Comparative analysis of the thermal properties of handmade clay bricks used in cultural buildings

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ABSTRACT In order to comply with the standards for the restoration of historic buildings in Morocco and the guidelines aimed at preserving as much of the original materials as possible during restoration projects, this study assesses the impact of conservation constraints on the thermal performance of materials while highlighting the importance of respecting the authenticity of old materials in restoration projects.A comparison of the thermal properties of two traditional building materials (terracotta bricks), old bricks and new bricks, was carried out. The main objective was to evaluate their performance in terms of thermal conductivity, an essential parameter for the energy efficiency of buildings. Experimental measurements, including SEM (Scanning Electron Microscopy) and EDX (Energy Dispersive Spectroscopy) tests, were carried out on samples of the two types of bricks considered in this study. The results show that old bricks have lower thermal conductivity than new bricks, suggesting better insulation capacity. However, this difference can be explained by the microstructural characteristics of the materials, in particular their porosity and composition, as revealed by SEM and EDX analyses.This study highlights the trade-offs between heritage conservation and thermal performance, offering avenues for restorations that respect authenticity while optimizing energy comfort.

Key words : Clay bricks , Thermal behavior, thermal conductivity , restoration , SEM-EDX..

1 Introduction

Morocco has an exceptional architectural heritage, ranging from kasbahs to mosques, zaouias, mausoleums, and more. These buildings, which bear witness to a high level of craftsmanship, are not only a cultural and historical treasure, but also an asset for sustainable

tourism and local development. However, many of these buildings are now suffering from advanced deterioration due to the ravages of time, weather, and increasing urbanization.

The restoration of this heritage is therefore becoming urgent, both to preserve collective memory and to respond to modern challenges of sustainability and energy efficiency. Traditional Moroccan techniques offer ecological solutions that are adapted to the climate, in particular through the use of local materials such as terracotta bricks.

In Morocco, historic terracotta buildings are a model of natural energy efficiency. Their passive design (high thermal inertia, hygrometric regulation) allows for substantial energy savings in the face of growing air conditioning needs. According to the Ministry of Energy Transition and Sustainable Development , Morocco has set ambitious targets, including: increasing the share of renewable energies in the electricity mix to 52% by 2030 , reducing energy consumption by 20% by 2030 and creating value in energy-intensive economic activities. The rehabilitation of this heritage is essential as a sustainable solution [11].

Compliance with energy performance standards between new and old bricks is a frequent issue in restoration projects. Traditional old bricks, with their porous microstructure and specific mineral composition, offer natural thermal inertia that is often superior to modern industrial bricks, and their insulating properties must be rigorously evaluated. A comparative analysis of key parameters (thermal conductivity, SEM, etc.) is therefore essential to ensure that replacements respect the original energy efficiency of historic buildings while meeting current standards.

2 Materials and methods

2 .1 Study area:

The study site is the Zaouïa Ouazzania in the old Medina of Marrakech (Figure 1) , built in the 14th century during the Merinid reign, which is an example of Morocco's ancient spiritual, architectural, and historical heritage. Affected by the Alhaouz earthquakes in 2023, it is currently undergoing an urgent restoration program supervised by the Ministry of Habous and Islamic Affairs.

Figure 1: The studied area: Zaouia Wazzania, Marrakech

2.2 Materials

2.2.1 Ancient bricks:

Taken from the collapsed parts of the Zaouïa Ouazzania following the earthquake, these historic terracotta bricks, handmade in various sizes (28-32 cm × 14; 16 cm × 5-7 cm...) (Figure 1) have a heterogeneous composition with natural inclusions (lime , marble...) and high porosity resulting from low-temperature firing in traditional kilns.

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Figure 2: Sample of old brick

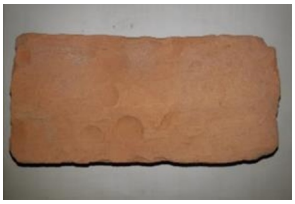


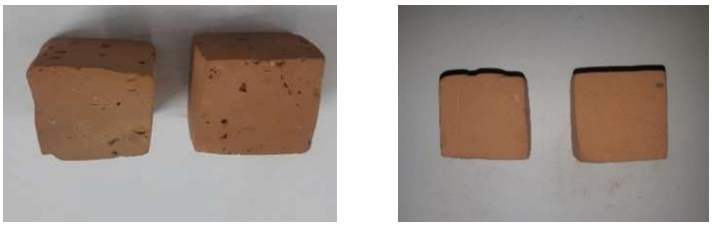
Figure 3: Sample of modern bricks

2.2.2 Modern bricks:

Produced by local workshops in accordance with current standards ,with standard dimensions (28×15×6 cm) (Figure 3), these bricks use traditional techniques while incorporating controlled improvements (firing temperature, fine sieving of clays, etc.). Their microstructure appears more homogeneous, with reduced porosity.

