République Algérienne Démocratique et Populaire
Ministère de l'Enseignement Supérieur et de la Recherche Scientifique
Université 8 Mai 1945 Guelma

Faculté des sciences et de la technologie
Département d'architecture
Laboratoire de Génie Civil et d'Hydraulique

THÈSE

EN VUE DE L'OBTENTION DU DIPLOME DE DOCTORAT EN 3ème CYCLE

Domaine : Sciences et Technologie

Filière : Architecture　　　　Spécialité : Architecture

Présentée par

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Intitulée

Improving the thermal capacity of natural stone used in residential buildings (Case of Tébessa North-Eastern Algeria)

Soutenue le : 01/03/2022　　　　Devant le Jury composé de :

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Année Universitaire : 2021/2022

To my parents

To everyone who was by my side without reason, without conditions and without interests,

& everyone who stood by me, supported me and shared with me every moment,

To all those I love and those who truly loves me,

& the soul of every dear who left me,

To the one how believed in me

Acknowledgements

Foremost, I would like to thank ***God Almighty*** *for giving me the opportunity and guidance to achieving my goal and to be successful in this part.*

Throughout the writing of this thesis, I have received a great deal of support and assistance. This work is the result of the combined efforts of several people; I take this opportunity to express my gratitude to who have been instrumental in the successful completion of this research.

I would like to thank the funders who contributed to this work, ***The Ministry of Higher Education and Scientific Research of Algeria*** *in the framework of the scholarship National Exceptional program (P.N.E).*

I am deeply grateful to my supervisors ***Dr. Gherzouli Lazhar & Dr. Elçi Hakan*** *who accepted to welcome me in the natural stone laboratory of Torbali vocational school, university of Dokuz Eylul in Turkey to realize this work, thanks for their assistance at every stage of the research project.*

I would like to offer my special thanks to ***the jury members, Pr. Alkama Djamel, Pr. Laazri Youcef, Dr.Haridi Fatma Zohra, Dr. Ahriz Atef*** *who accepted to examine this work.*

Special thanks are extended to ***the LGCA Laboratory of Tébessa University & laboratory of Torbali vocational school university of Dokuz Eylul in Izmir, Turkey & laboratory of ACME Analytical in Canada****.*

I would like to extend my sincere thanks to all of the administrative organizations in Tébessa province, Algeria; ***The meteorological station, Directorate of Culture, Directorate of Mines, Sonelgaz, APC Hammamet, Gaagaa quarry administration,*** *for their contribution to enrich the work with very important data, information and statistics.*

I gratefully acknowledges the deepest gratitude to ***the families of the buildings studied,*** *without their comprehensive this thesis would not have materialized.*

I would like to thank ***the members of academia, laboratory assistants and librarians*** *of the* ***University of 8 Mai 1945 Guelma, Larbi Tebessi University and Dokuz Eylul University.***

In addition, I would like to thank ***my parents*** *for all they have given me; you are always there for me, and* ***everyone who directly or indirectly, contributed to this resounding success.***

Abstract

This research topic is part of the improvement of the living environment of the inhabitants and focuses in particular on the impact of the thermal characterization of natural stone used in the construction of individual housing in Tébessa on thermal comfort. It was realized that it was possible to ensure a good level of comfort, and that through the use of natural stone known by its thermal performance that allow to regulate the conditions of indoor environments (temperature and humidity) and thus ensure the comfort of occupants. Therefore, our thesis focuses on the improvement of the energy performance of the house by improving the thermo-physical characteristics and resistance to different external conditions (humidity, rain, wind, temperature variation) in the semi-arid climate context. This study aims to evaluate and optimize the effect of interactions between the harsh climatic conditions and the properties of natural stone on the thermal inertia and then on the thermal performance of old residential buildings. As the type of natural building stone differs, its thermo-physical components differ; therefore, its interaction with environmental factors varies. For this purpose, an experimental measurement was carried out on many buildings with different orientations in the semi-arid climate, validated by a simulation carried out by the software "EnergyPlus 9.3". The results showed that the significant difference in the outdoor temperature between day and night has an influence on the thermo-physical properties of natural stones used in construction. On the other hand, an experimental study was conducted in the laboratory on samples of natural stones used in construction in Tébessa, to determine their thermo-physical properties and assess the impact of factors of the semi-arid climate on their hygrothermal performance. The results showed that the components of the stone affected by the effect of thermal shock are eroded over time, then they are saturated with water and affect the coefficient of thermal conductivity of the stone, however, this directly affects the indoor thermal comfort and thermal performance of the building on the one hand. On the other hand, the high percentage of indoor relative humidity and the lack of natural ventilation have a significant influence on the ambient temperature values recorded. The improvement of the thermo-physical properties of natural stone by thermal correction enhances its thermal performance. Therefore, ensure the improvement of the thermal performance of the buildings studied and the adaptation of natural stone buildings built in Tébessa to its context to design sustainable housing that meets the requirements of the lifestyle in terms of comfort and livability in its environment.

Key words

Thermal performance ; Building envelope ; Natural stone ; Thermal comfort ; Semi-arid climate ; Hammamet Tébessa.

Résumé

Cette recherche s'inscrit dans le cadre de l'amélioration du cadre de vie des habitants et porte en particulier sur la caractérisation thermique de la pierre naturelle utilisés dans la construction de l'habitation individuelle à Tébessa. On a pris conscience qu'il était possible d'assurer un bon niveau de confort, et cela par l'utilisation de la pierre naturelle connus par sa performance thermique qui permettent de réguler les conditions d'ambiances intérieures (température et degré d'humidité) et d'assurer ainsi le confort des occupants. Donc notre thèse s'articule sur l'amélioration de la performance énergétique de l'habitation par l'amélioration des caractéristiques thermo-physiques et la résistance aux différentes conditions extérieures (humidité, pluie, vent variation des températures) dans le contexte climatique semi-aride. Cette étude vise à évaluer et optimiser l'effet des interactions entre les conditions climatiques difficiles et les propriétés de la pierre naturelle sur l'inertie thermique, puis sur la performance thermique des bâtiments résidentiels anciens. Comme le type de la pierre naturelle de construction diffère, ses composants thermo-physiques diffèrent ; par conséquent, son interaction avec les facteurs environnementaux varie. Dans ce but, une mesure expérimentale a été effectuée sur de nombreux bâtiments avec différentes orientations dans le climat semi-aride, validée par une simulation effectuée par le logiciel "EnergyPlus 9.3". Les résultats ont montré que l'écart important de la température extérieure entre le jour et la nuit a une influence sur les propriétés thermo-physiques des pierres naturelles utilisées dans la construction. D'autre part, une étude expérimentale a été effectuée au sein de laboratoire sur des échantillons des pierres naturelles utilisées dans la construction à Tébessa, pour déterminer leurs propriétés thermo-physiques et évaluer l'impact des facteurs du climat semi-aride sur leur performance hygrothermique. Les résultats montré que les composants de la pierre affectés par l'effet de choc thermique sont érodés au fil du temps, puis ils sont saturés d'eau et affectent le coefficient de conductivité thermique de la pierre, cependant, cela affecte directement le confort thermique intérieur et la performance thermique du bâtiment d'une part. D'autre part, le pourcentage élevé d'humidité relative intérieure et l'absence de ventilation naturelle ont une influence importante sur les valeurs de température ambiante enregistrées. L'amélioration des propriétés thermo-physiques de la pierre naturelle par la correction thermique renforcer sa performance thermique. Par conséquence, assurer l'amélioration de la performance thermique des bâtiments étudiés et l'adaptation des bâtiments en pierres naturelle construits à Tébessa à son contexte pour concevoir des habitations durable qui répond aux exigences du mode de vie en termes de confort et d'habitabilité dans son environnement.

Mots clés

Performance thermique ; Enveloppe du bâtiment ; Pierre naturelle ; Confort thermique ; Climat semi-aride ; Hammamet Tébessa.

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Nomenclature

A	Area of surface, in meter.
A_b	Water absorption at atmospheric pressure, expressed as a percentage.
C	Specific heat in J/kg-K.
D	Diffusivity, in meter per second.
d	Thickness of the material, in meter.
D_m	Change in mass, in percent.
E	Effusivity, in J/m^2-K-$s^{1/2}$.
*E*0	Dynamic elastic modulus of the specimens before the thermal cycles, in MPa.
*E*f	Dynamic elastic modulus of the specimens after the thermal cycles, in MPa.
*F*f	Flexural strength tested on the specimens subjected to thermal cycles, in MPa.
*F*r	Flexural strength tested on the reference specimens, in MPa.
m	Mass in gram.
M	Percentage of mass loss, in gram.
m_0	Mass of the dry specimen before the test, in grams.
m_2	Mass of the pycnometer filled with water, in grams.
M_0	Mass of the dried specimen in grams.
m_1	Mass of the dry specimen after the test, in grams.
m_1	Mass of the pycnometer filled with water and the ground specimen, in grams.
m_d	Mass of the dry specimen, in grams.
M_{d1}	Mass of the dried specimen with label before first cycle, in grams.
m_e	Mass of the specimen ground and dried, in grams.
M_f	Mass of the dried specimen with label, after 15 cycles, in grams.
m_h	Mass of the specimen immersed in water, in grams.

M_{h0}	Apparent mass of the specimen in water before starting the cycles, in grams.
M_{hn}	Apparent mass of the specimen in water at *n* cycles, in grams.
m_i	Successive masses of the specimen during testing, in grams.
M_n	Mass of the dried specimen after n exposure cycles in grams.
m_s	Mass of the saturated specimen, in grams.
M_{s0}	Mass of the saturated specimen after immersion in water and before starting the cycles, in grams.
M_{sn}	Mass of the saturated specimen at Nc cycles, in grams.
p	Total porosity of the specimen, as a percentage.
p_o	Open porosity of the specimen, as a percentage.
Q	Heat capacity in Joule.
t	Time in second.
T_1	Temperature at time $t_{1,}$ in second.
T_2	Temperature at time $t_{2;}$ in second.
T_{cold}	Cold Temperature.
T_{hot}	Hot temperature.
$v0$	Ultrasound pulse velocity (UPV) before the test, in km/s.
V_b	Apparent volume of the specimen, in milliliters.
V_{b0}	Apparent volume of the specimen before freezing, in milliliters.
V_{bn}	Apparent volume of the specimen at Nc cycles, in milliliters.
vf	Ultrasound pulse velocity (UPV) after the test, in km/s.
V_o	Volume of open pores of the specimen, in milliliters.
V_s	Volume of liquid displaced by the mass me, in milliliters.
ΔE	Change in dynamic elastic modulus of the specimen, in %.
ΔF	Change in flexural strength between reference and exposed specimens, in %.

ΔT	Difference in temperature, in kelvin.
Δv	Change in Ultrasound pulse velocity of the specimen, in %.
$\Delta \rho$	Change in open porosity of the specimen, in %.
λ	Thermal conductivity of the material, in W/m.K.
ρ	Density of the material, its density expressed in kg/m^3.
$\rho 0$	Open porosity before the test, in %.
ρ_b	Apparent density of the specimen, in kilograms per cubic meter.
ρf	Open porosity after the test, in %.
ρ_r	Real density of the specimen, in kilograms per cubic meter.
ρ_{rh}	Density of water, in kilograms per cubic meter.

Abbreviations and acronyms

IPCC	Intergovernmental Panel on Climate Change.
GhG	Greenhouse gases.
UN	United Nations.
UNCED	United Nations Conference on Environment and Development.
UNFCCC or FCCC	United Nations Framework Convention on Climate Change.
APRUE	National Agency for the Promotion and Rationalization of Energy Use.
EPC	The energy performance certificate.
K-G	Köppen-Geiger climate classification.
DTS	The dynamic thermal simulations.
CEN	European Committee for Standardization.
UPV	Ultrasound pulse velocity.

Scientific productions

Publications

Djedouani, R., Gherzouli, L. and Elçi, H. (2021). Thermal behavior assessment of natural stone buildings in the semi-arid climate. The Scientific Journal of King Faisal University: Basic and Applied Sciences, 22(2). DOI: 10.37575/b/eng/210043

International communications

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Djedouani, R., Elçi, H., Hacımustafaoğlu, R., Gherzouli, L. (2021 August). Roman historical building in Tébessa and natural stone used in their construction. *The 6th International Stone Congress (ISC 2021)*, Izmir, Turkey.

"Theory is when you know everything and nothing works, practice is when everything works and nobody knows why"

Albert Einstein

1. General Introduction

Currently, global warming is disputed by the international scientific community, since significant effects can already be observed on a global scale; a rise in the average temperature of the atmosphere and the oceans, a massive melting of snow and ice and a rise in sea level. According to the latest forecasts of the Intergovernmental Panel on Climate Change (IPCC), the Earth could experience a global warming of 1.8 C° to 4 C° by 2100 if no action to reduce greenhouse gases (GhG) was taken (Kaemmerlen, 2009). Therefore, with the excessive energy consumption worldwide, the demand for energy saving strategies increases (El-Darwish & Gomaa, 2017). In this respect, many countries around the world often discuss global warming and related climate change. An action plan of the United Nations (UN) "Agenda 21" is moving in the same direction. It is related to sustainable development in the 21st century and is the result of the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992. It is a similar plan with a global scope, focusing on all areas where people can directly affect the environment, this agenda has been adopted by countries and sub-national UN organizations, governments, and majority groups related to the issue. Another initiative is European Project 20-20-20, whose goal is for the whole planet to reduce energy consumption by 20 %, reduce carbon emissions by 20 % compared with the 1990 level, and increase the use of renewable energy resources by 20 % by the year 2020. (Hroudová & Zach, 2017).

In the other hand, energy consumption in the building sector accounts for the major part 40% of the world's annual final energy use, most of the energy consumption is used for space heating and cooling needs, for this reason, the action to reduce energy consumption in this sector is one of the priorities. Therefore, the directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 laid the foundation stone for the regulation of the energy performance of buildings, it focuses on establishing a common methodology, creating minimum standards for energy performance, energy certification and regular inspections.

In addition, many organizations are enacting new and often stricter regulations and directives with the aim of improving the energy performance of buildings and reducing the environmental impact of building materials. The most famous one is probably the "Kyoto

Protocol" that passed in 1997 and entered into force in January 2005 and September 2011. It is a protocol to the United Nations Framework Convention on Climate Change (UNFCCC or FCCC), its focus is on tackling global warming and the goal is to reduce and control the concentration of greenhouse gases in the atmosphere.

In Algeria, the building sector is considered as an energy-consuming sector par excellence, which a large quantity is used mainly to meet the needs of thermal comfort, heating and cooling. According to the National Agency for the Promotion and Rationalization of Energy Use (APRUE) report in 2009, the energy consumption of residential buildings in Algeria represents more than 40% of final consumption and far exceeds other sectors.

In the wake of residential buildings, the climate factors affect the materials used in their construction, therefore, the ancient building are characterized by their lack of thermal comfort, excess heat in summer and cold problem in winter, they are, in fact, big consumers of energy more than the modern residential buildings. On this account, the building envelope considered as the main responsible of the thermal comfort and energy consumption in the building, therefore, the buildings envelope is a major issue for the architect as well as for the engineer because it represents a place of interaction and exchange between the interior and exterior, where its performance depends especially on construction materials.

In order to correct the conceptual gap, between the performance of the construction materials used in the ancient building envelope and the climatic context over the time, several researches are part of an approach aiming at optimizing the thermal behavior of the building envelope. These studies have focused on the construction material properties of the envelope, to evaluate and improve it role in the energy performance of the building. In this context, several research, states that the adequate construction materials used in the building envelope allows to control the thermal exchanges between the interior and the exterior and thus to improve the thermal and energy efficiency of the building. The present research is part of this approach; it is based on the optimization of the ancient building envelope properties in order to improve the thermal ambience and reduce the energy needs of residential buildings in the semi-arid climate.

2. Research problematic

In fact, Algeria, like other countries in the world, aims to reduce the energy consumption used in several sector, especially the buildings sector, which is classified as the largest consumer of the overall energy consumption before transport sector 30.6%, and industry sector 22.7% in terms of the energy bill. According to the national energy balance, it accounts for 46.7 % (Djedouani, et al., 2020), divided into 7% for tertiary buildings and 39% for residential buildings as it shown in the Fig. 1 below.

There are many efforts trying to reduce the residential building energy consumption, this objective can only be achieved through a massive effort of buildings thermal improvement to reduce the heating and cooling energy consumption, where this strategy considered as the main source of immediately exploitable energy savings. However, it comes up against the difficulty of reconciling heritage protection and adaptation of the old buildings, therefore, the thermal rehabilitation of the ancient residential buildings, i.e. work on improving their energy performance, appears to be a major challenge for sustainable urban development.

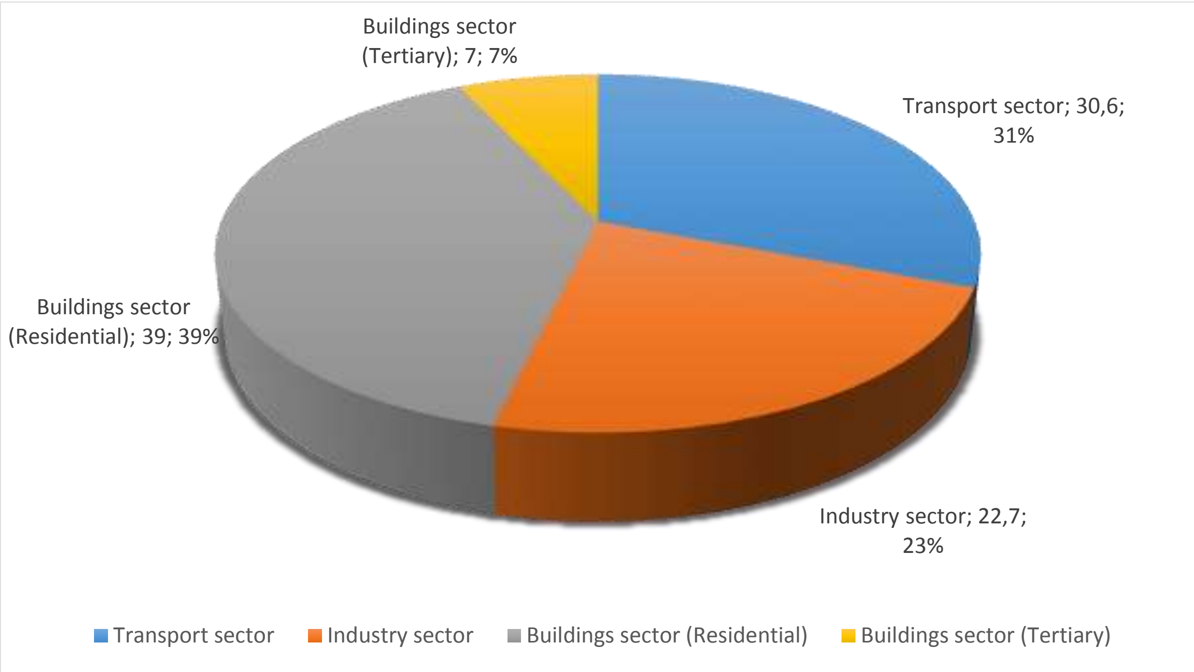


Fig. 1. Energy consumption of sectors in Algeria. *(Source: The national energy balance)*

In general, the modern buildings are built according to the thermal regulations; therefore, it does not considered as energy consuming compared to the ancient buildings in the harsh environment factors, which need a thermal rehabilitation occasionally. Since the rate of the building thermal improvement is very low in Algeria, it becomes necessary to optimize the energy performance of the ancient buildings especially, which were built with local materials and traditional techniques in the early 1900 s before the first thermal regulations 1974, when there was no performance criteria match current standards (Rabouille, 2014). It is interesting to note that these residential buildings represent more than 90% of the built environment in Tébessa Wilaya in Algeria; the region with a harsh climate, as is the case in the world, where the ancient stock exceeds the number of newly built buildings. While new constructions add annually 1% or less to the existing stock, the other 99% of buildings are already built and produce about 24% of the energy-use induced carbon emissions. Taking into account that the expectation for the structural life of a building often exceeds 60 years, while the envelope shows signs of obsolescence after only 20 or 30 years (Far, C., & Far, H.,2019). These buildings should have very high-energy performance and acceptable thermal comfort, which it related on its energy consumption.

As it is known, the main goal of a residential building is to provide an environment acceptable to building users (Hensen, 1991). Nevertheless, this issue is complex and multidimensional, as it is a cross section of the indoor environmental conditions, the inhabitant demands and the building envelope performance (Košir, 2016). The interaction of this last with its environment due to the different phenomena of conduction, convection and radiation generates important energy losses, where 30% of the heat escapes from a house through the walls which are the subject of our research, 25% through the roof, 10% or 15% through the windows and 7% or 10% through the floor as it shown in the Fig. 2. The big amount of the thermal exchange demonstrates the importance of improving the thermal performance of the building envelope.

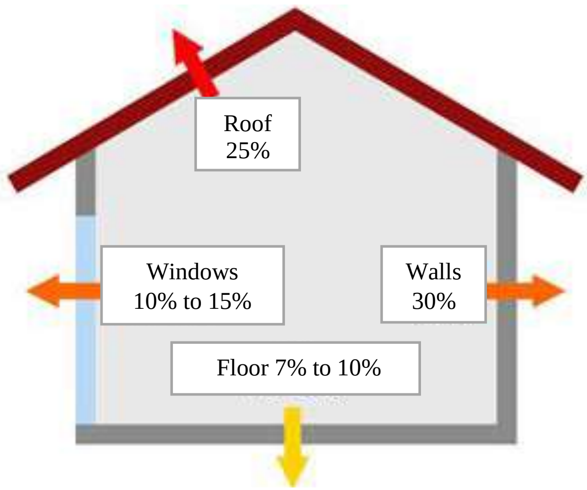


Fig. 2. Thermal exchange between building envelope and the environment. *(Source: The national energy balance)*

Moreover, envelope purpose is to prevent heat transfer from the interior to its exterior in winter and vice versa in summer, it still the physical barrier that separates the external environment and the internal space (El-Darwish & Gomaa, 2017), thus , it is considered as one of the key factors affecting the energy consumption of the building (Hailu, 2021). Thus improving the energy performance of building envelope, improve the energy performance of the whole building.

Many authors have carried out quantitative studies on the behavior of ancient buildings, confirmed that reduce the energy demand and regulate the indoor thermal comfort influenced by several parameters such as construction materials (Rais, et al., 2021). In addition, a study done by Evola et. al. (2017) compared, by means of experimental measurements and dynamic simulations, between the thermal behavior of modern and ancient envelope, showed that the ancient buildings is often characterized by a high thermal inertia due to the thickness of the walls.

In Tébessa Wilaya especially in the semi-arid climate region, which is the subject of our study in this research, all of the ancient buildings built on natural stone as local material. Where the major passive method used to control the indoor environment behavior of this buildings and storage the energy, were construction of the thick walls built with natural stone, the heavy construction materials, with the aim of valorization the building thermal inertia parameter, Leo Samuel et. al. (2017) proved this in their research, where they explain that increasing the thermal mass of the structure reduces the temperature fluctuation and delays the time when temperature extremes are reached, thus, the system with highest thermal inertia considered as the lowest energy system (Orosa & Oliveira, 2012).

In this respect, many studies proved the effectiveness of the thermal inertia parameter in the field of building energy storage and interior thermal comfort, these research confirmed that in terms of energy savings on the one hand, and thermal inertia on the other hand, stone walls are better compared to the other walls construction material. Besides, extensive research proved that the thermal inertia contributes to creating favorable indoor thermal comfort conditions without the need to use the cooling and heating energy, cause of the building walls stores the thermal energy during daytime, and then it dissipated during the night, especially in climates with high diurnal temperature fluctuations (Verbeke & Audenaert, 2018). Another study, conducted by Kazeoui et. al. (2008) showed that, in the harsh environments, buildings with local materials as natural stone offers better insulation and thermal comfort than modern materials in the hot and cold period.

Indeed, the thermal inertia parameter specifies how quickly the building reacts to external disturbances; therefore, the building’s response to the solicitation depends largely on the thermal properties of its construction materials, this is means that; according to their ability to store and transfer heat, buildings will react differently with the environment factor. Therefore, there is a coupling problem between the thermal conductivity (λ), the heat capacity (C), and the density (ρ) of the envelope materials, which introduces the two concepts of thermal diffusivity related to thermal inertia by transmission, and thermal Effusivity that related to the absorption inertia respectively.

On this account, controlling the thermos-physical characteristics of the construction materials of building envelope assist in reducing the energy consumption (Aste, et al., 2009). Moreover, the thermal inertia depends on the interactions of the environment with the thermos-physical properties of the building materials, it is related to several parameters such as their disposition within the building envelope and the climatic conditions (Chahwane, 2012), all of these parameters effect on the building thermal performance.

As long as, the climatic conditions affect the thermal performance of construction materials, especially in the regions influenced by the arid or semi-arid climatic context, where the recorded external temperature degrees is vary considerably, which affects the durability of construction materials, then its thermal inertia.; numerous studies was carried out in this respect, including a study done by Boumezbeur et. al. (2015) proved that the harsh environmental factors affect some type of natural stone used in historical construction in Tébessa over the time; consequently, this climatic factors changes and decreases their mineralogical contents as well as their properties and texture then the natural stone used get decayed. This defect contributes to reducing the building thermal efficiency; this done by reduce the resistance of the building envelope facing the harsh external factors.

Despite the importance of this issue, there are no studies on the effect of the climatic factors on the natural stone used in construction of the residential buildings in this region. Furthermore, the values of heating and cooling energy consumption recorded in the ancient residential buildings in this region by the Algerian Industrial Energy Company specialized in the distribution of electricity and natural gas (Sonelgaz Tébessa), are almost twice that the new residential buildings consume. Accordingly, it is clear that in the ancient villages as well as Hammamet, Tébessa Wilaya, that the ancient residential buildings are more energy consuming than the other modern buildings that built with new and lightweight construction materials, when it is supposed to be the reverse according to the natural stone thermal performance proven.

Therefore, in this research, we will discuss the impact of the climatic factors on the thermal inertia of the natural stone type used in construction in the semi-arid climatic context, and thus on the energy performance of these ancient residential buildings. This process requires a study of the thermal performance of the building, moreover, find the best ways of thermal improvement. All of this leads us to ask the following questions, which our work will try to bring, answer at its results:

Does the semi-arid climate factors affect thermos-physical properties of the natural stone type used in construction in Tébessa?

In this respect, does the natural stone type affect its interactions with the environment?

Then, how to improve the energy performance of the natural stone residential building in the semi-arid climatic context in this region by reinforce the thermal inertia of stone, taking into account the climatic, geographical and social context?

Moreover, by which approach can we concretize that?

3. Hypotheses

To answer these questions, we can formulate the following hypotheses:

- The harsh climatic factors affects the thermos-physical properties of the natural stone used in the residential buildings in the semi-arid climate context, this impact depends on the stone type, where, as the type of stone differs, its thermos-physical components differ; therefore, its interaction with environmental factors varies.
- Improving the thermos-physical properties of the natural stone used in the envelope buildings, improve the resistance to various external conditions such as variation of temperatures, the humidity and the wind. This contributes to improve the thermal performance of the building envelope, consequently, improving the energetic performance of the residential building.
- As the natural stone is inflexible material, this purpose can only be achieve by associating it with other natural materials, which respect the thermal quality of the stone, in order to adapt the ancients residential building to its climatic and social context in Tébessa Wilaya and the arid an semi-arid regions, where the same natural stone type is used there.

4. Purpose of the research

The main objective of this research is to produce reflections on the thermal improvement of residential buildings built with natural stone, and to achieve or attain a viable level of comfort and reduce energy consumption by improving the energy performance of the natural stone in the harsh climatic conditions. Therefore, the aim of the current research is define the impact of the semi-arid climatic factor, on the thermal properties of the stone used in construction of ancient buildings, and its effect on the thermal inertia of building. On the other hand, this study casting for adapt the natural stone building in Tébessa to its climatic context to acquire a sustainable residential building that meets the requirements of the lifestyle in terms of comfort and livability in this environment. In addition, our aim is also to develop new strategies for environmentally friendly construction from the natural stone building, for improving the quality of energy performance of building, accelerate development and reduce energy costs. In another term, this work contributes in improve the thermal performance respond to energy challenges while ensuring the thermal comfort of the buildings users.

5. Work methodology

In order to achieve the objectives of this research work, our methodology is organized in two main parts; a first theoretical part (thesis); a second experimental part (antithesis); and finally, an accumulation par (synthesis).

The first part consists of an applied research, which requires first, the understanding of the different concepts and key notions, related to the influence of the thermos-physicals properties of the building material on the thermal comfort, as well as its direct influence on the energy consumption and its effects on the environment. This first essential theoretical step allows us to better understand the relationship between the built environment and the external physical environment.

The second part deals with the investigation and diagnosis of several buildings for residential use, built entirely of natural stone, located in a semi-arid climate zone in Tébessa. It focuses on the capabilities of this material by which are built these houses in terms of hygrothermal comfort inside the spaces, in critical cold period and hot period characterized by high temperatures.

The investigation is based on hourly measurements of temperature, humidity and speed of the interior and exterior air with the help of adequate tools and instruments. Then, the energy simulation was carried out using the reliable and efficient EnergyPlus software. In the other hand, many tests and analyzes were carried out in the laboratory to determine the stone type used in construction in Tébessa Wilaya, and study its hydrothermal behavior by assess and evaluate the thermos-physical properties.

To understand the studied parameters and to give more reliability to the research in these two parts, it is necessary to combine several methods in order to verify and validate the obtained results. The methods used for the study of the thermal performance of natural stone residential buildings are below:

- Analytical method: allows describing the thermal functioning of the building by the principles of building physics.

- Experimental method: allows to test the variables in natural conditions by field study (empirical study), and controlled conditions by laboratory study (experimental study).

- Numerical method with EnergyPlus simulation software

The results obtained will allow the various actors in architecture to operate choices the suitable type of natural stone to use in the construction of the buildings. In addition, the method to improve the thermal performance of this material according to the climatic, geological and social context, which can be generalized on the region of Tébessa and the regions of Algeria which have the same specificities. The conclusion of the research shows the importance of choosing the suitable type of the natural stone used in building on the environmental, ecological and hygrothermal level.

6. Structure of the thesis

In order to achieve the expected objectives, this research was divided into two parts divided into five chapters constituting the body of the manuscript in addition to an introductory chapter and a general conclusion.

The first part is theoretical-consumptive, it includes the first two chapters devoted to the understanding of concepts and basic notions through a bibliographic analysis.

The second part is methodological, practical and analytical, they describe the context and the corpus of the study, the experimental part and explain the protocol of the measurements, the simulation, the laboratory tests, and the interpretation of the results in order to answer the problematic posed upstream and to verify the hypotheses which found it.

The structure of this thesis is as follows:

Introductory chapter devoted to the general introduction that summarizes the scope of the study, presents the formulation of the problem and the hypotheses of the research. It defines the context and objectives of the research, then describes the conceptual analysis, explains the methodology used and finally outlines the structure of the thesis.

The first chapter emphasizes the relationship between climate and building envelope. It describes the principle of heat transfer and the impact of thermal properties of building materials on thermal comfort.

The second chapter touch the geological field to understand the history of rock formation and the method of composition of the different stone type, in order to use this information in the building field. This chapter specify the type of stone used for construction and its thermos-physicals properties.

The third chapter defines the climatic context of the study, describes the cases of study and the protocol of taking the measurements. In addition, it analyzes the thermal behavior of the different residential buildings in natural stone built in semi-arid climate, in cold and hot period, by the measurement in situ and energy simulation by the software of the dynamic thermal simulation "EnergyPlus" which has been defined in this chapter. It compares the results found and analyze the thermal performance of these natural stone buildings in this climatic context.

The fourth chapter is dedicated to laboratory work, many tests and analyzes were carried out on natural stone samples extracted from the same quarry which provide the natural stone used in construction in Tébessa Wilaya. It define the thermos-physical properties of the material used and it resistance ability in the harsh climatic factor.

The fifth chapter assess and evaluate the thermal performance of the natural stone used in buildings studied. Afterwards, it reinforce the thermal inertia of the natural stone type used in building, in order to improves the thermal performance of the residential buildings built in the semi –arid climate.

Finally, this research is concluded with a general conclusion that summarizes all these steps of the research and gives a set of appropriate and convincing recommendations to improve the energetic performance of the buildings built with natural stone in the semi-arid climate, which is characterized by harsh condition, and ensure a comfortable thermal environment and a rational energy consumption.

FIRST PART

The interaction of climate and the building envelope

CHAPTRE I

ENERGY EFFICIENCY IN BUILDINGS

“We shape our buildings and afterwards our buildings shape us”

Winston Churchill

CHAPTRE I: Energy efficiency in buildings

Introduction

Buildings has a great impact on the environment, therefore, an extensive research has been conducted in the past few years interest in the development of low-energy building materials. In terms of building structure, efforts are made to optimize the design of low-energy consumption buildings, and environmentally friendly materials are widely used in buildings. The good energy performance of a building is closely related to the integrity of the building envelope, because it affects the total energy demand of the building. Reduce heating and cooling energy consumption, thereby reducing greenhouse gas emissions. At present, this problem is mainly solved by constructing low-energy, passive and nearly zero-energy buildings on the one hand, on the other hand, by improving the energy performance of ancient buildings.

I.1. Energy performance of buildings

The energy performance of a building can be defined as the calculated or measured amount of energy needed to meet the energy requirements of normal use of the building, which includes energy used for heating, cooling, ventilation, hot water and lighting. The amount of energy required is the result of a calculation that takes into account various factors that influence energy demand such as building location, solar exposure, construction materials and thermal insulation.

Minimizing the adverse effects of buildings on the environment is a key objective in achieving more sustainable development. This objective involves reducing the energy consumption of buildings, and thereby limiting CO^2 emissions to the atmosphere, while maintaining appropriate indoor environmental conditions. Since the residential buildings account for 70% of building floor area, and about two-thirds of existing buildings are over 30 years old and about 40% are over 50 years old (Gaterell & McEvoy., 2005), the thermal improvement of these buildings in particular provides considerable potential for energy conservation and further sustainable benefits.

In order to reduce the energy consumption, different variables can be taken into consideration, from the incorporation of renewable energy sources and the application of passive designs to the appropriate usage of the building by its occupants. Among these design variables, the hygrothermal performance of the building envelope is one of the most relevant factors that can be used to reduce energy losses, manage solar gains, and provide indoor healthy conditions. Therefore, the building envelope is a major lever for reducing energy needs and improving the energy efficiency of buildings.

Today, the quality of building envelopes of new or ancient buildings is regulated according to the requirements for the thermal performance of the building envelope of the SIA 380/1 standard; this standard aims at a rational and economical use of energy for heating in buildings. It thus contributes to the design of environmentally friendly buildings. The standard has undergone a number of adjustments in the course of a periodic review; the most important changes are the modified definition of the thermal building envelope according to SIA 380 edition 2009, following the adoption of the new Mopec by the Swiss Conference of Energy Directors in 2008.

On that account, improving the thermal performance of building envelope is an important way to save building energy consumption. In this respect, improving the energy efficiency of ancient buildings is a well-known problem worldwide. Given the very low renewal rate of the building. Several studies acknowledged that lack of knowledge, experience, and practice examples are barriers to thermal improving of the ancient buildings (Far, C., & Far, H., 2019). Therefore, the focus of this research is to develop recommendations for the most effective and feasible thermal improvement techniques for ancient buildings.

I.2. Building envelope behavior

The purpose of the thermal envelope is to prevent heat transfer from the interior of the building to its exterior in winter and vice versa in summer. In general, building envelopes include the resistance to air, water, heat, light, and noise transfer. As for thermal envelopes, they include outer walls, roof, foundation, windows and doors. The control function refers to the ability of a building envelope to control and moderate the exchange of mass (air and moisture) and energy (heat and sun) due to the separation of interior and exterior environments:

- Heat; controlling thermal (heat) exchange between inside and outside environment.
- Air; controlling airflow due to leakage, wind pressure.
- Moisture; controlling moisture transfer due to rain, vapor diffusion, or condensation.

- Sun; controlling solar transfer from fenestration (windows, doors, skylights).

In terms of the control function, the main purpose of the building envelope is to maintain a specific, comfortable internal climate despite changing conditions in the external environment (See Fig. I.1), its purpose is to make a building comfortable and livable (J.M.K.C. Donev et al., 2019).

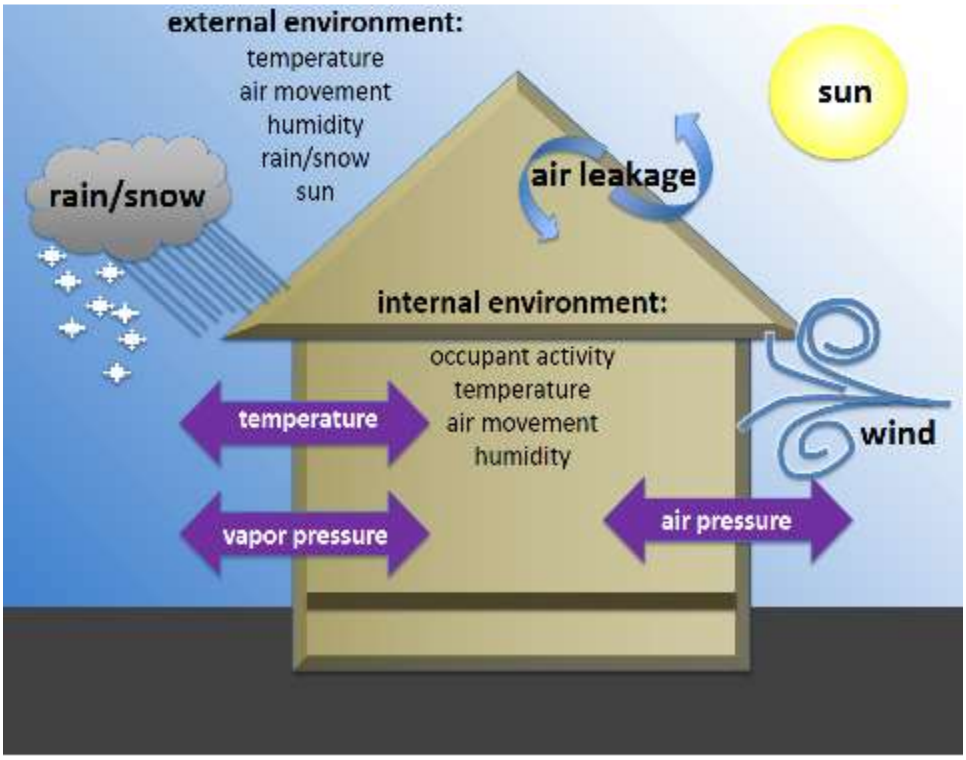


Fig. I.1. External stresses on the building envelope *(Source: J.M.K.C. Donev et al., 2019).*

In this respect, thermal and moisture transfers occur through the building envelope, between the interior and exterior sides of the building, determining its hygrothermal performance and energy consumption. The properties of the construction materials characterize these transfer processes, with their thermal conductivity being one of the most relevant properties. Therefore, it can be deduced that the precise characterization of the thermal conductivity of construction materials is a fundamental task for the adequate thermal design of buildings.

However, besides the intrinsic variability in many construction materials, the thermal conductivity of each material also varies according to its temperature and moisture content. The influence of this variation and its consequences on the energy calculations have been addressed by various studies. To consider the influence of both parameters, a design thermal conductivity that is representative of the actual conductivity of the material in the assumed environmental conditions of the building envelope is used (Perez-Bella et al., (2015).

Table I.1. Energy Flows in Building Shells *(Source: DOE, U., 2015).*

Residential Building envelope component	**Heating [Quads]**	**Cooling [Quads]**
Roofs	1.00	0.49
Walls	1.54	0.34
Foundation	1.17	-0.22
Windows	2.06	0.03
Windows	-0.66	1.14

As it is known, all of the elements of the envelope building control the heat flow, nevertheless, the previous research proved that the most of the heating load in residential buildings results from flows through walls as it shown in the Table I.1. (DOE, U., 2015), as previously, there is many factors affect the thermal exchange such as the constructions materials properties. Therefore, in the current research we will focus on the building walls thermal behavior, since improving the building walls contributes greatly to improving the thermal behavior of the building.

I.3. Building envelope heat transfer

Building thermic is a discipline that studies the energy needs of buildings; it mainly deals with the notions of transfer heat in order to offer the best thermal comfort to the occupants.

The heat transfer can be defined as the process of heat transfer from one object with a higher temperature to another object with a lower temperature. Building walls are affected by all three heat transfer mechanisms; conduction, convection and radiation. Solar radiation enters the surface of the external wall, converts into heat through absorption, and is transmitted to the building through conduction, at the same time, convective heat transfer occurs from the air outside the building to the external surface of the wall and the internal surface of the wall to the air inside the building. Due to the low temperature in the interior area of the building, most of the heat is obtained from the exterior of the building wall, through the building wall conduction and air leakage (Mahlia et al., 2007).

