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Thermal Behavior Assessment of Natural Stone Buildings in the Semi-Arid Climate

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Abstract

This paper aims to assess the effects of harsh climatic conditions' interactions with natural stone on thermal inertia properties and the thermal performance of ancient residential buildings. As the type of stone differs, its thermo-physical components differ; therefore, its interactions with environmental factors vary. For this purpose, an experimental measurement was conducted on many buildings with different orientations in a semi-arid climate and validated by a simulation performed by the "EnergyPlus 9.3" software. Results showed that the important outdoor temperature gap between day and night influences the natural stone thermos-physical properties used in construction. The stone components affected by the thermal shock effect weathering are eroded over time, then saturated with water, and affect the thermal conductivity coefficient of stone; however, this directly changes the indoor thermal comfort and performance of buildings. Additionally, the high indoor relative humidity percentage and the absence of natural ventilation have an important influence on the ambient temperature values recorded. This paper discusses the experimental measurement results compared to the simulation results.

KEYWORDS

Thermal performance, building envelope, thermal inertia, limestone, Tébessa, Algeria

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1. Introduction

Currently, global warming is hardly disputed by the international scientific community since significant effects can already be observed on a global scale. Indeed, it is noticed that there is a rise in the average temperature of the atmosphere and the oceans, massive melting of snow and ice, and rising sea levels. According to the latest forecasts from the Intergovernmental Panel on Climate Change (IPCC), the Earth could experience global warming from 1.8 C° to 4 C° by 2100 if no action to reduce greenhouse gases (GhG) is taken (Kaemmerlen, 2009). Otherwise, with globally excessive energy consumption, the demand for energy saving strategies increases (El-Darwish and Gomaa, 2017).

Algeria, like other countries, aims to reduce energy consumption in several sectors, with the buildings sector as the largest overall energy consumption consumer, accounting for more than 60% (Djedouani *et al.,* 2020). Since ancient buildings' renewal rate is low, this objective can only be achieved through a massive effort of thermal improvement to reduce heating and cooling energy consumption. Therefore, it becomes necessary to optimize the energy performance of ancient buildings, especially those built with local materials and traditional techniques before the first thermal regulations in 1974 and when no performance criteria matched current standards (Rabouille, 2014).

In other words, buildings should have a high energy performance to decrease their energy consumption. Nevertheless, this issue is complex and multidimensional as it spans building envelope performance, indoor environmental conditions, and user demands (Košir, 2016). One might argue that the main goal of a building is to provide an environment acceptable to building users (Hensen, 1991). The building skin is the physical barrier between the external environment and the internal conditioned space. The building envelope consists of doors and windows, a roof, walls, and insulating materials to prevent heat transfer from the interior to the exterior in the winter and vice versa in the summer. (El-Darwish and Gomaa, 2017). Since the building envelope separates the external environment from the internal space, it is one of the key factors affecting the buildings' energy consumption (Hailu, 2021). Thus, improving the energy performance of the building envelope improves the energy performance of the whole building.

For ancient buildings, which are the subject of our study, the major passive method used to control the indoor environment and store energy was to construct thick walls built on heavy construction materials to induce their thermal inertia parameter. Systems with the highest thermal inertia are considered the lowest energy systems (Orosa and Oliveira, 2012). This parameter contributes to creating favorable indoor thermal comfort conditions without using cooling and heating energy. The building walls store the thermal energy during the daytime then release it during the night, especially in climates with high diurnal temperature fluctuations (Verbeke and Audenaert, 2018).

In most cases, thermal inertia is defined as how quickly a building reacts to external disturbances. A building's response to the solicitation depends largely on the thermal properties of the construction materials. Buildings will react differently depending on their ability to store and transport heat. Therefore, there is a coupling problem between thermal conductivity (λ), heat capacity (C), and density (ρ), which introduces the two concepts of thermal diffusivity and thermal effusivity.

$$\text{Thermal diffusivity} = \lambda / \rho C \ [m^2/s] \quad (1)$$

$$\text{Thermal effusivity} = \sqrt{(\lambda \rho C)} \ [J/m^2.K.s.1/2] \quad (2)$$

Thus, thermal inertia depends on environmental interactions with the building construction materials, which relate to several parameters such as their thermos-physical properties, disposition within the building envelope, the architectural characteristics of the building, and the climatic conditions (Chahwane, 2012). All these properties affect thermal performance. Therefore, controlling the thermo-physical characteristics of the construction materials of the building envelope assists in reducing energy consumption (Aste *et al.,* 2009).

In this respect, many studies have proved the thermal inertia parameter effectiveness in the field of building energy storage and interior thermal comfort. However, it is clear in northeastern Algeria, specifically in the Tébessa province, which is influenced by a semi-

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arid climate, that ancient buildings consume more energy than modern buildings, which were built with new and lightweight construction materials. This refers to some inconsistencies. Hence, this paper will discuss climatic factors' impact on thermal inertia and, thus, on the energy performance of these ancient buildings. This process requires studying buildings' thermal performance to understand the effect of each parameter and find the best thermal improvements regarding building orientation.

Many authors have conducted quantitative studies on the behavior of ancient buildings and confirmed that reducing the energy demand and regulating indoor thermal comfort is influenced by several parameters such as construction materials (Rais *et al.,* 2021). In addition, a study by Evola *et al.* (2017) compared, using experimental measurements and dynamic simulations, the thermal behavior of modern and traditional envelopes and showed that ancient buildings are often characterized by high thermal inertia due to the thickness of the walls. Indeed, the relative impact of this phenomenon is influenced by several factors, including climate, especially in arid and semi-arid climatic contexts, where the recorded temperature degrees considerably vary.

