Abstract: Adobe masonry is one of the oldest construction systems still in use today. Mexico has an enormous cultural heritage with traditional adobe houses being very representative of the rural communities and their culture. The 2017 Puebla Earthquake on September 19th struck the country causing the loss, destruction, and damage of historic buildings in several Mexican states, with the traditional earthen dwellings being the most vulnerable structures to these events. The fast abandonment of the local materials and techniques entails further research regarding the characterization of these construction systems, therefore, reconstruction efforts first require the recovery of the construction technique. After the seismic events, adobe samples of the remaining adobe structures of Jojutla de Juarez were collected. This population was one of the most affected in all the country, and, because of the major losses suffered, the study was conducted to determine the material properties of the dwellings’ adobe shards and natural quarry clays of the region. The characterization included destructive and non-destructive tests, mineralogical and granulometry analyses, and composition of the adobe samples of the buildings, as well as the aggregates. As a novelty, the compressive strength of the pieces was tested by two methods: the traditional compression strength test and the point-load test, in order to obtain the indicative values and the correlation equations between both tests. From the formal analysis and the laboratory, it was observed that the adobes from Jojutla presented different compositions which combined with the building malpractices and alterations to the traditional systems caused unpredictable behavior during the earthquake. The conduction of point-load tests in situ, as a part of a complete characterization methodology, could be an alternative to study the mechanical properties of patrimonial or damaged building samples before its disappearance.

Keywords: earthen architecture; adobe masonry; materials properties; materials characterization; point-load test; mechanical properties; seismic affectation.
poses a great difficulty to any restoration work. The devastating 2017 Puebla earthquake on September 19th caused the loss of many historical buildings in central Mexico, with traditional earthen dwellings being the most vulnerable. The restoration process has made evident the need to recover the traditional construction techniques employed. In the present paper, adobe and soil samples were collected from Jojutla, Morelos, Mexico—one of the hardest hit areas—and an in-depth study was performed to elucidate the materials and techniques used in their manufacture.

These samples were tested with a complete methodology for material characterization using both destructive and non-destructive techniques, and including geotechnical, particle size and mineralogical tests, as well as the inclusion of the point-load test (PLT) as an innovation and alternative to calculate the mechanical resistance of earthen construction materials.

The results presented provide interesting details of the traditional building materials and systems used in the region studied, helping to understand the behavior of these structures and the way they were built. Furthermore, the PLT displayed promising results as a means to characterize in situ the mechanical properties of earthen architecture, providing a useful tool when working with cultural heritage and structures affected by natural phenomena.

1.1. Earthen Architecture in Mexico

Earth is one of the oldest construction materials known; archaeological evidence reports its use for over thousands of years, being a key factor in the development of ancient civilizations [1]. Its continued use over several millennia resulted in a variety of local constructive traditions and architectural earthen heritage in several regions of the world [2]. These construction systems can be found in all continents—except Antarctica—showing relevant local variations, and being present in all types of structures, including both residential and religious architecture [3,4]. There is evidence of vernacular and monumental examples from Latin America, Africa, Central Europe, and the Middle East [5].

In the American continent the magnificent structures of Peru are known worldwide, being earthen monuments very representative of the Incas [6]. The city of Chan Chan, developed from the Chimú culture, is the largest built entirely with adobe in the American continent, and the site of Caral, over 5000 years old presents a very interesting mixture of monumental and residential architecture with earthen materials, including adobe and “quincha”, a traditional construction system which combines earth and vegetative material [7].

Mexico, as well, has a wide and rich amount of earthen construction heritage, including both archaeological and architectural structures. There is evidence of the use of earthen systems in Pre-Hispanic cultures since their earliest periods, with several examples being found in both small and large archaeological sites, as well as historical buildings [8]. Most of the great pyramids, which today function as monumental touristic sites, were built with earth and then covered with stone coatings [8].

Even after the arrival of the Spanish and the colonization, the adobe masonry and rammed earth systems were still handed down from generation to generation, being commonly used in the housing and monumental construction of the cities [9]. Additionally, as the Iberian Peninsula had a widespread and old tradition of earthen architecture [10], adobe was one of the main building materials used by the first builders that arrived in the American continent, along with other techniques like rammed earth [11], but due to its simplicity and availability, it was implemented in the planning of new cities and urban centers.

Nevertheless, over the years, the earthen architecture has suffered a progressive abandonment, being displaced by modern materials and techniques. Currently, in Mexico, the traditional adobe buildings are closely associated with the lower social classes and are even considered unsafe materials [12], partly because of the constant earthquakes which the country suffers.
1.2. Characterization of Earthen Materials and the Case of the Mexican Cultural Heritage

In recent years, the literature about earthen materials has been very productive, with an increase in the number of articles, conference proceedings, guidelines, outreach, and training documents, with several works regarding the material characterization of these structures.

Furthermore, the celebration of scientific events, has helped to raise the awareness about the importance of these traditional techniques and its current situation in modern construction. Events like TERRA World Congresses, held since 1972 in different countries under the aegis of ICOMOS, and the Ibero-American SIACOT congress, have spread the results from scientific studies of earthen materials.

Additionally, the work of institutions and universities is extremely valuable, including the dissemination of knowledge by means of guidelines, technical reports, and handbooks; intended not for specialists but the users and craftsmen who are the real target. The Earthen Architecture Initiative of the Getty Conservation Institute has published meaningful guidelines about specific topics [13,14]. At the government level, during the last decades many countries have released technical codes for raw earth construction, such as Australia, New Zealand, Spain, France, Chile, or Peru [15].

Considering the scientific literature, some authors and institutions have gathered important information and results about these construction materials, including reviews concerning hygrothermal properties, natural fibers, or building codes and standards [5,15,16]. Other works place an emphasis on the identification, documentation, and cataloguing of cultural heritage and sites for their protection and preservation [17–22], while others focus on the technological enhancement and development of these sustainable materials [23–25].

