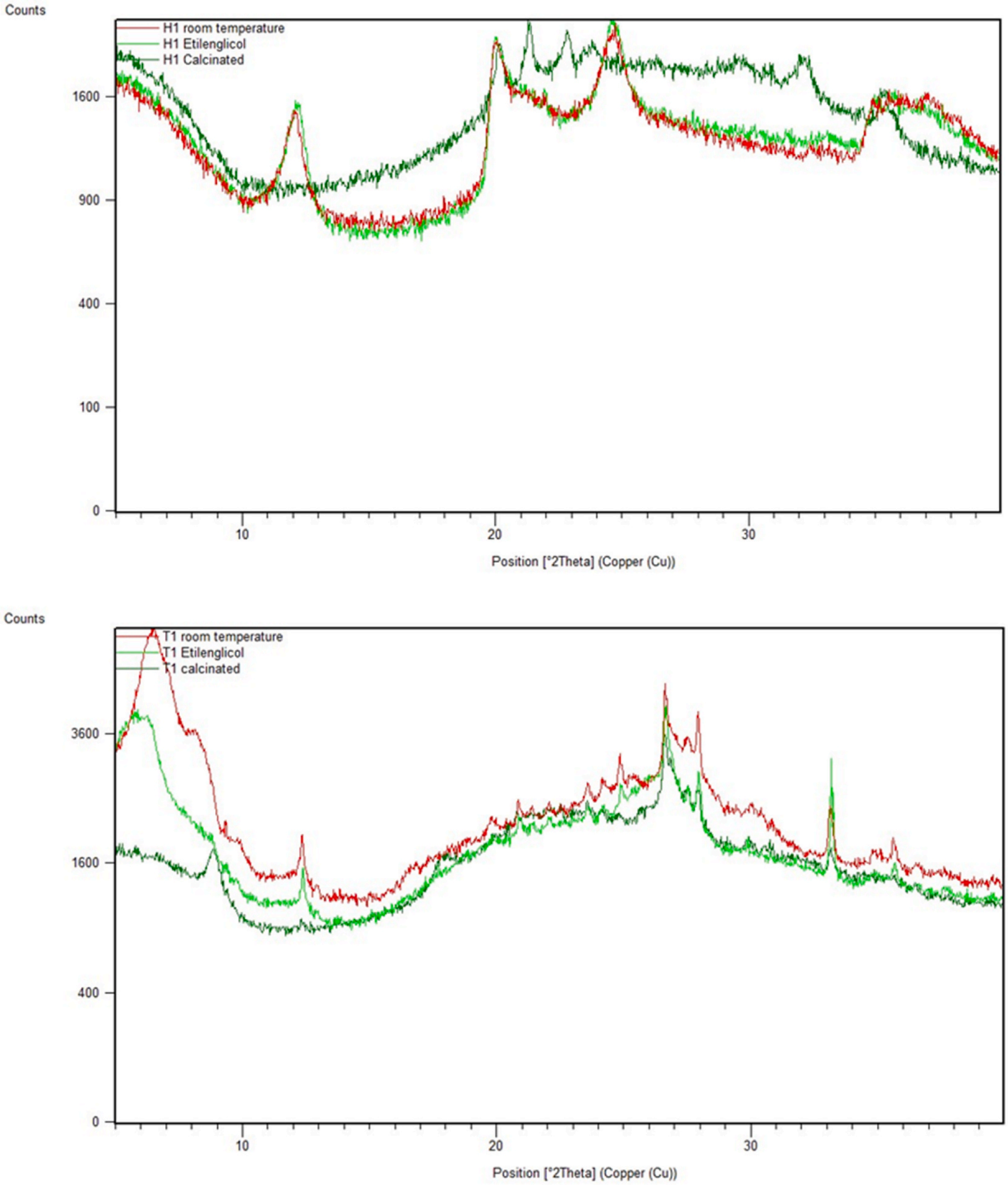

Fig. 6. X-Ray diffractograms: (a) H; (b) SC.

different methods, leading to disparate values [40,42,55].

The static elasticity modulus (E_s) was calculated by means of compression tests and the stress-strain curves [99], as it can be spotted in Fig. 9. It is remarkable the higher variability in the adobes from SC, with a stiffer behaviour and more deviation of the values (see Table 5). For the specimen with lower mechanical resistance we can see an initial phase where probably the structure is being rearranged but later the slope remains similar than the other two samples; this situation could be due to internal damages or cracks (see Fig. 10).

