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Final Study Project
For the Master's Degree in Energy

The Integration of PCMs with Local Materials in Arid Zones in Algeria

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ABSTARCT

This study explores the integration of Phase Change Materials (PCMs) with traditional local materials in the context of arid climatic zones in Algeria, with the aim of improving indoor thermal comfort and reducing energy consumption. A traditional Mozabite house in Ghardaïa was selected as a case study due to its compact architecture and passive design strategies.

Using Design Builder simulation software, the thermal performance of the house was analyzed in two scenarios: with and without the incorporation of PCMs. The results indicate that PCMs integration can reduce indoor temperature peaks by up to 3°C, improve thermal comfort rates, and lower CO_2 emissions. The study demonstrates the effectiveness of combining vernacular architecture with modern thermal materials to create sustainable and energy-efficient housing in hot climates.

Key words

Phase Change Materials (PCMs), Energy efficiency, Thermal storage.

RESUME

Cette étude examine l'intégration des matériaux à changement de phase (MCP) avec des matériaux traditionnels locaux dans le contexte des zones climatiques arides en Algérie, dans le but d'améliorer le confort thermique intérieur et de réduire la consommation énergétique. Une maison traditionnelle mozabite située à Ghardaïa a été choisie comme cas d'étude pour son architecture compacte et ses stratégies passives.

À l'aide du logiciel de simulation Design Builder, la performance thermique de l'habitation a été évaluée selon deux scénarios : avec et sans MCP. Les résultats montrent que l'intégration du MCP permet de réduire les pics de température intérieure jusqu'à 3°C, d'améliorer les taux de confort thermique et de diminuer les émissions de CO_2. Cette recherche confirme l'efficacité de combiner l'architecture vernaculaire avec des matériaux thermiques modernes pour construire des logements durables et performants dans les climats chauds.

Mots Clés

Les Matériaux à Changement de Phase (MCP), Efficacité énergétique, Stockage thermique,

ملخص

مع المواد المحلية التقليدية في المناطق الجافة في الجزائر، من أجل تحسين (PCMs) تهدف هذه الدراسة إلى دمج المواد المتغيرة الطور الراحة الحرارية داخل المباني وتقليل استهلاك الطاقة. وقد تم اختيار منزل تقليدي من وادي ميزاب في غرداية كحالة دراسية، نظراً لتصميمه المعماري المدمج واستراتيجياته المناخية السلبية.

أظهرت النتائج أن .PCMs ، تم تحليل الأداء الحراري للمنزل في حالتين: مع وبدون استخدام Design Builder باستخدام برنامج يمكن أن يقلل من درجات الحرارة القصوى داخل الغرف بما يصل إلى 3 درجات مئوية، ويحسن معدل الراحة PCMs استخدام الحرارية، ويقلل من انبعاثات ثاني أكسيد الكربون. تؤكد هذه الدراسة فعالية الجمع بين العمارة التقليدية والمواد الحرارية الحديثة في بناء مساكن مستدامة وفعالة في المناطق ذات المناخ الحار

الكلمات المفاتيح:

المواد متغيرة الطور(PCMs), الكفاءة الطاقوية، التخزين الحراري.

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General Introduction

Global energy consumption has been rising steadily, driven by population growth, economic development, and improved living standards. According to the International Energy Agency (IEA), global energy demand has increased by nearly 50% since 2000, with fossil fuels still comprising around 73% of the global energy supply as of 2023, despite a growing share of renewables [13]. This continued reliance on fossil fuels is responsible for over 70% of global greenhouse gas emissions, highlighting the urgent need to adopt more sustainable and efficient energy practices [9, 22].

The Mediterranean region, home to over 500 million people, faces unique energy challenges due to rapid urbanization, high population density, and increasing demand for cooling. The region's energy demand reached approximately 1,022 million tons of oil equivalent (Mtoe) in 2018, with projections indicating a return to pre-pandemic levels by 2023 [15]. The building sector is one of the largest energy consumers in Southern Mediterranean countries, accounting for up to 34% of final energy consumption in countries like Algeria [11].

In Algeria, domestic energy consumption has grown rapidly, increasing at an average rate of 5% per year from 2010 to 2019 and reaching about 70 Mtoe in 2023 [5]. The residential, tertiary, and agricultural sectors together consume around 66% of the country's natural gas, mainly for heating, cooking, and hot water production [23]. This trend underscores the need for energy-efficient solutions in the building sector.

Despite Algeria's significant potential for renewable energy, especially solar, the country remains highly dependent on hydrocarbons. Algeria's carbon dioxide emissions remain substantial, with the country's energy sector being a major contributor to national greenhouse gas emissions [10].

One promising approach to reducing building energy consumption is the use of Phase Change Materials (PCMs). PCMs can absorb or release large amounts of thermal energy during phase transitions, helping to regulate indoor temperatures and reduce reliance on mechanical heating and cooling systems [6, 18]. While research on PCM applications in Algeria is still limited, international studies suggest that incorporating PCMs into building envelopes can lead to significant energy savings and improved thermal comfort [6, 18].

However, the adoption of PCMs in Algeria and the broader Mediterranean region faces barriers such as high material costs, limited awareness among stakeholders, and insufficient regulatory support for passive energy strategies [6, 18]. Addressing these challenges is crucial as energy demand continues to grow and environmental concerns intensify.

In conclusion, the ongoing energy and climate crisis demands integrated and proactive approaches to energy management. Reducing energy consumption in buildings through advanced technologies like PCMs not only supports environmental sustainability but also enhances economic resilience and social well-being [6, 18]. As finite energy resources dwindle and the impacts of global warming become more evident, it is crucial to rethink construction practices and embrace smart, energy-efficient solutions for a sustainable future.

Thesis Structure

This thesis is organized into four main chapters:

- **Chapter 1: Generalities and Bibliography.** This chapter provides a comprehensive overview of various topics, including Algeria's geographical context and climate. Explores Algeria's energy landscape, renewable energy potential, and energy storage, particularly focusing on latent heat storage and Phase Change Materials (PCMs). It also examines building energy consumption, decarbonization efforts, and construction materials and techniques.

- **Chapter 2: Case Study Interpretation.** This chapter Focuses on the Ghardaïa region, detailing its climate, thermal comfort conditions, and urban characteristics. It includes a specific analysis of the Ksar of Béni Isguen, its architecture, and construction, culminating in case studies of houses in the region.

- **Chapter 3: Modeling.** This chapter presents details methodology for simulating the thermal performance of a traditional Mozabite house in Ghardaïa using DesignBuilder. It covers the digital modeling based on AutoCAD plans, the definition of thermal zones, and the configuration of materials, openings, occupancy, and lighting to accurately simulate the building's environmental behavior and passive design strategies.

- **Chapter 4: Simulation and Results.** This chapter presents and discusses the comprehensive thermal simulation results for a traditional Mozabite house in Ghardaïa, analyzing its performance in two distinct scenarios: without and with the integration of Phase Change Materials (PCMs). Finally, we will summarize with a conclusion.

Chapter 1

Generalities and Bibliography

1.1 Introduction

Oil and natural gas are the primary energy drivers, as they combust efficiently and play a role in nearly all human daily activities. Energy sources hold significant importance in the development of a country's technological, industrial, economic, and social sectors.

1.2 General Overview

The Covid-19 pandemic caused a significant drop in global primary energy consumption in 2020. Over the past decade, global consumption increased overall, while the EU saw a slight decline. Fossil fuels remained dominant, but renewable energy use steadily grew—from 0.24 Gtoe (2%) in 2012 to 0.95 Gtoe (6.7%) in 2021.

Renewable energy consumption rose significantly: it doubled in OECD countries, tripled globally, and increased nearly fivefold in **Non-OECD** countries. Renewable energy capacity also grew from 480 GW in 2012 to 1945 GW in 2021, with solar PV reaching 942 GW—an 842% rise.

Although global electricity production has generally increased, it dipped in 2020 due to the pandemic. Still, renewables' share in electricity generation grew from 7.4% in 2016 to 12.8% in 2021.

1.2.1 Geographical Context

Algeria is the largest country in Africa ($2,381,741$ km^2), forming a vast pentagon. It is located between the 18th and 38th parallels of northern latitude and between the 9th west and 12th east meridians. The Prime Meridian (0° Greenwich) passes near the city of Mostaganem, Algeria comprises two regional ensembles with distinct morphological domains:

The first, in the north, lies between the Mediterranean Sea and the Saharan Atlas. This region belongs to the "Alpine" geological formation that encircles the Mediterranean from Southern Europe to North Africa.

The second, encompassing the Saharan regions south of the Saharan Atlas, forms part of the ancient African continent. This vast, rigid, and monotonous terrain stretches across an immense expanse.

Algeria's climate varies significantly by region. Northern Algeria, with its 1,600 km of coastline, experiences a Mediterranean climate: mild and rainy winters, and hot, dry summers. In contrast, the Saharan region is marked by extreme aridity, interrupted only by rare and unpredictable rainfall. Temperature variations—both daily and seasonal—are drastic here, directly impacting agricultural and pastoral activities.

1.2.2 Climate

Energy

Algeria's climate is diverse due to the country's vast territory. The northern region has a Mediterranean climate (Köppen classification Csa). However, transitional climates exist between these two major types, including:

- A semi-arid climate (Köppen classification BSk), characterized by Mediterranean conditions with prolonged dryness extending beyond summer to much of the year;
- A Mediterranean climate with mountainous influences, slightly more continental.

Nevertheless, Algeria lies in the subtropical zone, where the dominant climate is hot and dry.

Regional Climates

Along the northern Mediterranean coast, the climate is typically Mediterranean: hot, dry summers and mild, rainy winters. Rainfall is scarcer in the western part (330–400 mm/year), resulting in more arid landscapes, while central and eastern areas receive abundant precipitation (600–800 mm/year). Temperatures remain relatively uniform:

- Average daily temperatures hover around 11°C–12°C in January,
- Average daily temperatures reach 25°C–26°C in July.

In central and southern Algeria, the vast desert region experiences a typical desert climate: hot and dry year-round. The hottest area lies deep in the south, where:

- Winter daytime highs remain around 25°C–28°C,
- Summer temperatures in the most scorching zone (between latitudes 24°N and 30°N) average 44°C–48°C, particularly in the "Triangle of Fire" (bounded by Adrar, Reggane, and In Salah). This region is one of the hottest on Earth in summer. Rainfall is extremely rare across the desert, with less than 50 mm/year [1].

Temperatures

In the Sahara, temperatures fluctuate drastically between day and night, as well as between summer and winter. Thermometers can exceed 50°C during daytime in summer, while nighttime

1.3 Energy Situation

1.3.1 National Energy Production

The primary sources are fossil fuels such as oil, coal, and natural gas. In this chapter, energy production and consumption data are collected from energy balance reports published by the Ministry of Energy on its official website (see reference [4]).

Primary Energy Production

Commercial primary energy production remained nearly stable (-0.2%) compared to 2016 levels, reaching 165.9 million tonnes of oil equivalent (Mtoe). The increase in natural gas production partially offset the decline in liquid fuel output (oil and LPG), primarily due to compliance with OPEC's production reduction agreement [4].

Figure 1.1 illustrates national primary energy production, showing a year-on-year increase. Total production in 2017 reached approximately 165.9 Mtoe. The distribution of primary energy production is as follows:

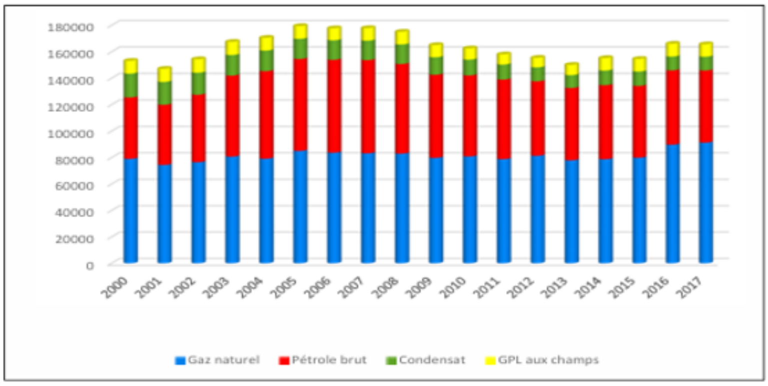


Figure 1.1: National Primary Energy Production, 2000–2017 (in ktoe) [4].

- Natural Gas: 55%
- Oil: 32.9%
- LPG (In-Field): 5.7%
- Condensate: 6.3%

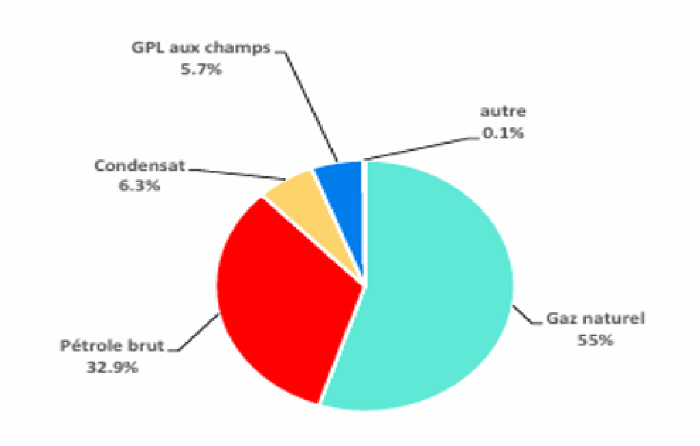


Figure 1.2: Structure of Primary Energy Production (%).

Figure 1.2 illustrates the proportion of primary energy production in 2017, with natural gas dominating the production share at 55%.

Derived Energy Production

Derived energy production reached 64.2 Mtoe, marking a 1.8% increase compared to 2016. This growth stemmed from higher output of:

- Liquefied natural gas (LNG) (+6.0%),
- Thermal electricity (+5.2%),
- LPG (+5.3%).

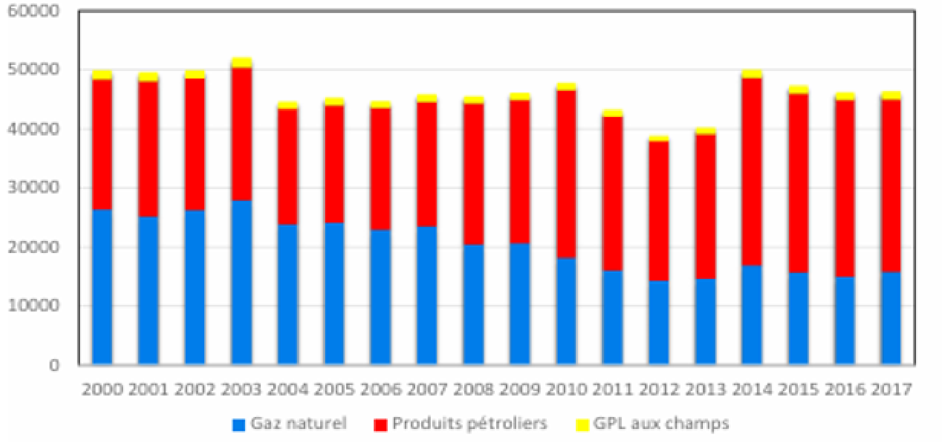


Figure 1.3: Derived Energy Production, 2000–2017 (in ktoe) [4].

This rise more than offset the decline in petroleum product production (-2.7%) [4].

Figure 1.3 illustrates Algeria's derived energy production, which shows year-on-year growth. In 2017, derived energy production reached 63.09 Mtoe. The distribution of derived energy is as follows:

- Petroleum products: 45.4%
- Electricity: 27.6%
- LNG (Liquefied Natural Gas): 24.7%

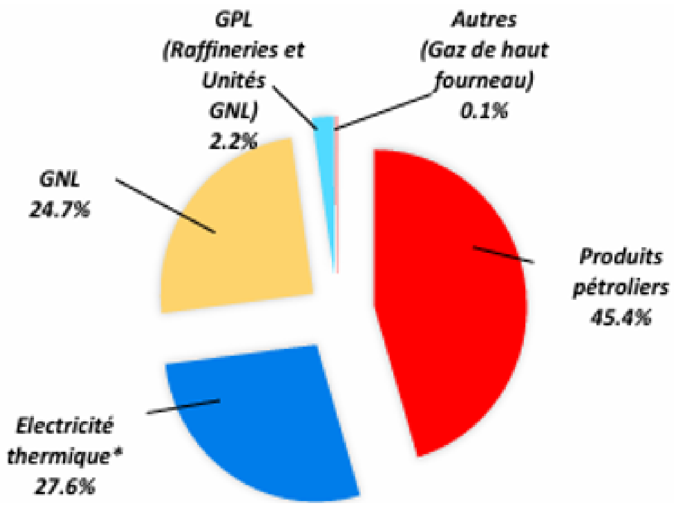


Figure 1.4: Structure of Derived Energy Production (%) [4].

Figure 1.4 illustrates the proportion of derived energy produced, with petroleum products dominating the production share at 45.4% (see Annexes, Table 1.e).

1.3.2 National Energy Consumption

The national consumption landscape is analyzed through two key dimensions: Consumption by Product. Consumption by Sector.

Energy Consumption by Product

Final energy consumption increased from 42.9 Mtoe in 2016 to 44.6 Mtoe in 2017, reflecting a rise of 1.8 Mtoe (+4.1%). This growth was driven by higher consumption of natural gas, electricity, and LPG, which more than offset the decline in petroleum products [4].

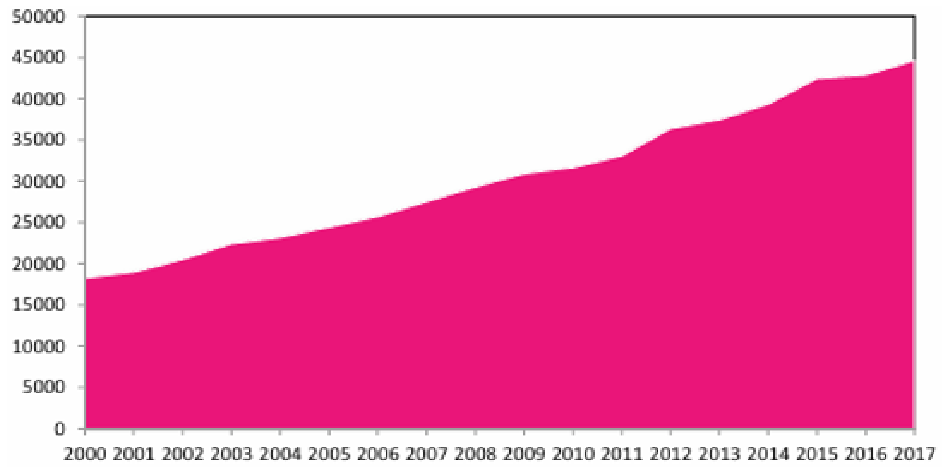


Figure 1.5: Final Energy Consumption by Product (in ktoe) [4].

Figure 1.5 illustrates the final consumption of each energy product. A significant increase in natural gas consumption is observed, driven by rising demand. The trend in final energy consumption by product is presented for the period 2000–2017.

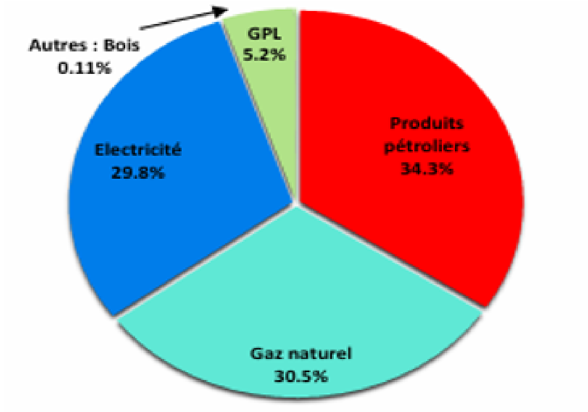


Figure 1.6: Structure of final energy consumption by product in 2016/2017.

Figure 1.6 shows the structure of final energy consumption by product, where we observe significant natural gas consumption.

Energy Consumption by Sector

The evolution of final energy consumption by sector is proposed from 2000 to 2017.

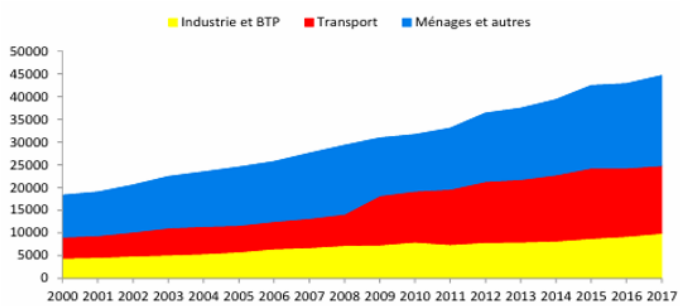


Figure 1.7: Final Energy Consumption by Sector in ktep.

The consumption in the "industry and construction" sector has experienced a significant increase compared to 2017 after 2000, largely driven by the growth of high-energy-intensive industries. This trend is part of broader energy consumption patterns observed across sectors, including transportation and households.

1.4 Renewable Energy

The introduction of renewable energy in Algeria has recently been adopted through the launch of a renewable energy development program by 2030, known as the "Algeria Green Energy Dynamics." This ambitious renewable energy program was adopted by the government in February 2011 and updated in May 2015. It was classified as a national priority in February 2016 by the government's board of directors, aiming to exploit initiatives and foster a spirit of innovation to diversify energy sources as a strategic solution for sustainable global development. Across all sectors, environmental conservation, and energy resource management, carbon reduction has increased by 193 million tons. The updated energy efficiency program aims to achieve energy savings of approximately 63 million tons of oil equivalent (TOE) by 2030 across all sectors (buildings and public lighting, transportation, industry). The program involves installing a renewable energy capacity of about 22,000 MW by 2030 for the national market, while maintaining the option of export as a strategic objective.

1.4.1 Wind Energy Potential

Recently, Algeria has embarked on a new phase of exploiting renewable energy, with a government program aimed at producing 22 GW of renewable electricity by 2030. Although the share dedicated to wind energy in the new program remains relatively low compared to photovoltaic solar energy, wind energy constitutes the second axis of development, with production expected to reach around 5 GW by 2030, including 1 GW by 2020.

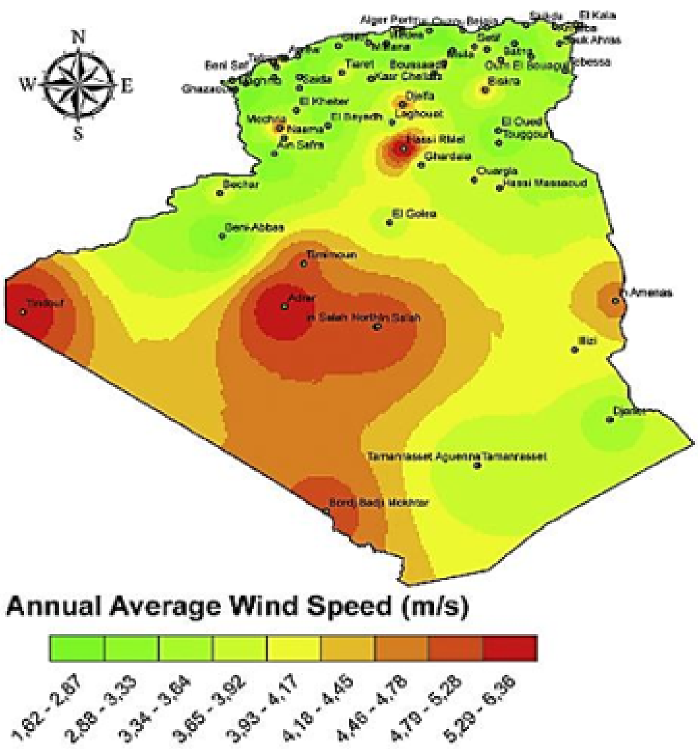


Figure 1.8: Wind Speed Map [1].

