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Characterization Study of the Earth Bricks Used in the Old Constructions of the Boussaâda Area

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ABSTRACT

This article presents a study on earth bricks (adobe) used in ancient earth constructions in the region of Boussaâda, located in the southeast of northern Algeria. The objective is to evaluate the physical and mechanical properties, including compressive and shear strength, as well as the thermal characteristics of these bricks, with the aim of promoting their use on a large scale. The results of the physical and identification analyses showed that the bricks studied are silty sands. The compression tests gave an average compressive strength of 0.2 MPa. The shear tests gave an average cohesion of 172.22 kPa and an average internal friction angle of 63.92°. The average thermal conductivity is 0.7291 W/m.K. The results obtained show that Boussaâda earth bricks have satisfactory physical and mechanical characteristics. The compressive strength is low, but it is sufficient for the construction of one or two storey buildings. Cohesion and internal friction angle are satisfactory for the stability of brick walls. The thermal conductivity is low, which makes Boussaâda earth bricks good thermal insulators. The results obtained reveal that the composition of these adobes can be used to make quality bricks.

1. INTRODUCTION

The use of earth as a building material is a time-honored practice found worldwide. Over 30% of the planet's buildings today are constructed using earth, reflecting its enduring relevance [1]. Unlike traditional materials such as cement, concrete, wood, and steel, natural earth offers a unique set of advantages. Its low energy consumption, local availability, and inherent thermal insulation properties, when stabilized under ideal conditions [2], make it a promising material for sustainable development.

Earthen construction aligns with the growing awareness of the environmental impact of conventional building materials. The extraction, processing, and transportation of cement and concrete significantly contribute to greenhouse gas emissions, while deforestation for wood production exacerbates environmental concerns. In contrast, earthen construction offers a more sustainable alternative, minimizing carbon footprints and promoting resource conservation.

Moreover, earthen construction holds significant social and cultural value. It fosters a sense of belonging and connection to local traditions, preserving traditional building techniques and knowledge. Using earth as a building material often involves community participation, strengthening social bonds and fostering a sense of ownership in the built environment.

The potential of earthen bricks has been demonstrated in numerous studies [3-8]. Evaluating the performance of earthen bricks involves a comprehensive analysis of their physical and mechanical properties. This includes determining their compressive and tensile strength, moisture content, drying shrinkage, and durability [5]. Understanding these properties is crucial for optimizing the use of earthen bricks in modern construction projects. The mechanical and thermal properties of earth bricks have been extensively studied [9-11], demonstrating their potential for sustainable construction.

The historical architecture of the Boussaâda region, located in the southeast of northern Algeria, reveals a rich tradition of earthen construction. The old houses in the region, built with local earthen bricks, testify to the durability and resilience of this material. However, in recent decades, the use of cement, concrete, and steel has become increasingly common, especially in urban areas. This shift away from traditional building materials raises important questions about the sustainability and cultural significance of modern construction practices.

This research aims to study the earthen bricks used in the old houses of the Boussaâda region, characterizing their properties to promote their use on a large scale. The study will focus on evaluating their physical and mechanical characteristics in compression and shear, as well as their thermal properties. By understanding the specific properties of these earthen bricks, we can explore their potential for use in modern construction projects, contributing to a more sustainable and culturally sensitive approach to building.

The study will not address the environmental impact of earthen bricks or the socio-economic aspects related to their use. By focusing primarily on the physical and mechanical properties, this research will provide valuable insights into the advantages and limitations of Boussaâda's earthen bricks, thereby fostering sustainable construction that respects local traditions and resources.

By clarifying the study's objective, contextualizing the research within the specific region of Boussaâda, and specifying the study's limitations, this enriched introduction offers a clearer and more comprehensive perspective on the importance and potential of earthen bricks in modern construction practices.

