

# Characterization of Earthen Bricks Used in Ancient Constructions in the Marrakech Region, Morocco

Jamil Youssef<sup>1,\*</sup>, Kouddane Bouchra<sup>2</sup>, Baghazi Larbi<sup>1</sup>, Baghdad Bouamar<sup>1</sup>,  
Fallahi Azzeddine<sup>3</sup>, Jamil Zakariae<sup>3</sup>

<sup>1</sup>Higher School of Architecture of Casablanca (EAC), Morocco

<sup>2</sup>Department of Civil Engineering, Moroccan School of Engineering (EMG), Morocco

<sup>3</sup>Team of Modelling and Simulating in Mechanics and Energetics Energy Research Centre, Faculty of Sciences, Mohamed V University, Morocco

*Received September 15, 2025; Revised December 25, 2025; Accepted January 6, 2026*

## **Cite This Paper in the Following Citation Styles**

(a): [1] Jamil Youssef, Kouddane Bouchra, Baghazi Larbi, Baghdad Bouamar, Fallahi Azzeddine, Jamil Zakariae, "Characterization of Earthen Bricks Used in Ancient Constructions in the Marrakech Region, Morocco," *Civil Engineering and Architecture*, Vol. 14, No. 1, pp. 613 - 629, 2026. DOI: 10.13189/cea.2026.140141.

(b): Jamil Youssef, Kouddane Bouchra, Baghazi Larbi, Baghdad Bouamar, Fallahi Azzeddine, Jamil Zakariae (2026). *Characterization of Earthen Bricks Used in Ancient Constructions in the Marrakech Region, Morocco*. *Civil Engineering and Architecture*, 14(1), 613 - 629. DOI: 10.13189/cea.2026.140141.

Copyright©2026 by authors, all rights reserved. Authors agree that this article remains permanently open access under the terms of the Creative Commons Attribution License 4.0 International License

**Abstract** Earthen construction, which has been used for a long time and involves many different methods, is currently re-emerging as a promising solution for revitalizing the building sector. In the Marrakech region (Morocco), the Toub or adobe technique remains a key component of the vernacular heritage and contributes to indoor thermal comfort. However, the long-term durability and mechanical performance of existing adobe structures are still not sufficiently documented. This study aims to provide an integrated characterization of earthen bricks taken from a traditional load-bearing building in the Marrakech region (Morocco), in order to assess their mechanical behavior, durability potential, and implications for sustainable construction and indoor comfort. The methodology combines in-situ sampling of adobe bricks from vertical load-bearing walls with laboratory investigations: macroscopic description, chemical analysis of major oxides, mineralogical characterization by X-ray diffraction (XRD), microstructural observations by scanning electron microscopy (SEM), and mechanical tests in compression and three-point bending. The results show a clay-rich and carbonate-rich soil, dominated by clay minerals, quartz and calcite, with an average density of about 1800 kg/m<sup>3</sup>. Compressive strengths between 0.98 MPa and 1.19 MPa and flexural strengths between 0.26 MPa and 0.44 MPa place the studied adobe within the typical range reported for traditional earthen constructions,

with a relatively ductile post-peak behavior due to the presence of straw fibers. The high calcium content and balanced minerals give good cohesion and strength, while the porous structure helps stabilize indoor comfort; however, the high sulfate content can threaten durability in humid conditions.

**Keywords** Earthen Construction, Earthen Brick, Mechanical Strength, Adobe, Straw, Durability, Marrakech

---

## 1. Introduction

At a time when architecture prioritizes sustainable construction, the preservation of the environment in the face of various impacts has become a fundamental objective of the sustainable development concept. To achieve this goal, it is essential to implement solutions that lessen the detrimental effects of different industries on the environment. The building sector, in particular, plays a major role in this effort. Due to its high consumption of natural resources and raw materials, as well as its significant energy needs, it is currently the second largest source of environmental pollution after the transport sector. This highlights the need to adopt specific strategies to

reduce its ecological footprint [1, 2].

In response to environmental challenges and sustainability goals, the use of natural and renewable materials emerges as a relevant alternative, promoting constructions adapted to the climatic and cultural specificities of each region. Among these solutions, raw earth construction, particularly the Toub technique used in the Marrakech region, stands out as a prominent example. In addition to reducing the ecological footprint of buildings, this method is fully aligned with the principles of eco-housing and bioclimatic design. Thanks to its thermal and hygric properties, it offers optimal comfort while minimizing energy consumption [3].

For centuries, hand-molded raw earth blocks, known as adobes, have served as a primary building material in many regions of the world, especially in arid and semi-arid areas. These blocks, mainly composed of clayey soil, water, and sometimes natural fibers such as straw, are manually shaped and air-dried without firing, hence the term unfired blocks [4]. Traditionally, adobe has been used in the construction of load-bearing masonry structures. It is particularly suited for single-story or low-rise residential buildings, where the loads applied to the walls are relatively low. However, despite this typical use in small-scale buildings, the structural performance of adobe has allowed for much more ambitious constructions. A remarkable example is found in Yemen, where adobe buildings reach up to ten stories in height, showcasing exceptional technical skill [4].

Earthen constructions, present across many regions of the world, highlight the exceptional potential of raw earth when applied according to best practices and integrated with traditional local knowledge. Nevertheless, these buildings require regular maintenance to preserve their integrity against weather-related deterioration. In fact, such constructions have led to seasonal activities involving local skills, including periodic repairs, reinforcement, and restoration. These practices, often passed down through generations, not only help maintain the buildings in good condition but also preserve a rich architectural and cultural heritage [5]. Structural rehabilitation of adobe buildings is crucial for improving safety and comfort, especially in seismic areas. However, limited knowledge of adobe's mechanical behavior poses challenges. Therefore, technical studies are essential to guide both restoration initiatives and the design of new adobe structures [6, 7].