1.4.2 Solar Energy Potential

Given its geographical location, Algeria boasts one of the world's most significant solar resources. The annual sunshine duration across most of the country exceeds 2,000 hours and can reach up to 3,900 hours in the high plateaus and Sahara regions. The annual energy received on a horizontal surface of 1 m^2 is approximately 3 kWh/m^2 in the north and exceeds 5.6 kWh/m^2 in the far south (Tamanrasset) [4].

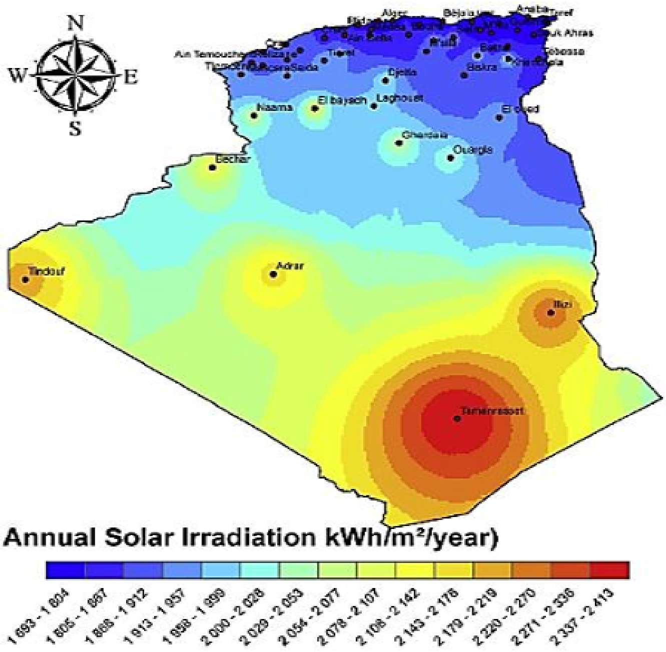


Figure 1.9: Solar Irradiation Map [4].

1.4.3 Geothermal Potential

Globally, Algeria has a significant geothermal potential. The country is endowed with substantial geothermal resources, estimated at 65 billion cubic meters, offering opportunities for various applications such as electricity generation, heating, and agriculture. Although the geothermal potential is not as widely exploited as solar energy, it presents a promising avenue for renewable energy development in Algeria.

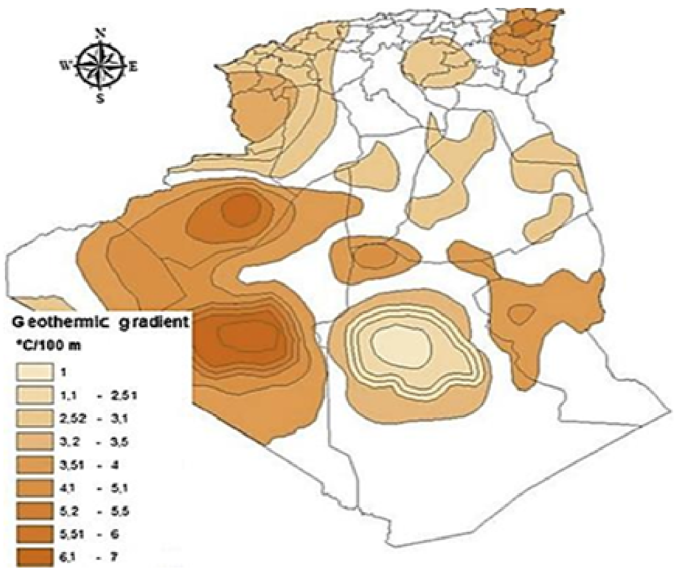


Figure 1.10: Geothermal Resource Map [4].

1.4.4 Hydro-power Potential

Algeria possesses significant but underutilized water resources, with 65 billion m³ of annual rainfall. However, only 25 billion m³ are considered usable and renewable due to:

- Uneven distribution: Rainfall concentrates in northern regions, declining sharply toward the south
- High evaporation rates: Arid climates, especially in the Sahara, lead to substantial water loss
- Rapid runoff: $\sim$ 1.7 billion m³ flows into the Mediterranean Sea annually, reducing retention
- Limited precipitation days: Exacerbates scarcity in western regions (e.g., Cheliff Basin at 11.17% dam capacity)

Biomass Potential

The biomass potential in Algeria is relatively limited. The forested area covers approximately 250 million hectares, representing about 10% of the country's total area, while the Sahara desert covers nearly 90% of the territory. Despite this limitation, biomass remains a promising renewable energy source, particularly when considering the utilization of agricultural waste and organic residues.

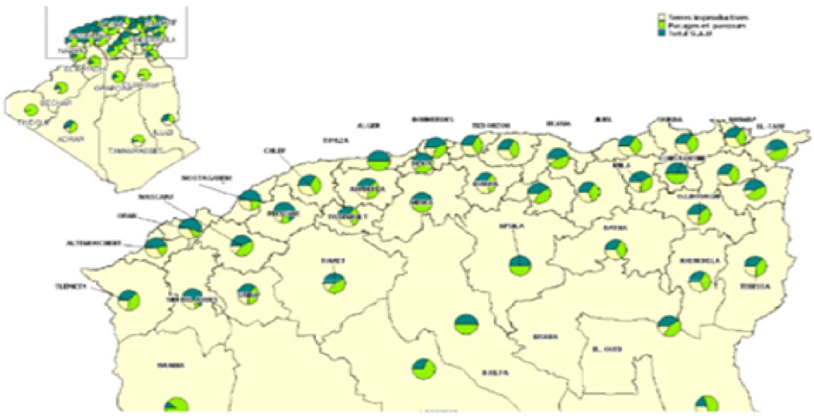


Figure 1.11: Distribution of Agricultural Land Use [4].

The forests cover an area of approximately 4.1 million hectares, representing about 1.7% of the country's total area, while the alfalfa zones occupy around 2.5 million hectares, accounting for slightly more than 1% of the territory. In contrast, unproductive lands extend over more than 188 million hectares, representing 79% of the total area.

1.4.5 National Renewable Energy Plan

The National Program for the Development of New and Renewable Energies (NRE) and Energy Efficiency for the period 2011-2030 aims to produce 40% of the national electricity consumption from solar and wind energy sources. This ambitious plan is part of Algeria's broader strategy to diversify its energy mix and reduce dependence on fossil fuels. By integrating renewable energy sources, Algeria seeks to enhance its energy security and contribute to sustainable development.

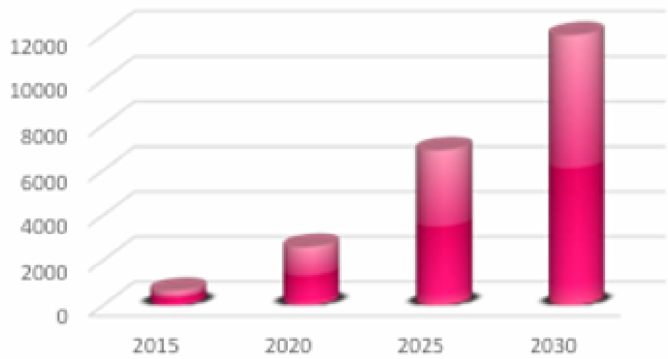


Figure 1.12: Evolution of Total Renewable Energy Production According to the National Renewable Energy Program (PNER) 2015-2030.

By technological sectors, photovoltaic solar energy will contribute to the realization of this program with a capacity of 13,575 MW, wind energy with 5,010 MW, biomass with 1,000 MW, cogeneration with 400 MW, and geothermal energy with 15 MW. The implementation of this program will enable Algeria to achieve a share of renewables of nearly 27% in the national electricity production balance by 2030 (CDER, 2015).

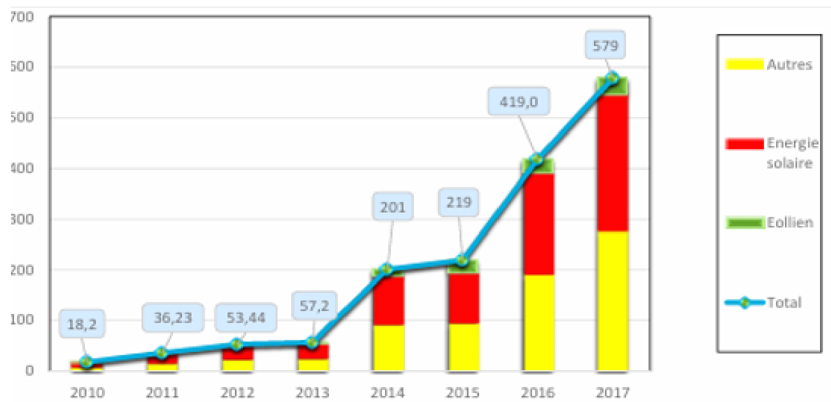


Figure 1.13: Renewable Energy Production 2010-2017.

According to Figure 1.13, renewable energy production in Algeria has evolved over the years from 2010 to 2017. During this period, Algeria has seen a gradual increase in its renewable energy capacity, albeit with modest installed capacities compared to the ambitious targets set by the national program. By 2017, the country had installed approximately 400 MW of renewable energy capacity, primarily in solar and wind power, with a focus on expanding these sectors to meet future energy demands.

1.4.6 Energy Storage

Energy storage is the action of placing energy in a given location to facilitate its immediate or future use. Given its importance in our energy-intensive civilization, energy storage is an economic priority. It contributes to energy independence, meaning a country's ability to meet its own energy needs [3]. As such, energy storage often receives special attention from policymakers, especially in countries heavily dependent on foreign energy sources. By extension, the term "energy storage" is often used to describe the storage of materials that will produce this energy.

1.4.7 Latent Heat Storage

To significantly reduce storage volumes and to avoid the temperature fluctuations associated with sensible heat storage, we can choose to use the energy involved during phase changes of matter. Latent heat is the energy involved during phase changes of matter. The heat supplied at rest during melting does not result in an increase in the speed of the molecules, but rather in an increase in their potential energy, allowing them to leave their equilibrium position. This is the reason why the temperature remains constant throughout the transformation. In the case of a phase change (melting), the amount of heat involved is written as:

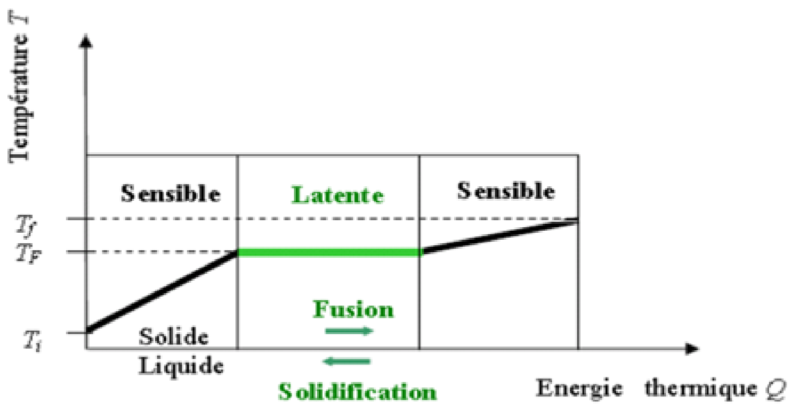
$$\Delta h_f \quad [\mathrm{J}]$$

Where Δh_f: specific enthalpy of fusion (J/Kg). Generally, it is necessary to bring the material from its initial temperature T_i to its melting temperature T_f and we write:

$$\Delta h[\mathrm{J}]$$

In the case of a pure substance, we find a curve of temperature variation analogous to that presented in Figure 1.14. During the heating of the material before its melting temperature, we observe a linear variation of temperature as a function of time, while during the phase change, the temperature remains constant.

$C_s(T)$: Specific heat of the body in the solid state. $[J.Kg^{-1}K^{-1}]$, $C_L(T)$: Specific heat of the body in the liquid state. $[J.Kg^{-1}K^{-1}]$, L: Latent heat of phase change. $[J.K^{-1}]$



1.4.8 The technological constraints of latent heat storage

Latent heat storage uses the enthalpy of phase change during the melting or solidification of the material used, but it can also utilize the sensible heat required to heat the solid up to its melting point. Therefore, it is necessary to:

- The storage system must withstand the phase change within the temperature range required for this transformation.
- The storage system must tolerate the volume change associated with the phase change.
- A container suitable for storing the materials according to their nature.
- A heat exchange surface to transfer thermal energy between the heat source and the phase change material.

1.4.9 Advantages of Latent Heat Storage

Compared to sensible heat storage [7], the main advantages of latent heat storage can be summarized as follows:

- **Phase Change Materials (PCMs)** can store 5 to 14 times more heat than sensible heat storage materials.
- When thermal energy is discharged, the surface temperature of the PCM remains close to the phase change temperature. This allows for passive temperature control of the surface. Therefore, the amount of discharged energy depends only on the ambient temperature.

1.4.10 Phase Change Materials (PCMs)

Phase Change Materials (PCMs) have the distinctive ability to store energy in the form of latent heat, with heat being absorbed or released during the transition from solid to liquid and vice versa. PCMs operate based on a simple physical principle: above a certain temperature—specific to each material—they melt by absorbing heat from the surrounding environment and release it again as the temperature drops. This property is directly related to their high fusion energy per unit volume: the greater this energy, the more efficient the material will be at storing (and releasing) heat [19].

1.4.11 Selection of Phase Change Materials

A large number of phase change materials have a melting temperature within the range of 0–120°C. However, they can only be used as storage materials if they meet certain thermodynamic, kinetic, chemical, and economic properties. These criteria must therefore be defined to help ensure the appropriate selection of PCM for a given application.

1.4.12 Classification of Phase Change Materials

There are many chemical substances that can be identified as PCMs based on their melting temperature and latent heat of fusion.

However, aside from having a melting point within the desired operating temperature range, the majority of these substances do not meet the other required criteria to serve as suitable heat storage media. Indeed, no material inherently possesses all the properties needed for an ideal thermal storage medium. Therefore, these materials are used while seeking ways to avoid or compensate for their drawbacks through appropriate techniques tailored to each application [8]. For example:

- Metallic fins have been used to improve the thermal conductivity of PCMs,
- Supercooling can be avoided by adding a nucleating agent to the storage material,
- Incongruent melting is prevented by adding a thickening or gelling agent to the PCMs.

PCMs can be classified according to their chemical nature into three main categories:

- Organic compounds: Paraffins, non-paraffinic substances, polyalcohols.
- Inorganic compounds: Salt hydrates, salts, metals, alloys.
- Eutectic mixtures of inorganic and/or organic substances.

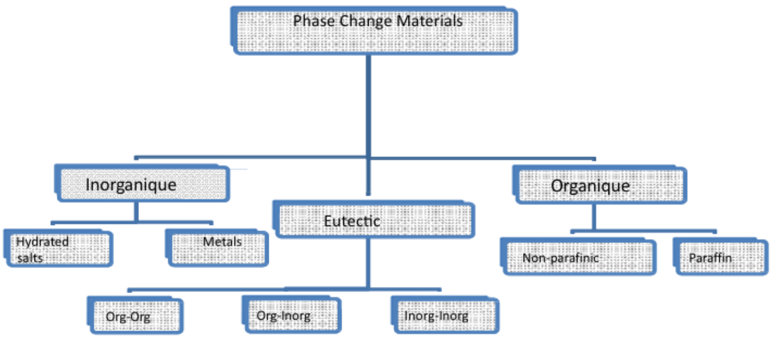


Figure 1.14: Classification of Phase Change Materials (PCMs).

1.4.13 Energy Consumption

Buildings consume nearly 151 EJ of energy, representing about 36% of the world's final energy consumption. Of this, approximately 130 EJ—or 30%—is used for the operation of buildings, while another 21 EJ is consumed in other construction-related services. The building sector alone is responsible for around 55% of global electricity usage. Although the buildings' energy consumption stabilized during the last two years due to the COVID-19 pandemic—marking the first such stabilization since 2012—the overall energy demand of the sector increased by more than 20% between 2000 and 2021, and by 7% between 2010 and 2022. In 2018, the combined effect of increasing floor area and appliance ownership in the residential sector led to an energy demand rise of over 2%, which significantly outweighed the 0.7% reduction resulting from improved energy efficiency. As a consequence of these structural trends, electricity use rose by 6.5 EJ—or 19%—between 2010 and 2018. Residential buildings are responsible for nearly 70% of the sector's energy consumption. From 2010 to 2022, residential energy consumption increased by 5 EJ. Energy used for hot water accounts for about 24.3 EJ, with an 11% increase between 2000 and 2019. Cooking consumes a similar amount of energy as water heating, with roughly two-thirds supplied by inefficient biomass systems and only 6% by electricity [12]. However, progress in improving the energy efficiency of the building sector is falling short of the IEA's decarbonisation targets. In 2018, energy intensity improved by just 1.2%. Between 2015 and 2019, final energy intensity per square metre of building dropped from 330 kWh/m² to 320 kWh/m², and was expected to decrease further to 300 kWh/m² by 2025.

1.4.14 Decarbonizing the Building Sector – Benefits and Potential Problems

The decarbonisation of the building sector demands substantial investments, which can in turn stimulate economic development, create employment opportunities, reduce poverty, and foster social equity. However, this global effort is not without its challenges. It may encounter significant technological, political, and social hurdles that could hinder the achievement of the expected outcomes. Various estimates highlight the scale of the investment required to meet decarbonisation goals. The total budget needed for fully decarbonising the building sector is estimated at nearly USD 14 trillion. Furthermore, according to one estimate [16], energy-efficient buildings in all emerging cities with populations exceeding half a million represent a financial market opportunity of up to USD 26 trillion by 2030, with 60% of these investments targeting the construction of new residential buildings.

1.4.15 Greenhouse Gas Emissions and Global Climate Change

In 2018, the buildings and construction sector was responsible for approximately 39% of energy-related and process-related greenhouse gas emissions. About 11% of these emissions came from the industrial production of building materials such as glass, steel, and cement. Direct CO_2 emissions from the combustion of fossil fuels for thermal needs—such as space and water heating, and cooking—were close to 3 Gt CO_2. When indirect emissions from electricity consumption in buildings are included, the total rises to 9.8 GtCO_2. Additionally, the manufacturing of building materials contributes a further 5 GtCO_2. The residential sector is the primary contributor to emissions within the building sector, accounting for around 60% of the total. This is despite residential buildings representing almost 80% of the total building surface. The disparity is mainly due to a 65% increase in total floor area and the associated growth in electricity demand. Since 2000, electricity use in buildings has increased nearly five times faster than the rate of decarbonisation in the electricity generation sector. Moreover, rising urban temperatures are exacerbating environmental issues. Higher ambient temperatures contribute to elevated concentrations of ground-level ozone and particulate matter. Urban overheating is now seen as a major factor behind pollution levels exceeding accepted thresholds. Future projections indicate a continued and significant rise in urban ozone concentrations [2].

1.5 Construction Materials

Humans have harnessed nature for their benefit, exploiting its resources—such as construction materials—for millennia. "Until the end of the 18th century, architecture was dependent on materials offered by nature. Buildings were made of wood, clay, and stone. The architectural form was dictated by the properties of these materials and by the limited strength of human labor [20]. However, with the discoveries of the 19th century and the advent of machinery, the extraction of these materials became easier, more abundant, and more diverse. These materials can be classified into five major categories:

- Stone
- Brick and terracotta
- Lime, cement, and mortars
- Wood
- Metals

1.5.1 Stone

Rocks are natural materials that differ based on their geological origin and mineral composition. These properties classify them as construction materials, commonly found in building stones. Their roles vary depending on function, availability, and cost. These parameters give each type of stone a specific function in the construction process. For example:

- Limestone is appreciated for general construction.
- Volcanic stones, such as trachyte, are used for masonry components.
- Granite is a heavy, hard stone that is very difficult to cut, used in maritime works (piers, lighthouses, etc.) and for the foundations of buildings.
- Slate splits into thin sheets and is resistant to mechanical action. Chemical (resistance) to the atmosphere, shiny and solid, used for paving and cladding.
- Marble is used in its raw state as rubble stone, cut, or even polished, for architectural decoration.
- Hard and economical stones such as sandstone are used for paving.

Algeria is rich in hard construction materials of all kinds. The locals make little use of quarries and generally only use loose stones for construction, such as rubble stones and river pebbles (from wadis) [21].

1.5.2 Brick and Terracotta

Terracotta is an artificial stone, with various forms and dimensions. Originating from the Middle East, it dates back thousands of years. It is a product made from clay (to which sand and crumbled stones are added). Initially raw, then after some time it is hardened by firing, which improves its resistance. A wide range of products are obtained and can differ in color.

- Bricks from massive structures are used in light masonry, especially in the making of arches and vaults, and for load-bearing masonry. It is easy to work with, very resistant, and has excellent decorative value.
- Tiles, made of terracotta in thin plates, are used for roof coverings. They offer good weather protection.
- Terracotta tiles are used as horizontal wall coverings and floor finishes.

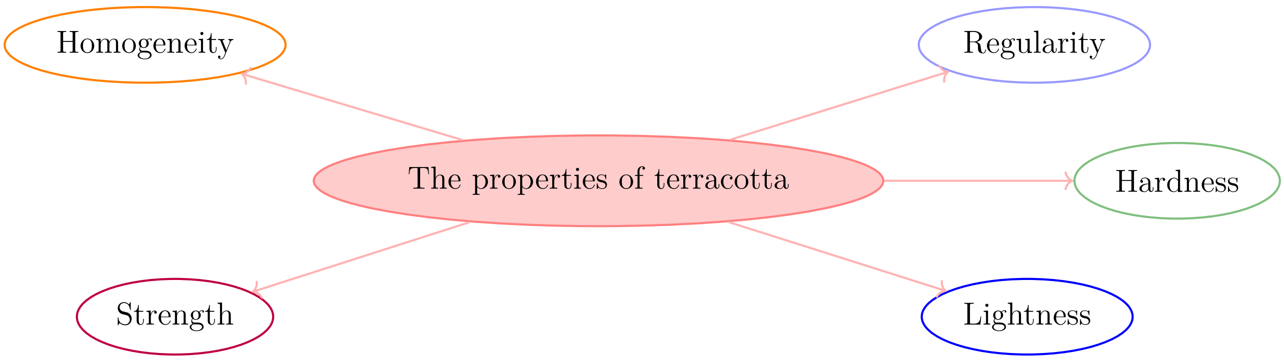


Figure 1.15: The properties of terracotta [21].

1.5.3 Binders

Lime

The production of lime is based on the calcination of limestone rocks, whether calcareous or mixed with other additives, depending on the type of lime desired.

