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Reproducing Archaeological Bricks from Qasr Touila: A Comparative Study of Physical, Chemical, and Mechanical Properties

Dr. Zaitri Ali [1], Dr. Cherouik Mohamed Elamine [2]
[1] University Center of Aflou, Algeria. Email: a.zaitri@cu-aflou.edu.dz
[2] University Center of Aflou, Algeria. Email: m.cherouik@cu-aflou.edu.dz
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Abstract
Clay-based building materials, particularly mud bricks, are among the main materials used in traditional and archaeological architecture. Their physical, chemical, and mechanical properties are influenced by the composition of the raw materials and by environmental factors that contribute to their deterioration over time. This study examined archaeological brick samples from the site of Qasr Touila and compared them with laboratory-manufactured samples prepared to simulate the original material. The aim was to evaluate the extent to which the manufactured samples could reproduce the characteristics of the archaeological bricks. The chemical composition of the samples was determined by X-ray analysis, and their surface features were examined using scanning electron microscopy. The investigated properties included released gas volume (VCO_2), carbonate content (CO_3), compressive strength, bulk density, and water absorption. The data were expressed as mean ± standard deviation and analyzed using one-way ANOVA, Tukey’s test, and Pearson correlation analysis. The results revealed significant differences among the studied samples in VCO_2, CO_3, and bulk density ($P \leq 0.05$), while compressive strength and water absorption showed no statistically significant differences ($P > 0.05$). Pearson correlation analysis showed a strong positive correlation between VCO_2 and CO_3 ($r = 0.714$) and a positive correlation between VCO_2 and bulk density ($r = 0.670$). Overall, the manufactured samples showed values close to those of the archaeological bricks, indicating that they were largely successful in reproducing their principal physical and mechanical properties, despite some differences related to mineral composition and internal structure.
Keywords: archaeological brick; mud brick; Qasr Touila; physicochemical properties; compressive strength.

Introduction
Clay-based building materials, particularly bricks, are among the most important components used in traditional and historic architecture across many regions of the world. Since ancient times, they have been widely employed in the construction of buildings and various architectural structures. Mud bricks are characterized by a range of physical and mechanical properties that depend on the nature of the raw materials used in their manufacture, as well as on the drying and firing conditions applied during production. The study of these properties contributes to a better understanding of traditional brick-making techniques and helps identify the factors that influence their durability and long-term stability.

In the field of architectural heritage conservation, the study of historic building materials is of particular importance, as it makes it possible to identify their composition and their physical, chemical, and mechanical characteristics. Such knowledge is essential for selecting suitable replacement materials in restoration and maintenance works. The analysis of the physical and mechanical properties of archaeological bricks is therefore a fundamental step toward understanding the behavior of these materials and their resistance to environmental factors such as moisture, temperature fluctuations, and weathering.

Research Problem

Many heritage buildings constructed with mud bricks face deterioration problems caused by various environmental factors, leading to the gradual loss of some of their physical and mechanical properties over time. In addition, the use of incompatible materials in restoration processes may result in the loss of architectural identity in the structure of desert palaces. Therefore, there is a need to study the physical and mechanical properties of archaeological bricks and compare them with those of manufactured samples designed to simulate these materials, in order to determine the extent to which such samples can be used in experimental studies and restoration works. Qasr Touila served as the case study for this research.

Significance of the Study

The importance of this study lies in its contribution to understanding the physical, chemical, and mechanical properties of the archaeological bricks of Qasr Touila, as well as identifying the relationships among their different components. The findings may help assess the possibility of producing manufactured samples with properties similar to those of the original bricks, thereby supporting scientific efforts in the conservation of historic buildings and the preservation of architectural heritage. In addition, the use of statistical analysis in the study of these properties provides a more accurate understanding of the relationships among the variables examined, such as bulk density, compressive strength, water absorption, and carbonate content.