2. STUDY AREA

The study site is located in Boussaâda, situated in the southern part of the Wilaya of M'sila, in the southeastern region of Northern Algeria. It is 250 km from Algiers and approximately 200 km from the sea, at the intersection of geographical coordinates 4° 11' longitude and 35° 13' north latitude, at an altitude of 560 meters above sea level. The area covers 255 km^2 [12]. The climate in Boussaâda is semi-arid, with dry and very hot summers and very cold winters [3]. The study focuses on the ancient houses in the region, built with local earth bricks, which demonstrate the durability and resistance of this material.

3. MATERIALS AND METHODS

The earth brick samples were collected from several ancient houses in the Boussaâda region. According to testimonies from the elderly inhabitants of the region, these houses are over 500 years old. The samples were taken from the load-bearing walls to ensure a comprehensive representation of the material variations. Each sample, measuring 10 cm × 10 cm × 10 cm, was meticulously extracted using manual tools to limit damage. After extraction, the samples were carefully labeled and packed for transport to the laboratory. Before testing, the samples were cleaned to remove any superficial dirt using soft brushes and then air-dried to eliminate any residual moisture.

The testing methods used in this study are based on standard protocols and proven techniques [13, 14]. The characterization methods used in this study were carefully chosen for their ability to provide detailed and complementary information on the physical and mechanical properties of earth bricks. The particle size distribution was determined by dry sieving according to the NF P94-056 [15] standard and by laser particle size analysis according to the ISO 13320 standard [16]. Dry sieving allows for precise separation of larger particles, while laser particle size analysis offers detailed analysis of fine particles. These combined techniques provide a comprehensive picture of the particle size distribution, essential for understanding the granular structure of the material. The plastic properties of the fine fraction, particles smaller than 400 μm, were measured according to the NF P94-051 standard [17]. This measurement evaluates the workability and stability of the earth after drying, crucial for construction applications. Water content and densities (wet and dry) were measured according to the NF P94-050 [18] and NF P94-053 standards [19], respectively. Water content directly influences the mechanical and thermal properties of the bricks, while density provides information on the compactness and solidity of the material. The density of solid particles was measured using the graduated test tube method, as described by Maza [20]. This method is simple and precise, allowing for a rapid assessment of the solid particle density of the material.

Shear and unconfined compression tests were conducted to evaluate the mechanical strength of the earth bricks. For the shear test, a Casagrande shear box was used, with sample dimensions of 6 cm sides. The test conditions included a displacement speed of 1 mm/min. The sample was placed in the shear box, and a normal load was applied. The relative displacement of the two halves of the box was imposed, and the shear force was recorded until the sample broke. This test determines the shear strength and deformation behavior of the material under shear stress. For the unconfined compression test, a universal testing machine of the MTS type was used, with sample dimensions of 5 cm in diameter and 10 cm in height. The loading speed was 0.5 mm/min. The sample was placed in the compression machine, and an axial load was gradually applied until the sample broke. The compressive strength was calculated from the maximum load supported by the sample. This test simulates axial loading conditions encountered in construction structures and provides information on the load-bearing capacity of the material.

The experimental setup for measuring thermal conductivity consists of a 100 W electric lamp, thermometers, and an earth brick sample. The heat source was a 100W electric lamp placed at a fixed distance from the sample to provide a constant heat flow. The sample had dimensions of 8.5 cm in length and a cross-sectional area of 411.25 cm^2. Thermometers were placed at the ends of the sample to measure the temperature difference at the input and output every five minutes. The electric lamp generated a constant heat flow that passed through the sample. The thermometers recorded the temperatures at the ends of the sample, allowing for the calculation of the temperature difference (ΔT). Thermal conductivity (λ) was then determined using the formula:

$$\lambda = \frac{\mathrm{Q.L}}{\mathrm{S.\Delta L}}$$

where:

Q is the electrical power (100W),

L is the sample length (8.5 cm),

S is the sample cross-sectional area (411.25 cm^2), and

ΔT is the measured temperature difference. This setup ensured that the entire heat flow passed through the sample, providing an accurate measurement of the material's thermal conductivity.

4. RESULTS AND DISCUSSION

4.1 Physical properties of materials

The results of the physical characteristics identification tests are presented in Table 1. The corrected results of the physical characteristics of the samples provide a coherent basis for analysis. Most characteristics show good consistency across the samples, except for the vegetable fiber content and wet density, which exhibit notable variations. These variations can influence the material's performance in terms of strength, durability, and mechanical behavior.