If harsh climatic conditions affect the thermal performance of construction materials, then Boumezbeur *et al.* (2015) proved that harsh environmental factors affect the natural stone used in construction in Tébessa, consequently changing and decreasing their mineralogical contents and properties and decaying their texture. As the type of stone differs, its thermo-physical components differ; therefore, its interaction with environmental factors varies. On this account, the objective of the current research is to define the impact of harsh climatic conditions of cold semi-arid contexts on the thermal properties of stones used in ancient building construction and its effect on a building's thermal inertia. This work contributes by improving thermal performance response to energy challenges while ensuring the thermal comfort of a building's users.

1. Case Study

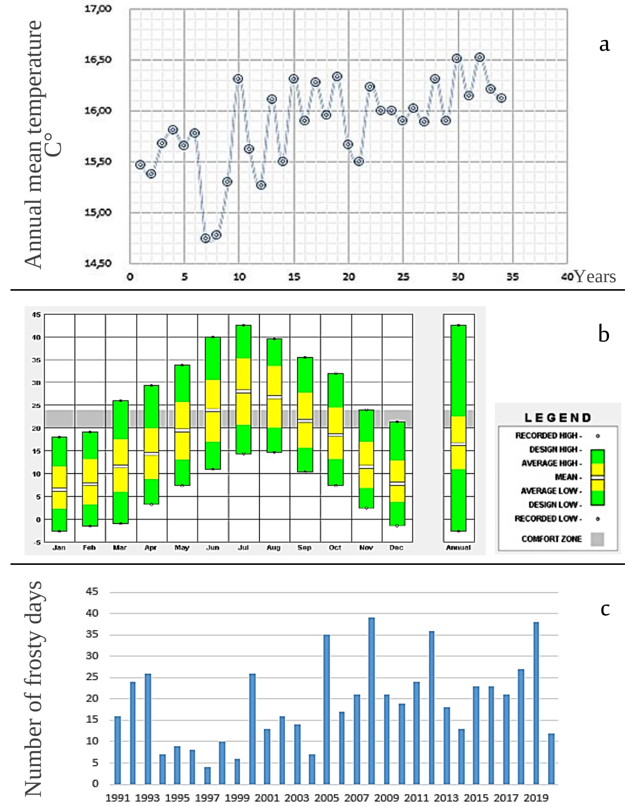
1.1. The Climatic Context:

This study focuses on residential buildings built in the colonial district of Hammamet city in the Tébessa province of northeastern Algeria. This region is influenced by a semi-arid cold climate Bsk, according to the Köppen-Geiger climate classification based on annual and monthly mean temperature and precipitation values (Szabó-Takács *et al.,* 2019). Figure 1(a) shows that the annual mean winter temperatures recorded by the meteorological station of Tébessa over 30 years do not exceed 18 C°, supporting Kottek *et al.* (2006). They explained that this climate is determined by the annual mean temperature, which should be less than 18°C, while the accumulated annual precipitation is more than a 5 mm dryness threshold; this last part depends on the annual precipitation cycle and the annual mean temperature. It is calculated by:

$$\text{Dryness threshold} = \begin{cases} 2\{\text{annual mean temperature}\} & \text{if at least 2/3 of the annual precipitation occurs in winter.} \\ 2\{\text{annual mean temperature}\} + 28 & \text{if at least 2/3 of the annual precipitation occurs in summer.} \\ 2\{\text{annual mean temperature}\} + 14 & \text{otherwise.} \end{cases}$$

Indeed, this semi-arid climate is characterized by different temperatures between day and night. The data climate from Tébessa's meteorological station for 30 years, illustrated in Figure 1(b), shows that January is the coldest month, with a mean temperature of 6 C°. The minimum average temperature is around 3 C °, and the maximum average temperature is around 11 C°. Additionally, the lowest temperature recorded during this month is -3 C°, while the average number of frosty days is 19 days a year (Figure 1[c]).

Fig. 1. Data climate of Hammamet, Tébessa; The annual mean temperature in Hammamet, Tébessa (a); Temperature range in Hammamet, Tébessa (b); Number of frosty days in Hammamet, Tébessa (c).



The region's precipitation is low at 342.5 mm, with March representing the wettest month with an average of 44.8 mm of precipitation. July is the hottest and driest month, with an average temperature of 27C° and average precipitation of 11.3 mm, as shown in Table 1.

Table 1. Average monthly precipitation in Hammamet, Tébessa.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Precipitation mm (in)	27.1 (1.07)	30.3 (1.2)	44.8 (1.8)	30.6 (1.2)	36.5 (1.4)	31.2 (1.2)	11.3 (0.4)	25.1 (1)	29.4 (1.2)	23.6 (0.9)	29 (1.1)	23.6 (0.9)	342.5 (13.5)