Objectives of the Study

This study aims to characterize the physical, chemical, and mechanical properties of brick samples from the archaeological site of Qasr Touila and to compare them with laboratory-manufactured samples. It also seeks to examine the relationships among key variables, including released gas volume, carbonate content, compressive strength, bulk density, and water absorption, through the application of statistical methods such as one-way ANOVA, Tukey’s test, and correlation analysis. Ultimately, the study evaluates the extent to which manufactured samples can reproduce the properties of the archaeological bricks and their potential suitability for experimental research and restoration purposes.

Theoritical Background

Numerous studies have investigated the physical, chemical, and mechanical properties of historic building materials, particularly mud bricks, in order to better understand traditional manufacturing techniques and the factors governing their durability and long-term stability. These studies have demonstrated that properties such as bulk density, water absorption, and compressive strength are closely linked to the porosity of the material and to the mineralogical composition of the raw materials used in its production. In general, an increase in porosity is associated with higher water absorption and a reduction in mechanical strength.

Other research has highlighted the role of carbonate compounds in influencing the thermal and physicochemical behavior of bricks, since their decomposition at elevated temperatures leads to the release of carbon dioxide and may alter the internal structure of the material. Comparative investigations between archaeological bricks and laboratory-manufactured samples have further shown that the successful reproduction of original material properties depends largely on the careful selection of raw materials and the control of manufacturing parameters such as drying conditions and firing temperature.

In parallel, statistical methods, including analysis of variance (ANOVA) and correlation analysis, have proved valuable in identifying significant differences among samples and in clarifying the relationships between their main physical and mechanical variables. Within this framework, the present study contributes to the characterization of archaeological bricks from Qasr Touila and to their comparison with manufactured samples through a combination of laboratory testing and statistical analysis, with the aim of evaluating the degree of similarity between them and their suitability for restoration purposes.

Methodology

For the determination of grain texture, a magnifying microscope was used to identify the texture of the samples. As for X-ray diffraction analysis, monochromatic X-radiation was employed. There are two principal methods based on diffraction patterns. The first is known as the Debye–Scherrer method, in which the diffraction pattern is recorded on a sensitive film in the form of a strip placed inside a chamber known as the Debye chamber. The second method provides more precise information and involves recording by means of a counter connected to a plotting device that produces a diffraction diagram showing radiation quantity or line intensity as a function of the Bragg angle (2θ).

The instrument used was the D8 Advance, manufactured by BRUKER, operating according to Bragg–Brentano geometry.

For measuring the calcium carbonate content, a Bernard calcimeter was used. This apparatus consists of a graduated tube ranging from 0 to 100 cm, containing a colored liquid to facilitate reading, and fixed on a stand. One end of the tube is connected to a bottle used to determine the liquid level (the initial volume, h0), while the other end is connected to a flask containing a small tube filled with acid and the material to be tested.

To determine bulk density, portions of each sample were first taken and crushed in a mortar, then the resulting powder was sieved through a 100 μm mesh. The pycnometer was washed and dried in an oven at a temperature between 100 and 110°C, then weighed to obtain K1. It was then filled with distilled water up to the neck mark and weighed again to obtain K5. After emptying the contents and drying the pycnometer, it was filled with toluene up to the neck mark and weighed to obtain K4. The contents were then discarded, and the pycnometer was washed with distilled water and dried in the oven. Next, 5 g of the powder sample were placed into the pycnometer and weighed to obtain K2. The same pycnometer was then filled with toluene up to two-thirds of its volume and placed in a water bath at 40–50°C for 40 minutes. It was then removed, cooled under running water, and topped up with toluene to the neck mark before being weighed to obtain K3. Finally, the contents were emptied, and the pycnometer was cleaned first with toluene and then with water in order to determine the pycnometer volume, H.