Lime is divided into three types as follows:

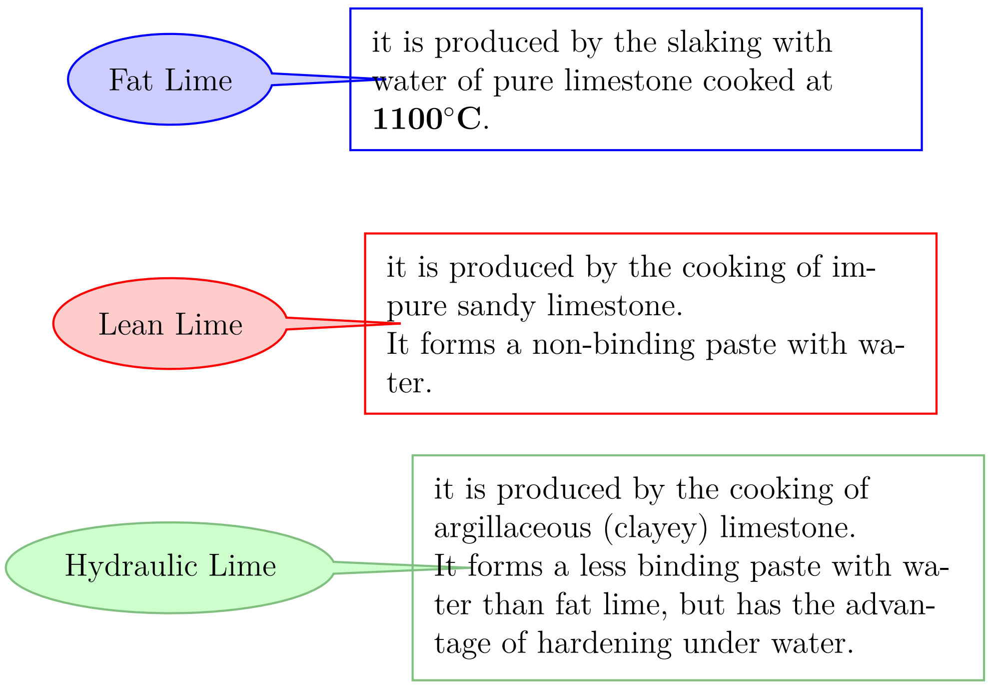


Figure 1.16: The types of lime [21].

The limestone was abundant in Algeria, especially in the province of GHARDAIA during the time of colonization. There was significant local manufacturing.

Cement

Cement is a hydraulic binder that, within a few days, develops maximum strength. It results from the burning and crushing of limestone with clay.

It is found that there are types of cement that are distinguished according to their burning: This product differs from hydraulic lime due to the nature of its constituent

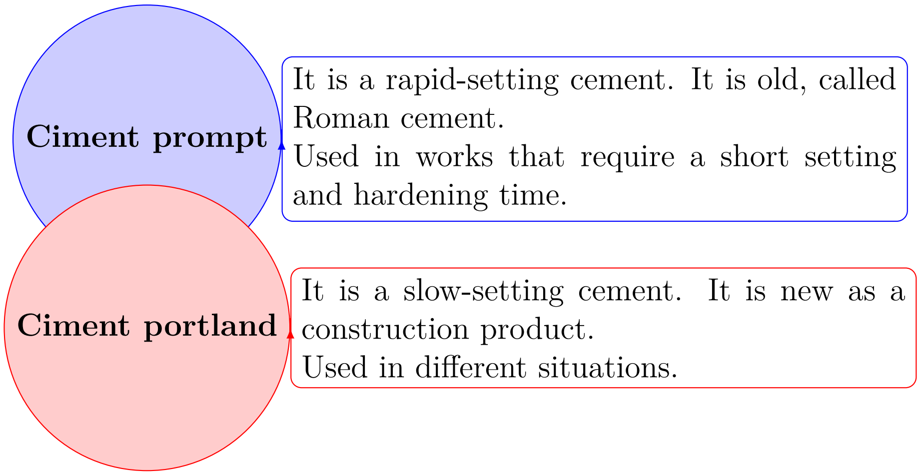


Figure 1.17: Types of Cement [21]

elements (silica, alumina) and their proportions.

Plaster

It is an artificial product that results from a manufacturing process:

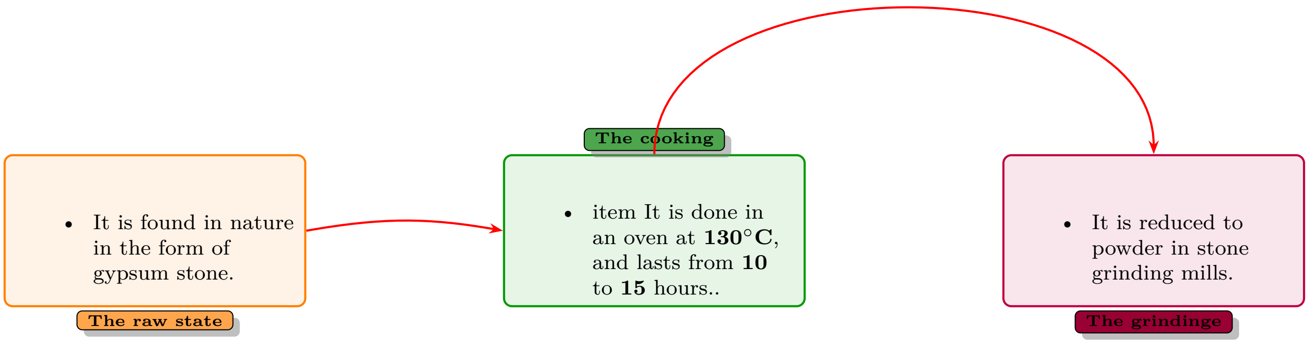


Figure 1.18: The manufacturing of plaster [21]

Upon contact with water, plaster sets and hardens very quickly.

It is important to avoid using it in humid places because it always remains soluble in water.

• Plaster stone is abundant in Algeria with its very high quality, and the majority of gypsum deposits are pure.

Wood

Wood is a primitive construction material. Each region of the world uses it according to its own techniques, guided by its availability and qualities.

There are three natural types of wood: hardwood, softwood, and resinous wood, in addition to artificial wood, each of which has its own characteristics, areas of use, and lifespan.

Thanks to new construction techniques, the material has contributed to the growth of cities, except that fire remains its greatest weakness. It was used for frameworks, floors, parquet flooring, stairs, windows, and doors,...

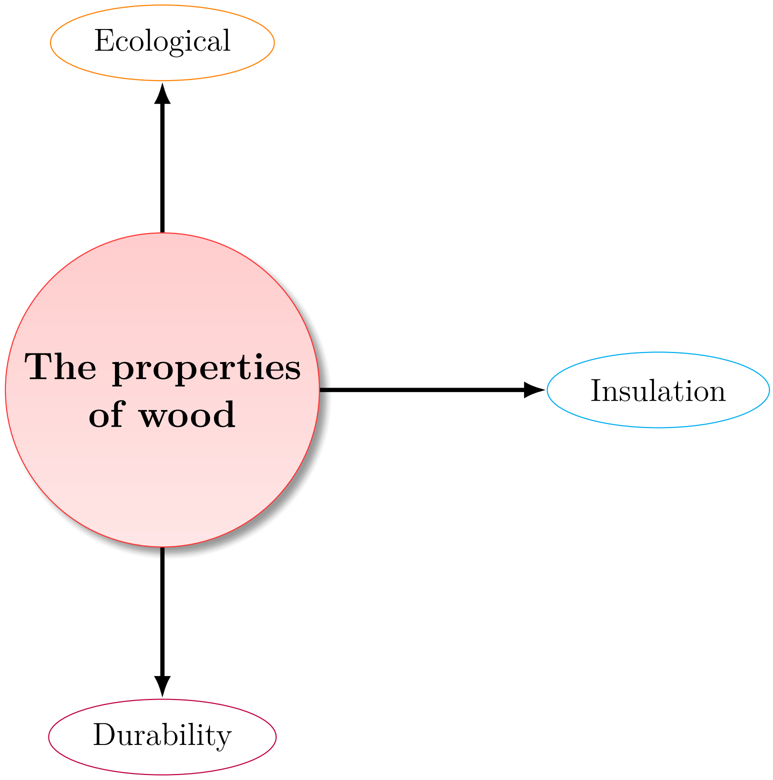


Figure 1.19: The properties of wood [21]

1.5.4 Metals

Iron

The development of technology in the 19th century led to the emergence of the steel industry, and metal gradually became a predominant construction material. Different manufacturing processes provide three products, which are

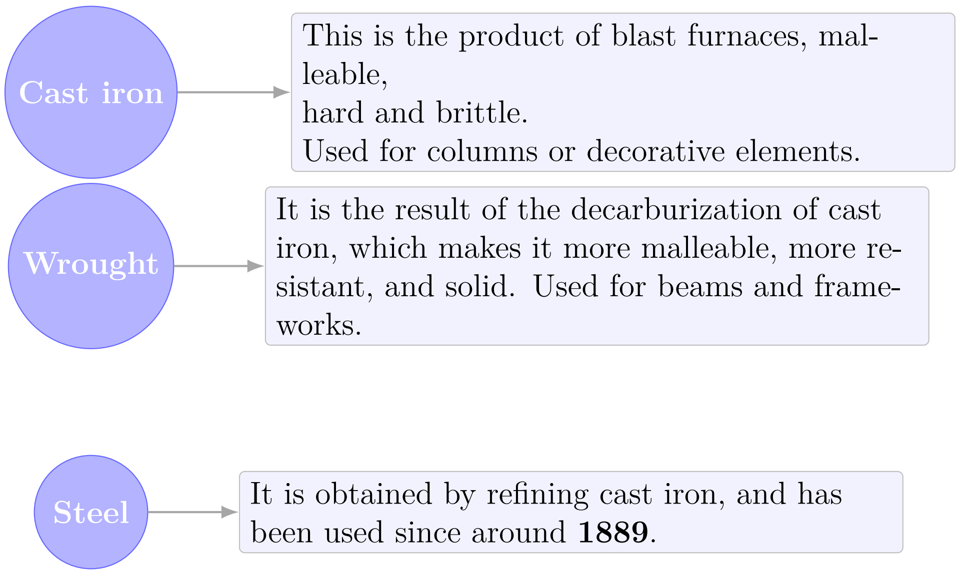


Figure 1.20: Iron products [21].

Glass

Glass is the result of the fusion of sand with soda, which is the main component of sand.

Paint

It is a material used to protect construction metals and other materials.

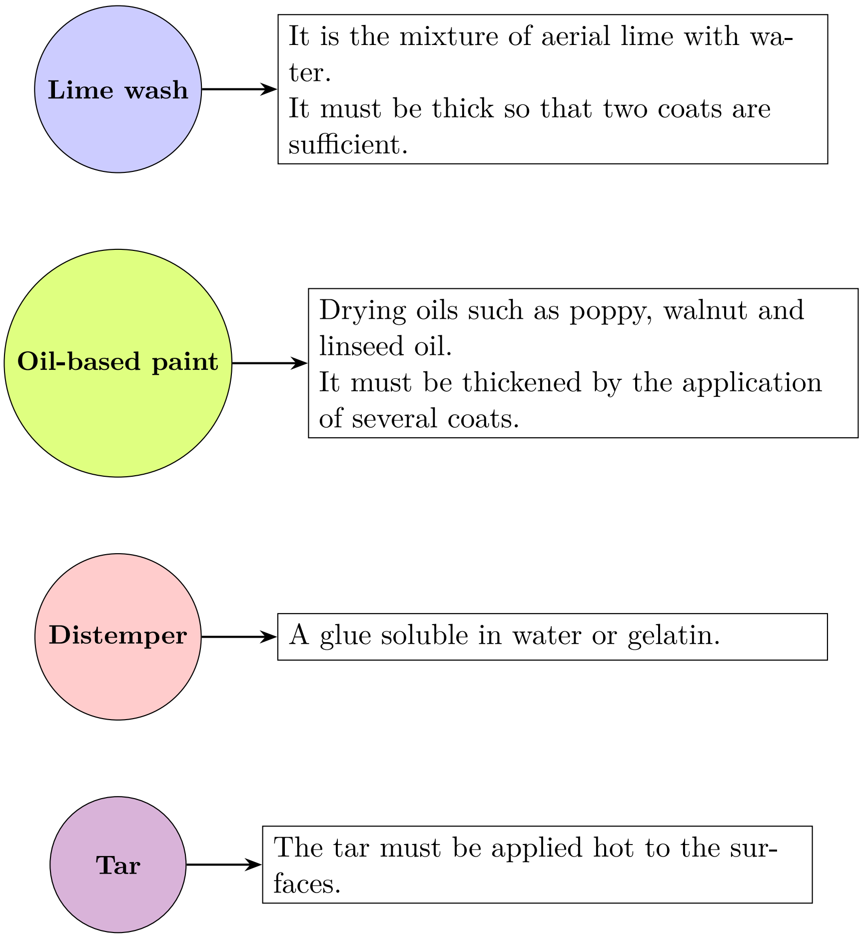


Figure 1.21: Types of paints [21]

1.6 Construction Techniques:

The choice of techniques depends on the construction materials used and the date of the project, as the field of construction is constantly evolving.

1.6.1 Infrastructure

This is the buried part of a building, built below the ground level, to anchor the construction in stable ground.

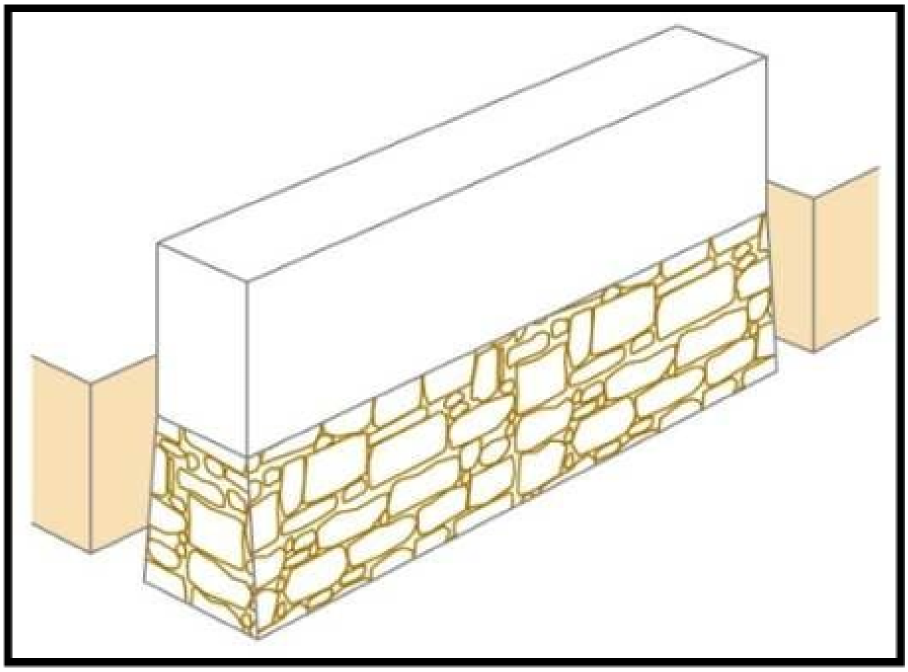


Figure 1.22: Rubble foundation [17].

Masonry footings

These are foundation walls made of rubble stone or dressed stone laid using mortar.

Cast-in-place concrete walls

These always follow the same principle as masonry walls, but this time the material used is concrete, composed of solid elements like crushed stone or gravel and a liquid binder such as cement. There are two types of concrete used in infrastructure:

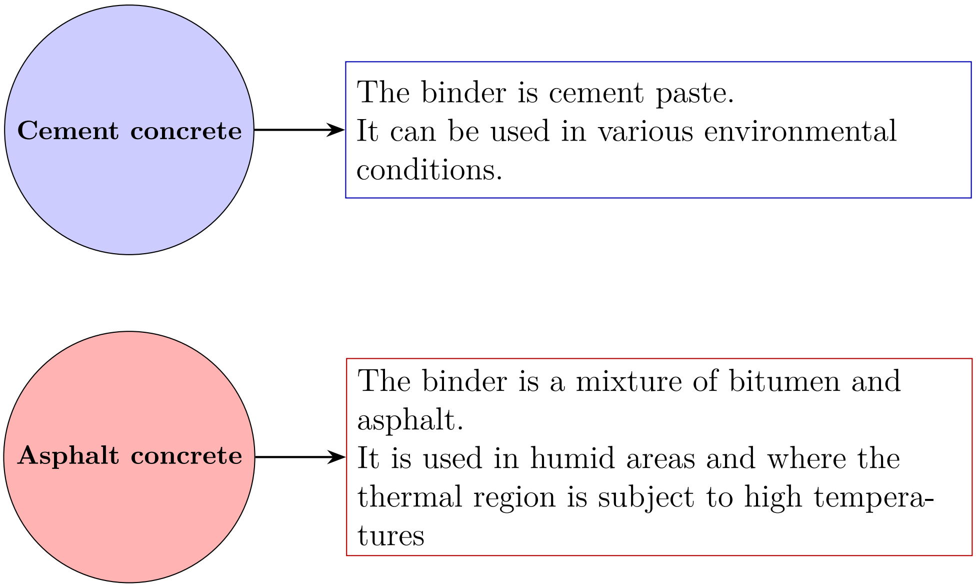


Figure 1.23: Types of concrete for cast-in-place walls [21].

- The use of form work is necessary because it shapes the concrete mix until it hardens.

Reinforced Concrete Foundations

These result from pouring concrete over steel reinforcements, which are placed in isolated excavations or in trenches.

1.6.2 Superstructure

Load-bearing wall systems

This consists of thick masonry walls that function by transferring loads (live loads and dead loads) to the foundations. They are built using masonry materials (stone, brick) under different configurations and are reinforced by selecting and placing vertical ties, corner ties, vertical chains, relieving arches, rectangular elements (wood, metal), bracing systems, and tie rods.

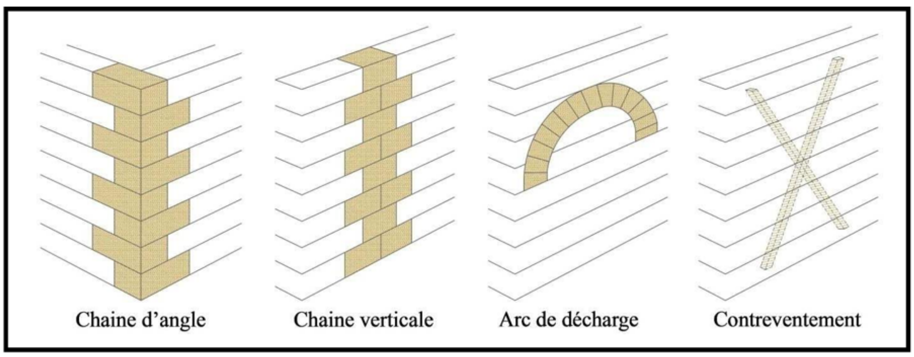


Figure 1.24: Masonry wall consolidation systems [17]

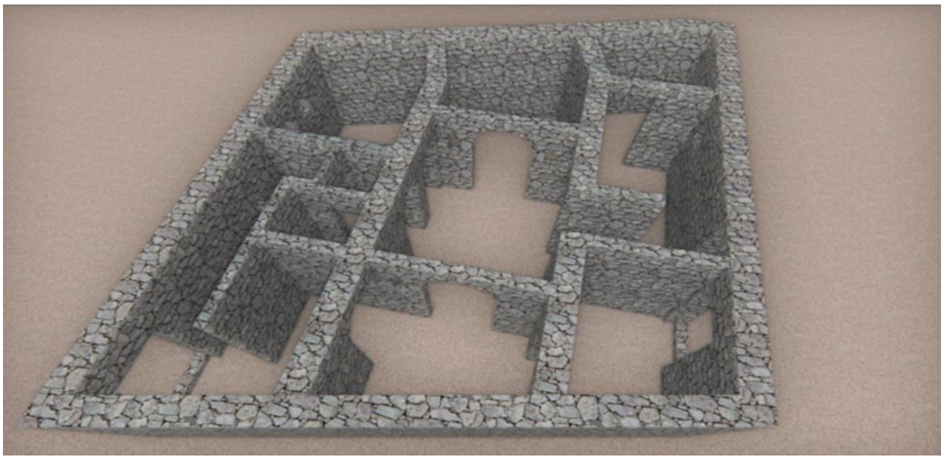


Figure 1.25: Stone walls [17]

The post-and-beam system

This system is based on the transmission of loads at the supports. It is composed of elements that have proven their resistance to different forms of stress to form a light and more practical framework.

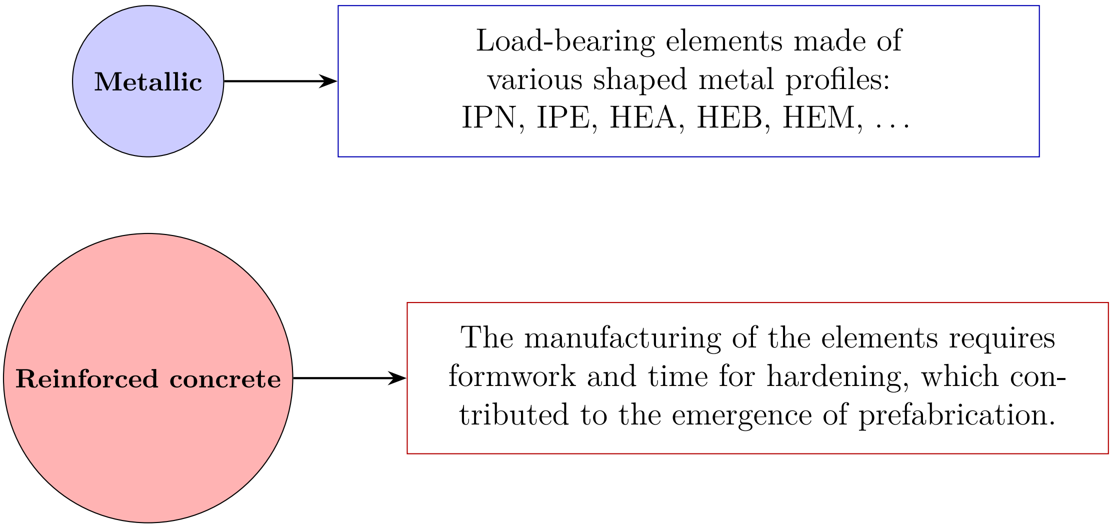


Figure 1.26: The types of materials used for the post-and-beam system [21].

1.6.3 The floors and Slabs

The floor

Horizontal and separating load-bearing element that forms the ceiling for some spaces and the floor for others.

The wooden floor Traditional structures with load-bearing masonry walls and wooden floors are found (Figure 3.9).

The vaulted floor It is composed of three main superimposed layers:

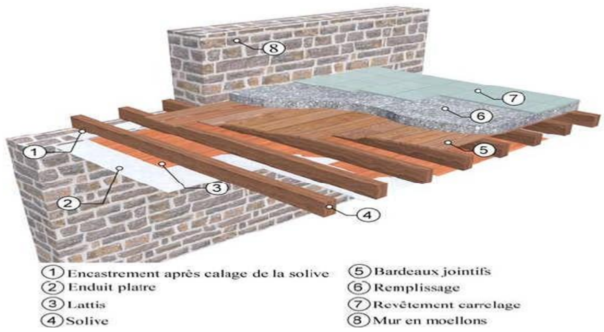


Figure 1.27: The types of wooden slabs [17].

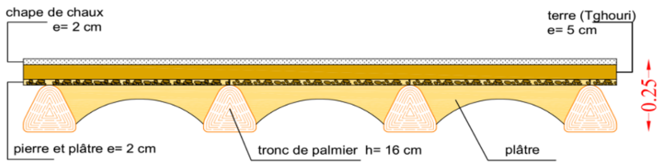


Figure 1.28: Floor section [17].