1.2. Energy Consumption:

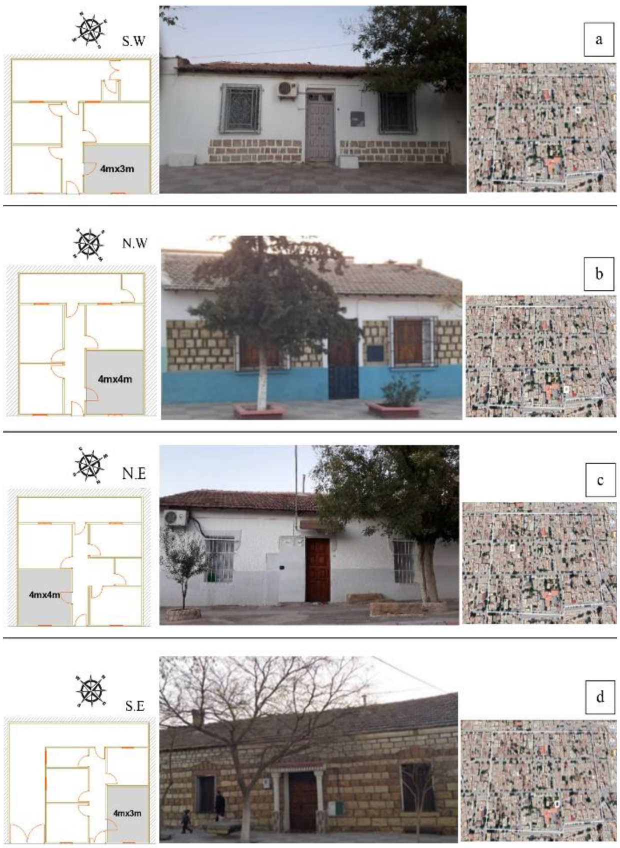
Recent research has proved that buildings' energy consumption is affected by climate. A study by Guedamsi *et al.* (2016) shows three climatic zones in Algeria according to heating energy consumption costs. In Tébessa, the cost of thermal energy requirements for heating is in the second zone due to their harsh winter conditions. According to the Algerian Industrial Energy Company, which specializes in the distribution of electricity and natural gas, the case study shows high energy consumption, while the heating energy consumption in the district study accounts for 11,037.6 m^3 per year of each residential building compared to the 1012 m^3average yearly gas consumption of a residential building. However, it is important to emphasize some contradictions in this case considering the characteristics of natural stone buildings to reduce energy consumption.

1.3. Case Study Description:

All the residential buildings in the studied colonial district are built of natural stone extracted from the Gaagaa quarry in Hammamet, Tébessa, during Algeria's colonial period (before the first thermal regulations in 1974). To cover all possible cases, the four residential buildings on the ground floor, denoted by Building 1, Building 2, Building 3, and Building 4 with different orientations, were chosen as studied buildings in this research, as shown in Figure 2.

All buildings contain three rooms, a kitchen, and a bathroom at a height of 3.20 m. They are covered with a sloped tile roof using wood supports, while the roof punch height is 1 m distance from the false ceiling to the ridge board. The openings are made of 0.03 m thick wood, and the door measurements are 2.20 m×0.9 m. The window measurements in Building 1 and Building 2 are 1.20 m×1.20 m, and the window measurements of Building 3 and Building 4 are 1.50 m×1.20 m. Figure 2 shows the buildings' details and the room where the experimental measurements were performed.

Fig. 2. Details of buildings studied (Room studied, Facade of building, Location, and Orientation); Building 1 (a); Building 2 (b); Building 3 (c); Building 4 (d) (Source the author, 2021).



This study is conducted on the facade of each building to study the stone wall thermal behavior in this climatic context. The details of the interior and exterior construction materials and their thermos-physical properties are illustrated in Table 2.

Table 2. Thermos-physical properties of the facade materials.

Materials	Layer thickness [m]	Conductivity [w/m.k]	Specific heat [kJ/kg.k]	Density [kg/m3]
Plaster coating	0.02	0.57	1008	1150
Cement mortar	0.03	0.80	850	1900
Naturel stone	0.30	1.40	1000	2475
Cement mortar	0.03	0.80	850	1900
Plaster coating	0.02	0.57	1008	1150

3. Materials and Methods

Three studies were carried out to understand and evaluate the thermal behavior of the natural stone buildings, starting from the measurement in situ to the chemical analyses to determine the stone type samples, then the validation and the verification of results with the energy simulation.

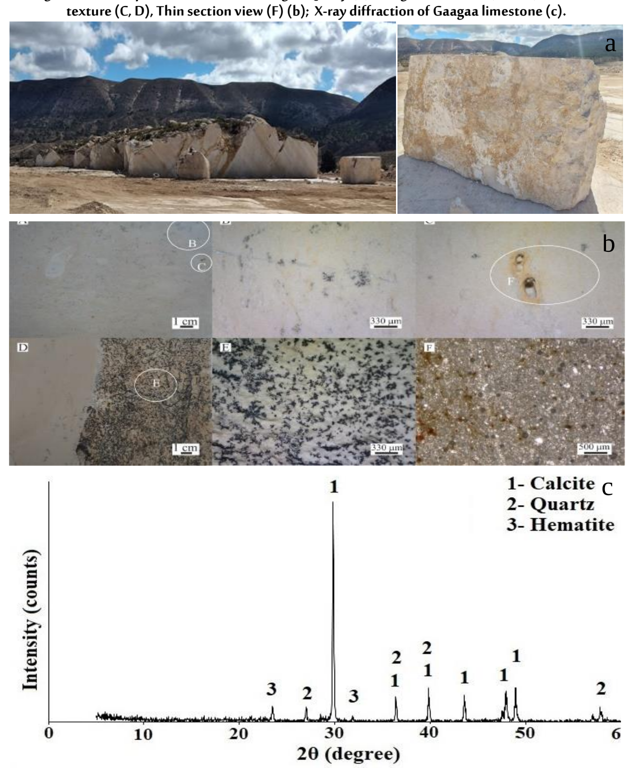
3.1. Determination of Stone Type:

Two methods can be used to classify natural stone. First, the classification of natural stone types according to geological origin, which are igneous rocks, sedimentary rocks, and metamorphic rocks. The second is based on an implementation basis, such as strength characteristics, hardness, porosity, color, and durability (Tumac and Shaterpour-Mamaghani, 2018). In general, igneous rocks, sedimentary rocks, and metamorphic rocks are classified according to their genesis, structure, texture, and mineral composition.