To determine porosity, the samples were dried at 100°C until a constant mass (K1) was obtained. They were then placed in a water bath at a specified temperature for two hours, removed and cooled with ordinary water, and their surface water was wiped off using a dry cloth. The samples were then weighed again to obtain K2. The total porosity can be calculated using the following relationship:

$$\text{Porosity} = 1 - \frac{\text{apparent density}}{\text{true density}} \times 100\%$$

For measuring hardness or compressive strength, the brick sample must be cut into cubes measuring 10 × 10 × 10 cm. This is done using a saw. The cubes are then coated with hot sulfur on the two loading faces to level their surfaces, ensure uniform pressure distribution, and avoid stress concentration on the sample surface.

2. Results

2.1 Comparison Between Original and Manufactured Bricks

Granular texture: Petrographic observation at 20× magnification revealed a fine and heterogeneous granular fabric, with the following defining characteristics:

A fine, irregular granular texture was observed, with grains measuring less than 180 µm. These grains were well bonded to one another within a clayey binding matrix containing non-homogeneously distributed lime, quartz grains, and some other impurities. Nearly the same observations were recorded for the original brick samples from Ain Madhi, with only a slight difference in grain size. The old samples had grain dimensions of about 190 µm. In terms of cohesion, they were almost identical, with the presence of a calcareous binding material and quartz grains, which was also observed in the ancient samples.

Figure.1. *Granular texture of the first brick sample under the optical microscope (original sample).*

Figure2. *The granular texture of the first brick sample under the optical microscope for the original sample.*

2.2 Analysis of X-ray Results for the Chemical Composition of the Brick

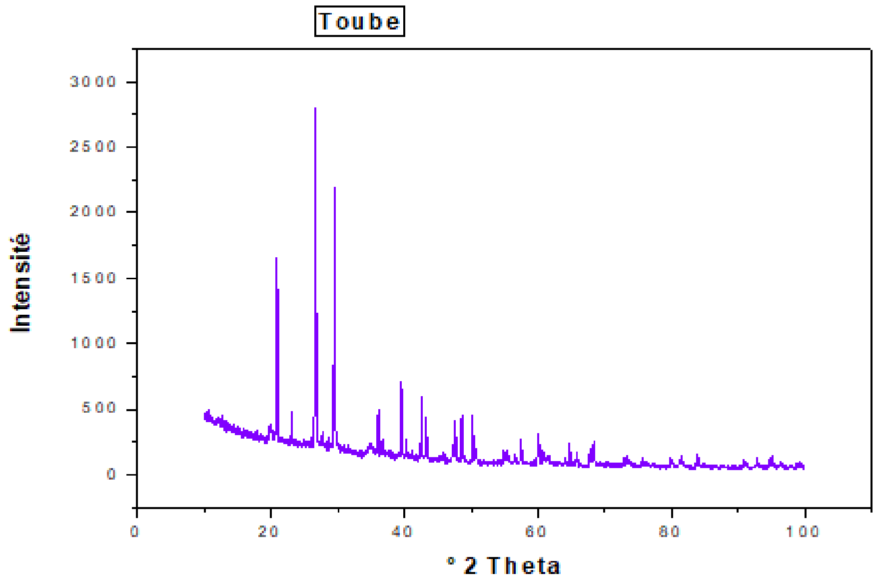
X-ray technology was used in this study to determine the chemical constituents of the brick and the weight percentages of the various elements present in its composition. The following table shows the results of the chemical analysis.

Table 1. *Chemical Composition of the Brick Sample Determined by X-ray Analysis*

Oxide / Component	Weight Percentage (%)
SiO2	51–55
Al2O3	11–13
Fe2O3	2–3
MgO	7–8
CaCO3	22–23
Other materials	About 9–10

These results indicate that the brick is mainly composed of SiO_2 (55%) and $CaCO_3$. Surface analysis was then carried out using a scanning electron microscope (SEM), and the results obtained are presented in the following figure.

Figure 3. *X-ray Diffraction Pattern of the Brick Sample*



In short , these modern materials possess nearly the same mechanical and physicochemical properties as traditional materials; therefore, their use is recommended in maintenance and restoration works.