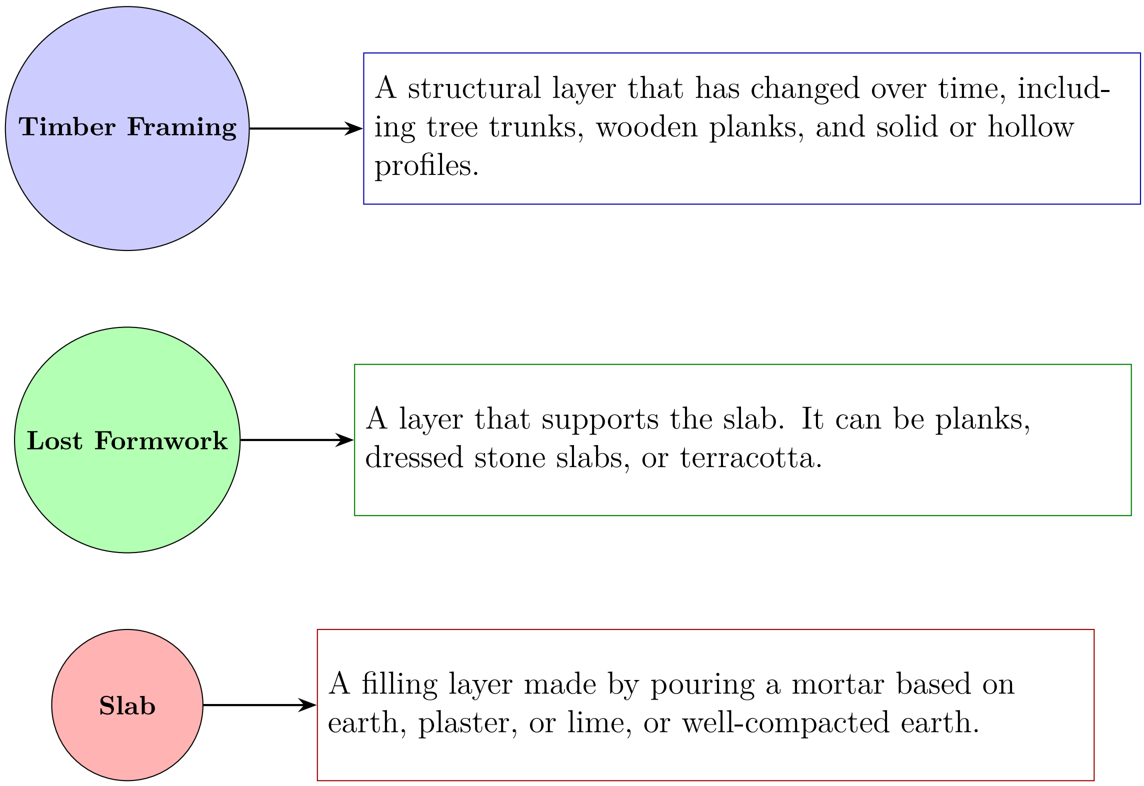


Figure 1.29: The components of a vaulted floor [21].

Concrete slabs These are reinforced concrete elements; they can be manufactured on-site or prefabricated:

During the year 1955, the birth of reinforced concrete structures with reinforced concrete foundations and monolithic floors in the form of solid slabs or prefabricated floors with hollow blocks and prefabricated reinforced concrete beams.

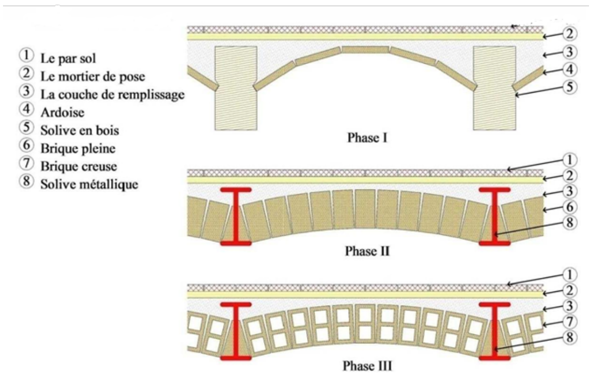


Figure 1.30: The main phases of the development of vaulted floors [17].

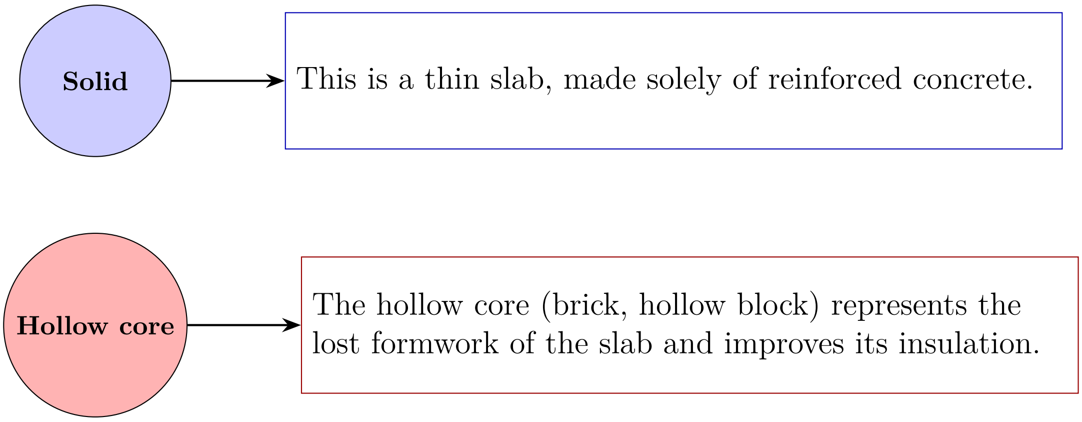


Figure 1.31: The types of concrete slabs [21].

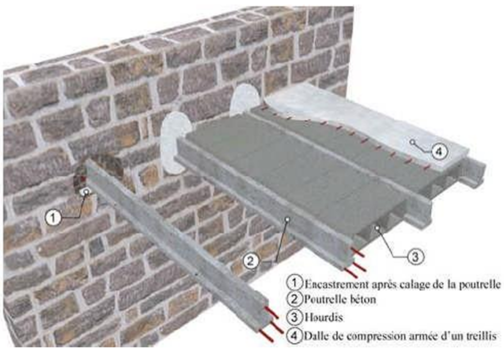


Figure 1.32: The types of concrete slabs [17].

1.7 Conclusion

This chapter highlights the current national context regarding geography and energy, emphasizing the undeniable rise in energy demand, continued reliance on fossil fuels, and the effects of climate change. In this evolving energy landscape, the adoption of renewable energy sources becomes not only a necessity but a responsibility to protect the environment and preserve biodiversity.

In parallel, the built heritage of previous centuries, largely composed of natural materials shaped by human craftsmanship, offers valuable lessons. Unlike today's industrialized construction focused on profit and efficiency, these traditional structures embody sustainability and cultural richness. As such, integrating renewable energies while valuing and conserving the architectural legacy of the past presents a dual opportunity: to build a cleaner future without losing the wisdom of historical practices.

Chapter 2

Case Study Interpretation

2.1 Introduction

The Mzab valley in the Algerian Sahara is character ized by 5 compact cities, each of them possessing an oasis. These cities, built in the 10th century and designated world culture heritage buildings by UNESCO since 1982, provide in addition to an architectural authenticity (Donnadieu et al. 1977, Ravérau 1981) a climatic-conscious design developed over centuries of building experience. It is commonly claimed that this type of compact urban structure is perfectly adapted to suit the surrounding climatic environment. However, this has not been proven and the current knowledge on this issue is still mainly qualitative. The climatic effectiveness of traditional solutions has been questioned, as these also reflect cultural specificities (e.g. Givoni 1997). The positive climatic effects of numerous traditional solutions may have been overestimated: Givoni (1997) and Meier et al. (2004) argue that the excessive thermal inertia of such architecture in hot-dry climates prevents the nocturnal cooling of the houses and leads to discomfort indoors at night. Also, Ouahrani (1993) found that day-lighting is insufficient in the typical inward-looking houses because of the small size of the courtyard, which is the only source of natural light Thus, more investigation is required to quantitatively evaluate common design concepts and establish the veracity of this common belief of climatic adaptation. Furthermore, available studies undertaken in such built environments focused on the architectural dimension, i.e. indoor climate (e.g. Ouahrani 1993, Krishan 1996, Potchter & Tepper 2002, Meier et al. 2004), whereas very few published studies are available to date which deal with the urban design level, i.e. outdoor spaces (e.g. Grundström et al. 2003) [14]. This experimental work focuses on the assessment of human comfort in relation to traditional design forms. This field study complements numerical simulations conducted for the same location (Ali-Toudert & Mayer 2005). Furthermore, eventual comparison with morefield studies to be conducted in new settlements in this region is also foreseen. The final goal is to use the information gathered from these studies in designing contemporary houses for hot-dry climates.

2.2 Presentation of Ghardaïa and climat conditions

The present study was conducted in Ghardaïa, a historic city located in the northern part of the Algerian Sahara, approximately 600 kilometers south of Algiers, the national capital. Geographically, Ghardaïa lies within the M'zab Valley, a semi-arid region renowned for its unique socio-architectural and environmental systems. The city occupies an area of 19,729 square kilometers and is positioned at a latitude of $32°37'$ North and a longitude of $3°77'$ East, with an average elevation of 450 meters above sea level. Ghardaïa serves as the main urban center of the M'zab region, which is inhabited primarily by the Ibadi Muslim community, known for their rich cultural and architectural heritage [14].

The M'zab Valley is distinguished by its five ksour—fortified settlements constructed using traditional earthen architecture. These settlements—Ghardaïa, Beni Isguen, Melika, Bounoura, and El-Atteuf—have been recognized as a UNESCO World Heritage Site since 1982 due to their outstanding example of human adaptation to a harsh desert environment. The geomorphology of the valley is defined by a vast rocky plateau called the Hamada, characterized by minimal soil cover and scarce vegetation.

Figure 2.1: Location of the city of Ghardaïa.

The terrain is dominated by steep escarpments and rugged rock formations known locally as the "Chebka," which refers to the network-like appearance of the eroded land surface. Unlike the typical sand dune landscapes commonly associated with the Sahara, this region is primarily stone-covered, making it distinct both geologically and ecologically.

From a climatic perspective, Ghardaïa is situated in a transition zone between arid and semi-arid environments. The area experiences extremely hot summers and relatively mild winters. During the summer months, temperatures can fluctuate between 14°C during the cooler nights and peak at 47°C during the day. In winter, the range extends from as low as 2°C to a maximum of around 37°C. This broad thermal amplitude reflects the desert's continental climate, marked by high diurnal and seasonal temperature variation. Moreover, Ghardaïa receives very low annual precipitation, averaging less than 100 mm per year, which further classifies it as a dry desert climate according to the Köppen-Geiger system.

One of the key environmental assets of the region is its high solar irradiance. The city receives an average of approximately 5,656 Wh/m^2/day of solar energy annually, with daily values ranging from 607 to 7,574 Wh/m^2/day depending on the season. This high solar potential makes Ghardaïa a strategic site for studying passive cooling techniques and renewable energy integration in architectural design.

The limited availability of water resources in the area has had a profound influence on both the settlement patterns and the local vegetation. Water is allocated with strict prioritization—first to the domestic needs of the population, followed by economic activities such as commerce or crafts, and finally to agricultural areas including palm groves and small irrigated gardens. Irrigation is not a primary concern unless it is directly linked to local economic productivity. The oued (seasonal river) that passes through the valley is highly intermittent, flowing only during occasional rainfall events. As such, it does not support urban vegetation or act as a cooling feature for adjacent neighborhoods. However, its geographical orientation plays a subtle but important role in the region's microclimate by channeling wind flows along its bed, contributing to natural ventilation within the valley.

In sum, the city of Ghardaïa represents a compelling case study of environmental adaptation in arid regions, where geography, climate, and cultural heritage intersect to create a unique human-environment relationship that is both resilient and sustainable. Topographies Béni isgen The ksour are fortified settlements that date back over a thousand years. They were strategically constructed on rocky promontories and are spread along the M'zab valley. In accordance with a logic that sought to preserve the balance between nature and culture, the elevated areas were used for construction and defense, while the valley floors were reserved for agriculture. At the base of the valley, oases composed of palm groves—each associated with a specific ksar—formed vital sources of livelihood for the local population (Figure 2.2). These green spaces provided not only food and agricultural resources, but also served as cooling micro climates within the arid ecosystem of the M'zab. The irrigation system used in these oases was ingeniously designed to conserve water, a scarce and precious resource in the desert.

Figure 2.2: The old city of Beni-Isguen and its oasis in the Mzab valley, Algeria.

2.3 Climate conditions and comfort requirements

Clear skies are a characteristic of the Saharan climate, resulting in a comparatively high solar irradiance in the daytime and a high long-wave net radiation during the night. Therefore, the summer is hot and dry, as well as long, owing to the subtropical location of the region. Air temperature (T_a) > 40°C is not rare and the daily T_a amplitude is relatively large. The atmospheric moisture content is low, with a relative humidity (RH) below 35sweeps dust and sand for several months of the year. The winters are short and cold, particularly at night (reaching freezing point). Rainfall is scarce but of high intensity when it occurs (ONM 1985). Mean 45 40 values of T_a, RH, VP and wind speed (v) for the hottest month of August during the decade 1975–1984 for Ghardaia (capital of the Mzab valley) are given in Fig. 1. The living conditions for people are very difficult in hot-dry climates. However, they can be improved by using an appropriate housing design. A number of strategies have been recommended (e.g. Koenigsberger et al. 1973, Golany 1982, Golany 1996, Givoni 1997). These include fabric compactness, the high inertia of the construction, shading, night ventilation and evaporative cooling. In the winter season, provision for sunshine is recommended with heat storage capacity. The Mzab cities typically illustrate these recommendations. The old settlements in the Mzab valley form a system where environmental concepts can be stated at the 3 consecutive design scales; (1) the location in the valley, (2) the urban fabric, and (3) the architecture of the house [14].

2.4 Urban fabric

The urban structure reveals the distinctive influence of the climatic conditions, which are just as important as the cultural dimension. The medium height houses are inward-facing buildings allowing an extreme com pactness of the urban fabric (Figure 2.3). Only the rooftops and a few facades are exposed to the intense solar radiation. The streets are very narrow and shaded by the neighbouring walls, in some places also covered or further protected from the sun with trellis, cloth and awnings. A solar right is rigorously observed (Donnadieu et al. 1977). Explicitly, no house may be cut-off from the di rect solar radiation by the neighbouring houses in the cold season. Therefore, the building height is limited by the maximum height attained by the sun in winter. The thermal inertia of the whole system is high, as a consequence of a minimal envelope to volume ratio (compactness) and also owing to the use of heavy materials, mainly stone, which has a high thermal capacity. The mostly horizontal configuration of the city increases the urban albedo, as noted by Aida & Gotoh (1982). The use of light colours (houses are gen erally whitewashed or painted in light colours) would further increase the urban reflectance (twice as much as modern cities; Taha et al. 1997). The roofs, being the main exposed surfaces, need to be carefully designed. These are flat and heavy, allowing, on one hand, a minimal conduction of heat indoors, because of a high diurnal heat storage capacity, and on the other hand, a rapid night-time release of heat ensured by a large sky view factor, SVF (close to 1.0). The placement of the cities on hill slopes supports ventilation within the streets despite the compact typology‘ [14].

2.5 Architecture of the house

s Self-shading and thermal inertia are important for indoor comfort. The intense solar radiation is generally controlled through the use of deep courtyard configurations and the extreme clustering of houses. The house design further controls radiant heat and glare through the use of superimposed courtyards. The courtyard is the main source of light as the outside facades generally are windowless. On ground level, there is a skylight that can be covered with a lattice screen. This level and underground spaces are refuges during the hottest time of the day. Moreover, the walls made of stone and gypsum together with their white washed coloured surfaces further prevent daytime summer overheating. Even if these houses were built to cope primarily with very hot and long summers, the winter conditions are improved with the southern orientation of the semi-outdoor living spaces on the ter races (galleries) and by taking advantage of the heat storage capacity of the buildings (Ravérau 1981). Air movement occurs through small openings in the walls, and doors are left open most of the time. Thermal differences between the cool street, the house and the warm terrace may promote indoor ventilation. Even though the urban fabric and the building envelope are the main climatic filters, the people of these cities also show adapation to the severe thermal regime by employing a ‘nomadic’ way of living in their houses. Spaces within the houses have to be non specialized or duplicated (e.g. being able to cook both indoors or outdoors). During summer when thermal conditions are extreme, people will move to their summer houses in the cooler palm grove. They also tend to go outside either early in the morning or in the late afternoon, when the solar radiation is less intense [14].

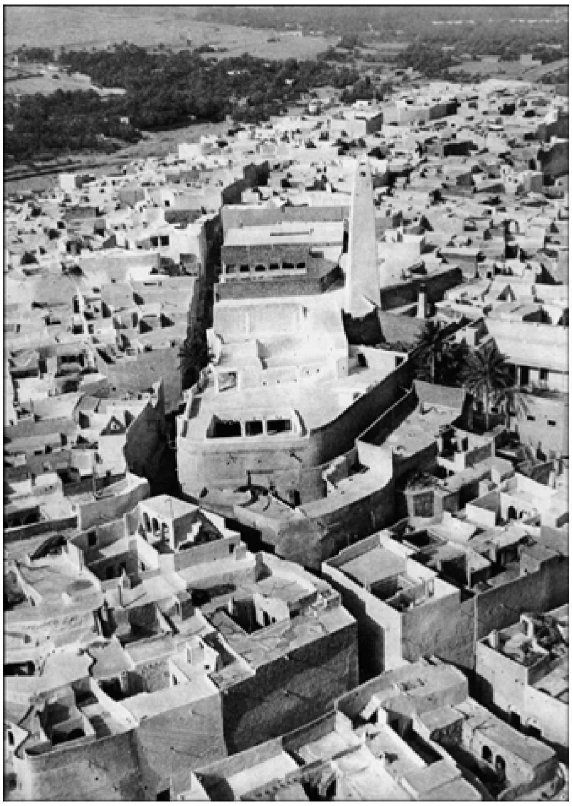


Figure 2.3: A view of the compact urban fabric of the upper part of the old city of Beni-Izguen (Roche 1970).

2.6 Outdoor Thermal Comfort

The outdoor thermal comfort in urban street canyons is influenced primarily by the geometry of the canyon, particularly the height-to-width (H/W) ratio and street orientation. These factors affect solar exposure, wind flow, and heat transfer, with deeper, narrow streets offering more shading and potentially cooler air temperatures, especially in N–S orientations. Surface materials also play a role in daytime heat storage and nighttime cooling. Although much research is based on physical models using comfort indices (e.g., air temperature, wind, radiation), few field studies directly assess comfort, especially considering urban form. More recent studies have highlighted the importance of solar and thermal radiation in human heat gain, showing that geometry greatly affects the radiation fluxes absorbed by pedestrians. Additionally, subjective surveys reveal that individual perceptions and past experiences significantly affect thermal comfort, and that people tend to accept warmer conditions outdoors than indoors due to limited control. The present study uses a physical model to analyze the role of urban form in comfort, while acknowledging the psychological complexities involved.

To better understand buildings from a given period, it is necessary to understand their composition and construction techniques. Thus, the construction materials and the level of scientific development from the 18th century to the early 20th century fall directly within our area of study, as they intersect with the main focus concerning the evaluation of this building. This chapter begins with a description of the construction materials and an explanation of the building systems used in the Ksar of Beni Isguen for more than a century, with reference to local specificity [14].

2.7 Thermal Comfort in Buildings

2.7.1 Thermal Comfort

Optimal thermal comfort is established when the heat released by the human body is in balance with its heat production (Figure 2.4). Fanger's comfort equation is derived from this fact. It creates a relationship between activity (e.g., sleeping, running…) and clothing, as well as the determining factors for the thermal environment, which are as follows (Schaudienst and Vogdt, 2017) [14]:

- Air temperature
- Temperature of surrounding surfaces, which can also be summarized as "radiant temperature"
- Air velocity and turbulence
- Air humidity
- Clothing and metabolism (physical activity)

There is a full range of combinations of these four comfort factors where the comfort level is very good; this is called the comfort zone. It can be determined by Fanger's equation, documented in the ISO 7730 standard. Furthermore, according to this standard, it is essential that:

- The dew point limit relative to air humidity is not exceeded,
- Air velocity remains within well-defined limits (for velocities below 0.08 m/s, the percentage of dissatisfied due to drafts is less than 6%),
- The difference between radiant temperature and air temperature remains low,
- The difference in radiant temperature in different directions remains low (below 5 °C, known as "radiant temperature asymmetry"),
- The stratification of indoor air temperature is less than 2 °C between the head and the ankles of a seated person,
- Perceived temperatures in the room do not vary by more than 0.8 °C at different locations.

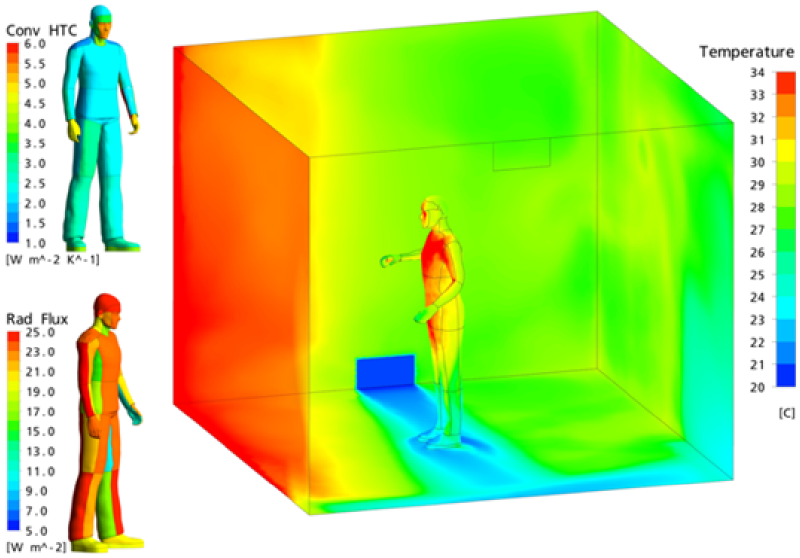


Figure 2.4: Thermal Comfort in a Bedroom.

2.7.2 Hours of Discomfort

The Thermal Comfort Report evaluates and rates the performance of buildings in maintaining occupant comfort based on six key parameters defined by the ASHRAE 55-2017 standard (air temperature, mean radiant temperature, air velocity, relative humidity, metabolic rate [physical activity], and clothing insulation [clothing level]). The number of discomfort hours inside is calculated according to the adaptive comfort model defined in ASHRAE 55-2017 (Semahi et al., 2020). This model is recognized as the most appropriate socio-climatic model, notably for its flexibility in omitting humidity constraints. Thermal discomfort hours due to heat represent the number of hours during which the operative temperature exceeds the comfort temperature (Semahi et al., 2020). Discomfort hours have been classified into three types:

The optimal comfort temperature (°C) :

$$T_c = 0.31 f(T_{out}) + 17.8 \quad \text{si } 10°\text{C} \leq f(T_{out}) \leq 33.5°\text{C}$$

Upper Acceptability Limit at 80% (°C):

$$T_c = 0.31 f(T_{out}) + 20.3 \quad \text{si } 10°\text{C} \leq f(T_{out}) \leq 33.5°\text{C}$$

Lower Acceptability Limit at 80% (°C):

$$T_c = 0.31 f(T_{out}) + 15.3 \quad \text{si } 10°\text{C} \leq f(T_{out}) \leq 33.5°\text{C}$$

Where $f(T_{out})$ is the prevailing mean outdoor air temperature ($t_{pma(out)}$) in ASHRAE 55 for 2013 and 2017, and the monthly mean outdoor air temperature in ANSI/ASHRAE 55 for 2004 and 2010. **Mean Outdoor Air Temperature (°C)**

$$\bar{t}_{pma(out)} = (1 - \alpha)[t_{e(d-1)} + \alpha t_{e(d-2)} + \alpha^2 t_{e(d-3)} + \alpha^4 t_{e(d-4)} + \ldots]$$

Where α is a constant between 0 and 1, and $t_{e(d-1)}$ is the average daily outdoor air temperature at time d of a series of equal intervals (day). In the last two versions, ANSI/ASHRAE 55 suggests a value of α equal to 0.9 for climates where the daily temperature variation is relatively minor, such as in humid tropics, and a lower α value of 0.6 for mid-latitude climates where the daily temperature variation is more pronounced (Semahi et al., 2020).