In contrast, H samples presen a more elastic behaviour, which could be due to the presence of fibers. This the role of fibers is really significant in the elasticity curves, since they produce a non-linear complex behavior where different phases can be identified [104]. For both E_d and E_s, H and SC presented reasonable values within the range for adobe testing in the literature; nevertheless, it is important to note that this range is massive, with a higher variability of results. Both elasticity modulus, E_d and E_s, were correlated through a coefficient, nevertheless [129,130] more experimentation will be necessary in this field in the following years [104].

The triaxial tests allows to calculate the failure envelope of the specimens with at least three Mohr circles (corresponding to the different confinement pressures) obtaining the cohesion value (c) and the friction angle (φ) (see Table 6) and (Fig. 10). In previous

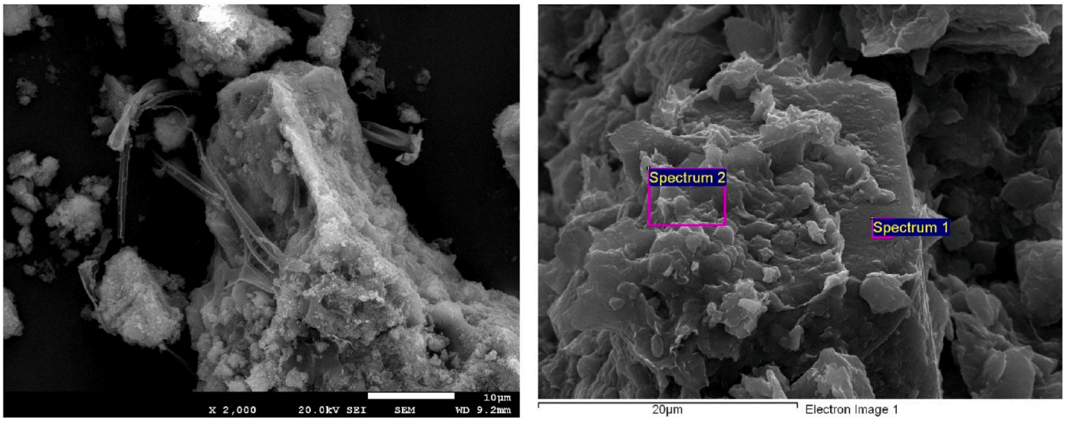

Fig. 7. SEM images: (a) H; (b) SC.

research works, natural clayey soils from the region were analyzed, to determine the changes of different volumetric stabilizers in the high plasticity behavior of the materials [131]; moreover, the suction and relative humidity can modify all these properties [132]. A greater cohesion means better union between the particles of soil and it is inversely proportional to the friction angle.

Clays have a higher cohesion value than other particles like silts and sands, therefore it was expected to obtain major result for H, which contains more fine material. It is important to note that adobes are construction components, and these soil mechanics test methods analyze the samples as unsaturated soils to obtain their shear strength [133]. Because of that the samples were tested with the same conditions and water content they were found, since we wanted to replicate the actual behavior of earthen constructions.

With the results of the cohesion (c) and the friction angle (φ), the following expressions (Eqs. (1) and (2)) were found to calculate the shear strength ($\boldsymbol{\tau f}$) of each study case, according to the Mohr-Coulomb failure criterion ($\boldsymbol{\tau f} = \boldsymbol{\sigma}' \times \tan(\varphi) + \mathrm{c}$), where in this case the normal stress ($\boldsymbol{\sigma}'$) is an intrinsic variable of the structure:

$$\tau fH = \sigma' \times \tan(54) + 1.53 \tag{1}$$

$$\tau fSC = \sigma' \times \tan(60) + 0.83 \tag{2}$$

3.3. *Durability characterization*

Fig. 11 shows the capillarity absorption curves of H and SC, pointing out the major absorption of the H adobes, which is directly related with the higher proportions of fine materials and the presence of vegetal fibers. The graphic shows the capillarity absorption of the adobes by mass in function of the time elapsed during the test. An inflecting point can be easily spotted in the graphic, corresponding to the first stage when saturation of the cubes occurs ($T_{ABS.I}$), and the much slower secondary absorption rate ($T_{ABS.S}$), which involves the evaporation of the water gained.