2.3 Sample preparation

The bricks were dried for 48 hours until they reached a constant mass and were gently cleaned by dry brushing to remove surface residues without altering their structure. Visual sorting was used to eliminate samples with visible cracks or major alterations, using a low-speed saw to obtain standardized samples (4×4×3 cm) (Figure 4).



(a) (b)

Figure 4 : Images of the prepared samples for thermal testing : (a) Sample of old brick (b) Sample of modern bricks

2.4 Experimental methods:

2.4.1 SEM-EDX method:

Scanning electron microscopy (SEM) combined with energy dispersive X-ray spectroscopy (EDX) is a powerful analytical method that allows for the precise examination of sample morphology, the determination of their elemental chemical composition, the establishment of structure-property correlations, and the production of high-resolution imaging. In this study, powders are prepared from old and modern bricks, ground separately, and deposited on a conductive stub covered with tape.

2.4.2 Thermal conductivity:

Thermal conductivity is the amount of heat transferred in a unit of time through a material of a unit area and a unit thickness. It is expressed in $W\cdot m^{-1}\cdot K^{-1}$. For a given body, its value can be influenced by temperature and the presence of impurities.

The thermal conductivity of the samples was determined using an FP2C device, consisting of a thermal shock probe placed between two material samples in a symmetrical arrangement. The device includes an electronic acquisition box and software with a graphical interface for controlling the tests and processing the results.

In this study, each brick was divided into two samples of identical and symmetrical dimensions. The hot wire probe was placed between the two facets of the samples, and measurements were taken according to the device's standard protocol. The results were processed and validated using the dedicated FP2C software [12], which allows the thermal conductivity values of the tested materials to be accurately determined.

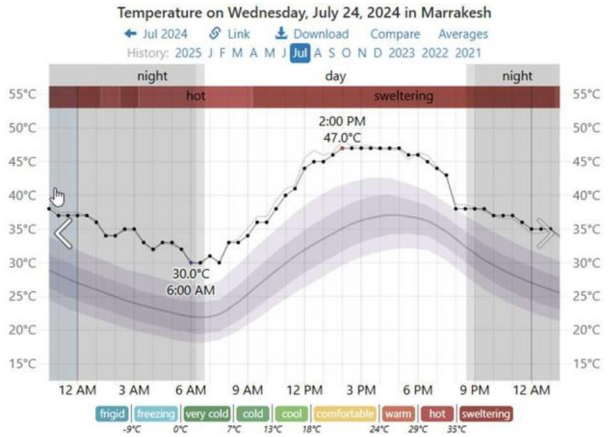


Figure 5 : Maximum temperature recorded in Marrakech, year 2024

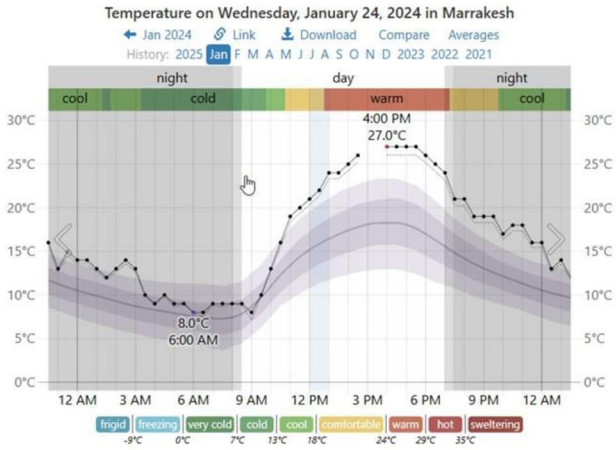


Figure 6 : Minimum temperature recorded in Marrakech, year 2024

The study of the thermal conductivity of bricks was conducted over a temperature range of 5 to 50°C, carefully selected to accurately reflect the extreme and varied climatic conditions of the Marrakech region (Figure 5) and (Figure 6) [13]. This temperature range comprehensively covers the actual thermal stresses to which buildings are subjected throughout the year, from cool winter nights when the mercury can drop to around 5°C, to scorching summer days when temperatures regularly exceed 47°C. Characterizing thermal properties across this range is essential to understanding how materials behave under realistic conditions, particularly in the context of preserving architectural heritage and optimizing energy efficiency.