2.7.3 The Ksar of Béni Isguen

The Ksar of Béni Isguen is one of the five *ksour* (fortified villages) of the M'Zab Valley and stands as a striking example of humanity's ability to adapt to harsh environments. Founded in the 10th century by the Ibadi, these traditional towns rose from the barren and unforgiving lands of the Sahara Desert. Today, Béni Isguen is regarded as a masterpiece of urban planning, renowned for its rich cultural heritage. Its distinctive architecture and urban design have inspired renowned architects such as Le Corbusier and Pouillon.

2.7.4 Presentation

The Ksar of Béni Isguen, located in the M'Zab Valley, extends over 25 kilometers and is situated in a desert region 600 km south of Algiers. It is characterized by a hot and arid climate (Figure 2.5). The site is located on a limestone plateau, dissected by a network of valleys and ravines that intersect to form a mesh-like pattern known as the Chebka Mozabite [14].

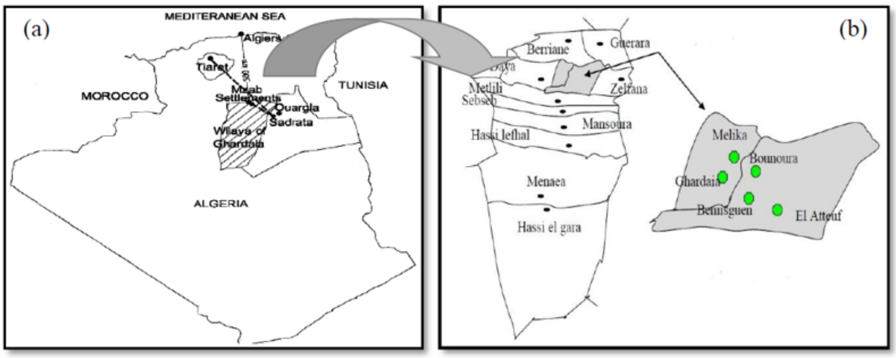


Figure 2.5: (a) Geographical location of the valley; (b) Location of the Ksar of Béni Isguen.

This valley, which represents a coherent urban and landscape ensemble, includes a network of five traditional towns (ksour) and vast palm groves. It covers approximately 6,000 hectares, between 32° and 33°20 north latitude and 2°30 east longitude, at an altitude of 450 meters. The total population is about 170,000 inhabitants. The urban development of the M'Zab Valley is organized around a central wadi, following a territorial model that integrates a unique agro-system. This model is based on a tripartite relationship: water / habitat / palm grove (Kadri et al., 2022).

2.7.5 The Climate of the Ksar Region

From a climatic point of view, the region of the Ksar is located in a transition zone between arid and semi-arid environments. The region experiences extremely hot summers and relatively mild winters. During the summer months, temperatures can fluctuate between 14°C on the coolest nights and reach up to 47°C during the day. In winter, the range extends from 2°C to a maximum of about 37°C. This wide thermal amplitude reflects the continental desert climate, characterized by strong diurnal and seasonal temperature variations. Furthermore, the region receives very low annual precipitation, averaging less than 100 mm per year, which still classifies it as a dry desert climate according to the Köppen-Geiger system.

One of the main environmental assets of the region is its high solar radiation. The city receives on average about 5,656 Wh/m^2/day of solar energy annually, with daily values ranging from 607 to 7,574 Wh/m^2/day depending on the season. This high solar potential makes the region a strategic site for studying passive cooling techniques and the integration of renewable energies in architectural design. Figure 2.6 shows the isotherms of the Ksar of Béni Isguen [14].

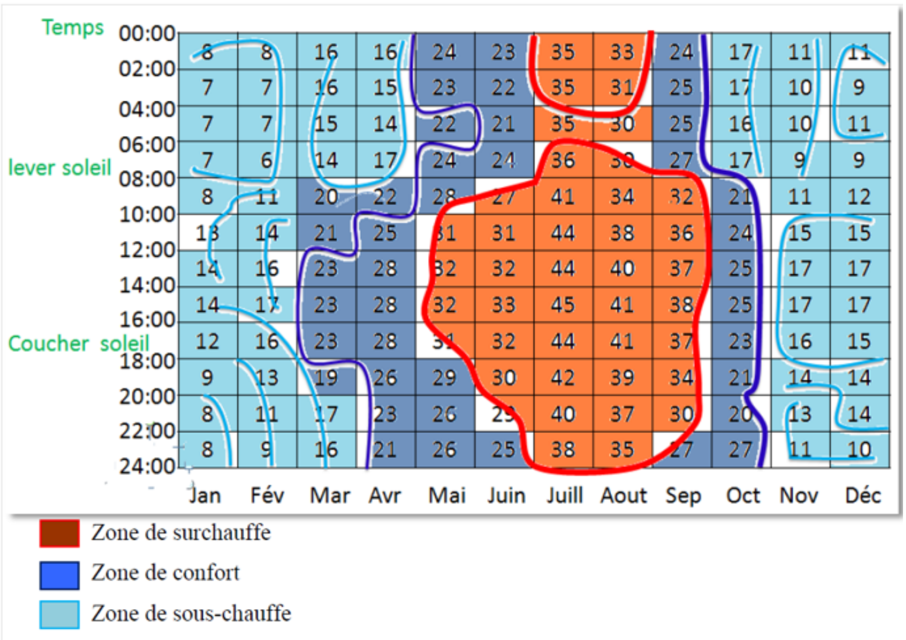


Figure 2.6: Isotherms indicating the different thermal zones of the Ksar of Béni Isguen.

2.7.6 Principle of Urban Organization of the Ksar

The urbanization principle of the Ksar of Béni Isguen is linked to the method of building placement on a hillock around a mosque. Around the mosque, houses are harmoniously clustered and arranged in terraces (Figure 2.7). The logic of the urban layout of the Ksar of Béni Isguen is based on a compact urban fabric with narrow alleys (Figure 2.8).

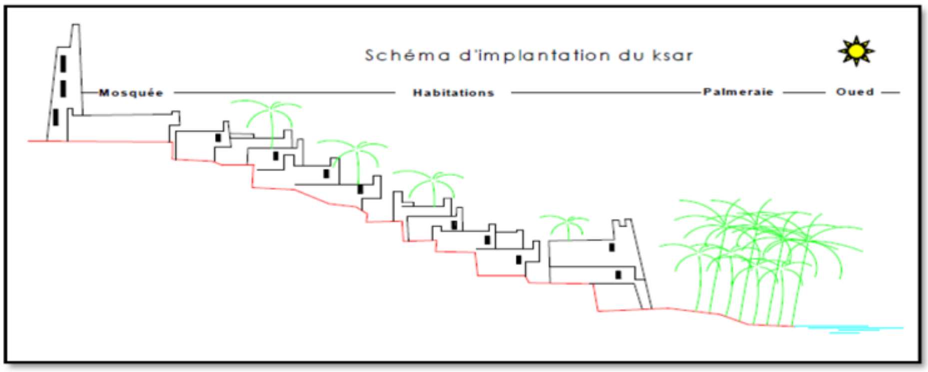


Figure 2.7: Layout of the Ksar.

Figure 2.8: Photo showing the compact urban fabric of the ksar.

2.7.7 Elements of the Mozabite House

The Mozabite house is characterized by its simplicity and functionality, devoid of any superficial decoration. It must not display any outward signs of wealth, following the principles of equality and social solidarity. The M'Zab house corresponds to the "patio house" type. There are two types of houses in the Ksar of Béni Isguen: those integrated into the urban fabric of the Ksar inside the rampart, and those located in the palm groves, or summer houses (Table 2.1) [14].

2.7.8 The Architecture of the Ksour House

The different spaces of the house are organized around the patio, based on principles and customs that reflect the lifestyle of the Mozabite people. For example, the Skiffa (the entrance of the house) provides privacy for the interior of the dwelling from the outside space. The houses are well oriented to take advantage of the sun in winter while protecting against the harsh solar rays during summer (Figure 2.9.a and b).

Natural lighting during the day is provided through the patio, which is considered the main source of light and sunlight for the house. During very hot days in the summer period, the Chebek (a ventilation opening in the roof) is covered to reduce strong solar radiation and minimize interior glare (Figure 2.10).

Ventilation of the ksour house is done through the patio. The pressure difference between the hot terraces exposed to solar rays and the shaded courtyard creates air

Table 2.1: **Types of Habitats in the Ksar**

Types of Houses	**Overview**
Urban House	
Palm House (Summer House)	

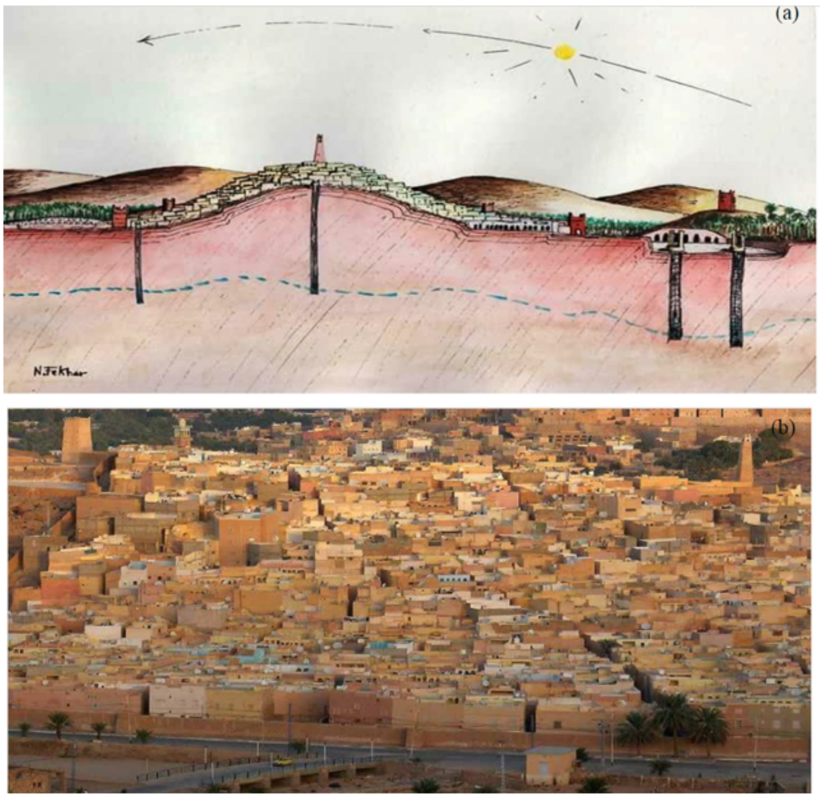


Figure 2.9: (a) Path of the sun across the Ksar; (b) View of the Ksar.

currents by ventilating through the exterior door and dissipating hot air through the Chebek opening in the roof. The addition of cooling devices, such as a water feature in the patio, increases air humidity, which improves indoor thermal comfort during

Figure 2.10: View of the patio covered by a carpet during a summer day.

summer. Local materials for roofs and thick walls are used as a bioclimatic solution and a passive strategy to provide cooling in summer and heating in winter. Figure 2.11 illustrates the passive ventilation and aeration strategies of ksour houses.

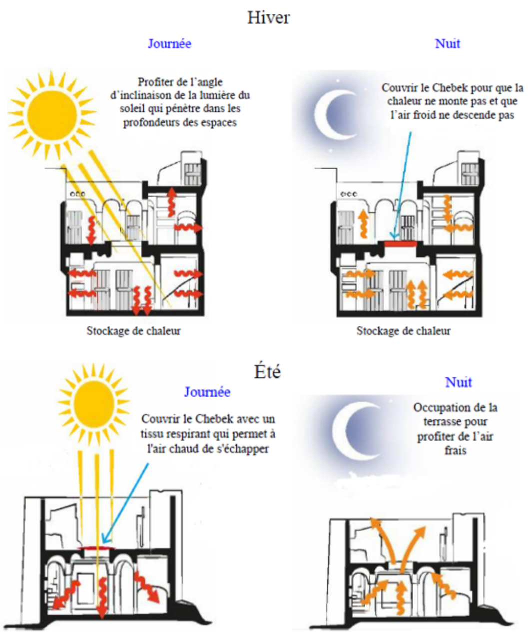


Figure 2.11: Passive Strategies for Aeration, Ventilation, and Sunlight.

2.7.9 Construction Materials

The traditional construction materials of the M'Zab valley are distinguished by their authenticity and adaptation to the environment. These include load-bearing walls made of masonry or earth with local stone (Figure 2.12.a), traditional floors built using palm trunks and branches (Figure 2.12.b), and roofs sealed with traditional techniques—a layered system using sand, traditional lime mortar, and lime wash applied in two layers. Exterior finishes often consist of a mixture of sand, traditional lime, *timchemt* (local traditional plaster), and facade elements such as narrow openings (meurtrières) for ventilation and lighting [14].

The houses are built with thick walls offering high thermal capacity, using locally sourced materials such as stone, mud, and lime. These choices reflect a construction philosophy that harmonizes with the Saharan climate while preserving cultural heritage.

Figure 2.12: (a) Earthen wall in the palm grove house of Béni Isguen; (b) Palm roof.

2.8 Presentation of Case Studies: The Ghardaïa Region

2.8.1 Case Study House

The case study is based upon a house located in Beni Isguen's Ksar. It has a single facade from which there is the only entrance to the house (Figure 2.13). The facade surface is small, which reduces exposure to intense sunlight. The houses of Beni Isguen's Ksar are characterized by the existence of a cellar, ground floor, floor, and terrace. So, like the majority of 'Mozabit' houses, this house has a cellar (basement) where there is a water well. Then, the ground floor contains the living rooms, namely: the Tizefri (Living room), a bedroom, the kitchen, toilet, and two stairwells. In addition, on the first floor are the bedrooms: parents, girls, and boys, and the bathroom [14].

For the terrace, there is a corner reserved for storage with the existence of a 'Chebek' to let in the light. The plans of the house are shown in Figure 2.14.

The ceiling consists either of a lath tightened with palm ribs, or of flat stones, or of vaults made of stones linked with Timchemt (local plaster) between the joists [57]. This base is covered with a layer of clay up to 30 cm thick, and above this layer a lime mortar screed is applied. As for the vaults, their construction is based on the same technique as that of the arches, with stones mounted with a "timchemt" on formwork of palm ribs. This type of roof is widely used in homes due to the availability of construction raw materials such as palm trunks and branches, clay, lime, and 'timchemt'. In the rooms, the 'Mozabits' use small stone vaults and lime mortar placed on the trunks of palm trees (Figures 2.15 and 2.16).

In the following, we will focus on the main characteristics of this dwelling, highlighting the architectural choices, the materials used, as well as the design principles that enable this housing model to meet climatic requirements, etc.

As part of our study on the thermal optimization of the traditional dwelling under consideration, it is essential to examine the various types of phase change materials (PCMs) available. Two main categories will be presented, followed by a comparative analysis aimed at identifying the most suitable solution for the climatic and architectural specificities of the case study.

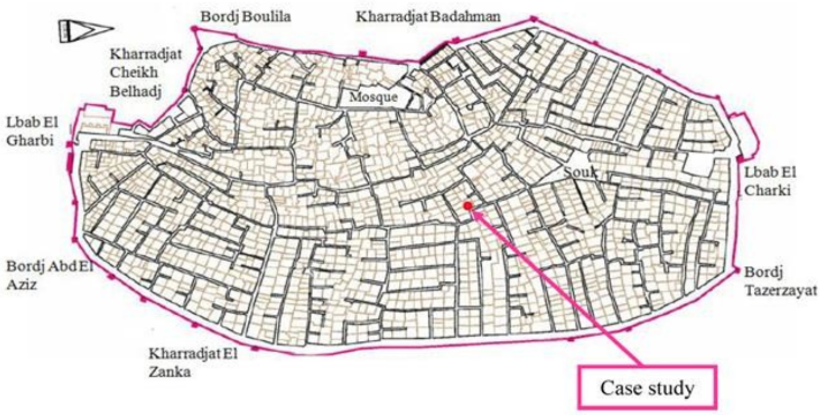


Figure 2.13: Case study on the map of Beni Isguen's Ksar.

Figure 2.14: House plan: (a) Basement plan, (b) Ground floor plan, (c) First floor plan, (d) Terrace plan, (e) Section AA, (f) Façade.

The following table presents a detailed comparison between lauric acid and capric acid as phase change materials (PCMs), based mainly on information gathered from the referenced articles and general PCM characteristics relevant to this study.

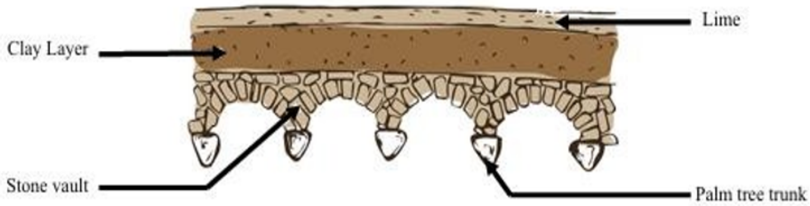


Figure 2.15: Section on a roof of palm tree trunks and vaults in the upstairs bedroom of the case study.

Figure 2.16: Photos showing roof of palm tree trunk sand vaults in the room of the case study.

Table 2.2: General Parameters for Simulations with Design Builder

Simulation Parameters	
City	Ksar de Béni Isguen (32° 17' N, 3° 25' E)
Climate	Hot and dry
Simulation Date	02, 03 and 04 June 2025
Simulation Time	From 06:00 to 00:00
Configuration Model	
Occupancy Period (Usage)	Night space + resting area
Orientation	Northeast
Simulated Space	Room on the upper floor of a traditional house: in contact with the roof (space under the roof)
Mask Orientation (Wall Directions)	- Northwest wall and northeast wall: shared wall with neighbors - Southeast wall: facing *Ikoumar* (Patio Gallery) - Southwest wall: facing outside

Additional Notes

- Lauric acid's melting temperature ($\sim$ 44–48 °C) makes it suitable for moderate temperature thermal energy storage applications such as solar heat storage and building temperature regulation.

Table 2.3: Layer Thickness, Wall Composition, and U-values for the Simulated Room Envelope

Component	**Layer Composition (Thickness in cm)**	**U-value ($W/m^2 \cdot K$)**
Exterior walls (neighbors)		1.34
Hard stone	38	
Lime mortar	4	
Sand (mixed with lime and water)	2	
Interior walls (adjacent)		2.65
Hard stone	20	
Lime mortar	2	
Sand (mixed with lime and water)	2	
Floor		0.57
Palm trunk	15 to 20	
Stone	13	
Timchemt mortar (for bonding)	/	
Dry earth	/	
Roof		0.53
Palm trunk	15 to 20	
Stone	13	
Timchemt mortar	/	
Earth layer	10	
Lime	5	

- Capric acid melts at a lower temperature (∼ 31–33 °C), which may be advantageous for applications requiring lower temperature phase change, such as cold storage or temperature regulation closer to ambient conditions.
- Both materials have relatively low thermal conductivity, which is typical for organic fatty acid PCMs, and may require enhancement techniques (e.g., adding fins or nanoparticles) to improve heat transfer.
- The mushy zone constant (A_{mush}) is a key parameter in numerical simulations affecting the accuracy of melting/solidification predictions. For lauric acid, values around 5×10^5 to 10^7 have been used to match experimental data accurately.
- Lauric acid has been extensively studied numerically using ANSYS FLUENT with iterative and non-iterative time advancement schemes to optimize simulation time without sacrificing accuracy.

Table 2.4: Parametric Study Variables Used for TRNSYS Simulations

Windows	Surface: 0.17 m^2 (0.59×0.29)	Glazing type: Single Frame	Area Frame/Window : 31.05%	U-Value: 5.74 W/m^2K Solar Absorption: 0.6
Infiltration	Air renewal rate (Vol/h): 0.5	Airflow temp.: 28°C	RH of airflow: 30%	–
Ventilation	Exchange rate (Vol/h): 0.6	Airflow temp.: 28°C	RH of airflow: 30%	–
Cooling	Set temp.: 28°C	–	–	–
Heating	Set temp.: 21°C	–	–	–
Internal gains	4 persons: 75 W/person	Artificial lighting: 10 W/m^2	Type: Fluorescent	–

At the end of this comparison, our choice fell on lauric acid as the phase change material. This decision is based on a series of technical, climatic, and architectural criteria, which we will elaborate on below in order to rigorously justify the selected option.

Table 2.5: Properties of Lauric Acid (C12H24O2) and Capric Acid (C10H20O2).

Property / Feature	**Lauric Acid (C12H24O2)**	**Capric Acid (C10H20O2)**
Chemical Nature	Fatty acid, saturated medium-chain fatty acid	Fatty acid, saturated medium-chain fatty acid
Purity Used in Studies	99% purity (as per experimental studies)	Typically, high purity (>98%) in PCM studies
Melting Temperature Range	316.65 K to 321.35 K (43.5 °C to 48.2 °C)	Approx. 31 °C to 33 °C (304 K to 306 K)
Latent Heat of Fusion	187.21 kJ/kg	Around 160-170 kJ/kg (literature typical range)
Specific Heat Capacity (Cp)	Solid: 2.18 kJ/kg·K; Liquid: 2.39 kJ/kg·K	Solid: ∼2.1 kJ/kg·K; Liquid: ∼2.3 kJ/kg·K
Thermal Conductivity	Solid: 0.16 W/m·K; Liquid: 0.14 W/m·K	Solid: ∼0.15 W/m·K; Liquid: ∼0.13 W/m·K
Density	Solid: 940 kg/m^3; Liquid: 885 kg/m^3	Solid: ∼940 kg/m^3; Liquid: ∼870-880 kg/m^3
Dynamic Viscosity (Liquid)	0.008 kg/m·s	Slightly lower than lauric acid, ∼0.006-0.007 kg/m·s
Thermal Expansion Coefficient	0.0008 K^{-1}	Similar order of magnitude (∼0.0007 - 0.0008 K^{-1})
Phase Change Behavior	Melting occurs over a narrow temperature range; good thermal stability	Melts at lower temperature, suitable for low temperature applications
Applications	Thermal energy storage, solar heat storage, temperature control in buildings, PV cooling, electronics cooling	Suitable for low-temperature TES, building temperature regulation, cold storage
Numerical Modelling Notes	Well-studied in ANSYS FLUENT with enthalpy-porosity method; mushy zone parameter (Amush) critical for accurate simulation (typical Amush $\sim 5 \times 10^5$ to 10^7)	Similar modelling approaches applicable; less detailed numerical data available but comparable behavior expected
Advantages	Higher latent heat storage capacity; stable melting point suitable for moderate temperature TES	Lower melting point suitable for applications requiring lower temperature phase change; slightly lower viscosity
Limitations	Higher melting temperature may limit use in low- temperature applications; relatively low thermal conductivity	Lower latent heat than lauric acid; melting point may be too low for some applications requiring higher temperature stability

Technical Justification

- **Suitable Melting Temperature:** Lauric acid has a melting temperature of approximately 43 °C, which makes it suitable for applications like solar heat storage and building temperature regulation. The phase change temperature range is critical for building energy conservation and is typically required to be around 20–40°C depending on specific climatic conditions.
- **Latent Heat Storage:** PCMs like lauric acid are effective in alleviating the energy crisis in buildings due to their latent heat storage capabilities. It can store up to fourteen times more heat per unit volume compared to sensible heat storage materials. However, its relatively low thermal conductivity may require enhancement techniques to improve heat transfer.
- **Thermal Stability:** Lauric acid-based binary eutectic mixtures exhibit excellent thermal stability within the range of 110.08°C to 135.7°C, retaining excellent thermal properties and chemical structure even after 500 thermal cycles.
- **Composite Performance:** The thermal conductivity and stability of lauric acid can be significantly improved by combining it with materials such as expanded graphite or graphene. For example, the addition of 2%–10% expanded graphite can enhance thermal conductivity by 29.7%–708.2%.
- **Modeling and Simulation:** Lauric acid has been extensively studied numerically using software like ANSYS FLUENT. These simulations help optimize computation time while accurately predicting melting and solidification behavior.