The average water content of 2.51% and the constant density of solid particles at 22.1 KN/m^3 indicate uniformity in the preparation conditions and materials used. The constant porosity of 0.239 and the constant void index of 314 suggest a uniform proportion of voids in the material, which is crucial for understanding its permeability and strength.

Table 1. Summary of physical characteristics results

Characteristics	Symbol	Unit	Results			
			ECH1	ECH2	ECH3	Avg
Water content (%)	w	%	2.45	2.35	2.73	2.51
Vegetable fiber content (%)	Tf	%	42.12	27.57	31.42	33.7
Wet Unit Weight	γh	KN/m³	15.588	21.023	15.294	17.3
(KN/m³)	γs	KN/m³	22.1	22.1	22.1	22.1
Solid Unit Weight	γd	KN/m³	16.481	17.168	16.775	16.81
(KN/m³)	n	/				0.239
Dry Unit Weight	e	/				0.314

However, the significant variation in vegetable fiber content, with values ranging from 27.57% to 42.12%, may require adjustments to optimize the material's properties. Similarly, the variation in wet density, from 15.294 KN/m^3 to 21.023 KN/m^3, indicates that the samples have different compositions or compaction states.

In conclusion, the results suggest that the studied material could be reliable for applications where low variability in physical characteristics is crucial, but adjustments in fiber content might be necessary to optimize its properties. The constant values for the density of solid particles, porosity, and void index indicate uniformity in the samples, which is positive for the material's homogeneity. Further analysis and precise adjustments may be needed to improve the overall performance of the material in practical applications.

4.2 Characteristics of materials identification

The results of the particle size analyses by sieving and LASER carried out on two samples of the old Boussaâda adobe are presented in the curve of Figure 1.

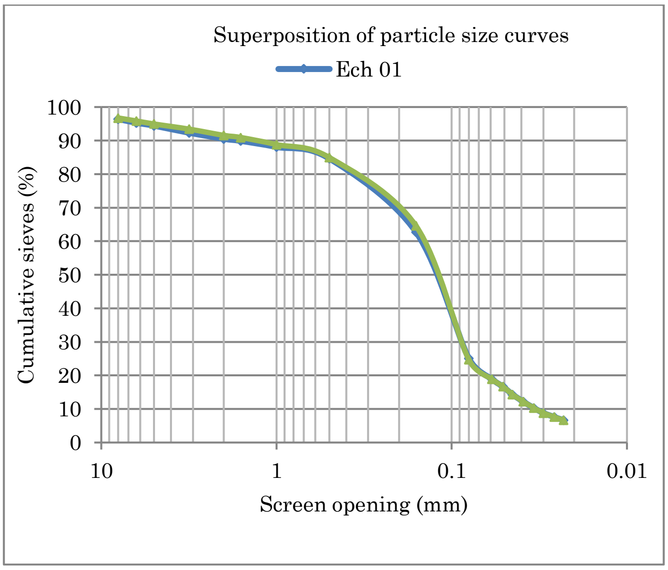

Figure 1. Superposition of the particle size curves of the 2 samples

The particle size distribution and identification tests indicate that the old Boussaâda adobe is a well-graded material with a high sand content and an acceptable amount of fines (Table 2a). The combination of these elements ensures that the adobe has a robust and stable structure, with good cohesiveness and plasticity, which are essential for its performance as a building material.

The variation in liquid limit values suggests that the material's moisture sensitivity can vary, which should be considered in its application to ensure optimal performance under different environmental conditions (Table 2b). The consistent plastic limit and low plasticity index values are positive indicators of the material's workability and resistance to deformation.

Overall, the Boussaâda adobe exhibits promising properties for construction applications, given its well-balanced composition and favorable physical characteristics. Proper adjustments and considerations regarding moisture content and compaction can further enhance its performance and durability in practical use.