The general capillarity absorption coefficient (C_{ABS}) was considerably higher for H, meaning that these adobes are more vulnerable to the water intake. Additionally, the C_{ABS} values can be compared with other study cases from vernacular earthen buildings, to put into perspective the results and better understand the behavior of the Tierra Caliente adobes. Samples from Leiria, in Portugal, presented closer coefficients to SC, while the rammed earth samples of the region obtained higher values [58]; on the other hand, unstabilized adobes from the southern region of Lisboa reported lower absorption ratios relating them with the presence of kaolinites [60]. Considering that the H and SC blocks didn't present signs of chemical stabilization, these results showcase the expertise and traditional knowledge of the constructors of the region.

Remarkable differences can be observed for the H samples, with unequal initial absorption rates and curves despite being the same material; Mendoza (2022) attributed this behaviour to the vegetal fibers content of the samples, which variated for the different *haciendas* studied [128]. The increase of the fiber content has reported lower absorption rates, especially when the stabilizer utilized is straw, since these larger fibers contribute to generate a microstructure of larger pores that have lower capillarity [107].

The C_{ABS} is a really important parameter, since the increase of the water content decreases the mechanical strength of earthen structures, and more amount of water causes the weakening of the mechanical bond between the clays and the coarse particles [12]. The relation with the compressive strength for both stabilized and non-stabilized earth materials has been proven with almost linear ratios [12], while other research works have reported the decrease of other proprieties like the cohesion and the friction angle [133, 134].

4. Conclusions

The characterization of earthen materials is essential for the preservation of our architectural heritage. Literature review revealed how the procedures tend to be partial and biased in function of the involved discipline. The archaeological and conservation studies