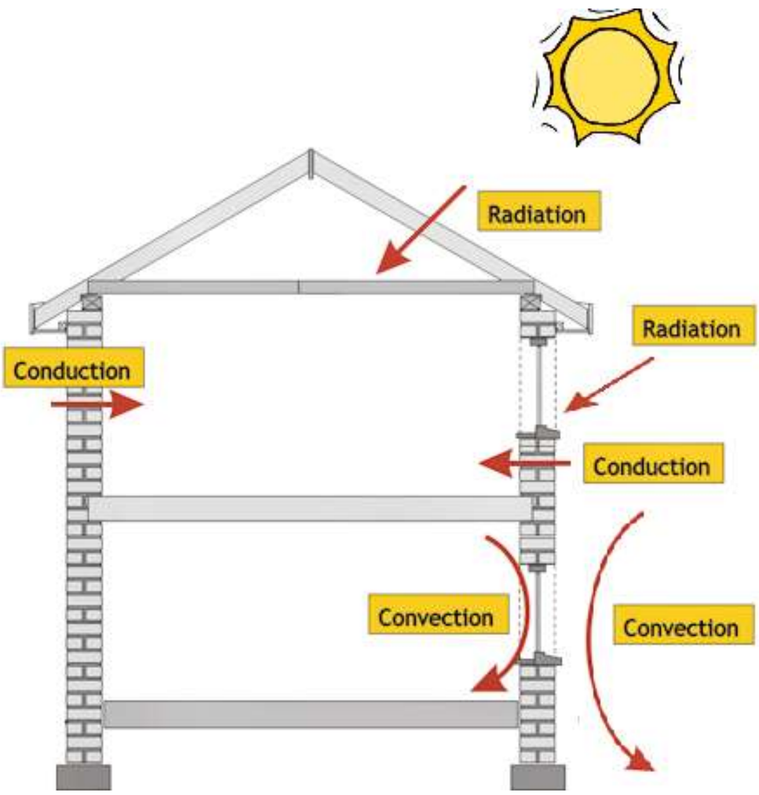


Fig. I.2. Modes of heat transfer through the building *(Source: Salih, T. W. M., 2016).*

The heat transfer process through the wall can be calculated by the following equation (Feilner et al.,2015):

$$Q=m.c.\Delta T \quad (1)$$

Where,

Q Heat transferred

m Mass

c Specific Heat

ΔT Difference in temperature

In this respect, the thermal engineering is considered as the field of physics that studies the exchange, generation, or storage of thermal energy in a system. In some cases, this may be accompanied by the transformation of materials. Heat transfer is the result of temperature differences within the system. Therefore, the measurement of temperature is the basic measure of this science.

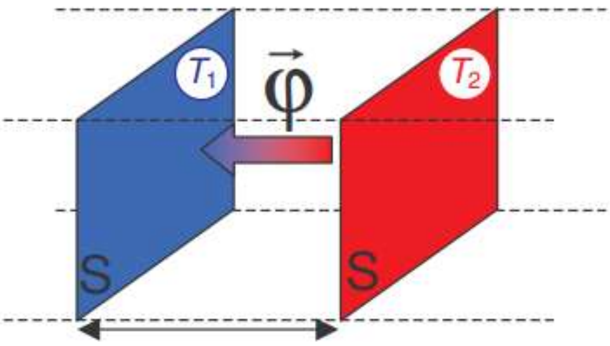


Fig. I.3. Heat transfer between two surfaces respectively at temperature T_1 and T_2 *(Source: Le Frious, 2010).*

Joseph Fourier developed an analytical theory to describe the conduction of heat in materials:

$$\Phi = -\lambda \,.\text{grad } T \tag{2}$$

Where,

T is the local temperature.

λ is the thermal conductivity of the material.

It translates, for example, that the flow of heat through a surface S is proportional to the temperature gradient $T_2 > T_1$ on the thickness considered, the surface and time, and that the heat transfer transferred from the hot area to the cold area as it shown in the Fig. I.3 (Le Frious, 2010). A system that is out of balance always tends to regain its equilibrium position, leading to heat exchange (heat flow). The physical phenomena describing heat exchange are mainly divided into three categories: heat conduction, heat convection and radiation (Gauthier, 2012).

I.3.1. Conduction

Thermal conduction is the mode of propagation of thermal energy through the materials. The elements which constitute the materials receive and transmit energy to the neighboring elements by contact of the hotter molecules with the colder ones.

The heat transferred by the process of conduction can be calculated by this formula (Vogt et al., 2015):

$$Q = \frac{kA(Thot - Tcold)t}{d} \tag{3}$$

Where,

Q Heat transferred

K Thermal Conductivity

T_{hot} Hot temperature

T_{cold} Cold Temperature

t Time

d The thickness of the material

A Area of surface

I.3.2. Convection

Convection occurs when molecules move from one place to another and exchange the heat and exchanging the heat it contains. The heat transferred by the process of convection can be calculated by this formula (Vogt et al., 2015):

$$Q=H_C A (T_{hot} - T_{cold}) \quad (4)$$

Where,

Q Heat transferred

HC Heat Transfer Coefficient

T_{hot} Hot temperature

T_{cold} Cold Temperature

A Area of surface

I.3.3. Radiation

Thermal radiation is the transmission of thermal energy from surface to surface by electromagnetic waves. Any material with a temperature higher than absolute zero emits such rays, which propagate in space, including in the vacuum. The heat transferred by the process of radiation can be calculated by this formula (Vogt et al., 2015):

$$Q= \sigma (T_{hot}- T_{cold}) A \quad (5)$$

Where,

Q Heat transferred

σ Stefan Boltzmann Constant

T_{hot} Hot temperature

T_{cold} Cold Temperature

A Area of surface

I.4. Thermal properties of building materials

The determining elements on the energy and thermal performance of the building are: building materials and building physics (Penu, 2015). The physical properties of material determine the heat transfer in any system. Usually, the material has many properties can be identified by these characteristics; the main properties of materials can be divided into the following categories:

- Mechanical properties of materials
- Chemical properties of materials
- Physical properties of materials
- Dimensional properties of materials

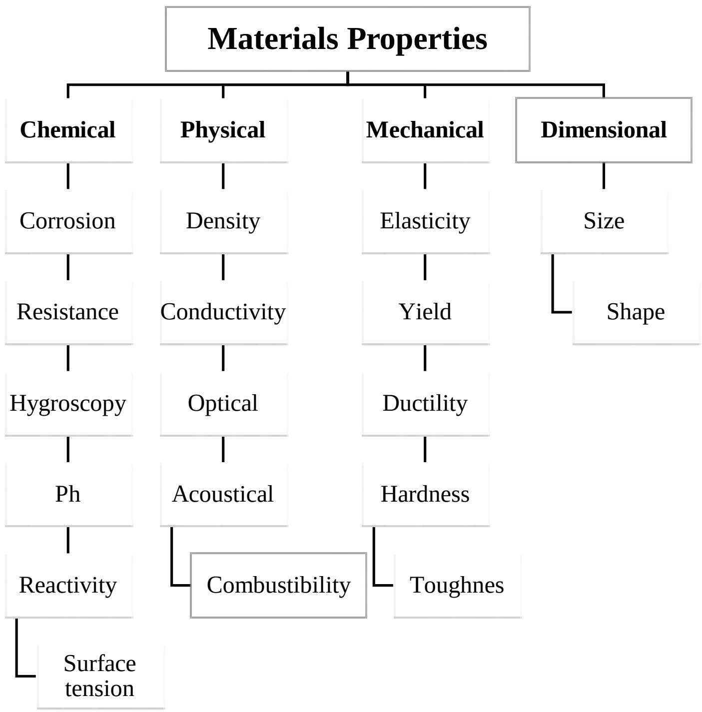


Fig. I.4. Material properties *(Source: madhavuniversity.edu.in).*

However, the thermal properties come under the broader topic of the physical properties of materials. The thermal properties of the building materials are those parameters, which characterize the behavior of the materials when they are subjected to a temperature variation whatever an excessive heat or very low heat, the study of these properties allows to model the thermal transfers and to predict the thermal performance of the building.

In that matter, there are two main material properties associated with heat transfer in materials; the thermos-physical properties, these are the ability of a material to store heat and the ability to transfer heat by conduction. Consequently, the ability of a material to store heat is characterized by the specific heat capacity (Cp) (Buck & Rudtsch, 2011). The different thermos-physical properties characterizing materials are detailed below:

I.4.1. Thermal conductivity

Thermal conductivity (λ) is the heat flow, per square meter, through a material of one meter thickness for a temperature difference of one degree between the two sides, expressed in watts per meter and per kelvin (W/m.K°). Which is expressed by this formula (Yang, 2004):

$$\frac{\Delta Q}{\Delta t\ A} = -\lambda \frac{\Delta T}{\Delta x} \tag{6}$$

Where,

$\frac{\Delta T}{\Delta x}$ is the temperature gradient,

$\frac{\Delta Q}{\Delta t\ A}$ is the thermal flux.

It define as the property of a material to conduct heat through itself, while materials with high thermal conductivity will conduct more heat than the ones with low thermal conductivity (Tritt, 2005). In general, a material with a large k is a good thermal conductor; a small k is called a good thermal insulator (Zhang, et al., 2001). Therefore, the ideal thermal conductivity refers to the lowest thermal conductivity in winter or summer day, and the highest thermal conductivity in summer night or transition season (Zhang et al., 2013).

The thermal conductivity of a material depends on its physical properties, temperature, density and moisture content. Generally, Lightweight materials have better insulation than heavy materials, because lightweight materials usually contain an air casing. The dry air has very low conductivity, but a layer of air is not always a good insulator, because heat is easily transferred through radiation and convection. When a certain material of construction (such as an insulating material) gets wet, the air enclosure will be filled with water, and since water is a better conductor than air, the conductivity of the material will increase. This is why it is very important to install construction materials when they are dry and take care to keep it dry.

The Table.1 in the Appendix F shows a list of building materials and their thermal conductivity for dry (indoor) and wet (outdoor) conditions. Where the air classified as the best insulator in the construction filed with a low thermal conductivity 0.023 (W/m.K°), while the thermal conductivity of most types of natural stone is generally above 1 or 3 (W/m.K°). A lower thermal conductivity is of course an advantage, in particular when natural stone is used as an external wall cladding material, as it improves insulation and consequently reduces energy consumption.

The thermal transmittance of a wall is the amount of heat passing through the wall in steady state, per unit of time, per unit of area and per unit of temperature difference between the environments on either side of the wall.

I.4.2. Thermal resistance

Thermal resistance is a thermal property and a measure of the temperature difference by which a material resists heat flow, The R-value is a measure of resistance to heat flow through a given thickness of material. So the higher the R-value, the more thermal resistance the material has and therefore the better its insulating properties. The R-value is measured in meters squared Kelvin per Watt (m^2K/W), is calculated by using the formula (Jannot et al., 2009):

$$R= e/\lambda \quad (7)$$

Where,

E is the thickness of the material in metres;

λ is the thermal conductivity in [W/mK].

I.4.3. Heat transmission coefficient

The thermal transmittance coefficient U (or k) is the inverse of the total thermal resistance R of the material, the lower the U-value is, the better the material is as a heat insulator, is expressed in W/m^2K, by the formula bellow (Abdel-Ghany & Kozai 2006):

$$U = 1 / R \quad (8)$$

Where;

R is the thermal resistance in [m^2K/W].

I.4.4. Heat capacity

The heat capacity of a material is defined as the amount of heat required to raise its temperature by one degree. It is an extensive quantity: the greater the quantity of material, the greater the thermal capacity. The heat capacity, expressed in joules per kelvin (J/K) and designated by the capital letter "C", reflects the ability of a material to absorb a quantity of heat (Q) and to heat up (raise its temperature) by ΔT (Zhou et al., 2010) :

$$C = \frac{Q}{\Delta T} \qquad (9)$$

In practice, the mass heat capacity is more often used, designated by the lower case letter "c", which is expressed in $J\text{-}K^{-1}\text{-}kg^{-1}$. It is related to one kilogram of the body considered (Zhou et al., 2010):

$$c = \frac{C}{m} \qquad (10)$$

The greater the heat capacity of a body, the greater the amount of energy exchanged during a transformation accompanied by a change in the temperature of this body.

I.4.5. Specific heat capacity

The specific heat capacity (Q) of a substance is the amount of heat required to raise the temperature of 1 kg of substance by 1 K°, the amount of heat is generally expressed in joules or calories and the temperature in Celsius or Kelvin.

The specific heat capacity determine by this formula (Ho & Taylor, 1998):

$$Q = m\ c\ \Delta T \qquad (12)$$

Where,

Q is the heat capacity in [J]

m is the mass in [g]

c is the specific heat in [J.K-1]

ΔT is the temperature change in [°K]

I.4.6. Thermal diffusivity

The thermal diffusivity (κ) is the thermal conductivity divided by the density and specific heat capacity at constant pressure. It measures the ability of a material to conduct heat energy and its ability to store heat energy. The high diffusivity means rapid heat transfer. It is found that the thermal diffusivity decreases with increasing temperature (Zhang, et al., 2001). The thermal diffusivity is given as the ratio of the thermal conductivity and the product of density and specific heat capacity. It determine by the formula below (Zhang, et al., 2001):

$$\kappa = \lambda / \rho C \ [m^2/s] \qquad (13)$$

I.4.7. Thermal Effusivity

The thermal Effusivity is a measure of a material's ability to exchange heat with the environment. It is defined according to this formula (Maliński, 2003):

$$e = \sqrt{(\lambda \rho C)} \ [J/m^2.K.s.^{1/2}] \qquad (14)$$

It characterizes the sensation of heat or cold provided by a material. If the Effusivity value is high, the material will quickly absorb a large amount of energy without significantly heating up on the surface (metal, stone, pottery). Conversely, a low Effusivity value indicates that the material heats up quickly on the surface while absorbing very little heat (insulating material, wood). The Ef value indicates how many kilojoules have penetrated a 1 m^2 material surface within 1 second after contacting another 1 m^2 surface for 1 °C. Like the diffusion coefficient, it is calculated using the heat capacity and thermal conductivity of the material.

I.5. Thermal inertia

The term inertia often used by scientists and engineers, is an analogy used in mechanics to link mass and velocity. In this case, inertia is the one that limits the acceleration of an object. Similarly, thermal inertia can be interpreted as a measure of "thermal mass" and the speed at which heat waves travel through a material. For this reason, it is common to find references to inertia, where inertia is directly referred to as thermal mass (Sala-Lizarraga et al., 2019).

From a scientific point of view, the diffusion of heat through a material is a well-known phenomenon. Thermal inertia concept is not easy to understand, it is defined as the concept that covers heat accumulation and its restitution, with a phase shift depends on the thermal physical characteristics of the construction materials of the building. While the speed at which heat is stored or destocked is determined by the thermal diffusivity (κ) and the thermal effusivity (e) (De Herde & Liébard, 2005). These two factors depend on the thermal conductivity, density and the specific heat capacity of material.

In most cases, the thermal inertia is defined as how quickly the building reacts to external disturbances. The building's response to the solicitation depends largely on the thermal properties of the construction materials. According to their ability to store and transport heat, buildings will react differently, so there is a coupling problem between conductivity and heat capacity, which introduces the two concepts of diffusivity and Effusivity. Thus, the thermal inertia depends on the interactions of the environment with the building construction materials, which related to several parameters such as their thermos-physical properties, their disposition within the building envelope, and the architectural characteristics of the building and the climatic conditions (Chahwane, 2012).

It is sometimes confused with insulation, but these two notions are different. Where insulation will limit heat loss, inertia is the ability of a material to store and then release heat and plays a role in the energy efficiency of building.

In order to improve the comfort of the occupants of a building or a dwelling while limiting energy consumption and environmental discharges, materials with high thermal inertia must combat both the penetration of cold in winter and heat in summer. This effect of inertia in the building's internal conditions and related energy consumption is well known and used for a long time, of course before the advent of cooling equipment. Throughout history and the world, there are countless examples of buildings dug in the mountains, where there, we can perceive the difference between indoor and outdoor environmental conditions as soon as we enter the door, and these are obtained in one way, the "natural" way.

On the one hand, these differences can be summarized as the greater attenuation of the internal temperature oscillation relative to the external oscillation, on the other hand, the instantaneous delay in reaching the peak of the internal temperature, compared to when the peak is generated externally. Unlike insulating materials that can be characterized by thermal resistance (Sala-Lizarraga, et al., 2019). Thermal inertia cannot be quantified by a single parameter, over the years, groups of researchers have used different indicators to characterize it such as thermal diffusivity and thermal diffusivity.

I.5.1. The inertia by transmission

Is characterized by the diffusivity, this quantity determines the speed at which a material is likely to transmit heat from one side to another of the same wall, in a variable temperature regime. It is calculated by the formula (Verbeke & Audenaert, 2018):

$$D = \lambda/(\rho C) \tag{15}$$

The transmission inertia of a material is all the more important as its diffusivity is low and as its thickness is important. Materials with low diffusivity must have a low conductivity coefficient λ with a high density ρ and a high specific heat C. Since the calculation formula is a ratio in which the characteristics of the materials have opposite actions, calculations must be made on a case-by-case basis, but it is usually the insulators that are the least diffusive materials.

I.5.1. The absorption inertia

is characterized by the Effusivity, this quantity determines the capacity of a material to store or destock rapidly a large quantity of thermal energy in a variable temperature regime. It is calculated by the formula (Verbeke & Audenaert, 2018):

$$E = \sqrt{(\lambda \rho C)} = \rho C \sqrt{D} \tag{16}$$

The absorption inertia of a material is more effective the larger its Effusivity and surface area. The minimum thickness of the materials varies with the duration of efficiency sought. In the case of traditional masonry constructions, the thicknesses necessary to ensure daily comfort are of the order of 10 cm per exposed face. Materials with high Effusivity must have a conductivity coefficient λ, a density ρ and a maximum specific heat C. Solid materials are always the most effusive materials.

In these formulas:

λ is the conductivity coefficient of the material, its ability to conduct heat expressed in [W/m-K],

ρ is the density of the material, its density expressed in [kg/m3],

C is the specific heat of the material, its ability to store heat per unit volume expressed in [J/kg-K],

D is the Diffusivity, its ability to slow down heat transfer expressed in [m^2/s], E is the Effusivity, its capacity to regulate the indoor environment expressed in [J/m^2-K-s1/2].

The purpose of the building envelope is to ensure maximum comfort whatever the outside climate and therefore, in the worst case, in dynamic regime. Its inertia by transmission and its inertia by absorption must, consequently, be simultaneously maximum, especially in climate with important daily temperature differences:

- The inertia by transmission is maximum when the speed of transmission, its diffusivity, is minimal.
- The inertia by absorption is maximum when its storage capacity, its Effusivity, is maximum.

I.5.3. Phase shift

When solar radiation hits the outside of a wall, it raises its temperature. It takes a certain time for the heat wave to reach the other side of the wall. As long as the temperature of the ambient air is high, walls with high inertia store energy without any consequent increase in temperature. They play the role of an "energy reservoir". Obviously, a reservoir never has an endless capacity, so it must be discharged regularly. As for the phase shift, it is essential to ventilate the interior abundantly during the night to empty the walls of the energy stored during the day. The phase shift is perfectly represented by the curves in the Fig.2; it is the shift between the outdoor temperature curve and the indoor temperature curve.

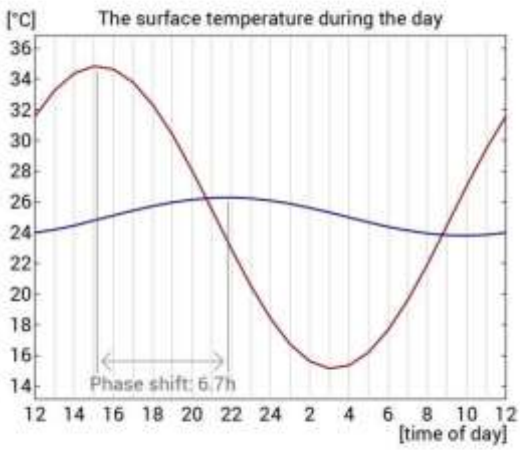


Fig. I.5. Phase shift time *(Source: Ciutina et al., 2019).*

The thermal phase shift is related to the inertia since it is the delay in hours and minutes that will take the heat to cross a material. This phase shift is mainly related to the nature of the usual materials of the construction (stone, wood, concrete, and brick) and it is thus not very flexible. A high phase shift will delay the moment when heat enters the building. Indeed, this data indicates the duration that a heat peak will take when the internal face of the insulation reaches its maximum temperature. A material with a high phase shift will therefore considerably increase thermal comfort. As a result, a comfortable temperature in the building reduces the energy consumption by limits the use of heating or cooling appliances, which can be very energy consuming, these can represent up to 20% of the energy bill.

In general, the winter comfort is determines by good thermal resistance of the walls, while the summer comfort is determined by a good thermal inertia of the building. Thermal inertia corresponds to the capacity of materials to store heat. The denser the material, the greater its thermal capacity. This is why stone buildings are relatively cool in summer. The natural stone can retain a significant amount of heat. On the other hand, it is a poor insulator, therefore, the relationship between conductivity and thermal capacity seem contradictory.

However, in order to understand the phenomena felt in terms of comfort, it is necessary to take in consideration that in their extreme configuration, summer is an alternation of hot days and relatively cool nights while winter is a continuum of cold days and nights. This is where the notion of phase shift comes in and presents an interest. The phase shift corresponds to the time it takes a material to reach the temperature of its environment, it is Expressed in hour for a given thickness of material, The research proved that 12 hours of sunshine that a summer day contains are not enough to saturate in calorie a stone wall of 50 cm. Then, the wall cools down in night, but in winter, the stone is a poor insulator. In order to obtain a good comfort, winter as well as summer, it must be able to combine a good resistance with a good thermal capacity. Therefore, the construction material is determining.

Conclusion

The envelope of a building is the construction element that separates the heated space from the outside environment. Its primary function is to protect its occupants against external climatic and sound aggressions. Its performance is measured, on the one hand, by its capacity to manage external contributions and, on the other hand, by the level of thermal comfort felt by its users. The materials used in the design of the building envelope play a considerable role in the absorption, storage and distribution of the energy provided by the solar flux. Therefore, the performance of the envelope is particularly related to the thermos-physicals properties of construction materials, and to the climatic conditions of the building.

CHAPTER II

THE NATURAL STONE AS BUILDING MATERIAL

"Build your architecture from what is beneath your feet"

Hassan fathy

CHAPTER II: The natural stone as building material

Introduction

Natural stone has been used as construction materials worldwide. In recent years, the demand of this building material used in the building envelope increase, regarding to its thermal performance, especially in the harsh climatic condition. In this chapter, we will touch the geological field to understand the history of rock formation and the method of composition of the different stone type. For instance, such information is used in the building field, since the more we specify the type of stone used for construction, the more its thermo-physicals properties become clear to us, consequently, it will be easier to study and evaluate it thermal performance.

II.1. The rock cycle

The rock loop is essentially a closed loop that repeats itself. Rock cycles not only represent the environment where igneous rocks, sedimentary rocks and metamorphic rocks are formed, but also the environment where they gradually transform into other types of igneous rocks, sedimentary rocks and metamorphic rocks.

The ideal cycle is represented by the circular cycle as it is shown in the Fig. II.1, which shows the transformation of igneous rocks into sedimentary rocks and sedimentary rocks into metamorphic rocks. This metamorphic rock ends the cycle by eventually transforming into igneous rock. A complete cycle is completed, and the second cycle begins.

If the continuous cycle can be repeated repeatedly, it is because the movement of tectonic plates is still active. Without tectonic plate movement, there would be no rock cycle, let alone the endless repetition of this cycle. Note that the rock loop is not always perfect, because the loop is often distorted due to frequent shortcuts and even long-distance changes.

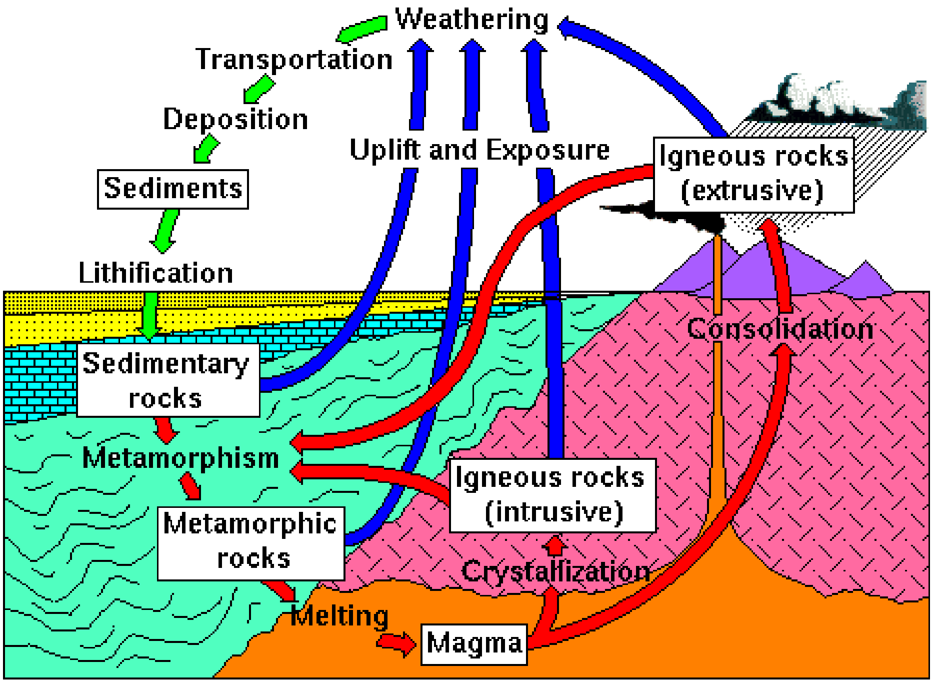


Fig. II.1. The rock cycle *(Source: www.thinglink.com).*

The red and blue arrows in the loop in the fig. indicate shortcuts and long detours, respectively. For example, ejecting igneous rocks can take shortcuts by transforming into metamorphic rocks, rather than simply transforming into sedimentary rocks. It is mainly the environment in which igneous, sedimentary or metamorphic rocks are found that will determine whether the rock is transformed along a perfect loop path or a shortcut or circuitous path.

II.2. Natural stone classification

Two different methods can be used to classify natural stone; the classification of natural stone types according to the geological origin, which based on the geological origin, which are the igneous rocks, the sedimentary rocks and the metamorphic rocks. The second is based on implementation basis, such as strength characteristics, hardness, porosity, color, and durability (Tumac, & Shaterpour-Mamaghani, 2018). Photos of some common rock types are shown on the Appendix G.

Igneous rocks, sedimentary rocks and metamorphic rocks are classified according to their genesis, structure and texture, and finally according to their mineral composition as shown in the Fig.II.2 Igneous rocks can be of intrusive (plutonic and vein-like) or eruptive (volcanic and pyroclastic) origin. Sedimentary rocks can be of detrital, chemical or biochemical origin, while metamorphic rocks can have leaf-like or non-leaf-like structures.

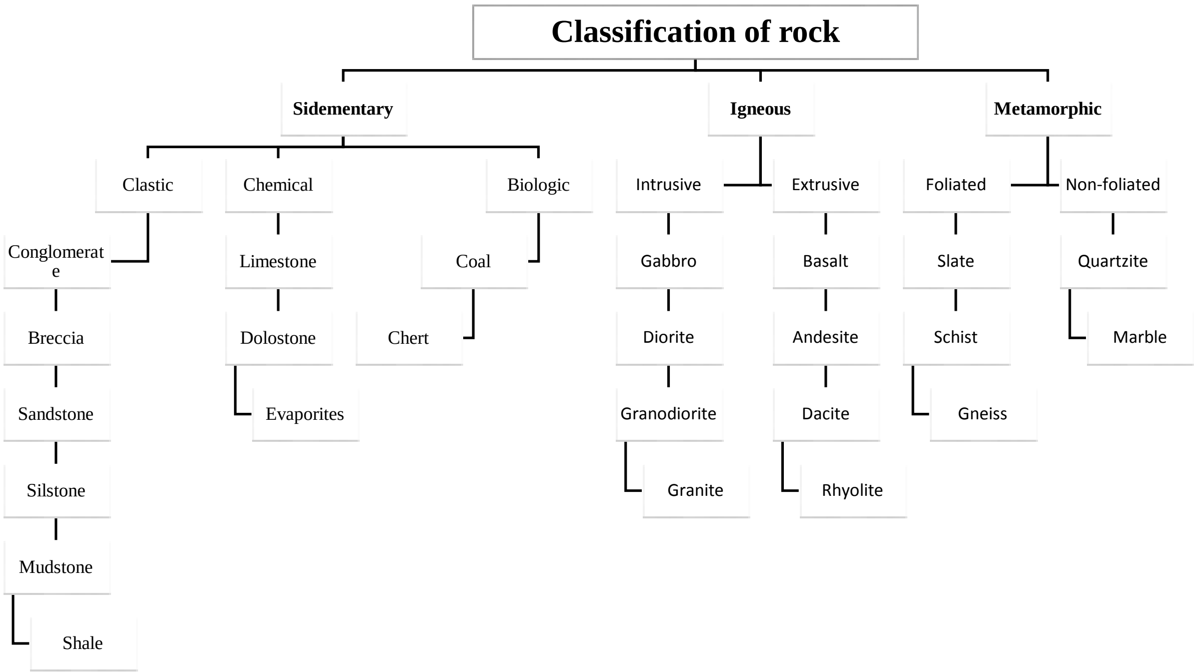


Fig. II.2. Classification of rocks *(Source: stonespecialists.net).*

II.2.1. Igneous Rocks

Igneous rock (See Fig.II.3) is formed by the cooling and crystallization of magma or lava. Their name comes from the Latin root "ignis", which means "fire". Igneous rock can be found nearly everywhere on the earth's crust, particularly near volcanic hot spots (Le Maitre, 2002).

Fig. II.3. Collection of igneous rocks *(Source: Vvoe/Shutterstock.com).*

II.2.1.1. Formation of igneous rock

Igneous rocks can be formed in a number of ways including:

- Through lava erupting on the surface of the earth.
- By the cooling of shallow to deep magma beneath the earth's surface.

After the lava erupts on the surface, it cools to form spewed igneous rocks. When shallow magma cools, intrusive igneous rocks are formed, and plutonic igneous rocks come from magma deep underground. Lava cools the fastest on the earth's surface, and magma that cools more slowly can form larger mineral crystals (Cox, 2013). Although magma is generally considered a liquid, it is actually a partially molten fluid containing minerals. As it cools, these minerals will crystallize at different times, causing the rock to undergo a compositional change. When magma encounters other types of rocks while passing through the earth's crust, further evolution occurs. (Mattox, 1994).

II.2.1.2. Classification of igneous rocks

Igneous rocks are classified according to their main minerals (Gill, 2011).

a. *Intrusive igneous rocks*

Intrusive igneous rocks crystallize below Earth's surface, and the slow cooling that occurs there allows large crystals to form. Intrusive igneous rocks include granite, diabase, diorite, pegmatite, gabbro and peridotite.

b. *Extrusive igneous rocks*

Extrusive igneous rocks erupt onto the surface, where they cool quickly to form small crystals. Some cool so quickly that they form an amorphous glass. Extrusive igneous rocks include andesite, basalt, dacite, obsidian, pumice, rhyolite, scoria, and tuff.

II.2.2. Metamorphic Rocks

Metamorphic rocks (See Fig.II.4) are rocks that change from one type of rock to another. Sedimentary rocks are formed from sediments, igneous rocks are formed from molten magma, and metamorphic rocks are rocks formed from pre-existing rocks (Turner, 1948). These rocks will change due to high temperature, high pressure or exposure to hot liquids rich in minerals, thereby transforming existing rocks into new types of rocks and changing the composition of minerals in the process (Bucher, 2011). Any one of these three factors or their combination may lead to the formation of metamorphic rocks.

Fig. II.4. Collection of metamorphic rock specimens *(Source: Vvoe/Shutterstock.com).*

II.2.2.1. Formation of metamorphic rocks

Due to the conditions necessary to transform rocks, namely heat and pressure, this process usually occurs deep in the earth's crust or in areas where tectonic plates collide. These are similar conditions for the production of igneous rocks (Robertson, 1999). However, the important difference is that the original rock or original rock that forms metamorphic rocks does not actually melt even if heated, but the molten rock or magma is the basic rock of the igneous rock. Igneous rocks are molten rocks that cool and crystallize, while metamorphic rocks can tolerate extreme conditions that change the actual mineral composition of the rock over time (Bucher, 2002). The Fig.II.5 shows the formation method of the different rock type.

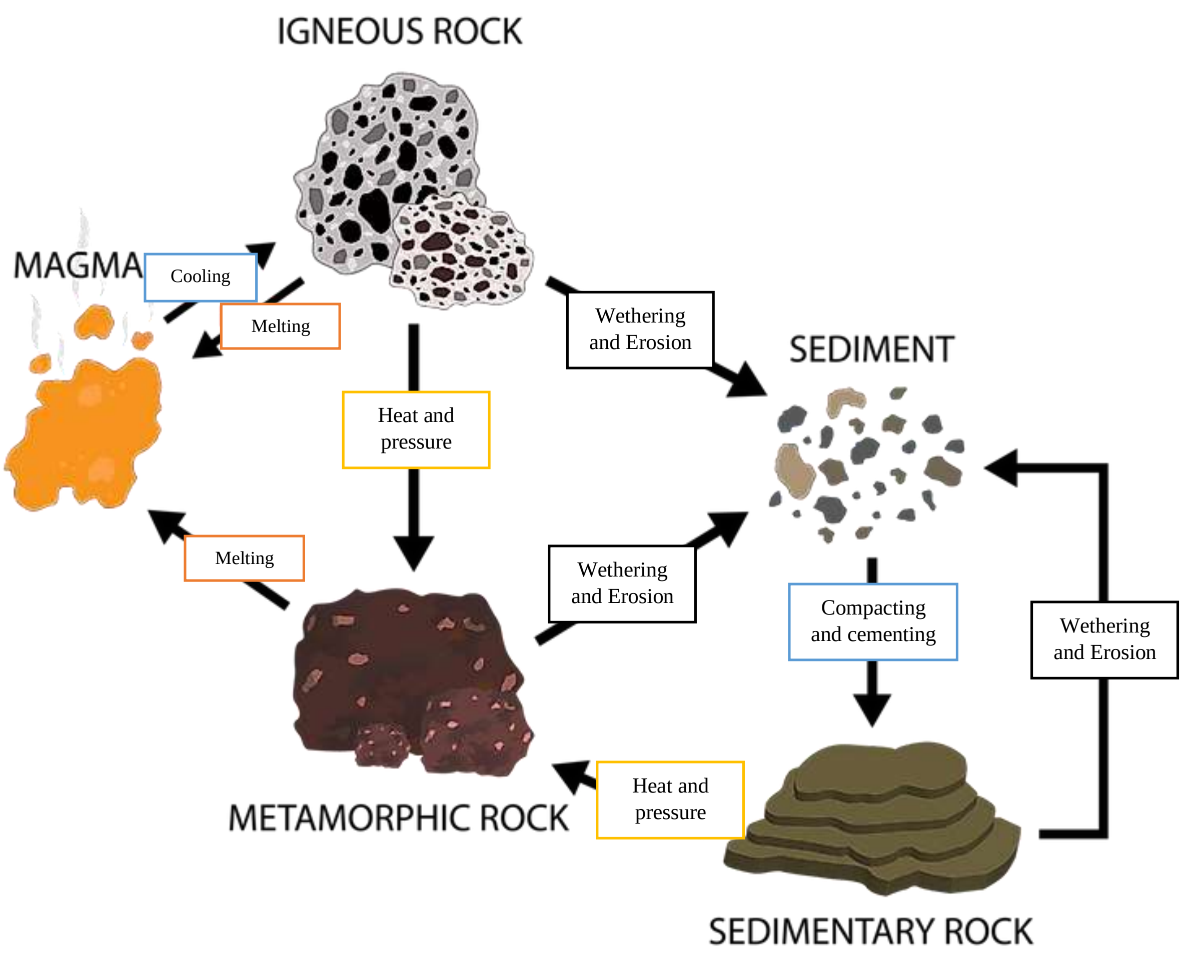


Fig. II.5. Method of formation of rock *(Source: worldatlas.com).*

Because this process takes place deep on the surface of the earth, these rocks are usually rarer than other types of rocks, or at least harder to find on the surface of the earth, and can only be found under the action of geological lift. This improvement occurs when the soil is eroded over time. Wind, rain, and faults can wash or erode the soil and rocks surrounding these metamorphic rocks deep underground. In this way, over time, metamorphic rocks will slowly be exposed to the surface of the earth (Fry, 2013).

II.2.2.2. Thermal metamorphism

When the rock changes due to heating, it is called thermal metamorphism. This means that temperature is the main cause of transformation and a catalyst for recrystallization of the original rock (Mason & Mason 1990). This often occurs in extremely hot areas, such as near cracks or igneous rock intrusions. These are the areas in the earth's crust where magma is formed or discharged. The upwelling of these lava creates an extremely hot environment, which in turn provides an ideal environment for the formation of metamorphic rocks. These rocks are transformed near the magma rather than inside the magma, so this area has very high temperatures, but does not expand directly in the lava.

a. Cataclastic or mylonitic metamorphism

Another way to form metamorphic rocks is through extreme pressure, which must exceed 100 MPa of force. There are moving and moving tectonic plates in the earth's crust. Where these plates meet, there is usually a lot of friction. When the plates rub against each other, these faults or cracks generate tremendous forces. This shearing and breaking of plates is the main cause of fragmentation and metamorphism, and causes rocks to have very small broken particles (Kornprobst, 2006).

b. Dynamothermal metamorphism

Sometimes heat and pressure work together to produce metamorphic rocks. In this process, the rock will produce new minerals and textures. Again, this occurs at the boundaries of tectonic plates, usually along mountains and mountains. The metamorphic rocks produced by this process are called dynamic thermal metamorphic rocks and are some of the most common metamorphic rocks.

II.2.2.3. Classification of metamorphic rocks

While metamorphic rocks can be formed in different ways, the resulting rocks can also be categorized based on the way in which minerals align in the newly formed rock (Grauch, 2018). These rocks are classified as either foliated or non foliated rocks (See Fig.II.6).

Fig. II.6. The difference between the foliated and non-foliated rocks *(Source: socratic.org).*

a. Foliated rocks

Foliated rocks are rocks where the minerals have become aligned. This is caused by mass amounts of pressure, usually in conjunction with heat, which force the elongated minerals to fall into a foliated pattern. It is this plating process which creates thin layers and directional patterns in the rocks. This sort of layer is very evident in may foliated rocks, such as slate, schist or gneiss (Jefferies. et al., 2006).

Gneiss can actually be further classified into one of two types: orthogneiss, which is derived from igneous rock, or paragneiss which is made from sedimentary rocks. This means the classification is dependent on the protolith which is used to form the metamorphic rock. For example, when granite undergoes extreme pressure and heat, it can be transformed into a type of gneiss.

b. Non-foliated rocks

Non-foliated rocks are formed in much the same way as foliated, in that parent rocks undergo extreme conditions in order to be transformed into other forms of rocks. The distinction is in the minerals within the original rock. While foliated rocks are formed where there are elongated minerals, non-foliated rocks occur when minerals are irregular or not elongated. When they undergo pressure, the minerals still compress, however they do not align into sheet or platy layers (Goldsmith, 1959).

Examples of non-foliated rocks are marble, quartzite and hornfels or soapstone. Marble is a beautiful type of non-foliated metamorphic rock which is actually derived from limestone, a carbonated sedimentary rock. Soapstone is an unusual type of rock, which is formed when mineral talc, which is rich in magnesium, is transformed into a solid, hard rock. Similarly, quartzite is metamorphosized quartz. Like quartz, it maintains a strong crystalline structure, and is very hard and dense.

II.2.3. Sedimentary Rocks

Sedimentary rocks (See Fig.II.7), as the name suggests, are formed by the accumulation of sediments. This means that they will form on the surface of the earth over time. Unlike other types of rocks, such as igneous or metamorphic rocks, they are formed deep in the earth under tremendous pressure or heat. Sedimentary rocks are believed to cover approximately 73% of the earth’s surface. However, their total contribution is about 8% of the total volume of the earth's crust. (Pettijohn, 1975).

Fig. II.7. Collection of sedimentary rocks *(Source: sandatlas.org).*

Sedimentary rocks are mainly caused by gradual but continuous natural changes in the environment. The main factors for the formation of sedimentary rocks are erosion, precipitation or natural weathering; as well as lithification and dissolution. These environmental phenomena will slowly erode the soil or rock surface, or wash the sediments together, and eventually form rock formations. Some of the more common types of sedimentary rocks include sandstone, shale, limestone, and coal (Shrock, 1948).

Fig. II.8. Sedimentary rocks *(Source: larousse.fr).*

Sediments are deposited at different rates mainly depending on the location they are found (See Fig.II.8). For instance, deposition on a deep ocean floor only accumulates a few millimeters of sediment every year, whereas deposition on a channel found in a tidal flat can result in the accumulation of several meters of sediments in a day. However, there is a distinction between sedimentation that results from catastrophic processes and normal sedimentation. The former comprises of all types of sudden special processes including flooding, mass movements, or rock slides. Such processes can result in the sudden deposition of sediments in large amounts at once. While other environments with sedimentary rocks are dominated by ongoing or normal sedimentation, most sedimentary rocks were formed because of some catastrophic processes (Tucker, 2003).

II.2.3.1. Formation of sedimentary rocks

The types of sedimentary rocks can be formed in many different ways. From natural causes to chemical interactions, rocks decompose or accumulate in various ways. With the passage of time and continuous pressure, sedimentary rocks change from fragments to solid rocks or rock formations. The following are the different ways in which sedimentary rocks are formed (Krynine, 1948).

a. Erosion

One of the main factors leading to the formation of sedimentary rocks is erosion. Wind, water, and rain break down the soil that passes through rocks and soil. This constant friction between the elements and the earth's surface will erode rocks and soil, turning them into small sedimentary particles or debris. In this way, large boulders, hillsides and rock formations are worn away, producing small dust like debris such as sand or mud.

b. Weathering

Various weather patterns or meteorological phenomena naturally break down rocks through a process called weathering. Wind and rain will slowly erode large rock formations, boulders, river beds and mountains, forming tiny rock fragments such as sand. Examples of this can be seen in places such as the Grand Canyon and waterfalls. The gorge is formed by the water flowing continuously through the same area, slowly opening a path underground and producing sedimentary rocks along the river bed. Similarly, rainwater will slowly decompose rocks, leaving minerals and rock particles behind. These debris, sand and mud formed sedimentary rocks.

c. Disband

Dissolution is another process of breaking down hard, larger rock formations into sediments. Chemical weathering or acid rain causes this type of decomposition. Climate change and greenhouse gases are the main causes of acid rain, which erodes stones and rocks.

d. Litification

Sediment can be composed of debris, minerals, and other small rock particles. These gradually accumulate, and when compressed, new rocks are formed. Especially when mud, clay, sand or other deposits are squeezed under the weight of water. These sediments can be found at the bottom of oceans or lakes and are compressed over a long period of time. This constant pressure from the overlying sediments and water compacts the sediments until they form a solid rock mass.

e. precipitation

Although the term "precipitation" is most commonly used in connection with rain, it has another meaning in the chemical sense. When the liquid settles, it separates the liquid (in this case, water) from any precipitate (that is, insoluble solids in the solution). When rainwater precipitates and evaporates into the atmosphere, it will leave behind various chemicals and minerals transported by rainwater.