According to the LPC classification (The French Laboratory for Civil Engineering) allowing to classify soils according to their granularity and plasticity [21], it follows that: the samples taken are Silty Sands (SS class soils).

4.3 Mechanical properties of materials

Box shear tests were conducted under different initial normal stresses (σ_{no}= 25, 50, and 100 kPa). The results of these tests are illustrated in Figures 2a, 2b, and 2c.

It was observed that the shear stress initially increases until it reaches a plateau, then slightly decreases from a tangential displacement of about 1.2 mm for a normal stress of 25 kPa, 3 mm for a normal stress of 50 kPa, and about 3.5 mm for a stress of 100 kPa (Figure 2a).

Regarding the evolution of normal displacement, the behavior is initially contractive up to a tangential displacement of about 0.5 mm and 1.2 mm for stresses of 25 kPa and 50 kPa respectively, and about 2.1 mm for a stress of 100 kPa, followed by a decrease in this displacement until the end of loading (Figure 2b).

The cohesion and internal friction angle (C, φ) are 172.22 kPa and 63.92° respectively (Figure 2c).

The material exhibits a high initial shear resistance, which increases to a plateau before decreasing slightly. This decrease is observed at different tangential displacements depending on the applied normal stress, suggesting some post-peak weakening or softening of the material. The normal displacement shows an initial contraction followed by dilation, indicating volume changes due to shear deformation. The cohesion of 172.22 kPa and the internal friction angle of 63.92° indicate a strong resistance to internal bonding and sliding, respectively.

Table 2a. Percentages of gravel, sand and fines in samples

Sample	Gravels % (>2mm)	Sands % (<2mm)	Fines % (<80µm)
Ech:1/	9.47	65,41	12.
Ech:2/	12.86	66.25	20.89
Average	11.17	65-83	23.00

Table 2b. Synthesis of the results of the identification tests

Characteristics	Symbol	Unit	Results			
			ECH1	ECH2	ECH3	Average
Liquid limit	WL	%	31.25	23.14	22.41	25 – 60
Plastic limit	WP	%	25	21.87	18.91	21,93
Plasticity index	IP	/	6.25	1.27	3.5	3.67
Uniformity coefficient	Cu	/	4.286	4.286	/	4.286
Curvature coefficient	Cc	/	1,376	1,376	/	1,376

4.4 Mechanical compression resistance

The simple compression test uses a sample with dimensions of 106 mm by 124 mm. The general shape of the curve (force – elongation) is given in Figure 3.

In Figure 3, it is mainly observed that the response is almost linear up to a force of 1000 N and an elongation of 0.5 mm. Beyond the elastic regime, the force continues to increase, but the elongation increases more significantly. Then, the force level approaches the breaking limit (Fpic), and the volume of the sample increases due to dilatant deformations in the transverse direction of the force. These deformations become more significant than those measured in the loading direction, accompanied by significant cracking. Cracks appear and propagate parallel to the direction of the force, rapidly reaching the ultimate state. As soon as the first visible cracks appear, the curve changes trajectory (Figure 3). This change can be attributed to a deterioration phenomenon of the earthen brick. The post-peak part has no mechanical significance as the test is prematurely stopped when the total failure of the adobe is imminent. The compressive strength results obtained in this study (0.2 MPa) is consistent with those reported in previous studies on similar materials [22, 23].

The force-elongation curve shows an elastic region followed by plastic deformation. Approaching the peak force, the sample volume increases due to dilatant deformations, indicating significant internal structural changes. The appearance and propagation of cracks parallel to the loading direction lead to a rapid decrease in load-bearing capacity. The post-peak portion of the curve has no mechanical significance as the test was prematurely stopped.