The visual inspection of the studied samples shows that they are classified as sedimentary rocks. Since sedimentary rocks can be of detrital, chemical, or biochemical origin, a chemical analysis is considered the best method to determine the stone type by revealing its chemical components. For this purpose, many laboratory studies were carried out to analyze the stone samples.

To determine the mineralogical and petrographic properties of the Gaagaa stone, sampling was completed to represent the general quarry, and five thin sections were prepared. According to TS EN 12407 (2019), mineral percentages were determined by making a petrographic analysis of the thin sections at 10X magnification of crossed nicol, using an Olympus BX41 polarizing microscope. The chemical properties of the stone belonging to the Gaagaa quarry and its main oxides (%) were determined in the Acme laboratory (in Canada), using the Inductively Coupled Plasma Emission Spectrometer (ICP-ES) method. Additionally, X-ray diffraction techniques were used to determine the mineralogical composition of the Gaagaa stone.

Fig. 3. Stone samples extracted from Gaagaa Quarry (a); Gaagaa limestone (A, B, C) Dendritic texture (C, D), Thin section view (F) (b); X-ray diffraction of Gaagaa limestone (c).



The stone from the Gaagaa quarry (Figure 3[a]) has the appearance of a carbonate rock with a pinkish light-yellow color, sometimes with brown and black spots (Figure 3[b] A, B, and C). Closed discontinuities are rarely observed in the stone (Figure 3[b] D). When these discontinuity planes are opened, a black dendritic texture predominates along the discontinuity surface (Figure 3[b] E). In the petrographic analysis of the stone, the main mineral component is calcite (90%), accompanied by a small amount of quartz (5%). Brown spots observed on the surface of limestone at the macro scale are recognized as iron oxide in the petrographic analysis. Bioclasts observed in the stone are lamellibranch remains and spicule fossils of echinoids, ostracods, rudists, and gastropods. The stone from the Gaagaa quarry is a fine-grained biomicritic-biosparitic limestone with varying pore sizes and geometry.

Chemical compositions of the Gaagaa stone are given in Table 3. The stone contains two main oxides: calcium oxide (CaO; 52.58%) and silicon dioxide (SiO2; 4.51%). The ignition loss value of the Gaagaa stone is 41.7%. The main crystalline compounds found were calcite, quartz, and hematite by the X-ray technique (Figure 3. [c]).

Table 3. Percentages of major element oxides in the Gaagaa limestone.

SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3	Ba	Ni	Sr	Zr	Y	Nb	Sc	*LOI	Sum
%											ppm							%	
4,51	0,34	0,14	0,37	52,58	0,14	0,03	0,02	0,07	0,02	0,004	8	<20	1104	7	5	<5	<1	41,7	99,97

The Gaagaa limestone is a highly porous, low-density limestone. Compressive strength, bending strength, and abrasion resistance are sufficient for general construction purposes, but its high porosity leaves it highly vulnerable to environmental effects (Djedouani *et al.,* 2021). The material properties of the Gaagaa limestone are given in Table 4.

Table 4. Material properties of the Gaagaa limestone.

Property	Standard	Mean ± Standard deviation
Apparent density - kg/m3	TS EN 1936	2475 ± 41
Open porosity - %	TS EN 1936	5,948 ± 0,873
Real density - kg/m3	TS EN 1936	2670 ± 4
Total porosity - %	TS EN 1936	7,302 ± 0,23
Water absorption -%	TS EN 13755	2,349 ± 0,383
Uniaxial compressive strength -MPa	TS EN 1926	132.76 ± 17,25
Flexural strength - MPa	TS EN 12372	9,59 ± 1,82
Böhme abrasion -mm3	TS EN 14157	24226 ± 1796
Sound speed - m/s	TS EN 14579	3782 ± 136
Hardness (mohs)	TS TS 6809	2.5-3

The age of the limestone is Turonian. Many researchers stated that the Turonian limestone, which is widely distributed in the region, was also used in the construction of historical buildings in Tébessa and that this stone is very sensitive to weathering due to environmental effects (Boumezbeur *et al.,* 2015; Nasri *et al.,* 2018).

3.1.1. The Measurements in Situ

This investigation was carried out during the winter to evaluate the thermal behavior of natural stone buildings at this time. The coldest measurement days were determined by the representative week and day method, "design week and day." It was calculated with the meteorological data of Hammamet, Tébessa, especially its temperature values. It determined the average daily temperature of the coldest month (January) over 30 years to obtain the average outdoor temperature for each day in the month, then the lowest value of the average temperature was matched to the coldest day (Khadraoui *et al.,* 2018). Table 5 shows that the third week in January (in blue) is the coldest week of the year in Hammamet, Tébessa province.

Table 5. Design week and design day.