Regarding the material characterization, the main topic of the present paper, we can find recent research works which have implemented various methodologies, including techniques listed by the Getty Conservation Institute guidelines [14], and incorporate innovative ones for the study of these materials. The Portuguese research contributions are very interesting [26–30], with a very productive activity in the last years; moreover we can find recent ones from North Africa [31,32], and in Latin America the works from Peru [33,34], and Chile [23,24], are very relevant.

Additionally, the seismic vulnerability of these structures has been studied from many perspectives, including the structural and technological aspects [34–38], as well as the social and cultural importance to transmit the original retrofitting strategies [39,40]. In Latin America, many countries are prone to seismic events.

On the other hand, most of the investigations have revised the earthen construction from the perspective of the construction technology and the cultural significance of the traditional architecture [10,11,19,20]. In Mexico, the research approach has been focused on this last perspective, while the technical knowledge and the materials engineering has been overlooked. We can find a vast knowledge and literature of earthen structures in the country and its sundry regions [41], nevertheless the articles and resources about material characterization are scarce.

Staying in Mexico, in the archaeology field, the construction systems of the Pre-Hispanic Mexican architecture have been identified, listed, and explained in previous research studies, creating a vast knowledge of the first earthen structures in the country. Complex techniques like the micromorphology have been applied in the study of archaeological earthen heritage [42], while the different construction systems, like adobes, earth mortars, and ‘bajareque’ from archaeological monuments have been characterized and the construction techniques have been identified with advanced analytical techniques [8,43].

Nevertheless, the adobe housing has been overlooked from the material characterization, especially regarding mineralogical studies and non-destructive laboratory tests. The majority of the research and academic works focused on the mechanical properties, determined by means of destructive tests [44]. The present paper intends to display a complete characterization of earthen materials in a Mexican case of study.
1.3. The Seismic Affectation on Mexican Earthen Architecture

Mexico is a large country prone to suffer important earthquakes which cause the destruction of its structures and cultural heritage. The country is located within five tectonic plates: the Pacific Plate, the North American plate, the Rivera Plate, the Cocos Plate, and the Caribbean Plate, causing a high seismic activity in the boundaries between plates. Some regions are really prone to suffer big impacts from earthquakes and the presence of the Trans-Mexican Volcanic Belt crossing a large territory contributes to this high seismic activity.

In September 2017, two major earthquakes struck the country, having a big impact on the regions and states affected. (Mexico is organized as a federal republic composed of 32 Federal Entities: 31 states and Mexico City as an autonomous entity.) The first event occurred on 7 September with an epicenter in the zone known as Gulf of Tehuantepec in the Pacific Ocean, 133 Km southeast of Pijijiapan in the state of Chiapas; and a magnitude of 8.2 Richter scale [45]. The affectation was strong in the southwestern part of the country, especially in the states of Oaxaca and Chiapas. The second event occurred on 19 September, just 32 years after the impactful 1985 Mexico City earthquake, which devastated the capital of the country. The epicenter was located 12 Km southeast of Axochiapan [46] (See Figure 1), in the boundaries between the states of Morelos and Puebla, also causing important harms in the states of Tlaxcala, Mexico State, Guerrero, and Mexico City.

Figure 1. Seismic intensity map of the 2017 Puebla Earthquake. (Source: Atlas Nacional de Riesgos, map generated by Earthquake Institute of the National Autonomous University of México).

Although the impact of earthquakes is immediate and the damages are easily visible, the population tends to forget the events over time, causing unawareness of the seismic danger and the oblivion of the traditional retrofitting strategies and techniques [35]. The different strategies of adaptation to a rugged environment and natural phenomena generated the “seismic culture” concept [39].

1.4. Case Study: Jojutla and the Destruction of Its Earthen Architecture

The state of Morelos has an important seismic history, considering its central location in the territory of Mexico. The infamous 1985 Mexico City earthquake had catastrophic consequences not only in the country’s capital but also in the rest of the central part of the country, including the destruction of many dwellings and displacing many people from their homes. Furthermore, the 1999 Tehuacan earthquake also had a big impact in the region, causing important damages on the historical and cultural heritage, being known for the collapse of religious buildings. Along with these major events, the state suffered other slight tremors in 1957, 1980, 2007, and 2008; nevertheless, all remained distant in the collective memory of the society, and the authorities did not develop any risk management plan to anticipate future disasters.

The 2017 earthquake was particularly pernicious to the material cultural heritage, causing the loss of several churches and many of the oldest buildings in historic centers.
Regarding the state of Morelos, the National Institute of Anthropology and History (INAH) quantified the damages suffered by heritage buildings, with a total of 259 constructions presenting damages [47], and being the focus of the heritage institutions from the entire country. Especially remarkable was the destruction of the 16th Century Mexican colonial monasteries, which are listed as UNESCO World Heritage Sites. Research efforts and resources were allocated to study and comprehend the failure modes and seismic response of these structures [48]. Besides the relevance and notority of these structures, religious monuments are an important part of the traditions, culture, and way of life of the local communities.

Regarding the residential architecture and traditional housing, the situation was totally opposite (See Figure 2). The reconstruction of the dwellings was done with industrial materials, mainly cement blocks provided by the authorities, for the walls; and metallic sheets for the roof structures. The traditional materials, particularly adobes, were rejected by the majority of the population, perceived as unsafe systems and the main cause of the structural damages. Although the seismic affectation was provoked by many factors, the organizations in charge did not protect and support the vernacular architecture and the traditional techniques [49], with the immediate consequence of the disappearance of this local culture.