II.2.3.2. Classification of sedimentary rocks

Sedimentary rocks can be classified according to the processes of how they were formed and can be divided into four different groups, which include chemical sedimentary rocks, clastic sedimentary rocks, other sedimentary rocks, and biochemical or biogenic sedimentary rocks (Rodgers, 1950).

a. Clastic sedimentary rocks

Clastic sedimentary rocks are further subdivided depending on their dominant particle size and the composition of other particles of rocks originally cemented by silicate minerals.

Clastic sedimentary rocks mainly consist of rock fragments, mica, quartz, clay minerals, and feldspar. Types of clastic sedimentary rocks include mudrocks, sandstones, conglomerates, and breccias.

b. Biochemical sedimentary rocks

Biochemical or organic sedimentary rocks form from the accumulation of plant or animal debris. Types of biochemical sedimentary rocks include coal, deposits of chert, some dolomites and most types of limestone.

c. Chemical sedimentary rocks

Chemical sedimentary rocks are formed when the mineral constituents in solutions are inorganically precipitated after being supersaturated; examples include barite, halite, gypsum, and stylite.

d. Other sedimentary rocks

Other sedimentary rocks are the category of sedimentary rocks that are formed by uncommon processes such as volcanic breccias, impact breccias, and Pyroclastic flows, among others.

II.2.3.3. Properties of sedimentary rocks

There are several factors that help classify sedimentary rocks, they include fossils, mineralogy, texture, color, and primary and secondary sedimentary structures. The texture of sedimentary rocks comprises of their orientation, size, and form. Despite texture being a small-scale property of a sedimentary rock, it can help determine other large-scale properties such as permeability, density, and porosity (Stow, 2005).

Fossils are most commonly found in sedimentary rocks compared to igneous and metamorphic rocks. Unlike the other two types of rocks, sedimentary rocks are formed at pressures and temperatures that do not obliterate the remains of fossils. However, most of the times such fossils may not be seen by the human eye but are seen only under a microscope. In nature, dead organisms are often rapidly removed by erosion, bacteria, scavengers, or rotting. However, sedimentation is a major contributor to special circumstances where such natural process are not able to work, thus resulting to fossilization. (Larsen & Chilingarian, 2010).

Color is a major property of sedimentary rocks and is usually identified by iron and its two main oxides which are iron (II) oxide and iron (III) oxide. For instance, iron (II) oxide or FeO forms only under circumstances that comprise of low oxygen also known as anoxic, thus giving the rock a greenish or grey color. On the other hand, iron (III) oxide or Fe2O3, which is usually found in the form of hematite, a mineral found in an environment that is richer in iron, contains more oxygen. Therefore, sedimentary rocks in such an environment are brownish or reddish in color. Mineralogy refers to the mineral structures found in rocks. A large number of sedimentary rocks comprise of either calcite or quartz. In comparison to metamorphic and igneous rocks, sedimentary rocks normally contain low levels of different significant minerals. Nonetheless, the origin of minerals in sedimentary rocks tends to be more complicated than in igneous rocks. The minerals in sedimentary rocks are either formed through diagenesis or precipitation during sedimentation. (James, 1966).

Primary sedimentary structures is also another property used in identifying sedimentary rocks. Sedimentary structures comprise of large-scale features that are easier to study in the field unlike textures, they are used in indicating something about the sedimentary environment. For instance, sedimentary structures can help tell which side of a sedimentary rock initially faced up in an environment where tectonics have either overturned or tilted the sedimentary veneers.

Secondary sedimentary structures are sedimentary structure that are only formed after deposition, these structures form within the sediment through biological, chemical, and physical processes. Such processes can indicate various circumstances after deposition and can even be used as geospatial indicator.

II.3. Natural stone building material in Tébessa

Tébessa Wilaya in Algeria is part of the Atlas of Eastern Sahara near the Algeria-Tunisia border, it marks that the stratigraphic characteristics of the study area show a variety of facies dominated by limestone (See Fig.II.9) (Belfar. et al., 2017). Moreover, there are many quarries situated in Tébessa (42) as shown in Table II.1 produce different natural stones type, but the most of them are limestone quarry, which is the predominant type available for use in construction in this region.

Table II.1. Quarries substances in Tébessa Wilaya *(Source: Statistical office of Tébessa).*

Substance	**Sand**	**Limestone**	**Tuff**	**Clay**	**Phosphate**
Number of quarries	17	15	06	03	01

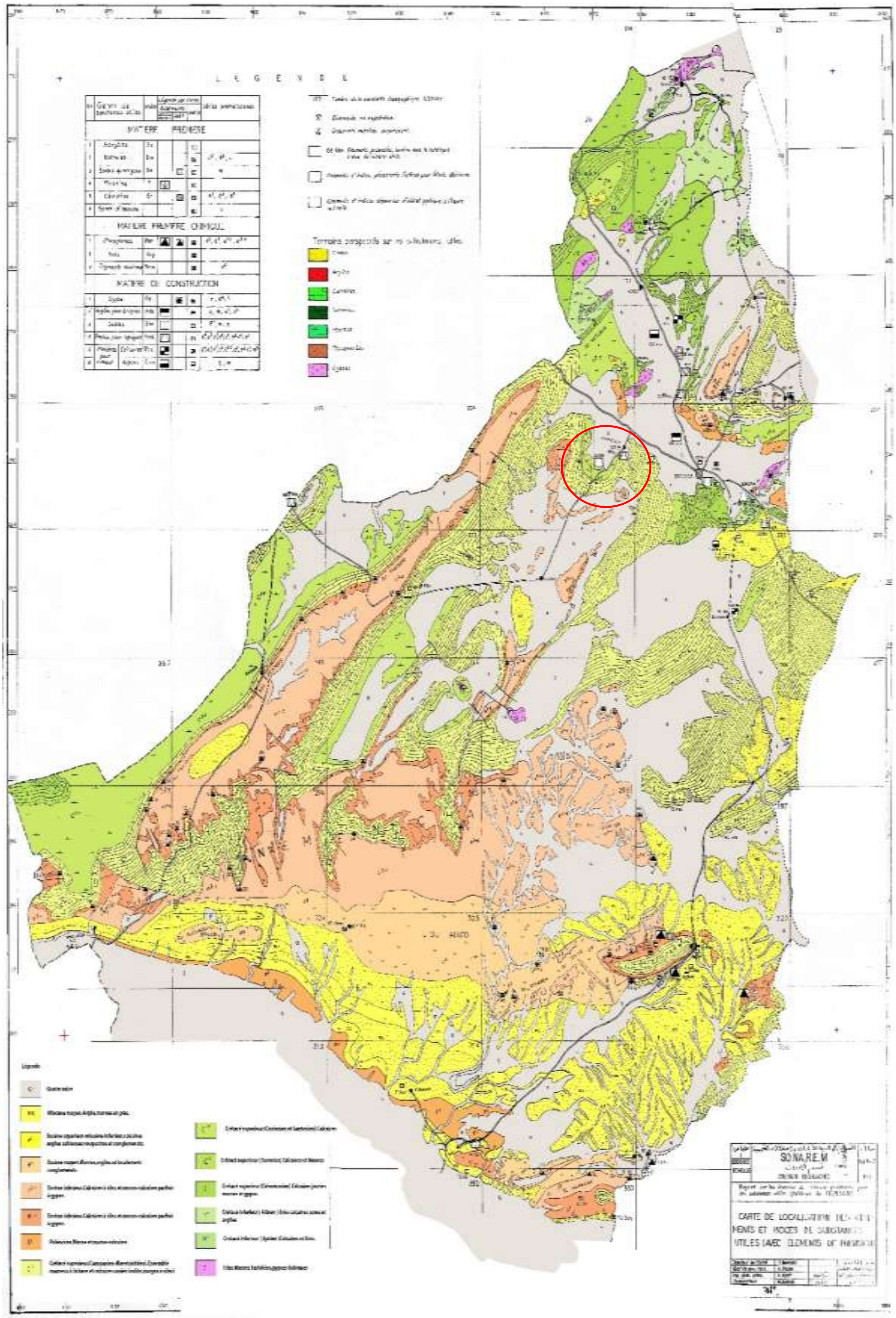


Fig. II.9. Geological map of Tébessa *(Source: Directorate of Mines, Tébessa Wilaya).*

Table II.2. Chemical analyses of the stone samples *(Source: Directorate of Mines, Tébessa Wilaya).*

	Components	Percentage %
Analysis 1	**Components**	**Percentage %**
	Insoluble	5.40
	Calcium carbonate	93.98
	Gypsum	Traces
	Sulphate	Traces
	Degree of aggression.	Zero
Analysis 2	**Components**	**Percentage %**
	Insoluble	4.70
	Calcium carbonate	94.74
	Gypsum	Traces
	Sulphate	Traces
	Degree of aggression.	Zero
Analysis 3	**Components**	**Percentage %**
	Insoluble	/
	Calcium carbonate	93.98
	Gypsum	Traces
	Sulphate	Traces
	Degree of aggression.	Zero
Analysis 4	**Components**	**Percentage %**
	Insoluble	/
	Calcium carbonate	97.28
	Gypsum	Traces
	Sulphate	Traces
	Degree of aggression.	Zero
Analysis 5	**Components**	**Percentage %**
	Insoluble	8
	Calcium carbonate	91.73
	Gypsum	Traces
	Sulphate	Traces
	Degree of aggression.	Zero

For determine the stone type used in construction in this region, many studies were undertaken in the laboratory of the direction of mines in Tébessa on different samples extracted from the Gaagaa quarry. The natural stone samples were taken from the most appropriate sites in accordance with the procedures in force in the laboratory of the quarry. Which stipulates taking samples from at least five sites, represented in the four sides of the quarry area and from the middle, this in order to cover the possibility of different samples. The following illustration fig. shows the places where samples were taken from a quarry.

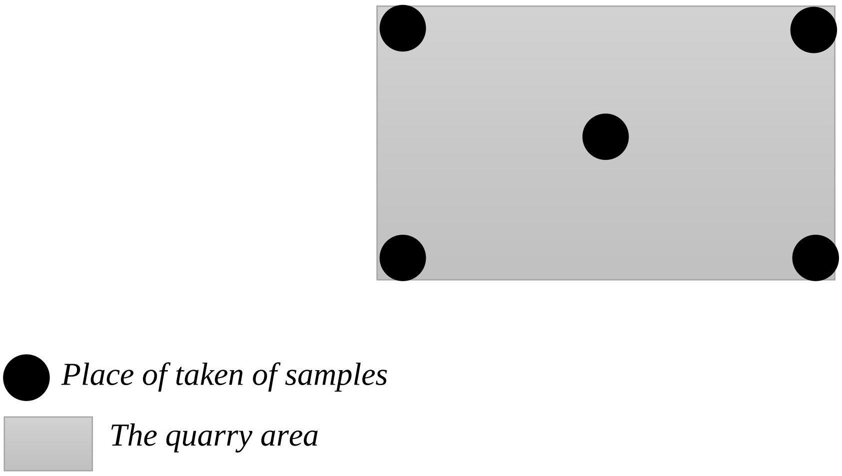


Fig. II.10. Places of samples stone extracted from the quarry *(Source: The Author).*

The results of the laboratory in Table II.2 show that the calcium carbonate is the most important element in the composition of the stone with a percentage greater than 90%, which mean that is a limestone, sedimentary rock.

Conclusion

As the type of stone differs, its thermos-physical components differ; therefore, its interaction with environmental factors varies. This section of the chemical analysis related with the determination of the stone type. In general, igneous rocks, sedimentary rocks and metamorphic rocks are classified according to their genesis, structure and texture, and finally according to their mineral composition. The visual inspection of the stone samples used in construction in Tébessa Wilaya shows that they are classified as sedimentary rocks. Since the sedimentary rocks can be of chemical or biochemical origin, the chemical analysis considered as the best method to determine the stone type by revealing its chemical components, for this purpose, many studies were carried out in the laboratory of Dokuz Eylul University to analyze the stone samples.

SECOND PART

Thermal behavior of natural stone building in the semi-arid climate

CHAPTRE III

EMPIRICAL STUDY

"If you cannot measure it, you cannot improve it"

William Thomson (Lord Kelvin)

CHAPTER III: Empirical study

Introduction

The thermal behavior of buildings depends on several parameters, the envelope of the building and its composition, on the other hand, the climatic context where the building is located, especially these factors; temperature variations, humidity, air speed, precipitation. The interaction between these two parameters influences the thermal comfort of buildings. However, to understand and control of any phenomenon requires extensive studies in real conditions, from this perspective, this study was carried out to understand and evaluate the thermal behavior of the natural stone buildings, starting from the measurement in situ, to the validation and verification of the experimental measurement results with the dynamic simulation results.

III.1. Presentation of the case studied

This study was carried out in the Hammamet city, Tébessa Wilaya, which is characterized by severe weather conditions and very large temperature difference between day and night. This city located in the east of Algeria as it shown in the Fig III.1 at an attitude of 35.483° North and Longitude of 8.133° East, and an attitude of 813 m above the sea level, with a land area of 184 km^2. The ancient buildings of Tébessa knew the use of local materials as the stone, appropriate to the climatic context.

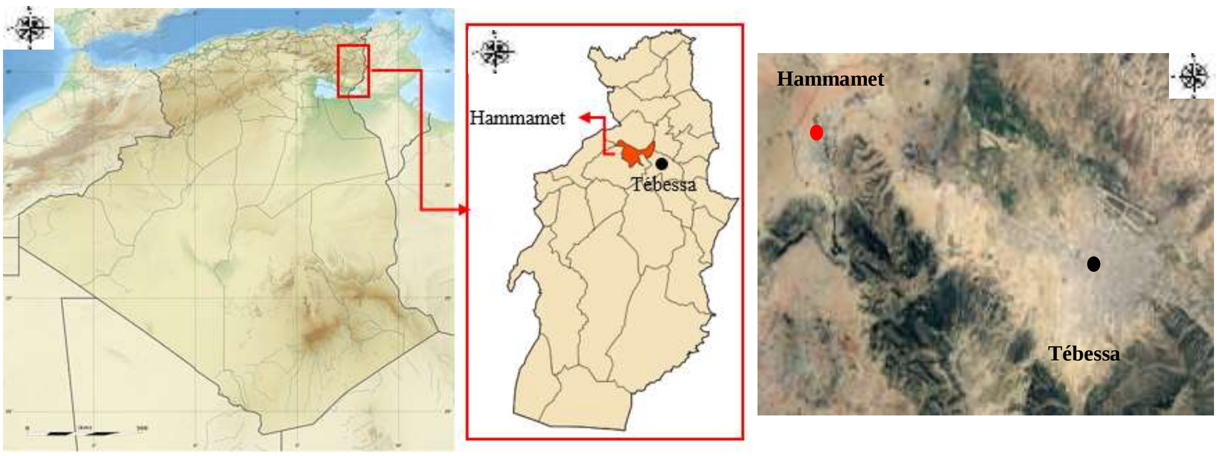


Fig. III.1. Geographical location of Hammamet, Tébessa Wilaya, Algeria *(Source: www.google.fr/maps).*

III.1.1. The climatic context

The climate in Tébessa Wilaya is varied because of its large surface area (See Fig. III2), three types are determined according to the Köppen-Geiger (K-G) climate classification illustrate in the Appendix A. The North of Tébessa Wilaya has a warm temperate climate, hot and dry in summer (Csa), the south characterized by a cold and dry desert climate (BWk), and the dry and cold (semi-arid) steppe climate (BSk) dominates the other parts of the Wilaya as shown in the Fig. III.2.

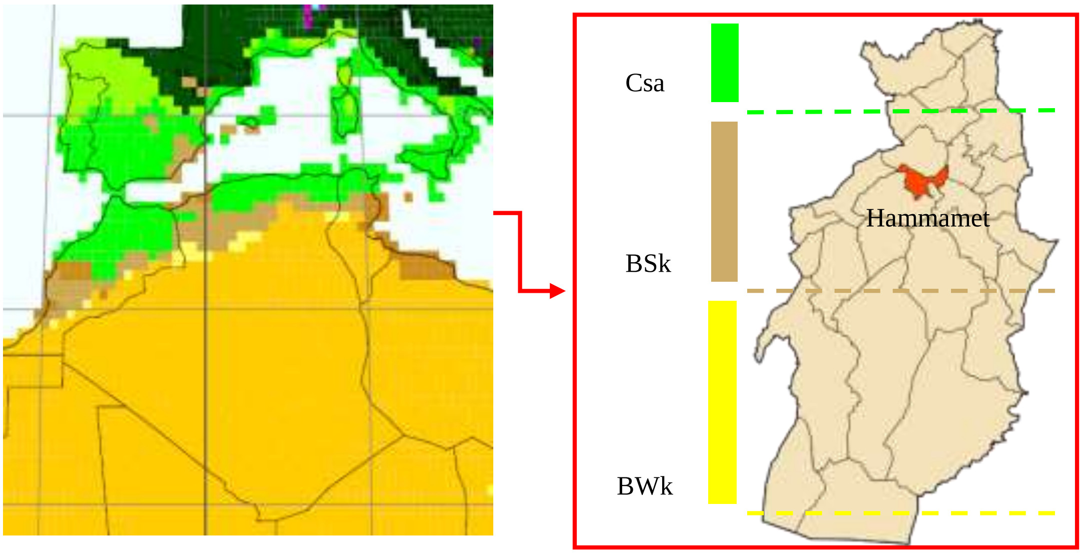


Fig. III.2. The Köppen-Geiger climate classification, Tébessa Wilaya, Algeria *(Source: The Author extracted from Köppen-Geiger climate classification map).*

The study cases are located in the city of Hammamet, which situated 10 km northwest of the city of Tébessa, this city influenced by a semi-arid cold climate (Bsk) according to the Köppen-Geiger climate classification. Kottek et al. (2006) explained in their study that this type of climate is determined by the annual mean temperature T_{ann} which should be less than 18°C, while the accumulated annual precipitation is more than 5 mm dryness threshold, this last depends on the annual cycle of precipitation and the annual mean temperature. The dryness threshold calculated by:

$$\text{Dryness thershold} = \begin{cases} 2\{\text{annual mean temperature}\} \text{ if at least 2/3 of the annual precipitation occurs in winter.} \\ 2\{\text{annual mean temperature}\} + 28 \text{ if at least 2/3 of the annual precipitation occurs in summer.} \\ 2\{\text{ annual mean temperature}\} +14 \text{ otherwise.} \end{cases} \quad (1)$$

III.1.2. Data climate

The data climate of Hammamet city from the meteorological station of Tébessa over 30 years since 1991 to 2019, illustrated in the Fig.III.3 shows that the annual mean temperature recorded does not exceed 18 C°, thus this is consistent with the previous study about the cold semi-arid climate.

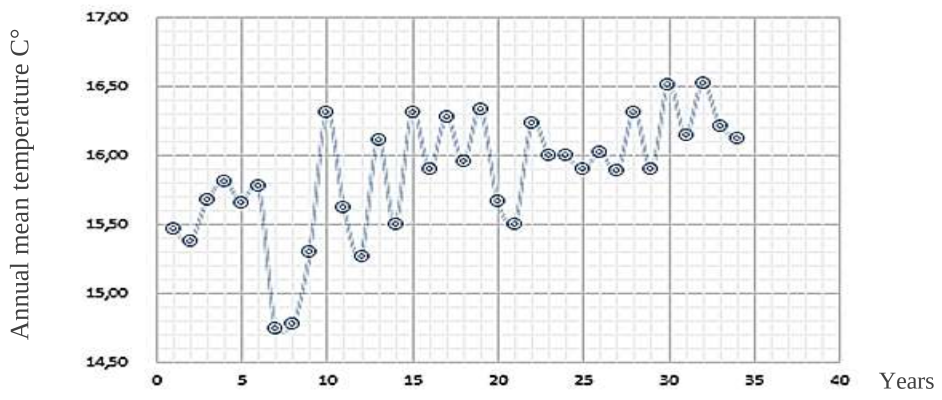


Fig. III.3. The annual mean temperature in Hammamet, Tébessa Wilaya, Algeria *(Source: The Author extracted from the meteorological station data of Tébessa).*

As it shown in the Fig. III.4 , the average number of the frosty days in this case is 19 days per years in the cold season, this is which proved that the climatic condition is almost harsh; we consider the frosty day if the recorded temperature in the cold season is equal to or less than 0 degree Celsius. We note that from the year 2000, the number of frosty days are increased; in these last years, it reach 39 days in the year 2008 as a maximum value recorded, then 38 days, 36 days, 35 days in the year 2019, 2012, 2005 in order. As the cold season is estimated at three months (90 days), these values are almost equivalent to one-third of the season (1/3 per season).

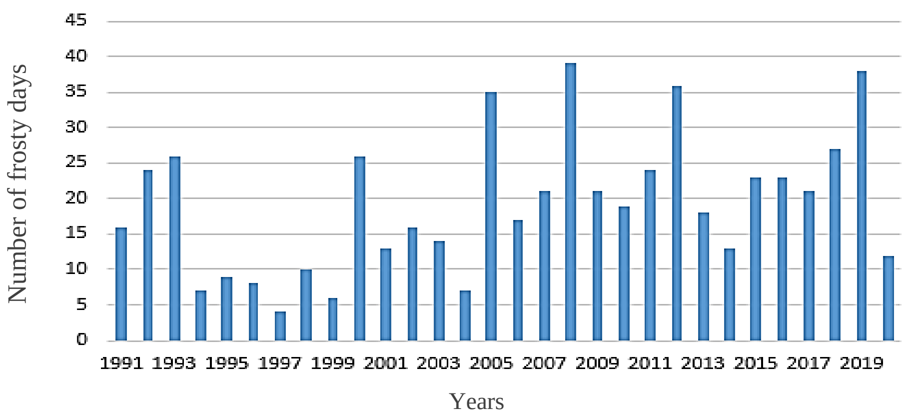


Fig. III.4. Number of frosty days in Hammamet, Tébessa *(Source: The Author extracted from the meteorological station data of Tébessa).*

The data climate from the meteorological station of Tébessa for more than 30 years (see Appendix 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°. As well as the low temperature recorded during this month is -3 C°. the climatic file also shows that there is an important different temperature between day and night in this case, this average gap reach 10 degrees in the cold season and 13 degrees in the hot season.

Table III.1. Average monthly precipitation in Hammamet, Tébessa *(Source: The meteorological station data of Tébessa).*

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

The precipitations in this region are low 342.5 mm, March represent the wettest month, when an average of 44.8 mm of precipitation occurs. July is the hottest and driest month when an average temperature of 27C° occurs, the average precipitation in this month is 11.3 mm, while the average amount of precipitation is 342.5 mm per year as shown in the Table III.1.

III.1.3. The natural stone buildings in Tébessa

The ancient residential buildings in Tébessa built of natural stone and traditional techniques during the colonial period in Algeria in the early 1900s before the first thermal regulations 1974, when there are no performance criteria match current standards (Rabouille, 2014). The stone blocks used in construction are extracted from the Gaagaa quarry situated 6 km south-west of Hammamet city according to the data of the Directorate of Industry and Mines in Tébessa Wilaya (See Fig. III.5).

Fig. III.5. Stone block extracted from Gaagaa quarry *(Source: The Author).*

The use of the natural stone as a building material in this climatic context, stems from the efficiency of this heavy material in order to improve the thermal comfort in the arid and semi-arid regions, where the temperature difference between day and night is very important. Some samples of ancient residential buildings built in natural stone in Tébessa shown in the Fig. III.6.

Fig. III.6. Ancient residential buildings in Tébessa *(Source: The Author)*

III.1.4. Description of the studied buildings

This study is focuses on residential buildings in the colonial district in the Hammamet city, Tébessa Wilaya, to cover all the possible cases, 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 it is shown in the Fig III.7. These buildings have been selected after a thorough analysis of a large number of residential buildings in the city, according to the assigned objectives of the study, and the feasibility of measurement. Where it was difficult to find all of the criteria in this social context; obviously, some habitant were not supportive of take the measurements in the natural conditions, without use any heating or cooling system in the harsh climatic conditions.

All of them contain three rooms plus kitchen and bathroom with a height of 3.20 m, these buildings covered by a sloping roof with tiles using wood supports, while the height of the punch of the roof is 1 m distance from the false ceiling to the ridge board. The openings were made of 0.03 m thick wood, where the measurements of all doors are 2.20 m× 0.9 m. The measurements of the Building 1, Building 2 windows are 1.20 m×1.20 m, while the measurements of the Building 3, Building 4 window are 1.50 m×1.20 m. the details of the buildings and the room where the experimental measurements have been performed illustrated in the Appendix D.

Fig. III.7. Details of buildings studied *(Source: The Author).*

This study is carried out also on the facade of each building to study the stone wall thermal behavior in the semi-arid climatic context, all of the details of the construction materials used from inside to outside and their thermos-physical properties are illustrated in Table III.2.

Table III.2. Thermos-physical properties of the facade materials *(Source: The Author).*

Materials	Layer thickness [m]	Conductivity [w/m.k]	Specific heat [kJ/kg.k]	Density [kg/m^3]
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

III.2. The energy consumption

The last researches proved that the energy consumption of buildings is affected by the climate, a study done by Guedamsi et al.(2016) shows that in Algeria there are three climatic zones according to the heating energy consumption costs. The cost thermal energy requirements for heating in Tébessa is classified in the second zone, due to the harsh climatic conditions in the winter there, while the cost thermal energy requirements for cooling in this region is classified in the last zone of energy consumption, so the case of study have shown high energy consumption (See Fig.8).

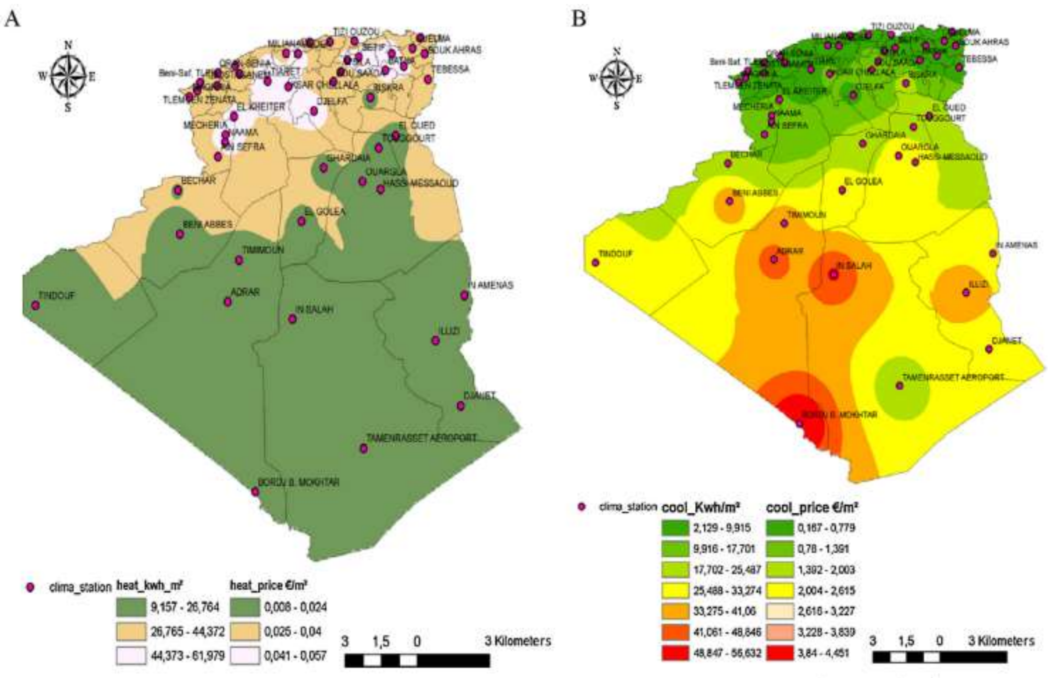


Fig. III.8. The climatic zones map for heating and cooling. *(Source: Guedamsi et al., 2016)*

According to the Algerian Industrial Energy Company specialized in the distribution of electricity and natural gas in Tébessa Wilaya (Sonelgaz); the case of study have shown high energy consumption. The heating energy consumption in the district studied (See Fig. III.9) accounts for 11037.6 m^3 per year for each residential building, while the average gas consumption by year for one residential building is 1000 m³ per year. On the other hand, the cooling energy consumption in this district reach 2795.4 kWh per year for each dwelling, while the average gas consumption by year for one residential building is 1500 kWh per year.

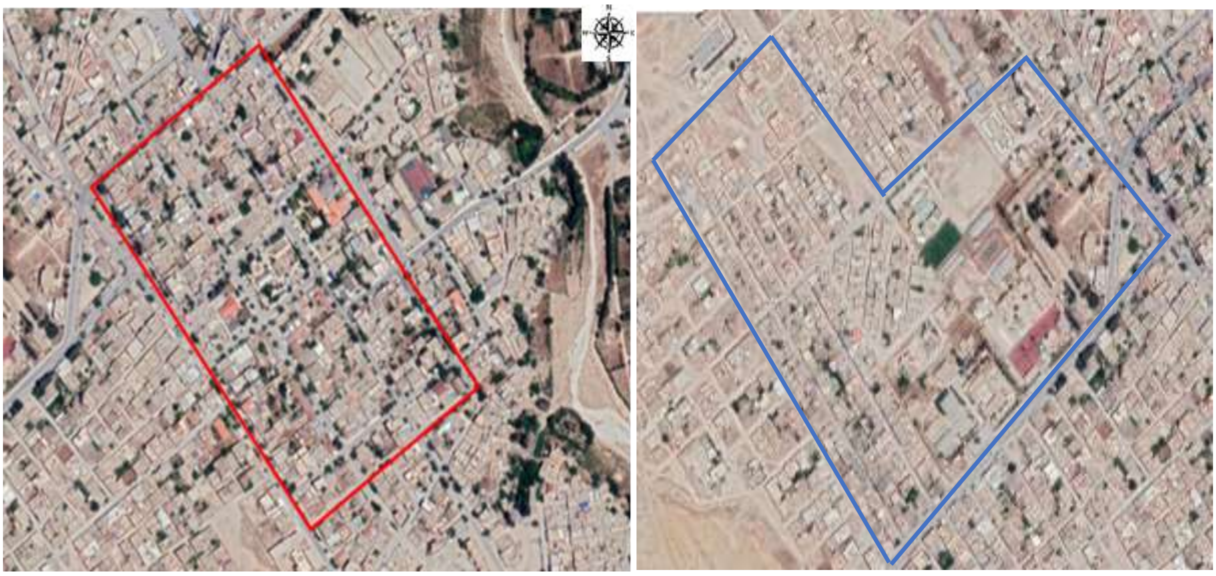


Fig. III.9. The energy consumption of the colonial district in red and the new district in bleu in Hammamet, Tébessa Wilaya. *(Source: www.google.fr/maps)*

Table III.3 compare the energy consumption for heating and cooling between the colonial district studied, where all buildings built with natural stone, and a new district built after the independence with cement blocks. However, it is important to emphasize that there is some contradiction can be noticed in this case, taking into account the efficiency of the natural stone wall as a thick wall and their properties in the improving the thermal performance and reduce the energy consumption.

Table III.3. The energy consumption of the ancient district and the new district in Hammamet, Tébessa Wilaya (*Source: the Algerian Industrial Energy Company specialized in the distribution of electricity and natural gas in Tébessa Wilaya (Sonelgaz)).*

The energy consumption	Ancient district	New district
Gaz [m^3/year]	11037.6	643.9
Electricity [kWh/year]	2795.4	16975

III.3. The measurements in situ

The experimental data allow to describing and evaluate the thermal behavior of these natural stone buildings during the cold and the hot season. However, the coldest and hottest week for taking measurements was determined by the method of the representative week "design week", it's calculated by using the meteorological data of Hammamet city in Tébessa Wilaya to determine the average daily temperature of the coldest and hottest month, then get the average outdoor temperature over more than 30 years (Khadraoui, et. al. 2018). Table III.4 shows that the 3rd week in January is the coldest week with average temperature of 6 C°, and the 1st week in July is the hottest week of year with average of 27 C° in this region.

Table III.4. Average monthly temperatures in Tébessa between 1985 and 2018. *(Source: Author extracted from th he meteorological station data of Tébessa).*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Average
1985	5,70	9,10	8,20	13,45	17,00	23,85	26,60	24,95	21,05	15,80	12,10	7,85	15,47
1986	6,05	7,35	9,20	12,95	19,05	22,50	25,45	26,50	21,70	17,10	10,25	6,45	15,38
1987	5,20	7,25	8,25	12,90	16,10	23,40	27,00	26,75	23,40	18,00	10,75	9,10	15,68
1988	7,55	6,95	9,85	13,65	19,45	23,35	27,00	26,20	20,60	18,00	11,15	6,05	15,82
1989	5,00	6,95	10,75	13,20	17,25	22,45	26,30	26,55	22,15	15,70	11,80	9,80	15,66
1990	6,30	9,35	10,20	12,55	17,80	24,20	25,95	24,90	23,75	17,70	11,05	5,65	15,78
1991	5,45	6,00	10,85	10,85	14,65	22,15	25,75	25,80	22,75	16,55	10,10	5,95	14,74
1992	4,50	6,30	9,10	12,15	16,80	21,85	23,90	25,65	22,00	16,45	11,55	7,00	14,77
1993	4,90	5,60	8,35	12,85	18,25	23,60	26,15	26,00	21,95	17,60	10,85	7,50	15,30
1994	7,10	8,05	10,30	12,05	19,40	23,55	26,80	28,05	23,35	16,70	12,30	8,05	16,31
1995	5,20	9,20	9,30	12,05	18,75	23,40	26,50	25,50	21,20	16,10	11,05	9,20	15,62
1996	7,60	6,30	9,75	12,65	17,55	22,25	25,70	26,35	20,20	14,85	11,35	8,70	15,27
1997	7,80	8,20	9,25	12,55	19,35	25,60	26,65	25,75	21,75	17,05	11,25	8,10	16,11
1998	6,30	7,70	9,00	14,15	18,05	24,85	26,80	25,85	22,35	15,10	9,65	6,20	15,50
1999	6,25	5,50	9,50	13,55	20,50	25,55	26,40	28,50	23,40	18,85	10,80	7,00	16,32
2000	4,10	6,65	10,50	14,70	19,95	23,25	26,90	26,40	22,00	16,00	11,70	8,60	15,90
2001	7,35	7,15	12,30	12,85	18,35	24,55	27,35	26,25	22,20	19,15	11,25	6,60	16,28
2002	5,20	7,35	11,15	13,80	17,80	24,50	26,75	25,80	21,65	16,80	11,95	8,70	15,95
2003	6,55	5,80	9,50	13,70	18,65	25,85	29,10	27,90	22,00	18,45	11,75	6,70	16,33
2004	6,50	8,15	9,90	12,95	16,55	23,00	26,40	26,95	21,55	18,75	9,70	7,55	15,66
2005	4,20	4,80	9,75	13,40	19,30	24,55	27,50	25,55	21,55	17,65	11,35	6,40	15,50
2006	4,60	6,55	10,60	15,40	20,10	24,50	27,35	25,85	21,35	18,35	12,05	8,15	16,24
2007	7,60	9,05	9,50	13,65	18,75	24,85	26,45	26,45	22,10	16,55	10,05	7,00	16,00
2008	6,65	7,20	9,90	14,55	19,25	23,55	27,70	26,40	22,45	17,05	10,50	6,75	16,00
2009	6,55	6,35	9,55	12,35	18,55	24,35	28,35	27,20	21,10	15,85	11,25	9,30	15,90
2010	7,25	8,80	10,90	14,25	17,50	23,20	27,20	26,10	21,50	16,30	11,15	8,15	16,03
2011	6,75	6,40	9,60	14,65	17,95	23,10	27,30	26,10	22,85	16,10	11,90	7,95	15,89
2012	6,20	4,40	9,65	13,90	18,50	25,90	28,25	27,60	22,40	18,00	13,05	7,90	16,31
2013	6,85	6,00	11,60	14,40	17,95	22,45	26,60	25,65	21,60	19,70	10,70	7,35	15,90
2014	7,30	8,60	9,30	13,90	18,15	24,20	26,60	26,75	24,10	18,20	13,20	7,80	16,51
2015	6,20	5,95	9,80	14,00	19,80	24,15	27,45	26,95	22,60	17,75	11,40	7,75	16,15
2016	7,70	8,90	10,05	15,00	18,60	24,20	26,90	25,40	21,85	18,90	12,00	8,80	16,53
2017	4,80	8,55	11,10	13,80	19,85	25,70	28,15	27,80	21,75	16,05	10,35	6,70	16,22
2018	7,75	6,45	10,90	14,50	17,70	23,70	28,55	25,15	23,10	16,40	11,10	8,15	16,12
Average	**6,21**	**7,14**	**9,92**	**13,45**	**18,33**	**23,89**	**26,88**	**26,34**	**22,10**	**17,16**	**11,25**	**7,61**	

III.3.1. Presentation and protocol for taking measurements

Three main parameters related of the thermal comfort; temperature, relative humidity and wind speed, are measured in this research to study the thermal performance of the natural stone buildings.

The measurements were taken for three days in the cold and hot season according to the design days calculated (See Appendix D), where the average outdoor temperature reach 6 C° in January 16th,17th and 18th, and 27 C° in July 5th , 6th , 7th . The measurements were taken twice hourly per day (bi-hourly), however, the windows were opened every morning for one hour simulated to the habitant's behavior from the 9h to the 10h in the cold season, and from the 8h to the 9h in the hottest season, while all doors were closed throughout the measurement period.

The measurements were taken in the living room of each building in natural conditions and without any heating or cooling system, while the dwelling was emptied of any habitants to make sure that the protocol was carried out in the passive control systems.

III.3.2. Measurement instruments

In order to carry out this experimental measurement, three types of instruments (See Appendix E) illustrated in Fig. III.10 are used in this investigation are:

Fig. III.10. Measurement instruments; (**a**) Infrared thermometer. (**b**) Hygro-thermometer. (**c**) Thermal anemometer *(Source: The Author).*

- Infrared thermometer was pointed in the middle of the wall studied to measure:
  - The temperature of the external surface of the wall.
  - The temperature of the internal surface of the wall.
- Hygro-thermometer, which measure:
  - The moisture content of the air to determine its outdoor relative humidity.
  - The moisture content of the air to determine its indoor relative humidity.
  - The ambient temperature.
  - The outdoor temperature.

- The thermal anemometer installed at 1.5 m above the floor, which used for measuring:
    - The outdoor wind speed.
    - The indoor wind speed.

The ambient inside temperature, the internal surface temperature, the external surface temperature and the outdoor temperature are measured in degrees Celsius. We point out that the lack of instruments connected with the PC that automatically save the measurement data, hampered the measurement process, moving between the buildings studied every two hours in a short period was rather difficult. All of the instruments are used before taking measurements to verify their performance and take into consideration the time taking to measure each building and moving to the other.

III.4. The dynamic thermal simulation DTS

The simulation experiment consists of a series of simulation runs, during which all factors stay constant, on the other hand, during the experiment, factors do change; that is, each factor has at least two values in the experiment. In the issue of statistical validation and verification, we compare the data on the real and the simulated systems if both systems are observed under similar scenarios, then the validation becomes possible, when the validation defined as the conceptual simulation model is an accurate representation of the real system (Kleijnen, 1998).

The simulation allows detailing several phenomena related to the internal environment of the building while giving coherent results, in the issue of reducing energy consumption of the building, the dynamic thermal simulations (DTS) allow identifying the ways of improvement (Rabouille, 2014). It allows simulating the thermal exchanges in the building, taking into consideration all the phenomena that have an important influence on the building's heat. There is a various variables influence on the DTS; the outdoor conditions (outdoor temperature and humidity, wind, solar radiation, soil temperature), the building (envelope, glazing, inertia), building uses (occupancy rate, occupancy schedule, electrical equipment, ventilation, lighting). It is carried out at an hourly or sub-hourly time step.

Building simulation programs such as EnergyPlus are used to calculate the dynamic heat load and cooling load of a room, zone or building. These programs require input of descriptions of thermal physical properties and dimensions of building components (such as walls, floors, ceilings, and windows). In addition to detailed building descriptions, weather data on the location of the building must also be provided. Building simulation programs are used to determine the most economical design or modification based on heating, cooling, equipment and material costs. (Seem, 1987).

III.4.1. EnergyPlus simulation program

A dynamic thermal simulation used in this research to validate the experimental results of the thermal behavior of the natural stone buildings studied, with the "EnergyPlus" building energy simulation software; for modeling building heating, cooling and other energy flows. Each year one to two new programs are released; the release used in this research is the 9.3.0 version, it is compatible with Windows systems and Linux & Mac (See Fig. III.11), the time steps used to model the interaction between thermal zones and the external environment in this study is and is defined 1hour.