Previous studies worldwide have documented the mechanical behavior and durability of adobe bricks, noting significant variability depending on local soil composition, fiber reinforcement, and manufacturing methods. Silveira [8] provided a comprehensive analysis of adobe's mechanical behavior, emphasizing that the bricks' strength varies depending on soil composition, moisture content, and curing processes. Their experimental results show that the addition of natural fibers such as straw or linen can significantly improve tensile strength and crack resistance.

Fiber reinforcement in adobe bricks has been extensively studied for its significant effect on enhancing mechanical properties and durability, which addresses the inherent brittleness and susceptibility to cracking of traditional earthen construction materials. Research conducted by Abdulla et al. [9] demonstrated through experimental studies that the inclusion of straw fibers results in improved tensile and flexural strength as well as enhanced ductility of adobe masonry, which increases its resistance to mechanical stress and deformation. This improvement is largely attributed to how fibers bridge microcracks, distributing stress more evenly and delaying crack propagation. Kasie and Mogne [10] further corroborated these findings, focusing on sisal fiber-reinforced adobe bricks. Their results showed marked increases in compressive strength and toughness, with fiber-reinforced bricks exhibiting superior load-bearing capacity compared to unreinforced ones. Their study also highlighted the importance of fiber content and length in optimizing mechanical performance, revealing a threshold beyond which additional fiber does not translate to significant strength gains. A comprehensive mechanical analysis by Khtou et al. [11] examined different fiber types and reinforcement percentages, utilizing standard tests such as uniaxial compression and bending tests. Their work confirmed that fiber reinforcement enhances mechanical resilience while maintaining the adobe's environmental benefits. The study underscored how fiber incorporation impacts the failure mode, shifting it from brittle fracture to a more ductile, energy-absorbing behavior.

Moreover, the review of Bailly et al. [12], and Chettri et al. [13] synthesizes a wide range of stabilization and reinforcement techniques developed and tested worldwide, emphasizing their effectiveness in enhancing mechanical strength, durability, and resistance to environmental factors such as moisture and frost. Key stabilization methods include the use of chemical additives like lime, cement, and natural polymers, which improve cohesion and reduce the material's susceptibility to water damage. The authors highlight how these additives modify the mineralogical and chemical properties of the earth mixture, leading to increased compressive strength and longevity.

Bailly et al. [12] conducted extensive experimental tests to assess the effects of additives on compressive strength, stiffness, and failure behavior of adobe walls. The study also compares the effectiveness of traditional wall setups versus interlocking assemblies, which provide enhanced stress distribution and improved structural stability. Additionally, the researchers developed numerical models calibrated with experimental results, allowing simulation of the mechanical performance of adobe walls with varying additive proportions and configurations. These models facilitate structural performance prediction and assist in optimizing adobe wall design within sustainable building contexts.

However, the absence of an integrated characterization

makes it difficult to reliably evaluate the durability and in-service performance of adobe bricks under real environmental conditions. As a result, the complex interactions between mineralogy, chemistry and mechanical response that govern degradation and structural failure remain poorly constrained. In the Marrakech region, the specific mineralogical composition of local soils, with distinct proportions of clay, quartz and calcite, is expected to strongly influence both the mechanical response and the weathering resistance of adobe, yet these effects remain insufficiently documented. Additionally, traditional manufacturing practices and environmental conditions in Marrakech contribute further variability that has not been comprehensively captured through integrated analytical studies. Building on and extending previous studies, the present research adopts a detailed multi-analytical methodology to characterize local adobe bricks used in the Toub technique.

This research is part of a broader effort to promote earth as a sustainable building material, focusing on the Toub technique that has been practiced for generations in the locality of Bounaga (Marrakech region). More specifically, this study aims to provide an integrated characterization of adobe bricks taken from a traditional load-bearing building in this area, by combining chemical and mineralogical analyses with macroscopic, microstructural and mechanical investigations. The objective is to assess the mechanical performance and durability potential of these local adobes and to discuss how their intrinsic properties support both the sustainability of the construction system and the provision of a comfortable indoor environment in the semi-arid context of Marrakech.

## 2. Materials and Methods

### 2.1. Study Area Presentation

The Marrakech-Safi region covers an area of approximately 39,000 km<sup>2</sup>, representing 5.5% of Morocco's national territory. It is characterized by significant geographical diversity. To the south lies the imposing High Atlas mountain range, peaking at over 4,000 meters in altitude, which is essential for controlling the climate and providing water to the nearby plains. These plains, including the arid expanses of Haouz, Abda and Rehamna, are important agricultural zones despite the challenges posed by the semi-arid climate. To the west, the region borders the Atlantic Ocean, where the coastline supports economic development through fishing, port trade, and tourism, particularly around the city of Safi, known for its port and traditional ceramic craftsmanship. This geographical diversity provides Marrakech-Safi with a balanced mix of mountains, plains, and coastal areas, shaping its economic development and natural resources [14].

The climate of the Marrakech-Safi region is marked by significant variability, ranging from arid to semi-arid across most of the territory, with sub-humid to humid conditions in the Atlas Mountains and along the coast. Precipitation is unevenly distributed, with less than half of the region receiving an average of under 300 mm of rainfall per year. In the higher elevations of the Atlas, low temperatures encourage snowfall above 2,500 meters, contributing to the replenishment of water resources and influencing the hydrological regime of rivers and aquifers in the region [14].

The building under study is located in the Rehamna Province, within the Marrakech-Safi region of Morocco (Figure 1), a geographically diverse area featuring rural landscapes, agricultural plateaus, and the foothills of the High Atlas. Located about 70 km from Marrakech, the building is situated at GPS coordinates (-7.959864, 31.983999), placing it within a semi-arid climate zone marked by hot summers and irregular precipitation.