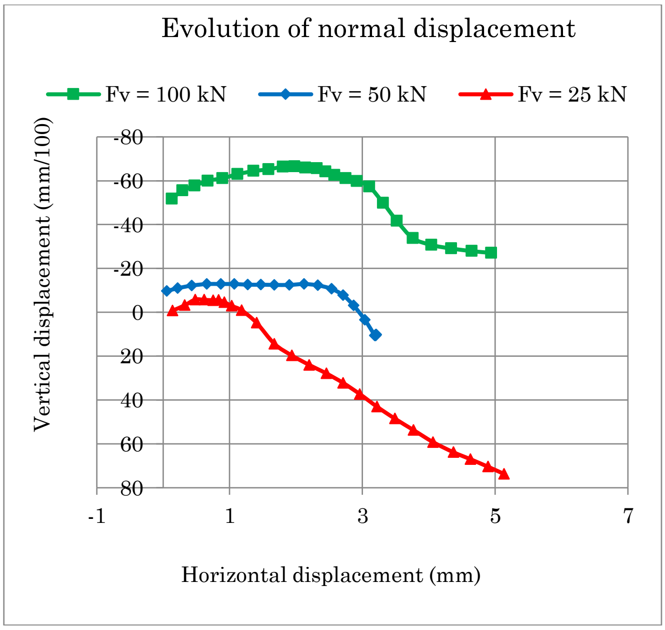

Figure 2b. Evolution of normal displacement

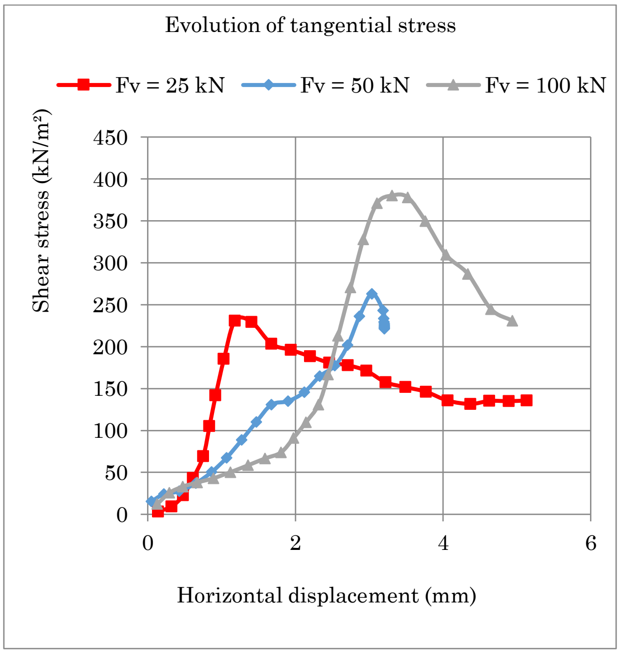

Figure 2a. Evolution of tangential stress

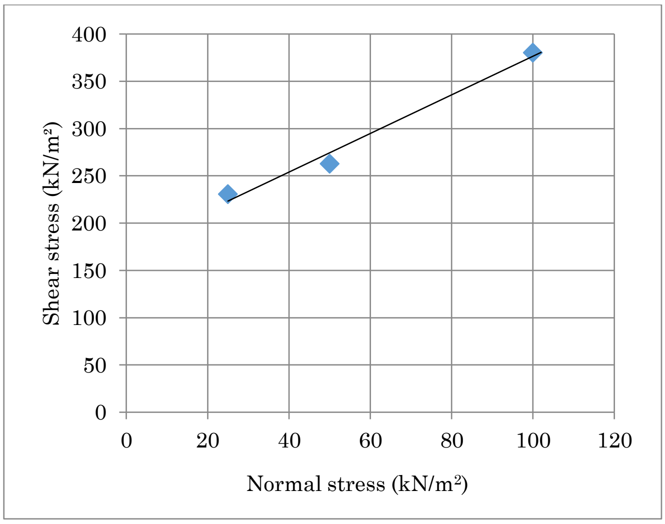

Figure 2c. Shear tests at constant normal stresses

The results of the execution of the simple compression test are presented as follows (Table 3):

Table 3. Results of the execution of the simple compression tests

Display Name	Unit	Values
Reason for end of test execution		Break detected
Width	mm	106.00
length	mm	124.00
Stress peak	MPa	0.2
Maximum strength	kN	2.899