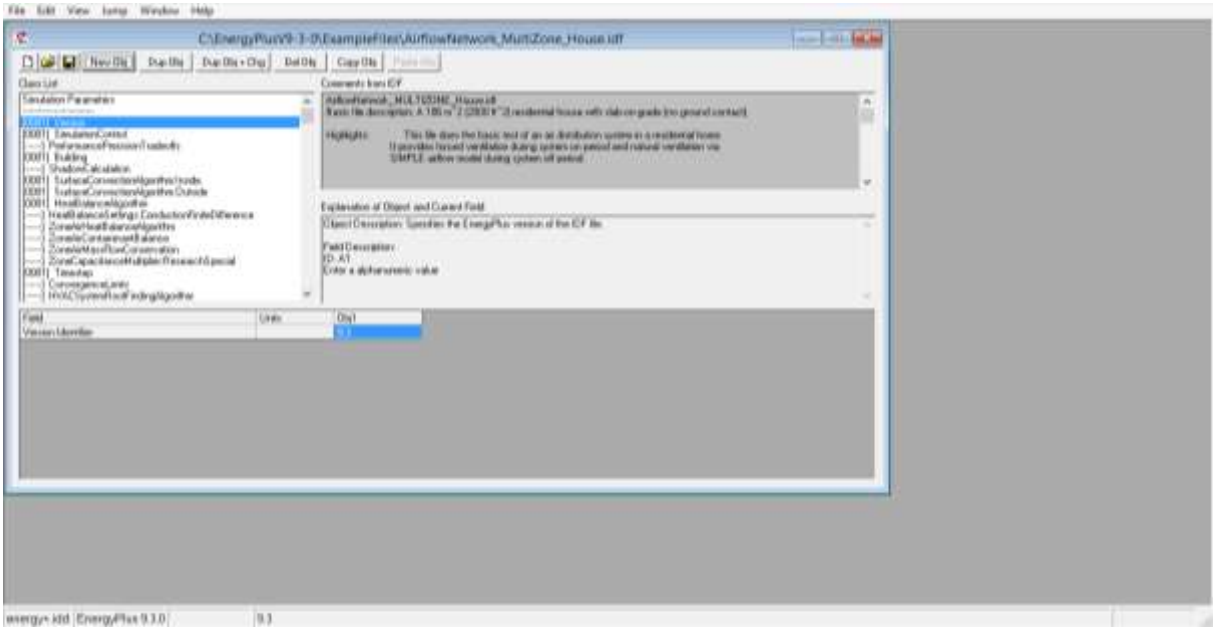


Fig. III.11. Interface EnergyPlus software. *(Source: energieplus-lesite.be)*

EnergyPlus is based on ASCII text input and output files, and there is no 'user-friendly' graphical interface, it is a stand-alone simulation program. An interface for the creation and modification of input data file is provided and called "IDF Editor" as it is shown in the Fig.III.11. Several interfaces have been developed to overcome the limitations and simplify the use of the tool, as OpenStudio (NREL) and DesignBuilder (UK) (Desideri & Asdrubali, 2018). A climate file (See Appendix C) based on the Tébessa meteorological station was generated by the "Meteonorme 7" software in "epw" format was used in this simulation (EnergyPlus Weather data).

This program simulates the environmental and energy performance of the building by considering the interaction of all the building components and systems, for instance, building envelope, windows, structure, heating, ventilation (Chowdhury. et al, 2016).

The EnergyPlus simulation software was chosen for many reasons (Spitz, 2012; Fumo. et al, 2010):

- It is one of the most programs used energy simulation tools available at academic level, where it has proven its effectiveness.
- It is open source and freely downloadable.
- It is a complete and multiplatform tool with an important development and modeling capacity of the developed energy systems.
- Moreover, it allows access to many internal variables of the calculation.
- The inputs and outputs are in text format and the tool can be used in parallel without a graphical interface.
- It has been the subject of several validations and has great acceptance from the scientific community.

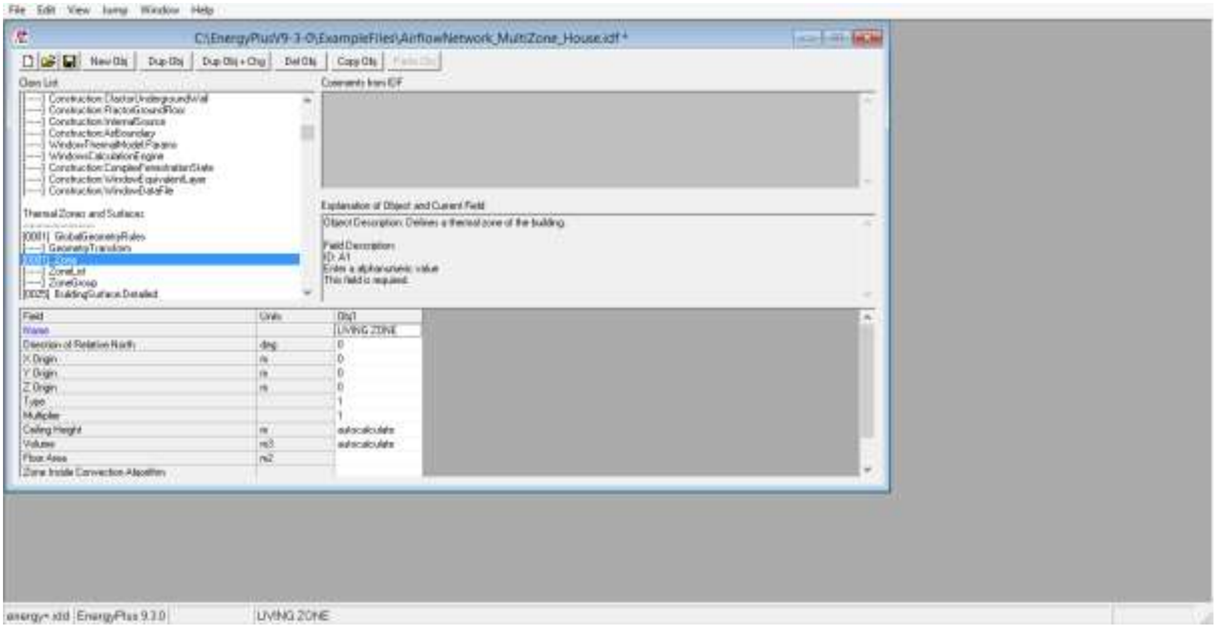


Fig. III.12. Editing vertices. *(Source: energieplus-lesite.be)*

The simulation of this research was carried out in the cold and hot season (in the design days). The input data used according to the protocol of taking the experimental measurements, where each space studied (living room) represents a thermal zone. The method of editing vertices (See Fig. III.12) is used in this simulation to alter the building geometry without having to redraw objects as it shown in the fig. As well as there are no outside obstructions were introduced, due the opposite buildings do not cast shadows on the facade of the studied buildings.

III.5. Results of the measurements in situ

III.5. 1. In the cold period

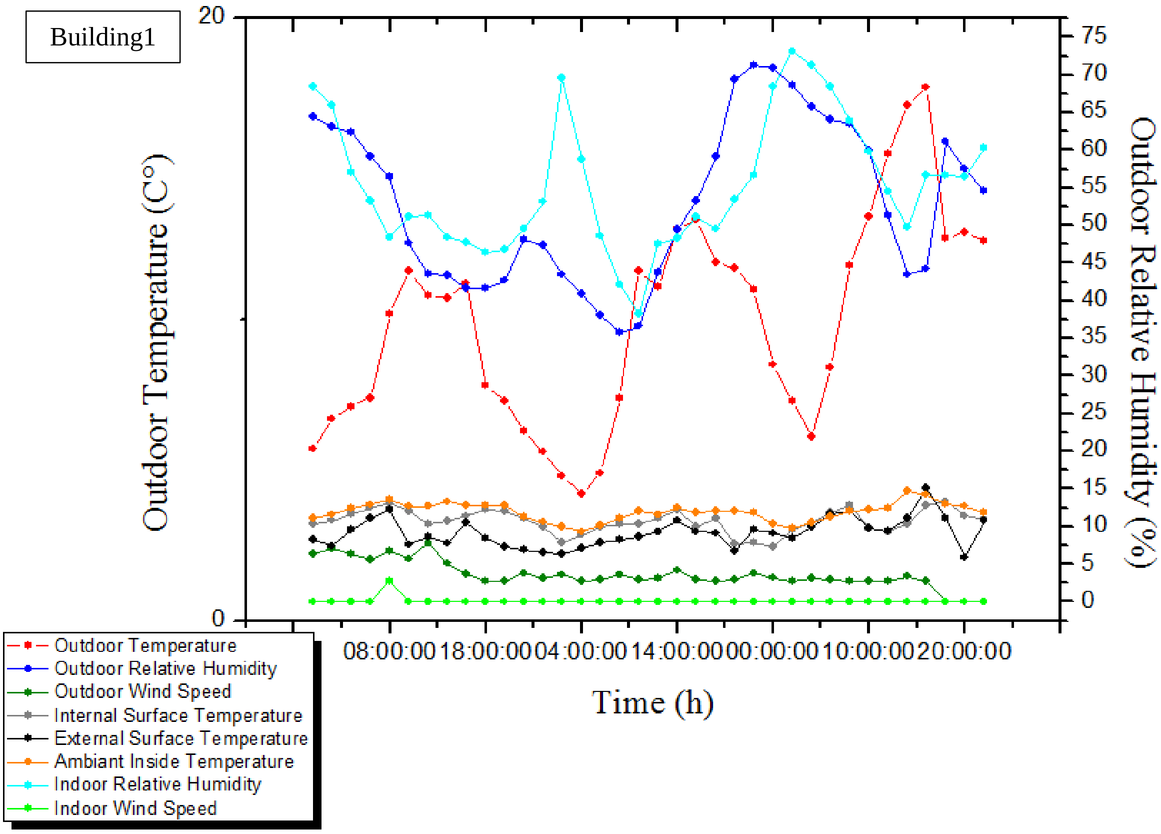
The graphs in Fig. III.13 illustrates the measurements in situ obtained for all buildings studied. As the orientation of the building changes, the heat gain of walls changes, depending on how long it is exposed to the sun during the day. Thermal inertia consists in the accumulation of heat in the envelope for a restitution inside by radiation. The complexity of this phenomenon lies in the fact that the flow of heat through the envelope successively increases the temperature of the materials (Chuayb, M. H. M. A, 2015), which affects their thermo physical properties, but not affect the thermal inertia of the envelope. In these cases studied, it was revealed that the different orientations of buildings did not affect the results obtained in the cold season where all the graphs of the external surface temperature are slightly different.

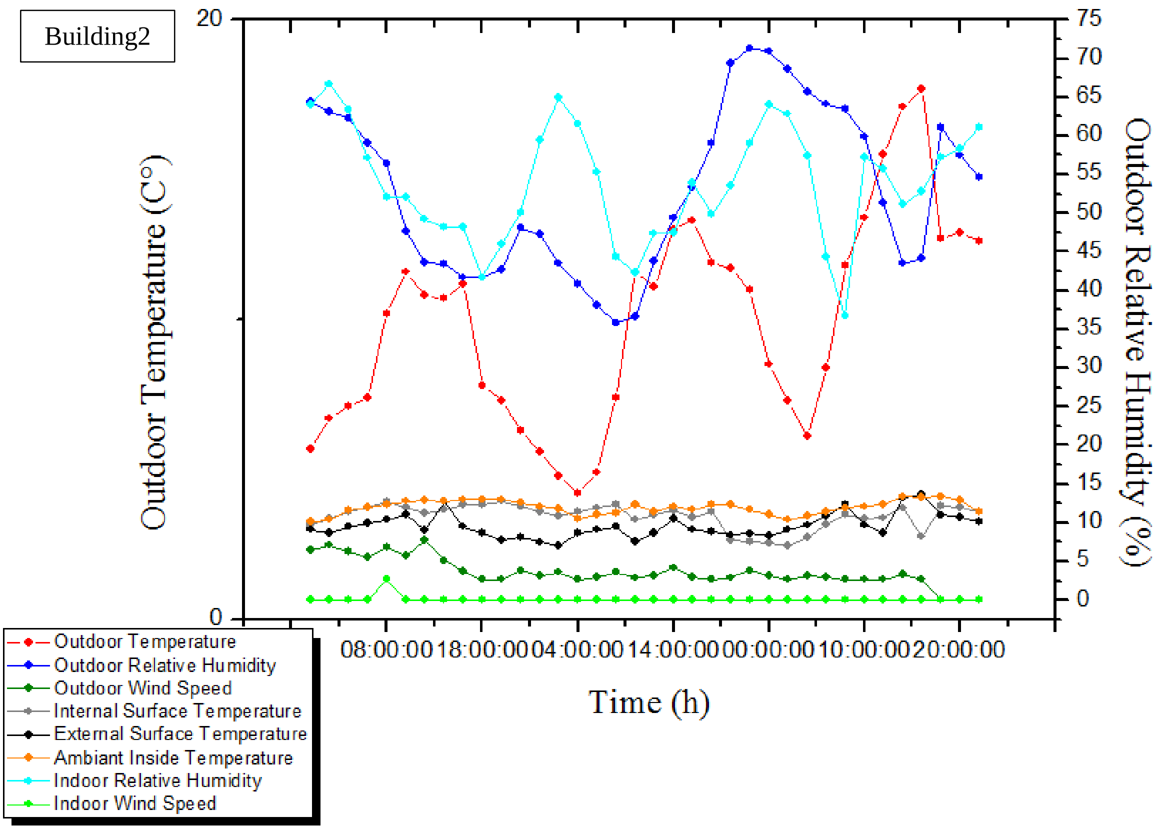
It was observed that the outdoor temperature rises during the day, and then decreases significantly at night in a short period not exceeding 12 hours. It was recorded 11.6 C° as maximum value at 10h in the first day. In the second and third day it was recorded a maximum temperature 13.3 C° and 17.7 C° at 16h. As well as the minimum temperature was recorded in the first day was 5.7 C° at 00h. A value of 4.2 C° and 6.1 C° are record on the second and third day at 16h.

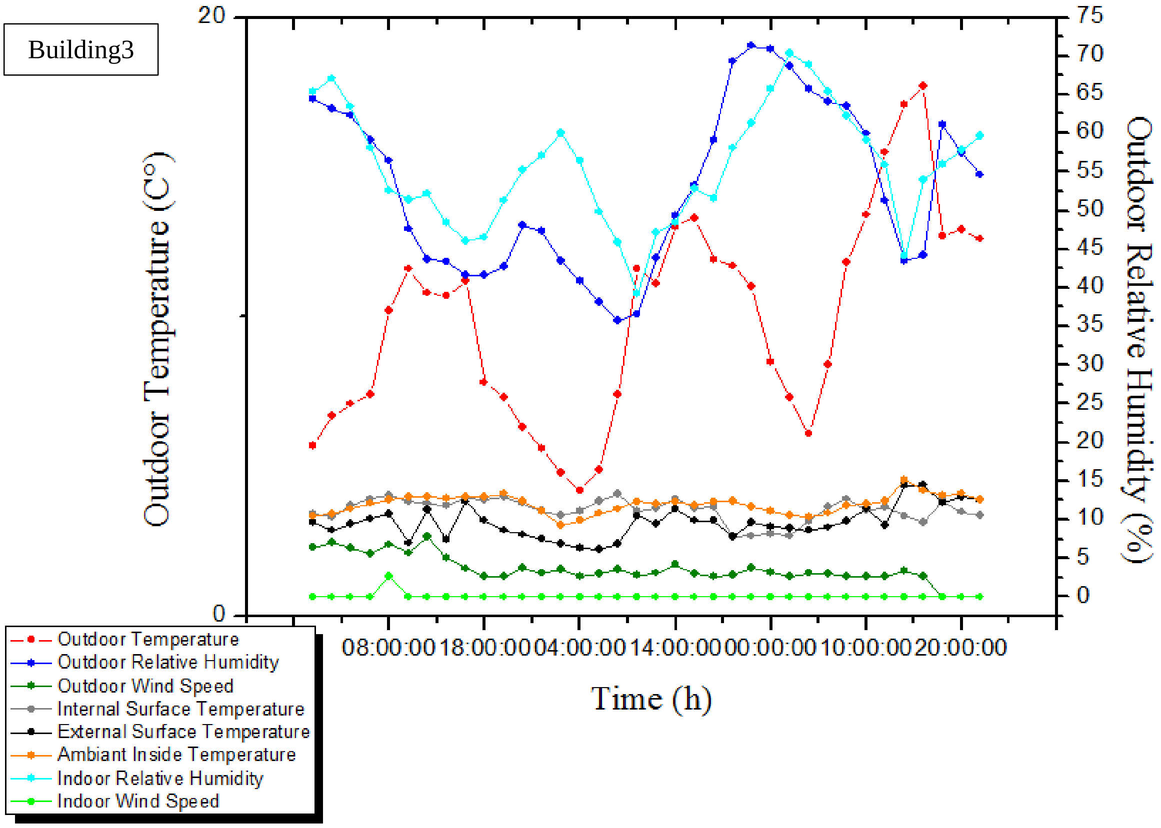
However, the temperature difference between the day and the night reach 5.7 C° and 9.1 C° and 11,6 C° in the three days in the order. This important gap has a significant influence on the limestone used in construction, where the heating and cooling of this stone type affects its components. As result, it deteriorates and erodes; this is called the thermal shock effect weathering (Yavuz, et al., 2006).

The indoor relative humidity rises at night to reach 73.1 % in the Building 1 and 66.7 % in the Building 2 and 70.3 % in the Building and 63.5 % in the Building 4. Then it decreases during the day to reach 38.2 % in the Building 1 and 36.2 % in Building 2 and 39.2 % in Building 3 and 44.3 % in Building 4.

It was noticed that there is a coherence between the indoor and outdoor relative humidity, which reach a maximum values of 84 % at night, and a minimum values of 24 % over the day.


Building1
20
0
Outdoor Temperature (C°)
Outdoor Relative Humidity (%)
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
08:00:00
18:00:00
04:00:00
14:00:00
00:00:00
10:00:00
20:00:00
Time (h)
Outdoor Temperature
Outdoor Relative Humidity
Outdoor Wind Speed
Internal Surface Temperature
External Surface Temperature
Ambiant Inside Temperature
Indoor Relative Humidity
Indoor Wind Speed


Building2
20
0
Outdoor Temperature (C°)
Outdoor Relative Humidity (%)
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
08:00:00
18:00:00
04:00:00
14:00:00
00:00:00
10:00:00
20:00:00
Time (h)
Outdoor Temperature
Outdoor Relative Humidity
Outdoor Wind Speed
Internal Surface Temperature
External Surface Temperature
Ambiant Inside Temperature
Indoor Relative Humidity
Indoor Wind Speed



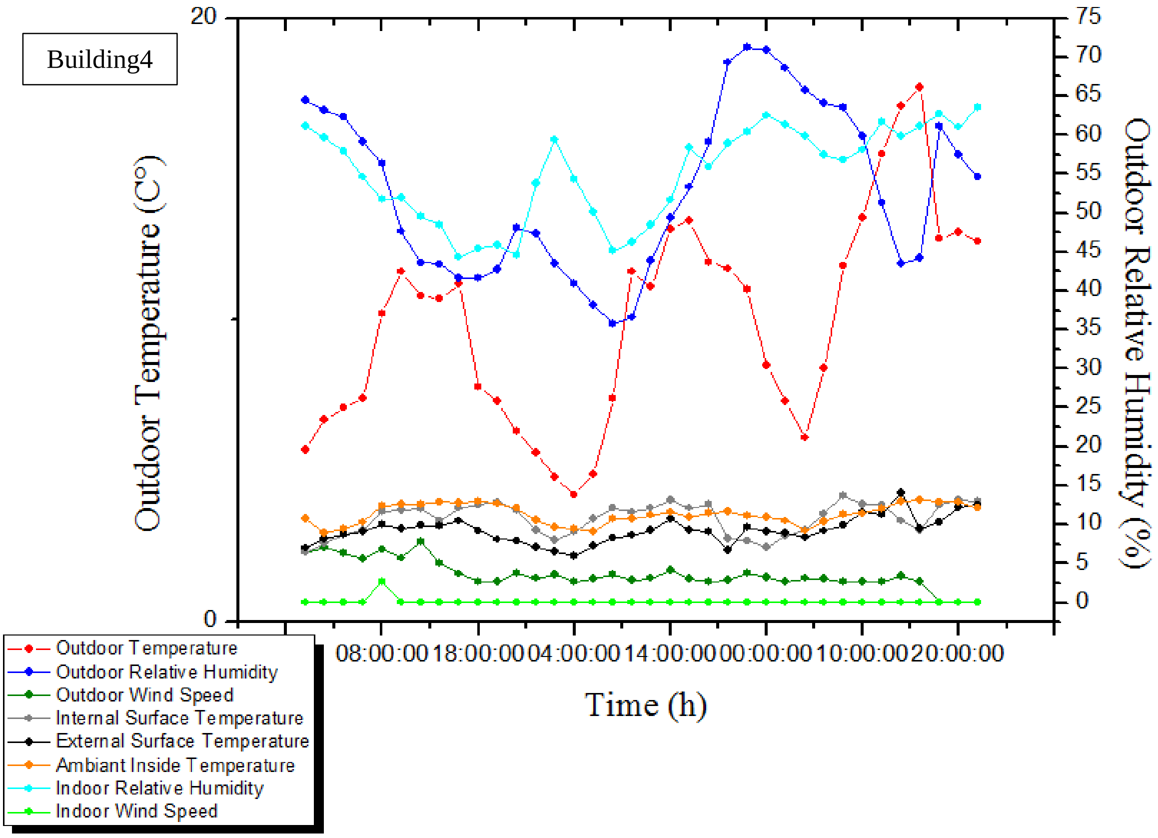


Fig. III.13. Results of the measurements in situ of the buildings in the cold period. *(Source: The Author)*

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

On the other hand, it was revealed that the ambient inside temperature values are low compared to the outdoor temperature values over the three days in the four cases. The values recorded in the Building range from (14.7 C° to 9.3 C°), (13.4 C° to 10.1 C°) in the Building 2, (15.1 C° to 9.3 C°) in the Building 3 and (13.1 C ° to 8.9 C °) in the 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, 20h in Building 1, Building 2, Building 3, Building 4 respectively, with a difference of 4 hours at maximum between the two pics. This low thermal phase shift contribute to reducing the thermal inertia of buildings (Yam, et al., 2003).

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

The convergence of these temperature results due to the influence of the thermal shock effect weathering on the thermos-physical properties of the limestone. Knowing that the stone saturated with water have a higher thermal conductivity coefficient than the dry stone. Consequently, the thermal inertia of stone decreases as shown in these cases studied, note that these buildings thermal inertia is almost low than buildings natural stone thermal inertia usual.

However, it was revealed that the outdoor wind speed was rather high, where it ranged between 7.1 m/s and 2.7 m/s. It was noticed that the indoor wind speed in the four buildings studied is void over the three days, even that the windows was opened in the morning. Except the first day where the outdoor wind speed estimated 6.8 m/s at 8h, it was recorded value of 2.7

m/s as indoor wind speed. The most important element was noticed that it could not get a good natural ventilation in buildings during the day only if the outdoor wind speed exceed 6 m/s. The very high indoor relative humidity percentage and the absence of the natural ventilation has a significant influence on the ambient inside temperature values (Sanchez, et al., 2016).

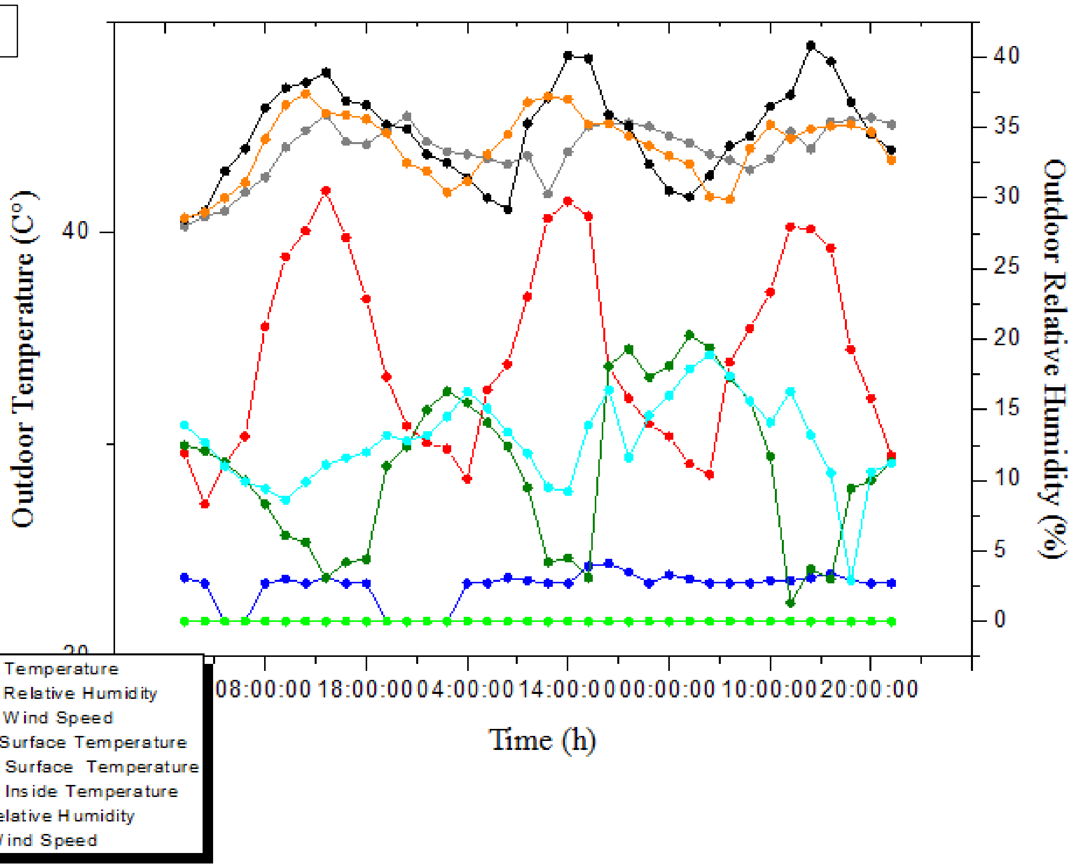
III.5. 1. In the hot period

The graphs in Fig. III.14 illustrates the measurements in situ obtained for all buildings studied in summer. It was recorded 42C°, 41.5C°, 40.3C° as outdoor temperature values at 14h, then it reach to 29.1C°, 28.6C°, and 28.6C ° at 4h in the three days respectively. While these high temperatures were recorded, the relative humidity values recorded was very low, 3.1%, 4.5%, 3% were recorded at 14h and it rise in the night to reach 12.5%, 15.5%, 17.3% at 6h in the three days respectively. We explain the decrease of the outdoor temperature and the increase of the outdoor relative humidity in the third day by the precipitation with a very small percentage for a short period. These results confirm the harsh climatic factors in this region, which affect the thermal behavior of the natural stone used in construction.

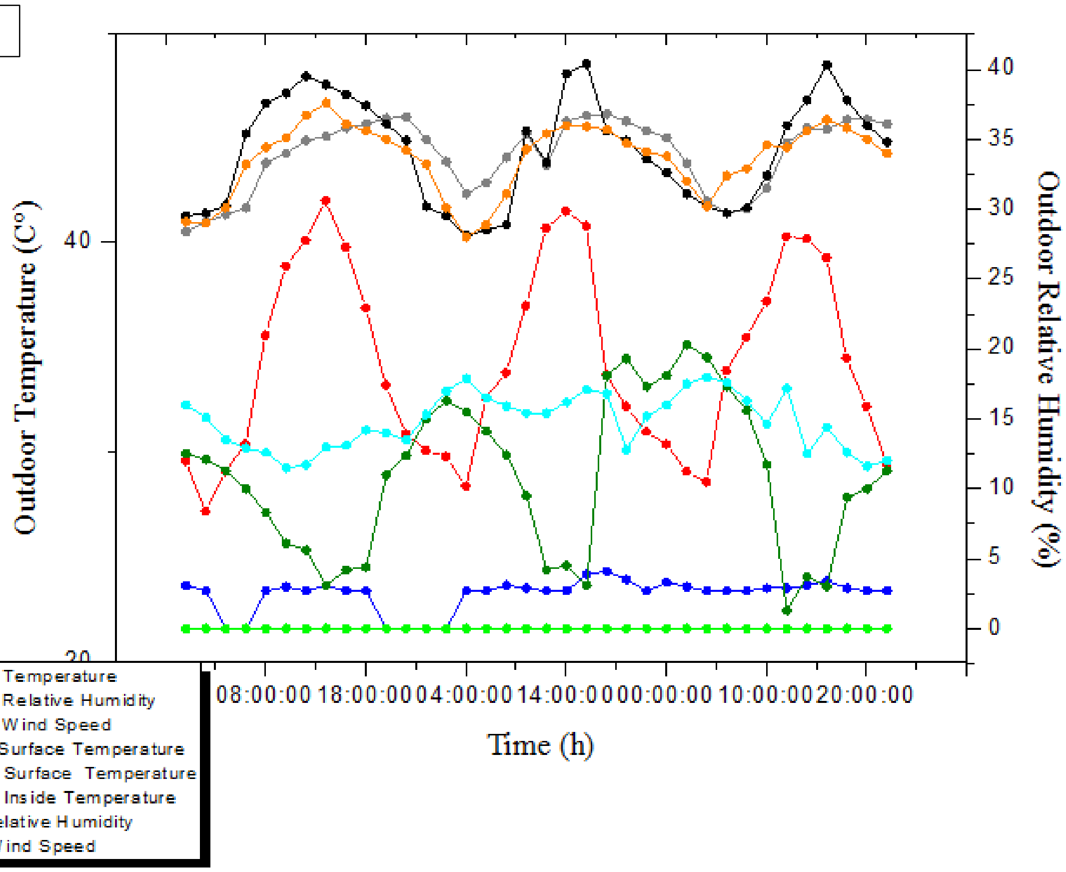
It was revealed that the different orientations of buildings affect the results obtained in the hot season. The graphs of the external surface temperature are different regarding to the building orientation. The solar gains of South-facing facades are easier to handle than, those of North East and North West facing facades. The external surface temperature of Building 1 exceed 41 C°, and reach 45.5C° in the Building 4 in the three days at 14h, then it decrease to reach 28C° at night in the four cases. While it reach 36.9 C° and 40C° at 14h in the Building 2, Building 3 respectively.

In addition, the curves of the external surface temperature in the Building 2 and Building 3 cases are almost the same as internal surface temperature, as the external surface temperature increases, the internal surface temperature increase at the same time gradually. It reach 36.8C° and 38.5C° in the Building 2 and Building 3 respectively at 14h, when it reach 35.8 C° and 37.9 C° in the Building 1 and 4 at 14h. Then it decrease to reach 28.3 C° at night in the four Buildings. The deference between the external surface and the internal surface temperature in the Building 1 and Building 4 is almost 6C° in day and 9C°, 2C° in the day and 8C° in the Building 2 and Building 3 respectively. This difference between the higher value and the lower value is recorded in 6 hours of time difference. This refers to weak phase shift time in the Buildings with northern facades compared to those with southern facades, and bad heat accumulation in the day compared to the night.

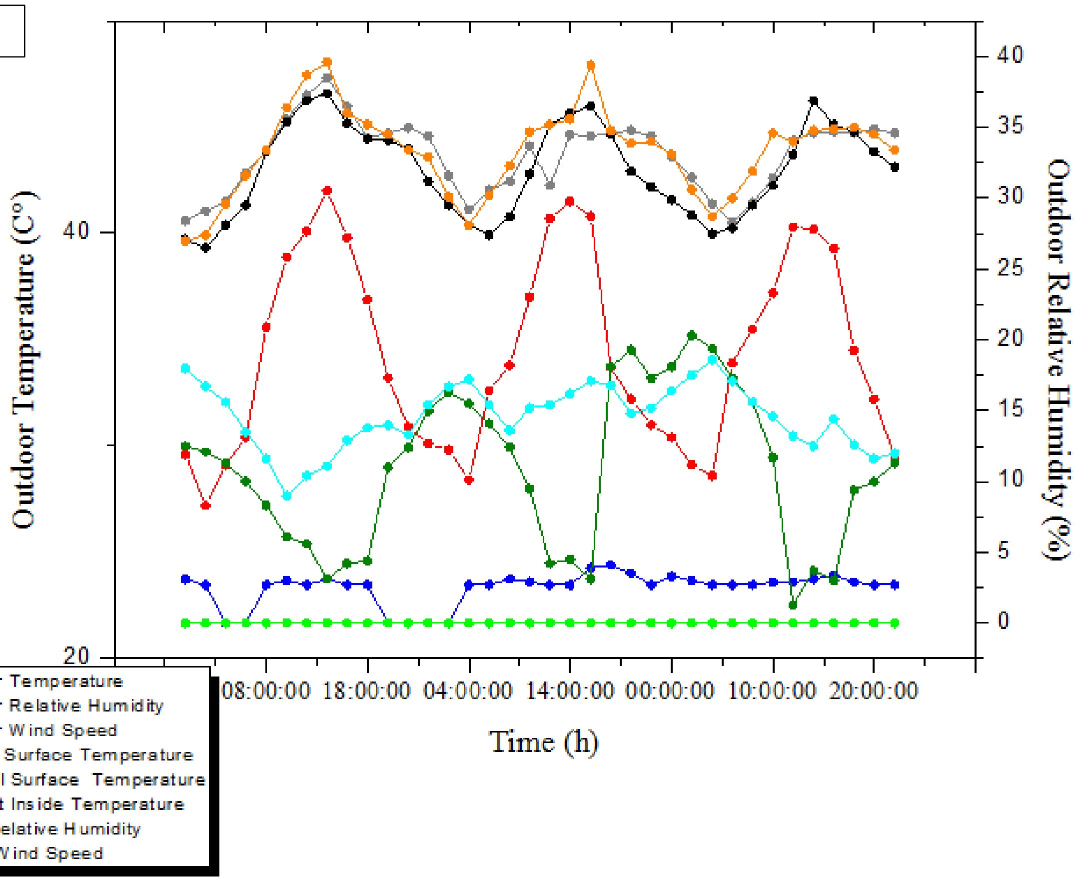
Building1



Building2



Building3



Building4

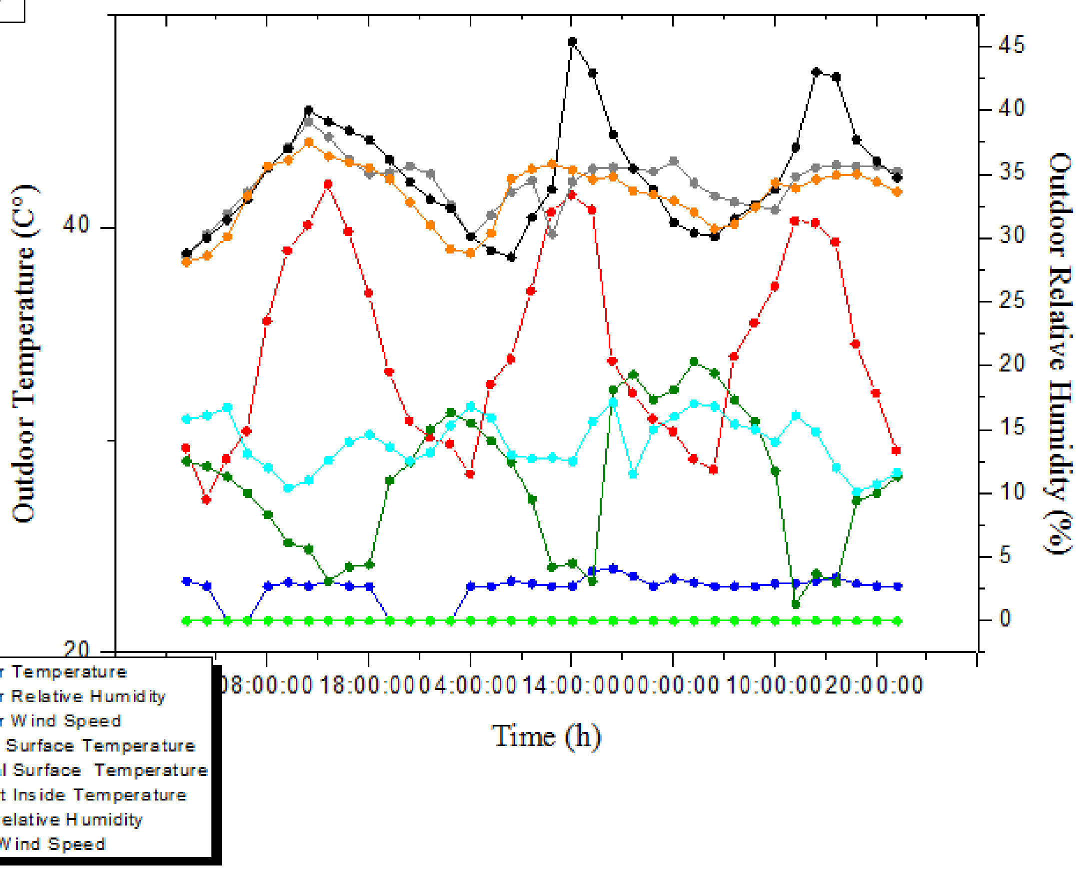


Fig. III.14. Results of the measurements in situ of the buildings in the hot period. *(Source: The Author)*

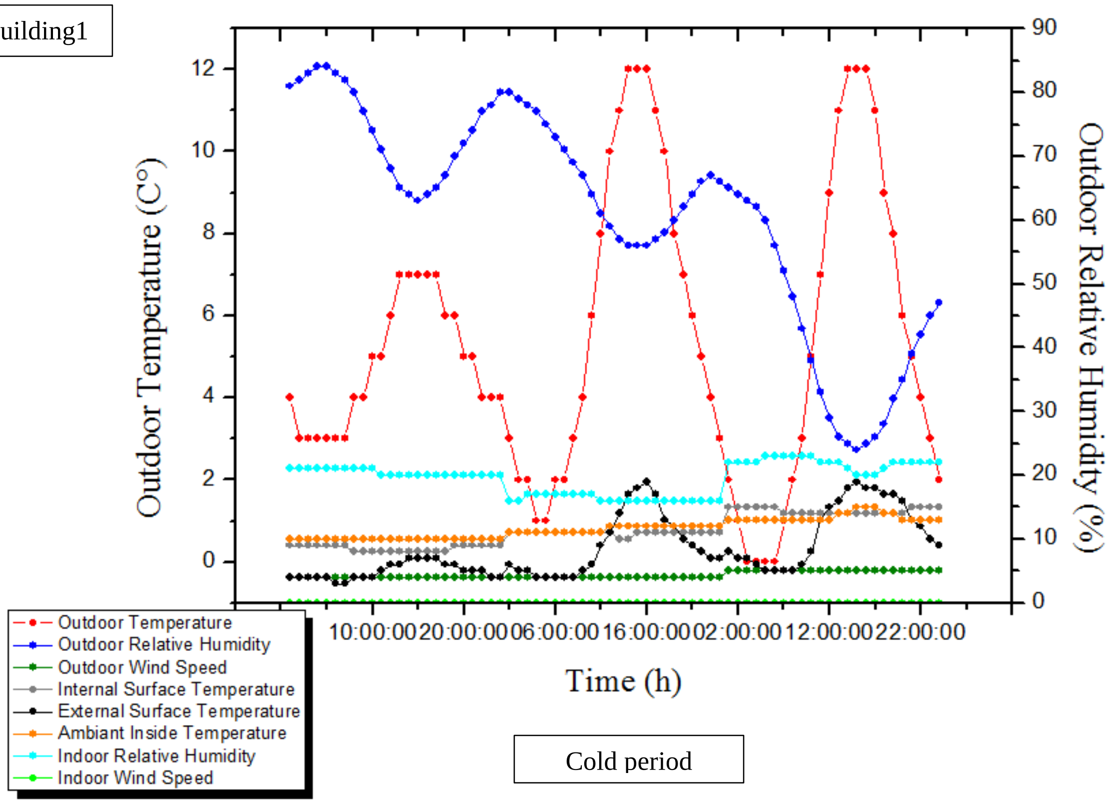
On the other hand, it was revealed that the ambient inside temperature values are very high compared to the outdoor temperature values at 14h over the three days in the four buildings. Where we notice a slight elevation in the Building 2 (37.6C°, 36C°, 36.4C°) and Building 3 (39.6C°, 39.4C°, 34.9C°) compared to the Building 1 (37.4C°, 37.1C°, 34.9C°) and Building 4 (37.5C°, 35.8C°, 34.6C°). Then it decrease to reach at 00h (29.1C°, 28C°, 30.2C°) in Building 2, (27C°, 28.1C°, 28.7C°) in Building 3, (28.6C°, 30.4C°, 29.9C°) in Building 1 and (28.1C°, 28.8C°, 30.7C°) in building 4. This is due the height of the outdoor temperature and the indoor surface of external walls temperature. The indoor relative humidity values range from (16.4% to 2.9%), (17.9% to 11.5%), (18.6% to 9%), (17.1% to 10.1%) in the Building 1, Building 2, Building3, Building 4 respectively. These values are very high compared to the outdoor relative humidity values recorded, this is due to the natural stone saturated water from the sub-basement and the lack of the internal ventilation.