Climatic Justification

- **Operating Temperature Range:** Capric acid, with a lower melting point of approximately 31–33°C, may be advantageous for cold storage or thermal regulation near ambient conditions. However, lauric acid remains more suited for moderate climate applications.
- **Energy-Saving Effect:** Thanks to its thermodynamic properties, lauric acid can be employed in the thermal cooling of electronic systems, building envelopes, and thermal storage in solar buildings, providing a notable energy-saving effect.

Architectural Justification

- **Integration with Building Materials:** Composite PCMs like lauric acid can be integrated into construction elements (e.g., gypsum boards), improving their heat storage and release performance. Studies show that stabilized composite PCMs can provide a relative thermal comfort time of 0.82 hours.
- **Customization via Mixtures:** Lauric acid can be combined with other fatty acids such as myristic acid, palmitic acid, or stearic acid to create eutectic mixtures with tailored melting temperatures. For instance, a 70:30 wt% lauric acid/myristic acid mixture has a eutectic melting point of 35.10°C.

Environmental and Economic Considerations

- **Eco-Friendly and Viable:** Lauric acid is recommended as an economic, eco-friendly, and commercially viable material for PCMs.

Governing Heat Transfer Equation with PCM

$$\rho \cdot c_{eff}(T)\frac{\partial T}{\partial t} = \nabla \cdot (k\nabla T) + q \tag{2.1}$$

Modeling the Phase Change (Latent Heat)

$$c_{eff}(T) = c + \frac{L}{\Delta T} \quad \text{for } T \in \left[T_m - \frac{\Delta T}{2}, T_m + \frac{\Delta T}{2}\right] \tag{2.2}$$

Enthalpy Method

$$\frac{\partial H}{\partial t} = \nabla \cdot (k\nabla T) \tag{2.3}$$

$$H(T) = \int_{T_0}^{T} \rho \cdot c(T')dT' + \rho L_f(T) \tag{2.4}$$

if Water (w) is Involved as a Heat Transfer Fluid

$$q'' = h(T_w - T_{PCM}) \tag{2.5}$$

2.9 Conclusion

In this chapter, we have highlighted how a large part of the materials that made up the buildings of the 18th and early 20th centuries came from nature, with a human touch in their creation. However, the concepts of industrialization, profit, and time optimization have changed the construction process. Thus, this period marks a pivotal moment in human development. The rich composition of the old buildings makes them a treasure that deserves conservation.

Chapter 3

Modeling

3.1 Introduction

This chapter presents the study framework and the methodology followed to simulate the thermal performance of a traditional Mozabite house located in the Ksar of Beni Isguen, Ghardaïa. The main objective is to model the thermal behavior of this vernacular construction in order to evaluate its energy efficiency and adaptation to the Saharan climate.

To achieve this, several steps were undertaken, starting with the selection of the case study and the analysis of its architectural features, followed by the digital modeling of the building using the Design Builder software. The architectural plans extracted from AutoCAD allowed an accurate geometric reconstruction of the house. Then, a presentation of the simulation tool, the hypotheses, and the climate data used provides a solid basis for the following chapter, which will focus on the simulation results.

3.2 Study Context

The selected case study for this simulation is a traditional Mozabite house located in the Ksar of Beni Isguen, one of the five ksour of the M'zab Valley in southern Algeria. This type of dwelling, typical of Mozabite architecture, is characterized by its compact structure, functional simplicity, and remarkable adaptation to the extreme desert climate.

The studied house is situated within the dense urban fabric of the fortified city. It has a single main façade, minimizing direct exposure to solar radiation. The house consists of a basement, a ground floor, an upper floor, and a roof terrace. Like most homes in the region, it features a water well in the basement and relies on natural ventilation through traditional architectural devices such as the Chebek and the El Manfass. This house was selected due to its architectural and environmental relevance, representing a model of bioclimatic design in arid regions.

3.3 Architectural Plans

The architectural plans of the traditional house were created using AutoCAD software. These drawings served as the geometric base for the 3D modeling in DesignBuilder. The following figures illustrate the different views of the building:

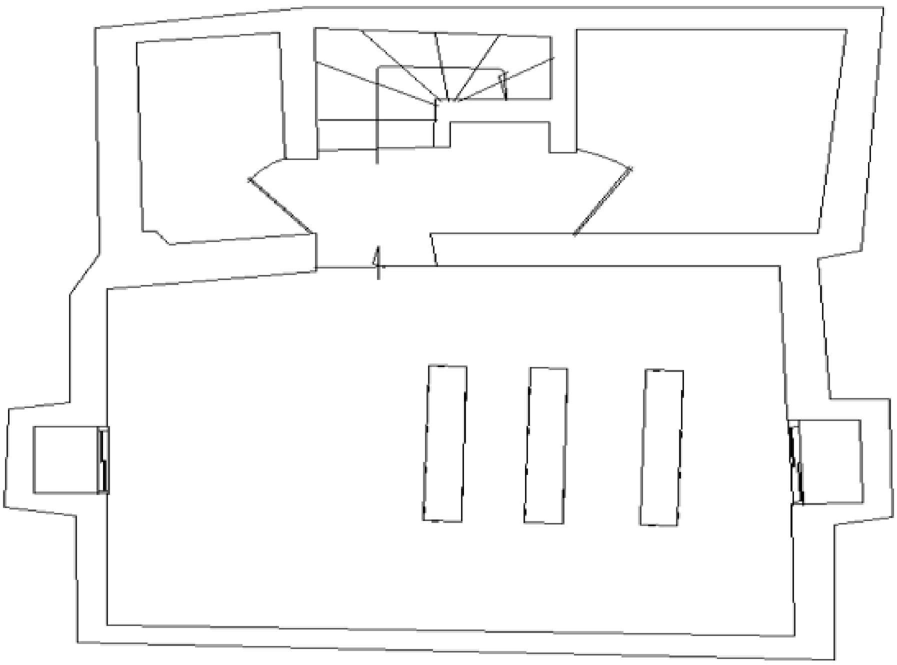


Figure 3.1: Under ground Plan.

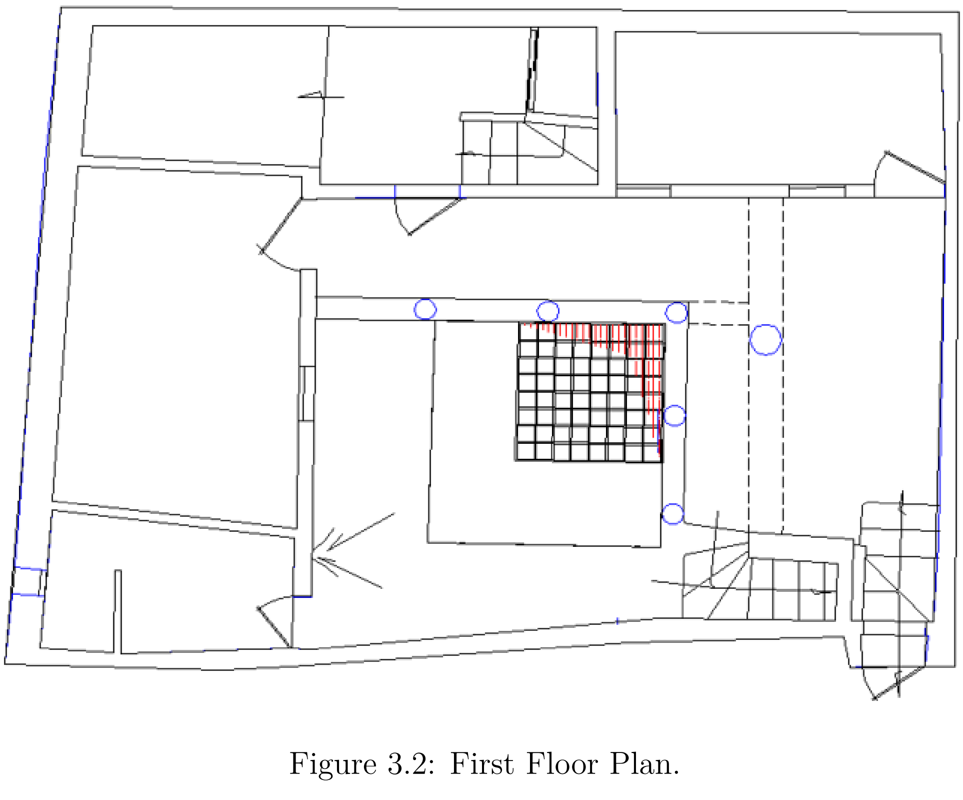


Figure 3.2: First Floor Plan.

These graphic representations help to better understand the spatial organization and dimensions of the building. They are essential for achieving an accurate and reliable thermal model.

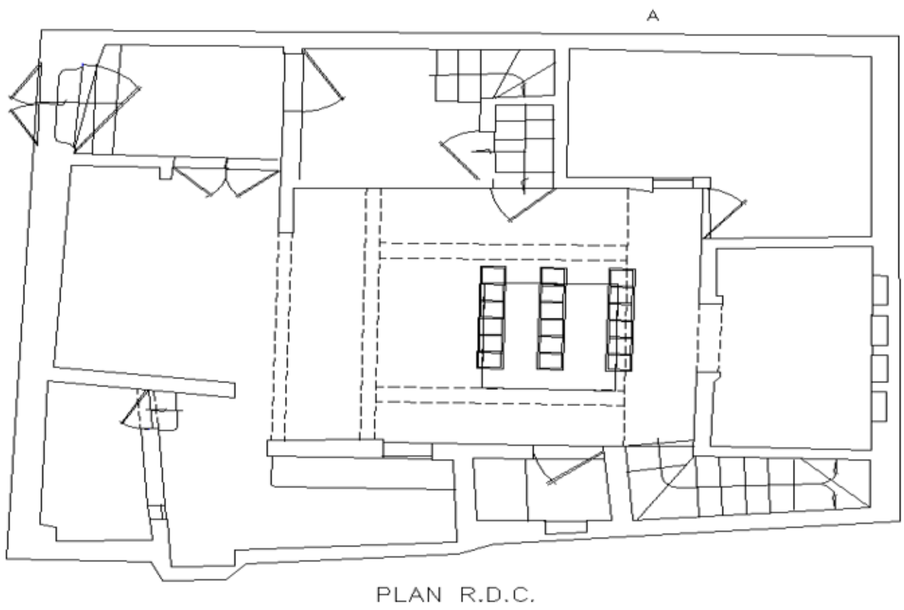


Figure 3.3: Ground Floor Plan.

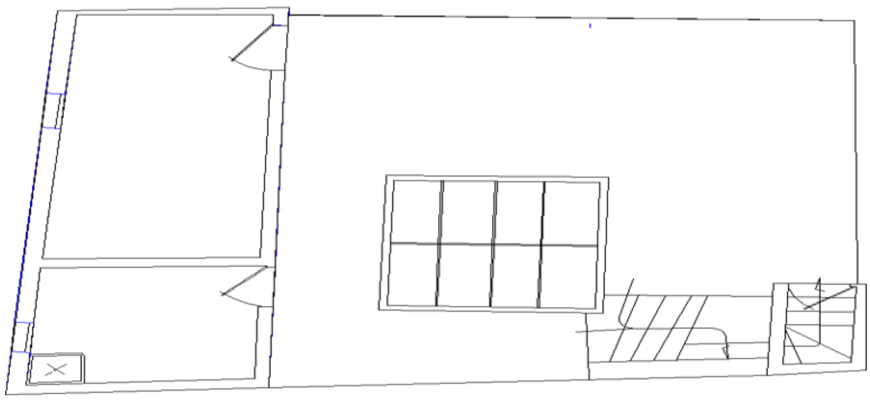


Figure 3.4: Terrace Plan.

3.4 Design Builder Software Overview

Design Builder is a building performance simulation software based on the EnergyPlus calculation engine. It enables the modeling of thermal behavior by considering several key parameters, such as 3D geometry, construction materials, climate conditions, ventilation strategies, internal gains, and occupancy schedules.

Design Builder is particularly suitable for simulating traditional buildings thanks to its user-friendly graphical interface and ability to handle custom thermal properties. In this study, it was used to digitally recreate the Mozabite house, simulate actual climate conditions in Ghardaïa, and prepare for future analysis of thermal comfort and energy behavior. Its selection is justified by its precision, flexibility, and wide use in international energy performance optimization projects.

3.5 Thermal Zoning Strategy

To analyze the building's thermal behavior more effectively, it was divided into several thermal zones. Each zone represents a space with homogeneous use, orientation, and exposure to external conditions. The main thermal zones are:

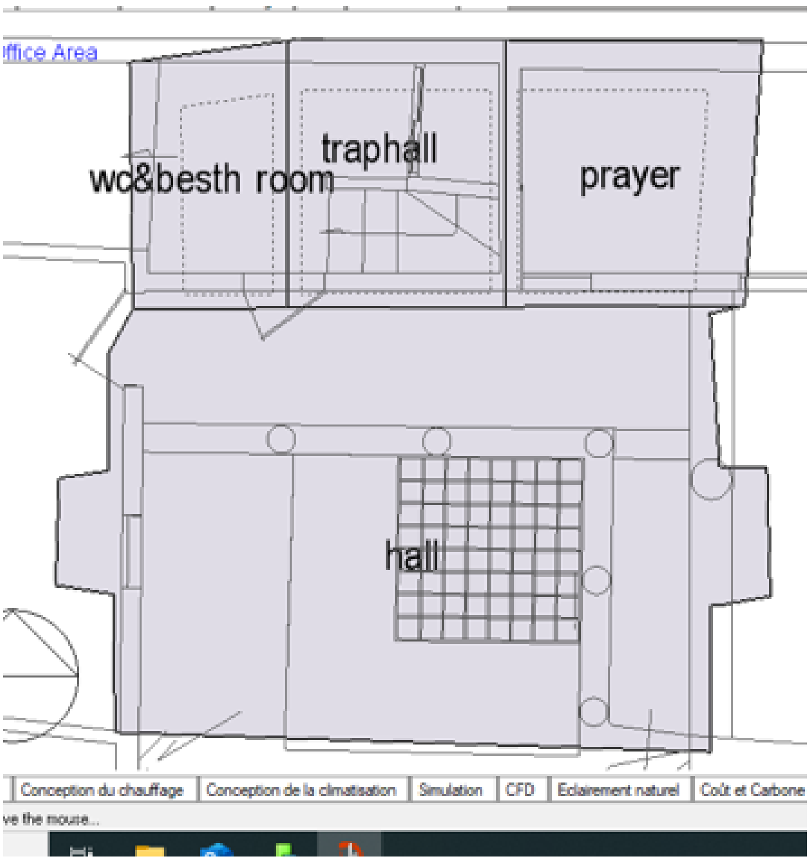


Figure 3.5: Under Ground Thermal Zone.

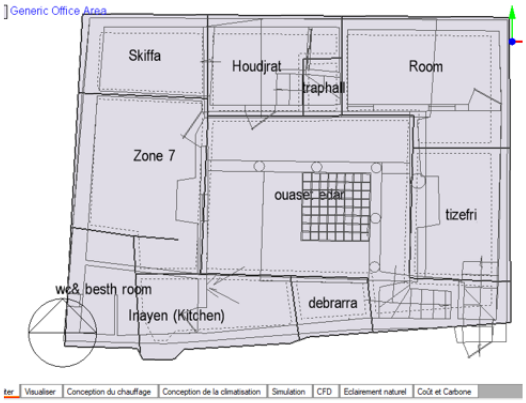


Figure 3.6: Under Floor Thermal Zone.

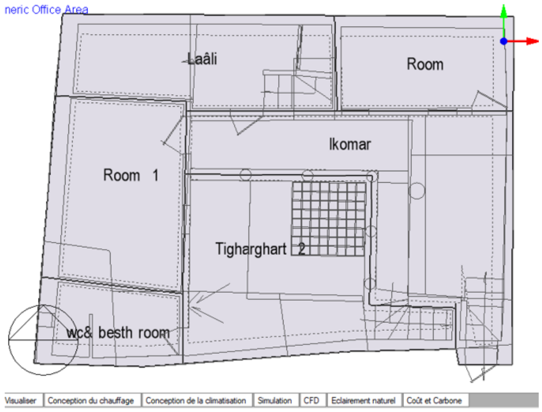


Figure 3.7: First Floor Thermal Zone.

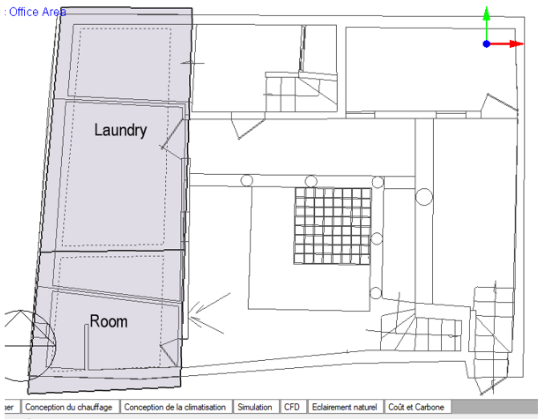


Figure 3.8: Roof Terrace Zone.

Each zone was assigned a specific occupancy profile, internal loads, and boundary conditions based on its function and construction. This zoning strategy allows for a more accurate evaluation of energy flows, especially between occupied and unoccupied spaces or between ventilated and enclosed zones.

After the 3D model of the building was completed, several simulation inputs were configured using the available modules in DesignBuilder. Each tab defines specific

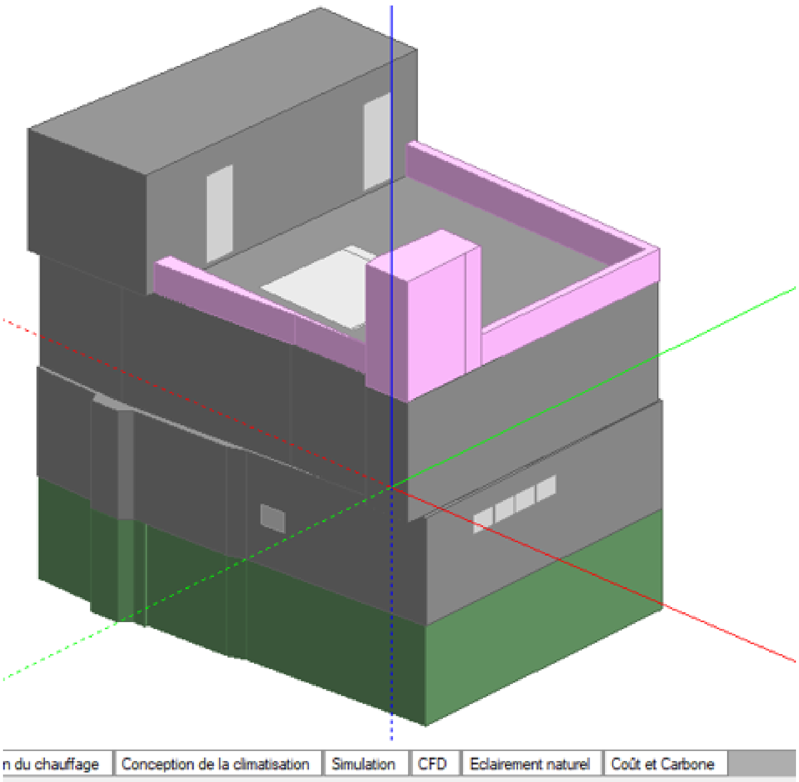


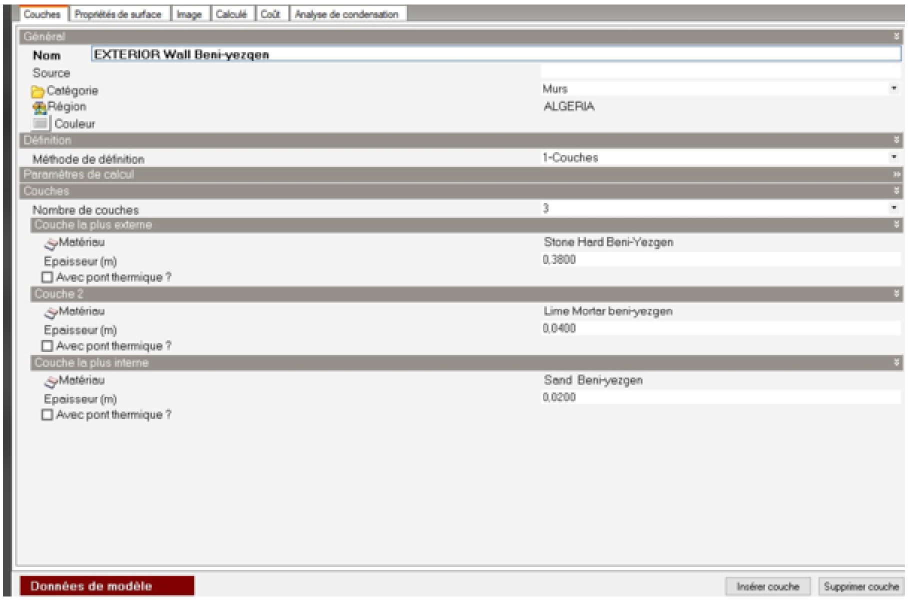
Figure 3.9: Final 3D Thermal Model.

characteristics that directly affect the accuracy and realism of the thermal simulation. To begin the simulation setup, we first defined the construction materials for each element of the building.