Morelos is one of the 32 total states which comprise Mexico, being located in the central part of the country, bordered by the states of Puebla, Guerrero, State of Mexico, and Mexico City. Regarding the earthen architecture, Morelos has an important tradition of adobe buildings [49], with well conserved examples in the south-eastern and north-eastern parts of the state. Several of the traditional dwellings have two or more centuries of existence, and they have resisted all types of natural phenomenon including seismic events. Adobe constructions present a set of earthquake-resistant strategies, like simple geometric proportions and forms, an adequate slenderness and thickness of the walls, roof flexible systems, compatibility between the materials, a good maintenance from the users, among others. The most well-preserved houses from these regions responded rather well to the 2017 Puebla earthquake [49], an inherent feature of the vernacular architecture, which has always responded to the local environment [39]. In Figure 3b, the choropleth map of the state can be observed, showing the municipalities with a higher preservation of earthen constructions, and the ones where modern materials and systems have substituted adobe.

The case study Jojutla is spotted in the south-western region of the state, an area where less traditional architecture predominates.
In contrast to other regions and localities of Morelos, Jojutla, showed drastic changes to the traditional buildings of Morelos. The dwellings were fairly modified over the last decades, integrating new interior spaces with modern industrial materials and facilities, but the implementation was commonly suboptimal. The repercussions of these constructive changes were also treated in a previous research from the authors, focusing on the physical damages observed in the buildings after the earthquake [50]. The adobe buildings of Jojutla presented changes in the morphology, original uses, and architectural plans, the addition of new floor levels and construction materials, lack of maintenance, and abandonment.

The town of Jojutla showed a local seismic-regionalization, with greater damages in some particular colonies or neighbourhoods, as seen in Figure 4, displaying areas with high and medium risk to its buildings. The high risk includes the collapse of the structures, since Jojutla experienced major material and human losses. Two colonies of the city were specially affected: the historic center, where most of the adobe dwellings and monuments were located; and the Emiliano Zapata colony, much more recently built with the majority of its constructions consisting of concrete structures.

The geotechnical survey of the Emiliano Zapata colony provided some of the reasons for the poor seismic performance of the buildings, including suboptimal resistance of the structural systems, issues with the foundations and construction malpractices [51]. The terrain presented a superposition of clay and silt layers and a travertine stratum formed by disposal of calcium carbonate [51], which is not well suited for building purposes.

Additionally, the use of incompatible materials with different elasticities, the poor connections between the structural elements, the changes in the morphology of the buildings, and the low mechanical properties have been reported as the main causes of the seismic vulnerability in historic earthen constructions and historic centers around the world [9,18,36,40,52].

Knowing the propensity of the region to seismic activity and with the experience of past events like the 1985 Mexico City earthquake or the 1999 Puebla earthquake, it was surprising that he municipal development plan of the city council of Jojutla, published on May of 2016, months before the seismic events, did not include any mitigation strategies against natural hazards like earthquakes, floods, or fires; and, more importantly, no risk maps had been made, nor a reorganization of the city [53].
Figure 4. Mapping of the damaged buildings in Jojutla after the 2017 Puebla Earthquake by the emergency brigades (Map source: ArcMap 10.3, map elaborated by A. Sanchez-Calvillo).

2. Materials and Methods

Thirteen samples of earthen architecture were collected from the remains of affected buildings left in the region of Jojutla after the seismic disaster of 2017. Considering that the structures were severely damaged and a whole study of the construction typologies would not be feasible, all the samples were carried to the laboratory “Ing. Luis Silva Ruelas” of the Faculty of Civil Engineering of the Universidad Michoacana San Nicolas de Hidalgo, in Morelia, Mexico.

2.1. Sampling Adobe and Soils

There were 11 representative shards of adobe bricks collected from 11 different traditional houses in downtown Jojutla (See Figure 5). These samples were collected before the demolition of the buildings, which was shortly after the field trip in May 2018. There also were two samples of quarry soils of the region taken, concretely in the extraction area for the manufacture of adobe bricks and ceramic bricks, and an excavation in the city (See Table 1). The region is recognized by their rice production, even the Morelos rice is a trade mark, and of course they have plenty of water. The superficial stratum of the town comprises fluvial and lacustrine deposits, which held large amounts of clays [51], very susceptible to volumetric changes with the moisture.

Figure 5. Location of the samples within the urban area. (Source: Google MyMaps).
Table 1. List of collected samples, type, date, and provenance.

| Sample | Type   | Collection Date | Provenance                                      |
|--------|--------|-----------------|------------------------------------------------|
| M1     | Soil   | 17/07/2018      | Excavation in Emiliano Zapata colony            |
| M2     | Adobe  | 18/07/2018      | Francisco Javier MinaSt., Jojutla downtown      |
| M3     | Adobe  | 18/07/2018      | Zayas Enriquez St., Jojutla downtown            |
| M4     | Adobe  | 18/07/2018      | Zayas Enriquez St., Jojutla downtown            |
| M5     | Adobe  | 18/07/2018      | Carlos Cuaglia St., Jojutla downtown            |
| M6     | Adobe  | 18/07/2018      | Zayas Enriquez St., Jojutla downtown            |
| M7     | Adobe  | 18/07/2018      | M. Cepeda Medrano St., Jojutla downtown         |
| M8     | Adobe  | 18/07/2018      | J. H. Preciado St., Jojutla downtown            |
| M9     | Adobe  | 18/07/2018      | Francisco J. Bocanegra St., Jojutla downtown    |
| M10    | Adobe  | 18/07/2018      | 21 de Marzo St., Jojutla downtown               |
| M11    | Adobe  | 17/07/2018      | Zayas Enriquez St., Jojutla downtown            |
| M12    | Adobe  | 17/07/2018      | Ricardo Sanchez St., Jojutla downtown           |
| M13    | Soil   | 17/07/2018      | Clay quarry near Jojutla                        |

Previous research works involving historical and archaeological heritage followed similar strategies for the sampling, collecting both adobe pieces or shards and local soils from clay quarries. Fratini et al. [54], gathered information regarding the production and manufacturing of the adobes following the artisans’ indications of the towns of Sambiasi and Nicastro. Mellakhaifi et al. [31], decided to study the vernacular heritage in southeast Morocco only from the samples of unaltered soils, extrapolating the results to the earthen traditional techniques and its properties. Regarding archaeological heritage, Pérez et al. [8], studied the Great Pyramid of Cholula, taking samples of complete adobe bricks of the inner construction, besides 5 soil samples corresponding to some important Pre-Hispanic development stages of the ancient city.