III.6. Results of the energy simulation

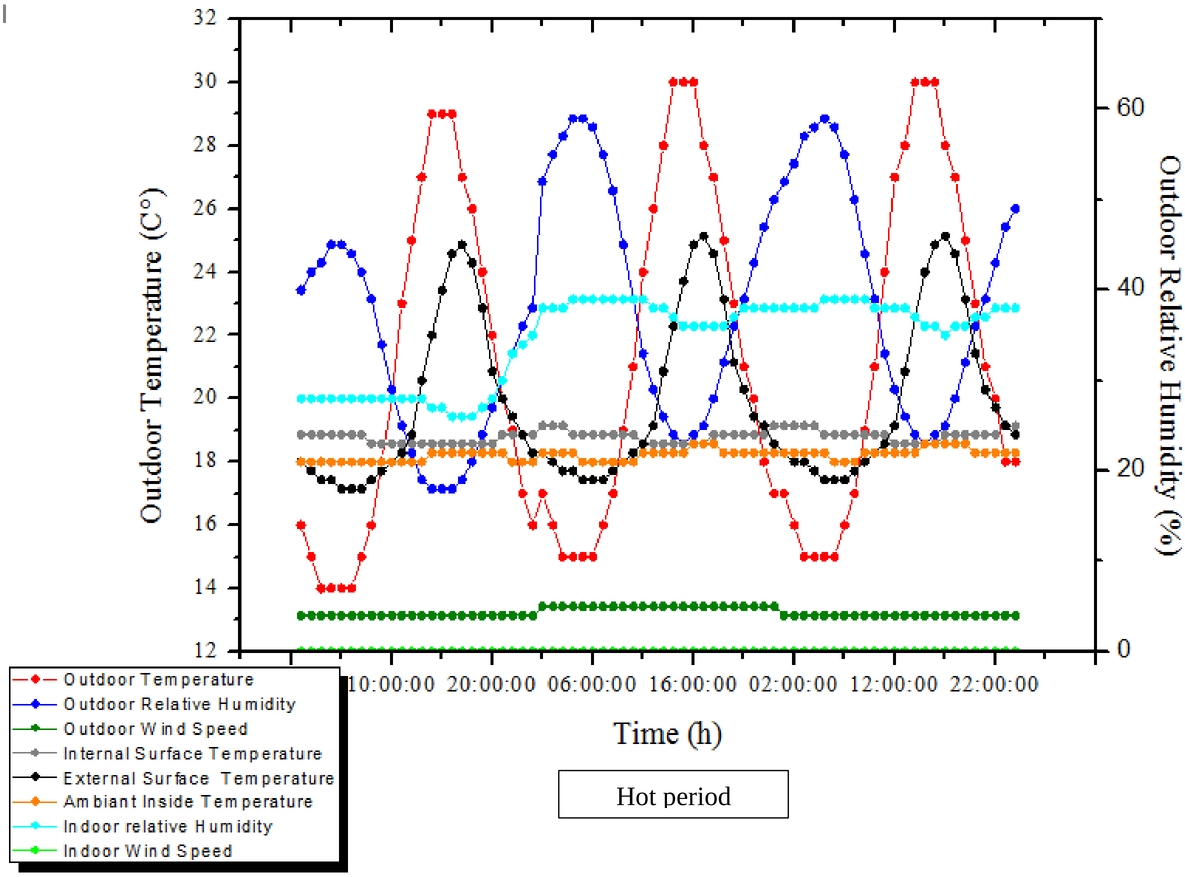
The results of the energy simulation in Fig. III.15 of the outdoor temperature, the outdoor relative humidity and the outdoor wind speed showed a weak agreement between the simulation and experimental results. This difference of the simulation outside temperature results, the outside relative humidity results, the outside wind speed results and the experimental results, is the consequence 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 that, in the cold period, there is a certain coherence between the measured and simulated curves of temperature and wind speed parameters in the four buildings, while 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 is the result that the energy simulation does not take into consideration the current state of degradation of the natural stone used in these buildings. Where the thermos-physical properties of the limestone used in the energy simulation are related with the normal state of the limestone. Thus, the change of the thermos-physical properties values due the climatic factors has 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 on the normal state, without the exposure to the harsh environmental factors over time.

Building1

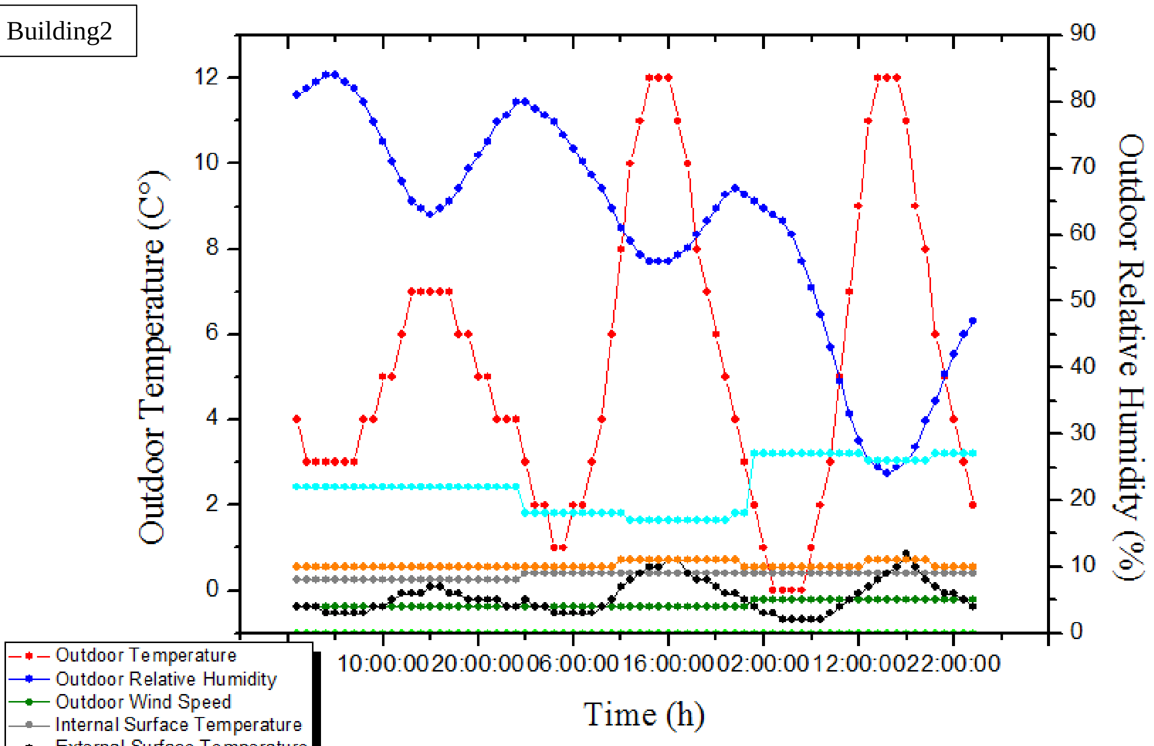


Cold period

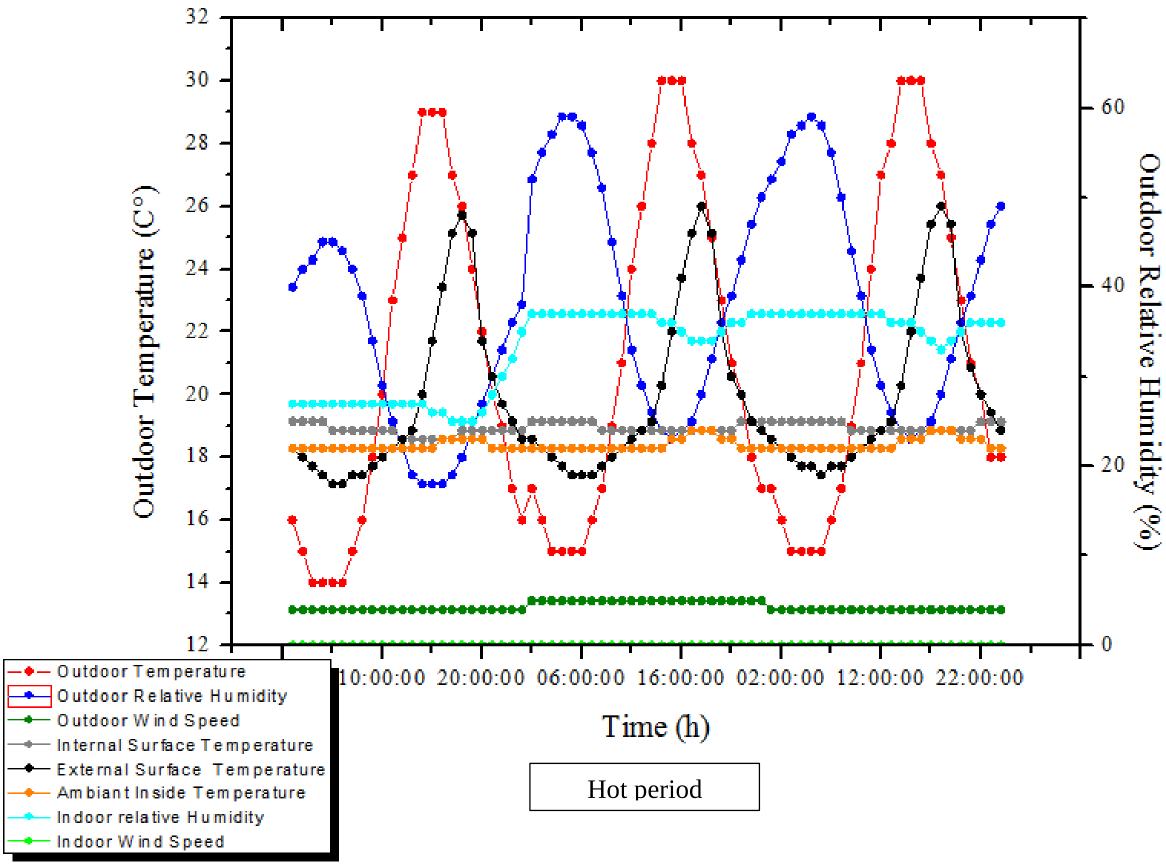


Hot period

Building2

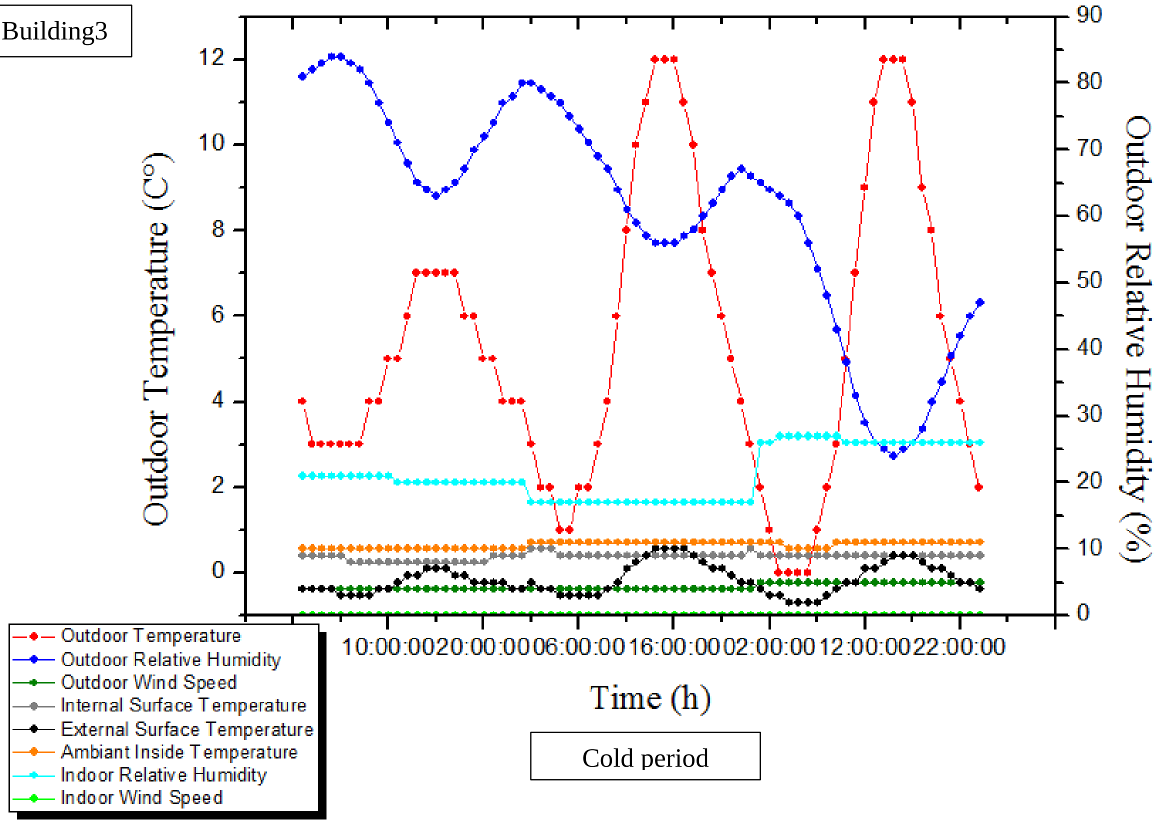


Cold period

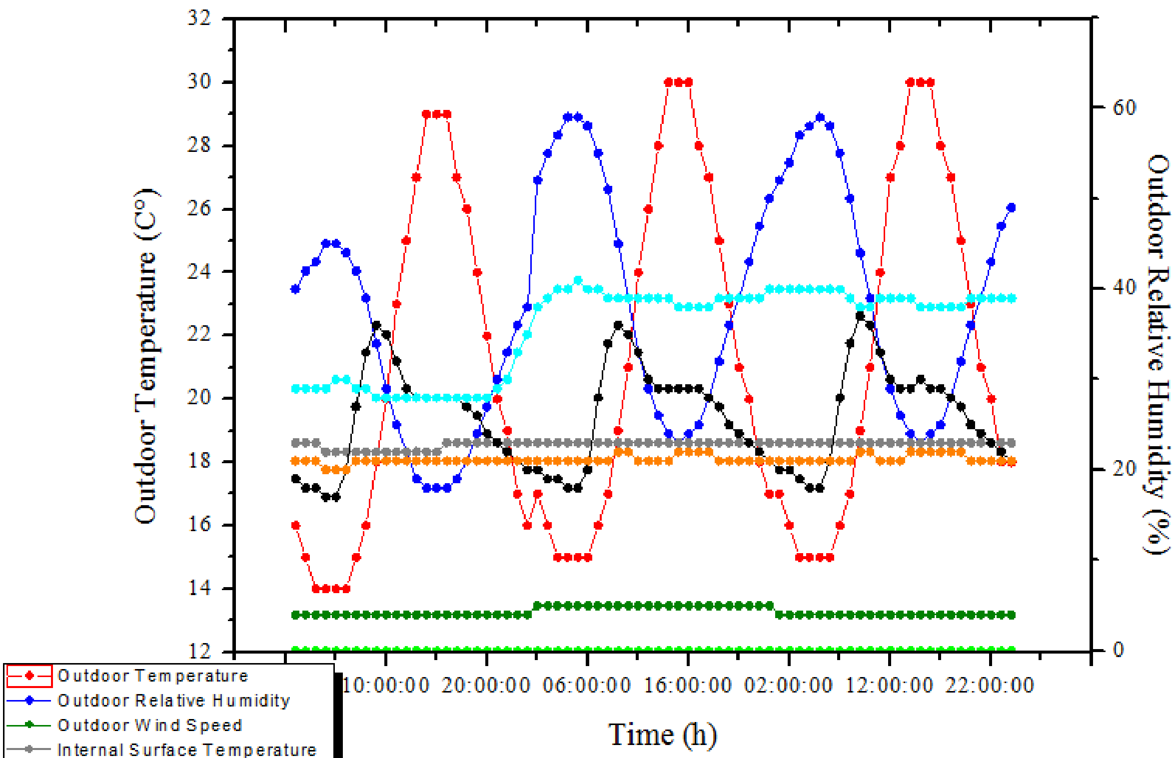


Hot period

Building3



Cold period



Hot period

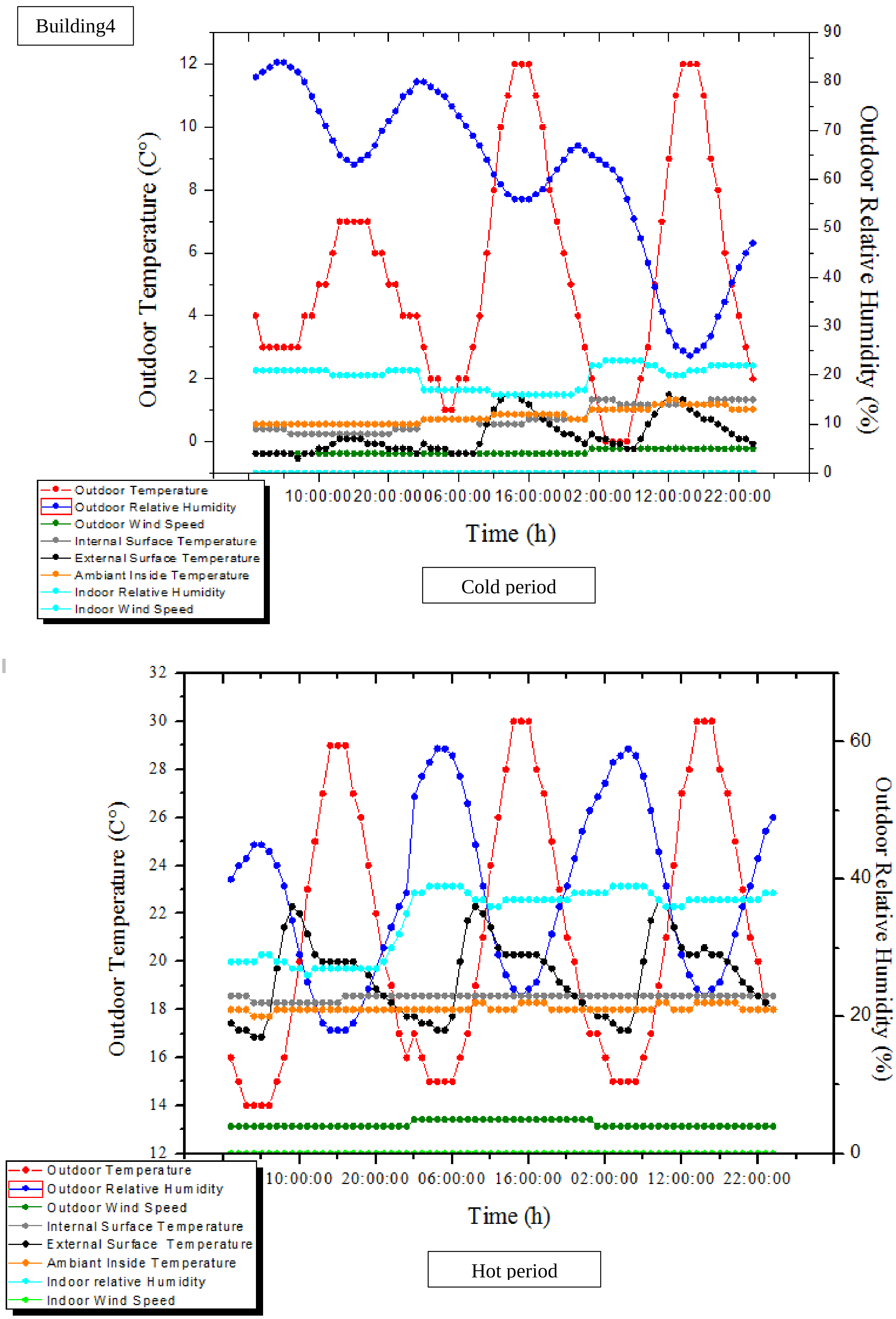


Fig. III.15. Results of the energy simulation of the buildings. *(Source: The Author)*

Conclusion

This chapter concentrates on analyzing the significant impact of the interactions of the harsh climatic factors with the thermos-physical properties of natural stone used in construction on the thermal inertia of the ancient residential buildings over time; however, the building orientation does not affect the thermal behavior of the natural stone walls.

The results of this chapter showed that the limestone showed a weak resistance in the semi-arid climate under the important gap of temperature between the day and the night, its components affected by the thermal shock effect weathering and saturated with water arising from the sub-basement of the building caused an increase of the thermal conductivity coefficient; therefore, the thermal inertia and the thermal efficiency of the natural stone wall are reduced.

On the other hand, the results show a low thermal phase shift contribute to reducing the thermal inertia of buildings, as well as the very high indoor relative humidity values recorded and the absence of the natural ventilation affects the indoor thermal comfort, this explain the buildings thermal performance decrease.

The weak agreement between the experimental and numerical results is the consequences 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.

CHAPITRE V

EXPERIMENTAL STUDY ON THE NATURAL STONE BUILDING SAMPLES

"The experimental hypothesis, in a word, must always be based on a previous observation. Another essential condition of the hypothesis is that it be as probable as possible and that it be experimentally verifiable"

Claude Bernard

CHAPTRE IV: Experimental study on the natural stone building samples

Introduction

Natural stones used in building are known by their high thermal performance, but the climatic effects can affect this last over the time. As it shown in the empirical study in this research, the natural stone residential buildings in Tébessa are not very comfortable for the inhabitant in the cold and hot period; this is the result of the interaction between the proprieties of the natural stone and the impact of climate factor. Therefore, in this chapter we will study the thermos-physical properties of the stone type used in construction and its hygrothermal performance to assess the resistance of the natural stone type used in construction in this climatic context.

IV.1. Determination of the natural stone type used in Building in Tébessa

Two different methods can be used to classify natural stone; the classification of natural stone types according to the geological origin, which based on the geological origin, which are the igneous rocks, the sedimentary rocks and the metamorphic rocks. The second is based on implementation basis, such as strength characteristics, hardness, porosity, color, and durability (Tumac, & Shaterpour-Mamaghani, 2018).

In general, igneous rocks, sedimentary rocks and metamorphic rocks are classified according to their genesis, structure and texture, and finally according to their mineral composition. The visual inspection of the studied samples shows that they are classified as sedimentary rocks (See Fig. IV.1). Since the sedimentary rocks can be of detrital, chemical or biochemical origin, the chemical analysis considered as the best method to determine the stone type by revealing its chemical components, for this purpose, many studies were carried out in the laboratory to analyze the stone samples.

Fig. IV.1. Gaagaa Quarry *(Source: The Author).*

For determine the mineralogical and petrographic properties of the Gaagaa stone, sampling was made to represent the general quarry and five thin sections were prepared. According to TS EN 12407, (2019) mineral percentages were determined by making 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, its main oxides (%) were determined in Acme Laboratory (Canada) using the Inductively Coupled Plasma Emission Spectrometer (ICP-ES) method. Additionally, the X-Ray diffraction techniques were used to determine the mineralogical composition of Gaagaa stone.

IV.1.1. Petrographic examination

The petrographic description of natural stone is not only important for the purpose of petrographic classification, but also important for highlighting the characteristics that affect its chemical, physical and mechanical behavior. This European Standard specifies the method for technical petrographic description of natural stone. The size of the sample is approximately (44 mm x 28 mm), which is large enough to represent the petrographic features of the gemstone being examined.

IV.1.1.1. Test procedure

Firstly, a macroscopic description of the sample is undertaken. The macroscopic description may involve a visual inspection aided by a hand lens or a stereoscopic microscope. Then more thin sections (See Fig. IV.2) prepared from the sample are examined using a petrographic microscope in order to give a microscopic description of the sample; a thin section is a portion of material mounted on a slide and mechanically reduced to a thin sheet measuring (0,030 ± 0,005) mm in thickness, and protected by a slide cover. The macroscopic description was carried out both on fresh cut samples and on polished samples

Fig. IV.2. Thin section preparation *(Source: The Author).*

The stone from the Gaagaa quarry has the appearance of a carbonate rock with a pinkish light yellow colour, sometimes with brown and black spots ((See Fig. IV. 3 .A, B and C). Closed discontinuities are rarely observed in the stone ((See Fig. IV.3.D). When these discontinuity planes are broken open, a black dendritic texture predominates along the discontinuity surface ((See Fig. IV.3 .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 macro scale are recognized as iron oxide in petrographic analysis. Bioclasts observed in the stone are lamellibranch remains and spicull fossils of echinoids, ostracods, rudists and gastropods. The stone quarried from the Gaagaa quarry is a fine-grained biomicritic-biosparitic limestone with varying pore sizes and geometry. 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, 2015; Nasri, 2018).

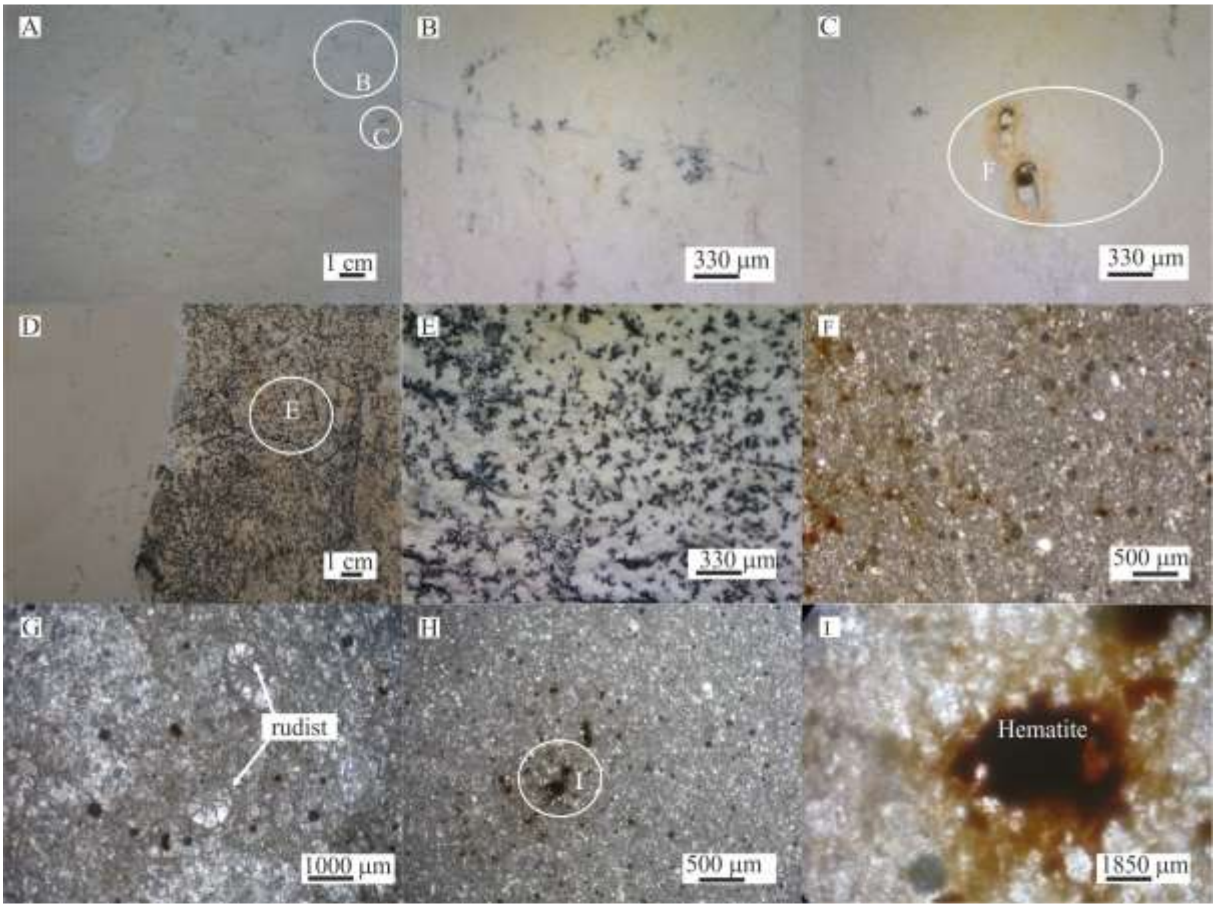


Fig. IV.3. Gaagaa limestone (A, B, C), dendritic texture (C, D), thin section view (F-I) *(Source: The Author).*

IV.1.1.2. Chemical and X-ray Diffraction Analysis

The chemical properties of the stone belonging to the Gaagaa quarry, its main oxides (%) were determined in Acme Laboratory in Canada using the Inductively Coupled Plasma Emission Spectrometer (ICP-ES) method. Additionally, the X-Ray diffraction techniques were used to determine the mineralogical composition of Gaagaa stone.

Chemical compositions of the Gaagaa stone are given in Table IV.1. Stone contain two main oxides; calcium oxide CaO: 52.58%, and silicon dioxide SiO_2: 4.51%. Ignition loss value of the Gaagaa stone is 41.7%. The main crystalline compounds found to be calcite, quartz and hematite in the Gaagaa stone by the X-Ray technique (See Fig. IV.4).

Table IV.1. Percentages of major element oxide of the Gaagaa limestone *(Source: The Author).*

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

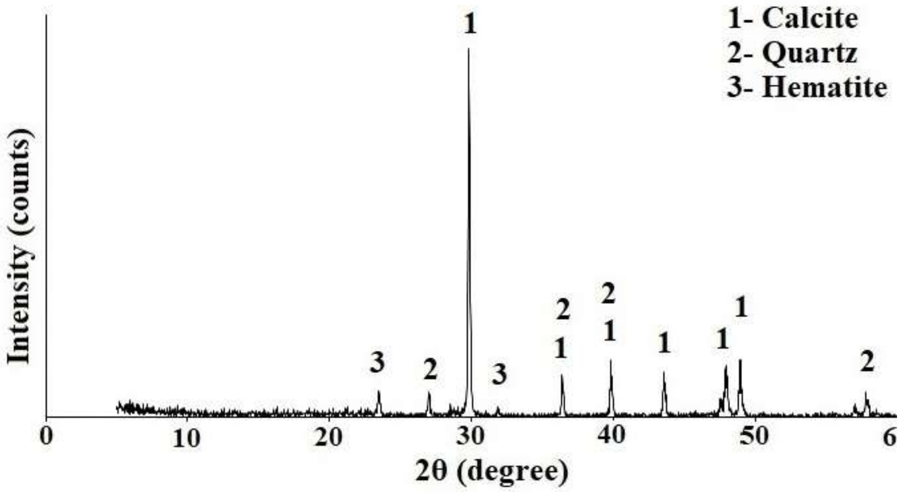


Fig. IV. 4. X-ray diffraction of Gaaga limestone *(Source: The Author).*

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; such as the Byzantine Wall, the Arch of Caracalla, and the Temple of Minerve, the Roman theatre, the amphitheatre and the Basilica (See Fig. IV.5). This stone is very sensitive to weathering due to environmental effects (Boumezbeur, et al., (2015); Nasri, et al., (2018); Rouili & Touahmia, (2019). The Table IV.2 below show the stone used in several historical building in Tébessa Wilaya.

Table IV.2. Stone type used in the historical building in Tébessa *(Source: (Boumezbeur, et al., (2015); Nasri, et al., (2018); Rouili & Touahmia, (2019)).*

Historical building	Stone type used
Arch of Caracalla Byzantine wall	Sedimentary limestone
Byzantine wall	Turinion limestone Travertine Maastrichtian carbonates
Arch of Caracalla Byzantine wall Basilica Temple of Minerva Amphitheatre	Limestone Carbonate Tufa The middle Turonion of limestone The actual formation for the carbonate Tufa
Ancient Thevest	Limestone

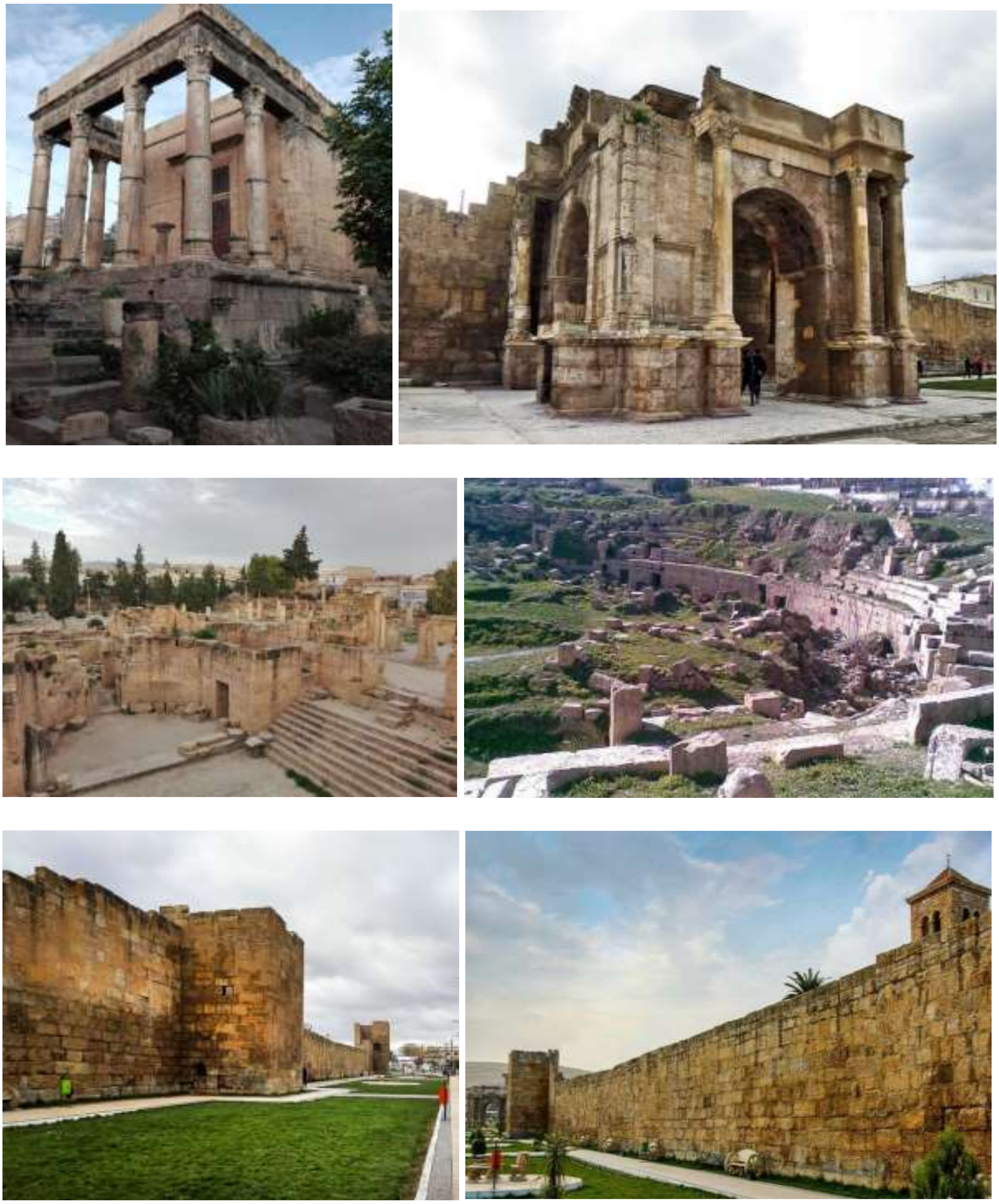


Fig. IV.5. Historical buildings in Tébessa *(Source: The Author).*

IV.2. Tests of the laboratory on the natural stone

The samples stone used in this study are extracted from the same quarry (Gaagaa quarry, Hammamet, Tébessa) , then it transfered to the laboratory of vocational school Torbali, Dokuz Eylul University to prepare the sample stone according the standard dimensions and start the analysis and tests as it shown in the Fig IV .6, all of the standards used are approved by the European Committee for Standardization (CEN).

Fig. IV.6. Samples stone extracted from the Gaagaa quarry *(Source: The Author).*

IV.2.1. Determination thermal properties

It is of primary importance to know the building materials, thermal insulators and coefficient of thermal conductivity to be used for practical calculations in the solution of heat conduction problems and in the building industry, heating-cooling technique.The measurement of the thermal conductivity of building materials and various insulation materials is made by two methods, stable and transitional. At steady state, the plate-shaped inspection sample placed symmetrically on both sides of a heated plate has an average thermal conductivity. Devices measuring in the transition state can detect the thermal conductivity of smaller materials in a shorter time. Among the transition methods, Angstrom method, Flash method and Hot Wire method are the main ones (BS EN 1745).

The coefficient of thermal conductivity measurements of the limestone were carried out at Dokuz Eylul University, Faculty of Engineering, Department of Geophysical Engineering. The measurements were made with the QTM 500 (KYTO ELECTRONICS) brand device, which operates the "Hot Wire" method on the samples prepared in dimensions of 30x60x100 mm (See Fig IV .7).

Fig. IV.7. Thermal properties test *(Source: The Author).*

In the measurement method of the QTM 500 device, the heating wire is placed between an insulating material whose coefficient of thermal conductivity is known and the material whose heat transmission coefficient is desired to be measured. In this case, the coefficient of thermal conductivity is calculated from the following formula (standard BS EN 1745):

$$\lambda = F \frac{Q \ln(t_1/t_2)}{T_2 - T_1} - H \quad (1)$$

F, H: Constants of the measuring device

Q: heat flux delivered to the heating wire,

t_1, t_2: measurement times (sec)

T_1: temperature at time t_1

T_2: temperature at time t_2

Each standard QTM 500 probe has different constants F and H. When these constants are known, the coefficient of thermal conductivity is calculated from the above formula with a microcomputer inside the device. Within 60 seconds, the heat transfer coefficient of the material for a certain temperature value is given on the screen digitally.

The coefficient of thermal conductivity of Gaagaa limestone were determined according to standard BS EN 1745 using the "Hot Wire" technique. The results are given in Table IV.3.

Table IV.3. Coefficient of thermal conductivity of Gaagaa limestone *(Source: The Author).*

Number	Dry, λ (W/m.Kel)	Saturated, λ (W/m.Kel)
R-1	2.723	2.9959
R-2	2.8516	2.9463
R-3	2.6577	2.8753
Art. Mean	2.7441	2.9392
Std. Dev.	0.0987	0.0606

IV.2.2. Determination of real density and apparent density, and of total and open porosity

This European standard specifies methods for determining the real density, apparent density, and open and total porosity of natural stone. The principle of this test is after drying to constant mass, the apparent density and open porosity are determined by vacuum assisted water absorption and submerged weighing of specimens, while the real density and total porosity require the specimen to be pulverized, where;

- Apparent density (ρb): is the ratio between the mass of the dry specimen and its apparent volume.
- Apparent volume: is the volume limited by the external surface of the specimen, including any voids.
- Volume of the solid part: difference between the apparent volume of the specimen and the volume of the voids (open and closed pores).
- Real density (ρr): is the ratio between the mass of the dry specimen and the volume of its solid part.
- Open porosity: is the ratio (as a percentage) between the volume of the open pores and the apparent volume of the specimen.
- Total porosity: is the ratio (as a percentage) between the volume of pores (open and closed) and the apparent volume of the specimen.

The samples used in this test are in the shape of a cube, dried at +70 C° until a constant mass is reached, then we kept them in a desiccator until room temperature is attained.

IV.2.2.1. Test procedure

a. Open porosity and apparent density

We weigh each specimen (md), then we put the specimens into an evacuation vessel and lower the pressure gradually to (2,0 ± 0,7) kPa = (15 ± 5) mm Hg, then we maintain this pressure for (2 ± 0,2) h in order to eliminate the air contained in the open pores of the specimens.

We introduce slowly demineralized water at (20 ± 5)C° into the vessel (the rate at which the water rises shall be such that the specimens are completely immersed more than 15 min) and we maintain the pressure of (2,0 ± 0,7) kPa during the introduction of water.

When all the specimens are immersed, we return the vessel to atmospheric pressure and we leave the specimens under water for another (24 ± 2) h at atmospheric pressure.

Then, for each specimen:

- we weigh the specimen under water and we record the mass in water: mh;
- we wipe quickly the specimen with a dampened cloth and we determine the mass ms of the specimen saturated with water.

b. Real density

For dense, low porosity stones the differences between real and apparent density, as well as between open porosity and total porosity, are very small. For these stones, it is sufficient to determine the apparent density and the open porosity. There is two methods for the determination of real density: the pycnometer (Method A) and Le Chatelier volumenometer (Method B), we choose to do the first method is more accurate despite the fact that it requires a very long time.

For each specimen, after having determined the apparent density and the open porosity, we grind each specimen separately until the particles pass through a sieve with 0,063 mm mesh, then we dry the ground specimen to a constant mass and we set apart a mass, m_e of approximately 10 g weighed to an accuracy of ± 0,01 g. We introduce deionized water into the pycnometer and we fill it approximately half full, then we add the weighed mass, m_e of the ground specimen into the pycnometer and we agitate the liquid to disperse the solid matter.

We expose the pycnometer to a vacuum of (2 ± 0,7) kPa until no further air bubbles rise, then we fill it with deionized water almost to the top and we leave the solid matter to settle until the water above the residue is clear. Next, we carefully top up the pycnometer with deionized water, and we fit the ground stopper and gently wipe off any overflow.

Finally we weigh the pycnometer to an accuracy of ± 0,01 g (m1), then we empty and wash the pycnometer, and we fill it with deionized water only and weigh to an accuracy of ± 0,01 g (m2). Before each weighing we make sure that the ambient air temperature is less than 20 C° and more than 5C°.

IV.2.2.2. Express results

The volume of the open pores (in mm) is expressed by the equation:

$$V_0 = \frac{ms - md}{\rho rh} \times 1000 \qquad (2)$$

The apparent volume (in milliliters) is expressed by the equation:

$$V_b = \frac{ms - mh}{\rho rh} \times 1000 \qquad (3)$$

Which can alternatively be calculated based on the dimensions of the specimen.

a. *The apparent density* (in kilograms per cubic meter) is expressed by the ratio of the mass of the dry specimen and its apparent volume, by the equation:

$$\rho_b = \frac{md}{ms - mh} \times \rho_{rh} \qquad (4)$$

b. *The open porosity* is expressed by the ratio (as a percentage) of the volume of open pores and the apparent volume of the specimen, by the equation:

$$P_o = \frac{ms - md}{ms - mh} \times 100 \qquad (5)$$

c. *The real density* (in kilograms per cubic metre) is expressed by the ratio of the mass of the ground dry specimen m_e to the volume of liquid displaced by the mass m_e, by the equations in method A (pycnometer):

$$\rho_r = \frac{me}{m2 + me - m1} \times \rho_{rh} \qquad (6)$$

d. *The total porosity* is expressed by the ratio (as a percentage) of the volume of pores (open and closed) and the apparent volume of the specimen, by the equation:

$$P = \frac{\frac{1}{\rho b} - \frac{1}{\rho r}}{\frac{1}{\rho b}} \times 100 = \left(1 - \frac{\rho b}{\rho r}\right) \times 100 \qquad (7)$$

Where:

m_d mass of the dry specimen, in grams;

m_h mass of the specimen immersed in water, in grams;

m_s mass of the saturated specimen, in grams;

m_e mass of the specimen ground and dried (for the tests using the pycnometer or the volumenometer), in grams;

m_1 mass of the pycnometer filled with water and the ground specimen, in grams;

m_2 mass of the pycnometer filled with water, in grams;

V_b apparent volume of the specimen, in millilitres;

V_o volume of open pores of the specimen, in millilitres;

V_s volume of liquid displaced by the mass me (volumenometer test);

ρ_b apparent density of the specimen, in kilograms per cubic metre;

ρ_r real density of the specimen, in kilograms per cubic metre;

ρ_{rh} density of water, in kilograms per cubic metre;

p_o open porosity of the specimen, as a percentage;

p total porosity of the specimen, as a percentage.

A stone, minerals form a strong skeleton, which does not occupy all the space. The rest of the stone form an empty space and form a porous network (whether connected or not). Density and porosity provide information about the voids present in the material. Many techniques are used to estimate porosity and highlight some geometric properties of porous networks. The technique used in this work is the total saturation of the water.