January	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	202	Averag
1	8,5	3,5	5	7	13	19	13	8,5	6,5	1	6	7,5	8	3,5	5	7,5	6,5	5	8,5	11,5	7,5	8,5	7,5	6,5	6,5	10	6,5	7	6,5	1,5	7,40
2	7,5	4,5	4,5	8,5	7	16	15	8	5	3	8,5	7,5	11,5	4	6,5	5,5	5	5,5	9,5	9	7	8	2,5	7	6,5	10	4,5	6	8	5	7,20
3	7,5	4,5	4,5	11,5	2,5	14	13,5	8,5	7,5	5,5	8,5	10	15	4	6,5	4	6,5	8,5	8	10,5	6,5	7	7	9	7	11	6	11	7,5	6	7,97
4	7,5	3	0,5	11,5	3	15	7	10	8,5	4,5	8,5	4,5	12,5	4	6,5	3,5	6,5	9	6	12,5	6,5	7	6,5	10,5	6,5	12,5	6	13	4,5	2	7,30
5	5,5	3	1,5	10,5	2,5	21	6	10,5	8	5,5	11	2	11,5	3,5	7	2,5	8	7,5	5,5	13,5	7,5	8	6	9,5	6	14,5	7,5	6,5	4	6	7,38
6	4,5	3	4,5	9,5	4	16	8	10	8,5	5,5	14	1	12	5,5	5	5,5	9	7,5	5	12	9	7,5	6,5	8,5	6,5	9	4,5	12	7,5	6	7,57
7	6,5	4	5	11,5	4	20	5,5	8	8,5	2,5	11,5	2,5	9	6,5	4,5	4,5	8,5	7,5	6,5	11	12	5,5	6,5	9	8	10	4	11,5	5,5	4	7,45
8	7	6	4	1	1,5	16	6,5	8,5	10	4,5	6	3,5	9,5	4	6,5	5	7	8	6	9	12	7,5	5,5	11,5	6,5	12	4	13,5	3	4,5	6,98
9	7	6,5	5,5	4	2	19	11	9	9	4	7	5	6,5	7,5	7	4	6,5	9	7	3	10,5	5,5	6	11,5	7	12,5	5	7	5	6,5	7,20
10	9	8	7	7,5	3	20	7,5	9,5	5,5	4,5	6	6	3	11,5	7,5	4,5	10	9,5	4,5	3,5	8,5	6,5	11,5	8,5	9	11,5	4,5	5	4,5	5	7,40
11	9,5	7	8	6	8	11	4,5	7,5	5,5	4	10,5	7	1,5	10	7	3,5	10	9,5	4	7,5	6,5	5	9	8	9	13,5	4,5	9	2	5	7,10
12	10	8	9	5,5	6,5	12	6	7,5	6,5	2,5	11	4,5	4	10,5	4,5	4,5	7	7	6,5	8	7,5	6	7	8,5	7,5	10,5	5,5	6	2	[illegible]	6,93
13	5	5	8	9	0,5	11	7	11	10,5	1	7,5	4	1,5	12	7	3,5	10	5,5	7,5	9,5	8,5	7	7,5	10	8,5	8,5	6	6	4	[illegible]	6,92
14	3	6,5	8,5	8,5	-1	12	6,5	7	9,5	2,5	7,5	5	4,5	11,5	6,5	5	10	7,5	7	10,5	9,5	5	7	7,5	11	10	5	6	8,5	[illegible]	7,10
15	6	6	6	7,5	0,5	14	6,5	5,5	8,5	4,5	7,5	8	4,5	7,5	6	3,5	12	10	6	7	9,5	6,5	5	5,5	11	11,5	3	7	7	[illegible]	6,92
16	5,5	7	7,5	6,5	2,5	15	7	6	7,5	5	7	5,5	9	6,5	4	4	10	7,5	6	6	10	6	7,5	8	7	3,5	2	4,5	6,5	[illegible]	6,48
17	6	4,5	6,5	6,5	2,5	11	9,5	5	8,5	3	7	4	9	8,5	5,5	4	9	8	7	8	10	5	10	10	6	1,5	1	4,5	6	[illegible]	6,38
18	4,5	3,5	6	7,5	4	9	8,5	6	6	4	8,5	5,5	7	8,5	6	5	7,5	6	8	9	7	5	8,5	11,5	6	6,5	2	7	3,5	5	6,40
19	5,5	3,5	6	8,5	7,5	7	7,5	8	5,5	5,5	10	4,5	8	5	4	4,5	7	9,5	7	7	8	5,5	12,5	9,5	6,5	5,5	7	8,5	4	6	6,80
20	2	4	5	7	8	11	11	10,5	6,5	2,5	6,5	4	7,5	5	4	8	11,5	9,5	10,5	10	5,5	3	8,5	7	6,5	7	4,5	9	5	[illegible]	6,98
21	5	4,5	4,5	6	7,5	13	14	4,5	8	3,5	6	8,5	7	5,5	8,5	7,5	12	9	6,5	6,5	8	6	10,5	7	5	6,5	5,5	9,5	8	[illegible]	7,47
22	4,5	6	3,5	6	8	13	12	4,5	8	4	8,5	7,5	8	7	8	5	10,5	7	7	7,5	3	7	8,5	7	6,5	7,5	6,5	12	3,5	11	7,27
23	5,5	7	4	7	9	15	12,5	4	7	3,5	9	9,5	6,5	8	7	5	11,5	8,5	10,5	6,5	3,5	7,5	7	7	4	7,5	5,5	9	2,5	[illegible]	7,42
24	5,5	6	5	5	8,5	15	10	5,5	7	5	11	9,5	5	8	6	2	6	5	13	10	6	9,5	6	8	4,5	6,5	4,5	5	3	[illegible]	7,05
25	6	0,5	4,5	5	10,5	14	10,5	5,5	6,5	6	12,5	7,5	3,5	9	1,5	3	8	4	9	8,5	8,5	8,5	5	7	5,5	8	4	5,5	1,5	6	6,50
26	8,5	2,5	5,5	7	11,5	10	8	5	6	8	8,5	6,5	4	12	0	2	10	4	8,5	9	7	8	5	8,5	3	9	6,5	8,5	4	[illegible]	6,82
27	6	4	4	6	8	14	13	5	5	8	7,5	7	4,5	9,5	1	6,5	7	6	4	8,5	11,5	8	6,5	8,5	5	10,5	7	8,5	7,5	6	7,12
28	6	5,5	5,5	6	9	16	9	7	8	3,5	11	8,5	7,5	8	0,5	10	7,5	6	6	8	10	7	5,5	6	5,5	9,5	7,5	8,5	5,5	7	7,35
29	4,5	6,5	6,5	7	10	11	9,5	10	7	10,5	6,5	12	9	4,5	3	11	9,5	9,5	7,5	6	9,5	6,5	7,5	5,5	7	8,5	6	7,5	5	[illegible]	7,75
30	5	6	8,5	5,5	10	11	8	8	4,5	9	4,5	13	4,5	5,5	2,5	7	12,5	8	9	7,5	9	2,5	7,5	10,5	8,5	8,5	7,5	6	6,5	[illegible]	7,55
31	4	4	7	9	10	13	8	11,5	-1	9	4,5	13	3	7,5	2	4,5	11	7,5	8,5	7,5	6	4	12,5	4	14	7	7,5	4,5	7	11	7,37