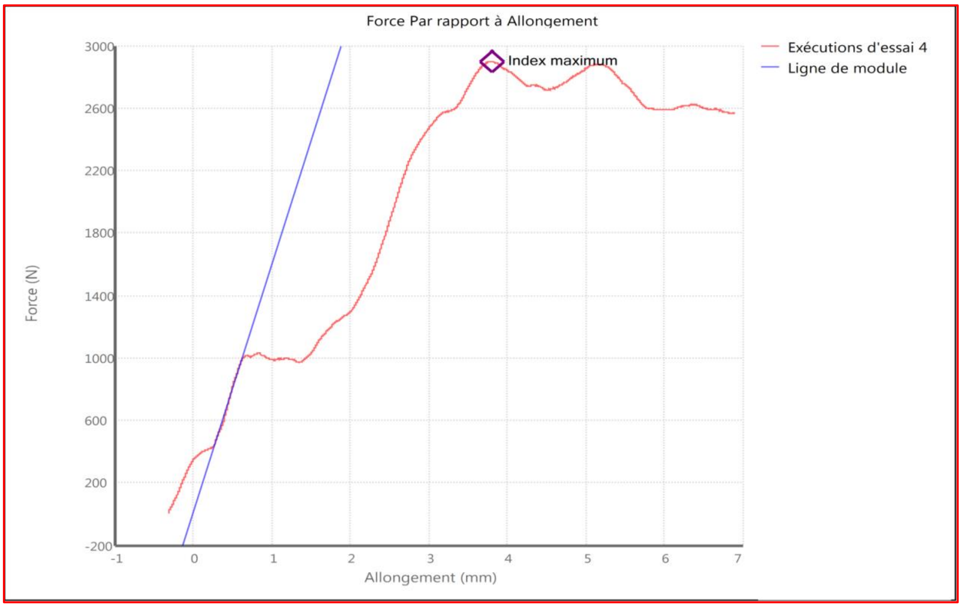

Figure 3. Simple compression test execution review graph

In Table 4, we present the summary of the results of the box shear tests and the simple compression test obtained:

Table 4. Summary of the results of the mechanical tests

Characteristics	Symbol	Unit	Results
Box shear strength	C	kPa	220
	Φ	Level	34.32°
Unconfined compressive strength	Rc	MPa	0.2

The box shear strength is 220 kPa, the internal friction angle is 34.32°, and the simple compression strength is 0.2 MPa. These values indicate good load-bearing capacity and resistance to shear deformation. However, the moderate compression strength suggests that the material may not be ideal for structural elements subjected to high compressive loads.

The material could be suitable for applications where shear resistance is crucial, such as retaining walls or foundations strength indicates that additional reinforcement or stabilization subjected to lateral loads. However, its moderate compression compressive loads. The observed post-peak weakening and might be necessary for applications subjected to high cracking behavior highlight potential areas for improvement, such as enhancing the material's ductility and post-peak performance.

4.5 Thermal conductivity

The results of the temperature measurement tests at the inlet and outlet of the samples, every five minutes, are summarized in Table 5.

Figure 4a shows the change in temperature at the inlet and outlet of the Boussaâda ancient adobe sample over a period of 250 minutes.

We notice a temperature progression at the inlet of the adobe sample while no significant temperature change appears at the outlet. Thus, the temperature at the inlet increases gradually, while that at the outlet is practically stable.

The calculation results of the thermal conductivity of the earth brick is given in the figures (Figures 4b and 4c). These figures show that the increase in temperature difference is compensated by a decrease in thermal conductivity.

The values of λ as a function of time are given in Figure 4b. All these measurements show that the thermal conductivity of the adobe gradually decreases over time.

The average value of λ in this temperature range is 0.7291 W/m.K, which corresponds to the good thermal insulator.

All these results confirm that the old earth brick of Boussaâda has good thermal insulation performance.