The assessment of stone porosity cannot be done directly. In fact, the estimation of the void volume in the connected content material requires the injection of a fluid whose properties are known. The total saturation of the wetting fluid (usually water) is the easiest way to obtain the porosity value. According to a suitable scheme, after degassing, the sample is completely saturated with water, and after different weightings, the total porosity value is calculated.

IV.2.3. Determination of water absorption at atmospheric pressure

This European Standard specifies a method for determining the water absorption rate of natural stone. The principle of the test is to weigh each sample after drying to a constant weight, and then immerse it in atmospheric water for a specified time. Determine the water absorption under atmospheric pressure, expressed as a percentage, by the ratio of the mass of the saturated sample (obtained with a constant mass) to the mass of the dry sample. This test used six cube-shaped samples, dried to constant weight at a temperature of 70C°, and then stored them in a desiccator until they reached room temperature of 19C°.

IV.2.3.1. Test procedure

We weigh the samples after drying (md) with an accuracy of 0.01 g, and then we place the samples on the holder provided in the water tank, with each sample being at least 15 mm away from adjacent samples (See Fig. IV .8), then;

Fig. IV.8. Weighing of samples in Archimedean scales in water and saturated with water *(Source: The Author).*

- We added tap water at (20 ± 10) C ° up to half the height of the specimens (time t0).
- At time t0 + (60 ± 5) min we add tap water until the level of the water reaches three-quarter of the height of the specimens.
- At time t0 + (120 ± 5) min we added tap water until the specimens are completely immersed to a depth of (25 ± 5) mm of water.

- At time t0 + (48 ± 2) h the specimens are taken out of the water, then we wiped them quickly with a damp cloth and then we weighed them within 1 min to an accuracy of 0,01 g (m_i).

We immerse the specimens again in water and continue the test up to constant mass of the specimens, where constant mass is reached when the difference between two successive weighings is not greater than 0,1 % of the first of the two masses. The result of the last weighing is the mass of the saturated specimen (m_s).

IV.2.3.2. Expression of results

The water absorption at atmospheric pressure Ab of each specimen is calculated by the equation:

$$A_b = \frac{ms - md}{md} \times 100 \quad (8)$$

Where;

m_d mass of the dry specimen, in grams;

m_i successive masses of the specimen during testing, in grams;

m_s mass of the saturated specimen (after immersion in water until constant mass is reached), in grams;

A_b water absorption at atmospheric pressure, expressed as a percentage.

The results of the test are given in the Fig IV.4, 5 and 6.

Table IV.4. Apparent density, open porosity and water absorption values of Gaagaa limestone *(Source: The Author).*

Number	m_s, (g)	m_d, (g)	m_h, (g)	ρ_{rh}(g/cm^3)	ρ_b (g/cm^3)	p_o, (%)	Ab (%)
R-1	490.03	479.55	297.89	0.99897	2.493	5.454	2.139
R-2	501.5	489.03	303.32	0.99897	2.465	6.292	2.487
R-3	515.97	504.43	314.17	0.99897	2.497	5.719	2.237
R-4	492.44	482.16	299.59	0.99897	2.498	5.331	2.088
R-5	494.05	484.12	300.45	0.99897	2.498	5.129	2.010
R-6	491.66	481.72	299.07	0.99897	2.499	5.161	2.022
R-7	501.2	489.25	304.55	0.99897	2.485	6.077	2.384
R-8	496.2	483.54	299.58	0.99897	2.457	6.439	2.551
R-9	507.11	495.37	308.12	0.99897	2.487	5.900	2.315
R-10	481.74	469.99	291.8	0.99897	2.472	6.186	2.439
R-11	429.58	414.68	253.05	0.99897	2.347	8.440	3.469
R-12	348.52	341.39	212.06	0.99897	2.499	5.225	2.046
R-13	372.04	363.31	225.79	0.99897	2.482	5.969	2.347

	Art. Mean	**2.475**	**5.948**	**2.349**
	Std. Dev.	**0.041**	**0.873**	**0.383**

Table IV.5. Real density values of Gaagaa limestone *(Source: The Author).*

Number	**me (g)**	**m1 (g)**	**m2 (g)**	**ρ_{rh}(g/cm^3)**	**ρ_h(g/cm^3)**
R-1	5.02	139.55	136.41	0.999404	2.669
R-2	5.03	145.97	142.82	0.999404	2.674
S-8	4.99	142.95	139.83	0.999404	2.667
				Art. Mean	2.670
				Std. Dev.	0.004

Table IV.6. Total porosity values of Gaaga limestone *(Source: The Author).*

Number	**ρ_r (g/cm^3)**	**ρ_b (g/cm^3)**	**1/ ρ_r**	**1/ ρb**	**Total Porosity**
S-1	2.674	2.475	0.404	0.374	7.431
S-2	2.667	2.475	0.404	0.375	7.186
S-3	2.670	2.475	0.404	0.375	7.288
				Art. Mean	**7.302**
				Std. Dev.	**0.123**

IV.2.4. Determination of water absorption coefficient by capillarity

This European Standard specifies a method for determining the water absorption coefficient of natural stone with an open porosity less than 1 % by capillarity (EN, 1999). The Principle of the test is after drying to a constant mass, immerse one side of the sample in 3 mm deep water and measure the increase in mass over time. The samples are a 50 mm cube, dried in a ventilated oven at +70 C° until a constant mass is reached; this is assumed to have been attained when the difference between two consecutive weightings with an interval of 24h to 2h is not more than 0.1% of the mass of the sample. We tried to keep the sample in a desiccator until it reaches room temperature 19 C°.

IV.2.4.1. Test procedure

The area of the base immersed of the specimens is 0.25 m^2. We weigh the specimens after drying (md) to an accuracy of 0.01 g, and then we place the specimens in the tank on the thin supports provided such that they only rest partially on their base as it is shown in the Fig.VI. 9.

Fig. IV.9. The specimens immersed *(Source: The Author).*

We immersed the base in the water to a depth of 3 mm and we kept the water level constant by adding water as needed throughout the test, and then started the timer device.

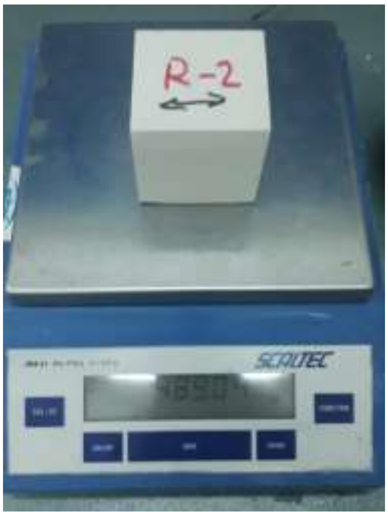


Fig. IV.10. Weighting the sample *(Source: The Author).*

Every once in a while, it is short at first and then longer, we take out each sample in turn, then gently wipe the immersed part with a damp cloth to remove all water droplets, and then immediately weigh to the nearest 0.01 g, as shown in the figure . Fig. IV.10, and then we replace it in the container. We record the elapsed time from the start of the test to each weighing.

IV.2.5. Determination of resistance to salt crystallization

This European Standard specifies a test method to assess the relative resistance of natural stones with an open porosity of greater than 5 %, to damage caused by the crystallization of salts. The principle of this test is after drying to constant mass; the specimen is immersed in a solution of sodium sulfate, dried and allowed to cool to room temperature. This cycle is carried out 15 times and the percentage mass change measured.

The samples used in this test are in the shape of a cube of 50 mm, dried in a ventilated oven at +70 C° until a constant mass is reached, they are then allowed to cool to room temperature and weighed to – 0,01 g (M_d). Each specimen is then labelled with a durable tag that is wired on to the cube. The specimen is then re-weighed to – 0,01 g (M_{d1}) where:

M_d is the mass of the dried specimen, in grams.

M_{d1} is the mass of the dried specimen with label before first cycle, in grams.

M_f is the mass of the dried specimen with label, after 15 cycles, in grams.

ΔM is the relative difference of masses before and after testing (mass loss or mass gain), in percent.

IV.2.5.1. Test Procedure

The procedure entails the use of a 14 % solution of sodium sulfate decahydrate. Each of the dried specimens is placed in a single container and covered with the sodium sulfate solution to a depth of 5 mm above the top of the specimen. The specimens are then left to soak for 2 h at (20 – 0,5) C°.

After immersion, the specimens are removed from the solution and dried in an oven. The oven shall be arranged to provide a high relative humidity in the early stages of drying and to raise the temperature of the specimens to (105 – 5) C° in not less than 10 h and not more than 15 h. The initial high relative humidity may be obtained by placing a tray of water in the cold oven, and switching on the heater for (30 – 5) min before putting in the specimens.

The specimens are left in the oven for at least 16 h and then they are cooled at room temperature for (2,0 – 0,5) h before resoaking in fresh sodium sulfate solution. The cycle of operation is carried out 15 times in all, After this cycles the specimens are removed from the oven and stored for (24 – 1) h in water at (23 – 5) C°, finally, they are washed thoroughly with flowing water. The specimens are weighed after drying to constant mass.

IV.2.5.2. Expression of results

The results are expressed as relative mass difference ΔM (mass loss or gain) as a percentage of the initial dry mass M_d or as the number of cycles required to induce failure if the specimen is too shattered to weigh after the final drying.

$$\Delta M = \frac{Mf - Md1}{Md} \times 100 \tag{9}$$

IV.2.6. Determination of frost resistance

This European standard specifies a method for evaluating the effects of freeze-thaw cycles on natural stone. The frost resistance of the natural stone unit is determined by tests that include cycles of freezing in air and thawing in water. Two sets of samples are required, one group is tested after the freeze/thaw cycle, and the other group is tested without the freeze/thaw cycle. The sample used in this test is a rectangular parallelepiped of 50mm×50mm×300mm, dried to constant weight at (70±5)C°.

Place the sample vertically in a container at least 15 mm away from the adjacent sample, and then we add tap water at (20 ± 10) C° until half the height of the sample (time t0). At time t0 + (60 ± 5) min, we add tap water until the water level reaches three-quarters of the height of the sample. At time t0+ (120 ± 5) min, we add tap water until the sample is completely immersed in (25 ± 5) mm of water, then we left the specimens completely immersed for (48 ± 2) h (See Fig. IV. 11).

Fig. IV.11. The specimens immersed *(Source: The Author).*

IV.2.6.1. Test procedure

a. *Arrangement of the specimens in the freezing tank*

We placed the specimens in the tank with the long axis vertical so that they do not touch each other or the sides of the tank. They should be at least 10 mm apart and at least 20 mm away from the side of the tank. After 14, 56, 84 and 140 cycles, we rotated the sample 180° around the horizontal axis.

b. Description of the freezing and thawing cycles

Each cycle consists of a 6-hour freezing period in air, followed by a 6-hour thawing period, during which the sample is immersed in water. The cycle shall be repeated until the specimen fails or the maximum number of cycles is reached.

c. Control measurements to determine the freeze/thaw resistance

After the completion of the required number of cycles, two criteria are used to assess the action of freezing and thawing cycles on the specimens:

- Before testing and after 14, 56, 84, 140 and 168 cycles (or after reaching the maximum number of cycles (Nc): visual inspection.
- Before testing and after having reached the maximum number of cycles (Nc): measurement of the apparent volume; we repeat the same measurements at the end of cycles (Nc) to determine *M*hn and *M*sn respectively and we dry the specimens to determine *M*dn. The initial apparent volume is expressed by:

$$V_{bo} = (M_{s0} - M_{h0}) \quad (10)$$

At Nc cycles, the apparent volume is expressed by:

$$V_{bn} = (M_{sn} - M_{hn}) \quad (11)$$

The percentage change in apparent volume (ΔV_b) at *n* cycles is calculated as follows:

$$\Delta V_b = \frac{\left((Ms0 - Mh0) - (Msn - Mhn)\right) \times 100}{(Ms0 - Mh0)} \quad (12)$$

Where;

M_{s0} mass of the saturated specimen after immersion in water and before starting the cycles, in grams

M_{h0} apparent mass of the specimen in water before starting the cycles, in grams

M_{sn} mass of the saturated specimen at Nc cycles, in grams

M_{hn} apparent mass of the specimen in water at *n* cycles, in grams

V_{b0} apparent volume of the specimen before freezing, in millilitres

V_{bn} apparent volume of the specimen at Nc cycles, in millilitres

IV.2.7. Determination of resistance to ageing by SO_2 action in the presence of humidity

European standards specify a method for evaluating the relative resistance of natural gemstones to sulfur dioxide damage in humid environments. In this test, the resistance of the natural stone unit to a combination of temperature, humidity and sulfur dioxide was determined by placing the test sample in two containers with two different sulfur dioxide concentrations 21. After this period, the mass loss and change of the sample are measured.

The sample size (120 mm x 60 mm x 10 mm) is cleaned to remove any paste residue or debris, and then dried to constant weight at 70C°. One sample is used as a control.

IV.2.7.1. Test procedure

We immerse the sample in water at 19 C° for 24 hours. Then we put three samples into the container with solution A, and put the other three samples into the container with solution B, where;

- Solution A: Dilute (500 – 10) ml of sulphurous acid (H_2SO_3) in (150 – 10) ml of de-mineralised or de-ionised water;

- Solution B: Dilute (150 – 10) ml of sulphurous acid (H_2SO_3) in (500 – 10) ml of de mineralised or de-ionised water.

The specimens are held vertically on a frame in the container approximately 100 mm above the acid solution. The temperature inside the container is kept at 19° C for the duration of the test. After 21 days, the specimens are removed from the containers, washed in de-ionised or de-mineralised water, and then dried again to constant mass. The weight of the dry specimen is the final value m_1, then we compare all test specimens with the reference specimen.

IV2.7.2. Expression of the results

a. Change in mass

The change in mass expressed as percentage for each specimen is calculated as follows:

$$m=\frac{(m0\ m1)}{m0}\times 100 \qquad (13)$$

Where;

m_0 is the mass of the dry specimen before the test, in grams;

m_1 is the mass of the dry specimen after the test, in grams;

D_m is the change in mass, in percent.

b. Visual appearance

We record any changes in appearance – color changes, spots, rust, swelling, cracking, surface deposition or surface flaking, etc.

IV.2.8. Determination of resistance to ageing by salt mist

This European Standard specifies a method to assess the resistance of natural stones to ageing by salt mist. The specimens are placed in a chamber and sprayed with a salt solution for 4 hours and, afterwards, dried for 8 hours, this cycle is repeated successively. Six cubes specimens of 50 mm dried at a temperature of (70 ± 5) C° to constant mass are used in this test, then they are then left to cool to room temperature and weighed. The weight of the dry specimen is the initial value M_0.

IV.2.8.1. Test Procedure

We placed the dry specimens into the chamber over non-corrosive supports (glass), each one apart from the others and in such conditions as to be subject only to salt fog. Then we exposed the specimens to salt fog for (4 hours to 15 minutes), and switched off the salt spraying system and dry the specimens in the chamber for (8 hours – 15 minutes); this constitutes one cycle. During the cycle, the temperature of the chamber is maintained at (35 – 5) C°. The test consists of 60 cycles.

Every 15 cycles, the specimens are taken from the chamber for a visual inspection. At the end of the test, the specimens are carefully removed from the chamber and immersed in de-ionised water so that all the deposited salts can be removed, then the volume of the rinsing water in the container is comprised between two and three times the total volume of the specimens.

This process is very slow, and the water must be changed every day until the removal of the salt is complete. Removal is considered complete when the conductivity of the solution in contact with the specimens does not exceed twice the characteristic value of the original water. After this, the specimens are dried at a temperature of (70 ± 5)° C to constant mass, left to cool to room temperature, weighed (Mn) and visually inspected.

IV.2.8.2. Expression of results

The results are reported in terms of the mass loss and of the results of visual inspection concerning the specimens aspect, existence of cracks or other relevant signs of degradation. For each specimen, the mass loss is calculated as percentage, as follows:

$$(M\%) = \frac{M0 \times Mn}{M0}\, 100 \qquad (14)$$

Where:

M_0 mass of the dried specimen in grams.

M_n mass of the dried specimen after n exposure cycles in grams.

M percentage of mass loss.

IV.2.9. Determination of resistance to ageing by thermal shock

This European Standard specifies a method to assess possible changes of natural stones under the effect of sudden changes in temperature (thermal shock). The principal of this test is after drying at (40 ± 5) C° for a week, the specimens are subjected to successive cycles, each formed by drying at (70 ± 5) C° followed by immediate immersion in water at (20 ± 5) C°, then we measure the potential strength loss. Twenty specimens are used in this test: a set of 10 specimens as references for flexural strength measurement of fresh material and the other set for the thermal cycles.

IV.2.9.1. Test procedure

The dried specimens are subjected to changes of temperature according to the following procedure: (18 ± 1) h in a ventilated oven at (70 ± 5) C°; immediately followed by (6 ± 0,5) h completely submerged in tap water, whose temperature before the immersion of the specimens is (20 ± 5) C°. Both in the oven and in the water container, the specimens are placed on the supports at a distance of 50 mm from one another and from the wall. In the water container, the specimens are placed on supports located at the bottom of the container which has been filled with tap water to such a height that the water level above the specimens is (60 ± 10) mm. The procedure described above constitutes one cycle.

After the 20^{th} cycle, the specimens are dried to constant mass at (70 ± 5) C°, and then they are visually inspected and compared with the reference specimens.

IV.2.9.2. Expression of results

a. *Visual appearance*

We describe the modifications observed visually by comparison with the reference specimen, such as cracking, scaling or exfoliation.

b. *Modulus of elasticity*

We calculate the change in dynamic elastic modulus according to Formula:

$$\Delta E = \frac{Ef - E0}{E0} \times 100 \qquad (15)$$

c. *Open porosity*

We calculate the change in open porosity according to Formula:

$$\Delta\rho = \frac{\rho f - \rho 0}{\rho 0} \times 100 \qquad (16)$$

d. *Ultrasound pulse velocity*

We calculate the change in ultrasound pulse velocity according to Formula:

$$\Delta v = \frac{vf - v0}{v0} \times 100 \qquad (17)$$

e. *Flexural strength*

We measure the flexural strength on dried reference and exposed specimens. The percentage change in flexural strength (ΔF) is calculated as follows:

$$\Delta F = \frac{Ff - Fr}{Fr} \times 100 \qquad (18)$$

Where:

Fr Flexural strength tested on the reference specimens, in MPa

Ff Flexural strength tested on the specimens subjected to thermal cycles, in MPa

ΔF Change in flexural strength between reference and exposed specimens, in %

$E0$ Dynamic elastic modulus of the specimens before the thermal cycles, in MPa

Ef Dynamic elastic modulus of the specimens after the thermal cycles, in MPa

ΔE Change in dynamic elastic modulus of the specimen, in %

$\rho 0$ Open porosity before the test, in %

ρf Open porosity after the test, in %

$\Delta\rho$ Change in open porosity of the specimen, in %

$v0$ Ultrasound pulse velocity (UPV) before the test, in km/s

vf Ultrasound pulse velocity (UPV) after the test, in km/s

Δv Change in Ultrasound pulse velocity of the specimen, in %

IV.2.10. Determination of sensitivity to changes in appearance produced by thermal cycles

This European Standard specifies a method to assess possible alterations of natural stones (mainly visible sensitivity to oxidation processes) under the effect of sudden changes in temperature (thermal shock). The principle of this test is subjection the specimens to successive cycles, each formed by drying at (105 ± 5) ºC followed by immediate immersion in water at (20 ± 5) ºC. In this test, seven specimens are used, where one of these specimens is used as reference specimen and is not subjected to any tests.

IV.2.10.1. Test procedure

a. *Control measurements before cycling*

The dried specimens are submitted to a thorough visual inspection, with the aid of a magnifying glass of at least five increases. All relevant features of its texture and also all visual and structural alterations of each specimen shall be noted, such as cracks, holes, swelling, spots, oxidations, or presence of metallic minerals or other sensitive minerals (e.g. biotite, hornblendes, etc.). A photographic (or scanner) record of all specimens to be tested shall be made.

b. *Description of the cycles*

The specimens are subjected to changes of temperature according to the following procedure: (18 ± 1) h in a ventilated oven at (105 ± 5) ºC, immediately followed by (6 ± 0,5) h of complete submersion in distilled or demineralised water, whose temperature before the immersion of the specimens is (20 ± 5) ºC.

Both in the oven and in the water container, the specimens are placed in vertical position on the supports at a distance of 50 mm from one another and from the wall. In the water container, the specimens are placed on supports located at the bottom of the container which has been filled with water to such a height that its level above the specimens is (60 ± 10) mm. The procedure described above constitutes one cycle. The test consists in a total of 20 cycles.

c. Control measurements after cycling

After the 20th cycle the specimens are visually inspected and compared general aspect or colour with the reference specimen. All alterations are noted. A photographic (or scanner) record is made, which includes both tested specimens and reference specimen placed next to one another.

IV.2.10.2. Expression of results

For each specimen: we describe the modifications observed visually, by comparison with the reference specimen, such as:

- In general, changes in the color of the stone or spots in their surface.
- Structural changes as swelling, cracking, micro cracking or exfoliations.

A photographic (or scanner) is recorded shall be made, which includes all tested specimens before and after the test and reference specimen placed next to one another.

IV.2.11. Determination of abrasion resistance

This European Standard specifies a method of "Böhme Abrasion Test" to determine the abrasion resistance of natural stones used for flooring in buildings (See Fig. IV. 12). The principal of this test is; the test specimen is placed on the test track of the Böhme disc abrader on which standard abrasive is strewn, the disc being rotated and the specimens subjected to an abrasive load of (294 + 3) N for a given number of cycles. Then the abrasive wear is determined as the loss in specimen volume.

Fig. IV.12. Böhme abrasion test *(Source: The Author).*

Table IV.7. Wide wheel abrasion of Gaagaa limestone *(Source: The Author).*

Number	I	II	III	Abrasion mm
R-1	21.67	22.3	24.3	22.76
R-2	22.17	22.27	22.22	22.22
R-3	21.01	22.39	23.67	22.36
R-4	22.3	22.1	22.09	22.16
R-5	22.09	22.37	22.7	22.39
R-6	21.87	22.4	23.7	22.66
		Art. Mean		**22.42**
		Std. Dev.		**0.24**

Table IV.8. Böhme abrasion of Gaagaa limestone *(Source: The Author).*

Number	V_0 (mm^3)	V_1 (mm^3)	ΔV (mm^3)
R-1	176.53	150.23	26300
R-2	136.46	113.31	23150
R-3	146.25	123.02	23230
R-4	175.96	150.4	25560
R-5	137.12	113.18	23940
R-6	145.72	119.22	26500
		Art. Mean	**24780**
		Std. Dev.	**1526**

Conclusion

As conclusion, stone type used in construction in Tébessa is limestone, this stone type known by weakness under the environmental condition. The laboratory tests and analyzes that were done on the stone samples proved that the thermos-physicals properties of the limestone do not resist the temperature changes between the day and night, in the cold and hot period in this region. This is due to its porous nature and its low density, which was unable to cope with the semi-arid climate conditions. This is leads to a very noticeable weakness in the sustainability of material, consequently, on the thermal performance of the building envelope. Therefore, it would be desirable to choose the suitable stone type used in construction regarding to each climate type, this depends on the interactions between them.

CHAPITRE V

ASSESSMENT AND OPTIMIZATION OF NATURAL STONE PERFORMANCE BY THE THERMAL CORRECTION

“Architecture should speak of its time and place, but yearn for timelessness”

Frank Gehry

CHAPITRE V: Assessment and optimization of natural stone performance by the thermal correction

Introduction

The Limestone type proved its weakness under the harsh environmental condition in this study, which effects the thermal behavior of the building envelop. Therefore, the aim of this chapter is to optimize its performance in order to improve the thermal efficiency of the residential building, this by reinforcing the thermos-physical properties of the limestone in order to improve the thermal inertia. In this part, we will determine the natural stone studied properties, then, assessment its thermal behavior, and finally improve it by a thermal correction.

V.1. Determine the hygrothermal properties of Tébessa natural stone

The results of the laboratory in this research shows that Tébessa limestone used in construction in Hammamet Tébessa Wilaya is:

- A highly porous, this high porosity leaves Tébessa limestone highly vulnerable to environmental effects and harsh climatic conditions.

The porosity of the natural stone has a great influence on the heat transfer because the pores contain dry air, liquid water and water vapor, where the water degrades the insulating quality of the stone.

- Low density limestone, which make it more conductive.

- The compressive strength, bending strength and abrasion resistance are sufficient for general use for construction purposes.

The properties of Tébessa limestone (Djedouani, et al., 2021) are given in Table V.1. In addition, some calculations are carried out in this work in order to define the other natural stone thermos-physical properties.

Table V.1. Properties of Tébessa limestone *(Source: The Author).*

Property	Standard	Mean ± Standard deviation
Apparent density - kg/m^3	TS EN 1936	2475 ± 41
Open porosity - %	TS EN 1936	5,948 ± 0,873
Real density - kg/m^3	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 -mm^3	TS EN 14157	24226 ± 1796
Sound speed - m/s	TS EN 14579	3782 ± 136
Hardness [mohs]	TS TS 6809	2.5-3

Calculate the thermos-physical values of the limestone used in construction in Hammamet, Tébessa Wilaya allow to evaluate the durability of this material, and improve it regarding the semi-arid climatic context.

V.1.1. Thermal conductivity

According to the results of the laboratory in this research, the thermal conductivity of the dry limestone studied is equal to 2.7 [W/(m.k)].

λ = 2.7 [W/(m.k)]

V.1.2. Density

According to the results of the laboratory of this current study, the density of the limestone samples studied is equal to 2475.

V.1.3. Heat Capacity

According to the British Standard BS EN 12524 (2000), the volumetric Heat Capacity of the limestone studied in this research, equal to 1000 [J/(kg.K)].

$\rho.C_p$ = 1000 [J/(kg.K)]

V.1.4. Thermal resistance

To calculate the thermal resistance, we used the thermal conductivity value of the limestone samples studied in this work, and the thickness of natural stone buildings wall studied, the result equal to 0.37 [$m^2.K.W^{-1}$].

$$R = e/\lambda \tag{1}$$

R= 0.3/2.7

R= 0.11 [$m^2.K.W^{-1}$]

V.1.5. Thermal Diffusivity

Thermal Effusivity and Thermal Diffusivity are the essential quantities to quantify the thermal inertia. The thermal diffusivity is an intensive quantity. It characterizes the efficiency of heat transfer by conduction; it is calculated by the following formula:

$$\alpha = \lambda / \rho \times Cp \tag{2}$$

To calculate the thermal diffusivity of the limestone studied:

$$\alpha = \frac{2.7}{2475 \times 1000}$$

$\alpha = 1.09 \times 10^{-6}$ [m^2/s]

The result showed that Tébessa limestone has a higher thermal diffusivity in comparison with the construction materials in the Table V.2.

Table V.2. Thermal diffusivity of materials *(Source: passivact.fr).*

Rang	Material	Thermal diffusivity 10^{-6} [m^2/s]
1	wood fiber	0.12
2	wood wool	0.15
3	OSB panel	0.17
4	sapin wood	0.19
5	oak wood	0.21
6	cellular concrete	0.26
7	cork	0.27
8	plasterboard	0.30
9	plaster tiles	0.30
10	solid brick	0.31
11	rock wool	0.43

12	polyurethane	0.63
13	solid concrete	0.78
14	extruded EPS	0.81
15	stone	0.85
16	glass wool	0.94
17	expanded EPS	1.06
18	Steel	14.25
19	aluminum	96.80
20	copper	112.36

V.1.6. Phase shift time

Time shift is related to the capacity that the material has to transmit a heat front; it is dependent on the relationship of its thermal diffusivity, its thermal capacity and its conductivity. The phase shift is calculated as follows:

$$\text{Phase shift} = \frac{Thickness}{Celerity} \tag{3}$$

The celerity is the speed of diffusion of heat through the wall, and is calculated as follows:

$$\text{Celerity} = \frac{2\times\pi}{T\times\sqrt{\frac{\pi}{T}}} \times \sqrt{\alpha} \tag{4}$$

The celerity depends on the period T of the oscillations of the outside temperature. For the calculation of the celerity, the period of oscillations of the outside temperature is 24 hours. This celerity depends only on the composition of the wall, through the diffusion coefficient, noted α is the diffusion coefficient, equal to 1.09×10^{-6} [m^2/s].

$\alpha = 1.09 \times 10^{-6}$ [m^2/s]

$\sqrt{\alpha} = \sqrt{1.09 \times 10^{-6}} = 0.001$

Finally, by combining the above equations, and considering that the period of outdoor temperature variation T wants 24 hours, we find that the phase shift is expressed by the following formula:

$$\varphi = \frac{e\times T\times\sqrt{\frac{\pi}{T}}}{2\times\pi\times\sqrt{\alpha}} \tag{5}$$

The phase shift is therefore proportional to the thickness, and inversely proportional to the diffusivity of the wall.

$$\varphi\ (T = 24h) = \frac{e \times \sqrt{(T/4/\pi)}}{\sqrt{\alpha}} \tag{6}$$

0.023 is the result of simplifying the formula by considering the period T as 24 hours.

With;

T = 24 h = 24 × 3600 s = 86400 s

If φ is expressed in [h] then the coefficient;

$$\sqrt{(T/4/\pi)} \tag{7}$$

Becomes:

$$\frac{\sqrt{(24 \times 3600\ /\ 4\ /\ \pi)}}{3600} = 0.023$$

So, the phase shift time formula becomes:

$$\varphi\ (T = 24h) = \frac{0.023\ e}{\sqrt{\alpha}} \tag{8}$$

$$\varphi = \frac{0.3 \times 0.023}{0.001}$$

φ = 6.9 [h]

The results showed that the phase shift time of the limestone studied is almost 7 hours; this time is not enough in the semi–arid climate context to ensure an acceptable interior thermal comfort. Generally, 10 to 12 hours is the optimal phase shift time, for that reason, we are working in this research to improve this time shift to be suitable for the climatic context of Tébessa semi-arid region.

V.1.7.Thermal Effusivity

The Effusivity indicates the speed, with which the surface temperature of the natural stone rises; we used the values obtained in this research to calculate the thermal Effusivity of the limestone studied to calculate its thermal Effusivity:

$$E = \sqrt{(\lambda.\rho.Cp)} = \rho C\ \sqrt{D} \tag{9}$$

E=√ (2.7×2475×1000) = √ 3465000

E= 2585.05 [SI]

The result showed that the thermal Effusivity equal to 2585.05 [SI], this value is lower than the thermal Effusivity of the ideal construction materials as shown in the Table V.3.

Table V.3. Thermal Effusivity of materials *(Source: passivact.fr).*

Rang	Material	Thermal Effusivity [$J/m^2.K.s^{1/2}$]
1	copper	35849
2	aluminum	23377
3	steel	13248
4	solid concrete	2035
5	stone	1844
6	solid brick	1154
7	wood oak	635
8	plasterboard	454
9	plaster tiles	453
10	sapin wood	346
11	OSB panel	288
12	wood wool	261
13	cellular concrete	177
14	wood fiber	116
15	cork	97
16	rock wool	67
17	extruded EPS	44
18	glass wool	41
19	expanded EPS	39
20	polyurethane	38

The higher the Effusivity of a material, the faster the heat flow is transferred and conducted to the amount of material that composes it, without significantly rising of temperature. On the contrary, the lower the Effusivity, the faster the temperature of the material rises to equilibrium with that of the contact surface. Taking into account the classification of the studied limestone in comparison with other construction materials, it is found that Tébessa limestone has a low thermal Effusivity; therefore, it must be improved in order to improve its thermal effectiveness, and removal the cold sensation of the buildings stone wall studied.

V.1.8. Contact temperature

Weakly effusive materials give an impression of warmth; they will adapt their temperature instantly with that of the surrounding surface and harmonize with the temperature of the environment. The higher the Effusivity, the longer it takes for material to raise and harmonize its temperature. On the other hand, it constitutes heat reservoirs in the cold period, and allow keeping a feeling of coolness despite the rise of the surrounding temperatures in the hot period.

The contact temperature is independent of time and is given by the average of the initial temperatures of the two environments. The formula to calculate this contact temperature is:

$$T_{contact} = \frac{T1 \times E1 + T2 \times E2}{E1 + E2} \quad (10)$$

Where;

$T_{contact}$ = (T of material 1 x Effusivity of material 1 + T2 of material 2 x Effusivity of material 2)/ (Effusivity of material 1 + Effusivity of material 2)

We calculated the contact temperature of the limestone wall studied; the results showed that the contact temperature in the cold period and hot period is almost 16C° and 30C° respectively.

In the cold period;

$$T_{contact} = \frac{T1 \times E1 + T2 \times E2}{E1 + E2} \quad (11)$$

Where,

T1 is the temperature of the human hand,

E1 is the Effusivity of the human hand.

$T_{Contact\ colde}$ = ((1200×37)+(2585.05×6)) / 1200 + 2585.05

$T_{Contact\ colde}$ = 15.8 C° = 16 C°

In the hot period;

$T_{Contact\ hot}$= ((1200×37) + (2585.05×27)) / 1200 + 2585.05

$T_{Contact\ hot}$ = 30.1 C° = 30 C°

To summarize, the results of the Tébessa limestone thermos-physical properties study illustrate in the Table V.4. below:

Table V.4. Thermos-physical properties of Tébessa Limestone *(Source: The Author).*

Thermal conductivity	Density	Thermal capacity		Thickness	Thermal resistance	Phase shift	Thermal Diffusivity	Thermal Effusivity
λ	ρ	Specific Heat Capacity Cp	Volumetric Heat Capacity ρ.Cp	e	$R= e/\lambda$	$\varphi =0.023e/\sqrt{\alpha}$	$\alpha= \lambda.\rho^{-1}.Cp$	$E=\sqrt{(\lambda.\rho.Cp)}$
[$W.m^{-1}.K^{-1}$]	[$Kg.m^3$]	[$J.kg^{-1}.K^{-1}$]	[$Wh.m^{-3}.K^{-1}$]	[m]	[$m^2.K.W^{-1}$]	[h]	[$m^2.s^{-1}$]	[SI]
2.7	2475	1000	2475×10^3	0.300	0.11	6.9	1.09×10^{-6}	2585.05

In this respect, in order to facilitate the calculations to define the thermos-physical properties of the natural stone used in construction or any other material, we have created an arithmetic table in file as Excel. This method makes it easier for researchers to obtain the thermos-physical values.

V.2. Assessment of the natural stone's thermal inertia

The thermal inertia played on the time, winter and summer, and the difference of the temperature between day and night. Thermal inertia is a different concept from phase shift, which is characterized by an attenuation of temperature variations. The thermal Effusivity, i.e. the capacity of the stone to absorb heat without heating up, is the thermal property corresponding to the inertia. Most of the time, natural stone with high inertia are good phase shifters, thus, it is the density of the material that is decisive.

The thermal phase shift is related to the inertia since it is the delay in hours and minutes that will take the heat to cross the natural stone. This phase shift is mainly related to the nature of the usual materials of the construction, therefore, it is not very flexible.

A material with a large phase shift will make it possible to naturally maintain an acceptable temperature during the day, and to reach the maximum temperature only once the night comes, when a simple ventilation of the building makes it possible to regulate the temperature.

The key to phase shift is in the thermal diffusivity property. In simple terms, the speed with which heat passes through the wall. This depends on the insulating capacity of the wall, its density and its heat storage capacity. If the material is a good insulator, it slows down the conduction of heat. Similarly, the higher the density of the material, the lower the diffusivity and the greater the phase shift.

To achieve a high phase shift, the optimal solution is therefore a material that is both heavy, insulating and a good heat accumulator. In order to improve the thermal performance of the natural stone we have to add another high performance material on the wall of building. On the other hand, insulating materials can have a strong phase shift but can never have a good inertia; their low conductivity hinders the diffusion of the heat in the whole mass and thus prevents a good storage of energy. Therefore, thermal insulation limits heat loss, while thermal inertia allows heat to be stored. In this case, the thermal correction is the best solution to improve the thermal performance of building by enhance the thermal inertia.

V.2.1. In the hot period

The use of the phase shift has its limits in the research of the summer comfort. Indeed, the phase shift has an impact only on the energy contributions through the walls. The energy contributions through the windows or the internal contributions, which related to the human activity and to the electric appliances in particular, are not treated by the phase shift. However, they represent a very important part of the risks of overheating in summer.

In the case of the semi-arid climate, in the hot period, when the temperature rises gradually during the day to reach 42C°, the Tébessa limestone is bad phase shifter, it is transmits the heat to the interior shortly afterwards and the building quickly overheats, whereas a good phase shifter delays the diffusion of heat until the cooler night. It is then possible to ventilate the interior abundantly to compensate for the out-of-phase solar gain. Thus using the phase shift makes sense only if the building can be cooled during the night when the heat front enters the building.

V.2.2. In the cold period

In winter, the greater the thermal inertia, the longer the natural stone building will take to heat up. Therefore, to optimize the thermal inertia of these buildings, it is better to insulate from the outside to limit thermal losses as it shown in the Fig. V.1, because of;

- In winter with an interior insulation, the stone wall will store the outdoor cold, that will be fortunately stopped by the interior insulation, but this system is not optimal.
- In winter with an exterior insulation, the stone wall will store the indoor heat and the outdoor cold will be stopped by the insulation. Then the thermal inertia of the stone walls will be used in the right way.

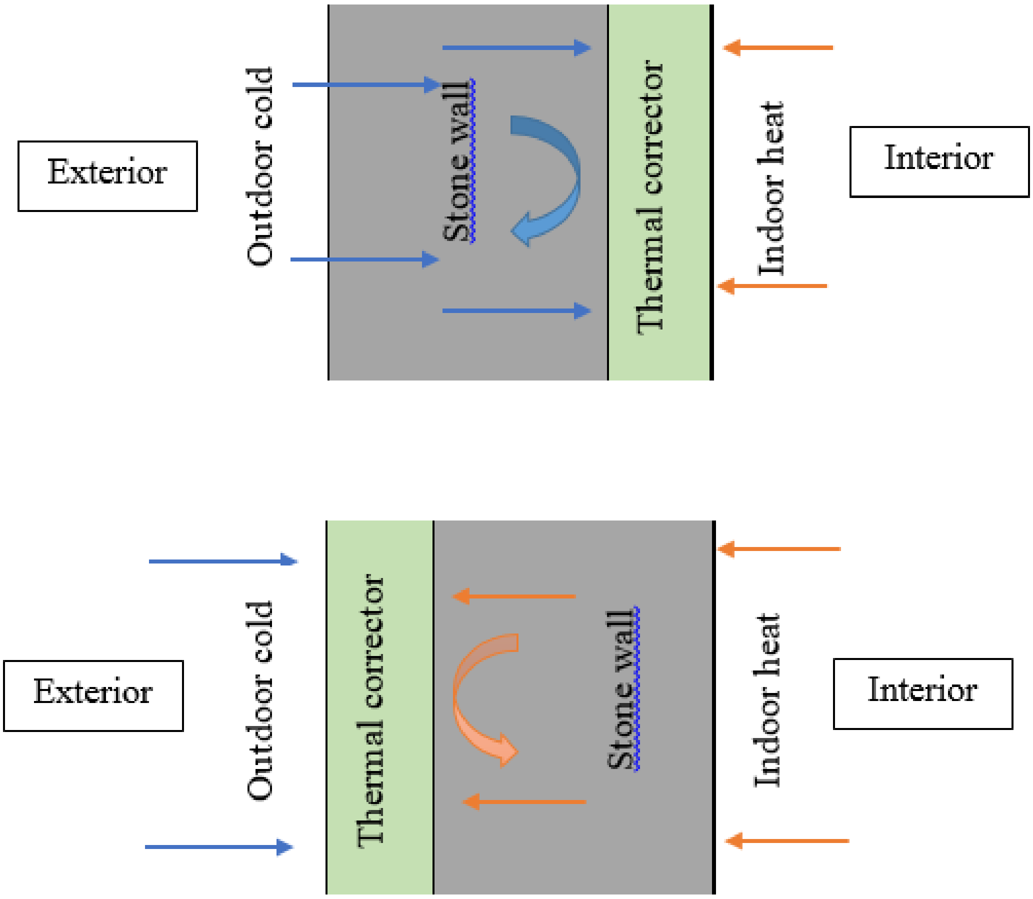


Fig. V.1. Section of stone wall performance *(Source: The Author).*

V.3. Optimization of the thermal properties of natural stone

Our purpose in this research is to improve the thermal performance of a residential building by improving the thermal properties of the stone used, this is by enhancing the thermal inertia. We can achieve this just by modifying the thermal diffusivity and thermal Effusivity of the natural stone to obtain an ideal building material as it shown in the Fig. V.2.

Otherwise, building Materials with high transmission and absorption inertia cannot exist, therefore, an ideal material, optimized for comfort, should have minimal diffusivity and maximum Effusivity. Physics shows that this is perfectly impossible since the two are interdependent as specified by the relationship:

$$E = \rho C \sqrt{D} \qquad (12)$$

The Effusivity of a material depends on its diffusivity, when one is maximum, the other is maximum to; in other words, the more effusive a material is and the more diffusive, it is, the more energy it is able to store, and the faster it conducts heat from one side to the other. Consequently, Materials that are both weakly diffusive and strongly effusive cannot exist, therefore, the natural stone with high inertia by transmission and, simultaneously, with high absorption inertia cannot physically exist.