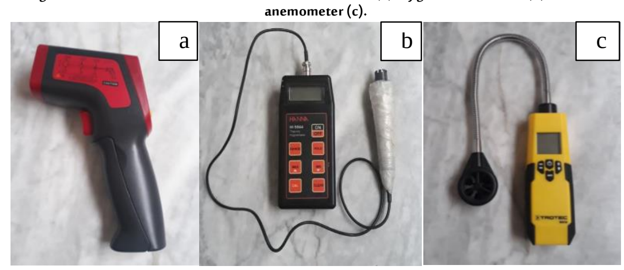
3.1.2. Presentation and Protocol for Taking Measurements

The measurements were taken twice every hour for three days in January (the 16th,17th, and 18th), 2021. The windows were opened every morning for one hour to simulate the residents' behavior from 9:00 h to 10:00 h, while all doors were closed throughout the measurement period. The measurements were taken in the living room in natural conditions and without any heating system while the dwelling was uninhabited to ensure that protocol was carried out in passive control systems.

3.1.3. Measurement Instruments

To conduct measurements, three types of instruments, illustrated in Figure 4, were used in this investigation. An infrared thermometer was pointed at the middle of the studied wall to measure the internal and external surface temperature. In addition, the hygrothermometer measured the air's moisture content to determine its relative indoor and outdoor humidity and ambient temperature. The thermal anemometer was used for measuring the indoor and outdoor wind speed and installed in the middle of the studied room 1.5 m above the floor.

Fig. 4. Measurement instruments; Infrared thermometer (a), Hygro-thermometer (b), Thermal anemometer (c).



3.2. The Energy Simulation:

A thermal dynamic simulation with the "EnergyPlus 9.3" software was used to validate the experimental results of the thermal behavior of the natural stone buildings. A climate file based on the Tébessa meteorological station was generated by the "Meteonorme 7" software in "epw" format and used in this simulation. The simulation was conducted according to experimental measurement protocol, where each space represents a thermal zone. Additionally, no outside obstructions were introduced because the opposite buildings did not cast shadows on the facade of the studied buildings.

4. Results and Discussion

The three main thermal comfort parameters of temperature, relative humidity, and wind speed were measured to study the thermal performance of the natural stone buildings.

4.1. Results of the Measurements in Situ:

Figure 5 illustrates the measurements in situ obtained for all buildings studied. It was revealed that the different building orientations did not affect the results obtained where all the graphs of the external surface temperature are slightly different. As the building orientation changes, the heat gain of walls changes, depending on how long it is exposed to the sun during the day. Thermal inertia consists of the accumulation of heat in the envelope for restitution inside by radiation. The complexity of this phenomenon lies in the fact that the heat flow through the envelope successively increases material temperatures (Chuayb, 2015), which affects their thermo-physical properties, but not the thermal inertia of the envelope.