### 2.2. Vertical Load-Bearing Structures

The building is made of adobe bricks, a timeless and earth-friendly material crafted from natural clay, sand, and straw. These bricks are made by hand-mixing the raw ingredients, then left to dry naturally under the sun. The use of adobe gives the building excellent thermal insulation, helping maintain stable indoor temperatures. The thick earthen walls retain heat to moderate the chilly nighttime temperatures, while the interior stays cool during the sweltering summer days. Architecturally, the structure is characterized by thick walls, simple shapes, and modest openings to optimize insulation. The roofs are typically flat and made from local materials. The building's orientation and the thickness of its walls contribute to indoor temperature regulation, while the interior spaces are designed to be multifunctional and well-ventilated.

To assess the building's structural stability, we conducted a detailed sampling campaign, focusing on key load-bearing walls and supports. We carefully collected targeted samples from both intact structural elements and degraded areas to analyze the materials (composition, condition, mechanical properties) and construction techniques. These investigations combine on-site inspections with laboratory analyses (microscopic examinations, physico-mechanical tests) to provide an accurate diagnosis of pathologies (cracks, deterioration, structural disorders). The samples were collected systematically, taking into account the architecture and specific characteristics of the structure in order to gather as much relevant information as possible on the vertical elements.

Since mechanical tests on adobe bricks are destructive in nature, they result in the irreversible deterioration of the tested samples. It is therefore essential to optimize the

experimental protocol in order to obtain meaningful results while minimizing the impact on this historical material, an approach that combines scientific rigor with respect for architectural heritage. In this context, six samples were taken from different parts of the structure (Figure 2). To facilitate identification, monitoring, and analysis of experimental results, a rigorous classification and labeling system was established for all adobe samples (Figures 3 and 4). The three samples labeled  $E_{c1}$ ,  $E_{c2}$ , and  $E_{c3}$  were subjected to compression tests. Meanwhile, the remaining three samples, labeled  $E_{f1}$ ,  $E_{f2}$ , and  $E_{f3}$ , were tested under flexural stress. The findings from these samples will serve as an essential starting point for a thorough examination of the walls under study's mechanical and structural properties. Whether the structure needs more substantial renovation or localized reinforcements, our assessment will help precisely identify the best course of action.

When evaluating earthen masonry, compressive strength is a key parameter for assessing the mechanical performance of earthen masonry, as it reflects the material's capacity to bear vertical loads without deforming or failing. However, this property should not be assessed on its own, as it is strongly influenced by the material's composition, especially its mineralogy, particle size distribution, and physical properties like the Atterberg limits [15]. For instance, a high content of

plastic clay or minerals such as quartz or calcite can significantly impact the strength and durability of the material. Additionally, the brick formulation can be improved by adding plant fibers to help prevent cracking, using binders to boost cohesion, or adjusting moisture levels and mixing methods to make the material easier to work with. Compaction can also be increased to reduce porosity and make the bricks denser, while adding stabilizers like lime or cement can enhance their resistance to moisture and weathering.

### 2.3. Chemical and Mineralogical Characteristics of Adobe Blocks

#### 2.3.1. Macroscopic Analysis

In general, a good-quality earthen material suitable for earth construction must demonstrate adequate flexibility and a comparatively elevated clay content (typically > 20%), as clay acts as a natural binder, ensuring cohesion and strength. Conversely, lean soil, which is low in clay, lacks cohesion and requires stabilization. That said, the ideal composition depends on the construction technique: a rich, clayey soil is suitable for adobe due to its malleability and strength after drying, while a coarser soil enriched with sand or gravel is preferable for rammed earth (*pisé*) to ensure proper compaction and limit shrinkage.