2.3 Statistical Analysis

Statistical analysis was performed to evaluate the physical, chemical, and mechanical properties of the studied brick samples and to determine the significance of the differences observed between the original and manufactured samples. The results were expressed as mean values ± standard deviation, and one-way analysis of variance (ANOVA) was used to assess the existence of statistically significant differences among the samples. When significant differences were detected, Tukey's test was applied for multiple comparisons at a significance level of $P \leq 0.05$. The results obtained for the studied samples are summarized in **Table 1 and 2**

Table 1. *Physical and Mechanical Properties of the Brick Samples Studied (Mean ± Standard Deviation)*

CHEN	VCO2(ml)	CO3 %	P(pasc)	m/v (g/cm3)	APS(%)
CHEN 1	20.51±0.26a	23.49±0.22a	65.00±2.24a	3.86±0.14a	14.32±0.14a
CHEN 2	21.75±0.17b	26.52±0.24b	60.53±1.55a	3.89±0.07a	13.93±0.47a
CHEN 3	22.49±0.23b	26.47±0.22b	62.50±1.12a	5.54±0.24b	12.90±0.49a
MOYEN	21.58±0.23	25.50±0.36	62.68±1.02	4.43±0.21	13.71±0.26
Minimum	19.50	22.97	56.95	3.48	11.71
Maximum	23.06	27.32	70.08	6.14	15.00
Variance	0.979	2.408	18.904	0.806	1.249

Different letters indicate the presence of significant differences among the samples according to Tukey's test at a significance level of $P \leq 0.05$.

The table of mean values shows the physical and mechanical properties of the original and manufactured brick samples. The results are presented as arithmetic means ± standard deviation. Tukey's test was used to determine the significant differences among the samples at a significance level of $P \leq 0.05$. The results revealed significant differences among some samples in the volume of released gas

(VCO_2), carbonate content (CO_3), and bulk density, reflecting variations in the mineral composition and internal structure of the bricks between the original and manufactured samples.

Some manufactured samples recorded values close to those of the original samples for certain physical properties, indicating the success of the preparation process in reproducing the properties of the archaeological brick. In contrast, no clear significant differences were observed in compressive strength and water absorption among some samples, suggesting a similarity in the mechanical properties of the original and manufactured bricks. These results indicate that the manufactured samples were largely successful in reproducing the physical and mechanical properties of the original samples, with some differences related to mineral composition and density.

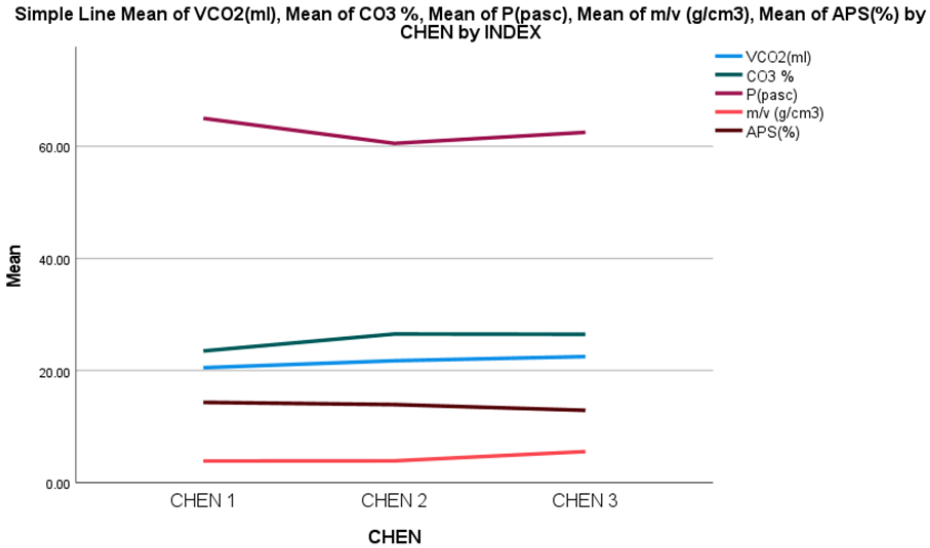
To verify the statistical significance of these differences, a one-way ANOVA was conducted, as shown in Table 2.