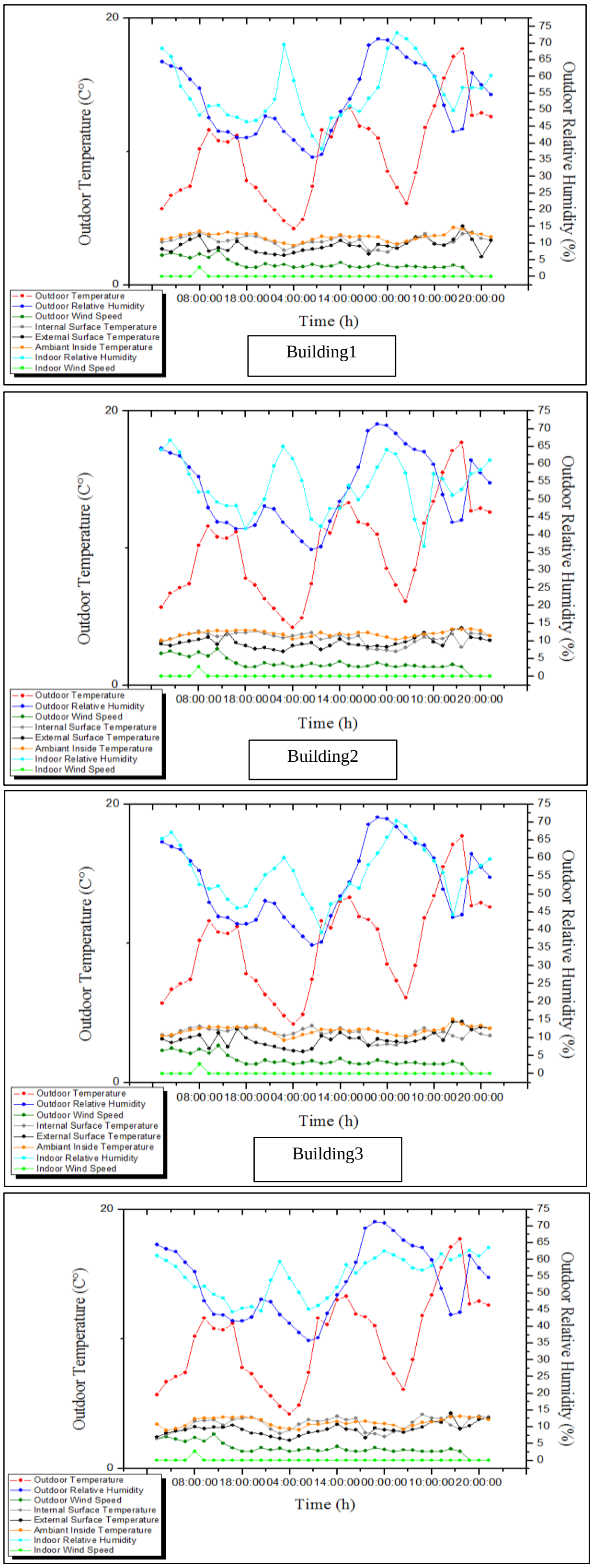
It was observed that the outdoor temperature increases during the day and then significantly decreases at night in a short period (less than12 hours). The maximum value of 11.6 C° was recorded at 10:00 h on the first day. On the second and third day, the highest recorded temperatures were 13.3 C° and 17.7 C° at 16:00 h. The lowest temperature was recorded on the first day (5.7 C°) at 00h. The values of 4.2 C° and 6.1 C° were record on the second and third days at 16:00 h.

The temperature difference between day and night reached 5.7 C°, 9.1 C°, and 11.6 C° each day, respectively. This important gap significantly influences the limestone used in construction because the heating and cooling of this stone type affect its components. As a result, it deteriorates and erodes; this is called the thermal shock effect weathering (Yavuz *et al.,* 2006).

The indoor relative humidity rises at night to 73.1% in Building 1, 66.7% in Building 2, 70.3% in Building 3, and 63.5% in Building 4. It decreases during the day to 38.2% in Building 1, 36.2% in Building 2, 39.2% in

Building 3, and 44.3% in Building 4. There was a coherence between the indoor and outdoor relative humidity, which reached a maximum value of 84% at night and a minimum value of 24% during the day.

Fig. 5. Results of the measurements in situ of the buildings.



These high indoor relative humidity values were due to the water saturation of the limestone used in construction. The components affected by the thermal shock effect weathering are eroded over time, then filled with water coming from the sub-basement of the building (Nguyen *et al.,* 2020).

On the other hand, it was revealed that the ambient inside temperature values were low compared to the outdoor temperature values over the three days in the four buildings. The values recorded in Building 1 ranged from 14.7 C° to 9.3 C°, 13.4 C° to 10.1 C° in Building 2, 15.1 C° to 9.3 C° in Building 3, and 13.1 C ° to 8.9 C ° in Building 4. It was noticed that these values are lower than the standards recognized in the thermal comfort of residential buildings. The highest outdoor temperature recorded in the last two days was at 16h, while the highest ambient inside temperature recorded was at 14h, 18h, 20h, and 20h in Building 1, Building 2, Building 3, and Building 4, respectively, with a maximum difference of four hours between the two peaks. This low thermal phase shift reduces the thermal inertia of buildings (Yam *et al.,* 2003).

The external and internal surface temperature curves in the four cases are almost the same as the ambient inside temperature. It was noticed that there was a considerable coherence between them. The values of the external surface temperature recorded in Building 1 range from 15.1 C° to 5.9 C°, 13.6 C° to 7 C° in Building 2, 14.5 C° to 6.2 C° in Building 3, and 14.1 C ° to 6 C° in Building 4. The values of the internal surface temperature recorded in Building 1 range from 13.3 C° to 7.3 C°, 12.8 C° to 7 C° in Building 2, 13.3 C° to 7.8 C° in Building 3, and 13.7 C° to 6.4 C° in Building 4. A difference of two degrees was recorded between the external and internal surface temperatures in the day, while the highest difference of six degrees was recorded at night.