Figure 1. Geographical location of the study area





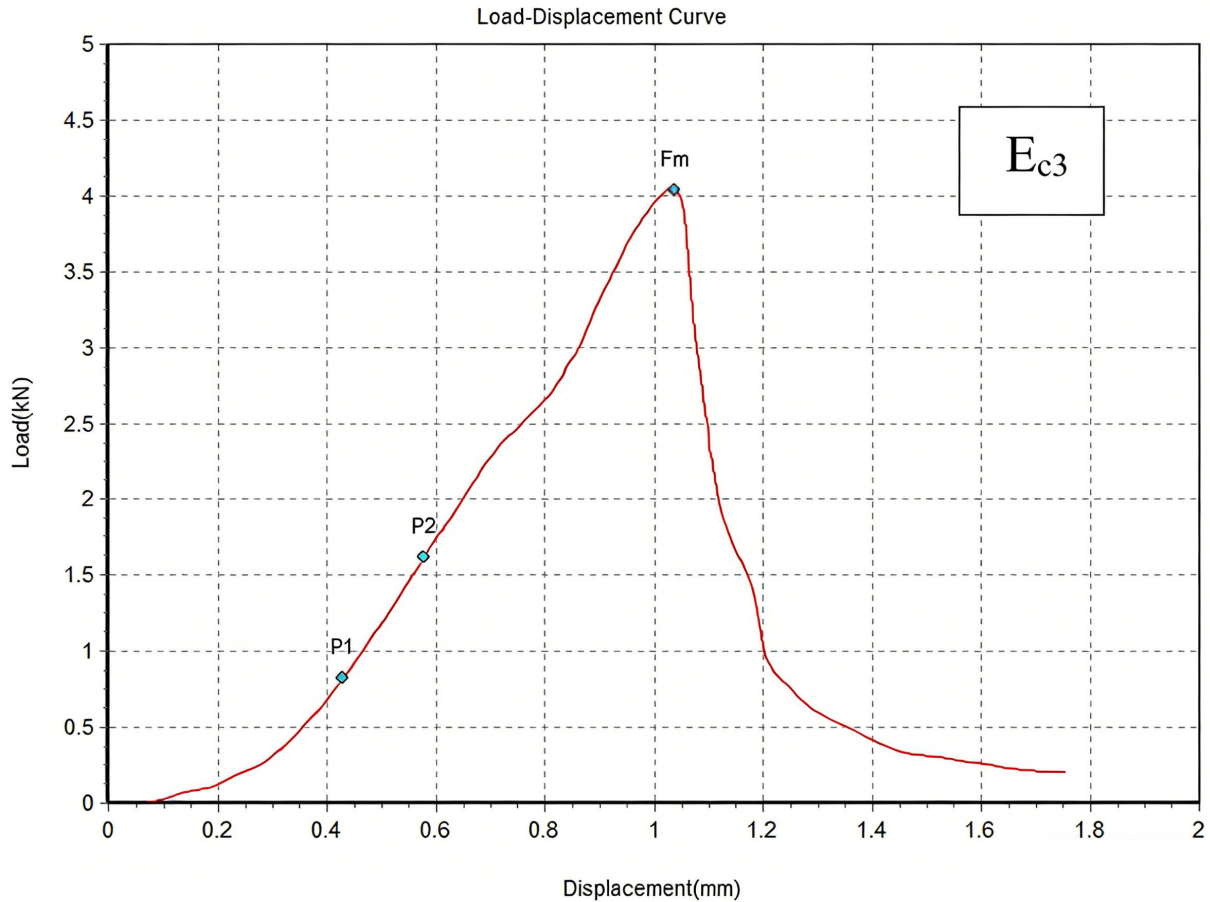












**Figure 9.** Experimental force–displacement ( $F$ – $d$ ) curves for compression tests

**Table 3.** Geometric and mechanical properties of the three samples for compression tests

Sample	$a \times b \times h$ (mm)	$\rho$ (Kg/m <sup>3</sup> )	$F_{max}$ (N)	$R_c$ (N/mm <sup>2</sup> )
$E_{c1}$	60 x 60 x 105	1865	4319	1,054
$E_{c2}$	57 x 60 x 100	1740	3523	0,978
$E_{c3}$	63 x 65 x 118	1820	4067	1,189

First, variations in dimensions were noted, highlighting the typical irregularities associated with handcrafted materials. The densities range from 1740 kg/m<sup>3</sup> ( $E_{c2}$ ) to 1865 kg/m<sup>3</sup> ( $E_{c1}$ ), suggesting differences in compaction or homogeneity of the soil-fiber mixture. This variability has a direct influence on the mechanical performance. Indeed, the densest sample ( $E_{c1}$ ) achieves the highest maximum force (4319 N) and shows good compressive strength (1.054 N/mm<sup>2</sup>). Conversely,  $E_{c2}$ , which has the lowest density (1740 kg/m<sup>3</sup>), records the lowest strength (0.978 N/mm<sup>2</sup>), demonstrating a correlation between density and mechanical strength.  $E_{c3}$  shows higher performance (1.189 N/mm<sup>2</sup>), despite having a slightly lower density than  $E_{c1}$ , which may be related to better compaction or fiber distribution within the sample.

The experimental compressive strength results obtained for the tested samples ( $E_{c1}$ ,  $E_{c2}$ ,  $E_{c3}$  respectively), ranging between 0.978 MPa and 1.189 MPa, fall within a range

comparable to that reported in the literature (Table 2) for adobes from traditional constructions in various countries. Indeed, these values are close to those measured in Portugal (1.17 MPa) and Mexico (1.18 MPa), slightly higher than some values observed in Italy (0.29 to 1.56 MPa), but lower than the higher strengths reported in Colombia (3.03 MPa) and Morocco (2.83 MPa), the latter having been obtained through in situ rebound hammer tests. This comparison reveals that the tested adobe bricks display moderate mechanical performance, consistent with what is typically seen in traditional construction. It also indicates that their strength could be improved by refining the mix design or optimizing manufacturing conditions.

Figure 9 shows the force–displacement curves of three adobe samples ( $E_{c1}$ ,  $E_{c2}$  and  $E_{c3}$  respectively) subjected to a compression test. Overall, the material shows a relatively ductile behavior, with a gradual increase in force followed by a plateau or post-peak softening without sudden failure. A common initial linear phase is observed in all three curves, corresponding to elastic behavior, followed by a nonlinear phase as microcracks begin to develop within the earthen matrix. The  $E_{c1}$  curve reaches the highest maximum force (4319 kN) with significant displacement (0.47 mm), indicating good mechanical

strength and a strong ability to deform before reaching failure. Moreover, the undulating shape of the post-peak segment in the  $E_{c1}$  curve suggests progressive failure through localized damage and fiber pull-out. This behavior, more ductile than that of conventional concrete, could help adobe structures perform better during earthquakes by allowing them to absorb more energy. The  $E_{c2}$  curve, on the other hand, shows a lower maximum force (3523 kN) and an earlier failure (1.05 mm), suggesting lower compaction or a local defect.  $E_{c3}$  exhibits an intermediate response, providing a good balance between strength and ductility.