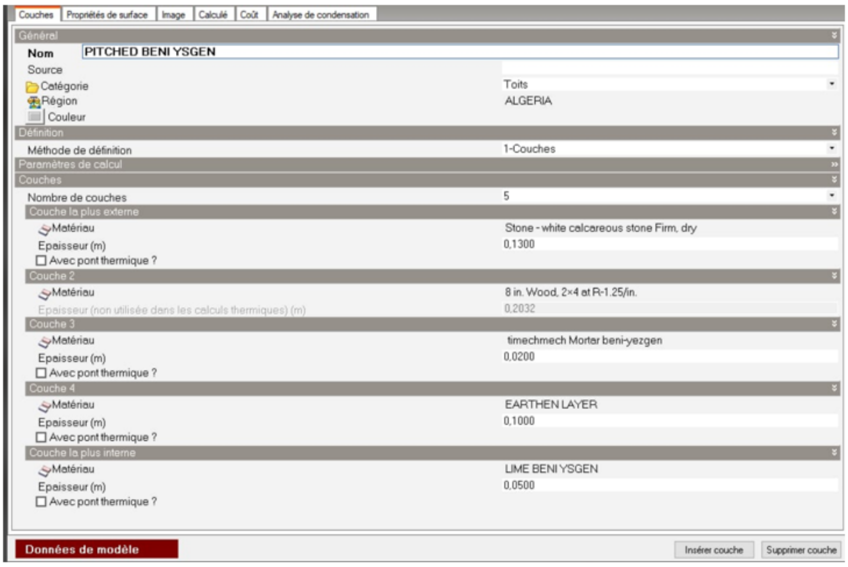
Construction Tab

This tab was used to assign the correct construction materials to the different elements of the building envelope: walls, floors, roofs, and internal partitions. The materials were chosen based on the properties listed in Chapter 2 (e.g., stone, earth, lime plaster, wood). Each surface in the model was assigned:

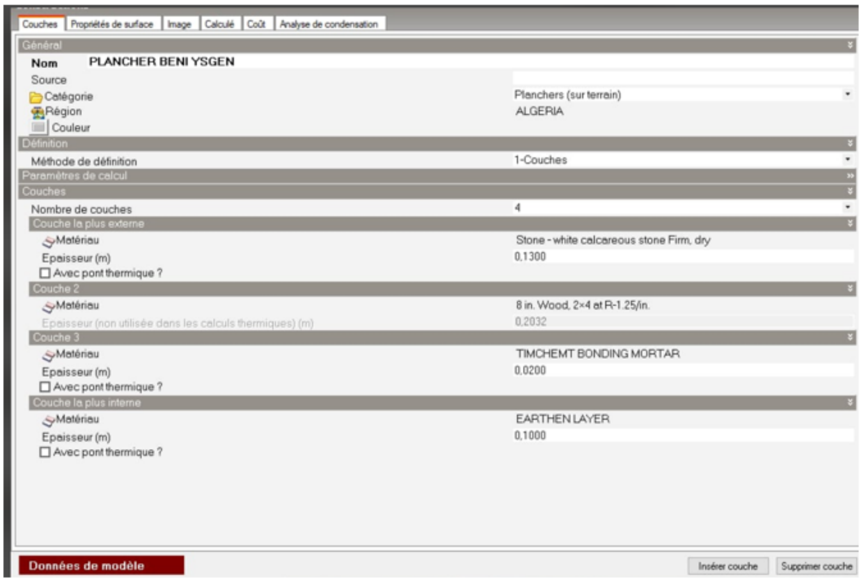
- External walls:



- Roof: Flat, earth-covered slab with high thermal inertia,



- Floors: Contact with ground (with assumed ground thermal resistance),



- Internal partitions

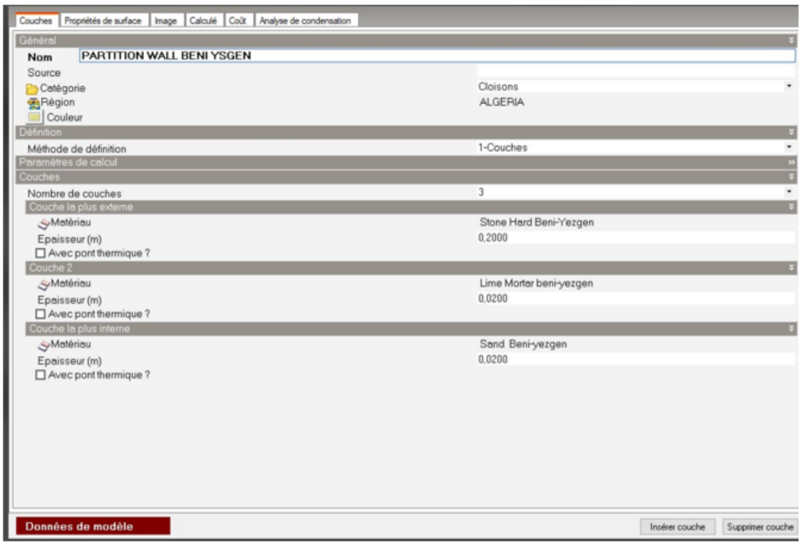
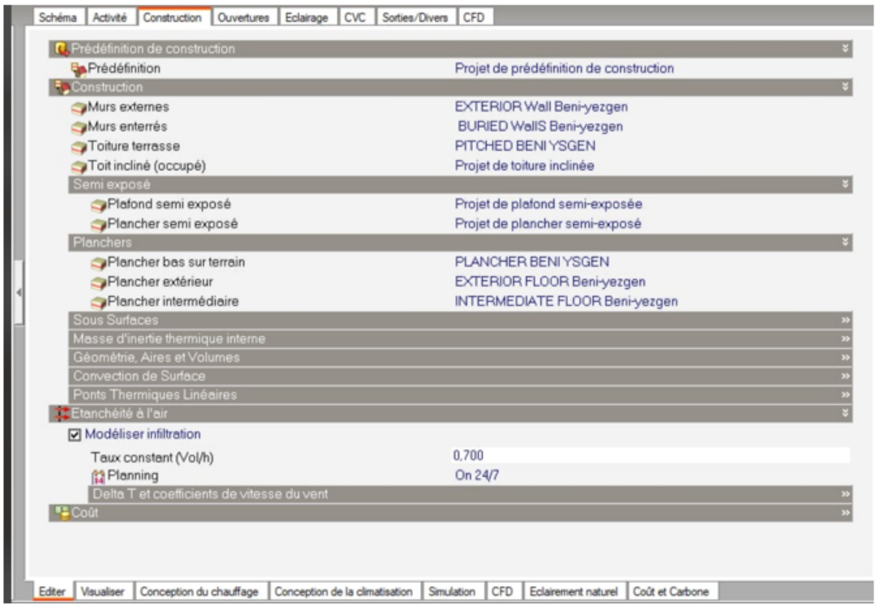


Figure 3.10: : Construction material assignment interface in DesignBuilder.



Once the materials were assigned, we moved on to defining the openings, a crucial aspect for modeling solar gains and natural ventilation.

Openings Tab

In this tab, all windows, doors, and natural ventilation features were defined. Each opening includes:

- Type: Window or door (with orientation),
- Size: Based on AutoCAD plan dimensions,
- Glazing properties: Single or double glazing, solar gain coefficient (if available),
- Shading elements: Such as overhangs or traditional devices like chebek or small roof projections.

The goal was to simulate solar gain and air exchange realistically through these openings (Figure 3.11). After configuring the openings, the next step involved defining occupancy profiles and internal loads, which directly influence thermal performance.

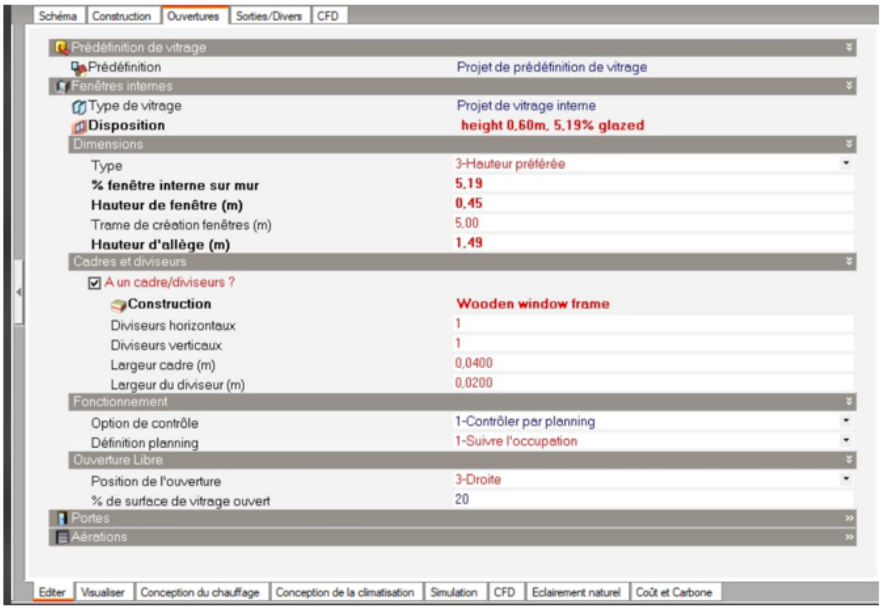


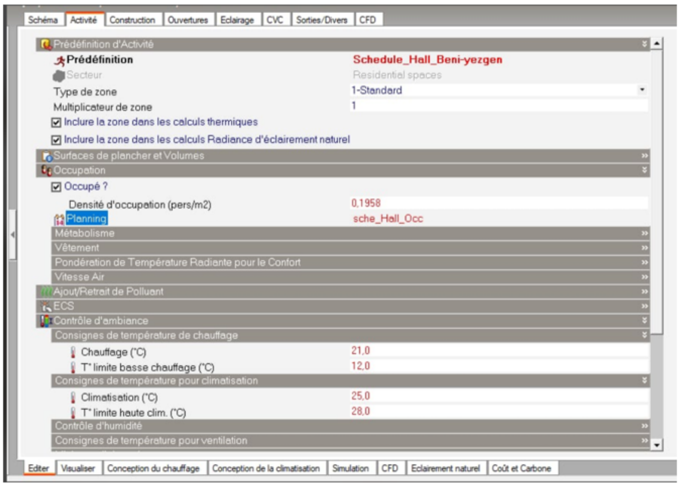
Figure 3.11: Window and opening configuration in the "Opening" tab.

Activity Tab

This section defines the thermal loads and usage patterns for each zone, including:

- Occupancy: Number of people, their presence schedule,
- Internal gains: Equipment, appliances, and lighting,
- Ventilation and infiltration profiles,
- Comfort setpoints: Targeted temperature ranges (if applicable).

For this project, each zone (e.g., Tizefri, kitchen, bedrooms) was assigned a typical residential activity profile, simulating occupancy mostly during the evening and night (Figure 3..



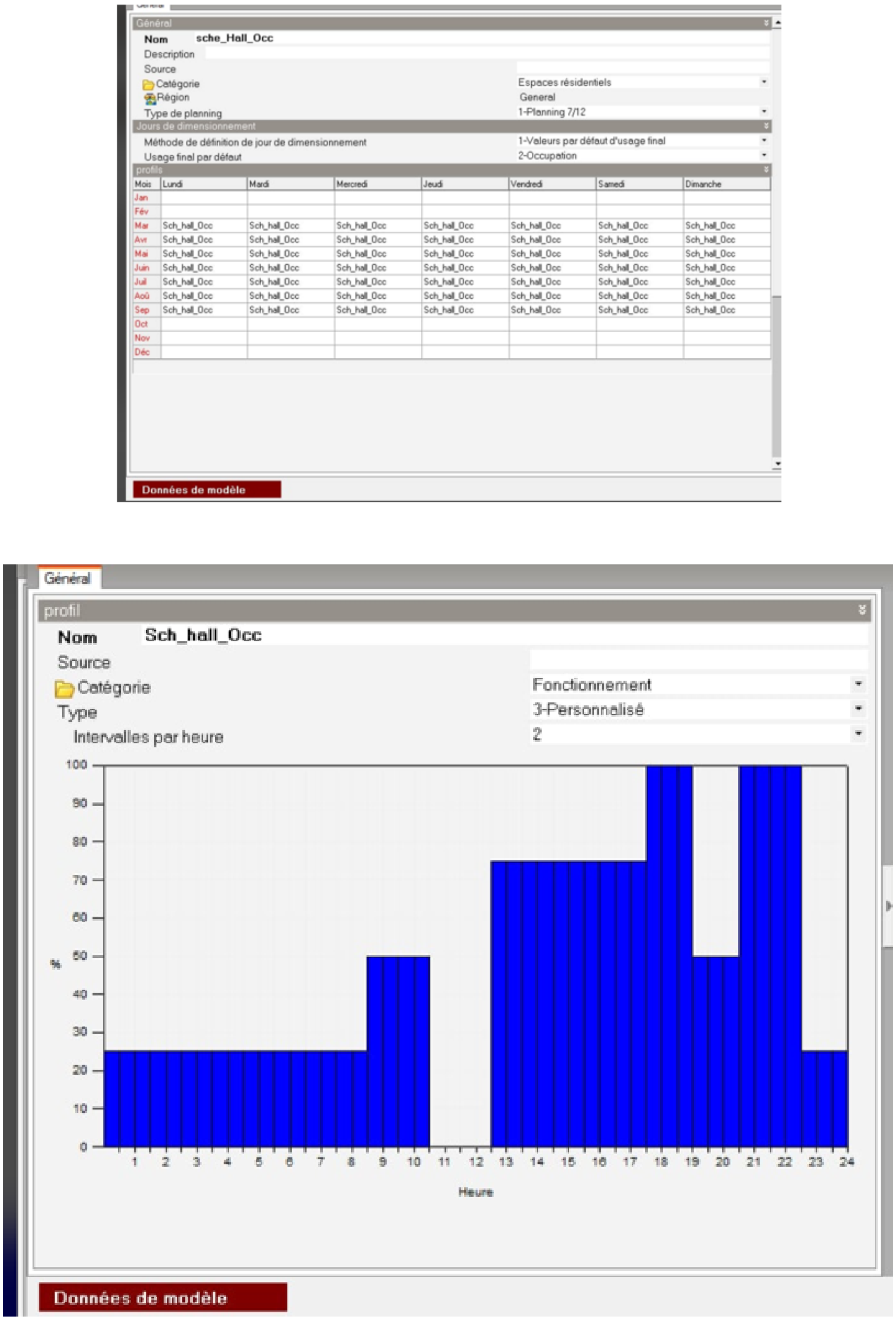


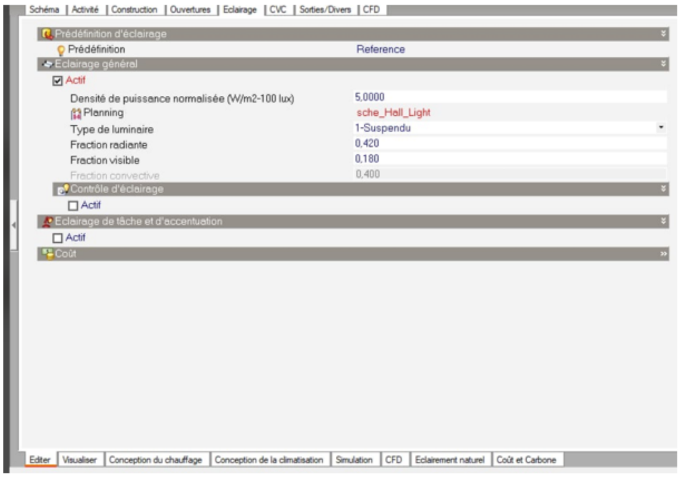
Figure 3.12: Internal gains and occupancy schedules defined in the “Activity” tab.

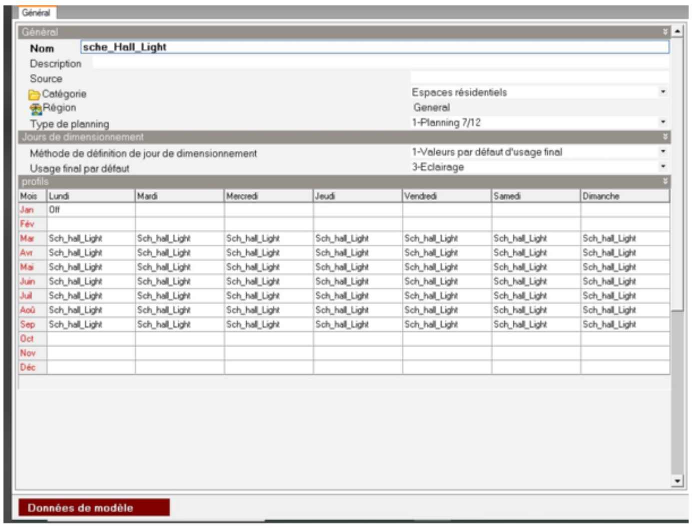
Finally, the last step was the definition of lighting parameters, taking into account both natural light and artificial lighting.

Lighting Tab

The lighting configuration determines the electric lighting load and the use of natural day lighting. Design Builder estimates daylight availability based on window size, room orientation, and reflectivity. In traditional Mozabite homes, natural lighting is limited due to small windows and thick walls. This was reflected in:

- Low daylight factors,
- Limited use of artificial lighting during the day,
- Basic lighting gains modeled per zone (W/m^2).





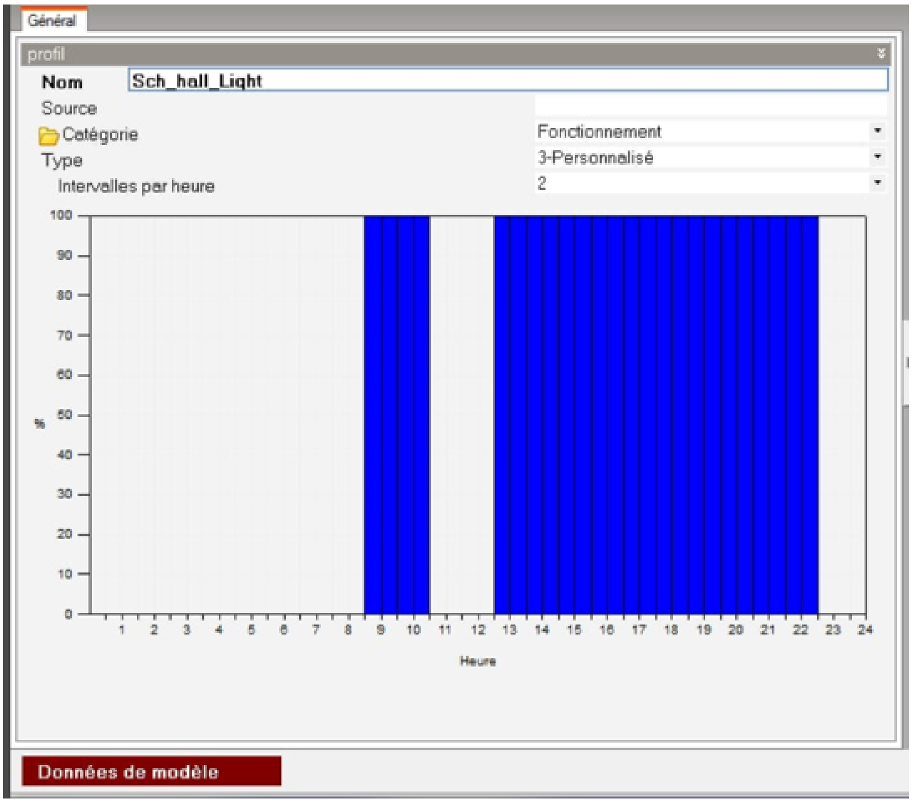


Figure 3.13: Lighting inputs and day lighting settings in the "Lighting" tab .

Thanks to all these configurations, the thermal simulation could be closely adjusted to reflect the actual usage conditions and the architectural specificities of the building.

3.6 Conclusion

This chapter presented the modeling and simulation setup of a traditional Mozabite house located in Ghardaïa, with a particular focus on integrating a phase change material (PCMs) to improve thermal performance. The process began with the architectural design using Auto CAD, followed by 3D modeling and thermal zoning in Design Builder. Various parameters were defined, including construction elements, activity types, internal loads, openings, and natural lighting strategies, in order to reproduce the building's behavior as accurately as possible. Particular attention was given to the environmental context and vernacular design features of the region, such as compact form and passive ventilation. Additionally, different configurations were tested — both with and without PCMs — to enable a comparative thermal analysis. This comprehensive setup provides a reliable basis for the next chapter, which will present and discuss the simulation results and their implications on comfort and energy efficiency.

Chapter 4

Simulation and Results

4.1 Introduction

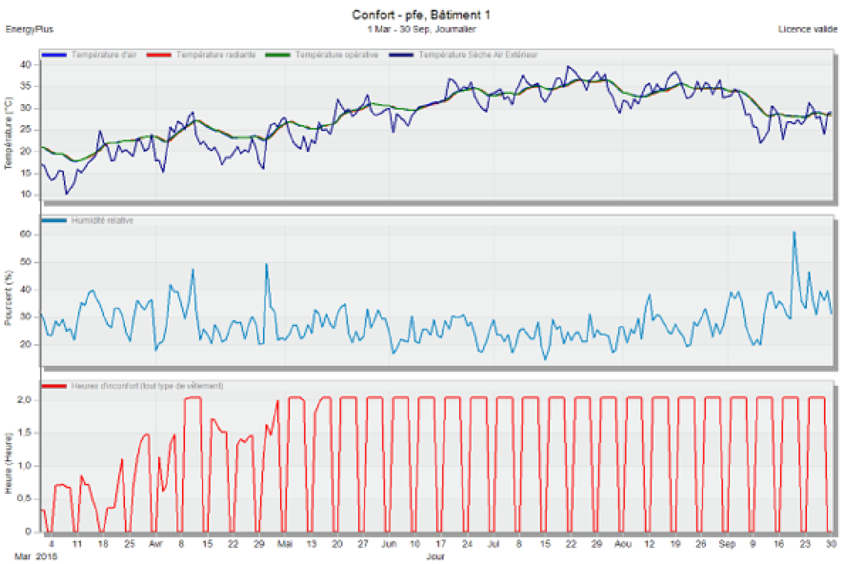
This chapter presents the results obtained from the thermal simulations carried out on a traditional Mozabite house, both with and without the integration of Phase Change Materials (PCMs). The purpose of this analysis is to assess the impact of PCMs on indoor thermal comfort, temperature stability, and energy performance under arid climatic conditions typical of southern Algeria.

Two scenarios were modeled using the DesignBuilder software:

- The first without PCMs, representing the original state of the traditional building.
- The second with PCMs integrated into key envelope elements, aiming to enhance thermal storage.

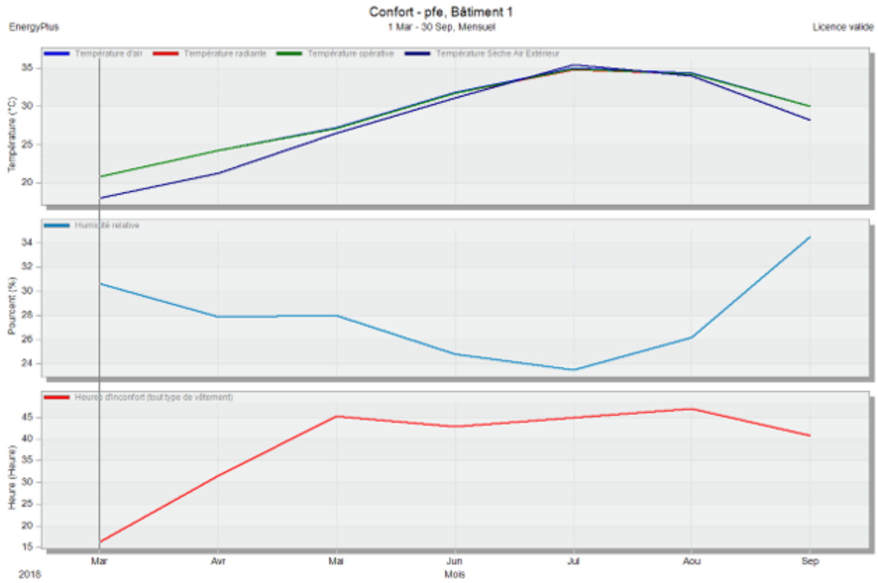
Through a series of graphs and indicators, including indoor air temperature, CO_2 emissions, and thermal comfort levels, this chapter compares and discusses the effectiveness of PCMs as a passive thermal strategy. The results are interpreted in light of architectural context, climatic constraints, and existing scientific literature, in order to validate the proposed approach and draw meaningful conclusions for sustainable building design in hot regions.