Taking into account the emergency state of Jojutla de Juarez and the situation between the inhabitants and their damaged buildings, the sample collection responded to the criteria of taking the maximum possible amount of material before the demolition of the remaining houses (See Figure 6). Our group also had the opportunity to talk with the owners of the buildings and families of the town; some of the owners from collapsed buildings said they were taking good care of their properties, even if they had collapsed, by protecting the remaining structures from inclement weather. They let the group take the samples from broken adobes, a family from the town even gave the group adobe samples from two buildings more than 200 years old.

Although some of the owners from the land plots and the damaged dwellings planned on reusing the adobe bricks preserved in good condition, most of them thought that earthen materials are unsafe and preferred to wait for the concrete blocks provided by the authorities. One of the main advantages of earthen architecture is that the materials can be reused perpetually since clays are sustainable resources [21,55].

The traditional mortar plasters from the samples collected were in poor condition. The plasters operate as the skin of the adobes and passivate them from the environmental attack, being really important to preserve cultural heritage [8,56,57]. Usually the plasters and adobes from historic constructions come from the same quarry but are stabilized with different additions [46].
owners of the buildings and families of the town; some of the owners from collapsed buildings said they were taking good care of their properties, even if they had collapsed, by protecting the remaining structures from inclement weather. They let the group take the samples from broken adobes, a family from the town even gave the group adobe samples from two buildings more than 200 years old. Although some of the owners from the land plots and the damaged dwellings planned on reusing the adobe bricks preserved in good condition, most of them thought that earthen materials are unsafe and preferred to wait for the concrete blocks provided by the authorities. One of the main advantages of earthen architecture is that the materials can be reused perpetually since clays are sustainable resources [21,55].

Figure 6. Sample collection. (a) Semi-complete adobe bricks from an old demolished building; (b) Collecting samples from a building in the city centre; (c) Clay quarry for the production of adobes and ceramic bricks; (d) Excavation in the Emiliano Zapata colony. (Image source: A. Sanchez-Calvillo and E. G. Navarro-Mendoza).

2.2. Preparation of the Samples

In order to perform the mechanical tests of the samples and some non-destructive trials, these had to be prepared. First, all the material was dried for one to two weeks in the oven at a maximum temperature of 50–60 °C; a higher temperature could change composition of the clay materials. The samples were weighed every day until they presented a constant weight, then, they were left cooling for 24 h.

As most of the samples were collected from badly damaged building remains, they were in a precarious state that did not allow all of the original samples to qualify for the compression strength test nor the ultrasonic pulse velocity (UPV), as they didn’t have the minimum dimensions or were extremely inconsistent. From the 11 patrimonial samples only 6 could be eligible for the mechanical characterization trials, needing a previous preparation, as can be seen in Figure 7. The samples were smothered and then covered with liquid sulphur to achieve the regularity conditions to be tested with the universal machine.

For the mineralogical studies each of the samples were selected, crushed and sieved by the sieve nº200 ASTM till obtain a powder type material for X-ray diffraction and X-ray fluorescence analyses. The specimens were tested in the LANCIC Laboratory [The specimens were tested in the National Science Laboratory for the Research and Conservation of Cultural Heritage, of the Physics Institute of the National Autonomous University of Mexico (LANCIC-IFUNAM)].
the oven at a maximum temperature of 50–60 ℃; a higher temperature could change the composition of the clay materials. The samples were weighed every day until they presented a constant weight, then, they were left cooling for 24 hours. As most of the samples were collected from badly damaged building remains, they were in a precarious state that did not allow all of the original samples to qualify for the compression strength test nor the ultrasonic pulse velocity (UPV), as they didn’t have the minimum dimensions or were extremely inconsistent. From the 11 patrimonial samples only 6 could be eligible for the mechanical characterization trials, needing a previous preparation, as can be seen in Figure 7. The samples were smothered and then covered with liquid sulphur to achieve the regularity conditions to be tested with the universal machine. For the mineralogical studies each of the samples were selected, crushed and sieved by the sieve nº 200 ASTM till obtain a powder type material for X-ray diffraction and X-ray fluorescence analyses. The specimens were tested in the LANCIC Laboratory [The specimens were tested in the National Science Laboratory for the Research and Conservation of Cultural Heritage, of the Physics Institute of the National Autonomous University of Mexico (LANCIC-IFUNAM)].

Figure 7. Preparation and capping of the adobe samples with sulphur for the compressive strength test. (Image source: A. Sanchez-Calvillo).

2.3. Characterization Methodology

Four types of tests were undertaken with the adobe and soils samples: non-destructive tests, destructive tests, geotechnical, and mineralogical analysis. All the samples were classified by the Unified Soil Classification System (USCS) to obtain the composition of the adobe bricks and the type of soils used for construction materials in the region [58]. The fiber percentage was also obtained, actually straw in the case of study, for each one of the adobes.

The moisture content of the samples was determined by two methods: first, with the moisture meter equipment Delmhorst DH-BD2100, which provides the relative humidity and can be taken in situ; secondly, calculating the percentage between the wet weight and the dried weight of the samples after drying them in the oven for one to two weeks. This step is very important before fulfilling the non-destructive tests and the physico and micro-characterization.

For Color Spectroscopy, we followed the CIE system (Acronym of Commission Internationale de l’Eclairage) [59], and using the CLRM-200 colorimeter equipment, the adobe samples were measured, obtaining three parameters: the coordinates a* and b* (red to green and yellow to blue axis), and the luminosity L*.