### 3.2. Flexural Tests

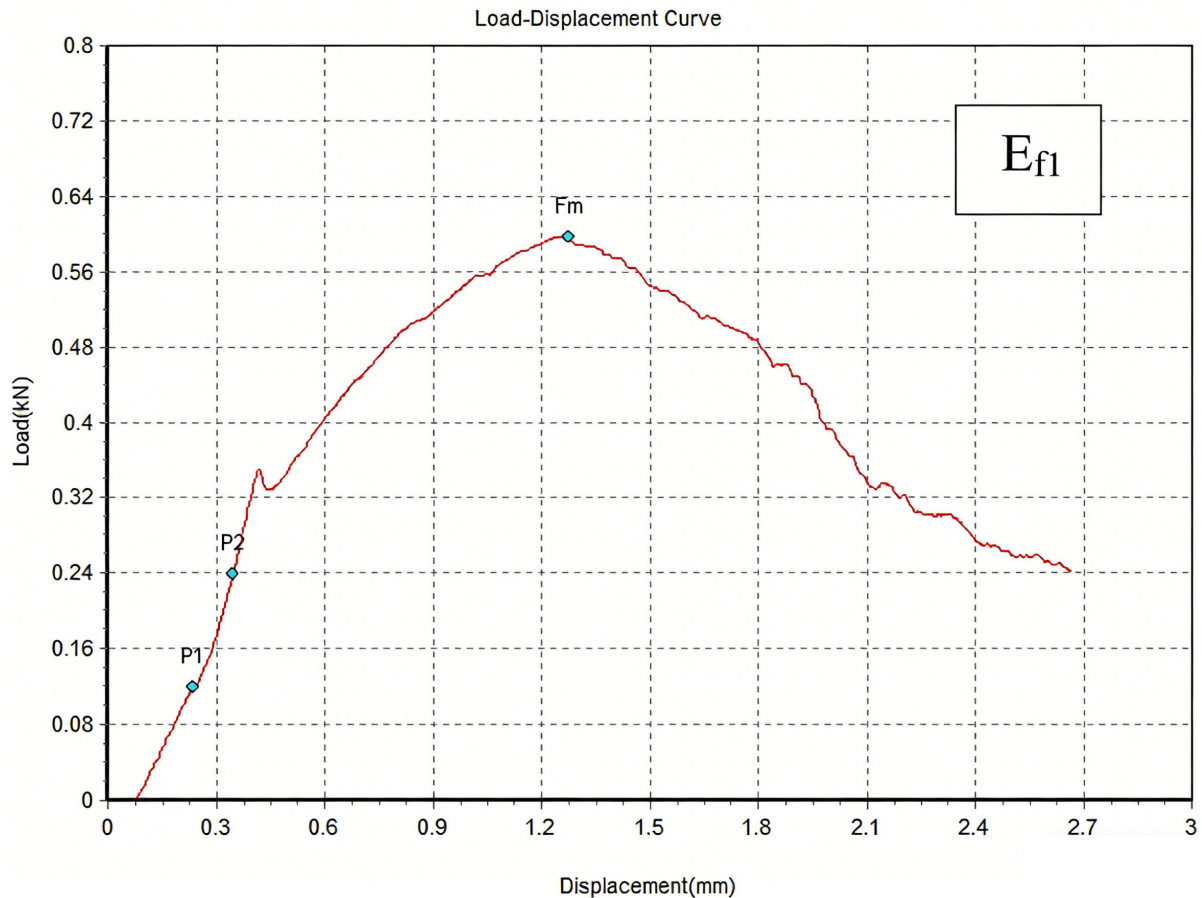
The tensile strength values reported by various researchers [15, 26, 34, 35, 36], for adobe bricks taken from buildings in different countries are presented in Table 4. These data provide context for our study's results,

while also showing how mechanical properties can vary depending on the region, manufacturing methods, and the way the materials are used.

**Table 4.** Tensile strength of adobe bricks from buildings located in different countries

Location	Tensile Strength (MPa)
Aveiro – Portugal [26]	0,19
Mexico [35]	0,27
Colombia [36]	0,41
Morocco [15]	0,18-0,35
Italy [34]	0,17-0,40

The force–displacement curves obtained from the bending tests (Figure 10) were used to determine flexural strength. Table 5 presents the geometrical characteristics, density, maximum force, and flexural strength of the three adobe samples ( $E_{f1}$ ,  $E_{f2}$ ,  $E_{f3}$ ).