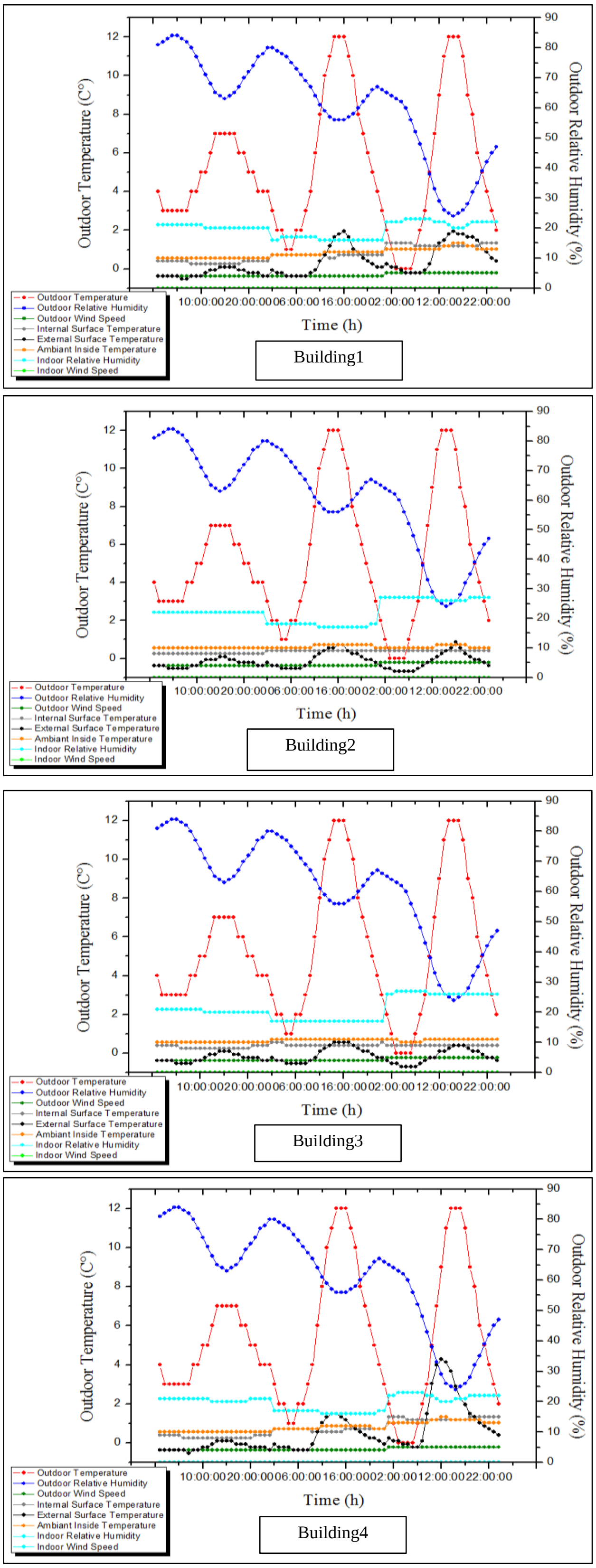
The convergence of these temperature results is due to the influence of the thermal shock effect weathering on the thermos-physical properties of the limestone, where this allows the voids caused by this phenomenon to be filled with water, and make the stone more conductive, knowing that the stone saturated with water has a higher thermal conductivity ecoefficiency than the dry stone. Consequently, the stone's thermal inertia decreases, as shown in this case study. Additionally, these buildings' thermal inertia is almost lower than natural stone buildings' usual thermal inertia.

However, it was revealed that the outdoor wind speed was rather high, ranging between 7.1 m/s and 2.7 m/s. The indoor wind speed of the four buildings studied is void over the three days, even when the windows were open in the morning, except the first day where the outdoor wind speed was estimated at 6.8 m/s at 8h, and the indoor wind speed was 2.7 m/s. The most important element noticed was a lack of good natural ventilation in the buildings during the day, except when the outdoor wind speed exceeded 6 m/s. The very high indoor relative humidity percentage and the absence of natural ventilation had a significant influence on the ambient inside temperature values (Sanchez *et al.,* 2016).

4.2. Results of the Energy Simulation:

The energy simulation results in Figure 6 of the outdoor temperature, the outdoor relative humidity, and the outdoor wind speed showed a strong agreement between the simulation and experimental results.

Fig. 6. Results of the energy simulation of the buildings.



The simulation outside temperature result differences, the outside relative humidity results, the outside wind speed results, and the experimental results are consequences of the gap between the measurements in situ values and the climatic file values (Khadraoui *et al.,* 2018), which has a direct influence on the external surface temperature and the internal surface temperature on the ambient inside temperature. In addition, it affects the indoor relative humidity and the indoor wind speed simulation results.

It is important to notice a certain coherence between the measured and simulated curves of temperature and wind speed parameters in the four buildings. The simulated indoor relative humidity curve is almost constant and does not exceed 27% in the four cases studied. This significant difference between the simulation and experimental indoor relative humidity results shows that the energy simulation does not consider the current degradation state of the natural stone used in these buildings, where the thermos-physical properties of the limestone used in the energy simulation are related to the normal state of the limestone. Thus, the thermos-physical properties' value changes due to climatic factors have an important influence on the simulation results. However, the simulated indoor relative humidity curves show the results of the relative humidity in the buildings built in natural stone in the normal state, without exposure to harsh environmental factors over time.

5. Conclusion

This paper analyzed the significant impact of harsh climatic factor interactions with the thermos-physical properties of natural stone used in construction on the thermal inertia of ancient residential buildings over time. The research results showed that building orientation does not affect the thermal behavior of the natural stone walls. Limestone showed weak resistance in the semi-arid climate under the important temperature gap between day and night. Its components were affected by the thermal shock effect weathering and saturated with water arising from the sub-basement of the building, causing an increase in the thermal conductivity coefficient; therefore, the thermal inertia and the thermal efficiency of the natural stonewall are reduced.

On the other hand, the results show a low thermal phase shift reducing the thermal inertia of buildings, the very high indoor relative humidity values recorded, and how the absence of natural ventilation affects the indoor thermal comfort, explaining the buildings' thermal performance decreasing. The wicked agreement between the experimental and simulation results is the consequence of the gap between the measurements in situ values and the climatic file values, and the difference between the currents thermos-physical properties of stone affected by the climatic context and the normal state of the thermos-physical properties.

6. Suggestions and Recommendations

More research is needed to study climate effects on natural stone durability used in construction and define suitable stone types in the harshest climates. All ancient natural stone buildings need a thermal correction to improve their thermal performance.

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