With the carved samples of the adobes it was also possible to effectuate non-destructive tests, such as the ultrasonic pulse velocity (UPV), calculating and correlating it with the bulk density of the adobes. For this purpose V-Meter MK IV from James Instruments Non Destructive Test Equipment was used; with a frequency range from 24 to 500 kHz, based on transducers selected, and receiver sensitivity between 30 and 100 kHz.

X-ray diffraction analysis (XRD) was carried out to measure the mineralogical composition of the natural soils and the adobes; clay minerals are most easily identified using this technique rather than other physical tests. The measurements were performed using a bench-top Thermo Scientific™ ARL™ Equinox 100 Diffractometer using a 50 W microfocus Cu X-ray tube and a curved position sensitive detector (CPS) that measures all diffraction peaks simultaneously (0–100° 2θ range).
Elemental analysis was performed using X-ray Fluorescence (XRF) spectrometry with an X-ray spectrometer developed at LANCIC [60]. This system has a SDD X-ray Amptek detector and a 75 W Mo X-ray tube. Measurements were undertaken at 45° X-ray detection for 180 s with 35 kV and 0.2 mA, the spot at the surface has 1 mm diameter.

The use of scanning electron microscope (SEM) images coupled with EDS, a technique with widespread use in cultural heritage [61], allowed us to confirm the chemical composition of the mineralogical phases in those soils [62]. The microphotographs and EDS microanalyses were performed in a benchtop SEM Hitachi 3030+ to quantify their presence in soils under low vacuum using a 18 kV electron beam. The samples were not covered with any metallic or carbon thin film.

The mechanical strength is the most important index test in construction materials. Adobes are patrimonial and historical masonry pieces designed to protect human beings from the elements, and it is, therefore, essential for them to possess the mechanical behavior required to withstand different loads. Recovering the building technology of adobes improves the conservation and restoration of the original bricks, as well as allowing the production of new ones that will better adhere to the original structure, preserving it against environmental and acute attacks [37].

It was decided to apply compressive strength and PLT in order to obtain the indicative values of mechanical resistance, which could be compared to other patrimonial and vernacular study cases. For being able to perform the analysis the samples were carved till appropriate dimensions were obtained, and later capped with melted sulphur, due to the irregularities presented in their surface. Once prepared, they were introduced in the Tinius Olsen Universal Test Machine to obtain their ultimate resistance to compressive strength, (See Figure 8).

![Figure 8. Compressive strength testing of one adobe sample. (Image source: A. Sanchez-Calvillo).](image)

### 2.4. Point Load Test

PLT allows determining mechanical resistance of non-carved samples of several types of masonries and rocks, both: natural or artificial, being especially designed for the study of rocks [63]. The first research works which utilised the test achieved to associate the uniaxial compressive resistance with the PLT index (Is), creating the basis to apply the analysis to rock fragments [64], and geotechnical applications [65].

Recent studies have concluded that the relation between uniaxial compressive strength (UCS) and Is is not linear for other materials like soft rocks [66], granites in different weathering conditions [67], or basalt aggregates [68]. Research works in Bukit Timah, Singapur, have sampled from residual soils to non-weathered rocks, concluding that the conversation ratio should vary from the original one. Nevertheless, the materials researched in this work are adobe bricks, being a first approximation to the characterization of solid clay fragments with this technique.

The equipment used during the trial was digital rock strength apparatus 100 KN cap by the Controls Group (See Figure 9). The best asset of this equipment is the possibility to
use it in situ due to its portability; having the choice to perform the analysis both in the field or in the laboratory.

The guidelines followed for the fulfilment of the test were the ASTM standards, and the previous experience with the PLT procedure in the materials laboratory [69–71]. The samples of fragments of adobes were measured and listed before the trial was performed, recording the values of each piece. Later, all the samples were compressed with the Point Load apparatus till cracking and reaching the failure. The new fragments obtained by rupture could be tested again, only if they meet the requirements of dimension and proportion. The result of the analysis is a rupture load value, which needs to be transformed by an equation system explained later in this manuscript, that leads to the ultimate unconfined uniaxial compression resistance.

The PLT index ($I_s$) without correction factor is calculated with the following equation:

$$I_s = \frac{P \times 1000}{D_e^2}$$  \hspace{1cm} (1)

where:

- $I_s$ = Point-load index, MPa;
- $P$ = Maximum load, kN;
- $D_e$ = Equivalent core diameter, mm.

The resistance index value ($I_s$) is a non-corrected value which varies depending on the thickness of the fragments tested. To obtain the corrected resistance index ($I_{s(50)}$) it is necessary to multiply the first index by the correction factor:

$$I_{s(50)} = F \times I_s$$  \hspace{1cm} (2)

Depending on the size of the fragments, there will be two different correction factors. The election between one or the other will be the proximity of each sample to the standard value of 50 mm [12]. For the specimens near to this 50 mm thickness ($D_e$), the correction factor is calculated with the following equation:

$$F = \sqrt{\left(\frac{D_e}{50}\right)}$$  \hspace{1cm} (3)

Instead, when calculating fragments with thickness distant of 50 mm, the following formula will be used:

$$F = \left(\frac{D_e}{50}\right)^{0.45}$$  \hspace{1cm} (4)
The estimation of the compressive strength \( \sigma \) or UCS (Uniaxial Compressive Strength) is obtained with the following equation:

\[
\sigma = (C) \ I_{d50} = 24 \ I_{d50}
\]

(5)

The value \( \sigma \) is the main purpose which the PLT follows and it is going to be compared with other values of mechanical resistance obtained by other tests. Another interesting aspect of the test is to observe the rupture mode of the fragments, finding relations between the composition of adobes, their morphology, size, fibers and aggregates distribution (See Figure 10).