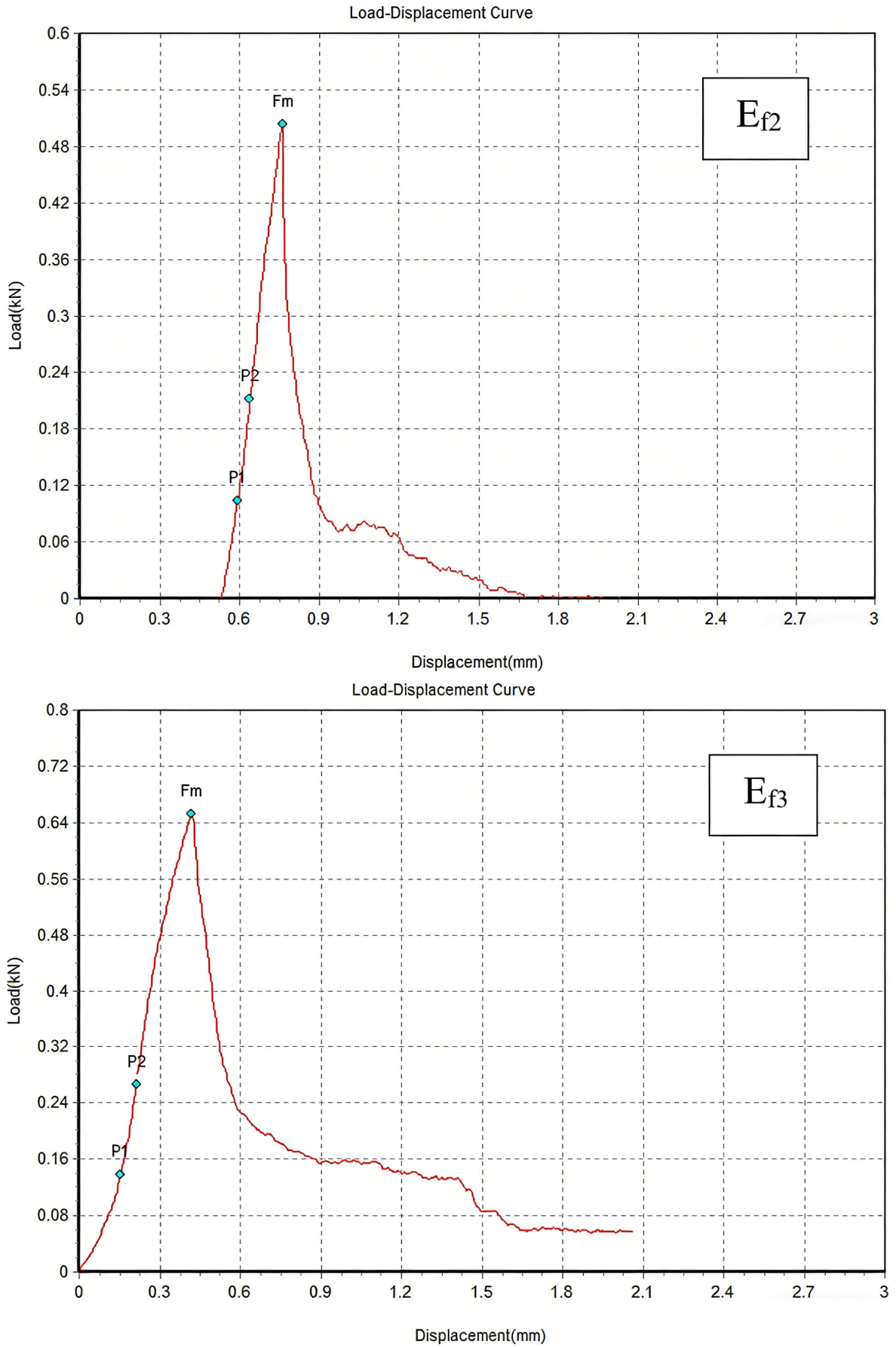


Figure 10. Experimental force–displacement (F–d) curves from the flexural tests

**Table 5.** Geometric and mechanical properties of the specimens used in the bending tests.

Sample	a x b x h (mm)	$\rho$ (Kg/m <sup>3</sup> )	F <sub>max</sub> (N)	R <sub>f</sub> (N/mm <sup>2</sup> )
E <sub>f1</sub>	80 x 55 x 107	1853	592,64	0,39
E <sub>f2</sub>	83 x 60 x 102	1846	511,29	0,26
E <sub>f3</sub>	75 x 55 x 98	1815	684,51	0,44

Figure 10 shows the experimental force–displacement curves obtained during the three-point bending test on three specimens (E<sub>f1</sub>, E<sub>f2</sub> and E<sub>f3</sub> respectively). A generally linear behavior is observed during the initial loading phase, reflecting an elastic response of the material without major cracking. However, the slope of the curves and the maximum force values differ from one sample to another, indicating variability in stiffness and flexural strength. E<sub>f3</sub> shows the greatest strength and rigidity among the samples, reaching a maximum force of about 684.51 N for a displacement of approximately 0.51 mm. E<sub>f1</sub> follows with intermediate strength, while E<sub>f2</sub> shows the lowest strength and deformation. This dispersion of results may be attributed to heterogeneities in the material composition or slight dimensional differences. Finally, no sudden drop is observed after the peak force, indicating a certain degree of ductility and the material's ability to redistribute stresses, possibly related to the presence of vegetal fibers in the matrix. The failure generally appeared as a vertical crack located at mid-span in each specimen, except for sample E<sub>f2</sub>. Due to its low aspect ratio (L/h), E<sub>f2</sub> developed an arch-shaped crack that originated near the support.

## 4. Conclusions

This experimental study provides a comprehensive characterization of traditional adobe used in the Marrakech region by combining physical, chemical, mineralogical, microstructural and mechanical analyses of bricks sampled from a historical load-bearing structure. Beyond supplying reference values for rehabilitation projects, the results clarify how the intrinsic properties of these earthen materials relate to both structural performance and the sustainability of the construction system.

Macroscopic observations and SEM images confirm that the studied bricks are handcrafted products made from a heterogeneous mixture of clayey soil, quartz, calcite and straw fibers. The mineralogical composition, dominated by clay minerals, quartz and calcite, explains much of the balance between strength, plasticity and workability. Quartz contributes to hardness and wear resistance, while calcite and clay enhance cohesion and improve the material's ability to accommodate deformations without sudden failure. Straw fibers act as natural reinforcement, bridging microcracks and

increasing ductility, which is reflected in the gradual post-peak behavior observed in both compression and bending tests.

Chemical analysis indicates a high calcium content, which supports cohesion and long-term strength, but also a significant sulfate content that may lead to efflorescence and internal expansion in humid environments. This dual effect highlights the need for careful moisture management, appropriate detailing, and compatible repair mortars when rehabilitating adobe structures in order to limit degradation mechanisms related to soluble salts.

From a mechanical point of view, compressive strengths in the range 0.98–1.19 MPa and flexural strengths between 0.26–0.44 MPa place the examined adobe within the typical interval reported for traditional earthen constructions worldwide. The force–displacement curves reveal an overall ductile response, with a clear elastic phase followed by progressive damage and limited post-peak softening, which is favorable for the energy dissipation capacity of the material under variable loading, including seismic actions. These moderate but satisfactory strength levels confirm that, when properly maintained and detailed, local adobe can safely support low-rise, load-bearing structures of the type commonly found in the Marrakech region.

In terms of sustainability and indoor comfort, the measured density (around 1800 kg/m<sup>3</sup>), the porous microstructure, and the presence of clay minerals and fibers all point to a material with significant thermal mass and hygrothermal buffering capacity. Although this study did not directly measure indoor temperature and humidity, the combination of mineralogical composition, microstructure and density is consistent with a good ability to dampen daily temperature fluctuations and regulate indoor humidity, thus contributing to a comfortable interior environment in a semi-arid climate. When combined with passive design strategies (wall thickness, orientation, window sizing), adobe walls of this type can therefore play an important role in reducing cooling and heating needs and in lowering the overall environmental impact of buildings.

Future work should build on these findings by coupling mechanical characterization with in situ hygrothermal monitoring of inhabited adobe buildings, in order to quantify more precisely the contribution of earthen walls to indoor comfort and energy performance. In addition, the development of non-destructive testing protocols, such as correlations between rebound hammer measurements, ultrasound and laboratory compression tests, would facilitate large-scale diagnosis of existing earthen structures while minimizing material loss. Such approaches would support the design of targeted strengthening and maintenance strategies, helping preserve adobe heritage and promote its adaptation for contemporary sustainable construction in the Marrakech region and beyond.

## Acknowledgements

The authors would like to thank the Modeling and Simulation in Mechanics and Energy (MSME) team at the Faculty of Sciences in Rabat for their technical support during the compression tests.