3 Results and Discussion

3.1 SEM and EDX

SEM images show marked differences between old and modern bricks;
For old bricks, the microstructure has high porosity (20-30%) with interconnected voids of irregular shapes (Figure 7), resulting from low-temperature firing and the decomposition of organic inclusions. The grain morphology shows fairly high heterogeneity, whereas modern bricks exhibit a compact matrix (porosity <5%) (Figure 8), typical of sieved clay and controlled firing. The homogeneous distribution of elements confirms the absence of inclusions and reflects standardization of raw materials.

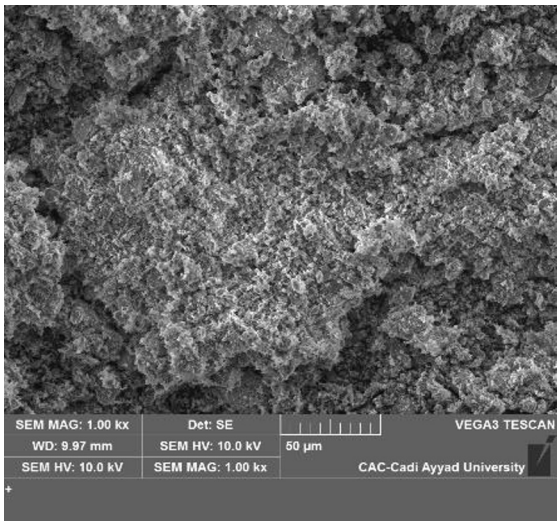


Figure 7: SEM image of old brick powder

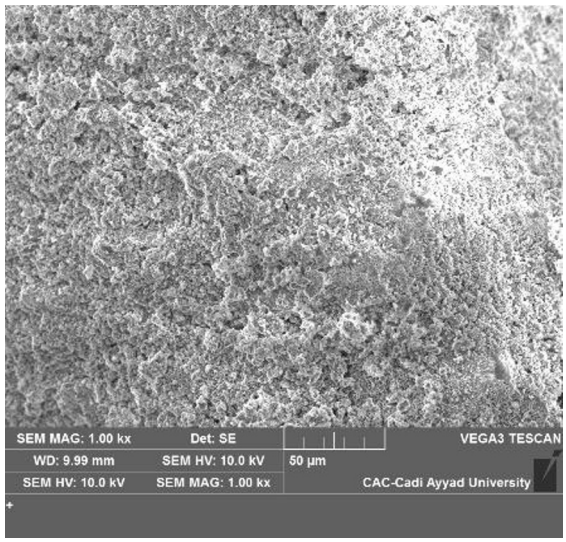


Figure 8: SEM image of modern brick powder

According to EDX analyses of the two clay bricks, The first sample is shown in (Figure 9) and Table 1 shows the presence of carbon (2.66% by weight), oxygen (34.96%), magnesium (2.78%), aluminum (5.34%), silicon (12.51%), and calcium (41.75%) , while the second sample (Figure 10) and Table 2 reveals a composition dominated by oxygen (40.71%), with significant contributions from aluminum (12.54%), silicon (25.74%) and calcium (14.39%), as well as traces of potassium (3.98%); For the first type of brick (old), the high calcium content suggests the presence of lime (CaO), resulting from the decarbonation of limestone ($CaCO_3$) during firing:

$$CaCO_3 \rightarrow CaO + CO \quad (1)$$

Typical of old mortars or intentional additions to improve durability and thermal comfort; For the second type of bricks (new), there is a notable absence of significant lime: reduced calcium (CaK: 14.39% by weight) and no significant carbon peak, and a dominant composition: silica (SiK: 25.74% by weight) and aluminum (AlK: 12.54% by weight), indicating less modified clay.