Table 2. *One-Way ANOVA Results for the Studied Brick Samples*

Variable	F	Sig.	Df	Significance
VCO2(ml)	19.574	.000	2	Significance
CO3 %	55.636	.000	2	Significance
P(pasc)	1.726	.211	2	Not significance
m/v (g/cm3)	32.422	.000	2	Significance
APS(%)	3.277	.066	2	Not significance

The one-way analysis of variance table shows the presence of significant differences among the studied brick samples in some physical and chemical properties. The results revealed statistically significant differences at the level of $P \leq 0.05$ for the volume of released gas (VCO_2), carbonate content (CO_3), and bulk density (m/v), reflecting differences in the mineral composition and internal structure of the studied samples. In contrast, no significant differences were observed in compressive strength (P) and water absorption (APS) among the samples, since the significance values were greater than 0.05, indicating similar mechanical properties between the original brick and the manufactured samples. These results suggest that the preparation of the experimental samples was largely successful in reproducing the mechanical properties of the archaeological brick, while some differences remained related to the mineral composition and structural density of the samples.

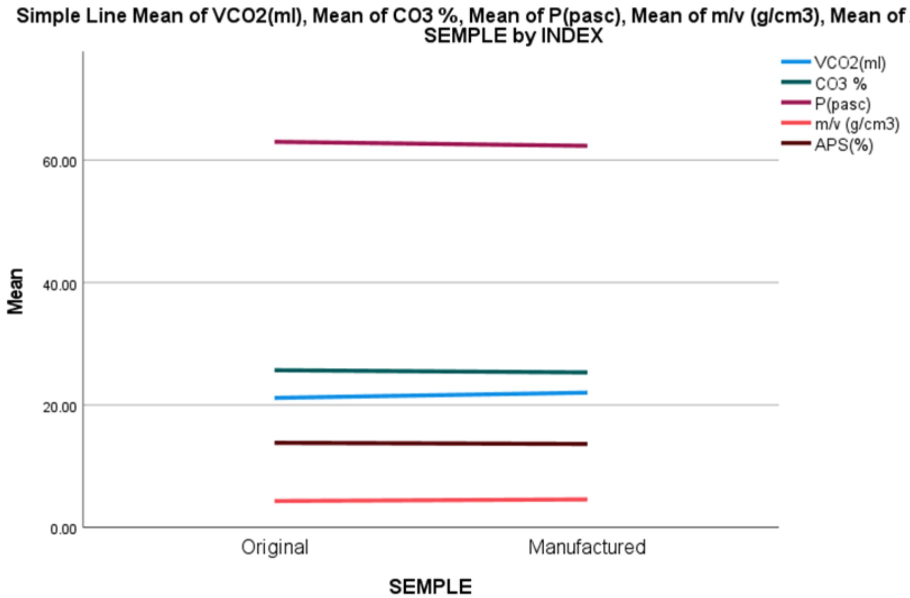
Figure 1. *Variation in the Mean Physical and Mechanical Properties of the Studied Brick Samples (VCO_2, CO_3, Compressive Strength, Bulk Density, and Water Absorption) According to Sample Type*



The figure illustrates the variation in the mean physical and mechanical properties of the studied brick samples, showing relative differences among the three samples (CHEN1, CHEN2, and CHEN3) in some of the investigated variables. A gradual increase can be observed in the volume of released gas (VCO_2), carbonate content (CO_3), and bulk density from the first sample to the third, which may reflect differences in the mineral composition and internal structure of the samples. In contrast, the values of compressive strength remain relatively close among the samples, with a slight decrease in the second sample followed by an increase in the third, while water absorption shows only limited variation among the samples. These results indicate variability in some physical properties related to bulk density and mineral composition, whereas the mechanical properties remain relatively similar among the studied samples.