## REFERENCES

- [1] Kibert, C.J., "Sustainable Construction: Green Building Design And Delivery," John Wiley & Sons, 2016, pp. 1-608,
- [2] Ragheb, A., El-Shimy, H., Ragheb, G., "Green Architecture: A Concept Of Sustainability," *Procedia - Soc. Behav. Sci., Urban Planning And Architectural Design For Sustainable Development*, Vol. 216, pp. 778–787, 2016. <https://doi.org/10.1016/j.sbspro.2015.12.075>
- [3] Melalih A, Mazour M, "Analysis of water and soil conservation techniques at the Ain Sefra arid watershed (Ksour Mountains, southwest Algeria)," *J Environ Monit Assess*, Vol. 193, pp. 1–18, 2021. <https://doi.org/10.1007/s10661-020-08842-w>
- [4] Houben, H., Guillaud, H., *Earth Construction Technology*, 1992, pp. 1-200.
- [5] Silveira, D., Varum, H., Costa, A., "Rehabilitation Of An Important Cultural And Architectural Heritage: The Traditional Adobe Constructions In Aveiro District," *WIT Transactions on Ecology and the Environment, Sustainable Development and Planning III - 2 Volume Set*, Vol. 102, 2007. <https://doi.org/10.2495/SDP070682>
- [6] Costa, C., Cerqueira, Â., Rocha, F., and Velosa, A., "The Sustainability of Adobe Construction: Past to Future," *Int. J. Archit. Herit.* Vol. 13, pp. 639–647, 2019. <https://doi.org/10.1080/15583058.2018.1459954>
- [7] Illampas, R., Ioannou, Ioannis, and Charmpis, D.C., "Overview of the Pathology, Repair and Strengthening of Adobe Structures," *Int. J. Archit. Herit.* Vol. 7, pp. 165–188, 2013. <https://doi.org/10.1080/15583058.2011.624254>
- [8] D. Silveira, Dora & Oliveira, Cristina & Varum, H. & Ioannou, Ioannis & Miccoli, Lorenzo & Tarque Ru ž, Nicola & Parisi, Fulvio & Fenu, Luigi & Sol í, Mario & Rodr íguez-Mariscal, Jos é, "Mechanical Characterization of Adobe Bricks," in *Structural Characterization and Seismic Retrofitting of Adobe Constructions. Building Pathology and Rehabilitation*, Vol. 20. Springer, 2021. [https://doi.org/10.1007/978-3-030-74737-4\\_3](https://doi.org/10.1007/978-3-030-74737-4_3)
- [9] Abdulla, K.F., Cunningham, L.S., Gillie, M., "Experimental Study on the Mechanical Properties of Straw Fiber-Reinforced Adobe Masonry," *J. Mater. Civ. Eng*, Vol. 32, pp. 04020322, 2020. [https://doi.org/10.1061/\(asce\)mt.1943-5533.0003410](https://doi.org/10.1061/(asce)mt.1943-5533.0003410)
- [10] Y. M. Kasie and A. Y. Mogne, "Improvement of mechanical properties of adobe brick reinforced with sisal fiber," *Discov. Mater.*, Vol. 5, No 1, pp. 69, 2025. <https://doi.org/10.1007/s43939-025-00245-3>
- [11] O. Khtou, I. Aalil, M. Aboussaleh, and F. Z. E. Wardi, "Mechanical Analysis of Fiber Reinforced Adobe," *Civ. Eng. Archit.*, vol. 9, no 7, pp. 2160–2168, 2021. <https://doi.org/10.13189/cea.2021.090705>
- [12] G. C. Bailly, Y. El Mendili, A. Konin, and E. Khoury, "Advancing Earth-Based Construction: A Comprehensive Review of Stabilization and Reinforcement Techniques for Adobe and Compressed Earth Blocks," *Eng*, Vol. 5, No. 2, pp. 750–783, 2024. <https://doi.org/10.3390/eng5020041>
- [13] N. Chettri, P. Leki, T. K. Dorji, K. Dorji, and D. Gautam, "Mechanical characterization and numerical modeling of adobe walls with additives in normal and interlocking configurations," *J. Build. Eng.*, Vol. 111, p. 113454, 2025. <https://doi.org/10.1016/j.jobte.2025.113454>
- [14] Choukrani, G., Hamimsa, A., Saidi, M.E.M., Babqiqi, A., "Diagnosis and Future Projection of Climate Change in Arid Zone. Case of Marrakech-Safi Region (Morocco)," *Larhyss Journal*, Vol. 36, pp. 49–63, 2018. <https://www.researchgate.net/publication/330168523>
- [15] Baglioni E., Fratini F., Rovero L., "The materials utilized in the earthen buildings sited in the Dr ā Valley (Morocco): mineralogical and mechanical characteristics," *Coimbra, Portugal, Conference: 6th Seminar on Earthen Architecture in Portugal – 9th Ibero-American Seminar on Architecture and Construction with Earth*, 2010, pp. 20–23.
- [16] Alioui, A., Idrissi Kaitouni, S., Azalam, Y., Al Armouzi, N., Bendada, E.M., Mabrouki, M., "Effect of Straw Fibers Addition on Hygrothermal and Mechanical Properties of Carbon-Free Adobe Bricks: From Material to Building Scale in a Semi-Arid Climate," *Build. Environ*, Vol. 255, pp. 111380, 2024. <https://doi.org/10.1016/j.buildenv.2024.111380>
- [17] Ramakrishnan, S., Loganayagan, S., Kowshika, G., Ramprakash, C., Aruneshwaran, M., "Adobe Blocks Reinforced With Natural Fibres: A Review," *Mater. Today Proc.*, *International Conference On Mechanical, Electronics And Computer Engineering 2020: Materials Science*, Vol. 45, pp. 6493–6499, 2021. <https://doi.org/10.1016/j.matpr.2020.11.377>
- [18] Ali, A., Chiang, Y.W., Santos, R.M., "X-Ray Diffraction Techniques for Mineral Characterization: A Review for Engineers of the Fundamentals, Applications, and Research Directions," *Minerals*, Vol. 12, pp. 205, 2022. <https://doi.org/10.3390/min12020205>
- [19] Adorni, E., Co řson, E., Ferretti, D., "In Situ Characterization Of Archaeological Adobe Bricks," *Constr. Build. Mater.*, Vol. 40, pp. 1–9, 2013. <https://doi.org/10.1016/j.conbuildmat.2012.11.004>
- [20] Hansen, T. W., DeLaRiva, A., & Datye, A. K., "Nanoparticle Mobility and Coalescence During Sintering of a Ni/MgAl<sub>2</sub>O<sub>4</sub> Methane Steam Reforming Catalyst," *Microscopy and Microanalysis*, Vol. 29, pp. 1618–1619, 2023. <https://doi.org/10.1093/micmic/ozad067.831>
- [21] Morel, J.-C., Pkla, A., Walker, P., "Compressive Strength Testing of Compressed Earth Blocks," *Constr. Build. Mater.* Vol. 21, pp. 303–309, 2007. <https://doi.org/10.1016/J.Conbuildmat.2005.08.021>
- [22] XP P13-901 Compressed earth blocks fo walls and partitions : definitions - Specifications - Test methods - Delivery acceptance conditions, 2001, pp. 1–37.