4.2 1st Simulation Without PCMs



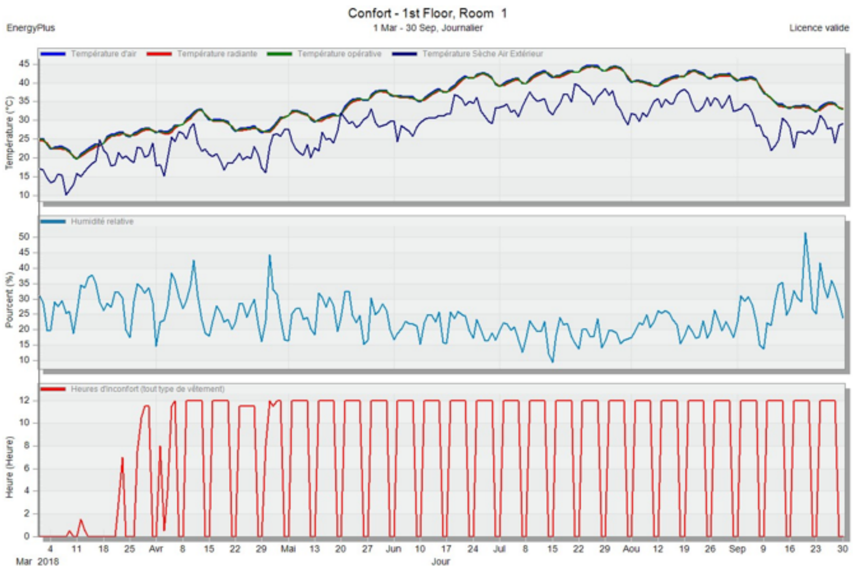
- The operative and dry bulb indoor temperatures gradually rise from around 20°C in March to 30–33°C in August, indicating high heat accumulation.
- Relative humidity remains low, between 20% and 30%, which intensifies the perceived heat.
- Hours of discomfort peak in summer, with almost 2 hours per day of thermal stress—critical in a Saharan climate.

This graph displays the percentage of time the indoor environment remains within the comfort range. The comfort rate is significantly low, suggesting that the interior spaces experience extended periods of overheating. This confirms the inability of the building to passively maintain thermal comfort without PCMs, especially during peak summer periods.



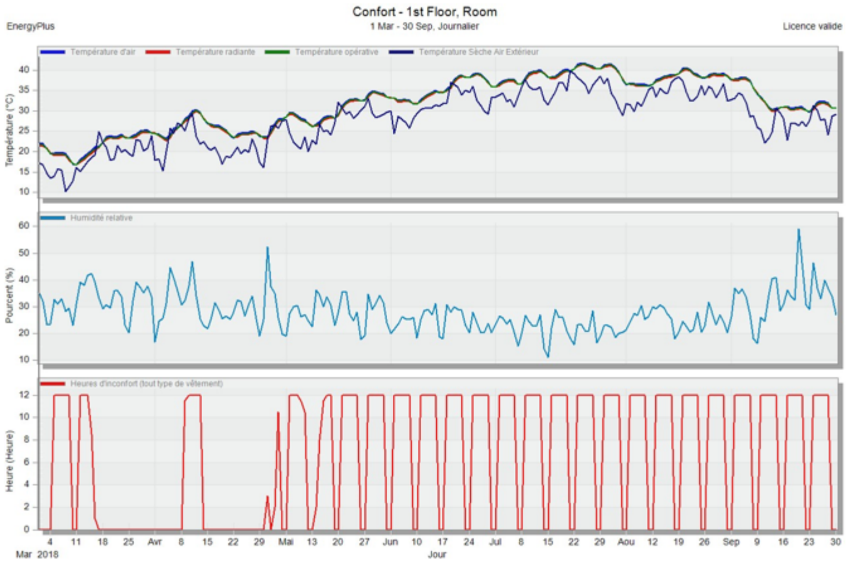
- Monthly temperatures increase clearly until August (≈33°C), then slightly decrease in September.
- Relative humidity drops from March to August (≈18%), before rising again—amplifying heat stress.
- Discomfort hours exceed 40 hours/month in May–August, showing poor passive performance without PCMs.

The ground floor experiences strong temperature variations, with clear peaks exceeding comfort thresholds during the afternoon. The lack of buffering leads to rapid indoor heating, making spaces uncomfortable despite the presence of thick traditional walls.



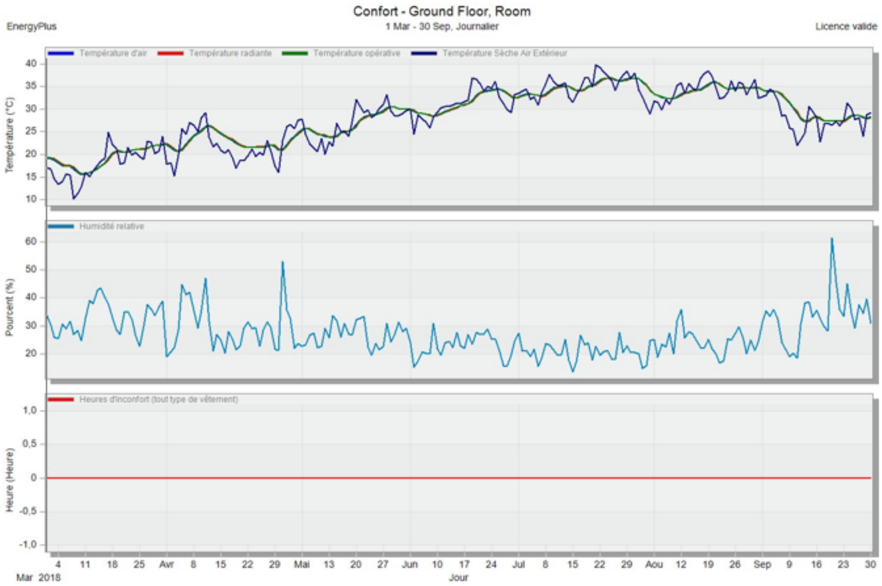
- The temperature profile on the first floor shows consistent overheating, with peak values often exceeding 32°C.
- This level, being more exposed to direct sunlight, demonstrates the limits of passive materials without PCMs in buffering heat.
- Discomfort is particularly evident in the afternoon hours, when heat gain is at its maximum.

The first floor shows even more pronounced overheating, due to its greater exposure to solar radiation. The absence of insulation and PCMs results in poor thermal regulation and elevated indoor discomfort, especially during midday hours.



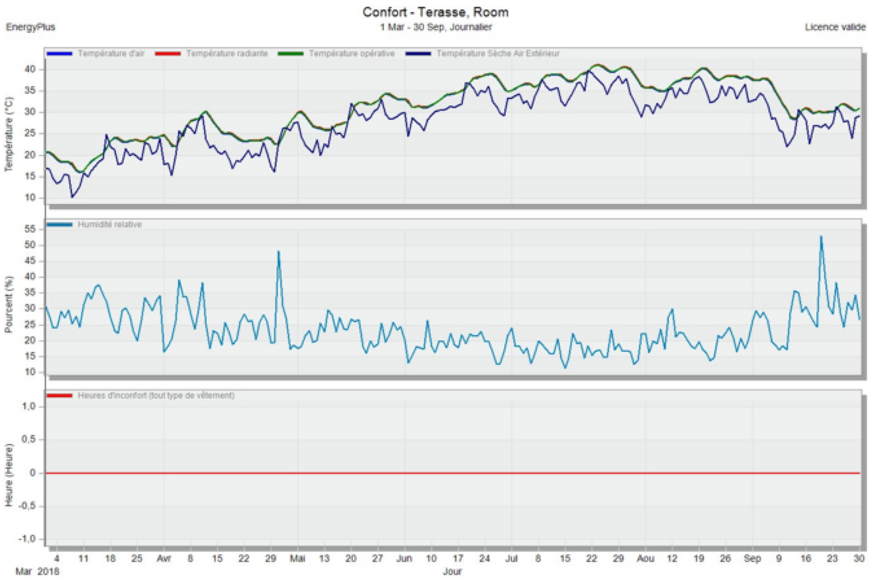
- The roof zone experiences the highest indoor temperatures among all levels, often exceeding 34°C.
- The lack of insulation or PCMs on the roof surface results in rapid indoor heat gain.
- This highlights the importance of addressing roof performance in hot-arid climates.

The roof level, being the most exposed surface, shows the highest temperature fluctuations. Heat is absorbed directly through the roof and transferred rapidly inside, causing thermal spikes. Without PCMs, the roof acts as a major contributor to indoor overheating.



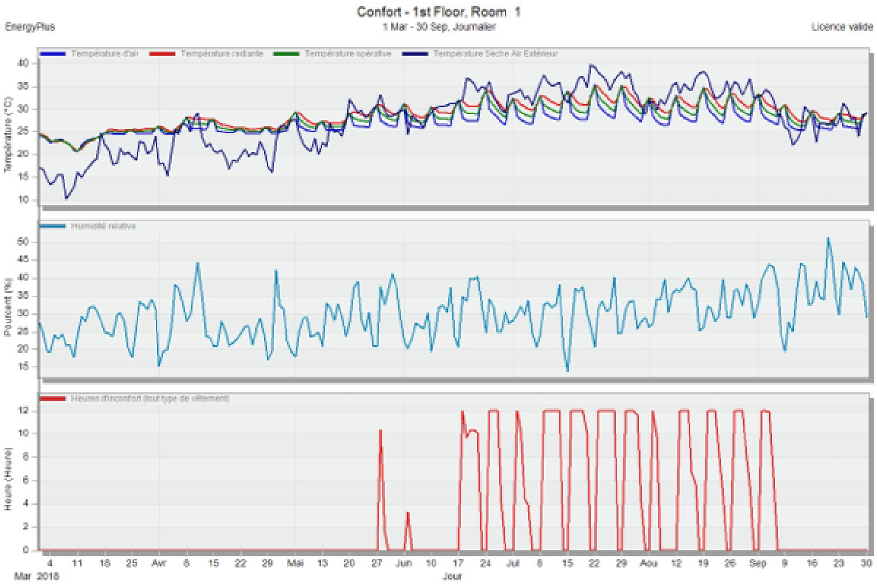
- Temperatures in the underground zone remain more stable and significantly lower than upper levels.
- This confirms the natural buffering capacity of earth-covered spaces, even without PCMs.
- These areas are the most thermally comfortable in the traditional Mozabite home.

The underground level shows more stable temperatures, due to the insulating properties of the surrounding earth. This confirms its role as a thermal buffer zone, but also highlights that without PCMs, only this level maintains some form of thermal stability.



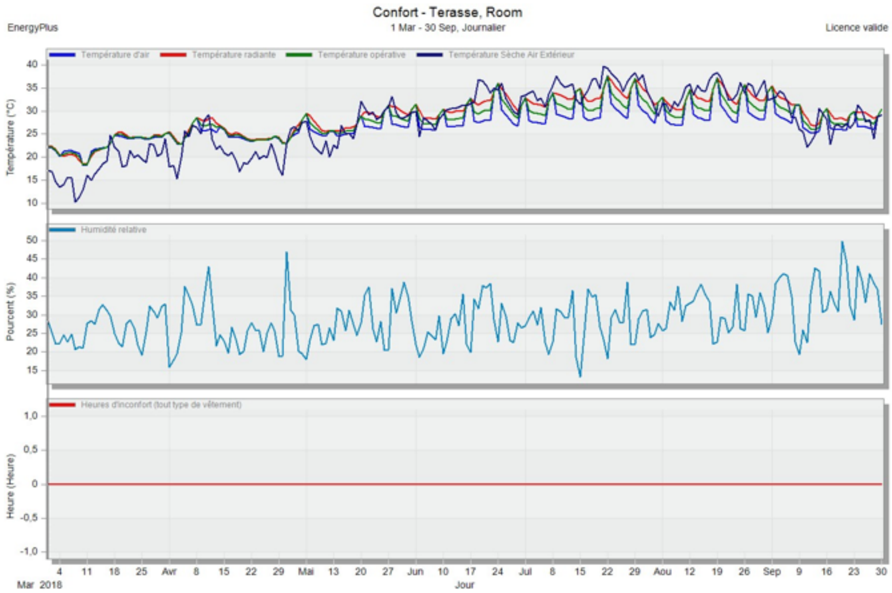
- Comparing all zones over a 24-hour cycle reveals a strong contrast in thermal behavior.
- Daytime heat peaks and nighttime cooling are sharply defined in upper zones, while the underground remains consistent.
- PCMs could help to harmonize this imbalance by reducing temperature extremes.

This comparative graph shows the performance of different zones over a 24-hour cycle. Significant temperature drops at night and peaks during the day are observed. The sharp contrast reflects the lack of thermal inertia and emphasizes the building's dependence on external conditions.



- This figure summarizes the highest temperatures reached in each zone.
- The roof and first floor are clearly the hottest, with values exceeding thermal comfort limits.
- This reinforces the need for a passive intervention to reduce peak indoor temperatures.

This figure consolidates the maximum temperatures reached in each zone. The roof and first floor show the highest values, further confirming the poor passive performance of upper levels. The temperature frequently exceeds 32–34°C, which is well beyond comfort limits.



- Comfort analysis shows that only the underground zone occasionally meets acceptable conditions.
- All other spaces remain thermally uncomfortable for a significant part of the simulation period.
- This underscores the limitations of the current setup and the potential benefit of integrating PCMs.

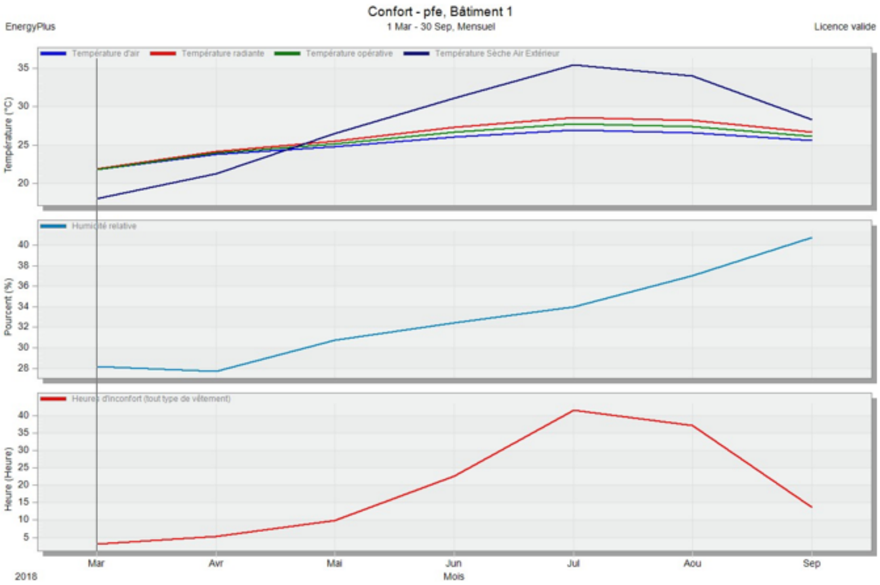
This final graph provides a comfort breakdown per zone. Only the underground zone occasionally meets comfort standards, while all other areas show low comfort performance. This reinforces the conclusion that without PCMs, passive design alone is not sufficient to ensure occupant comfort.

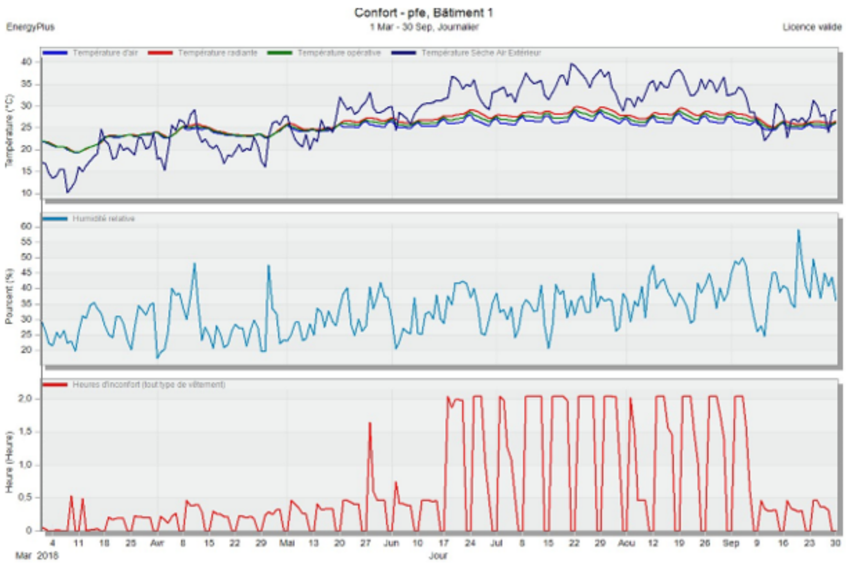
4.3 2nd Simulation With PCMs

- The comfort percentage increases substantially, indicating that indoor temperatures are better stabilized.
- PCMs absorbs thermal energy during peak hours and releases it at night, reducing overheating and discomfort.
- This results in a more comfortable indoor environment, particularly during the harsh summer months.

This graph demonstrates a clear improvement in thermal comfort, with a higher percentage of time within acceptable comfort levels. The PCMs stabilizes indoor temperatures by absorbing excess heat during peak hours and releasing it during cooler periods, minimizing fluctuations.

- Compared to the non-PCMs scenario, the temperature curve is smoother, with lower daily peaks and less variation.

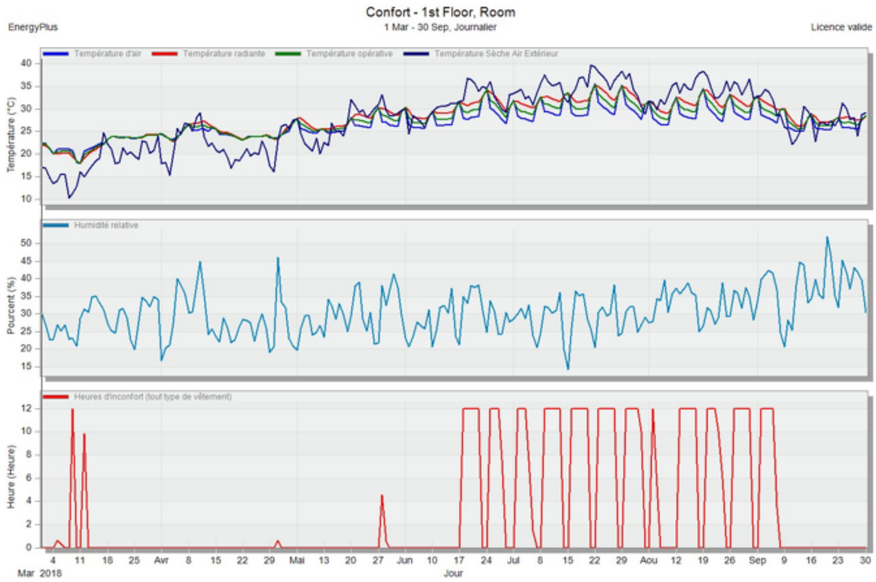




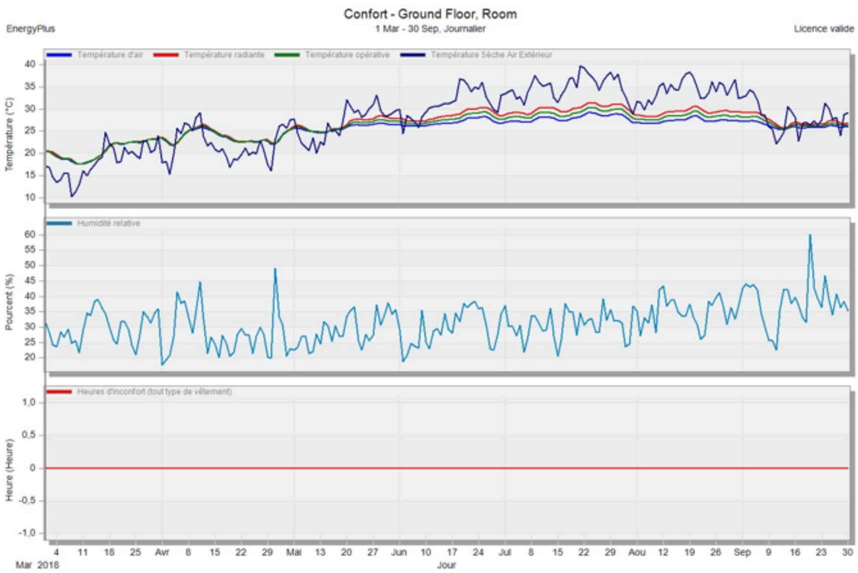
- The maximum temperature drops by about 2–3°C, showing the thermal buffering effect of PCMs.
- This improvement enhances the thermal comfort of the most exposed floor level.

The temperature curve shows a flattening effect, with peak temperatures reduced and night-time values more stable. This demonstrates PCMs effectiveness in smoothing out daily thermal variations, especially in upper zones exposed to direct sunlight.

- The roof zone, which previously experienced the highest overheating, now shows markedly lower indoor temperatures.
- This confirms PCMs capacity to mitigate solar heat gains at roof level, which is often the most critical point of heat transfer.
- It helps maintain acceptable temperature levels even during periods of intense radiation.



Compared to the simulation without PCMs, the roof level shows lower maximum temperatures. The PCMs layer significantly improves the roof's thermal performance, preventing sharp heat transfer into interior spaces and enhancing comfort.



- The temperature variation between zones becomes much more consistent and aligned.
- PCMs reduces the thermal gap between zones like the roof, first floor, and ground floor, leading to a more uniform thermal environment.
- This confirms the effectiveness of PCMs as a passive solution for achieving overall thermal balance in the building.

This figure highlights the improved thermal behavior across all zones when PCMs is applied. Temperature ranges are more moderate and closer to the comfort zone, especially during critical hours. This confirms that PCMs contributes to uniform indoor conditions, reducing the thermal gap between different levels of the house.

CONCLUSION

This work has presented a comparative analysis between two thermal simulation scenarios applied to a traditional Mozabite house in Ghardaïa: one without Phase Change Materials (PCMs), and one integrating PCMs into the building envelope.

The results revealed that, without PCMs, the building suffers from:

- Frequent overheating, especially in upper floors and roof zones.
- Low comfort levels during the hottest periods of the year.
- High CO_2 emissions, linked to greater cooling energy needs.

By contrast, the integration of PCMs significantly improved the building's performance:

- Indoor temperature peaks were reduced by 2 to 3°C.
- Thermal conditions became more stable and comfortable across zones.
- CO_2 emissions decreased, indicating improved passive energy efficiency.

These findings align with existing literature and confirm the potential of PCMs as a viable passive design strategy, particularly for hot and arid climates. Moreover, this study demonstrates that combining vernacular architecture with modern thermal solutions such as PCMs can lead to sustainable, low-energy housing models that respect both tradition and climate constraints.

The work conducted in this project emphasizes the relevance of simulation tools such as Design Builder for evaluating and optimizing the performance of traditional buildings, and it opens the door to further research and application of advanced materials in heritage architecture.

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