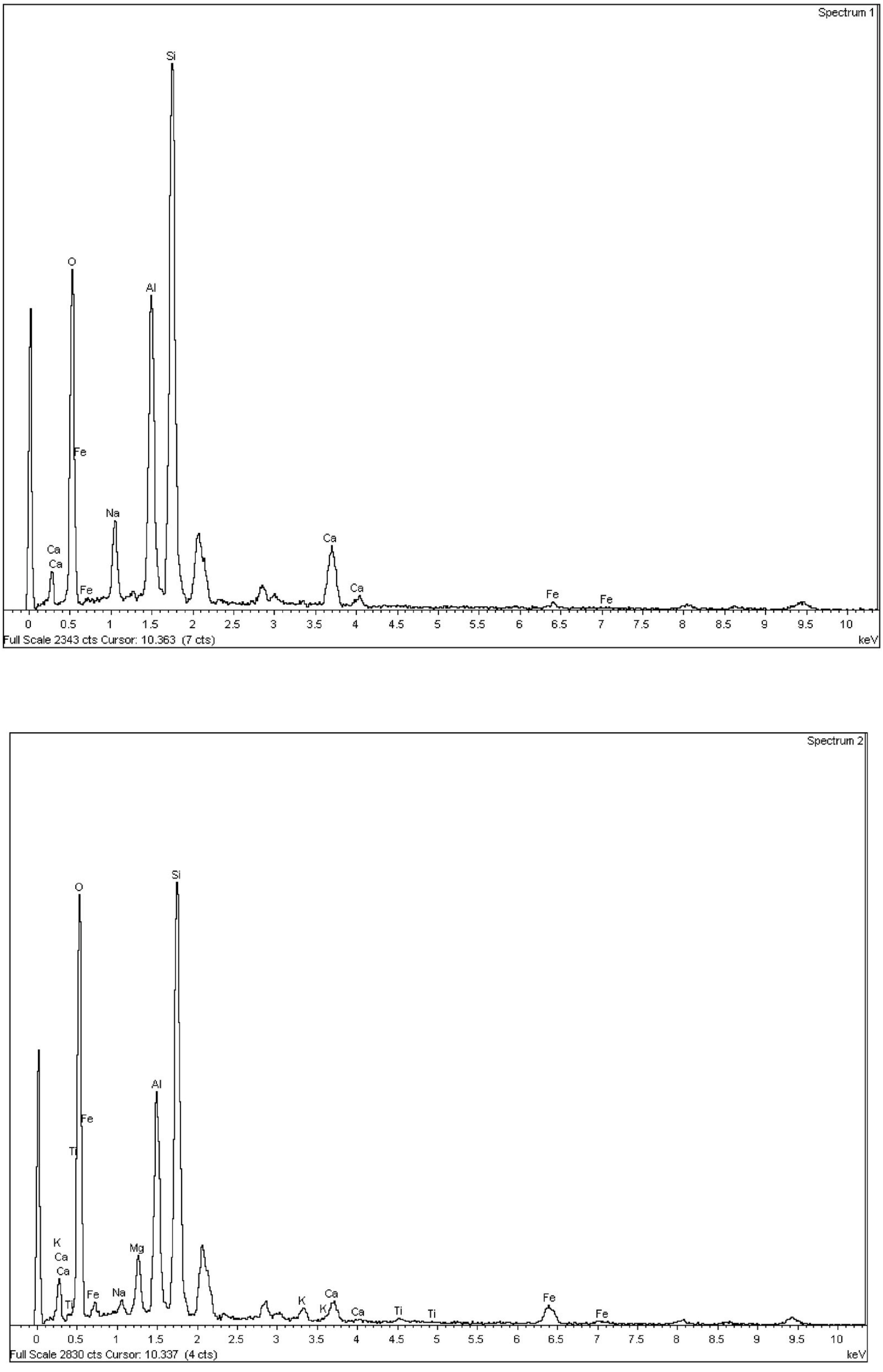

Fig. 8. EDX analysis of the adobes from SC: (a) Spectrum 1; (b) Spectrum 2.

Table 5
Mechanical resistance characterization values, dynamic and static elastic modulus values and correlation coefficients.

	P_{ap} (kg/m^3)	σ_{UCS} (kg/cm^2)	σ_F (kg/cm^2)	σ_{PL} (kg/cm^2)	σ_{CSU}/σ_F	σ_{CSU}/σ_{PL}
H	1724.16	10.48 ± 3.36	4.65 ± 2.48	25.14 ± 11.72	2.25	0.42
SC	1609.09	9.71 ± 1.69	3.85 ± 1.69	20.50 ± 9.61	2.52	0.47
	P_{ap} (kg/m3)	**UVP** (m/s)	**E_d** (kg/cm^2)	**σ_{Max}** (kg/cm^2)	**E_s** (kg/cm^2)	**E_d/E_s**
H	1724.16	1075.00 ± 122.09	4488.14 ± 1407.25	7.21 ± 0.93	4112.22 ± 1461.00	1.09
SC	1609.09	1094.67 ± 162.37	4299.83 ± 1025.50	11.83 ± 4.60	3781.46 ± 1975.72	1.14

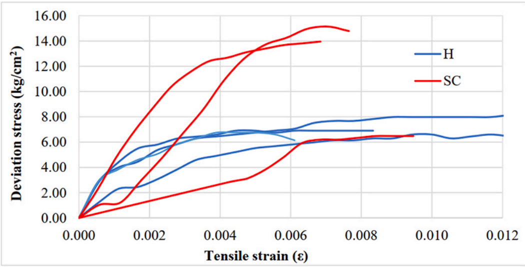

Fig. 9. Stress-strain curves obtained with the standard compression test for static modulus of elasticity.

Table 6
Results of the undrained unconsolidated triaxial test with different confinement pressures.

	Confinement (kg/cm^2)	σ_{Max} (kg/cm^2)	τ_f (kg/cm^2)	ρ_{ap} (kg/m^3)	ω (%)	c (kg/cm^2)	φ (°)
H	0.30	12.04	18.10	1724.16	6.77	1.53	54
	0.60	12.19	18.31				
	0.90	17.42	25.51				
SC	0.30	9.96	18.08	1609.09	2.69	0.83	60
	0.60	8.60	15.73				
	0.90	17.58	31.28				