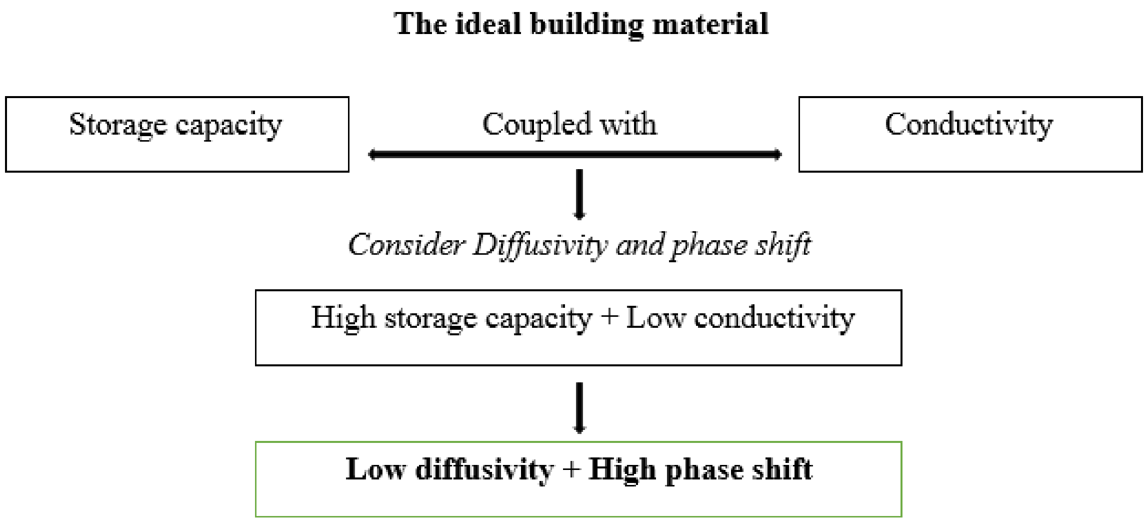


Fig. V.2. Ideal building material properties *(Source: The Author).*

To improve the thermal behavior of the building envelope, there is no other solution than to have two different materials as it is shown in the Fig. V.3 The one subject to the vagaries of the climate, located outside the building, must have a maximum inertia by transmission and therefore a minimum diffusivity, while the one located inside must have a maximum inertia by absorption and therefore a maximum Effusivity. In other word;

- The exterior building materials must have a low thermal diffusivity.
- The interior building materials must have a high thermal Effusivity.

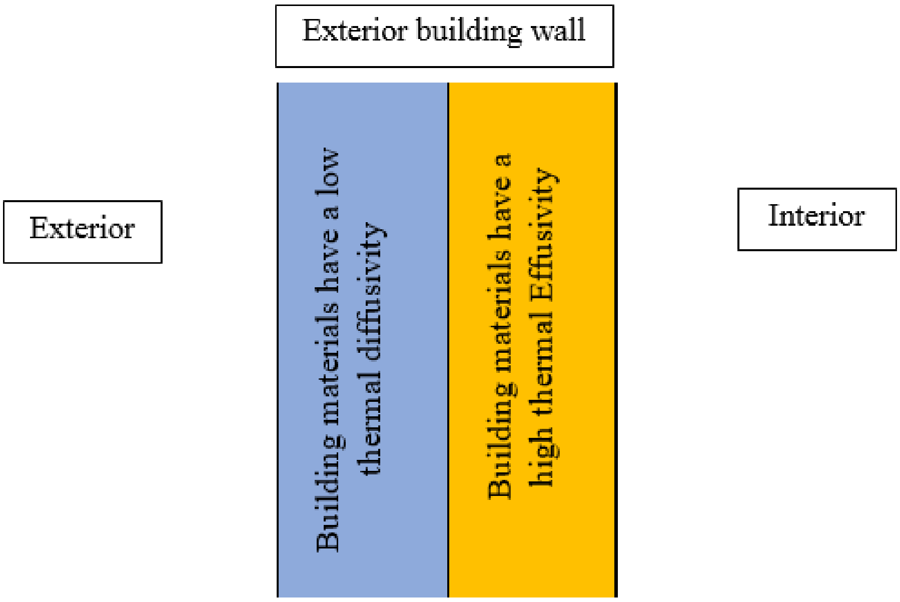


Fig. V.3. Ideal wall material properties *(Source: The Author).*

In the case studied, the natural stone is inflexible material, in order to achieve this aim we are required to add another material, taking into account the climatic and social aspect of Tébessa region. The thermos-physical properties of Tébessa Limestone showed that this type have a low thermal diffusivity and low thermal Effusivity. Therefore, the second material must be have a high Effusivity.

V.4. Thermal correction of natural stone building

Since buildings use the most energy for heating and cooling, improving thermal insulation standards is still one of the most cost-effective means to ensure thermal comfort and reduce energy use, thereby reducing carbon emissions (Latif, et al., 2014a).

This study implies that, from the point of view of inertia, in a variable temperature regime, especially in arid and semi-arid climates, the best solution that ensures the best thermal comfort, and by application of the rules of physics, is the thermal correction. In the other hand, a conclusion of the previous research is that insulating materials cannot be the most efficient in terms of comfort inertia since they cannot simultaneously satisfy the optimization of both types of inertia (Djedouani, et. al., 2020). The corrective coatings do not insulate but correct the Effusivity of natural stone walls, it considered as hygrothermal regulator. It was chosen as thermal corrector in this study, given the considered thickness of the limestone wall studied, where laboratories experiments have shown that 0.08 m of thickness at maximum will be enough to ensure the thermal comfort and correct the Effusivity of the natural stone wall.

In general, the corrective coating contains a classical mortar plus a binder such as cement, clay and lime; in addition, the insulating granules as the hemp micro beads and the cork as it shown in the Fig.V.4, these natural materials are very promising in terms of environmental protection. The use of green thermal insulation materials brings a significant reduction of energy requirements of buildings, which is their major benefit (Hroudová & Zach, 2017), as well, previous research shows that crop-based thermal insulating materials exhibit very good thermal insulation. Among the thermal repair coatings used in ancient buildings, lime hemp is a plant-based fiber insulation material. Because it comes from renewable resources, it is considered an environmentally friendly material and is easy to recycle.

Fig. V.4. Composition of lime hemp coating *(Source: The Author).*

Research on performance and hygrothermal properties of the hemp insulations are mostly based on experimental works in laboratories. Many research determined the hygrothermal properties of this insulation material, which provide very good thermal insulation properties, and respect the hygroscopy of ancient stone walls (Nicolajsen, 2005), (Korjenic, et al., 2011), (Latif, et al., 2014b).

In the case studied, the hemp-lime considered as the best thermal corrector, especially to solve the moisture problem in the natural stone building, where the water coming from the subbasement affects the thermal behavior of the limestone wall. A study done by Hroudová & Zach (2017), on samples of hemp insulation, in order to examine the effect of moisture on the hygrothermal behavior of the samples of insulation and to study the dependence of their thermal insulation properties on relative humidity, proved that these insulation types have a high hydrothermal performance. As long as the natural-fibrous material is not exposed to high relative humidity above 60 % for an extended period, there is no important harm to its thermal insulation function.

Another study done by Patrick et al. (2011) proved the thermal effectiveness of the lime-hemp by many experiments studies in the laboratory. The results of the thermos-physical properties of the hemp-lime are given in the Table V.5.

Table V.5. The thermos-physical properties of the hemp-lime *(Source: Patrick et al., 2011).*

Thermal conductivity λ	Density ρ	Specific Heat Capacity Cp	Thermal Diffusivity α
$[W.m^{-1}.K^{-1}]$	$[Kg.m^3]$	$[J.kg^{-1}.K^{-1}]$	$[m^2.s^{-1}]$
0.145	520	42×10^4	3.5×10^{-7}

Taking into account these values, we calculate the other thermos-physical properties of 0.08 m thickness of hemp-lime in order to regulate the thermal diffusivity and the thermal Effusivity of the limestone walls studied.

V.4. 1. Phase shift time

The result showed that the phase shift time of the hemp-lime is 3.1[h], this value improve the phase shift time of the limestone walls studied, which equal to 6.9 [h]. We conclude that, by applying a hemp-lime layer of 0.08 m, we reach an optimum phase shift time in the semi-arid climate equal to 10 hours.

$$\varphi\ (T = 24h) = \frac{0.023\ e}{\sqrt{\alpha}} \qquad (13)$$

Where,

e = 0.08 m

$\alpha = 3.5\times10^{-7}\ [m^2.s^{-1}]$

$\varphi = \frac{0.08\times0.023}{59160.79}$

$\varphi = 3.1\ [h]$

V.4. 2. Thermal Effusivity

The result showed that the thermal Effusivity of the lime-hemp coating is equal to 5627.43[SI], by adding this value to the thermal Effusivity limestone wall value, which equal to 2585.05[SI], we obtain an optimum thermal Effusivity of the natural stone building walls studied, which improve its thermal behavior.

$$E=\sqrt{(\lambda.\rho.Cp)} \quad (14)$$

$E=\sqrt{(0.145 \times 520\times (42\times10^4))} = \sqrt{31668000}$

E= 5627.43 [SI]

The results of the thermos-physical hemp-lime coating are given in the Table V.6

Table V.6. The thermos-physical properties of the hemp-lime coating thermal corrector *(Source: The Author).*

Thermal conductivity	Density	Specific Heat Capacity	Thickness	Thermal resistance	Phase shift time	Thermal Diffusivity	Thermal Effusivity
λ	ρ	Cp	e	R= e/λ	φ =0.023e /$\sqrt{\alpha}$	α= $\lambda.\rho^{-1}.Cp$	E=$\sqrt{(\lambda.\rho.Cp)}$
[$W.m^{-1}.K^{-1}$]	[$Kg.m^3$]	[$J.kg^{-1}.K^{-1}$]	[m]	[$m^2.K.W^{-1}$]	[h]	[$m^2.s^{-1}$]	[SI]
0.145	520	42×10^4	0.08	0.55	3.1	3.5×10^{-7}	5627.43

The results obtained confirm the thermal and energetic efficiency of the optimized wall by the thermal correction (See Fig. V. 5), which has a positive influence on the thermal sensation and satisfaction of the users, as well as on the energetic performance of the natural stone residential building built in the semi-arid climate.

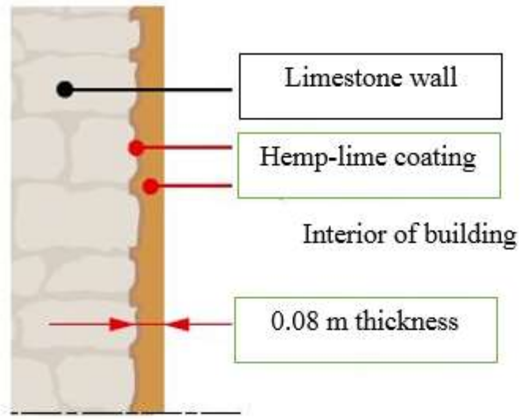


Fig. V.5. Natural stone wall with a thermal corrector *(Source: The Author).*

Conclusion

As conclusion, to potentiate the thermal inertia of natural stone building in the semi-arid climatic context, the most widespread solution is the realization of a thermal corrector of the walls by the inside to correct the thermal diffusivity and thermal Effusivity of the material. To ensure the thermally efficient building envelope, the exterior building materials must have a low thermal diffusivity, while the interior building materials must have a high thermal Effusivity.

GENERAL CONCLUSION

General conclusion

Reducing the energy consumption of the building is a basic problem in all countries in the world, especially in the harsh climate region such as arid and semi-arid climate. The nature of these climates is that there are low temperatures in the cold season and high temperatures in the hot season, with wide range of cold and hot months throughout the year, which increases the energy consumption of buildings. Regarding to the importance of this topic, we tried in this research to assessment and improve the building envelope. It represents the main shaft of all thermal exchanges and the internal environment and external heavy construction material, which is usually followed in traditional buildings and being responsive and adaptive to changes in the external environment through its dynamic behavior by preventing the effects of the external environment.

In addition, the building envelope is a major lever for reducing energy needs, reducing CO^2 emissions and improving the energy efficiency of buildings. Its offers users a durable protection against external weather conditions such as wind, rain, frost, heat. During the cold period, it minimizes heat loss to the outside while maximizing solar energy gain. Conversely, in the hot period, a good envelope helps to maintain a certain coolness inside the building.

The materials used in the design of the building envelope play a considerable role in the absorption, storage and distribution of the energy provided by the solar flux. Therefore, the performance of the envelope is particularly linked to the thermos-physicals properties of construction materials and to the knowledge of the climatic conditions in which the building will be built. In this respect, for the natural stone building envelope, as the type of stone differs, its thermo-physical components differ, therefore, its interaction with environmental factors varies.

In general, Igneous rocks, sedimentary rocks and metamorphic rocks are classified according to their genesis, structure and texture, and finally according to their mineral composition. The visual inspection of the stone samples used in construction in Tébessa province in Algeria, the case studied, shows that they are classified as sedimentary rocks. Since the sedimentary rocks can be of chemical or biochemical origin, the chemical analysis considered as the best method to determine the stone type by revealing its chemical components.

This research concentrates on analyzing the significant impact of the interactions of the harsh climatic factors with the thermos-physical properties of natural stone used in construction on the thermal inertia of the ancient residential buildings over time; however, the building orientation does not affect the thermal behavior of the natural stone walls.

The results of this study showed that the limestone showed a weak resistance in the semi-arid climate under the important gap of temperature between the day and the night. Its components affected by the thermal shock effect weathering and saturated with water arising from the sub-basement of the building caused an increase of the thermal conductivity coefficient; therefore, the thermal inertia and the thermal efficiency of the natural stone wall are reduced.

On the other hand, the results show a low thermal phase shift contribute to reducing the thermal inertia of buildings, as well as the very high indoor relative humidity values recorded and the absence of the natural ventilation affects the indoor thermal comfort, this explain the buildings thermal performance decrease. The comparison between the results showed a weak agreement between the experimental and numerical values, this is the result 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.

In this respect, the limestone type used in construction in Tébessa is known by weakness under the harsh environmental condition. The laboratory tests and analyzes that were done on the stone samples proved that the thermo-physicals properties of the limestone do not resist the temperature changes between the day and night, in the cold and hot period in this region. This is due to its porous nature and its low density, which was unable to cope with the semi-arid climate conditions.

This is leads to a very noticeable weakness in the sustainability of material, consequently, on the thermal performance of the building envelope. In this case, the best solution is the thermal correction by coating, this hygrothermal regulator ensure the interior thermal comfort by the thermal inertia valorization. It proved its thermal effectiveness to optimize the thermal diffusivity and the thermal Effusivity of the limestone wall in the semi-arid climate. As conclusion, it would be recommended to choose the suitable stone type used in construction regarding to each climate type, where this depends on the interactions between them.

Recommendations and perspectives

It is recommendable to take into consideration the following points in order to improve the thermal comfort of the users and the energy performance of the natural stone building located in the semi-arid climatic context;

- Given that the orientation of buildings and their architectural features are restricted by the densely built urban environment and architectural limitations, thermal insulation is still an important tool for optimizing building energy behavior.
- Thermal inertia is more efficient the more temperature changes are important, and it cannot function without efficient ventilation.
- Thermal inertia only exists in a dynamic environment. It is even more efficient when the atmosphere evolves strongly and quickly, as, for example, when the sun hits a building envelop and then disappears a few hours later. It is of no use in a stable system, when the temperature varies very little or very slowly, as, for example, when the night temperature does not drop and night ventilation cannot therefore be effective.
- In order to potentiate the thermal inertia of natural stone building in the semi-arid climatic context, the most widespread solution is the realization of a thermal corrector of the walls by the inside to correct the thermal Effusivity of the material.
- To provide a low thermal conductivity of the natural stone used in the construction of buildings, it is necessary to keep it dry from the water coming from the subbasement.
- To ensure a thermally efficient building envelope, the exterior building materials must have a low thermal diffusivity, while the interior building materials must have a high thermal Effusivity.
- Insulating materials cannot be the most efficient in terms of comfort inertia since they cannot simultaneously satisfy the optimization of both types of inertia.
- The impact of climate factors on the thermal behavior of natural stone must be studied, because not all types of natural stone are suitable for construction in the harsh climatic condition, the more different the type of stone, the more different its thermo-physical properties.
- The limestone proved it weakness in the semi-arid climate context; it will be more suitable for construction in a less harsh climatic context.

- More research is needed to study the effect of climate on the durability of the natural stone in order to define the suitable stone type used in construction in the harsh climatic condition.

Limitations of the research

- The lack of means is considered as a limitation that did not allow us to elaborate the experimentation after the thermal correction by test models on a real or reduced scale, in order to analyze the thermal performance of the walls and to study the impact of the climatic factors on the thermally corrected natural stone wall.
- In addition to that, the lack of measuring instruments that allow to record the values automatically during the whole day in order to understand the hygrothermal performance of natural stone walls.
- The insufficiency of the study cases due to the difficulty of finding understanding families living in the buildings built in natural stone, which allow us to take measurements in situ in the coldest and warmest period in passive way (turn off heating and cooling devices in the harsh climatic condition).
- The curfew that applies on all the Algerian territory because of the world sanitary crisis and the propagation of the COVID-19 from the evening to the morning during the period of taking the measurements prevents us from moving between the residential buildings with freedom, which entails a loss of time. This was mitigated by taking bi-hourly measurements instead of hourly.
- Some tests on the natural stone samples and analyses that will have to be performed in the laboratory within the framework of the P.N.E. grant, have been cancelled due to the closure of the universities during the whole 6 months of the grant in 2020. Then we could not reach the laboratory after that because of the closure of the air space in 2021.

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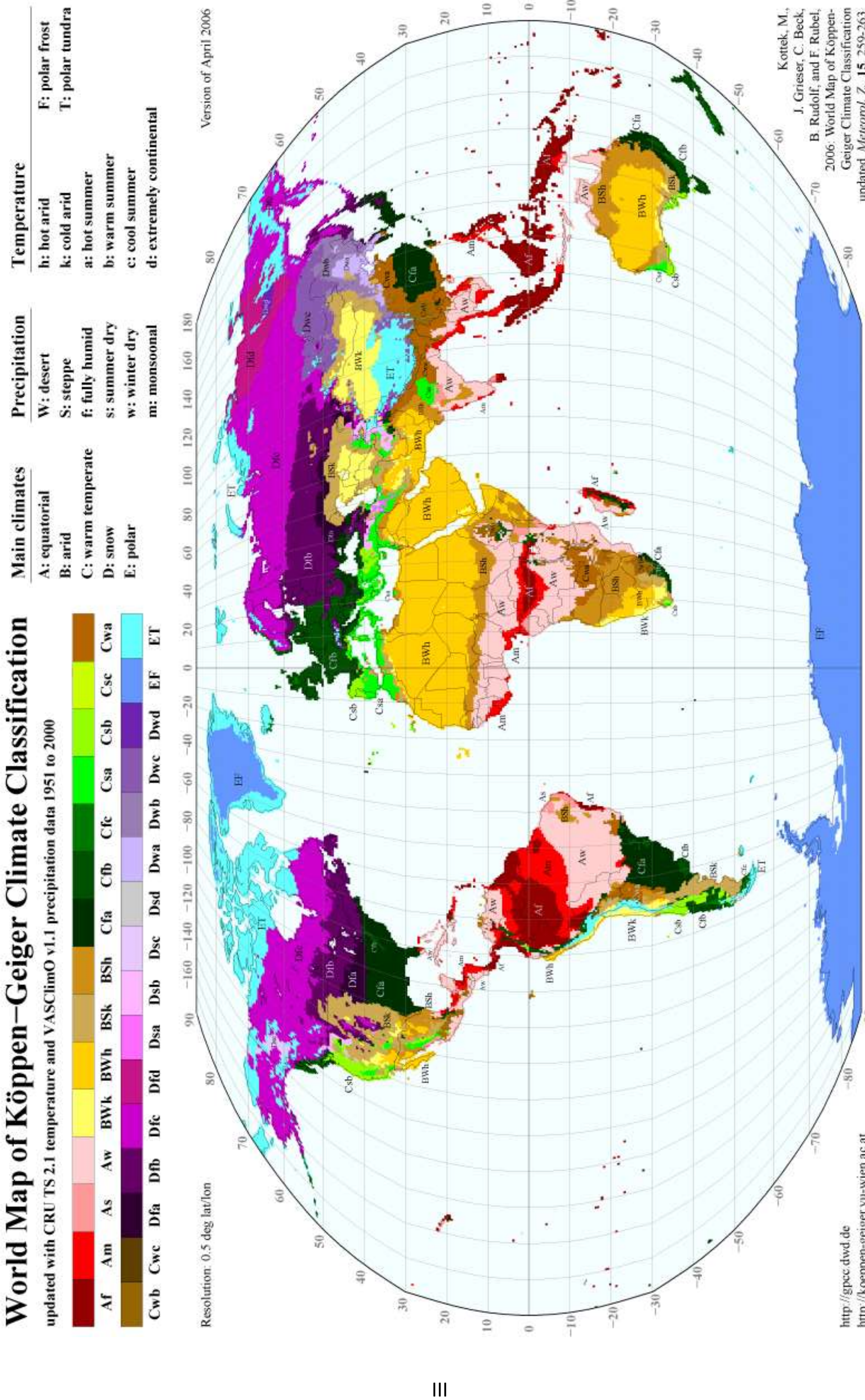
APPENDIXES

Appendix A: climate classification

Fig.1. World map of Köppen-Geiger climate classification *(Source: Kottek et. al,. (2006).*



Appendix B: The meteorological data of Tébessa

Table 1. Calculation of the typical week in January *(Source: The Author extracted from the climatic data of meteorological station of Tébessa).*

January	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1	2,5	7	5	3,5	7	8	8,5	3,5	5	7	13	19	13	8,5	6,5	1	6	7,5	8
2	5	11,5	7	4,5	5,5	7	7,5	4,5	4,5	8,5	7	16	15	8	5	3	8,5	7,5	11,5
3	5,5	10	5,5	6,5	4,5	6	7,5	4,5	4,5	11,5	2,5	14	13,5	8,5	7,5	5,5	8,5	10	15
4	8	7,5	4,5	8	4	7,5	7,5	3	0,5	11,5	3	15	7	10	8,5	4,5	8,5	4,5	12,5
5	9,5	5,5	4	9,5	3,5	7	5,5	3	1,5	10,5	2,5	21	6	10,5	8	5,5	11	2	11,5
6	10	5,5	4,5	9	4,5	8	4,5	3	4,5	9,5	4	16	8	10	8,5	5,5	14	1	12
7	5,5	6	5,5	7,5	4	6,5	6,5	4	5	11,5	4	20	5,5	8	8,5	2,5	11,5	2,5	9
8	3,5	5,5	4	5,5	6,5	8	7	6	4	1	1,5	16	6,5	8,5	10	4,5	6	3,5	9,5
9	1,5	6	4,5	4	8	6,5	7	6,5	5,5	4	2	19	11	9	9	4	7	5	6,5
10	0	4	2,5	6	10	6,5	9	8	7	7,5	3	20	7,5	9,5	5,5	4,5	6	6	3
11	0	8	7,5	5	7	7,5	9,5	7	8	6	8	11	4,5	7,5	5,5	4	10,5	7	1,5
12	3,5	7	7	5,5	6,5	7	10	8	9	5,5	6,5	12	6	7,5	6,5	2,5	11	4,5	4
13	2,5	4,5	16	8,5	7	7	5	5	8	9	0,5	11	7	11	10,5	1	7,5	4	1,5
14	2	8,5	7,5	8	2,5	8	3	6,5	8,5	8,5	-1	12	6,5	7	9,5	2,5	7,5	5	4,5
15	6,5	8	3	11	8	6	6	6	6	7,5	0,5	14	6,5	5,5	8,5	4,5	7,5	8	4,5
16	2	6,5	2	10,5	7,5	6,5	5,5	7	7,5	6,5	2,5	15	7	6	7,5	5	7	5,5	9
17	0	4	2	11,5	8	5	6	4,5	6,5	6,5	2,5	11	9,5	5	8,5	3	7	4	9
18	4	4,5	3	10,5	5,5	6,5	4,5	3,5	6	7,5	4	9	8,5	6	6	4	8,5	5,5	7
19	5,5	6	4,5	8	7	5	5,5	3,5	6	8,5	7,5	7	7,5	8	5,5	5,5	10	4,5	8
20	6	5,5	2,5	7	6,5	6	2	4	5	7	8	11	11	10,5	6,5	2,5	6,5	4	7,5
21	11	4,5	3,5	6,5	8,5	5,5	5	4,5	4,5	6	7,5	13	14	4,5	8	3,5	6	8,5	7
22	9,5	5,5	7	6	7	5	4,5	6	3,5	6	8	13	12	4,5	8	4	8,5	7,5	8
23	12	6,5	9	8	3	7	5,5	7	4	7	9	15	12,5	4	7	3,5	9	9,5	6,5
24	12	7	3	10	6	7	5,5	6	5	5	8,5	15	10	5,5	7	5	11	9,5	5
25	7,5	6	7	9	4,5	5,5	6	0,5	4,5	5	10,5	14	10,5	5,5	6,5	6	12,5	7,5	3,5
26	11,5	3,5	7	11	5	8	8,5	2,5	5,5	7	11,5	10	8	5	6	8	8,5	6,5	4
27	7,5	5	13,5	12	4,5	9	6	4	4	6	8	14	13	5	5	8	7,5	7	4,5
28	7,5	7	13,5	13	5	10	6	5,5	5,5	6	9	16	9	7	8	3,5	11	8,5	7,5
29	5,5	7	16,5	11,5	6	8,5	4,5	6,5	6,5	7	10	11	9,5	10	7	10,5	6,5	12	9
30	5,5	8,5	10,5	13,5	7	7,5	5	6	8,5	5,5	10	11	8	8	4,5	9	4,5	13	4,5
31	5,5	8	8,5	9,5	4,5	9	4	4	7	9	10	13	8	11,5	-1	9	4,5	13	3

2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average	
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	**7,22**	1
4	6,5	5,5	5	5,5	9,5	9	7	8	2,5	7	6,5	10	4,5	6	8	5	**7,06**	2
4	6,5	4	6,5	8,5	8	10,5	6,5	7	7	9	7	11	6	11	7,5	6	**7,69**	3
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	**7,15**	4
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	**7,22**	5
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	**7,44**	6
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	**7,26**	7
4	6,5	5	7	8	6	9	12	7,5	5,5	11,5	6,5	12	4	13,5	3	4,5	**6,87**	8
7,5	7	4	6,5	9	7	3	10,5	5,5	6	11,5	7	12,5	5	7	5	6,5	**7,03**	9
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	**7,26**	10
10	7	3,5	10	9,5	4	7,5	6,5	5	9	8	9	13,5	4,5	9	2	5	**7,06**	11
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	6,5	**6,88**	12
12	7	3,5	10	5,5	7,5	9,5	8,5	7	7,5	10	8,5	8,5	6	6	4	5,5	**7,24**	13
11,5	6,5	5	10	7,5	7	10,5	9,5	5	7	7,5	11	10	5	6	8,5	5,5	**7,03**	14
7,5	6	3,5	12	10	6	7	9,5	6,5	5	5,5	11	11,5	3	7	7	4,5	**6,93**	15
6,5	4	4	10	7,5	6	6	10	6	7,5	8	7	3,5	2	4,5	6,5	4,5	**6,50**	16
8,5	5,5	4	9	8	7	8	10	5	10	10	6	1,5	1	4,5	6	4,5	**6,41**	17
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**	18
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	**6,72**	19
5	4	8	11,5	9,5	10,5	10	5,5	3	8,5	7	6,5	7	4,5	9	5	9,5	**6,81**	20
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	10,5	**7,29**	21
7	8	5	10,5	7	7	7,5	3	7	8,5	7	6,5	7,5	6,5	12	3,5	11	**7,15**	22
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	12,5	**7,34**	23
8	6	2	6	5	13	10	6	9,5	6	8	4,5	6,5	4,5	5	3	10,5	**6,99**	24
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**	25
12	0	2	10	4	8,5	9	7	8	5	8,5	3	9	6,5	8,5	4	8,5	**6,93**	26
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	**7,43**	27
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	**7,71**	28
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	8,5	**8,09**	29
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	10,5	**7,79**	30
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	**7,43**	31

Table 2. Calculation of the typical week in July *(Source: The Author extracted from the climatic data of meteorological station of Tébessa).*

July	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1	30	23	24	32,5	25	31	20,5	21	28,5	24,5	27,5	25,5	26	31,5	24	28,5	25	25,5	31,5
2	30,5	23,5	23,5	27,5	24,5	26	23,5	19,5	30,5	25	29	26,5	29	32,5	24,5	30,5	24,5	26,5	30
3	30	27,5	23,5	27,5	22	27	24,5	19,5	31,5	28	30	27	28,5	32	27	31	25	26	29,5
4	30	26	27,5	29,5	24	25	26,5	23,5	33	28,5	26	28	27,5	29,5	29,5	29,5	27	28	27
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Appendix C: The climate file of the city of Tébessa according to Meteonorm
(Treated by climate consultant 0.6 V)

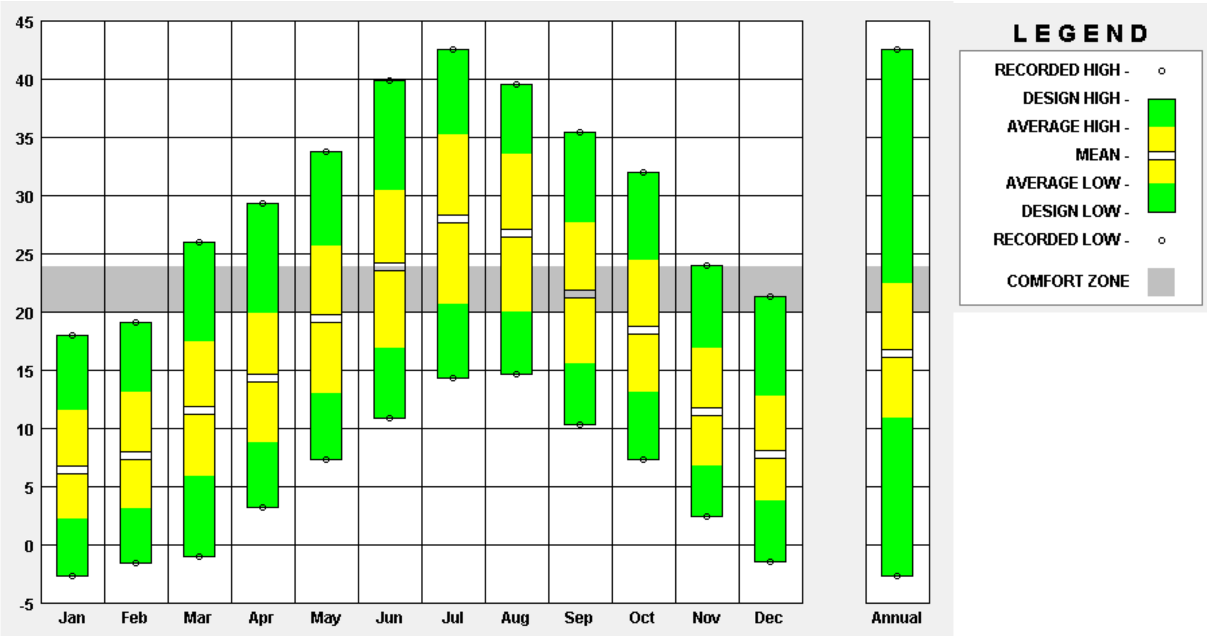


Fig. 1. Temperature range *(Source: meteonorm).*

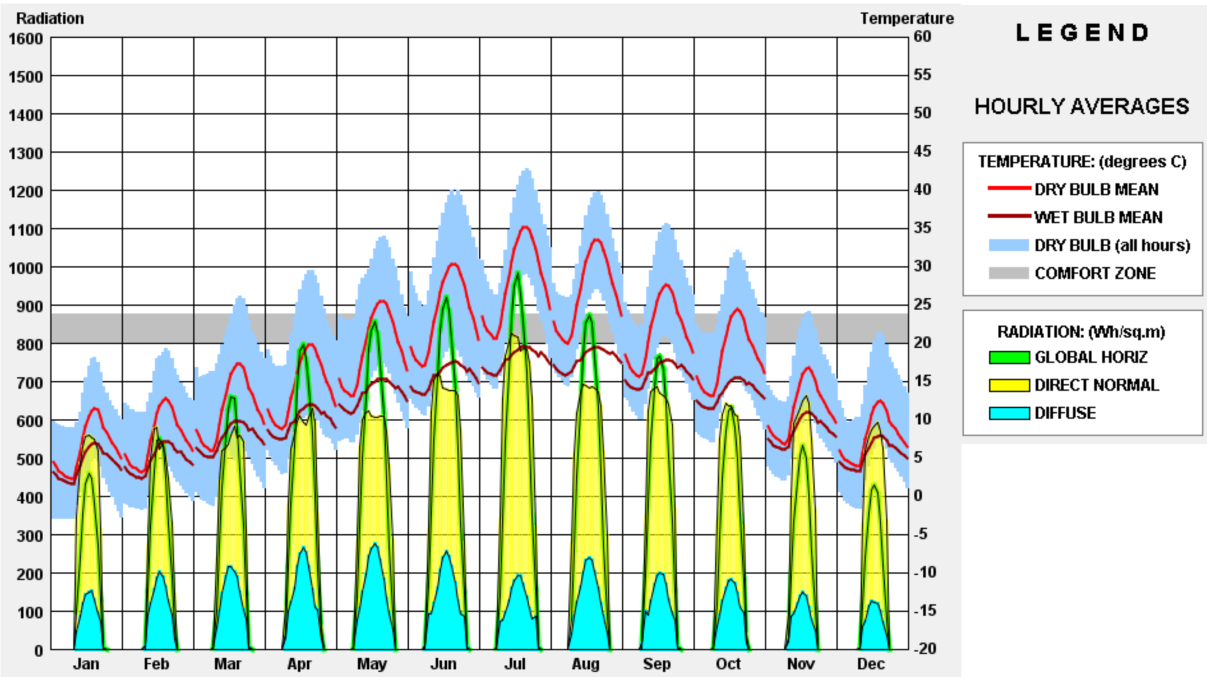


Fig. 2. Monthly diurnal averages *(Source: meteonorm).*

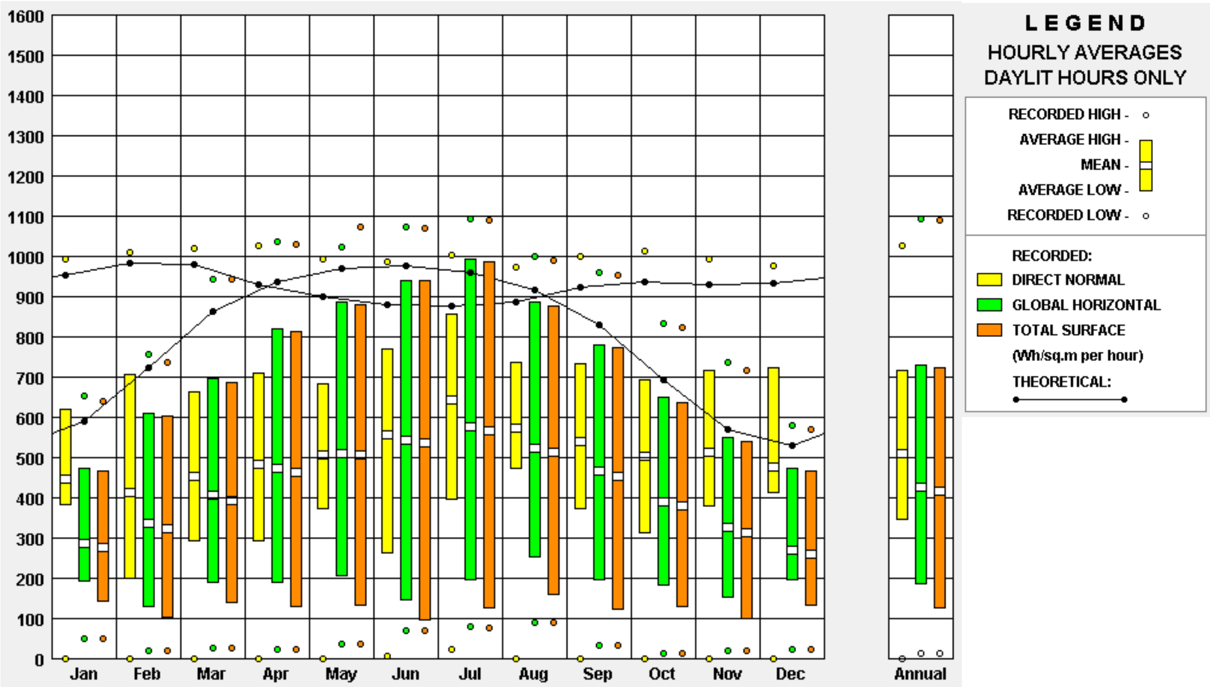


Fig. 3. Radiation range *(Source: meteonorm).*

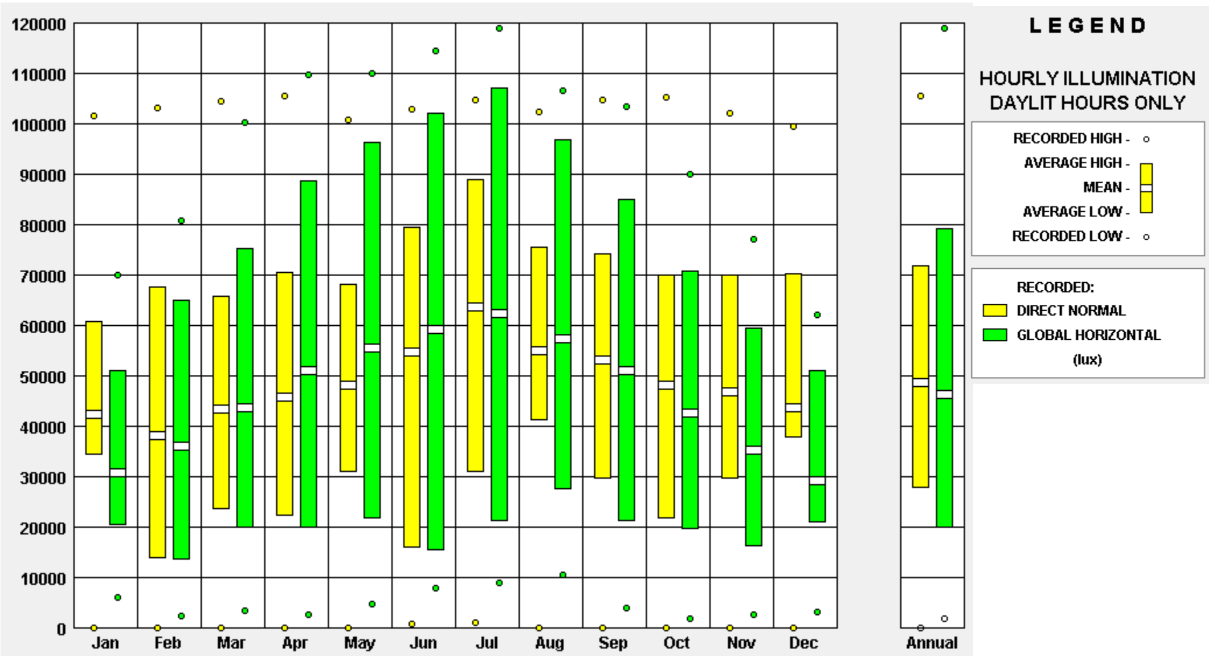


Fig. 4. Illumination range *(Source: meteonorm).*

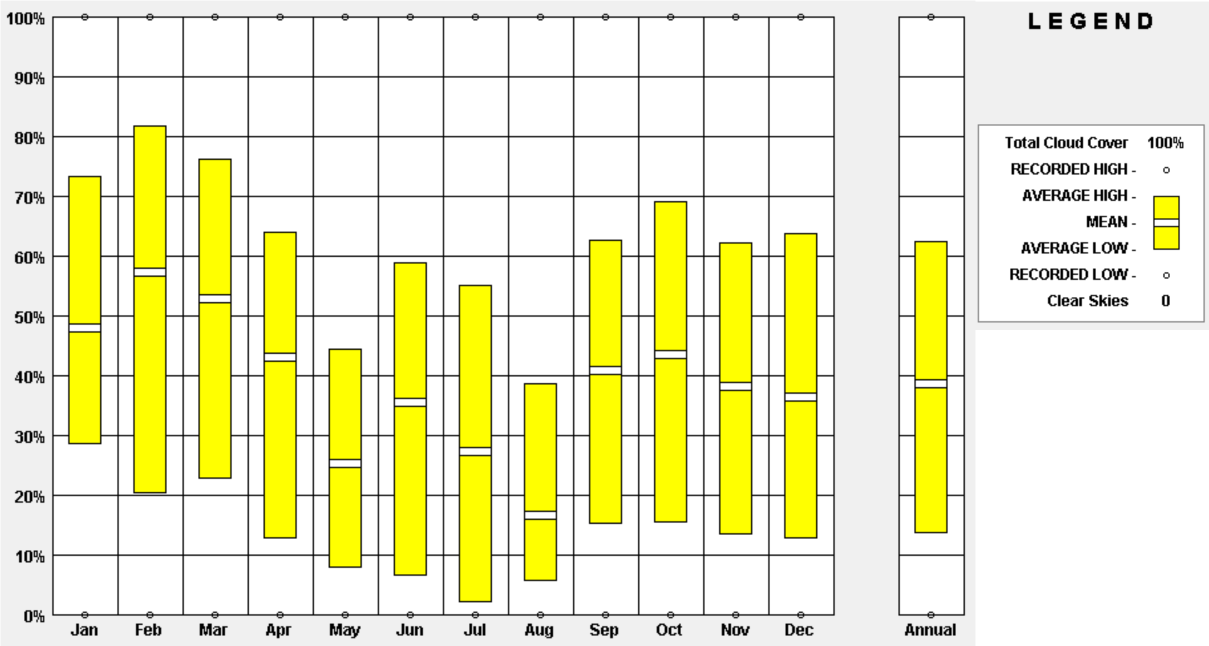


Fig. 5. Sky cover range.