3. Results and Discussion
3.1. Non-Destructive Tests

Regarding the colorimetry test, the adobe samples had a significant increase in their luminosity in relation to the natural clays, showing the transformation process of adding stabilisers to the construction materials. Table 2 shows the values of a* (red to green axis), b* (yellow to green axis), and L* (luminosity); we can also see the representation of the true color of adobes and soils. Previous research works done in Jojutla confirmed the use of lime and lithic material, correlating the colorimetric values with the particle size and USCS classification and microscopic techniques like XRD [62].

Table 2. Colorimetric values according to the CIE coordinates system.

| Specimens | a*   | b*   | L*   | Color     |
|-----------|------|------|------|-----------|
| Adobes    | 4.92 | 11.45| 42.15|           |
| Soils     | 3.94 | 5.76 | 30.30|           |

The different additives and the addition percentage have a big influence in the aesthetic perception of the constructions made of adobe masonry [72]. The stabilizers with a more similar color to the selected original clays have a lesser impact on the final variation.

The average ultrasonic pulse velocity (UPV) for the adobes was 634.58 m/s. UPV allows us to estimate the dynamic properties of the material, as well as internal composition and porosity of the blocks, and if they have irregularities or construction flaws. Other research works with patrimonial earthen heritage showed larger values of UPV [73], the lower values obtained in Jojutla could be directly related to the effects of the 2017 Puebla Earthquake on the constructions and building systems, decreasing most of the properties and causing material fatigue and propagating microcracks which exfoliate pieces.
3.2. Mineralogical Analyses

XRD results (see Table 3) show the percentage of various minerals detected in the samples, including calcite contents in almost every sample. As indicated in the methodology section, M1 and M13 came from a local excavation and the clay quarry of the region; while the rest came from damaged adobes of the historic centre of Jojutla. M1 was from a zone where buildings collapsed, a clay stratum, and the soil was improved with lime for foundations, because the community was building a new structure at the moment the sample was taken; therefore, the material appeared in the XRD analysis. Instead, M13 did not contain lime considering it was taken from a clay quarry surrounding Jojutla, before the stabilization of the raw material for handmade ceramic bricks. M2–12, except M9 and M11, contain lime, used to stabilize the adobes, being the most common material in all Mexico for these purposes in earthen structures [74,75].

Table 3. XRD results on the analyzed samples.

| Mineral   | M1  | M2  | M3  | M4  | M5  | M6  | M7  | M8  | M9  | M10 | M11 | M12 | M13 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Albite    | 6.90| 38.00| 32.80| -   | -   | 33.30| 9.90| 2.20| -   | -   | -   | -   | 8.50 |
| Anothite  | 14.50| -   | -   | 53.00| 44.00| 16.90| 48.10| 77.10| -   | 68.60| 53.20| 79.60| 49.50|
| Calcite   | 25.40| 10.80| 8.00| 1.20| 5.20| 1.00| 16.10| 3.20| -   | 7.90| -   | 2.60| -   |
| Cordierite| -   | -   | -   | -   | -   | 1.60| -   | 4.20| -   | 1.00| -   | 2.00| -   |
| Cristobalite| -  | -   | 2.60| -   | -   | -   | -   | -   | -   | 4.50| -   | -   | -   |
| Hematite  | -   | -   | -   | 1.60| -   | -   | -   | -   | -   | -   | -   | -   | -   |
| Illite    | 47.40| -   | -   | -   | -   | 16.10| -   | 25.80| -   | -   | 5.60| -   | 27.70|
| Kaolinite | -   | 29.60| 28.10| -   | -   | 28.70| 46.00| -   | 10.50| -   | -   | 36.70| -   |
| Magnetite | -   | 1.00| 2.10| 1.00| -   | -   | -   | -   | -   | -   | -   | -   | -   |
| Muscovite | -   | 13.40| 17.20| -   | -   | -   | -   | -   | -   | -   | 9.80| -   | -   |
| Nacrite   | -   | -   | 5.10| 40.70| -   | -   | -   | -   | -   | 17.30| -   | -   | -   |
| Pargasite | -   | -   | -   | -   | -   | -   | -   | -   | -   | 0.20| -   | 13.40| 10.80|
| Pyrophyllite| -  | -   | -   | -   | -   | -   | -   | -   | -   | 5.60| -   | -   | -   |
| Quartz    | 5.80| 7.10| 4.00| 2.50| 6.00| 1.20| -   | 2.80| 4.10| 8.20| 4.50| 2.40| 3.50|

The presence of kaolinite can also be observed in significant proportions for six of the samples. Kaolinites have low shrink-swell capacity, which makes them better for building purposes, being a great choice for the production of adobes.

3.3. Elemental Analyses

XRF results average 5 measurements. The region of Jojutla is located on an agricultural place, mainly producing sugar cane, rice, corn, and sorghum, then the XRF could detect some aggregates which are imperative for farming purposes. The soils contained the elements indicated in Figure 11a,b, to have a better display according to the intensity. The vertical axis of the graphic refers to intensity and in the horizontal axis we find the different elements. Sometimes the intensity of certain elements is very low and it is difficult to identify the element, but anyway they were present in the samples.
The region of Jojutla is located on an agricultural place, then the heritage. In 2021, in concentration elements.

**Figure 11.** XRF results of the analyzed samples, in intensity by element. (a) Higher concentration elements; (b) lower concentration elements.

### 3.4. SEM-EDS

The microphotographs and EDS microanalyses were performed in an Environmental SEM to quantify their presence in soils. The samples were analysed under low vacuum and were not covered with a metallic thin film. We also got mapping of some elements to qualify their distribution and compare between them. Figure 12 shows the BSE (Backscattered electron) high quality images, which also confirm the presence of lithic materials in the adobes.
Figure 11. XRF results of the analyzed samples, in intensity by element (a) M1; (b) M4; (c) M9; (d) M12.