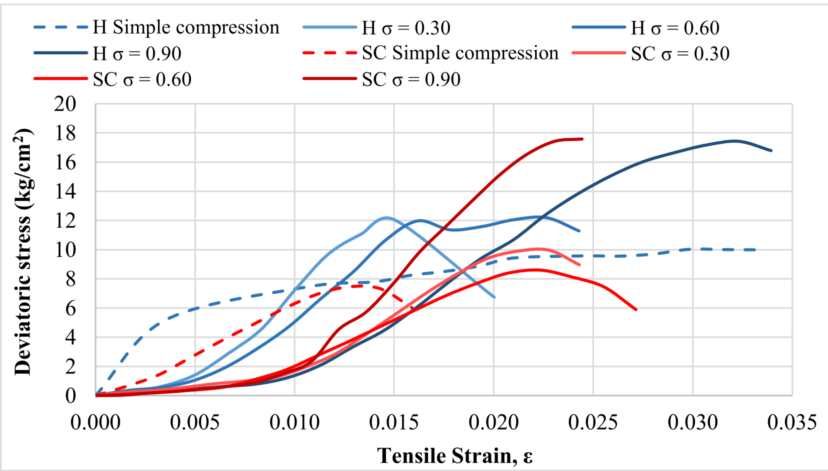

Fig. 10. Deviator stress – tensile strain graphic obtained with the unconsolidated undrained triaxial test.

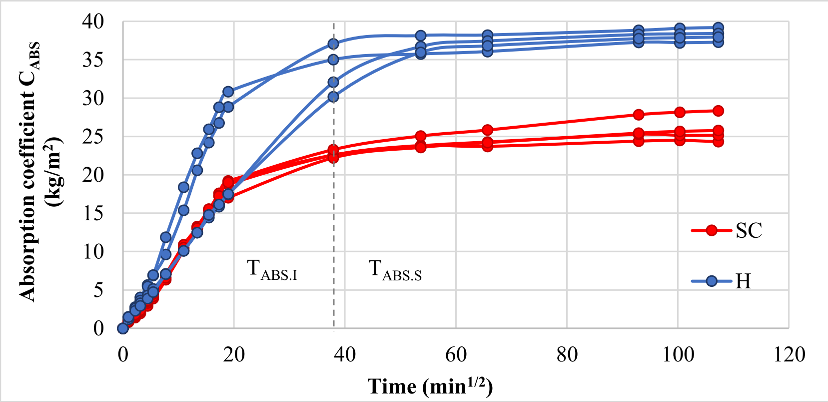

Fig. 11. Capillarity absorption curves.

rely on the chemical analysis, while the civil and materials engineering focus on the mechanical tests. This document proposes a methodological framework to characterize historical adobes from the physical-chemical, the mechanical and the durability properties.

From the physico-chemical results it can be concluded that the two case studies from the same cultural and geographic region presented totally different compositions and variations of the construction technique: H contained large proportions of fine material and some fiber content, while SC showed a granulometric distribution closer to the referenced literature but no fibers. Regarding the chemical analyses, the XRF technique has not been as extended as the XRD for the analysis of historical earthen constructions, since researchers prioritize knowing the mineralogical phases rather than the elemental composition; nevertheless, it is interesting to know the last before identifying the clay minerals, and this situation has led researchers to questionable interpretations.

From the mechanical characterization results it can be concluded that the resistance was very similar for both cases, with H presenting slightly major values. It is remarkable how earthen materials can be very inconsistent at the time of performing mechanical trials, therefore, they also should be studied from the soil mechanics theories and their standard methods. Additionally, adobes should not be considered homogenous pieces because earth is a really complex anisotropic material; for this reason, the NDT should be incorporated since they present high reliability and can be performed in heritage buildings to assess some relevant properties and estimate the mechanical resistance.

From the durability characterization results it can be concluded that the analysis of the erosion mechanisms can be useful to design optimal preservation solutions for earthen masonries, helping to design non-invasive proposals for heritage constructions. The test methods to assess the durability of earthen materials should be expanded, certainly being instrumental to comprehend the behaviour of adobe buildings against water and deterioration.

This research demonstrates how the guidelines for the selection of soils not necessarily match the existing heritage, and how the principles of vernacular architecture work, employing local resources with an optimal design. Future research will be focused on improving and expanding the methodological framework to characterize adobes with some aspects like: the geometry of the samples in the testing procedures, the correction of the Poisson's ratio for earthen materials, or the inclusion of other NDT and durability methods.

CRediT authorship contribution statement

Adrià Sánchez Calvillo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Elia M. Alonso Guzmán:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Antonia Navarro Ezquerra:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Melissa Ruiz Mendoza:** Visualization, Methodology, Investigation, Formal analysis. **Wilfrido Martínez Molina:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **José Ignacio Álvarez Galindo:** Software, Resources, Project administration, Investigation, Funding acquisition. **Lídia Rincón:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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