For a clearer interpretation of these results, the mean values of the main physical and mechanical properties were compared graphically. This representation highlights the variations among the studied samples and facilitates the comparison between the original and manufactured bricks, as shown in Figure 2.

Figure 2. *Comparison of the Mean Values of Released Gas Volume (VCO_2), Carbonate Content (CO_3), Compressive Strength, Bulk Density, and Water Absorption between Original and Manufactured Brick*



The figure illustrates a comparison between the mean physical and mechanical properties of the original and manufactured brick samples, revealing a clear similarity in the values of some of the studied variables between the two groups. The results indicate that the manufactured samples recorded values close to those of the original samples in terms of released gas volume (VCO_2), carbonate content (CO_3), and bulk density, reflecting the success of the production process in reproducing the mineral composition and physical structure of the archaeological brick. Compressive strength also showed similar values between the original and manufactured samples, indicating comparable mechanical properties. In contrast, a slight difference was observed in water absorption, which may be related to the degree of porosity and the microscopic structure of the material. Overall, these results suggest that it is possible to produce samples with physical and mechanical properties close to those of the original brick, supporting their potential use in experimental studies and restoration work.

Overall, these findings demonstrate the possibility of producing samples with physical and mechanical properties similar to those of the original brick, which supports their potential application in experimental studies and conservation-restoration work.

Table 3. *Pearson Correlation Coefficient Matrix between the Physical and Mechanical Properties of the Studied Brick Samples*

To further display the relationships among the studied physical and mechanical properties, Pearson correlation analysis was performed. This analysis helps identify the strength and direction of the associations between the different variables and provides a better understanding of how these properties interact within the studied brick samples. The results are presented in Table 3.

	VCO2(ml)	CO3 %	P(pasc)	m/v (g/cm3)	APS(%)
VCO2(ml)	1				
CO3 %	0.714**	1			
P(pasc)	-0.222-	-0.467-	1		
m/v (g/cm3)	0.670**	0.510*	-0.348-	1	
APS(%)	-0.389-	-0.104-	0.026	-0.288-	1

(‘’) indicates a statistically significant correlation at the 0.01 level, whereas (*) indicates a statistically significant correlation at the 0.05 level.**

The Pearson correlation coefficient matrix above demonstrates varying relationships between the physical and mechanical properties of the studied brick samples. A strong positive correlation was observed between the volume of released gas (VCO_2) and carbonate content (CO_3), with a correlation coefficient of 0.714, indicating that an increase in carbonate content in the samples may lead to an increase in the amount of gas released during the analysis. The results also revealed a positive correlation between the volume of released gas and bulk density (0.670), reflecting the influence of mineral composition and internal structure on the physical properties of the brick. In contrast, a negative correlation was found between compressive strength and some other variables, such as carbonate content and bulk density, which may reflect the effect of porosity and the microstructure of the material on the mechanical properties of the brick. In addition, a negative correlation was observed between water absorption and some physical properties, which is consistent with the well-known relationship between porosity and bulk density in clay-based building materials.

3. Conclusion

The results of this study revealed variations in some of the physical and chemical properties of the studied brick samples. One-way analysis of variance (ANOVA) showed significant differences in the volume of released gas, carbonate content, and bulk density. In contrast, no clear significant differences were observed in compressive strength and water absorption among the studied samples. Tukey’s test also showed differences among some samples in the properties related to mineral composition and the physical structure of the material. The correlation coefficient matrix further demonstrated relationships among several of the studied variables, with positive correlations observed among some physical properties such as released gas volume, carbonate content, and bulk density, while some negative relationships appeared with water absorption and compressive strength. These results indicate that the manufactured samples were largely successful in reproducing the physical and mechanical properties of the original brick, with some differences related to mineral composition and the internal structure of the material. This study confirms the importance of statistical analysis in evaluating the properties of archaeological building materials and in understanding the relationships among their different components. It also contributes to the development of experimental models that can be used in restoration studies and in the conservation of historic buildings.

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