- [23] Fratini, F., Pecchioni, E., Rovero, L., Tonietti, U., "The Earth in the Architecture of the Historical Centre of Lamezia Terme (Italy): Characterization for Restoration," *Applied Clay Science*, Vol. 53, pp. 509–516, 2024. <https://doi.org/10.1016/j.clay.2010.11.007>
- [24] Piattoni, Q., Quagliarini, E., Lenci, S., "Experimental Analysis and Modelling of the Mechanical Behaviour of Earthen Bricks," *Constr. Build. Mater.*, Vol. 25, pp. 2067–2075, 2011. <https://doi.org/10.1016/j.conbuildmat.2010.11.039>
- [25] Martins, Tiago & Varum, H., "Adobe's Mechanical Characterization in Ancient Constructions: The Case of Aveiro's Region," *Materials Science Forum*, Vol. 514-516, pp. 1571-1575, 2006. <https://www.scientific.net/MSF.514-516.1571>
- [26] Silveira, D., Varum, H., Costa, A., Martins, T., Pereira, H., Almeida, J., "Mechanical Properties of Adobe Bricks in Ancient Constructions," *Constr. Build. Mater.*, Vol. 28, pp. 36–44, 2012. <https://doi.org/10.1016/j.conbuildmat.2011.08.046>
- [27] Quagliarini, E., Lenci, S., Iorio, M., "Mechanical Properties of Adobe Walls in a Roman Republican Domus at Suasa," *J. Cult. Herit*, Vol. 11, pp. 130–137, 2010. <https://doi.org/10.1016/j.culher.2009.01.006>
- [28] Aymerich, F., Fenu, L., Meloni, P., "Effect of Reinforcing Wool Fibres on Fracture and Energy Absorption Properties of an Earthen Material," *Constr. Build. Mater.*, vol. 27, pp. 66–72, 2012. <https://doi.org/10.1016/j.conbuildmat.2011.08.008>
- [29] Binici, H., Aksogan, O., Shah, T., "Investigation of Fibre Reinforced Mud Brick as a Building Material," *Constr. Build. Mater.*, Vol. 19, pp. 313–318, 2005. <https://doi.org/10.1016/j.conbuildmat.2004.07.013>
- [30] Bouhicha, M., Aouissi, F., Kenai, S., "Performance of Composite Soil Reinforced with Barley Straw," *Cem. Concr. Compos.*, Vol. 27, pp. 617–621, 2005. <https://doi.org/10.1016/j.cemconcomp.2004.09.013>
- [31] Caporale, A., Parisi, F., Asprone, D., Luciano, R., Prota, A., "Critical Surfaces for Adobe Masonry: Micromechanical Approach," *Compos. Part B Eng.*, Vol. 56, pp. 790–796, 2014. <https://doi.org/10.1016/j.compositesb.2013.08.087>
- [32] Galan-Marn, C., Rivera-Gomez, C., Petric, J., "Clay-Based Composite Stabilized With Natural Polymer And Fibre," *Constr. Build. Mater.*, Vol. 24, pp. 1462–1468, 2010. <https://doi.org/10.1016/j.conbuildmat.2010.01.008>
- [33] Morel, J.C., Pkla, A., "A Model To Measure Compressive Strength Of Compressed Earth Blocks With The '3 Points Bending Test'," *Constr. Build. Mater.*, Vol. 16, pp. 303–310, 2002. [https://doi.org/10.1016/s0950-0618\(02\)00023-5](https://doi.org/10.1016/s0950-0618(02)00023-5)
- [34] Liberatore, D., Spera, G., Mucciarelli, M., Gallipoli, M.R., Santarsiero, D., Tancredi, C., Masini, N., Racina, V., Caprioli, A., Cividini, A., Tedeschi, C., "Typological and experimental investigation on the adobe buildings of Aliano (Basilicata, Italy)," *Proc. 5th Int. Conf. on Structural Analysis of Historical Constructions* (P.B. Loureno, P. Roca, C. Modena, S. Agrawal Eds.), New Delhi (India), Macmillan India Ltd, 2006, pp. 851–858.
- [35] Gavrilovic, P., Sendova, V., Ginell, W. S., & Tolles, L., "Behaviour of adobe structures during shaking table tests and earthquakes," In *Earthquake Engineering: Proceedings of the 11th European Conference*, Paris, France, 1998, pp. 6–11.
- [36] Rivera, J. C., & Munoz, E. E., "Structural characterization of materials of earth structural systems: adobe," *Revista Internacional de Desastres Naturales. Accidentes e Infraestructura Civil*, Vol. 5, pp. 135–48.