Table 5. Results of the temperature measurement tests at the inlet and outlet of the adobe sample

Time (min.)	Input T°	T° output	Time (min.)	Input T°	T° output	Time (min.)	Input T°	T° output
5	25	20	**80**	31	21	**155**	32	21
10	28	20	**85**	31	21	**160**	32	21
15	28	20	**90**	31	21	**165**	32	21
20	29	20	**95**	31	21	**170**	32	21
25	29	20	**100**	31	21	**175**	32	21
30	29	20	**105**	32	21	**180**	32	21
35	30	20	**110**	32	21	**185**	32	21
40	30	20	**115**	32	21	**190**	32	21
45	31	21	**120**	32	21	**195**	32	21
50	31	21	**125**	32	21	**200**	32	21
55	31	21	**130**	32	21	**205**	32	21
60	31	21	**135**	32	21	**210**	32	21
65	31	21	**140**	32	21	**215**	33	21
70	31	21	**145**	32	21	**220**	34	21
75	31	21	**150**	32	21			

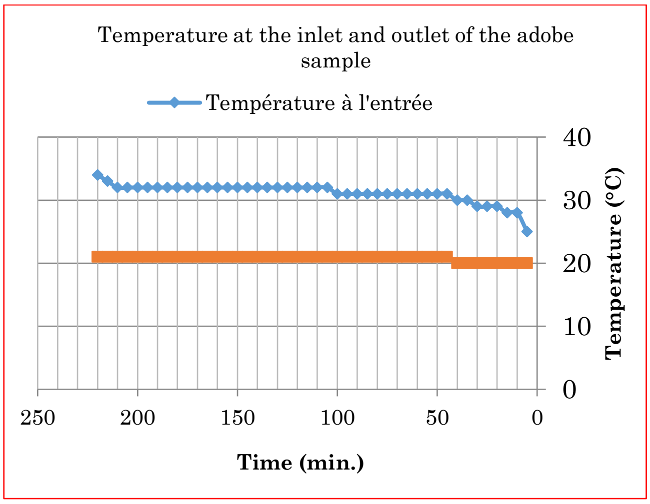

Figure 4a. Evolution of the temperature at the inlet and outlet of the adobe

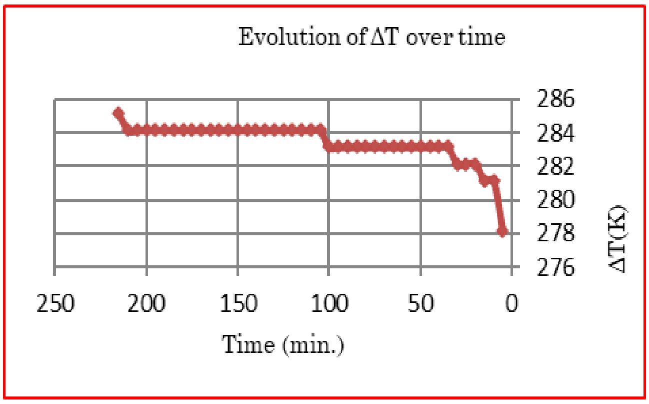

Figure 4b. Evolution of the temperature difference over time

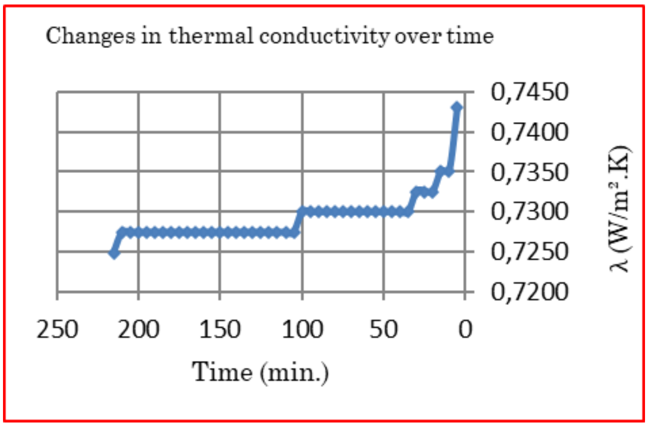

Figure 4c. Evolution of thermal conductivity over time

The thermal conductivity (λ) of the adobe sample studied is 0.7291 W/m.K, which is slightly higher than the values reported by Atoke (0.75 W/m.K) and Malanda et al. (0.44 - 0.75 W/m.K). However, this value falls within the same range as the results of Moevus (0.46 - 0.81 W/m.K) and Doat et al. (0.4 - 0.8 W/m.K) [7]. This suggests that the thermal conductivity of the adobe sample is comparable to that of other similar materials, but slightly higher than some references.