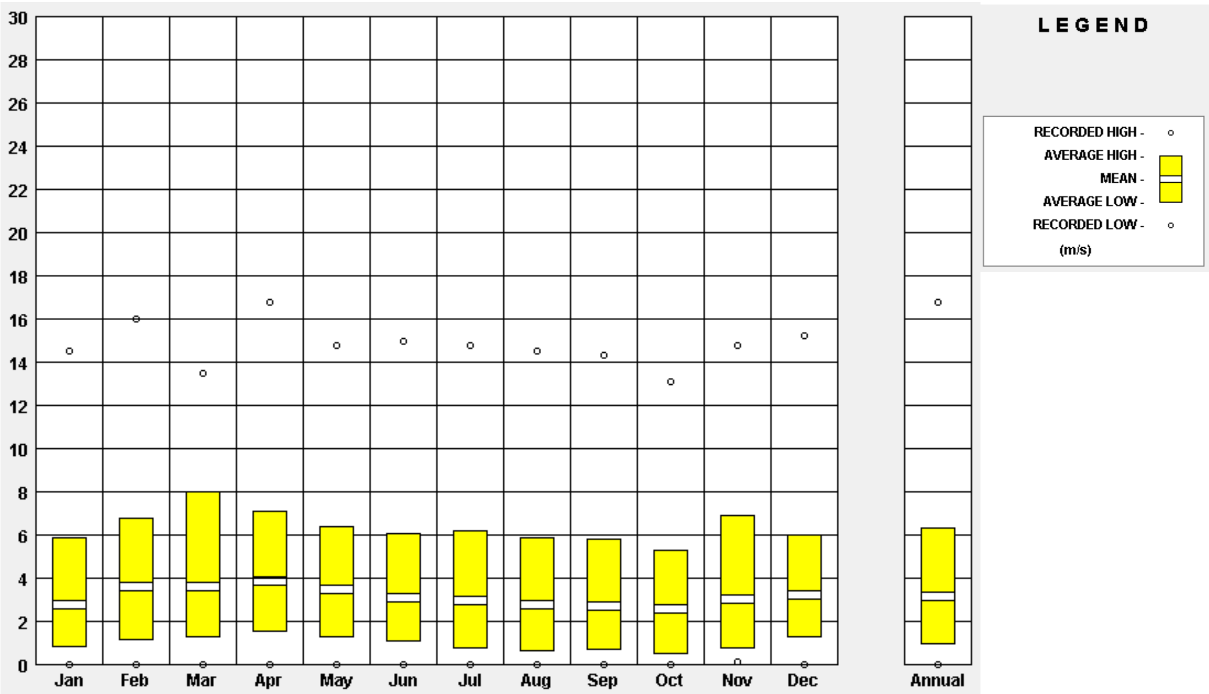


Fig. 6. Wind vilocity range*(Source: meteonorm).*

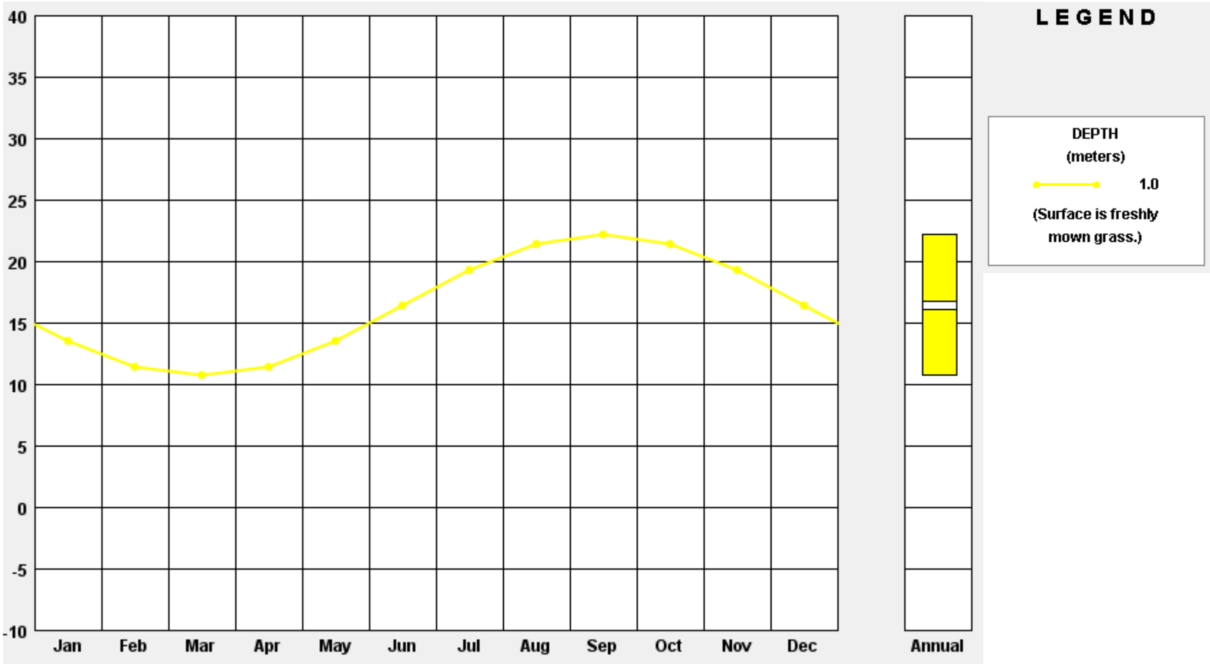


Fig. 7. Ground temperature *(Source: meteonorm).*

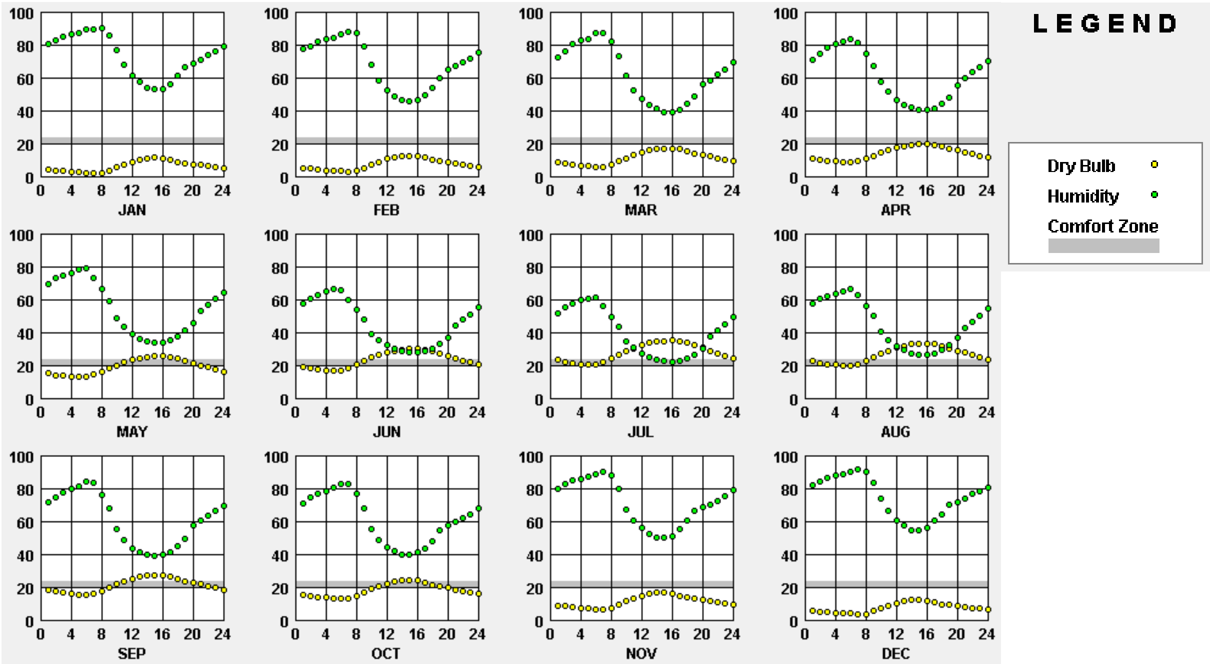


Fig. 8. Dry bulb and relative humidity *(Source: meteonorm).*

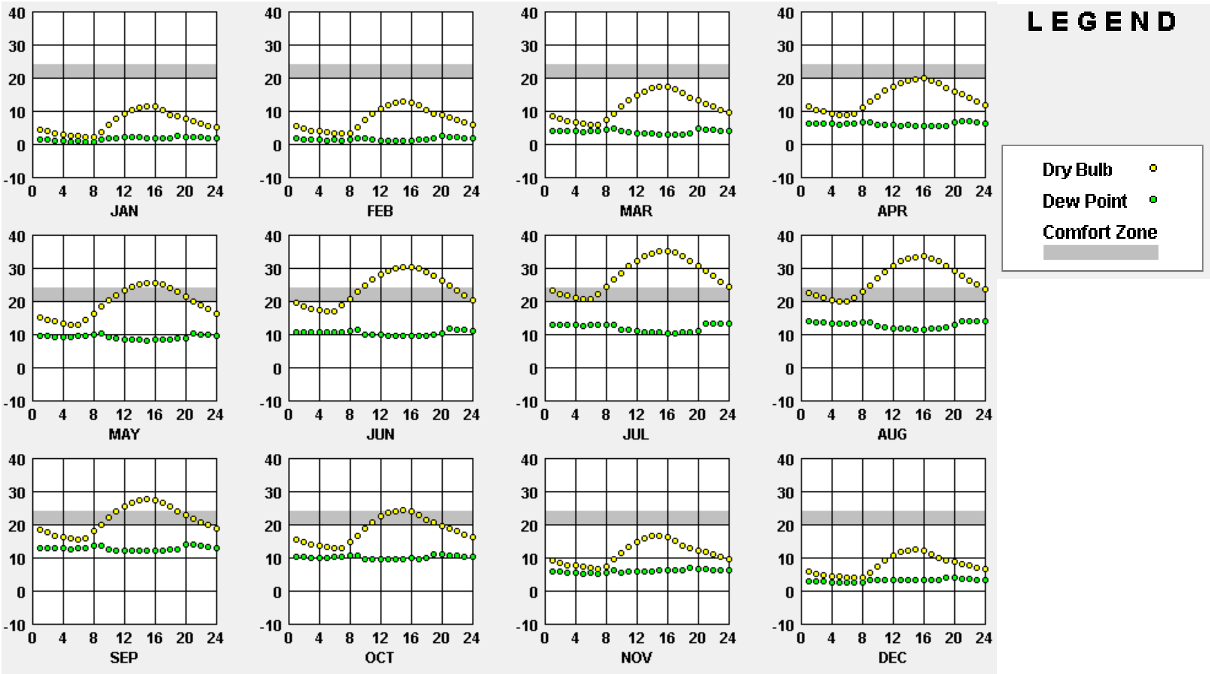


Fig. 9. Dry bulb with DWE point *(Source: meteonorm).*

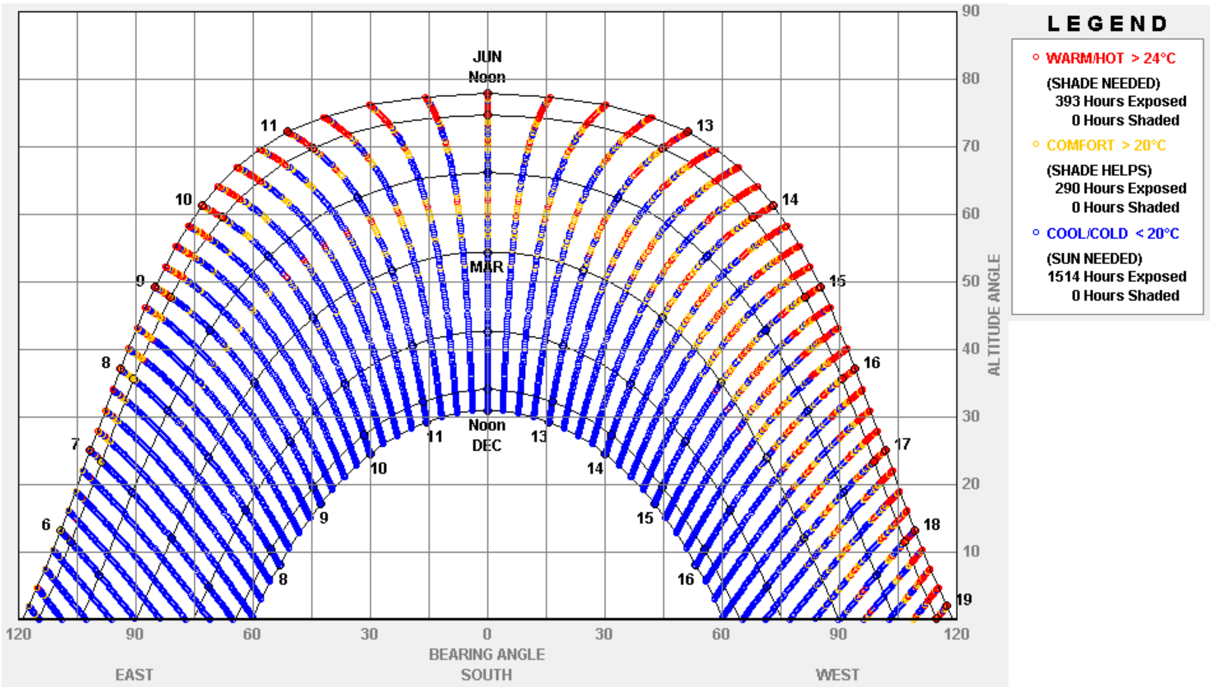


Fig. 10. Sun chading chart , Winter Spring (December 21 to Juin 21) *(Source: meteonorm).*

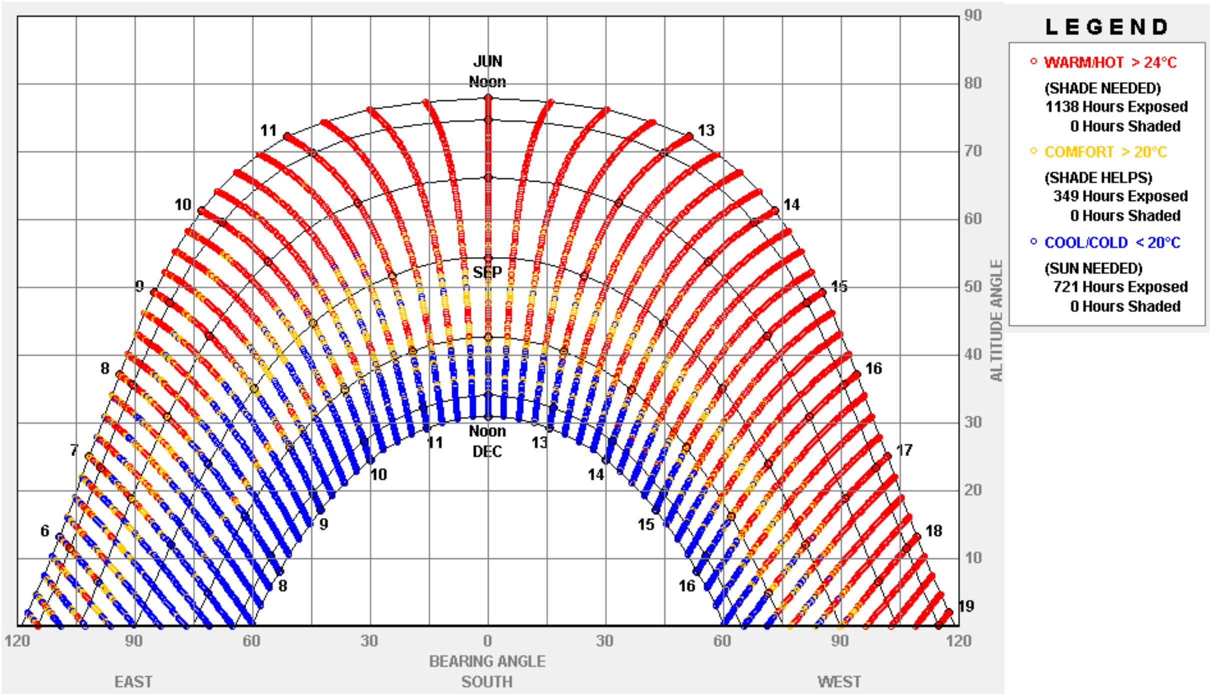


Fig. 11. Sun chading chart , Summer Fall (Juin 21 to December 21) *(Source: meteonorm).*

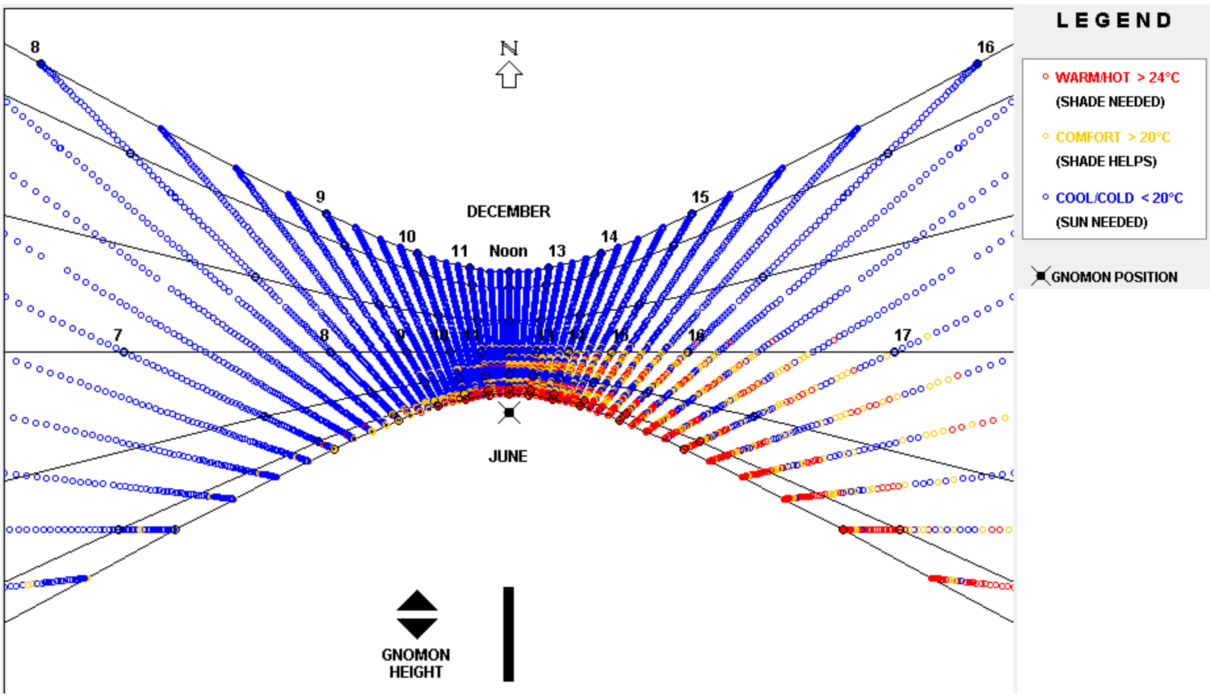


Fig. 12. Sun chart , Winter Spring (December 21 to Juin 21) *(Source: meteonorm).*

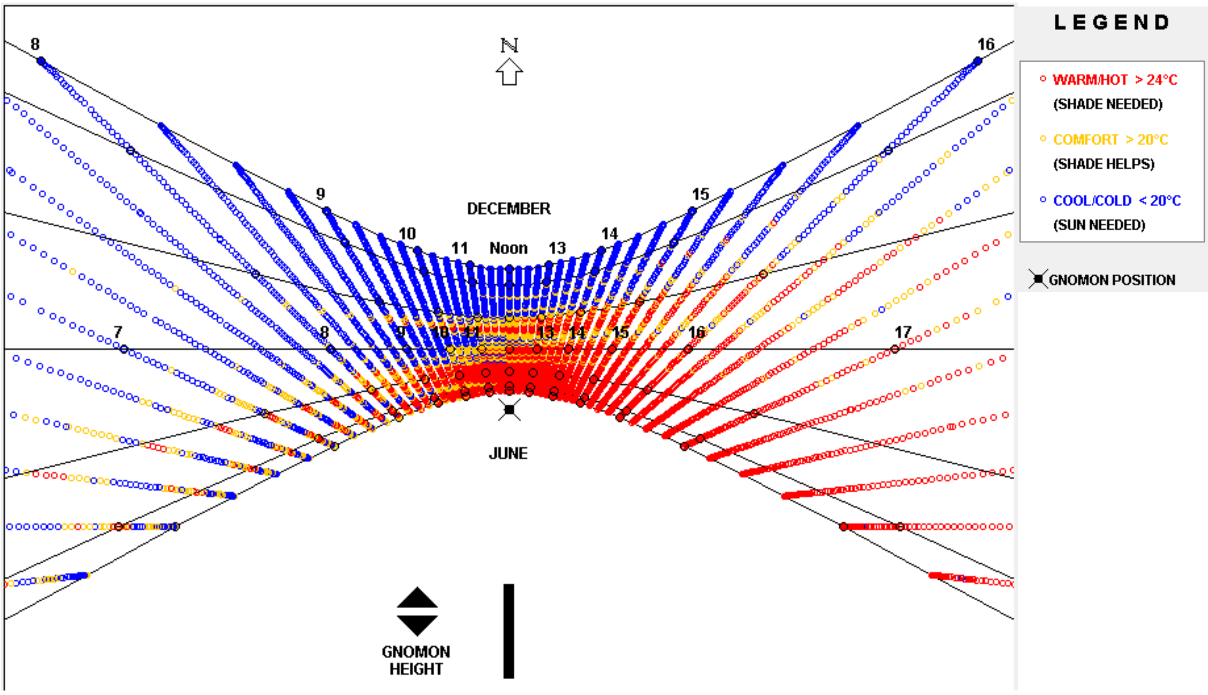


Fig. 13. Sun chart , Summer Fall (Juin 21 to December 21) *(Source: meteonorm).*

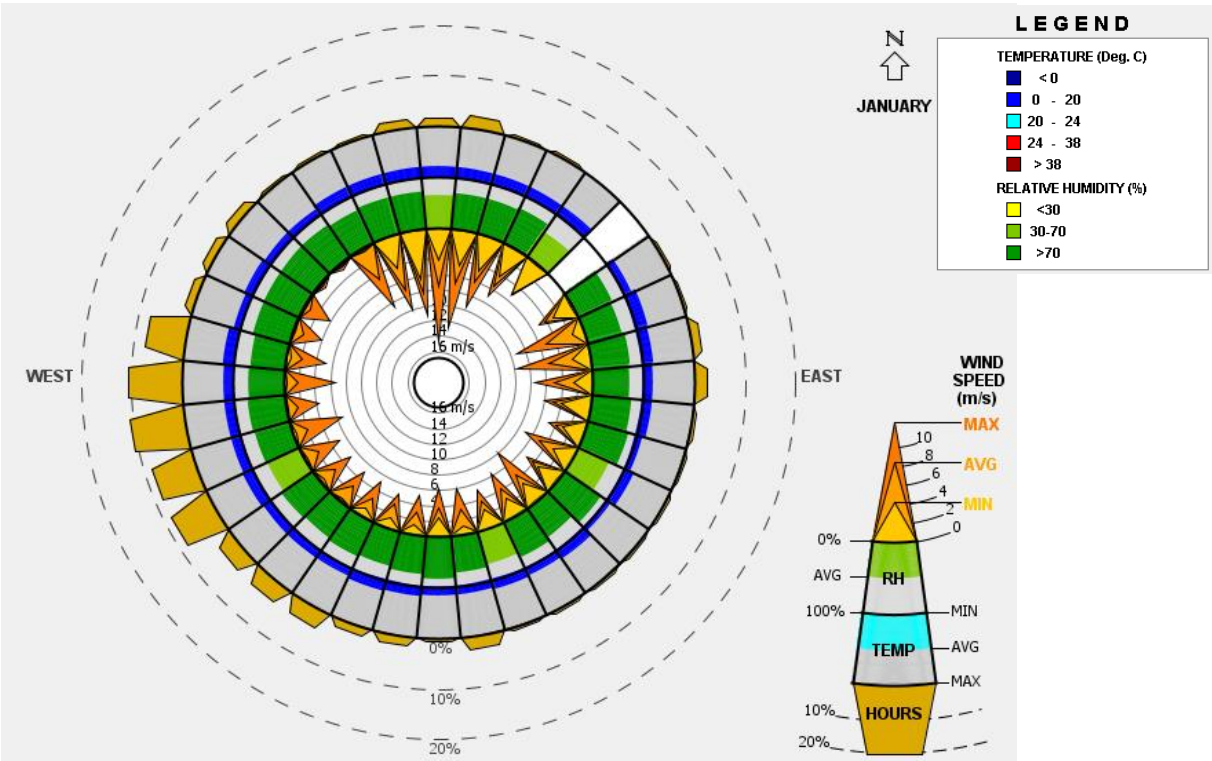


Fig. 14. Vitesse du vent in January *(Source: meteonorm).*

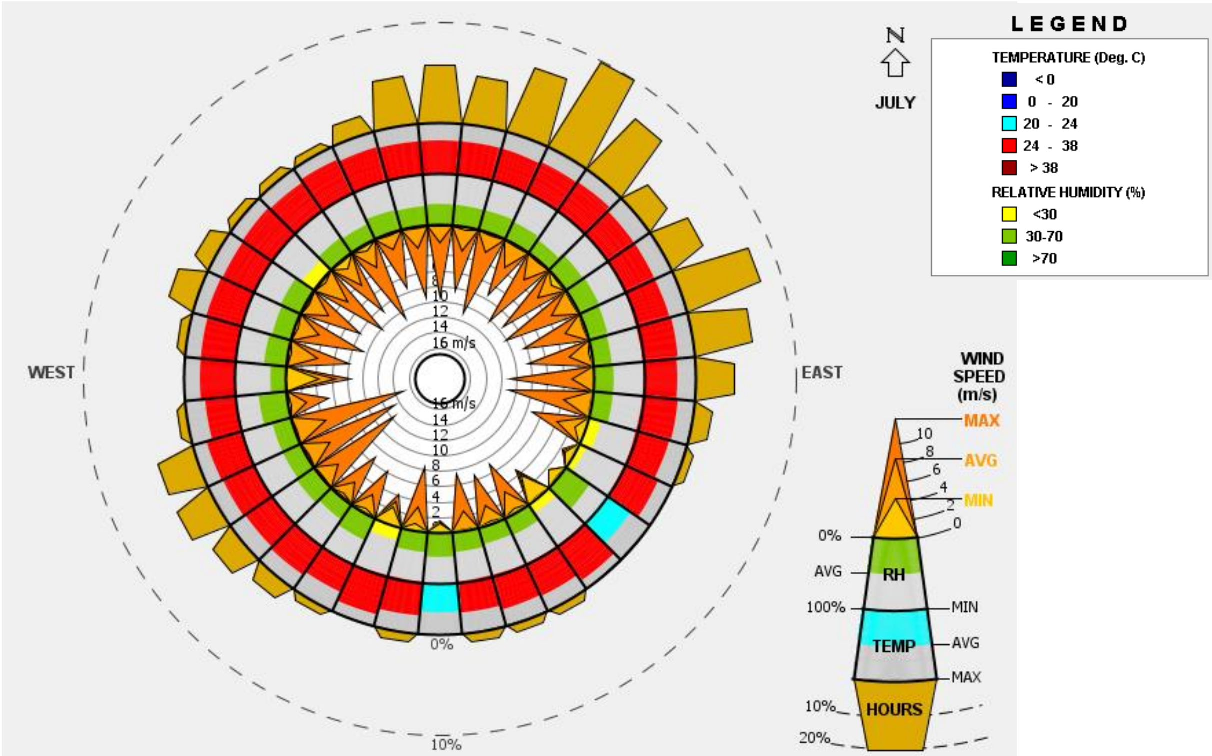
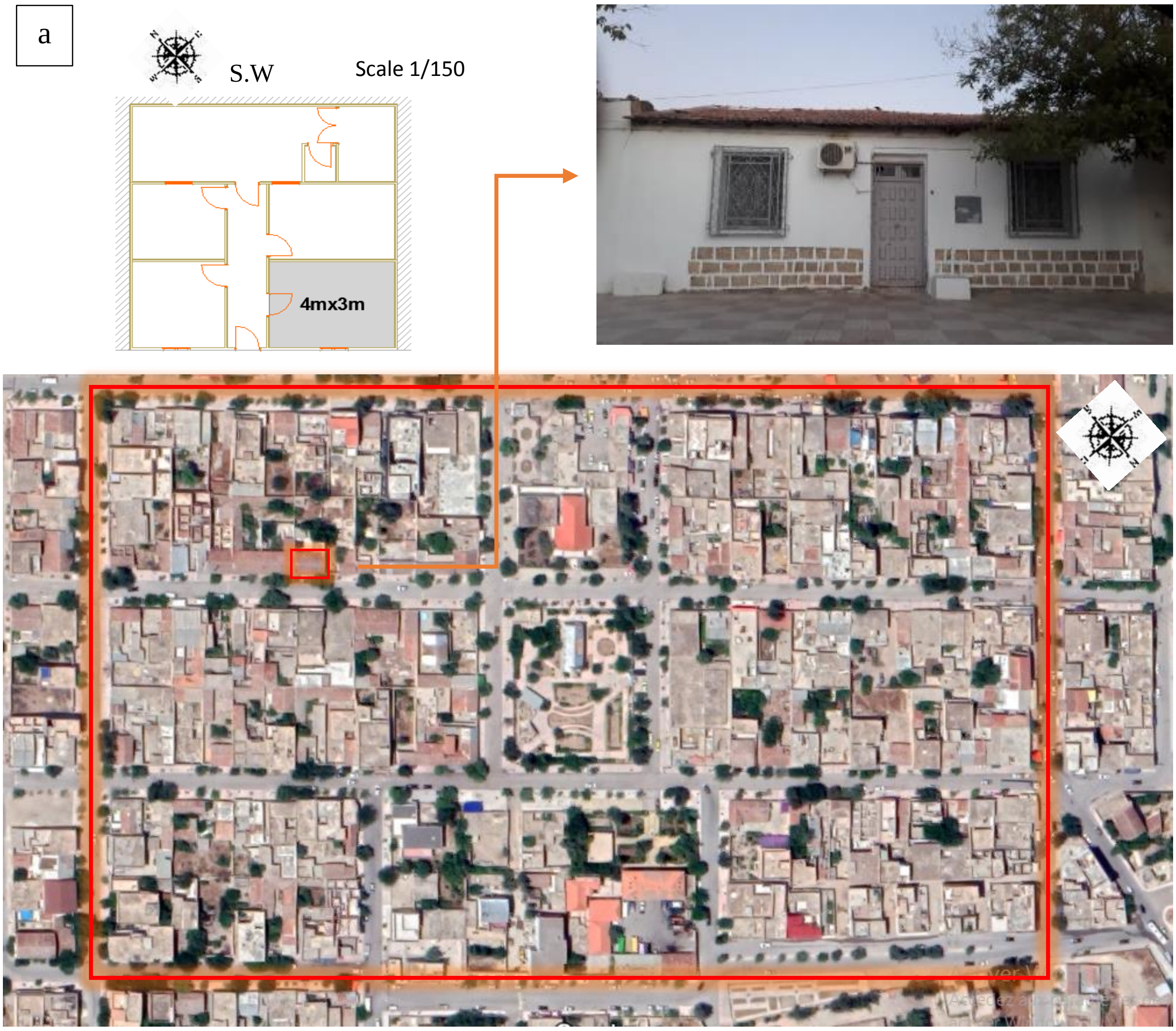


Fig. 15. Vitesse du vent in July. *(Source: meteonorm).*

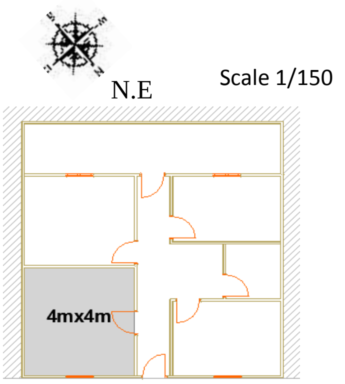
Appendix D: Buildings studied

Fig. 1. 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).*

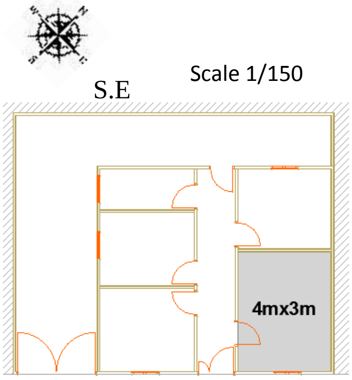


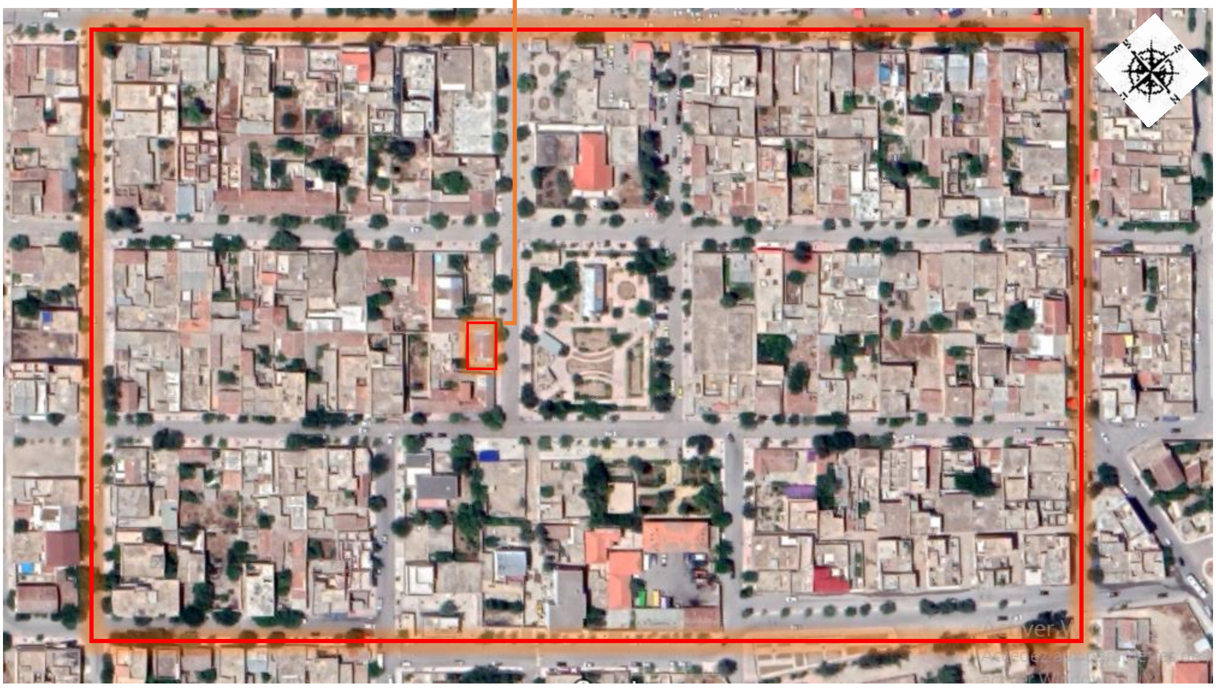
b

c



d





Appendix E: measurements instruments

- ✓ *Technical data of the thermo hygrometer HI 9564:*

Range

RH 20.0 to 95.0% / 20.0 to 95.0%.

Temperature 0.0 to 60.0°C / 32 to 140.0°F

Resolution

RH 0.1% / 0.1

Temperature 0.1°C / 0.1°F

Accuracy

RH 3% RH (50 to 85% RH)

±4% RH (outdoor)

Temperature ±0.5°C / ±1°F

HI 70602 combined RH probe with integrated temperature sensor and microchip, 1 m cable

Environment 0 to 60°C (32 to 140°F); max RH 98% non-condensing

- ✓ *Technical data of the infrared thermometer UA550:*

Material: ABS.

Model: UA550.

Temperature measurement range: -32 ~ 550 ℃.

Accuracy: 0.1 °C.

Measuring time: 0,5 s.

Measuring distance: D: S = 12:1 (measurement of distance and object target ratio).

Battery: 9 V (battery not included).

- ✓ *Technical data of the anemometer TROTEC BA16:*

Air flow velocity

Measuring range: 1.00 - 30.00 m/s; 196 - 5,900 ft/min; 3.6 - 108.0 km/h

Resolution: 0.01 m/s, 1 ft/min, 0.1 km/h

Accuracy: ± 3 % ± 0.2 m/s, ± 3 % ± 40 ft/min, ± 3 % ± 0.8 km/h

Volumetric flow

Measuring range: 0 - 999.9 m^3/min (CFM)

Resolution: 0.1 CMM

Temperature

Measuring range: -10.0 to +60.0 °C (+14.0 to +140.0 °F)

Resolution: 0.1 °C (0.1 °F)

Accuracy: ± 1.5 °C (± 3.0 °F)

Appendix F: Properties of building materials

Table 1. Thermal conductivity of building materials *(Source: standards).*

Group	**Material**	**Specific mass [kg/m³]**	**Thermal conductivity [W/mK]**	
			Dry	Wet
Metal	Aluminium	2800	204	204
	Copper	9000	372	372
	Lead	12250	35	35
	Steel, Iron	7800	52	52
	Zinc	7200	110	110
Natural stone	Basalt, Granite	3000	3.5	3.5
	Bluestone, Marble	2700	2.5	2.5
	Sandstone	2600	1.6	1.6
Masonry	Brick	1600-1900	0.6-0.7	0.9-1.2
	Sand-lime brick	1900	0.9	1.4
		1000-1400	0.5-0.7	
Concrete	Gravel concrete	2300-2500	2.0	2.0
	Light concrete	1600-1900	0.7-0.9	1.2-1.4
		1000-1300	0.35-0.5	0.5-0.8
		300-700	0.12-0.23	
	Pumice powder concrete	1000-1400	0.35-0.5	0.5-0.95
		700-1000	0.23-0.35	
	Isolation concrete	300-700	0.12-0.23	
	Cellular concrete	1000-1300	0.35-0.5	0.7-1.2
		400-700	0.17-0.23	
	Slag concrete	1600-1900	0.45-0.70	0.7-1.0
		1000-1300	0.23-0.30	0.35-0.5
Inorganic	Asbestos cement	1600-1900	0.35-0.7	0.9-1.2
	Gypsum board	800-1400	0.23-0.45	
	Gypsum cardboard	900	0.20	
	Glass	2500	0.8	0.8
	Foam glass	150	0.04	
	Rock wool	35-200	0.04	

	Tiles	2000	1.2	1.2
Plasters	Cement	1900	0.9	1.5
	Lime	1600	0.7	0.8
	Gypsum	1300	0.5	0.8
Organic	Cork (expanded)	100-200	0.04-0.0045	
	Linoleum	1200	0.17	
	Rubber	1200-1500	0.17-0.3	
	Fibre board	200-400	0.08-0.12	0.09-0.17
Wood	Hardwood	800	0.17	0.23
	Softwood	550	0.14	0.17
	Plywood	700	0.17	0.23
	Hard-board	1000	0.3	
	Soft-board	300	0.08	
	Chipboard	500-1000	0.1-0.3	
	Wood chipboard	350-700	0.1-0.2	
Synthetics	Polyester (GPV)	1200	0.17	
	Polyethene, Polypropene	930	0.17	
	Polyvinyl chloride	1400	0.17	
Synthetic foam	Polystyrene foam, exp. (PS)	10-40	0.035	
	Ditto, extruded	30-40	0.03	
	Polyurethane foam (PUR)	30-150	0.025-0.035	
	Phenol acid hard foam	25-200	0.035	
	PVC-foam	20-50	0.035	
Cavity isolation	Cavity wall isolation	20-100	0.05	
Bituminous materials	Asphalt	2100	0.7	
	Bitumen	1050	0.2	
Water	Water	1000	0.58	
	Ice	900	2.2	
	Snow, fresh	80-200	0.1-0.2	
	Snow, old	200-800	0.5-1.8	

Air	Air	1.2	0.023
Soil	Woodland soil	1450	0.8
	Clay with sand	1780	0.9
	Damp sandy soil	1700	2.0
	Soil (dry)	1600	0.3
Floor covering	Floor tiles	2000	1.5
	Parquet	800	0.17-0.27
	Nylon felt carpet	0.05	
	Carpet (with foam rubber)	0.09	
	Cork	200	0.06-0.07
	Wool	400	0.07

Appendix G: Type of natural stone

Fig. 1. Igneous rocks. *(Source: www.geology.com)*

Andesite

Basalt

Dacite

Diabase

Diorite

Gabbro

Granite

Obsidian

Pegmatite

Periodotite

Pumice

Rhyolite

Fire Opal

Scoria

Trap Rock

Unakite

Welded Tuff

Fig. 2. Metamorphic rock. *(Source: www.geology.com)*

Amphibolite

Anthracite

Geneiss

Hornfels

Lapis Lazuli

Marble

Mariposite

Novaculite

Phvlite

Quartzite

Schist

Skarn

Slate

Soapstone

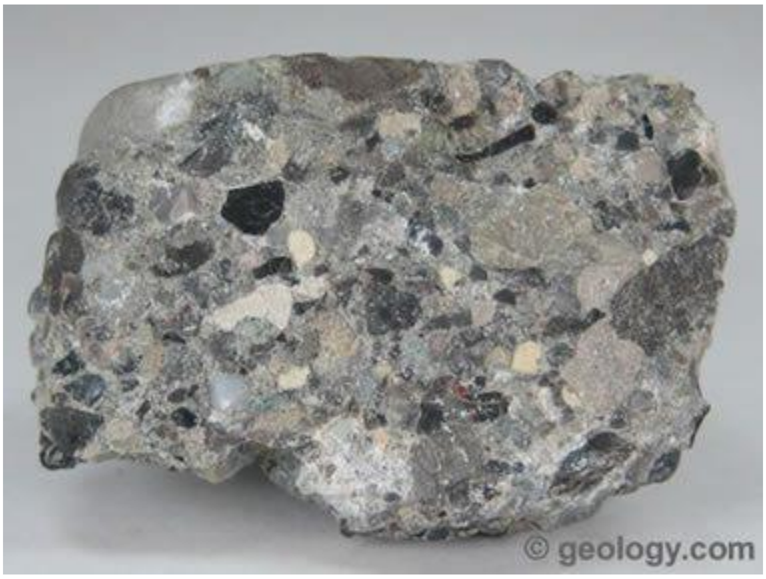
Fig.3. Sedimentary rocks. *(Source: www.geology.com)*

Caliche

Chalk

Chert

Coal



Conglomerate

Coquina

Dolomite

Dolomite Dolostone

Flint

Iron Ore

Limestone

Oil Shale

Rock Salt

Sandstone

Shale

Siltstone

Breccia