3.5. Sieve Analysis and USCS Classification

The adobes had an average bulk density of 1279.06 kg/m³. Table 4 presents the measured moisture content percentage for the samples while Table 5 indicates the classification of all the samples tested, including the adobes and the soils of the region, by the Unified Soil Classification System (USCS); while Figure 13 shows the results of the plasticity index and liquid limit and the position of each one of the specimens which were subdued to the mechanical analysis; Figure 14 also shows the granulometric curves of all the samples, differentiating the soils and the adobes by their graphical representation. M1 and M13, the two soil samples from the clay material quarry were classified as high plasticity clays, while the adobes vary from clays of low plasticity to mods. The low plasticity was probably due to the stabilization with other materials, for example, lime was found by XRD in some specimens.

Figure 12. BSE images of selected samples. (a) M1; (b) M4; (c) M9; (d) M12.

Figure 13. Plasticity graphic and position of the adobes and soil samples.
Table 4. Moisture content percentage.

| Sample | Wet Weight (g) | Dried Weight (g) | Moisture (%) |
|--------|----------------|------------------|--------------|
| M1     | 2652.10        | 2206.51          | 20.19        |
| M2     | 1913.34        | 1859.93          | 2.87         |
| M3     | 1523.20        | 1471.36          | 3.52         |
| M4     | 1281.86        | 1261.25          | 1.63         |
| M5     | 1397.40        | 1309.49          | 6.71         |
| M6     | 1481.30        | 1443.48          | 2.62         |
| M7     | 683.00         | 664.31           | 2.81         |
| M8     | 972.92         | 959.78           | 1.37         |
| M9     | 1389.50        | 1361.08          | 2.09         |
| M10    | 195.55         | 192.54           | 1.56         |
| M11    | 1106.30        | 1052.42          | 5.12         |
| M12    | 2194.30        | 2054.93          | 6.78         |
| M13    | 1713.20        | 1402.10          | 22.19        |
| Adobes average |             |                  | 3.37         |
| Soils average |              |                  | 21.19        |

Table 5. USCS classification of the specimens.

| Sample | LL % | PL % | IP % | USCS Classification                       |
|--------|------|------|------|-------------------------------------------|
| M1     | 79.13| 25.89| 53.25| CH Clay of high plasticity                |
| M2     | 35.05| 22.96| 12.09| CL Clay of low plasticity                 |
| M3     | 27.07| 17.78| 9.27 | CL Clay of low plasticity                 |
| M4     | 32.36| 16.12| 16.24| CL Clay of low plasticity                 |
| M5     | 33.62| 26.09| 7.53 | ML Silt                                   |
| M6     | 38.70| 26.26| 12.45| OL Organic silt/Organic clay              |
| M7     | 36.65| 23.88| 12.76| CL Clay of low plasticity                 |
| M8     | 21.65| 19.01| 2.64 | ML Silt                                   |
| M9     | 22.12| 19.91| 2.21 | ML Silt                                   |
| M11    | 31.95| 24.14| 7.81 | OL Organic silt/Organic clay              |
| M12    | 25.25| 22.17| 3.08 | ML Silt                                   |
| M13    | 70.21| 25.65| 44.56| CH Clay of high plasticity                |

The percentage of fine grained soils (clays and silts) of the adobes was in a range between 15% and 40%, coinciding with the indicative values of adobe production found in the literature [76]. The graphic matches perfectly with the granulometric curves found in historical adobe bricks in Peru; where the samples were extracted from colonial buildings with two or three stories in the cities of Lima, Cusco, and Ica [33].

The soil and grain size classification of the adobes showed insufficient or absent amounts of fibers, however there were no significant proportions of gravel or lithic material in the pieces. Figure 13 shows how the healthy clays of the soil samples are in a very different zone of the graphic than the adobe samples. To diminish the plasticity of the adobes from high to low there could have been some type of stabilization with local materials, for the age of the adobes it could be lime, as it was confirmed with the XRD analyses.
farming in the region there were plenty of different straws. Soils are Vertisol and Kastanozem at almost 70%. In Jojutla, the medium precipitation is around 1000 mm/year, and soils are mainly clay/silt packed rocks, strata, varying from 1–5 m.

Table 6. Fibre percentage results (only adobe samples).

| Sample | Fibre Percentage (% Weight) |
|--------|-----------------------------|
| M2     | 0.38                        |
| M3     | 0.00                        |
| M4     | 0.68                        |
| M5     | 0.00                        |
| M6     | 1.33                        |
| M7     | 1.84                        |
| M8     | 1.00                        |
| M9     | 0.06                        |
| M10    | 0.77                        |
| M11    | 0.27                        |
| M12    | 0.23                        |

3.6. Mechanical Properties

From the destructive tests, specifically the compressive strength, the mechanical resistance varies between 5 and 13 kg/cm², with 7.26 kg/cm² being the average of the adobe bricks. These values obtained with the UCS and the PLT are lower than values from other researches which have similar characteristic cases in México [44,49]. The adobe blocks of Jojutla presented low performance, probably due to the inefficient manufacture and the absence of fiber material or other stabilizers or previous micro-cracking. Nevertheless,
the proportion of the fibers does not seem to have a direct relation with the compressive mechanical resistance, as samples M5 and M9 that had the lowest amount of straw reached some of the highest values during the test.