The bulk density (γh) and dry density (γd) of the adobe sample are slightly higher than the values reported by Moevus (12-17 kN/m³). It is possible that the composition of the adobe sample, its water content, or its manufacturing process may influence its density (see Table 6).

Table 6. Comparison between results and bibliography

Parameter	Results	[4]	[5]	[6]	[7]
CS (MPa)	0.2	0.2-0.5	0.2	0.4-5	0-5
λ (W/m.K)	7291	0.75	0.44-0.75	0.46-0.81	0.4-0.8
γh (kN/m³)	17.3	15			12-17
γd (kN/m³)	16.81			12-17	
	2.51			0-5	

5. CONCLUSIONS

This study highlights that traditional adobe from Boussaâda exhibits a certain heterogeneity, complicating its analysis. However, the properties measured, even after over 500 years of building existence, indicate that traditional adobe from Boussaâda could be an interesting raw construction material. The numerous similarities observed between Boussaâda adobe and other studies on earth bricks reinforce this conclusion.

Traditional adobe from Boussaâda can be used for thermal insulation, partition walls, and ceiling coverings. The results obtained show promising mechanical performance, with optimal values of compression and shear strength. Thus, this composition could be selected for the production of high-quality bricks.

Further research on the durability and potential treatments of these bricks will help assess their potential for production and use in the construction industry, as well as in the restoration of ancient buildings.

In conclusion, the study of Boussaâda adobe reveals that this traditional material presents some heterogeneity, complicating consistent characterization. Despite this, the analysis demonstrates that Boussaâda adobe retains promising mechanical and thermal properties, indicating its potential as a viable construction material. The thermal conductivity of the sample, measured at 0.7291 W/m.K, aligns well with values reported in the literature, although it is slightly higher than some references, suggesting good thermal insulation properties comparable to other earthen materials. Notably, the thermal performance of Boussaâda bricks is significant. The measured thermal conductivity of 0.7291 W/m.K is consistent with values reported for similar materials in other arid regions [9, 10]. This consistency in thermal performance across various arid regions underscores the suitability of local earth materials for construction in such climates [11, 13, 14, 22, 23] Moreover, the densities of the sample (both bulk and dry) were found to be higher than those reported by Moevus, which could be due to variations in composition, water content, or manufacturing processes. The consistent density of solid particles and uniform porosity of the material indicate a homogeneous internal structure, beneficial for its strength and durability.

The mechanical tests, including shear and unconfined compression tests, confirm the material's suitability for construction applications, demonstrating optimal values for compression and shear strength. These results, along with the observed stability and workability, underscore the material's robustness and its potential for use in building walls, partitions, and ceilings.

Given these findings, traditional adobe from Boussaâda appears to be a viable material for modern construction, offering both thermal insulation and mechanical strength. However, further research on the durability and possible treatments of these bricks is recommended to enhance their performance and ensure their suitability for contemporary construction and restoration projects.

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NOMENCLATURE

w	Water content (%)
Tf	Vegetable fiber content (%)
γh	Wet Unit Weight (KN/m^3)
γs	Solid Unit Weight (KN/m^3)
γd	Dry Unit Weight (KN/m^3)
n	Porosity
e	Voids ratio
C	Cohesion (kPa)
Φ	Friction angle (°)
Rc	Unconfined compressive strength (MPa)
λ	Thermal conductivity (W/m.K)
ΔT	Temperature difference (°C)
σ_{n0}	Initial normal stress (kPa)
WL	Liquid Limit (%)
WP	Plastic Limit (%)
IP	Plasticity Index
Cu	Uniformity Coefficient
Cc	Curvature Coefficient
Q	Electric power (W)
L	Sample length (cm)
S	Sample area (cm^2)