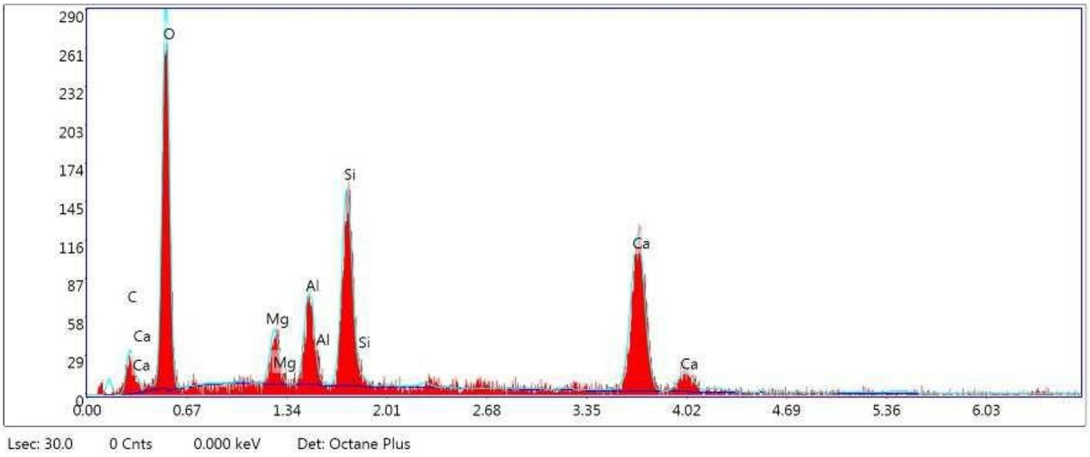


Figure 9: EDX analysis of old-style bricks

Table 1: Chemical composition of old-style bricks

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	A	F
C	2.66	5.26	9.26	17.02	0.0136	1.1624	0.4416	1.0000
O	34.96	51.95	124.71	9.99	0.1451	1.1008	0.3771	1.0000
Mg	2.78	2.72	21.99	12.13	0.0228	1.0018	0.8191	1.0028
Al	5.34	4.71	40.53	8.50	0.0455	0.9618	0.8807	1.0043
Si	12.51	10.59	88.28	6.24	0.1125	0.9801	0.9132	1.0044
Ca	41.75	24.77	94.25	6.26	0.3789	0.9096	0.9948	1.0030

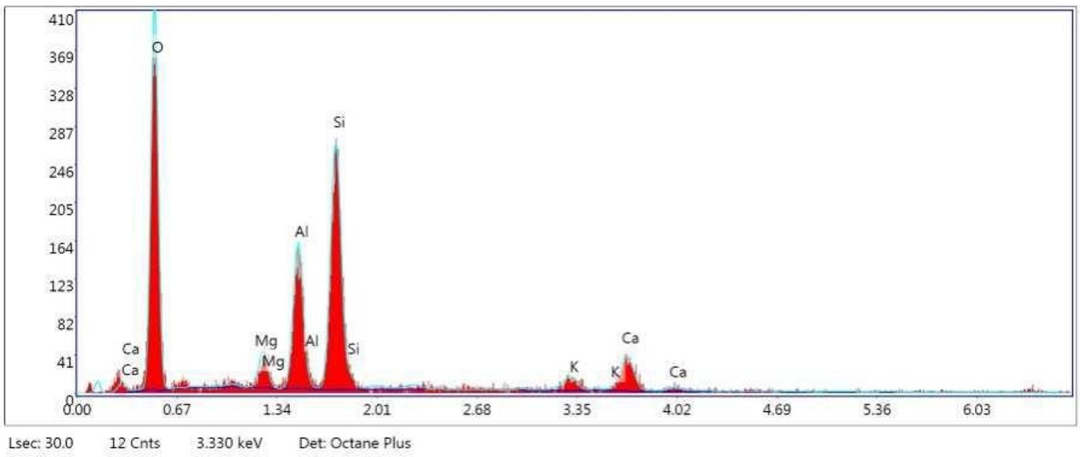


Figure 10 : EDX analysis of modern bricks

Table 1: Chemical composition of modern bricks

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	A	F
O	40.71	56.60	173.89	8.26	0.2307	1.0849	0.5224	1.0000
Mg	2.64	2.42	18.84	12.95	0.0223	0.9862	0.8538	1.0044
Al	12.54	10.34	84.50	6.18	0.1081	0.9467	0.9056	1.0053
S	25.74	20.39	155.62	5.17	0.2262	0.9645	0.9085	1.0025
K	3.98	2.26	10.24	24.00	0.0352	0.8808	0.9793	1.0258
Ca	14.39	7.99	27.79	15.17	0.1274	0.8937	0.9839	1.0066

3 2 Conductivity results

The graphs show that the thermal conductivity of old bricks is lower than that of new bricks, suggesting that insulating properties change over time (Figure 11). For both samples, conductivity decreases gradually with temperature, indicating similar thermal behavior but with distinct performance characteristics. The old brick, which is less dense and probably more porous, has lower conductivity, which could be explained by an altered microstructure or the presence of less conductive components (such as lime). The new brick, which is more homogeneous and compact, conducts heat better, reflecting optimized manufacturing processes. However, the decreasing trend for both materials implies that they become slightly better insulators at high temperatures, an interesting feature for construction applications. These results highlight the importance of age and composition in the thermal performance of clay bricks.