The PLT allowed quantifying the strength in some of the samples after the compressive strength test. Because those fragments of lower dimensions can be tested again with the equipment, it resulted in more specimens to study. The values obtained were more variable, with 4.52 kg/cm$^2$ being the average of all the adobes, lower than the compression strength results. The ratio between compressive strength and PLT values was 1.72:1 (See Table 7), something comprehensible considering that the PLT is designed for the analysis of different types of rocks.

| Sample | UCS (Kg/cm$^2$) | PLT $\sigma$ (Kg/cm$^2$) | UCS/PLT |
|--------|----------------|-----------------|---------|
| M2     | 5.97           | 3.66            | 1.63    |
| M4     | 9.35           | 3.64            | 2.57    |
| M5     | 12.33          | 5.78            | 2.13    |
| M9     | 5.08           | 4.69            | 1.08    |
| M11    | 9.13           | 3.91            | 2.34    |
| M12    | 7.09           | 2.52            | 2.81    |
| Average| 7.26           | 4.52            | 1.72    |

The compressive strength and PLT values were compared (see Figure 15) in a graphic to observe the correlation between the two tests. Considering the compressive strength values are slightly higher, most of the samples showed a lineal reciprocity, while some showed deviation, near the 1.72:1 ratio calculated for both tests interrelation.

In Figure 16, it is possible to find the coefficient of determination and the second-degree polynomial which correlates the two variables. The coefficient of determination or $R^2$ has a value of 0.8723 and represents the proportion of the variance between the two variables (PLT and compressive strength). Additionally, all the samples are inserted into the confidence limits for a confidence level of 95%.

![Figure 15. Correlation between the compressive strength and the point-load tests.](image-url)
The coefficient of determination $R^2$ indicates how well a model can predict the data. The higher the value of $R^2$, the better the model will be at predicting [78]. This value of $R^2$ will always be in a range between 0 and 1, then the results of PLT test had acceptable and reliable values of mechanical resistance.

4. Conclusions

When seismic affectations occur on adobe vernacular housing, the owners and inhabitants cannot wait until they are re-built, as earthquakes have a big impact on the society because of the great destruction they cause. To preserve mental health, the demolition processes begin as soon as possible, to allow the immediate reconstruction of the housing and infrastructures. Before the total loss of the heritage it is necessary to design a way to test the shards of pieces before they will be carried out of the places or before they will be reused to protect the buildings. The study of traditional Mexican adobe buildings from the perspective of material characterization needs to be improved with more complete evaluations and a more extensive use of non-destructive tests which could be conducted in situ.

These in situ tests could contain the PLT, the UPV, and spatial evaluation with drones. The PLT could feed mathematical models and equations to predict and calculate the performance under loads, hazards, and promotes the design of conservation and restoration works without the necessity of carrying out plenty of samples, which could break down during the travel to laboratories, choosing the complete samples to research the materials and techniques employed in the buildings. If PLT studies are accompanied with densities it could be possible to get a lot of information to plan a way to characterize clay materials.

Various researchers have studied the relationship between UCS and PLT for different types of rocks, but there is no study applied in adobes. Therefore, in this research work, the PLT was used to obtain the relationship with UCS and point load index by means of a correlation equation. ASTM D5731-16 specifies that specimens in the form of rock cores, blocks, or irregular shards with a test diameter of 30 to 85 mm can be tested [63]. Consequently, irregular shards were used, which allows a non-cost and fast test to estimate the UCS compared to sampling, transportation and preparation of regular cubes in the laboratory. In addition, this test can be performed in the field or the laboratory.

Even though the PLT was not designed for adobes but for sandstone rocks [63], the ratio we found was 1.72:1, near to ratios found for local stones in Michoacan, Mexico (ratio = 2:1) [71]. The ratio found is the first approximation of a ratio between mechanical tests for compressive strength in adobes, similar to other comparisons in research works of earthen materials [32]. Because of the convenient in situ of the test capability, further experimentation will be required with other study cases in future research.
The point load test is justified since an acceptable coefficient of determination R^2 of 0.8723 was obtained, and a correlation equation is proposed to estimate the uniaxial compressive strength for the adobe bricks under study. Therefore, this test could be used in other study cases and monuments where adobe bricks could be tested in situ.

Regarding the results obtained, both compressive strength and PLT showed low values of mechanical resistance, particularly comparing them to the previous studies in traditional buildings of the state of Morelos. Nevertheless, these low values did not justify the bad seismic behavior of the dwellings, which were very vulnerable due to multiple factors, like the lack of reinforcements and confinement of the structures, the incompatibility between the construction materials or the poor maintenance of the buildings, among others. Additionally, the social-economic necessity of dividing the land into minor spaces due to the growth of the families and the necessity to inherit the properties to the descendants caused alteration to the houses and the impossibility to continue using the traditional thickness of adobe. In the case study, all these conditions converged, resulting into the loss of most of its architectural heritage and infrastructure. The adobe walls did not present any reinforcement, being this method unknown by the local population, who preferred to substitute the traditional materials for modern ones representing for them a better social status.

In addition to the mechanical tests, the rest of the methodology to study patrimonial adobes has proven to be effective and it is possible to correlate the mineralogical studies with the non-destructive analysis and the sieve analysis. The results of the granulometric curves could be correlated to the standard values for soils in adobes and the guidelines published by earthen architecture organizations [76]. Nevertheless, some of the adobes did not have any fibers, which could be a clear sign of the oblivion and abandonment of the traditional techniques. This loss of the traditional earthen construction techniques has provoked a poor manufacture of the adobe houses, creating new scenarios where people do not trust in the material and substitutes the earthen architecture with modern materials.

Although each country has different architectural typologies, the adobe houses in Latin America show the same type of alterations and modifications over the original systems. The abandonment and substitution of vernacular architecture is a global concern, and when an earthquake occurs the consequences are very similar for these buildings, as we have seen in the recent major events. The manufacturing of adobe is almost identical, as well as the building process and structural performance of the pieces.

The primary focus of future research works will be to compare the results obtained from the material characterization of the Jojutla samples with other study cases from traditional Mexican adobe buildings, verify the results obtained with the PLT with other historic constructions and upgrade the correlation equations.

By replicating the methodology and improving it, incorporating water vapor and erosion resistance tests, it will be possible to generate a more precise knowledge about earthen materials and necessary data for the conservation of this cultural heritage.

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