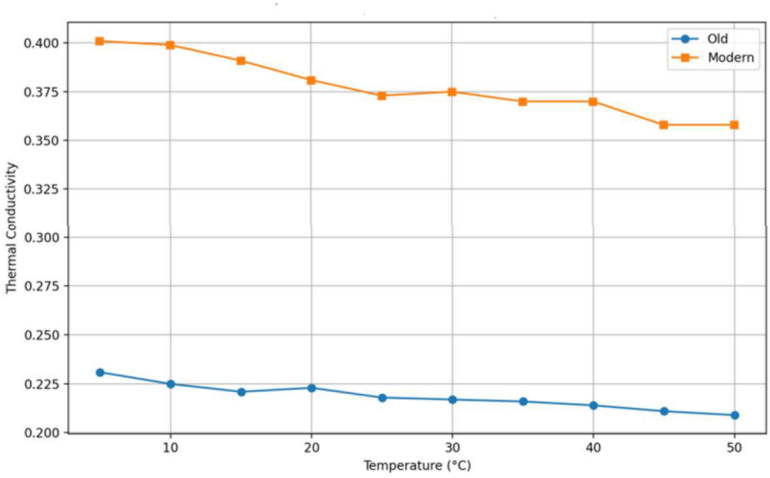


Figure 11 : the thermal conductivity behavior of the two types

Comparative analysis of the thermal behavior of old and modern bricks, carried out using scanning electron microscopy (SEM) and thermal conductivity measurements with the FP2C device, shows significant differences in their physical and thermal properties. SEM images reveal a highly porous and interconnected microstructure in old bricks, contrasting with a denser and more homogeneous structure in modern bricks. These microstructural observations are directly correlated with thermal conductivity measurements: the old brick has a conductivity between 0.200 and 0.225 $W•m^{-1}•K^{-1}$, while that of the modern brick varies between 0.350 and 0.400 $W•m^{-1}•K^{-1}$, an increase of 57%; This difference can be explained by the dominant influence of porosity on heat transfer.

Heat transfer in a porous material is controlled by the respective contributions of its solid matrix and the air contained in its pores (cavities). The solid phase, which is relatively conductive, provides a preferential path for heat, while the air, which is considered an excellent insulator, is present in the pores and opposes heat flow. Thus, the greater the porosity, the greater the presence of air, creating an effective barrier to conduction. This is the case with old brick, whose highly porous microstructure traps a quantity of air, which increases its thermal resistance and gives it high insulating power. Conversely, modern brick, with lower porosity, offers more space for the conductive solid phase, which facilitates heat transfer and reduces its insulating performance.

These results highlight the effectiveness of traditional manufacturing techniques, which produce materials that are naturally suited to thermal comfort in hot climates. They also call for a reassessment of modern building standards.

Conclusion

This study sheds light on the fundamental relationships between microstructural characteristics, chemical composition, and thermal performance of traditional and modern clay bricks. Through rigorous multi-technique characterization combining SEM-EDX analyses with precise thermal conductivity measurements over an environmentally relevant temperature range (5-50°C), this research establishes quantitative structure-property

relationships that significantly advance our understanding of heat transfer mechanisms in porous building materials.

The study clearly demonstrates that the superior thermal performance of old and historic bricks stems from a relationship between their high lime content (41.75% for old bricks compared to 14.39% in modern bricks) and their complex porous architecture. Beyond its traditional role as a binder, lime promotes the development of an interconnected porous network that significantly amplifies thermal resistance through air confinement mechanisms.

The correlations established between pore morphology, particle size distribution, and thermal conductivity provide a powerful predictive framework for the design of innovative building materials. Experimental validation across the entire environmental thermal gradient ensures that the results can be directly transferred to practical applications in real-world conditions, which is particularly crucial in the current context of climate change and energy efficiency requirements.

These discoveries open up significant scientific and industrial prospects for:

- The design of innovative composites, inspired by the optimal porous microstructures identified in traditional materials, in order to improve the energy efficiency of contemporary buildings.
- Preserving and enhancing built heritage through a deeper understanding of the intrinsic thermal performance of ancient and traditional materials, paving the way for more effective restoration methods that respect structural authenticity.

In summary, these results highlight the impact of manufacturing techniques and materials on thermal performance, with ways to optimize modern bricks by drawing inspiration from the properties of traditional materials. Further studies (XRD, hygrothermal measurements) could refine these conclusions.

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